A Stabilized Frequency Reference Transfer System for the Square Kilometre Array

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Abstract

The quest to peer ever deeper into distant regions of the universe and understand its origins and evolution requires the construction of ever larger telescopes such as the Square Kilometre Array (SKA). The SKA must be phase-synchronized by providing frequency reference signals that are phase-coherent over the observing integration times to the array’s antenna sites. This will maximize the fidelity and dynamic range of the astronomical data obtained by the telescope, and will be achieved by transmitting frequency reference signals that are synthesized from a central atomic frequency standard to the widely dispersed antenna sites via fiber-optic links. Mechanical disturbances to the links, such as vibrations and thermal effects, impose unwanted phase noise on to the signals that are received at the antenna sites. Due to the long transmission distances involved, the magnitude of the phase noise acquired by the reference signals during transmission is sufficient to degrade the phase coherence between antennas to the extent that it impairs the performance of the telescope.

This thesis describes the development and testing of actively stabilized frequency reference transfer systems for the two SKA telescope variants: a 160 MHz radio frequency transfer system optimized to the requirements of SKA1-LOW; and an 8 GHz microwave transfer system optimized to the requirements of SKA1-MID. Both systems sense the link phase perturbations in the optical domain, and achieve stabilization of the transmitted signals using acousto-optic modulators (AOMs). The systems have a low power consumption, and the use of AOMs means that they are compact and robust, which are important considerations owing to the large number of units required to supply the many SKA antenna sites. Field tests verified the performance of the transfer systems on existing radio telescope systems and on the aerial fiber links proposed for SKA1-MID. The frequency transfer systems achieve coherence losses two to three orders of magnitude better than required over the
distances involved in SKA1. The applications of these systems to other scientific experiments and future telescopes are also discussed.
To my brother Andrew.
Declaration of Contribution to Published Work

This thesis is presented as a series of papers which have been published in, or submitted to, peer-reviewed journals. The bibliographic details of published and submitted works appearing in this thesis are given below.

The author’s proportional input for each work is stated in terms of contribution to experimental work and manuscript preparation.

Refereed Journal Articles

1. Gozzard, D.R., Schediwy, S.W., Grainge, K., “Simultaneous Transfer of Stabilized Optical and Microwave Frequencies Over Fiber”, Accepted to IEEE Photonics Technology Letters, pre-print: DOI 10.1109/LPT.2017.2776243
   Section(s): Chapter 3
   Contributions: Experimental - 50%, Manuscript preparation - 80%

   Section(s): Chapter 4
   Contributions: Experimental - 50%, Manuscript preparation - 60%

   Section(s): Chapter 5
   Contributions: Experimental - 80%, Manuscript preparation - 10%

**Section(s):** Chapter 6  
**Contributions:** Experimental - 50%, Manuscript preparation - 90%


**Section(s):** Chapter 7  
**Contributions:** Experimental - 70%, Manuscript preparation - 90%


**Section(s):** Chapter 8  
**Contributions:** Experimental - 70%, Manuscript preparation - 80%

The proportional contributions of the author have been truthfully stated, and permission from each author has been sought to include the published material in this thesis.

Candidate: 

Primary Supervisor: 

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<tr>
<td>ACES</td>
<td>Atomic Clock Ensemble in Space</td>
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<td>ADC</td>
<td>Analogue-to-Digital Converter</td>
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<td>ALMA</td>
<td>Atacama Large Millimetre Array</td>
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<tr>
<td>ASIC</td>
<td>Application-Specific Integrated Circuit</td>
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<tr>
<td>ASKAP</td>
<td>Australian Square Kilometre Array Pathfinder</td>
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<tr>
<td>ATCA</td>
<td>Australia Telescope Compact Array</td>
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<tr>
<td>CPF</td>
<td>Central Processing Facility</td>
</tr>
<tr>
<td>CS-SSB</td>
<td>Carrier-Suppressed Single Sideband</td>
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<tr>
<td>CW</td>
<td>Continuous-Wave</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
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<td>DSN</td>
<td>Deep Space Network</td>
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<td>EDFA</td>
<td>Erbium-Doped Fiber Amplifier</td>
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<td>EMRP</td>
<td>European Metrology Research Program</td>
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<tr>
<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>FBA</td>
<td>Fiber Brillouin Amplifier</td>
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<td>FFT</td>
<td>Fast Fourier Transform</td>
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<td>FM</td>
<td>Faraday Mirror</td>
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<td>Abbreviation</td>
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<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>GVD</td>
<td>Group-Velocity Dispersion</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<td>ITU</td>
<td>International Telecommunications Union</td>
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<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>LNE</td>
<td>Laboratoire Nazionali del Gran Sasso</td>
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<tr>
<td>LO</td>
<td>Local Oscillator</td>
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<tr>
<td>MW</td>
<td>Microwave</td>
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<td>MZ</td>
<td>Mach-Zehnder</td>
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<td>MZI</td>
<td>Mach-Zehnder Interferometer</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>NEAT-FT</td>
<td>Network for European Accurate Time and Frequency Transfer</td>
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<tr>
<td>ngVLA</td>
<td>next-generation Very Large Array</td>
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<tr>
<td>OPGW</td>
<td>Optical Ground Wire</td>
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<tr>
<td>PD</td>
<td>Photo-Detector or Photo-Diode</td>
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<tr>
<td>PLL</td>
<td>Phase-Locked Loop</td>
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<tr>
<td>PM</td>
<td>Polarization-Maintaining</td>
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<td>PMD</td>
<td>Polarization Mode Dispersion</td>
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<td>PPS</td>
<td>Pulse Per Second</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
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<td>RF</td>
<td>Radio-Frequency</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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<td>RPF</td>
<td>Remote Processing Facility</td>
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<td>RTT</td>
<td>Round Trip Time</td>
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<tr>
<td>SBS</td>
<td>Stimulated Brillouin Scattering</td>
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<tr>
<td>SI</td>
<td>Système International (d’unités)</td>
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<tr>
<td>SKA</td>
<td>Square Kilometre Array</td>
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<tr>
<td>SKA1</td>
<td>SKA Phase 1</td>
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<tr>
<td>SKA2</td>
<td>SKA Phase 2</td>
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<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<tr>
<td>SoP</td>
<td>State of Polarization</td>
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<tr>
<td>SOPC</td>
<td>State of Polarization Change</td>
</tr>
<tr>
<td>SYRTE</td>
<td>Systèmes de Référence Temps-Espace</td>
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<td>UWA</td>
<td>University of Western Australia</td>
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<td>VLA</td>
<td>Karl G. Jansky Very Large Array</td>
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<td>VLBI</td>
<td>Very Long Baseline Interferometry</td>
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<td>YIG</td>
<td>Yttrium-Iron-Garnet</td>
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Introduction

Seeing Further

In 1609 Galileo Galilei pointed his newly completed telescope at the night sky. What Galileo discovered shattered established beliefs and tore Earth from its position at the centre of the universe. Astronomers have never looked back. As telescopes grew in size and power, our solar system became just one of billions in a medium-sized spiral galaxy, in a vast and growing universe.

Today, telescopes continue to get bigger, allowing astronomers to peer into the deepest, darkest regions of the universe. The Square Kilometre Array (SKA) telescope is the next step in this journey of discovery. The SKA project is an international initiative involving over 600 engineers and scientists from more than 20 countries to build the world’s largest and most sensitive radio telescope. The SKA will be one of a handful of “cornerstone” observatories spread around the world and across the electromagnetic spectrum that will provide astronomers, astrophysicists, and cosmologists with a transformational view of the universe. Like the telescopes that came before it, the SKA will revolutionize our understanding of the universe.

The work presented in this thesis owes its origins to two of the sciences revolutionized by Galileo: astronomy, and timekeeping. Galileo famously used his heartbeat and music to time balls rolling down an inclined plane during his research into falling
bodies. In 1581, he discovered the nearly isochrone property of pendulums, which lead him to design the first pendulum clock in 1637. Galileo never built his clock, but after Dutch astronomer Christiaan Huygens built a working pendulum clock in the 1650s, improved pendulum clocks reigned supreme in terms of stability and precision well into the 20th century, when they were surpassed by atomic clocks. Today, the transmission of high-precision atomic clock signals plays a crucial part in applications ranging from navigation to tests of fundamental laws of physics.

Galileo pioneered optical telescope development, and in the process discovered craters on the Moon, moons orbiting Jupiter, and the phases of Venus, supporting Copernicus’ idea of a Sun-centred solar system. Since the 1940s, radio telescopes have opened up a previously invisible swathe of the electromagnetic spectrum for astronomers to study. Radio telescope arrays such as the SKA use the transmission of frequency reference signals produced by atomic clocks (typically hydrogen-masers) to synchronize the array and maximize the imaging capability of the telescope. However, the scale of the SKA makes the transmission of frequency references with sufficient stability a significant challenge.

This thesis describes the development and testing of an actively stabilized frequency reference transfer system for the SKA. The design and laboratory testing of radio- and microwave-frequency variants of the system is described, followed by details of “astronomical verification” tests of prototype systems, as well as other field trials undertaken in support of the SKA’s synchronization and timing design work. The potential of these systems developed for the SKA, and the significance of their results, is also discussed in relation to other applications of high-precision time and frequency transmission.
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CHAPTER 1. INTRODUCTION

1.1 Thesis Outline

This thesis is arranged into nine chapters that describe research I conducted at The University of Western Australia between 2014 and 2017. The thesis is presented as a series of papers (Chapters 3–8) which have been published in, or submitted to, peer-reviewed academic journals.

Chapter 1 describes the aims and motivations of this thesis. The chapter gives a brief overview of modern timekeeping and its broader applications before presenting an introduction to the SKA and the necessity for actively stabilized phase synchronization of the telescope. The chapter mentions applications of the present work beyond the SKA, and the relevant technical considerations influencing design choices.

Chapter 2 provides an introduction to many of the key technical concepts relevant to this thesis with an aim to familiarize the reader with important terminology and give a working knowledge of relevant background, theory, experimental techniques, and the state-of-the-art in this field.

Chapter 3 describes the theory and experimental verification of an early stabilized frequency transfer system concept for SKA1-LOW and SKA1-MID. Subsequent field tests exposed an issue with the system not apparent in laboratory testing, resulting in a redesign to overcome the deficiency. The original system is presented because it has potential uses in other frequency transfer applications. It also provided important results for later tests.

Chapter 4 presents the theory and laboratory verification of a stabilized radio frequency (160 MHz) transfer system, redesigned to solve the deficiencies encountered with the system presented in Chapter 3. The stability of the frequency transfer over 166 km of metropolitan fiber network was measured. The potential applications of this system to frequency transfer experiments beyond the SKA are discussed in this chapter.
Chapter 5 presents the theory and laboratory verification of a stabilized microwave frequency (8 GHz) transfer system, redesigned to solve the deficiencies encountered with the system presented in Chapter 3. The stability of the frequency transfer over 166 km of metropolitan fiber network was measured. The chapter also discusses other applications of the system and compares the relative merits of the design to other stabilized microwave frequency transfer systems.

Chapter 6 describes the astronomical verification tests of the stabilized microwave transfer system presented in Chapter 5. The chapter explains how the system was installed at the Australia Telescope Compact Array and the observations that enabled the performance of the system under real-world conditions on an operational telescope to be analyzed.

Chapter 7 describes the results of tests of a radio frequency transfer system based on the design in Chapter 4 over aerial suspended fiber cables at the South African SKA site. The performance of the system over the aerial cables is compared to buried links of similar length, and these results are used to estimate the performance of the microwave transfer system from Chapter 5 over these aerial links.

Chapter 8 presents the characterization of optical frequency transfer over aerial suspended fiber links at the South African SKA site. The dominant sources of noise are shown to be the wind causing oscillation of the cable spans and solar-thermal effects on the cable. The chapter also describes an attempt to stabilize the optical transmission over these links. The implications of these results are discussed with reference to potential future frequency transfer networks.

Chapter 9 summarizes the main achievements of the work presented in this thesis and considers future work on these systems as the SKA heads into its construction phase, as well as applications of the design to other scientific experiments.
Appendix A catalogues the papers presented in this thesis that have been published in scholarly journals.

Appendix B is a copy of an SKA Signal and Data Transport Consortium paper published in *Astronomy Reports*. The paper gives an overview of the Consortium’s design. Work presented in this thesis contributed to the publication. The paper is included to give a complete record of published work arising from the research presented in this thesis.

1.2 History and Motivation

1.2.1 Modern Timekeeping

The pendulum clocks invented by Galileo and realized by Huygens ushered in the era of precision timekeeping. Constant innovation and improvement of pendulum clocks kept them at the forefront of timekeeping accuracy and precision into the 1920s, when they were surpassed by clocks that exploited the piezoelectric properties of crystalline quartz. Despite this, pendulum clocks could still be found in observatories into the 1960s. By 1932, quartz clocks were able to measure variations in the rate of rotation of the Earth over a period of days. Early quartz clocks were physically large and heavy items by virtue of their primitive vacuum tube-based electronics, which limited them to laboratory applications, but by 1969 advances in electronics and manufacturing resulted in the commercialization of the first quartz wristwatch.

The idea of using atomic transitions to measure time, to build a clock based on electromagnetic oscillations rather than mechanical oscillations, was first put forward as early as the 1870s by eminent scientists James Clerk Maxwell and Lord Kelvin. The first atomic clock, an ammonia maser built at the US National Bureau of Standards in 1954 [1], successfully demonstrated the concept, though it was less accurate than contemporary quartz clocks. The first hydrogen maser was developed in 1960 and, though inferior in terms of overall accuracy and precision to caesium-
based atomic clocks, the reliability of hydrogen masers means that they are the most widely used atomic frequency standard.

The first clock based on the transition between the two hyperfine levels of the ground state of the caesium-133 atom was constructed in 1955 by Louis Essen at the UK’s National Physical Laboratory [2]. Within a decade of Essen’s clock, the fractional uncertainty of caesium-standards had improved by two orders of magnitude, leading to the redefinition of the second in 1967. These “microwave” atomic clocks have continued to improve and in recent years have reached fractional uncertainties of $10^{-16}$ [3–5].

After half a century at the pinnacle of timekeeping precision, the dominance of microwave atomic clocks looks set to be usurped in the near future by optical atomic clocks, clocks exploiting transition frequencies in the hundreds of terahertz. The invention of the optical frequency comb technique in the late 1990s greatly accelerated the development of optical atomic clocks by offering a relatively simple process for the measurement, control, and translation of optical frequencies [3, 6]. Optical clocks have already surpassed microwave clocks in terms of stability, with recent improvements allowing optical clocks to achieve fractional uncertainties at the $10^{-18}$ level [5, 7–9]. Figure 1.1 (reproduced from [5] and [10]) shows key milestones in the evolution of microwave (caesium) and optical frequency atomic clocks, and compares the fractional uncertainty performance of current leading microwave and optical clocks. In the next few years, it likely that the second will be redefined in terms of an optical frequency [5,10].

1.2.2 Applications of Precise Frequency Standards and Timekeeping

The ability of atomic clocks to make measurements with uncertainties at the $10^{-16}$ and $10^{-18}$ level is certainly impressive, and this ability has meant that frequency has for a long time been the most accurately measured physical quantity [11]. However, to those who do not work in atomic timekeeping and related fields, the purpose and
importance of such accuracy and precision is often obscure. For this reason, I will elaborate on the uses and applications of atomic clocks and precision timekeeping.

The ability to make accurate and precise measurements is crucial for science to progress our understanding of our universe. Fundamental questions in physics relate to quantities of energy, space, and time — quantities that are directly related to frequency. Beyond scientific research, much of our modern technology relies on the accurate measurement and communication of time.

**Metrology**: The *second* is the most accurately and precisely measured quantity in the International System (SI) of units and is currently defined as “the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom”. Other SI base units, such as the *metre*, and derived units, such as the *coulomb*, are defined or measured in terms of the second. Accurate and precise frequency measurement and the accurate and precise *transmission* of those measurements and their derived
quantities is key to the scientific and legal standards that metrologists and metrology institutes are responsible for.

**Global Navigation Satellite Systems (GNSS):** Arguably, the application of atomic clocks that has the greatest impact outside of scientific research is their use in navigation systems including the American *GPS*, the Russian *GLONASS*, the European *Galileo*, and the Chinese *BeiDou* systems. In addition to the safety and reliability that accurate navigation brings to air and sea travel, a large fraction of the world’s population carry a compatible GNSS receiving device on a daily basis. Each GNSS satellite carries an accurate atomic clock, and transmitter equipment to transmit the time signals from the clock to the ground. GNSS receivers, receiving signals from at least four satellites, use the time lag due to the transmission distance to calculate their spatial and temporal coordinates relative to the satellites.

**Network Synchronization:** The transmission and accurate calibration of time signals across a network is important for both legal and practical reasons. Regulatory monitoring and high-frequency trading require accurate and legally traceable time signals. More practically, accurate network synchronization for the mobile phone system, distributed computing, and the electricity grid is important for maximizing the utility and efficiency of these systems. Network synchronization also extends to scientific facilities such as accelerator facilities, where accurate synchronization of components that can be kilometres apart is critical to the effective running of experiments.

**General Relativity and Geodesy:** The predicted time dilation effects related to differences in local gravitational fields have been verified to ever increasing precision using atomic clocks. Indeed, the continued efficacy of GNSS is a daily confirmation of the accuracy of the predictions of General Relativity. With clocks that are able to achieve fractional uncertainties on the $10^{-18}$ level, altitude differences
on the order of centimetres can now be measured between clocks \[3,12\]. However, this introduces problems for experiments that require two separated clocks to be compared, because the altitude of the clocks above the Earth’s geoid (the Earth’s gravitational equipotential surface) must be known with sufficient accuracy to account for systematic uncertainty in the clocks’ measurements. Conversely, optical atomic clocks could be used to map the Earth’s geoid to the required accuracy to account for these systematic effects. One such experiment is the ESA’s upcoming Atomic Clock Ensemble in Space (ACES) mission, which will use comparisons between atomic clocks at a number of ground stations and clocks aboard the International Space Station to make high-precision measurements of Earth’s geoid and gravitational redshift \[13,14\]. Measurements such as these, and improvements in transportable atomic clocks, could lead to the use of atomic clocks for surveying purposes.

**Fundamental Physics:** The precision of optical frequency clocks, translated to measurements of other physical quantities, can be used to make high-precision tests of fundamental physical phenomena. One such test that has received a lot of attention in recent years is the possible time variation of fundamental constants such as the fine structure constant, \( \alpha \). Variations in \( \alpha \) could be detected by comparing the frequency of two atomic clocks of sufficient stability whose atomic transitions exhibit differing sensitivities to changes in \( \alpha \) \[11\]. A successful detection of variations in fundamental constants would open a path to the development of new unified theories.

**Radio Astronomy:** The resolution, \( \theta \), of any telescope is limited by its diameter, \( D \). This is particularly limiting for radio telescopes because resolution is proportional to the wavelength, \( \lambda \), of the received radiation (as shown in Equation 1.1 \[15\]). Radio telescopes, which observe wavelengths several orders of magnitude larger than optical telescopes, have correspondingly poorer resolution.
However, the resolution of radio telescopes can be greatly enhanced by phase-coherently combining signals from multiple antennas, thereby improving the resolution of the telescope by simulating a telescope with a diameter equal to the distance between the connected antennas. This technique is called interferometry. When taken to the extreme, with antennas spaced hundreds or thousands of kilometres apart, the technique is called Very Long Baseline Interferometry (VLBI).

Radio interferometer arrays must maintain adequate phase synchronism across the array in order to preserve the coherence of the astronomical signals being fed to the correlator used to process the signals. The greater the coherent integration time or coherence time of the array at a particular observing frequency, the greater the fidelity and dynamic range of the data obtained [16–19]. To achieve this, the antennas making up the interferometer array must be phase-synchronized by referencing them to frequency and time reference signals from a master oscillator or timescale [17, 19]. By reproducing signals at each antenna that are derived from high-precision frequency standards, it is possible to preserve the coherence of the signals for time intervals long enough to measure interference fringes. The received signals are converted to an intermediate frequency low enough to be recorded directly. In VLBI, which generally uses a small number of antennas separated by long distances, each observatory contributing to the VLBI array will have its own atomic clock (often a hydrogen maser), while localized arrays that have antennas no more than a few kilometres apart will use a single centralized clock and transmit the reference signals the short distance to each antenna.

The SKA, comprising hundreds of antennas separated by distances on the order of 100 km, straddles the engineering gap between VLBI and localized interferometers.
CHAPTER 1. INTRODUCTION

1.2.3 The Square Kilometre Array

The SKA is an international project to build a next generation radio telescope with unprecedented sensitivity to study fundamental questions about the nature and evolution of the universe including, how the first stars and galaxies formed after the Big Bang; how dark energy is accelerating the expansion of the universe; the role of magnetism in the evolution of galaxies; tests of General Relativity and strong gravity; and the search for life beyond Earth [20]. The SKA was conceived as an instrument that would continue the trend of exponential increase in sensitivity of radio telescopes, shown in Figure 1.2 [21,22].

When completed, the SKA will comprise thousands of antennas separated by up to 3000 km, with a combined effective collecting area of approximately one square kilometre. The construction of the SKA has been split into two phases: phase-1 (SKA1), scheduled to begin construction in 2018, will account for approximately the first 10% of the SKA’s capacity, while in future phase-2 (SKA2) will expand the SKA to its full receiving capabilities [23]. The SKA will comprise two separate telescopes,
1.2. HISTORY AND MOTIVATION

Figure 1.3: Artist’s impression of SKA1-LOW and SKA1-MID. (Image credit: SKA Organization)

A low-frequency aperture array constructed in Western Australia (SKA-LOW) and a mid-frequency dish array constructed in South Africa (SKA-MID). The low- and mid-frequency telescopes to be constructed during SKA1 are designated SKA1-LOW and SKA1-MID respectively. SKA1-LOW will comprise approximately 100,000 log-dipole antennas grouped around a core station and 36 remote processing facilities (RPFs), while SKA1-MID will be made up of 197 dish-antennas (incorporating the 64 dishes of the MeerKAT precursor telescope [20, 24]). An artist’s impression of the SKA1-LOW and SKA1-MID telescopes is shown in Figure 1.3.

As with previous interferometers, the SKA will need to be synchronized using phase-coherent frequency signals distributed to each of the antennas in the array. A frequency reference synthesized from a hydrogen maser ensemble in each observatory’s Central Processing Facility (CPF) will be transmitted via optical fiber to the core station and each of the 36 RPFs of SKA1-LOW, and each of the 197 dishes of SKA1-MID. (Absolute time dissemination will be handled separately by the ethernet-based White Rabbit precision time protocol [20, 25].) The frequency references received at the RPFs and dishes will be used to synthesize local oscillator (LO) signals, digitizer clocks for analog-to-digital conversion of the astronomical
CHAPTER 1. INTRODUCTION

signals, and low frequency square waves or Walsh functions for phase switches and noise diodes.

The degree of phase coherence of the frequency reference ultimately affects the fidelity and dynamic range of the recorded astronomical data [16], and thus the performance of the telescope. However, over the transmission distances involved (up to 175 km for SKA1-MID [20]), the transmitted frequency references acquire unwanted phase noise due to mechanical disturbances on the fiber link sufficient to degrade the performance of the telescope. In VLBI, this is overcome by each observatory having its own atomic frequency and time standard, but, because of the number of atomic clocks that would be required to serve the widely dispersed receiver elements of the SKA, this solution is impractical and expensive. To overcome the reduced phase coherence across the array, the reference signals will be transmitted from the CPFs to the RPFs and dishes using actively stabilized frequency transfer systems\(^1\) as shown in Figure 1.4. The centralized architecture reduces cost and helps to maintain a high degree of synchronization between remote stations by avoiding the relative frequency drift between different reference signal sources. (A detailed discussion of stabilized frequency transfer systems is given in Section 2.4.) The development and testing of stabilized frequency reference transfer system designs for SKA1-LOW and SKA1-MID are the focus of this thesis.

1.2.4 Beyond the SKA

The actively stabilized frequency transfer systems developed for the SKA, or related systems based on similar technologies and principles, will have useful scientific applications beyond the SKA. The University of Western Australia (UWA) is planned to be one of several ground stations for the ACES mission [13]. Signals generated by atomic clocks at UWA will be phase-coherently transmitted to the optical

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\(^1\)The term “frequency transfer” is used to be consistent with optical metrology literature, whereas the systems that are the subject of this thesis are often referred to as “phase transfer” systems in radio astronomy literature. The systems discussed in the following chapters exploit the relationship between phase and frequency (i.e. phase error is the integral of frequency error) to stabilize both.
1.3 Engineering Considerations Affecting this Work

The stabilized frequency transfer systems described in this thesis are designed from the outset to be optimized for application to the SKA1-LOW and SKA1-MID tele-

laser timing link at the Yarragadee Geodetic Observatory. The improved precision this enables will result in an improvement in the overall fundamental and applied science objectives of the ACES mission [26]. Proposed future telescopes such as the next-generation Very Large Array (ngVLA), a successor to the existing VLA with 10 times the collecting area and baseline length [27], will require active phase-synchronization systems. Stabilized frequency transfer systems also have exciting potential to transform VLBI experiments [28] by achieving greater long-term phase synchronization than is possible with separately located hydrogen masers, enabling globe-spanning VLBI arrays such as the Event Horizon Telescope [29] to achieve greater sensitivity through longer coherence times.

Figure 1.4: Schematic representation of SKA frequency reference distribution from a CPF to RPFs and dishes.
CHAPTER 1. INTRODUCTION

scopes. Engineering consideration and system requirements that influence design decisions are outlined below.

- **Coherence requirements** — the SKA design requirements stipulate that the maximum coherence loss between any two antennas caused by the frequency transfer system must not exceed 1.9% (the majority of a 2% budget after subtracting allowances for other telescope systems) over timescales of 1 s and 60 s, and a maximum phase drift of 1 rad over a period of 10 minutes. These are the primary stability parameters the SKA1-LOW and SKA1-MID frequency stabilization systems are designed to meet. More details of coherence loss and methods to calculate it are presented in Section 2.2.1.3.

- **Scale (number of receptors)** — SKA1-LOW requires the stabilized frequency reference to be delivered to the main core and to the 36 RPFs, while SKA1-MID requires the reference signal to be delivered to 197 dish pedestals. At this scale, the physical size of transmitter-end and receiver-end units becomes an important consideration. Such a large quantity of units also means power requirements have to be carefully considered. Consideration must also be given to later expansion to SKA2, when the number of units will increase by an order of magnitude. Small size, particularly at the transmitter-side, is critical.

- **Size and form factor** — The size limitations strongly influence the choice of actuator used to suppress the unwanted phase noise, which is considered further in Section 2.4.1. Group-delay actuators such as piezo-electric fiber stretchers and thermally-controlled fiber spools used in many leading phase noise compensation systems are too large to be practical for the hundreds (and later, thousands) of units required by the SKA. Currently, in SKA1-MID, the stabilized frequency transfer system receiver module is to be located in the dish pedestal. However, a future design revision may result in the receiver module being mounted on the feed indexer at the dish focus. This means that
1.3. ENGINEERING CONSIDERATIONS AFFECTING THIS WORK

the stabilization system receiver will, ideally, be designed to accommodate this change, placing further size and form factor constraints on the design.

- **Cost** — With hundreds, and eventually thousands, of units required to service the SKA, the cost of each additional transmitter and receiver module must be minimized, meaning that components duplicated across the modules must be cheap. This also precludes the use of large amounts of expensive fiber such as the dispersion-compensating fiber used in many leading phase noise compensation systems.

- **Other considerations include** — resilience to minor seismic events; immunity to expected operating temperature range and temperature gradients (and other climatic effects such as humidity); and reliability (the systems are required to have a 99.9% inherent availability).
Never measure anything but frequency!
– Arthur Schawlow

2

Technical Background

Overview

High-precision transfer of time and frequency references has a long and extensive history of active research. Frequency measurements can be made to higher precision than any other fundamental physical measurement and are an integral part of realizing internationally defined standard quantities of energy, space, and time, making high-precision frequency measurements important for probing fundamental physical questions. Scientific uses of frequency transfer range from radio astronomy [23] and geodesy [30], to high-precision spectroscopy [31] and time variation of fundamental constants [32].

This chapter gives an introduction to the tools and techniques of high-precision frequency transfer relevant to the experiments described in this thesis. Key technical concepts are defined, the principles of phase noise cancellation are described, and important practical implementation considerations are discussed in the following sections. A review of previous and current international work in stabilized frequency transfer is provided to place the research presented in this thesis in the context of previous systems and achievements.
# CHAPTER 2. TECHNICAL BACKGROUND

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2.1 Noise and Frequency Stability of Oscillators

Physical oscillators exhibit instabilities in the form of amplitude and phase and, therefore, frequency, and this is *noise*. A mathematical description of a physical oscillator and definition of key terms is given in the following sections.

2.1.1 Mathematical Description of an Oscillator

An ideal oscillator is described by a simple sine wave which is written as:

\[ x(t) = A_0 \cos(\omega_0 t + \phi(t)), \]  

(2.1)

where \( A_0 \) is an arbitrary amplitude, \( \omega_0 \) is the angular frequency of the oscillator, and \( \phi(t) \) is the phase of the wave at time \( t \).

However, real oscillators are affected by amplitude, frequency, and phase fluctuations. These fluctuations are related to environmental effects, random processes such as thermal noise, and frequency or phase drifts caused by internal changes in the oscillator. We model the noisy signal of a real oscillator as [33]:

\[ x(t) = A_0 [1 + \alpha(t)] \cos(\omega_0 t + \phi(t) + \varepsilon(t)), \]  

(2.2)

where \( \alpha(t) \) and \( \varepsilon(t) \) are random processes corresponding to fluctuations of the amplitude and phase respectively. However, Equation 2.2 does not take into account frequency drift of the oscillator. An illustration of amplitude and phase fluctuations is shown in Figure 2.1. The instantaneous frequency of the oscillator signal is given by:

\[ \omega(t) = \frac{d}{dt}(\omega_0 t + \phi(t) + \varepsilon(t)) \]

\[ = \omega_0 + \frac{d(\phi(t) + \varepsilon(t))}{dt}. \]  

(2.3)

The frequency noise can be defined as the difference between the nominal, \( \omega_0 \), and instantaneous, \( \omega(t) \), frequencies:
From this, we define the dimensionless quantity, the instantaneous fractional frequency deviation, $y(t)$:

$$y(t) = \frac{\Delta \omega(t)}{\omega_0}. \tag{2.5}$$

Because the instantaneous fractional frequency deviation is a dimensionless and normalized quantity, it provides a useful stability comparison between oscillators of different frequencies.

### 2.1.2 Accuracy and Stability

It is worth recalling the definitions of accuracy and stability as they apply to physical experiments. **Accuracy** is the degree to which the result of a measured or calculated
value conforms to the “correct” value determined by international standards. **Stability** is the variation of a physical quantity over time. These concepts are illustrated in the typical example shown in Figure 2.2.

### 2.2 Characterization and Measurement of Frequency Stability and Phase Noise

The stability of a frequency source is typically characterized using the “Allan deviation” [35,36] or the “timing jitter spectral density” [33] depending on which method is the most convenient or useful to use in a given experiment. The Allan deviation measures the frequency stability in the time domain and expresses the measured fractional frequency variations of a source as a function of the time over which the frequency is averaged, while the timing jitter spectral density is a measure of the phase noise spectrum in the frequency domain and gives a representation of the frequency modulation surrounding the carrier signal.

These two alternative methods used to describe the same properties of a frequency source are mainly differentiated by practical constraints. The resolution of a frequency counter is proportional to the measurement time (the sample, or aver-
aging time) so many counters cannot effectively measure the short term stability of modern oscillators. Because of this, if the stability of an oscillator is to be characterized over time intervals of one second or more, frequency stability measurements in the time domain are often used while phase noise measurements in the frequency domain are used to measure the stability when fast fluctuations (typically, those with a period of less than one second) of the frequency are to be characterized.

The frequency stability of a source is usually expressed in terms of the fractional frequency which is given by dividing the absolute frequency fluctuations of the source by the nominal or average frequency of the source. This gives a dimensionless quantity, the fractional frequency, which is convenient to compare the stability of oscillators and frequency sources working at different frequencies. The phase noise is expressed as the power spectral density (PSD) of the phase fluctuations. The PSD is often interpreted as a statistical description of how often the frequency source assumes values other than the nominal frequency.

2.2.1 Allan Variance

The Allan variance, $\sigma_y^2(\tau)$, is a measure of oscillator frequency stability that was endorsed by the IEEE in 1971 [35–39]. In practice, the stability of an oscillator is usually presented as the the square root of the Allan variance, the Allan deviation.

2.2.1.1 Allan Deviation

The Allan deviation, $\sigma_y(\tau)$, is obtained from a series of consecutive frequency measurements averaged over a period of time $\tau$. This averaging time is the gate time of the frequency counter used to make the frequency measurements. The Allan deviation is computed as follows [40].

The instantaneous fractional frequency deviation from the nominal centre frequency, $\nu_0$, of a signal is given by
2.2. CHARACTERIZATION AND MEASUREMENT OF FREQUENCY STABILITY AND PHASE NOISE

\[ y(t) = \frac{1}{2\pi \nu_0} \frac{d}{dt} (\phi(t) + \varepsilon(t)). \]  

(2.6)

From this, the Allan variance for an averaging time \( \tau \) is given by

\[ \sigma_y^2(\tau) = \left\langle \frac{1}{2} [\overline{y}(t+\tau) - \overline{y}(t)]^2 \right\rangle, \]

(2.7)

where \( \langle \rangle \) indicates an infinite time average, and \( \overline{y}(t) \) is the time average of \( y(t) \) over the period \( \tau \). However, we cannot take an infinite time average so \( \sigma_y(\tau) \) is estimated from the finite set of \( N \) consecutive averages of the centre frequency \( \nu_i \) over the period \( \tau \).

\[ \sigma_y(\tau) \approx \left[ \frac{1}{2(N-1)\nu_0^2} \sum_{i=1}^{N-1} (\overline{\nu}_i - \overline{\nu}_{i+1})^2 \right]^{1/2} \]

(2.8)

When this is used to estimate the Allan deviation, the uncertainty associated with the value of the Allan deviation for a certain \( \tau \) should be given.

The Allan deviation provides a useful tool for characterizing a frequency source because the noise processes affecting the system can be determined from the dependence of \( \sigma_y(\tau) \) on \( \tau \), that is, from the slope of the stability trace on a log-log plot as shown in Figure 2.3. The power-law (slope) relations for the five recognized noise processes are [15,35]:

1. **White phase noise** \( (\tau^{-1}) \) is usually caused by broadband additive phase noise outside of the oscillator, such as that introduced by amplifiers. This process dominates at short averaging times and is often observed in phase compensated fiber links such as the ones presented in this thesis.

2. **Flicker phase noise** \( (\tau^{-1}) \) is seen in transistors and so is usually added to the system by noisy control electronics and amplifiers.

3. **White frequency noise** \( (\tau^{-1/2}) \); also called random walk of phase) is due to internal additive noise within the oscillator, such as thermal noise, and is observed in lasers stabilized to cavities and quartz clean-up oscillators.
4. **Flicker frequency noise** ($\tau^0$) along with **random walk of frequency** limits the long-term stability of oscillators.

5. **Random walk of frequency** ($\tau^{1/2}$) and **flicker frequency noise** are related to random changes in the physical environment of the oscillator (such as temperature, pressure, magnetic field vector) that produce random shifts and long-term drifts in the output frequency [41–43]. They are observed in hydrogen masers, caesium clocks, and fiber lasers.

A limitation of using the slope of the Allan deviation to determine the dominant type of noise process present in the frequency measurements is the fact that white phase noise and flicker phase noise exhibit the same slope ($\propto \tau^{-1}$). There is a loss of information in the conversion to Allan deviation that conflates these two noise processes. More recently, overlapping Allan deviation [44] and modified Allan deviation [45–47] analysis methods have been developed that overcome this limitation by exhibiting different power-law slopes for the different noise types. However, the data and results in this thesis are presented in terms of Allan deviation and a
hybrid fractional frequency deviation (see Section 2.2.3.3) and so overlapping Allan deviation and modified Allan deviation will not be covered here.

For the Allan deviation to provide a reliable indication of the type of noise process present on the system, the counter used to make the frequency measurements must have no dead time between consecutive average frequency measurements [48, 49]. The dead time between measurements will result in loss of coherence between data points and may bias the computed Allan deviation. (This point is considered further in Section 2.2.3.3.)

2.2.1.2 Triangle Variance

The Allan variance can only be accurately determined using data from II-type frequency counters (Section 2.2.3.1). Modern resolution-enhanced, Λ-type, frequency counters (Section 2.2.3.2), such as the Agilent 53132A, measure average signal zero-crossings in a staggered windowing mode, rather than discrete rectangular windows like conventional II-type counters. Multiple averaging during a single gate time improves the resolution of the measurement, but also reduces the sensitivity of the measurement to frequency fluctuations at Fourier frequencies significantly higher than the reciprocal of the gate time [50, 51]. When the Allan deviation calculation method is applied to this data, it produces a distorted representation of the Allan Variance which has become known as the *Triangle variance*. Table 2.1 shows the bias caused by this Triangle variance procedure, as determined by Dawkins *et al.* [51] in terms of Allan variance for various common noise sources. [Note: a high “cutoff” frequency, $f_H$, is applied to the corrections for white and flicker phase noise. This cutoff frequency is applied in the Allan variance algorithm itself and is necessary to eliminate the high Fourier frequency components of the noise and allow the Allan variance algorithm to converge. The cutoff frequency is a factor of the bandwidth of the instrumentation and, in the case of a frequency counter, is determined by its effective bandwidth (as a function of its resolution). Test sets such as the Microsemi]
units discussed in Section 2.2.3.1 usually implement a low-pass filter to define their effective bandwidth and allow reliable comparison of results.

Table 2.1: Triangle variance for common characteristic noise sources expressed in terms of the Allan variance, $\sigma_y^2(\tau)$ [51]. (Note: $f_H$ is a cutoff frequency, that depends on the measurement application, introduced to avoid an infinite result.)

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<th>Noise Type</th>
<th>Triangle Variance</th>
</tr>
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<td>White Phase Noise</td>
<td>$\frac{8}{3f_H^2}\sigma_y^2(\tau)$</td>
</tr>
<tr>
<td>Flicker Phase Noise</td>
<td>$\frac{3.12 + 33.5\pi f_H}{\tau}\sigma_y^2(\tau)$</td>
</tr>
<tr>
<td>White Frequency Noise</td>
<td>$1.33\sigma_y^2(\tau)$</td>
</tr>
<tr>
<td>Flicker Frequency Noise</td>
<td>$1.30\sigma_y^2(\tau)$</td>
</tr>
<tr>
<td>Random Walk Frequency Noise</td>
<td>$1.15\sigma_y^2(\tau)$</td>
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</tbody>
</table>

2.2.1.3 Coherence Loss

While Allan deviation and other estimates of the fractional frequency stability of the transmitted signal are of interest to the metrology community, the quantity of interest to the radio astronomy community is the coherence loss resulting from the instabilities in the delivered reference signal [15,17,18]. Because the instabilities in the frequency reference contribute to the coherence loss of the astronomical data, and this coherence loss can only be measured by a functioning interferometer array, the radio astronomy community has developed methods to estimate the coherence loss from the measured Allan deviation of the reference oscillator [18,52].

The coherence is given by

$$\langle C^2(T) \rangle = \frac{2}{T} \int_0^T (1 - \frac{\tau}{T}) \exp(-\pi^2\nu_0^2\tau^2[\sigma_y^2(\tau) + \sigma_y^2(2\tau) + ...])d\tau,$$  \hspace{1cm} (2.9)

where $\langle C^2(T) \rangle$ is the mean-square value of the coherence, $C$, at an arbitrary integration time, $T$, $\nu_0$ is the observing frequency, and $\sigma_y^2(\tau)$ is the Allan variance of the frequency reference. This integral can be calculated by constructing a numerical approximation of the measured Allan variance.

For white phase noise, the integral in Equation 2.9 above becomes [15]:

$$\langle C^2(T) \rangle = \exp(-\frac{4\pi^2\nu_0^2\sigma_y^2}{3}),$$  \hspace{1cm} (2.10)
where $\sigma^2_y$ is the Allan variance in one second.

The stabilized frequency transfer systems discussed in this thesis exhibit noise profiles that are dominated by white phase noise (see Chapters 4 and 6), and so Equation 2.10 provides a good estimate of the coherence achieved by the transmitted frequency reference.

The fractional coherence loss, $L_c$, is then given by

$$L_c = 1 - \sqrt{\langle C^2(T) \rangle}.$$  \hspace{1cm} (2.11)

An alternative method of estimating the coherence loss from the Allan variance was used by members of the ALMA project [53–55]. This method aims to achieve a better estimate of the coherence loss by taking into account the contributions of the different noise processes present in the frequency reference signal and is given by

$$L_c = \omega_0^2 \left[ \frac{\alpha_p}{6} + \frac{\alpha_f}{12} T + \frac{\alpha_c}{57} T^2 \right],$$  \hspace{1cm} (2.12)

where $\omega_0$ is the angular frequency of the frequency reference, $\alpha_p$ is the Allan variance of white phase noise at one second, $\alpha_f$ is the Allan variance of white frequency noise at one second, and $\alpha_c$ is the Allan variance of flicker frequency noise [55].

These two coherence loss estimation methods were found to be in good agreement with each other as shown in Section 6.5.2.

2.2.2 Phase Noise and Timing Jitter

Phase noise on a frequency source creates sidebands on the carrier signal that are separated from the carrier signal by the frequency at which the process producing the phase noise occurs. This has the effect of reducing the power of the carrier signal since power goes into the noise sidebands. The phase noise of a frequency source is determined by measuring the phase variations of that source against a frequency reference with a lower phase noise. The most common phase measurement technique is where two signals of the same frequency are mixed in a frequency mixer. As a
result of the mixing, the output voltage of the mixer contains both a direct current (DC) term, resulting from small phase differences between the mixed signals, and a periodic term at twice the frequency of the input signals, resulting from the addition of the two input frequencies. The PSD is obtained by using a low-pass filter to remove the periodic term, leaving only the DC term which is amplified and sent to a Fast Fourier Transform (FFT) analyzer.

Phase noise measurements of high-stability signals are difficult to do since this technique is susceptible to power fluctuations of the input signals, power supply noise, and thermal fluctuations, all of which can act to mask the actual phase noise being measured. The PSD of the phase fluctuations, $S_\Phi(f)$, is given in units of $\text{rad}^2/\text{Hz}$ and is defined as [40]:

$$S_\Phi(f) = |\Phi(jf)|^2$$ (2.13)

where $\Phi(jf)$ is the Fourier transform of the phase $\phi(t)$ and in which $f$ is the offset frequency from the nominal signal. The phase noise of a frequency source is also often represented by the single-sideband phase noise $\mathcal{L}(f)$:

$$\mathcal{L}(f) = \frac{1}{2} S_\Phi(f)$$ (2.14)

which is expressed in units of decibels with respect to the carrier in a 1 Hz measurement bandwidth, dBc/Hz.

For purposes involving event synchronization, such as communications and radio astronomy, the phase noise of a transmitted signal is expressed as a root mean square (RMS) timing jitter estimated from the PSD of the phase fluctuations. Timing jitter can be visualized as fluctuations in the zero-crossing of a signal. The RMS timing jitter is expressed in units of seconds and is given by

$$T_{RMS} = \frac{1}{2\pi\nu_0} \sqrt{\int_{f_{low}}^{f_{high}} [S_\Phi(f)]^2 df}$$ (2.15)
where \( f_{\text{low}} \) and \( f_{\text{high}} \) define the bandwidth over which the timing jitter is calculated and are determined by the specific application of the transmitted frequency signal. Higher sampling rates correspond to higher bandwidths and so a higher value of \( f_{\text{high}} \). In this thesis, timing jitter will typically be considered in relation to phase-locking of an oscillator to a reference signal (e.g. clean-up oscillators at the location of the radio telescope receivers) and so only the portion of the jitter spectral density within the locking bandwidth contributes to the timing jitter calculation. As such, the RMS timing jitter should be specified for a particular bandwidth.

2.2.3 Practical Aspects of Measurement

Frequency counters measure the frequency of an applied signal by counting the zero-crossings of the signal under test within a specified gate time. A direct stability measurement of a signal can usually be achieved using frequency counter data. However, differences in the design and operation of different frequency counters must be considered. Frequency counters are generally classed into two groups — \( \Pi \)-type frequency counters, and \( \Lambda \)-type frequency counters. The different types of counter are designated by Greek letters because the shapes of the letters represent the weighting function applied to the frequency samples [50, 51].

As stated previously, the dead time between frequency readings in many frequency counters can affect the calculation of the Allan deviation and will produce an altered slope for some noise processes. Some frequency counters can operate in a zero dead time mode.

Spurious signals such as “leakage” of the 50 Hz frequency of the mains electricity supply into the electronics can affect the frequency count, usually appearing as a “bump” in the Allan deviation plots. However, this problem is mostly limited to values of less than one second since few processes other than mechanical disturbance to the system have sub-hertz frequencies.
The resolution of frequency counters can be affected by factors such as the frequency and slew rate of the input signal and the particular timing reference used. For state-of-the-art frequency metrology it may sometimes be the case that the resolution of the frequency counter needs to be tested to ensure the validity of the measurements being performed. If possible, frequency stability measurements should be compared with complementary phase noise measurements to validate the consistency of the results. As previously stated, phase noise measurements are susceptible to power fluctuations and power supply noise that can cause errors in the stability measurement, and so require more care in performing the measurement.

2.2.3.1 Π-type Frequency Counters

Π-type frequency counters have become the most widely used model of frequency counter because the data from the counters can directly produce Allan deviation as well as other fractional frequency stability estimators such as modified Allan deviation and overlapping Allan deviation. These counters are not resolution enhanced (Section 2.2.3.2) and are generally able to measure up to a few hundred MHz.

Popular models of Π-type frequency counters include the Stanford Research SR620 and the Symmetricom/Microsemi 5125A. The Microsemi 5125A was used for some of the experiments reported in this thesis.

2.2.3.2 Λ-type Frequency Counters

Λ-type frequency counters make use of resolution enhancement algorithms during the frequency counting process. These high resolution frequency counters measure in a staggered windowing mode, rather than the discrete rectangular windows used by Π-type counters. This produces multiple averaging during a single gate time and improves the resolution of the measurement, but also reduces the sensitivity of the measurement to frequency fluctuations at Fourier frequencies significantly.
2.2. CHARACTERIZATION AND MEASUREMENT OF FREQUENCY STABILITY AND PHASE NOISE

greater than the reciprocal of the gate time. This means A-type frequency counters produce a measurement that gives a distorted representation of the Allan Variance [50, 51]. This has been called the Triangle Variance because the windowing function can be approximated by a A-estimator. The Triangle Variance is discussed in Section 2.2.1.2.

Despite this complication, A-type frequency counters are still used for their greater resolution. Popular A-type frequency counters include the Pendulum CNT-90 and CNT-91, and the Agilent 53132A. Most of the experiments presented in this thesis used the Agilent 53132A. The Agilent counter is much smaller and lighter than the Microsemi 5125A, which was an important consideration for field work campaigns such as those described in Chapters 6, 7, and 8. The Agilent also proved to be more sensitive to rapid frequency “glitches” that would sometimes go unnoticed by the Microsemi, making the Agilent an important tool for ensuring the robustness of a stabilization system.

2.2.3.3 Frequency Counters with Dead Time

Another complication is that many frequency counters exhibit dead time between successive frequency readings, which results in loss of coherence between data points and may bias the computed Allan variance for some noise processes when successive frequency readings are juxtaposed and averaged to simulate a longer counter gate time [48, 49, 56] as is done in many Allan variance computation algorithms. A common frequency counter that exhibits dead time is the Agilent 53132A used for many of the experiments throughout this thesis.

An example of the effects of juxtaposing successive measurements that have dead time is shown in Figure 2.4. Figure 2.4 shows fractional frequency stability measurements of an 8 GHz microwave signal made concurrently with an Agilent 53132A frequency counter (A-type with dead time; dark-blue circles) and a Microsemi 5125A phase noise test set (Π-type, zero dead time; light-blue squares). The Microsemi produces fractional frequency stability measurements with a slope close to $\tau^{-1}$, in-
indicating that the noise processes are dominated by white phase noise, while the Agilent results exhibit a slope close to $\tau^{-1/2}$. The loss of coherence between successive frequency measurements by the Agilent 53132A has biased the slope of the calculated fractional frequency, making white phase noise indistinguishable from white frequency noise. (The fractional frequency stability of white frequency noise is independent of counter dead time [49,57].)

Despite the fact that the Agilent 53132A does not produce true Allan deviation values for some noise processes, the Agilent counter’s enhanced resolution and popularity as a test device have led to many users presenting the fractional frequency

**Figure 2.4:** Concurrent frequency stability measurements made by an Agilent 53132A frequency counter (Λ-type with dead time; dark-blue circles) and a Microsemi 5125A phase noise test set (Π-type, zero dead time; light-blue squares). The difference in slope of the two traces shows how the dead time of the Agilent counter masks some frequency noise processes.
2.2. CHARACTERIZATION AND MEASUREMENT OF FREQUENCY STABILITY AND PHASE NOISE

computed from Agilent data as a “hybrid” fractional frequency stability [58–61].

2.2.3.4 Counter Resolution and Resolution Enhancement

Modern frequency counters, such as the Agilent 53132A used for many of the experiments in this thesis, are reciprocal counters — that is, they measure the period of the input signal as a multiple of the reference clock cycle. This should make the resolution of the counter independent of the input frequency. In practice, resolution starts decreasing at lower frequencies because of the reduced slew rate of the signal which makes the measurement of the exact zero-crossing point of the signal less precise. Other researchers [62] have measured the resolution of the Agilent 53132A counter to be best at a frequency of around 50 kHz.

Operations such as the sum or the division of frequencies, described in detail below, are important tools in frequency metrology. These operations have different effects on measurements of frequency stability and phase noise and can be used to enhance the resolution of stability measurement techniques.

1. **Up or down-conversion of frequencies using algebraic summation:**

   When two signals are fed into a frequency mixer, the mixer produces both the sum and the difference of the two frequencies at its output. Filters are used to select the *down-converted* beat frequency or the *up-converted* combination. The absolute frequency deviation or modulation of either one of the two inputs will also be imprinted onto the beat frequency. This is the principle on which heterodyne radio receivers work. In frequency metrology this technique is usually used to reduce the frequency of a signal to one that can more readily be counted. The signal that is to be measured is mixed with a highly stable frequency reference, so any fluctuation on the output beat signal is dominated by fluctuations of the signal that is being measured. For example, if a 100 MHz signal that has 1 Hz fluctuations, corresponding to a fractional frequency stability of $1 \times 10^{-8}$, is mixed with a highly stable 101 MHz signal,
the resulting beat will have a frequency of 1 MHz and will still possess the 1 Hz fluctuations. These 1 Hz fluctuations on the lower beat frequency now correspond to a fractional frequency stability of $1 \times 10^{-6}$. This effect can be used to bring measurements of high-stability signals into the resolution of a frequency counter or phase noise measurement set up. Mixing of frequencies can be done in electronics for radio- and microwave-frequency signals, or in fiber for optical frequencies. Optical frequencies separated by a radio or microwave frequency combine on a photo-diode (PD) to produce a beat that can easily be measured by a frequency counter.

2. **Multiplication and division of frequencies:** Multiplying up or dividing down the frequency of a signal has no effect on the fractional frequency stability of the signal since the frequencies of the phase fluctuations are also multiplied or divided. For example, if the 100 MHz signal with 1 Hz fluctuations in the previous example is frequency divided by a factor of 100, the resulting 1 MHz signal will have phase fluctuations at a frequency of 0.01 Hz, still corresponding to a fractional frequency stability of $1 \times 10^{-8}$. This is particularly problematic when synthesizing a higher frequency from the frequency that has been transferred since the absolute value of the instabilities of transmitted signal will be scaled up by the ratio of the final and initial frequencies. Frequency division is useful when creating an error signal for a feedback loop, since the lower frequency allows greater resolution but the fractional frequency stability is left unchanged. When used in phase noise measurements, frequency division can be used to reduce the phase fluctuations of a signal down to the linear range of a phase detector because the phase noise of the signal scales with $N^2$ where $N$ is the division ratio. A signal divided by a factor of 10 will have phase noise 20 dB lower than the input signal.
2.2. CHARACTERIZATION AND MEASUREMENT OF FREQUENCY STABILITY AND PHASE NOISE

2.2.3.5 Non-link noise sources

In many of the experiments described in this thesis, the stability of the signals delivered to the remote “user” end of the fiber are measured by comparing the signals with the original signal source, whether the original signal source be a laser, or radio-frequency or microwave-frequency synthesizer. The fiber link effectively acts as a delay line, meaning that the signal at the remote site is being compared with a signal produced by the signal source at a later time, and not the exact same signal that was originally transmitted. This “self-heterodyne” effect can cause the frequency and phase noise of the signal source to appear as instabilities in the signal detected at the remote site. This is particularly problematic for laser sources because small fractional frequency deviations represent relatively large absolute frequency deviations.

The detection of optical signals and their conversion into microwave signals is also affected by sources of noise that can degrade the performance of the stabilization servo, or affect the stability measurement. These noise sources include:

- Shot noise;
- Thermal noise; and
- Amplitude-to-phase conversion noise.

**Shot noise** is the result of the quantum nature of the photons arriving at the photodetector, that is, the discrete (particle) nature of electromagnetic radiation, and also occurs in electric circuits due to the quantization of electric charge. Shot noise current, $i_{\text{shot}}$, is given by

$$i_{\text{shot}} = \sqrt{2e i_{\text{avg}}}, \quad (2.16)$$

where $e$ is the charge of the electron, and $i_{\text{avg}}$ is the average DC photocurrent [40].

If the PD has characteristic system impedance $R$ (and the PD is terminated with
a load of impedance $R$), the single sideband phase noise $L_{\text{shot}}$ resulting from shot noise is

$$L_{\text{shot}}(f) = \frac{e_i \Delta_f R}{P_{\text{signal}}} \propto \frac{P_{\text{opt}}}{P_{\text{signal}}} \propto \frac{1}{P_{\text{opt}}},$$

(2.17)

where $P_{\text{signal}}$ is the power of the radio- or microwave-frequency signal, and $P_{\text{opt}}$ is the power of the average optical power incident on the PD [40].

**Thermal noise** occurs in the electronics used to convert the optical signal into an electronic signal. The phase noise resulting from the thermal noise $L_{\text{thermal}}$ is given by

$$L_{\text{thermal}}(f) = \frac{kT R}{2V^2_{\text{signal}}} \propto \frac{1}{P_{\text{signal}}} \propto \frac{1}{P^2_{\text{opt}}},$$

(2.18)

where $k$ is the Boltzmann constant, $T$ is the temperature of the electronic system, and $V_{\text{signal}}$ is the RMS voltage of the electronic signal [40].

**Amplitude-to-phase conversion** (also referred to as *intensity* or *amplitude noise*) results from fluctuations in the amplitude of the optical signal [63–65]. Typical PDs have a power-dependent phase shift between the detected optical signal and the resulting electronic signal, meaning that amplitude fluctuations in the optical signal can cause phase fluctuations after the PD. This is especially problematic at high incident optical power levels. As a result, at low signal strengths, thermal noise and amplifier noise will generally dominate the measurement noise, while shot noise and amplitude-to-phase conversion noise dominate at higher signal strengths. Thermal noise and shot noise dictate the fundamental limits for phase detection. Generally, due to the attenuation of the optical signals by long fiber links, optical power levels incident on the PDs in the experiments described in this thesis were relatively low. In all experiments, optical power levels were kept well below the levels required to saturate the PDs.
Other noise sources that contribute to degrading the performance of phase measurement systems include noise from frequency mixers and the mechanical stability of the apparatus.

**Frequency mixers** are used as phase detectors in the experiments described in this thesis. They are used to mix a radio or microwave frequency with a stable local oscillator reference to ultimately produce a DC error signal that encodes the phase fluctuations present in a detected signal. Mixers are sensitive to amplitude fluctuations in the input signals, which are converted into voltage noise at the output of the mixer [66, 67].

**Mechanical stability** of experimental apparatus becomes important when measuring the stability of signals with frequencies greater than around 1 GHz. Thermal and acoustic noise can create strains in the electronic components, connectors, and cables, creating signal path length fluctuations that have an impact on the measured stability of the microwave signals. Marra [62] showed that to measure the stability of a 1 GHz signal at the $10^{-15}$ level over 1 s, an experiment with 1 m of microwave signal path must be kept within a temperature range on the order of 10 mK over the measurement period. This is generally easily achieved over short timescales by the thermal mass of the apparatus, but, this level of temperature stability is difficult to achieve over periods on the order of 100 s or more and components must be rigidly mounted to a large thermal mass with good insulation from the surrounding air mass. Even so, the laboratory in which many of the experiments in this thesis were conducted had temperature variations exceeding 2°C/day. The problem was exacerbated during field trials (such as those presented in Chapter 6) where thermal stability of the test facility was poor and the ability to mount components rigidly to a large thermal mass was impeded by the need to construct transportable test equipment.
2.3 Principle of Phase Noise Cancellation

The goal of a frequency transfer network is to produce a phase-coherent copy of a local frequency reference at a remote site. Environmental noise in the transmission medium, in this case, a fiber-optic cable, induces phase-noise perturbations on the transmitted signal, reducing the phase coherence between the local and remote copies. Stabilized frequency transfer systems detect and act to cancel the phase noise perturbations affecting the transmission, enabling transfer of coherent signals over noisy links. The detection of phase noise perturbations is achieved by sending one or more signals on a round-trip through the link, enabling the returning signal to be compared to a local copy. The unwanted phase noise can then be cancelled out in real-time using pre-compensation of the transmitted signal, or recorded and removed at a later time by computational means [68–70]. (This latter practice is often referred to as passive correction. However, passive correction is also used to refer to some real-time phase correction techniques [71–73]. For the purposes of this thesis, I shall refer to later removal of phase noise via computational techniques as post hoc correction.)

2.3.1 Round Trip Phase Detection

Figure 2.5 shows a basic schematic for an actively stabilized frequency transfer system. The outgoing reference signal, which can be a continuous wave (CW) optical carrier, a modulated optical carrier, or a frequency comb, is actuated to pre-compensate for the phase perturbations detected by the previous round trip of the signal. The signal passes through the link where it acquires phase noise perturbations $\phi_{\text{link}-1}$ before reaching the remote site. A partial reflection or re-transmission of the signal at the remote site returns through the link, acquiring phase perturbations $\phi_{\text{link}-2}$, to the local site where the phase of the returning signal is compared to the...
2.3. PRINCIPLE OF PHASE NOISE CANCELLATION

Figure 2.5: Basic configuration of actively compensated fiber frequency dissemination systems. A partial reflection or re-transmission of the signal from the remote site to the local site allows the round trip phase to be measured. The actuator adjusts the phase of the outgoing signal to counteract the phase perturbations measured on the link.

phase of the original reference signal $\phi_{\text{ref}}$. The round trip signal has double-passed the actuator, which applies $\phi_{\text{act}}$ to the signal on each pass.

The noise processes on the link are assumed to be stationary between the incident and return transmissions, that is, they are coherent within the round trip time (RTT) of the signal, and the propagating signal is assumed to sample the same polarization modes in both directions. This means that we consider only those perturbations with frequencies less than the reciprocal of the RTT and assume $\phi_{\text{link}-1} = \phi_{\text{link}-2} = \phi_{\text{link}}$. Further, by limiting the bandwidth of the actuator to frequencies lower than $1/\text{RTT}$, and ensuring that the coherence time of the reference is longer than the RTT the phase difference between the returning signal, $\phi_{\text{rt}}$, and the reference signal is

$$\phi_{\text{rt}} - \phi_{\text{ref}} = 2(\phi_{\text{act}} + \phi_{\text{link}}). \quad (2.19)$$

The phase of the signal at the remote end is

$$\phi_{\text{rem}} = \phi_{\text{ref}} + \phi_{\text{act}} + \phi_{\text{link}}. \quad (2.20)$$

The servo electronics steer $\phi_{\text{act}}$ to maintain $\phi_{\text{rt}} - \phi_{\text{ref}}$ from Equation 2.19 at a constant value. Thus the phase combination $\phi_{\text{act}} + \phi_{\text{link}}$ is maintained at a constant value and so Equation 2.20 becomes:
\[
\phi_{\text{rem}} = \phi_{\text{ref}} + \phi_{\text{act}} + \phi_{\text{link}} = \phi_{\text{ref}} + \text{constant}.
\] (2.21)

Thus, we have established a phase-coherent copy of the local reference signal at
the remote site.

### 2.3.2 Noise Sources, Bandwidth, and Dynamic Range

The main sources of phase noise affecting the optical fiber are from mechanical and
thermal perturbations that alter the optical path length of the link [40]. (Note: the
thermo-optic coefficient of optical fiber is two orders of magnitude larger than the
thermal expansion coefficient [74], so optical path length changes related to thermal
perturbations are dominated by changes in the refractive index of the fiber.) These
perturbations can also cause excess noise from fiber connections, stimulated Brillouin
scattering (SBS), and polarization mode dispersion (PMD).

The fiber transmission links can be designed to minimize these effects. For exam-
ple, novel fiber types such as polarization maintaining fiber can be used to prevent
PMD, and temperature-insensitive fiber [75,76] can be used to greatly reduce prop-
agation time variations. The architecture of the fiber link can also contribute to
reducing noise sensitivity. The fiber could be buried (with appropriate trenching
for the local soil type) sufficiently far below ground to even-out daily temperature
changes. However, all of these options are expensive, and may not be possible un-
der some circumstances, or if existing fiber infrastructure is to be used. Specialty
fibers such as the polarization maintaining and temperature-insensitive fibers are not
generally available as fully cabled optical fiber with fiber-count and jacket options.
Specialty fiber also limit options for connectors and splicing methods. Installation of
new fiber reticulation of any sort is usually extremely costly. For these reasons, sta-
bilized frequency transfer systems that are robust against all of these noise processes
are usually the more economic and desirable option.
2.3. PRINCIPLE OF PHASE NOISE CANCELLATION

PMD, birefringence, and group-velocity dispersion (GVD) of the fiber can lead to problems for systems transmitting signals other than a CW optical carrier because the assumption that $\phi_{\text{link}-1} = \phi_{\text{link}-2}$ may not hold, even if the noise processes are stationary within the RTT. For systems transmitting a modulated carrier, polarization scrambling over time scales significantly faster that the RTT can be used to average-out the effects of PMD to improve transfer stability [77, 78].

As stated previously, the feedback bandwidth is ultimately limited by the RTT. If the servo system attempts to cancel phase noise at higher frequencies, the system will simply write excess noise onto the frequency transfer. The signal-to-noise ratio (SNR), dynamic range, and total noise of the fiber link also have an impact on the achievable feedback bandwidth. The servo must have sufficient range to effectively cancel the noise affecting the link. Longer fiber links (or links that are relatively more exposed to the elements) exhibit greater total noise [79], and the ability to cancel large-magnitude fluctuations is limited by the range of the servo actuator. Longer links also mean greater attenuation and a reduced SNR, which can have an impact on the ability of the servo to counteract phase fluctuations.

2.3.3 Optical Amplification

On long fiber links (those exceeding roughly 70 km) the attenuation of the photonic signal becomes great enough to require amplification to deliver a usable signal. This is particularly important in phase-noise compensation systems where signals often make a round-trip through the link, and good SNR is important for accurate phase measurement. Amplification is typically achieved using erbium-doped fiber amplifiers (EDFAs), which are able to coherently amplify optical signals in the 1.5 $\mu$m wavelength telecommunications region. For the purposes of stabilized time and frequency transfer, bi-directional EDFAs have been developed [80] which can amplify optical signals in both directions, helping to maintain path-symmetry of the outgoing and returning signals. (More recently, high-gain fiber Brillouin amplifiers
have been developed [81], but only EDFAs will be discussed here since only EDFAs were used for the experiments described in this thesis.)

The bi-directional EDFAs used in the experiments presented in this thesis were produced by IDIL Fibres Optiques. Figure 2.6 shows a simplified schematic of a bi-directional EDFA to illustrate the basics of how such a device works. The EDFA comprises optical couplers, an erbium-doped single-mode fiber gain medium (the active fiber), and one or two pump laser-diodes. The laser diodes pump the active fiber with a wavelength of 980 nm, exciting the erbium ions, enabling them to amplify light in the 1.5 \( \mu \text{m} \) region through stimulated emission to the ground state. However, erbium ions also spontaneously decay, emitting photons that are then amplified by the gain medium and contribute to unwanted noise and reduce the SNR. Bi-directional EDFAs can be susceptible to back reflections from the fiber link, which will be amplified and can result in spontaneous lasing, saturating the amplifiers and the link, and washing out the desired signals. This is overcome by limiting the output power injected into the link (typically < 5 dBm) to reduce the incidence of Brillouin scattering in the link.

The broadband gain of EDFAs also means that they have broadband amplified spontaneous emission. A typical output spectrum for the EDFAs used in the experiments presented in this thesis is shown in Figure 2.7. It is useful to note that there is substantially greater spontaneous emission at 1530 nm than at the 1550 nm working frequency used throughout the work presented in this thesis. Bandpass filtering
2.4. FREQUENCY TRANSFER OVER OPTICAL FIBER

Figure 2.7: Measured output spectrum of the IDIL Fibres Optiques EDFAs used in the experiments presented in this thesis. Black trace – input spectrum (CW laser signal at 1552.4 nm), red trace – EDFA output spectrum with no input, blue trace – EDFA output spectrum with CW laser input.

to reject large amount of stimulated emission at undesired frequencies significantly reduces the susceptibility of a link with EDFAs to oscillation and spontaneous lasing.

2.4 Frequency Transfer over Optical Fiber

Research into the stabilized transmission of ultra-stable frequencies over fiber-optic links originated in the 1980s [82] and activity in this field has increased considerably in the last few years as technological progress has created a demand for the distribution of ever more precise frequency signals. Techniques for the distribution of ultra-stable frequency references over optical-fibers fall into three categories:

1. Direct transfer of an optical frequency carrier from a CW laser;

2. Microwave or radio frequency transfer by modulation of a CW laser; and

3. Simultaneous radio, microwave, and optical frequency transfer using an optical frequency comb.
CHAPTER 2. TECHNICAL BACKGROUND

Stabilization techniques for all three transmission methods assume that the noise sources are static during the RTT of the transmitted signal, that the servos do not attempt to compensate noise at frequencies greater than the link bandwidth and so introduce noise, and that the coherence time of the reference oscillator is longer than the RTT [40].

2.4.1 Servo-actuators

Regardless of which compensation technique is used, the phase adjustment range of the servo actuators must exceed the range of phase variation produced by the fiber optic network. The need for servos with a large range is particularly true for fiber links approaching 100 km in length because the range of phase variation on the link increases with link length [40, 79]. Servos with low range such as piezo-electric stretchers can suffer from having insufficient range to compensate longer fiber links. This is because they can only stretch the optical fiber, and therefore alter the optical path length, a finite amount. Multiple stretchers can be placed in series to achieve the required range. However, these stretchers are large and bulky items and series linking enough stretchers can cause problems in situations where space is limited. AOMs provide unlimited range for optical phase compensation because they act directly on the optical frequency [40]. AOMs rely on a direct relation between phase stability and frequency stability at the remote end. A change in the phase at the remote end is observed as a change in the frequency of the retro-reflected signal from the remote end. Long links extending several tens of kilometres can suffer from burst fluctuations, which are sudden, large phase delays. To avoid cycle slips in such a situation, the compensation servo must have a sufficiently high dynamic range and slew rate.

Most of the devices mentioned above for stabilizing signal transfer act directly on the optical path length of the fiber link or the frequency of the signal. However, stabilization of reference signals can also be achieved using a phase-locked loop
2.4. FREQUENCY TRANSFER OVER OPTICAL FIBER

(PLL) [71,83] or in the digital domain using an application-specific integrated circuit (ASIC) [84] or field-programmable gate array. Digital systems such as those that employ ASICs are becoming more common as the cost and difficulty of prototyping dedicated integrated circuits declines. However, analogue systems are often at an advantage since their continuous response is usually faster than digital and so has greater bandwidth.

All of the feedback systems presented in the body of thesis achieve stabilization of the signal by frequency modulating the nominal frequency input to one or more AOMs. The modulation of the AOM closes a phase-locked loop. The frequency source driving the AOM incorporates a proportional-integral (PI) controller that attempts to drive an applied DC error signal to zero. The transfer function of the control system exhibits a simple $1/f$ (inverse frequency) roll-off with the unity gain frequency limited by the round trip time of the link plus further delays introduced by the electronics. The total loop gain is set manually and is simply increased until the control loop begins to oscillate.

2.4.2 Direct Optical Carrier Transfer

The simplest approach to optical frequency transfer is the direct dissemination of a CW optical carrier over the fiber link. Optical frequencies are more sensitive to phase noise accumulated during the transmission and the optical signal must be actively stabilized. However, optical frequency systems offer the benefit of much greater phase resolution than microwave-based phase detection systems [40].

In optical frequency transfer, an unmodulated optical carrier is passed through an AOM and injected into the fiber link. (Fiber stretchers can be used in place of the AOM, but have mostly been supplanted by AOMs.) The frequency, and therefore phase, of the returning signal is directly compared to the frequency reference at the local site, usually using heterodyne detection in an optical interferometer [40, 85]. The AOM produces a frequency shift that directly compensates the Doppler-induced
frequency shift of the returning signal due to fluctuations in the link. Therefore the phase of the signal at the remote site is stabilized while the optical path length varies over time. The dissemination of a single frequency on the fiber link avoids the problem of chromatic dispersion. The birefringence of typical fiber can cause problems due to slow polarization rotation which leads to amplitude fluctuations in the heterodyne beat used for direct optical transfer (as discussed in Section 2.2.3.5) and can be overcome using polarization maintaining (PM) fiber or polarization scrambling [40]. However, a now more widespread, passive technique is the use of Faraday mirrors (FMs) to produce the retro-reflection at the remote end. The FM rotates the state of polarization (SoP) of the incoming optical signal by 90°, returning the optical signal in an orthogonal polarization. The result is that SoP fluctuations on the fiber (that are stationary within the RTT) are suppressed [86], producing a beat signal with a stable amplitude at the local PD.

Direct optical transfer has the drawback that it does not directly provide a modulated frequency signal at the remote end. An optical frequency comb must be used to recover radio and microwave signals from the stabilized optical frequency [28, 87, 88]. Optical frequencies offer very little flexibility when used for frequency comparison or locking. Comparing an optical frequency that is even a factor of ±0.0005 different to the transmitted signal would correspond to a frequency difference of around 100 GHz for a typical telecommunications band laser (that is, lasers with a frequency around 200 THz). The remote user would require an optical frequency comb to span the gap between frequencies and make a measurement. Recently, hybrid transfer systems have been proposed and tested that transfer a stabilized optical signal as well as stabilized radio and microwave frequencies (and 1PPS time signals) [89, 90]. The challenge with these techniques is to produce and stabilize multiple coherent signals while avoiding significant adverse effects from chromatic dispersion in the link.

The first experiment demonstrating stabilized optical carrier transfer was undertaken by Ma and colleagues in 1994 [85]. This experiment was conducted over only
2.4. FREQUENCY TRANSFER OVER OPTICAL FIBER

Table 2.2: Stabilized optical frequency transfer fractional frequency results from a selection of significant works. L is the length of the fiber link, $\sigma_y(1 \text{ s})$ is the fractional frequency stability at 1 s integration time, and $\sigma_y(10^3 \text{ s})$ is the fractional frequency stability at 1000 s integration time. (N/A – value not reported.)

<table>
<thead>
<tr>
<th>Author and year</th>
<th>L (km)</th>
<th>$\sigma_y(1 \text{ s})$</th>
<th>$\sigma_y(10^3 \text{ s})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jiang et al. 2008 [91]</td>
<td>86</td>
<td>$1.3 \times 10^{-16}$</td>
<td>$5 \times 10^{-19}$</td>
</tr>
<tr>
<td>Grosche et al. 2009 [92]</td>
<td>146</td>
<td>$3 \times 10^{-15}$</td>
<td>$3 \times 10^{-18}$</td>
</tr>
<tr>
<td>Fujieda et al. 2011 [60]</td>
<td>90</td>
<td>$2 \times 10^{-15}$</td>
<td>$4 \times 10^{-18}$</td>
</tr>
<tr>
<td>Lopez et al. 2012 [94]</td>
<td>540</td>
<td>$5 \times 10^{-15}$</td>
<td>$6 \times 10^{-18}$</td>
</tr>
<tr>
<td>Predehl et al. 2012 [95]</td>
<td>920</td>
<td>$4 \times 10^{-14}$</td>
<td>$3 \times 10^{-17}$</td>
</tr>
<tr>
<td>Droste et al. 2013 [96]</td>
<td>1840</td>
<td>$2 \times 10^{-15}$</td>
<td>N/A</td>
</tr>
<tr>
<td>Chiodo et al. 2015 [93]</td>
<td>1100</td>
<td>$4 \times 10^{-16}$</td>
<td>$1.2 \times 10^{-19}$</td>
</tr>
</tbody>
</table>

25 m of fiber but established the key implementation details still used in optical frequency transfer experiments today.

Since then, optical frequency transfer has been improved in terms of overall stability [91–93] and has been pushed to ever longer transfer distances [94–96]. The current longest stabilized optical transfer link is 1840 km in a loop between the Max-Planck-Institut für Quantenoptik in Garching, Germany to the Physikalisch-Technische Bundesanstalt in Braunschweig, achieved by Droste and colleagues [96, 97]. Table 2.2 shows a summary of significant optical frequency transfer experiments.

These record-breaking links, as well as other experiments developing tools and techniques in support of long-distance frequency transfer over fiber [92,93,95,98–104] have enabled the implementation of national and regional high-stability time and frequency transfer networks [105–108], the most extensive of which is the European NEAT-FT [31,97,105,106]. NEAT-FT and other time and frequency transfer links based on the stabilized transfer of a narrow range of optical frequencies are cost-effective to implement because the stabilized signals occupy only one telecommunications channel, meaning dark-fiber links are not required, and the stabilized signals can co-exist with data traffic. There was initial concern that cross-talk between the channels used for data transmission and the channel for the stabilized signal transfer would degrade the achievable transfer stability. However, no or neg-
ligible degradation has been observed [94].

2.4.3 Modulation of a Continuous-Wave Laser

In practice the most straightforward solution for the transfer of radio and microwave frequencies is by the direct modulation of a CW laser carrier signal [40]. An optical oscillator at the local site is modulated at the desired frequency and is inserted into the link. The laser is typically free-running and can be modulated using a variety of techniques including directly driving the current of the laser or external modulation with a Mach-Zehnder interferometer (MZI). The frequency references are extracted at the remote end by demodulation of the received signal. A retro-reflector, circulator, or transceiver is used to return a related signal to the local site, where the phase of the radio or microwave frequency signal is compared to a reference signal. In many systems, group delay actuators are used to compensate for phase fluctuations at the remote end by altering the total optical path length [109–111], while many recent systems employ phase-conjugate signal mixing to feedback to the laser modulator [71, 73, 83, 112].

Although this is the simplest transmission method, transceivers and phase detectors can quickly cause stabilization systems to become more complicated [71, 78, 83, 109]. The use of bulky group-delay actuators can become a problem where equipment space is limited. These transmission schemes suffer from signal fading at certain points along the fiber link where the modulation sidebands destructively interfere with each other due to chromatic dispersion within the fiber [40, 113]. These problems can be overcome through the use of dispersion compensating fiber or single-sideband modulators. Despite these limitations, amplitude modulated stabilized microwave transfer systems have recorded frequency instabilities as low as $1.3 \times 10^{-15}$ at one second of integration time [109].

Some of the earliest work on microwave transfer over fiber was conducted by the Jet Propulsion Laboratory (JPL) in the 1980s [114] for application to NASA’s Deep
Space Network (DSN). The DSN is a network of radio antennas, situated approximately 120° apart around the world, supporting interplanetary spacecraft missions as well as other radar and radio astronomy observations. The three DSN sites are near Goldstone in the USA, Madrid in Spain, and Canberra in Australia. Each site incorporates multiple antennas that need to be referenced to a master hydrogen-maser that can be several kilometres away. Initially, the DSN employed coaxial cable to transfer time and frequency references, but the advent of optical fibers and increasingly stringent phase stability requirements to enable higher precision radio science experiments led to the development and testing of a series of fiber-based high-precision frequency distribution systems [82, 114–117], eventually culminating in a system that transmitted a stabilized microwave frequency reference over nearly 20 km of buried fiber cable using a thermally controlled fiber spool for actuation [82].

Stabilized radio and microwave frequency transfer systems have since been successfully employed on other antenna arrays such as on the Atacama Large Millimetre Array (ALMA) and are discussed in detail in Section 2.4.5 below.

Researchers at LNE-SYRTE improved on the technique, demonstrating world-leading stabilities at both radio and microwave frequencies [78, 90, 109, 110, 118]. The LNE-SYRTE researchers implemented a technique of using a piezo-electric fiber stretcher (fast feedback, low range) in combination with a thermally controlled spool (slow feedback, high range) to achieve much higher compensation bandwidths and superior noise suppression than the DSN technique. The LNE-SYRTE groups also implemented polarization scrambling to overcome the link phase noise symmetry violation caused by PMD (as discussed in Section 2.3.2). These techniques have allowed the LNE-SYRTE groups to achieve the state-of-the-art in both radio and microwave frequency transfer.

A number of groups have also implemented stabilized radio and microwave frequency transfer systems in which the phase noise detection and correction is achieved in the radio or microwave domain rather than the optical domain [119, 120], using techniques such as opto-electronic delay-locked-loops [121, 122].
Table 2.3: Stabilized radio and microwave frequency transfer fractional frequency results from a selection of significant works. Freq is the transmitted radio or microwave frequency, L is the length of the fiber link, \( \sigma_y(1 \text{ s}) \) is the fractional frequency stability at 1 s integration time, and \( \sigma_y(10^3 \text{ s}) \) is the fractional frequency stability at 1000 s integration time. (N/A — value not reported.)

<table>
<thead>
<tr>
<th>Author and year</th>
<th>Freq (MHz)</th>
<th>Distance (km)</th>
<th>( \sigma_y(1 \text{ s}) )</th>
<th>( \sigma_y(10^3 \text{ s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daussy et al. 2005</td>
<td>100</td>
<td>86</td>
<td>( 3 \times 10^{-14} )</td>
<td>( 1.3 \times 10^{-16} )</td>
</tr>
<tr>
<td>Lopez et al. 2008</td>
<td>1000</td>
<td>86</td>
<td>( 5 \times 10^{-15} )</td>
<td>( 4 \times 10^{-17} )</td>
</tr>
<tr>
<td>Lopez et al. 2010</td>
<td>9150</td>
<td>86</td>
<td>( 1.3 \times 10^{-15} )</td>
<td>( 7 \times 10^{-18} )</td>
</tr>
<tr>
<td>Fujieda et al. 2010</td>
<td>1000</td>
<td>204</td>
<td>( 6 \times 10^{-14} )</td>
<td>( 1.5 \times 10^{-15} )</td>
</tr>
<tr>
<td>Wang et al. 2012</td>
<td>9100</td>
<td>80</td>
<td>( 7 \times 10^{-15} )</td>
<td>( 4 \times 10^{-17} )</td>
</tr>
<tr>
<td>He et al. 2013</td>
<td>20</td>
<td>100</td>
<td>( 3 \times 10^{-13} )</td>
<td>( 5 \times 10^{-16} )</td>
</tr>
<tr>
<td>Śliwczyński et al. 2015</td>
<td>10</td>
<td>2960</td>
<td>( 2 \times 10^{-12} )</td>
<td>( 7 \times 10^{-14} )</td>
</tr>
<tr>
<td>Krehlik et al. 2016</td>
<td>10</td>
<td>615</td>
<td>N/A</td>
<td>( 1 \times 10^{-15} )</td>
</tr>
</tbody>
</table>

Other stabilized radio and microwave frequency transfer techniques have been developed that use phase-conjugation to achieve a stable transfer [71,72,123]. This technique (often described as passive stabilization [71, 73, 107]) employs a second modulated laser at the remote site transceiver, transmitting a harmonic of the received frequency reference. Special mixing techniques enable the link phase noise to be cancelled out and a stable reference signal to be extracted and used to modulate the remote site laser. This technique has been demonstrated over distances on the order of 100s of kilometres [123], and has been adapted to enable transfer over branching fiber networks [73,107,112].

A summary of significant radio and microwave frequency experiments is shown in Table 2.3.

2.4.4 Optical Frequency Comb Transfer

As discussed in the previous sections, optical frequency transfer provides better short-term absolute frequency and phase stability than radio or microwave frequency transfer, but often requires the use of an optical frequency comb at the remote end in order to make useful measurements [28,87,88]. Similarly, microwave transfer such as that discussed in Section 2.4.3 requires an optical frequency comb in order
to make optical frequency measurements. Simultaneous transfer of optical and microwave frequencies can be achieved by directly transmitting an optical frequency comb. The optical frequency comb is produced by the pulse train of a mode-locked laser [127, 128]. The comb can be stabilized to either a microwave or optical frequency reference at the transmitter end and provides the end user with a large number of harmonically related microwave frequencies, which can be extracted using a PD, or the optical frequencies can be used directly. When the transmitted comb is stabilized to an optical frequency standard, both the microwave and optical frequencies produced by the comb possess the stability of the optical standard [40, 129]. However, optical frequency combs greatly increase the technical complexity of the transfer systems since detection of the comb signal suffers from amplitude-to-phase conversion, dispersion of the pulse train, and the requirement to stabilize the frequency comb in two degrees of freedom (frequency offset and repetition rate). The expense and complexity of optical frequency combs tends to limit their application to specialized laboratory applications.

Another limitation of optical frequency comb transfer is the large bandwidth occupied by the comb. This means that optical comb transfer requires a dedicated dark fiber with no other telecommunication signals on the line. Renting a dedicated fiber from telecommunications companies is logistically complicated and expensive, and this expense sometimes precludes the use of frequency comb transfer techniques. Optical carrier transfer and modulated carrier techniques use minimal bandwidth and only require a single ITU channel, meaning these signals can coexist on fiber links with telecommunications data, making the use of commercial fiber networks more practical and affordable.

Possibly the earliest work on frequency comb transfer was by Holman and colleagues in 2004, first transmitting an unstabilized frequency comb [130], and then implementing stabilized transfer in a later experiment [131]. These experiments were followed by Hou and colleagues several years later [132], and by the work of
CHAPTER 2. TECHNICAL BACKGROUND

Marra and colleagues [62, 128, 129, 133], and their publications currently represent the definitive work on stabilized frequency comb transfer.

The flexibility of frequency comb transfer in terms of usable output signal has meant that the technique enjoys continued interest and development [127, 134]. Recent developments in stabilized frequency comb transfer include the use of feedback via ethernet network for phase noise correction [135]. This feedback method (amusingly dubbed “carrier pigeon control” by its authors) severely limited the bandwidth of the phase noise correction, but was shown to be reliable and flexible to implement. Another recent frequency comb development includes the high-precision transfer of time signals at the 100 ps accuracy level by Lessing and colleagues [136].

2.4.5 Application to Antenna Arrays

The work undertaken on the DSN [82] discussed in Section 2.4.3 represents the first attempts to provide real-time reference signal phase stabilization for antenna arrays. Around the same time, post hoc phase noise correction methods in which the phase deviations of a round trip reference signal were recorded and removed during correlation of the data from the antenna array were implemented on the Very Large Array (VLA) [137], e-Merlin in the UK [138], and the Australia Telescope Compact Array (ATCA) [139]. The VLA and e-Merlin systems have proved to be very successful and have operated for many years with occasional improvements and upgrades. The ATCA system was found to be unnecessary and its use was discontinued.

The ALMA telescope in Chile employs real-time phase correction of the local oscillator (LO) reference signals disseminated to each antenna in the array [16, 111, 140–144]. The ALMA systems use a slave laser offset-locked to a master laser to provide the large microwave frequency modulation (> 100 GHz) required by the ALMA receivers. The group delay of the resulting photonic signal is stabilized using fiber stretchers and thermally controlled spools. The basic concepts of this design
formed the basis for the stabilized radio and microwave frequency transfer systems presented in this thesis (described in detail in Chapters 3, 4, and 5). Although not used on the final ALMA systems, LO phase correction technologies developed and tested as part of the ALMA project include several features that are common to the systems presented in this thesis including: generation of a photonic MW signal using a dual-parallel Mach-Zehnder modulator [145], photonic measurement of the round-trip phase of the MW signal and phase correction of the transmitted signal without mechanical actuation [146], and separation and detection of the phase error signals in the RF domain rather than the optical domain [147]. The design of the systems presented in this thesis differ substantially from the ALMA systems because they are optimized to the frequencies and other engineering requirements of the SKA1-LOW and SKA1-MID radio telescopes.

Recently, tests of long-distance stabilized frequency transfer for VLBI have generated a great deal of interest because of the obvious advantages of these techniques in terms of flexibility of reference source and the promise they hold of increasing the resolution and sensitivity of VLBI experiments in the coming years [15, 17, 18]. In 2013, Baldwin and colleagues [123] performed tests of stabilized radio-frequency transfer over a 310 km fiber link that produced VLBI measurements that were indistinguishable from those using the local hydrogen maser. In 2015, a group in Italy used frequency combs and a coherent optical frequency link to calibrate an observatory’s hydrogen-maser against a caesium fountain clock 550 km away [148]. The same group then modified their experiment to deliver the stability of a remote hydrogen maser [149] and a caesium fountain [28, 150] for use as the observatory’s frequency reference, showing in both cases that the reference delivered using the 550 km link was as good as the local hydrogen-maser. A group in Poland have also successfully used remote standards to reference antennas for VLBI [151,152], demonstrating effective delivery over 345 km of a hydrogen-maser signal using stabilized radio frequency transfer, as well as preliminary results using a stabilized optical frequency link and optical frequency comb to reference the observatory to a strontium
lattice optical clock. The hydrogen-maser signal transmitted using the stabilized radio frequency dissemination method proved so robust that the observatory has switched to permanent use of the remote hydrogen-maser signal.
When God said “Let there be light”, he surely must have meant perfectly coherent light!

— Charles H. Townes

3

Dual-Servo Frequency Transfer

Foreword

This chapter is based on a manuscript accepted for publication in IEEE Photonics Technology Letters (Pre-print available: https://doi.org/10.1109/LPT.2017.2776243) and is a reproduction of the author accepted manuscript. The chapter describes an early prototype version of a stabilized microwave frequency transfer system initially considered for application in the SKA1-MID radio telescope. The system could be converted, with minimal modification, to a radio frequency transfer system suitable for SKA1-LOW. Laboratory testing of the system was carried out between July and October 2014 and proved very successful but, during field tests at the ASKAP telescope, it was found that the transmitter module was sensitive to low frequency acoustic vibrations from cooling fans in the observatory’s correlator room. The transfer system was subsequently redesigned to be robust against this noise source. (The modified systems are described in Chapters 4 and 5.) However, the work is still of interest to the time and frequency transfer community because it describes a simple way of constructing a hybrid frequency transfer system capable of delivering stabilized optical, microwave, and radio frequency signals simultaneously to a remote user. The manuscript was written with this application in mind and does
CHAPTER 3. DUAL-SERVO FREQUENCY TRANSFER

not refer to the design’s origin as an SKA prototype system.

The work presented in this chapter is a reproduction of the manuscript accepted for publication in IEEE Photonics Technology Letters reformatted to be consistent with the rest of this thesis.

My contribution to the research was 50% of the experimental work, which was undertaken jointly with Dr Sascha Schediwy, and I contributed approximately 80% of the preparation of the manuscript.

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Simultaneous Transfer of Stabilized Optical and Microwave Frequencies Over Fiber

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3.1 Abstract

We demonstrate simultaneous stabilization of optical and microwave signals on an optical-fiber link by independently stabilizing two optical signals that are separated by a nominated microwave frequency. This system can be implemented on conventional stabilized optical frequency transfer networks without degrading the stability of the optical signal, increasing the scope of applications of existing and future large-scale frequency transfer networks. For a 30 km optical-fiber link, we demonstrate a 193 THz optical carrier transfer absolute frequency stability of $4.9 \times 10^{-5}$ Hz at $10^3$ s, and a 10.02 GHz microwave signal transfer absolute frequency stability of $1.3 \times 10^{-4}$ Hz at $10^3$ s.

3.2 Introduction

The push to apply the unrivalled performance of optical atomic clocks to scientific experiments including geodesy [153], radio astronomy [28, 151], and tests of fundamental physics [31, 154], has driven scientific communities to begin implementing permanent frequency transfer networks such as the European NEAT-FT [31, 97] and the Beijing Regional Time and Frequency Network [107, 108].

The NEAT-FT network and other high-precision frequency comparison experiments [95–97], have employed stabilized optical frequency transfer because of the superior fractional frequency stability of optical-frequency signals over radio-frequency
(RF) and microwave (MW) signals [31,110]. However, many applications of frequency transfer in science, commerce, and industry require RF or MW signals in order to interface with their electronic systems [40]. While optical-to-RF and optical-to-MW conversion methods using optical frequency combs are well tested [28,87,88], the required equipment is expensive and complex. The range of applications and experiments supported by frequency transfer networks can be improved by the direct provision of stabilized RF and MW signals. Many of the applications of RF and MW transfer will benefit even at the expense of inferior fractional frequency stability compared with optical frequency transfer.

A stabilized MW transfer technique based on optical phase-sensing and actuation has been demonstrated previously [155]. This MW transfer technique exploited the technology and techniques of stabilized optical frequency transfer to provide a stabilized MW frequency to the remote end of a link previously used for optical frequency transfer. In this paper, we present a related technique that provides a stabilized MW signal to the remote site, and without degrading the stability of the optical frequency.

### 3.3 Theory

Other stabilized MW transfer techniques use physically bulky group delay actuators [109], or relatively complicated receiver units at the remote site [71,72], to achieve stabilization and to mitigate unwanted reflections on the fiber link. The technique presented here uses optical phase sensing and actuation and so is able to benefit from the advantages of optical frequency transfer in terms of reduced size and complexity of the stabilization equipment.

The technique involves splitting the optical carrier signal into two physically separate paths, applying a fixed microwave-frequency shift to one of the optical paths, and simply duplicating the conventional optical stabilization servo system, before
recombining the two optical paths into a single fiber link. This creates two, independently stabilized optical signals that are separated by a given microwave frequency. We show that the microwave frequency is also stabilized and that the optical transfer stability is not degraded by the presence of a second optical frequency. Previously, comparable stabilized MW transfer systems have used a second laser slaved to the master laser using an offset lock [16]. Any phase noise in the offset locking system is imprinted onto the MW signal received at the remote end, meaning that complex offset locking systems are required to minimize this noise contribution. Frequency shifting the optical carrier by means of Carrier-Suppressed Single Sideband (CS-SSB) modulation, as presented here, provides a simple way of generating a second optical signal with minimal phase noise relative to the original carrier.

Currently available commercial acousto-optic modulators (AOMs) can generate positive or negative frequency shifts of on the order of 200 MHz, and commercial dual-parallel Mach-Zehnder modulators (DP-MZMs), can generate frequency shifts up to around 20 GHz [145, 156].

The dual-stabilization technique described only occupies one 100 GHz ITU optical fiber telecommunications channel (and also the 50 GHz and 25 GHz grid subdivisions), so frequency references can be transmitted simultaneously with data traffic (assuming a properly configured link architecture as in [110] and [90]), and only a standard photodetector (PD) is required at the remote site to generate the received microwave signal. The theory behind this dual-stabilization technique is outlined below.

The optical signal $\nu_{Opt}$ from a laser is split into the two arms of a Mach-Zehnder interferometer (MZI, see Figure 3.1). A frequency shift, $\nu_{MW}$, is applied to one of the arms (designated Arm-B) while the optical signal passing through the other arm (Arm-A) is un-modified. Each signal then passes through its servo AOM (correspondingly designated AOM-A and AOM-B). The AOMs apply a frequency shift $\nu_{AOM}$ centered on a nominal value plus a correctional frequency shift, $\Delta \nu_{AOM}$, determined by the feedback from the servo electronics. Prior to these servo AOMs,
CHAPTER 3. DUAL-SERVO FREQUENCY TRANSFER

the two optical signals will have also picked up phase perturbations $\Delta \phi_{A1}$ and $\Delta \phi_{B1}$ in the arms of the MZI. The two optical signals are then recombined at the output of the MZI and inserted into the optical-fiber link, where they experience phase perturbations $\Delta \phi_{A,\text{Link}}$ and $\Delta \phi_{B,\text{Link}}$ due to environmental noise on the link. At the remote site, prior to the PD, the signals pass through a remote AOM, Re.AOM. The frequency shift imposed on the optical signals by Re.AOM is used to separate the desired round-trip signal from spurious reflections on the fiber link. The optical signals reaching the remote site are then:

$$

\nu_{A,\text{Rem}} = \nu_{\text{Opt.}} + \nu_{AOM-A} + \Delta \nu_{AOM-A} + \Delta \dot{\phi}_{A1}/2\pi + \nu_{\text{Re.AOM}}, \quad \text{and}

$$

$$

\nu_{B,\text{Rem}} = \nu_{\text{Opt.}} + \nu_{\text{MW}} + \nu_{AOM-B} + \Delta \nu_{AOM-B} + \Delta \dot{\phi}_{B1}/2\pi + \nu_{\text{Re.AOM}}.

$$

The resulting electronic beat frequency between the two is

$$

\nu_{\text{Remote}} = \nu_{\text{MW}} - (\nu_{AOM-A} + \Delta \nu_{AOM-A}) + (\nu_{AOM-B} + \Delta \nu_{AOM-B}) - (\Delta \dot{\phi}_{A1}/2\pi - \Delta \dot{\phi}_{B1}/2\pi) - (\Delta \dot{\phi}_{A,\text{Link}}/2\pi - \Delta \dot{\phi}_{B,\text{Link}}/2\pi).

$$

The optical signals are reflected from the remote site by a Faraday mirror (FM), and return along the fiber link to the transmitter. Noise processes that occur more slowly than the light round-trip time (RTT) impose coherent phase noise components on the outgoing and returning signals. The returning signals are split into the two arms of the MZI where they make a second pass through the AOMs and are received at a separate PD in each arm. The returning signals beat against optical reference frequencies at the PD where $\nu_{\text{Opt.}} + \nu_{\text{MW}} + \Delta \dot{\phi}_{B1}/2\pi$ is the reference for Arm-B, and $\nu_{\text{Opt.}} + \Delta \dot{\phi}_{A1}/2\pi$ is the reference for Arm-A. The transmission laser has been selected with a coherence length that is longer than the RTT of the transmitted signals and so it can be assumed that $\nu_{\text{Opt.}}(0) = \nu_{\text{Opt.}}(\text{RTT})$. Electronic band-pass filtering after the PDs is used to reject the unwanted signals resulting from the portion of
3.3. THEORY

![Schematic diagram of our dual-optical stabilization technique.](image)

\[ \nu_{\text{Opt.}} = 193 \, \text{THz}; \ \nu_{\text{LO} - \text{A}} = 11.25 \, \text{MHz}; \ \nu_{\text{LO} - \text{B}} = 20 \, \text{MHz}; \ \nu_{\text{Re.AOM}} = 50 \, \text{MHz}; \ \text{FM}, \ \text{Faraday mirror}; \ \text{AOM}, \ \text{acousto-optic modulator}; \ \text{PD}, \ \text{photodetector}; \ \text{LO}, \ \text{local oscillator}; \ \text{Mix}, \ \text{frequency mixer}; \ \text{DP-MZM}, \ \text{dual-parallel Mach-Zehnder modulator}; \ \text{C}, \ \text{frequency counter}. \]

the Arm-A signal returning through Arm-B and vice versa. The resulting, filtered, electronic signals are:

\[ \nu_{\text{A,Loc}} = 2\nu_{\text{AOM} - \text{A}} + 2\Delta \nu_{\text{AOM} - \text{A}} + 2\Delta \dot{\phi}_{\text{A,Link}}/2\pi + 2\nu_{\text{Re.AOM}}, \quad \text{and (3.4)} \]

\[ \nu_{\text{B,Loc}} = 2\nu_{\text{AOM} - \text{B}} + 2\Delta \nu_{\text{AOM} - \text{B}} + 2\Delta \dot{\phi}_{\text{B,Link}}/2\pi + 2\nu_{\text{Re.AOM}}. \quad \text{(3.5)} \]

The beat signals described by Equations (3.4) and (3.5) are frequency divided by a factor of \( \gamma \) to reduce the likelihood of servo cycle-slip when encountering large link fluctuations.

\[ \nu_{\text{A,Loc,Div}} = \frac{2\nu_{\text{AOM} - \text{A}} + 2\Delta \nu_{\text{AOM} - \text{A}} + 2\Delta \dot{\phi}_{\text{A,Link}}/2\pi + 2\nu_{\text{Re.AOM}}}{\gamma_A}, \quad \text{and (3.6)} \]

\[ \nu_{\text{B,Loc,Div}} = \frac{2\nu_{\text{AOM} - \text{B}} + 2\Delta \nu_{\text{AOM} - \text{B}} + 2\Delta \dot{\phi}_{\text{B,Link}}/2\pi + 2\nu_{\text{Re.AOM}}}{\gamma_B}. \quad \text{(3.7)} \]
The signals described by Equations (3.6) and (3.7) are mixed with appropriate local oscillators, $\nu_{LO}$, in this case, twice their servo AOM frequency plus twice the Re.AOM frequency, divided by the frequency division factor, $\gamma$.

$$\nu_{LO,A} = \frac{2\nu_{AOM,A} + 2\nu_{Re,AOM}}{\gamma_A}, \text{ and} \quad (3.8)$$

$$\nu_{B,Loc} = \frac{2\nu_{AOM,B} + 2\nu_{Re,AOM}}{\gamma_B} \quad (3.9)$$

This results in two error signals that contain the phase noise information of the relevant optical signal, and are used to steer the synthesizers driving the AOMs. The control signals are:

$$\nu_{\alpha} = 2\nu_{AOM,A} + 2\Delta \dot{\phi}_{A,Link}/2\pi, \text{ and} \quad (3.10)$$

$$\nu_{\beta} = 2\nu_{AOM,B} + 2\Delta \dot{\phi}_{B,Link}/2\pi \quad (3.11)$$

Engaging the stabilization servos has the effect of driving $\nu_{\alpha}$ and $\nu_{\beta}$ to zero. As a result, the magnitude of the $\Delta \nu_{AOM}$ signals are such that they cancel the phase noise resulting from a single pass of the link (within the bandwidth defined by the RTT).

$$\Delta \nu_{AOM,A} = \Delta \dot{\phi}_{A,Link}/2\pi, \text{ and} \quad (3.12)$$

$$\Delta \nu_{B} = \Delta \dot{\phi}_{B,Link}/2\pi. \quad (3.13)$$

Substituting these values into Equation (3.3) gives
\[ \nu_{\text{Remote}} = \nu_{\text{MW}} - \nu_{\text{AOM-A}} - \nu_{\text{AOM-B}} - \Delta \dot{\phi}_A / 2\pi + \Delta \dot{\phi}_B / 2\pi. \] (3.14)

So at the remote site, the phase noise resulting from perturbations on the fiber link, is suppressed for both of the optical signals, as well as the microwave signal (with some contamination from the \( \Delta \dot{\phi}_A \) and \( \Delta \dot{\phi}_B \) terms).

### 3.4 Experimental setup

This frequency transfer technique was demonstrated over 30 km of optical fiber spool in the laboratory because this was the longest single length available to us within the coherence length of our laser source. A Grade 4 RIO PLANEX diode laser (spectral line width < 3 kHz) was used to transmit a 1552 nm (193 THz) optical signal. In Arm-A the signal was frequency shifted +50 MHz by AOM-A. In Arm-B the optical signal was shifted +10.00 GHz by a DP-MZM configured to produce CS-SSB modulation, and then further shifted +70 MHz by AOM-B. This, resulted in a 10.02 GHz frequency difference between the two optical signals.

The DP-MZM used in this experiment was constructed in-house from two dual-drive Mach-Zehnder modulators (DD-MZMs). The DD-MZMs were connected in parallel, with a piezoelectric fiber stretcher in-line with one of the units to provide optical phase control, essentially mimicking the functionality of a commercial DP-MZM. Electronic and optical signal phases were adjusted appropriately to produce CS-SSB modulation.

The remote site was co-located in the same laboratory as the signal source, allowing an independent measurement of the transfer stability of the three signals (the two optical signals plus the resulting MW modulation). The Re-AOM frequency was +40 MHz. Three Agilent 53132A Λ-type frequency counters were used to produce triangle-weighted estimates of the absolute frequency stability of the microwave sig-
nal and the two optical signals. The out-of-loop fiber connections were kept as short and as thermally isolated as practicable.

The division ratios used for the local PD beat signals, as described in Equations (3.6) and (3.7), were a factor of 16 for Arm-A and a factor of 11 for Arm-B because these were available.

3.5 Results and discussion

Figure 3.2 shows the absolute frequency stability of the optical and microwave signals, as measured by the frequency counters, plotted as a function of integration time. The absolute stability of the signals is reported here because this more clearly highlights the relationship between the stabilities of the optical and microwave signals. It is the absolute stability of optical signals, rather than their fractional stabilities, that govern the absolute stability of the MW signal. The fractional frequency stability can be easily obtained by dividing the absolute frequency stability by the frequency of the signal.

In this plot, dashed lines with open markers indicate the absolute frequency stability of the optical and microwave signals at the remote site when the frequency dissemination was unstabilized. Solid lines with filled markers indicate the stability of the signals with active stabilization.

The unstabilized absolute frequency stability of the optical signals (light-green open triangles and dark-green open circles, dashed lines) are 3.0 Hz at 1 s and 1.2 Hz at $10^3$ s of integration, while the absolute frequency stability for the microwave signal (blue, open diamonds, dashed line) is more than three orders of magnitude lower at $2.0 \times 10^{-3}$ Hz at 1 s and $2.9 \times 10^{-4}$ Hz at $10^3$ s. Although the instability of the MW is a combination of the instabilities of optical signals, much of the noise on the two optical signals will be common to both signals because the environmental noise affecting the optical link will affect the signals in similar ways. This means that
Figure 3.2: Absolute frequency stability in Hz of optical and microwave signals plotted against integration time in seconds. The traces for the unstabilized optical signals lie on top of each other.
large frequency fluctuations in the optical signals do not necessarily correspond to 
large frequency fluctuations in the MW signal.

With the stabilization servos engaged, the stability of the optical signals is im-
proved by more than three orders-of-magnitude. The optical signals from Arm-
A (dark-green, filled circles, solid line) achieves absolute frequency stabilities of 
$1.7 \times 10^{-3}$ Hz at 1 s and $4.9 \times 10^{-5}$ Hz at $10^3$ s. The stability of the optical signal 
from Arm-B (light-green, filled triangles, solid line; which includes the DP-MZM) 
is $1.7 \times 10^{-3}$ Hz at 1 s and $1.3 \times 10^{-4}$ Hz at $10^3$ s. These absolute stabilities 
are equivalent to fractional frequency stabilities of $8.8 \times 10^{-18}$ at 1 s, placing these 
results amongst the best stabilized optical frequency transfer performances reported 
for comparable fiber link lengths [31, 97]. We attribute the poorer performance of 
the Arm-B optical signal at long time-scales to thermal changes in the DP-MZM, 
which was not actively stabilized and, being constructed from discrete components, 
comprised several meters of fiber, making it very sensitive to temperature changes. 
The microwave transfer stability (blue, filled diamonds, solid line) improves to an 
absolute frequency stability of $1.7 \times 10^{-3}$ Hz at 1 s and $1.1 \times 10^{-4}$ Hz at $10^3$ s. 
At integration times greater than 10 s this overlaps, within the measurement uncer-
tainty, the absolute transfer stability of the optical signal from Arm-B, showing that 
the microwave transfer can be stabilized to the same absolute level as the optical 
transfer. When the stabilization systems are active, common frequency fluctuations 
between the two optical signals are mostly suppressed and no longer dominate the 
instability of the optical signals. The stability of the MW signal is then set by 
the absolute stabilities of the optical signals. In situations, such as the experiment 
reported here, where one of the two optical signals exhibits significantly poorer sta-
bility than the other, the absolute stability of the stabilized MW signal then follows 
the absolute stability of the least-stable of the two optical signals. The MW transfer 
stability is similar to several other reported techniques (e.g. [155] and [157]), and 
two orders of magnitude worse that the best performing systems [109].
With AOM-B disabled, thus not allowing an optical signal to propagate from Arm-B, the system functions as a conventional optical-frequency stabilization system. The transfer stability of the optical signal from Arm-A was measured and found to remain unchanged when the signal from Arm-B was disabled. The stabilized MW transfer is achieved without degradation of the stability of the optical signals. While both optical signals are present at the remote site, the frequency separation between them allows for easy electronic filtering after frequency comparison and mixing in the optical domain has been completed.

Because the optical transfer is unaffected by the inclusion of the MW transmission modifications, and the absolute frequency stability of the MW signal is set by the absolute frequency stability of the optical signals, the fractional frequency stability of the MW transfer can easily be increased by increasing the MW frequency. For example, doubling the value of the MW frequency will not affect the achieved absolute frequency stability, but will improve the fractional frequency stability by a factor of two.

3.6 Conclusions

We have demonstrated that by using this dual-stabilization technique, existing optical transfer networks may be modified to also disseminate stabilized microwave signals without degradation of the optical transfer stability. The technique enjoys several advantages of optical phase sensing and optical phase actuation systems over other stabilized RF and MW signal transfer techniques including compact size, large feedback bandwidth, and infinite feedback range. We expect that the overall stability at longer integration times will be improved by the use of a commercial DP-MZM unit instead of the two parallel DD-MZM device used in these tests due to the reduced sensitivity to thermal changes and mechanical noise. The achieved stability and effective transmission distance can also be significantly improved by employing
a laser source with a smaller line-width and longer coherence length. Better thermal isolation of the local-site systems will greatly improve the transfer stability at integration times beyond $10^3$ s. The fractional frequency stability of the transferred MW signal can immediately be improved by increasing the magnitude of the MW frequency shift. A less complex RF dissemination system (not requiring a DP-MZM and associated electronics) for frequencies up to around 200 MHz can be implemented without the microwave frequency shifter by simply utilizing the frequency difference between two servo AOMs. Multiple, additional RF and MW signals can be transmitted by employing an extra servo system per desired transfer frequency. The stabilized frequency transfer is compatible with active telecommunication links if the non-bidirectional components of the link are bypassed as in [110] and [90].
Radio Frequency Transfer for SKA1-LOW

Foreword

Following on from the stabilized frequency transfer system design presented in Chapter 3, the SKA system prototypes were redesigned to be robust against acoustic frequency noise impacting on the transmitter unit. The re-design made it necessary to develop two substantially different frequency transfer systems, a radio frequency transfer system for SKA1-LOW presented here, and a microwave frequency version for SKA1-MID presented in Chapter 5.

This chapter gives a mathematical description of the functionality of the system, explaining how phase noise resulting from mechanical vibrations affecting the Mach-Zehnder modulator used to encode the radio frequency modulation are suppressed, along with compensating the phase noise of the fiber link. The performance of the system is then experimentally verified over a 166 km fiber link (which had become available after the conclusion of the experiments presented in Chapter 3), significantly longer than the longest fiber links required by SKA1-LOW. The potential benefits of the new radio frequency transfer system design to the time and frequency metrology community are also discussed, because the system offers a quick and simple way of converting existing stabilized optical frequency transfer networks into
stabilized radio frequency transfer networks, which may have uses in applications of frequency transfer or phase synchronization where optical transfer is not suitable.

The development of the system described in this chapter was undertaken before the development of the microwave frequency version presented in Chapter 5. However, the paper describing the design and performance of the microwave frequency transfer system ([155]), and which comprises the body of Chapter 5, was published before the work presented here. As a result this chapter contains references to the microwave frequency transfer paper and so, in effect, to Chapter 5. The author has made the decision to present the work in this order because it provides a clearer exposition of the research and corresponds to the chronological order of the work undertaken.

The work presented in this chapter is a reproduction of a manuscript accepted for publication in *IEEE Photonics Technology Letters*. The manuscript has been reformatted to be consistent with the rest of this thesis.

My experimental contribution to this research was 50% and I prepared 60% of the manuscript.

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Simple Stabilized Radio-Frequency Transfer with Optical Phase Actuation

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\subsection{Abstract}

We describe and experimentally evaluate a stabilized radio-frequency transfer technique that employs optical phase sensing and optical phase actuation. This technique is achieved by modifying existing optical frequency transfer equipment and also exhibits advantages over previous stabilized radio-frequency transfer techniques in terms of size and complexity. Acousto-Optic Modulators (AOMs) are used to modulate an optical carrier. Stabilization of frequency fluctuations in the link is achieved by steering the frequency of one of the AOMs. We demonstrate the stabilized transfer of a 160 MHz signal over a 166 km fiber optical link, achieving an Allan deviation of $9.7 \times 10^{-12}$ at 1 s of integration, and $6.4 \times 10^{-15}$ at $10^4$ s. This technique was considered for application to the Square Kilometre Array SKA1-low radio telescope.

\subsection{Introduction}

Fiber-optic frequency transfer networks, such as the European NEAT-FT\cite{31,97,105} and the Beijing regional time and frequency network\cite{107,108}, are now being rolled-out on national and international scales, driven by cutting-edge research in metrology and other physical sciences including the distant comparison of optical atomic clocks, high-precision remote spectroscopy, radio astronomy, geodesy, and tests of...
fundamental physics [31, 40, 110]. The NEAT-FT network, and other long-distance frequency comparison experiments [95–97], have typically transmitted stabilized optical-frequency signals because of their superior fractional frequency stability over optically disseminated radio-frequency (RF) and microwave (MW) signals [31, 110]. However, many applications of stabilized frequency transfer in science, commerce, and industry require RF transmissions [40], and will benefit even at the expense of inferior stability performance compared to optical frequency transfer. These applications cannot be interfaced directly with optical frequencies, and while optical-to-RF conversion methods exist [28, 87, 88], the required equipment remains expensive and complex.

Stabilized RF and MW dissemination systems typically require bulky group-delay actuators (thermally controlled fiber spools) [78, 109] or a separate remote-site transmission system operating in a phase-locked-loop [71, 72], and are not compatible with existing optical frequency transfer infrastructure such as that demonstrated in [97], [96] and [95].

In this paper, we present a modification of the technique reported in [155] to create a simple and compact stabilized RF transfer system that uses only the optical and electronic components used in standard stabilized optical transfer systems [85], to enable existing optical transfer infrastructure to readily be converted to provide stabilized RF transfer.

4.3 Theory

The RF transfer technique presented here is significantly simpler to implement than the technique described in [155] because it does not use a dual-parallel Mach-Zehnder modulator to frequency-shift the optical carrier signal, and employs a different arrangement of Michaelson (MI) and Mach-Zehnder (MZI) interferometers. Instead of the dual-parallel Mach-Zehnder modulator, the optical signal from the laser is
frequency shifted using acousto-optic modulators (AOMs). The AOMs are setup in a MZI arrangement within one arm of a MI, requiring fewer alterations to the optical architecture of optical transfer systems than the technique in [155]. Furthermore, this arrangement of MI and MZI produces a different set of signals at the servo photodetector (PD) compared with [155], which require significantly simpler servo electronics.

As shown in Figure 4.1, an optical signal with frequency $\nu_L$, is generated by a laser located at the Local Site. Just as is the case in standard stabilized optical transfer techniques [85], the optical signal enters an imbalanced MI via an optical isolator (to prevent reflections returning to the laser). The short arm of the MI provides the physical reference for the optical phase sensing. The frequency $\nu_{ref}$ of the optical reference signal at the photodetector is:

$$\nu_{ref} = \nu_L + \frac{1}{2\pi}(2\phi_{MI}), \quad (4.1)$$
where $\Delta \dot{\phi}_{MI}$ is the undesirable phase noise picked up by the optical signals passing through the MI reference arm.

In the long arm of the MI the optical signal is then split into two arms of a Mach-Zehnder interferometer (MZI), each arm of which contains an AOM. In the case shown in Figure 4.1, the bottom arm of the MZI contains the servo AOM, which has a nominal frequency $\nu_{A_{-srv}}$, and also applies the frequency correction $\Delta \nu_{A_{-srv}}$. The frequency fluctuations due to optical path length changes in the bottom arm of the MZI are represented by $\frac{1}{2\pi} \Delta \dot{\phi}_{MZI,1}$. The top arm of the MZI contains the local anti-reflection AOM, with frequency $\nu_{A_{-lar}}$. The frequency fluctuations in this arm of the MZI are given by $\frac{1}{2\pi} \Delta \dot{\phi}_{MZI,1}$. A combination of up- and down-shifting AOMs gives the greatest RF separation, but any unique combination can be used. (Note — the anti-reflection AOM is not essential for this technique. It serves to provide reflection mitigation as well as increase the frequency separation.)

At the output of the MZI, the two optical signals to be transmitted are now:

$$\nu_{tr,1} = \nu_L + \nu_{A_{-lar}} + \frac{1}{2\pi} \Delta \dot{\phi}_{MZI,1}, \text{ and}$$

$$\nu_{tr,2} = \nu_L + (1 + \Delta)\nu_{A_{-srv}} + \frac{1}{2\pi} \Delta \dot{\phi}_{MZI,2}. \quad (4.3)$$

As the two optical signals pass through the link, they pick-up frequency fluctuations, $\Delta \dot{\phi}_{Lk,i}$, due to optical path length changes in the link that are unique to their specific transmitted frequency.

At the remote site, the two optical signals pass through a remote anti-reflection AOM (again, this AOM is not essential for the technique, but allows rejection of unwanted optical reflections) to give

$$\nu_{rm,1} = \nu_L + \nu_{A_{-lar}} + \nu_{A_{-rar}} + \frac{1}{2\pi} (\Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{Lk,1}), \text{ and}$$

$$\nu_{rm,2} = \nu_L + (1 + \Delta)\nu_{A_{-srv}} + \frac{1}{2\pi} \Delta \dot{\phi}_{MZI,2}. \quad (4.4)$$
At the Remote Site, the signal is split with one part going to a photodetector. The electronic signal $\nu_{rm,e}$ from the beat of $\nu_{rm,1}$ and $\nu_{rm,2}$ is

$$\nu_{rm,e} = \frac{1}{2\pi}(\Delta\dot{\phi}_{MZI,2} - \Delta\dot{\phi}_{Lk,1} + \Delta\dot{\phi}_{Lk,2} - \Delta\dot{\phi}_{Lk,1}) + (1 + \Delta)\nu_{A-srv} - \nu_{A-lar}. \quad (4.6)$$

A Faraday mirror (FM) reflects the two optical signals back through the link to the Local Site where they then pass back through the MZI. The returning reflected optical signals reaching the photodetector for the MI are then:

$$\nu_{rf,1} = \nu_L + 2(\nu_{A-lar} + \nu_{A-rar} + \frac{1}{2\pi}(\Delta\dot{\phi}_{MZI,1} + \Delta\dot{\phi}_{Lk,1})), \quad (4.7)$$

$$\nu_{rf,2} = \nu_L + 2((1 + \Delta)\nu_{A-srv} + \nu_{A-rar} + \frac{1}{2\pi}(\Delta\dot{\phi}_{MZI,2} + \Delta\dot{\phi}_{Lk,2})), \quad \text{and (4.8)}$$

$$\nu_{rf,3j} = \nu_L + (1 + \Delta)\nu_{A-srv} + \nu_{A-lar} + 2\nu_{A-rar} + 2\Delta\dot{\phi}_{Lk,j} + \frac{1}{2\pi}(\Delta\dot{\phi}_{MZI,1} + \Delta\dot{\phi}_{MZI,2}). \quad (4.9)$$

where $j$ is 1 or 2 corresponding to the signals on the link. The three signals are at unique frequencies as long as $\nu_{A-srv}$ does not equal $\nu_{A-lar}$. At the photodetector these optical frequencies mix with $\nu_{ref}$ to give the following RF signals.

$$\nu_{RF,1} = 2(\nu_{A-lar} + \nu_{A-rar} + \frac{1}{2\pi}(\Delta\dot{\phi}_{MZI,1} + \Delta\dot{\phi}_{Lk,1} - \Delta\dot{\phi}_{MI})), \quad (4.10)$$

$$\nu_{RF,2} = 2((1 + \Delta)\nu_{A-srv} + \nu_{A-rar} + \frac{1}{2\pi}(\Delta\dot{\phi}_{MZI,2} + \Delta\dot{\phi}_{Lk,2} - \Delta\dot{\phi}_{MI})), \quad \text{and (4.11)}$$
\[ \nu_{RF,3j} = (1 + \Delta)\nu_{A-srv} + \nu_{A-lar} + 2\nu_{A-rar} + \frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{MZI,2} + 2\Delta \dot{\phi}_{Lk,j}). \] 

(4.12)

as well as intermodulation signals. In the electronic domain, the signals are split and bandpass filtered. The RF bandpass filter values are set to \( \nu_{BP,1} = 2(\nu_{A-lar} + \nu_{A-rar}) \) and \( \nu_{BP,2} = 2(\nu_{A-srv} + \nu_{A-rar}) \). The bandpass filters eliminate \( \nu_{RF,3j} \) and the intermodulation signals. The filtered signals are then mixed together, producing the following upper- and lower-sideband frequency products:

\[ \nu_{Mix,1} = 2((1 + \Delta)\nu_{A-srv} + \nu_{A-lar} + 2\nu_{A-rar} + \frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{MZI,2} + \Delta \dot{\phi}_{Lk,1} + \Delta \dot{\phi}_{Lk,2} - 2\Delta \dot{\phi}_{MI})), \] and

\[ \nu_{Mix,2} = 2((1 + \Delta)\nu_{A-srv} - \nu_{A-lar} + \frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,2} - \Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{Lk,2} - \Delta \dot{\phi}_{Lk,1})). \] 

(4.13)

(4.14)

Note that in \( \nu_{Mix,2} \) the frequency perturbation \( \Delta \dot{\phi}_{MI} \) cancels out. A bandpass filter with the center frequency at \( 2 \times (\nu_{A-srv} - \nu_{A-lar}) \) is used to reject \( \nu_{Mix,1} \), before mixing \( \nu_{Mix,2} \) with the servo local oscillator \( \nu_{LO} \) also set at \( \nu_{LO} = 2(\nu_{A-srv} - \nu_{A-lar}) \) to produce an error signal of

\[ \nu_{err} = 2(\Delta \nu_{A-srv} + \frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,2} - \Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{Lk,2} - \Delta \dot{\phi}_{Lk,1})). \] 

(4.15)

When the servo is engaged, the error signal is driven to zero, \( \nu_{err} = 0 \), so:

\[ \Delta \nu_{A-srv} = -\frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,2} - \Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{Lk,2} - \Delta \dot{\phi}_{Lk,1}). \] 

(4.16)

Substituting this into equation (4.6) gives

\[ \nu_{rm,e*} = \nu_{A-srv} - \nu_{A-lar}, \] 

where \( \nu_{rm,e*} \) is the electronic remote signal with the servo engaged.
4.4 Experimental Setup

We describe an experiment using 160 MHz RF transfer, with all optical elements fiberized. An NKT Photonics Koheras BASIK X15 laser (spectral linewidth < 100 Hz) situated at the Local Site, and operating at a wavelength of 1552 nm, produced a laser signal $\nu_L = 193$ THz. The AOMs were Gooch & Housego with $\nu_{A-srv} = +75$ MHz, $\nu_{A-lar} = -85$ MHz, and $\nu_{A-rar} = +40$ MHz. All fiber in the Local Site was polarization-maintaining to ensure the optical power output of the MZI remains maximized. The signal was transmitted through metropolitan optical fiber networks 166 km in length (total one-way loss of 46 dB), with two IDIL Fibres Optiques bi-directional optical amplifiers (with a gain of +18.7 dB and a noise figure of 7.6 dB) used to boost the signal strength. One amplifier was installed at the midpoint of the link (after 83 km), and the other at the Remote Site. The Remote Site components attenuated the reflected signal by a further 12 dB.

Menlo FPD-510 photodetectors were used for the optical-to-electronic conversion in both the Local Site and Remote Site. Faraday mirrors were used at the ends of the two arms of the MI to ensure the signals mixing at the transmitter side photodetector were aligned in polarization.

The combination of AOM frequencies resulted in the following electronic signals within the servo electronics: $\nu_{RF,1} = 90$ MHz, $\nu_{RF,2} = 230$ MHz, and $\nu_{RF,3} = 70$ MHz. The mixer frequencies are $\nu_{Mix,1} = 140$ MHz and $\nu_{Mix,2} = 320$ MHz. After filtering, $\nu_{Mix,2}$ was mixed with a 320 MHz LO frequency.

Both the Local Site and Remote Site were co-located in the same laboratory, permitting an independent measure of the transfer stability. The 160 MHz received signal was terminated on a Π-type Microsemi 5125A phase noise test set to produce an Allan deviation estimate of the fractional frequency stability (noise equivalent bandwidth: 0.5 Hz).
CHAPTER 4. RADIO FREQUENCY TRANSFER FOR SKA1-LOW

Figure 4.2: Allan deviation of 160 MHz transfer over 166 km of metropolitan fiber. Stabilization servo engaged filled blue circles, solid line. Stabilization disengaged open blue circles, dashed line. Electronic noise floor of the phase-noise test set filled red triangles, solid line.

4.5 Results

Figure 4.2 shows the Allan deviation measured for the stabilized (filled blue circles, solid lines) and unstabilized (open blue circles, dashed lines) 160 MHz signal transmitted over the 166 km link. The red trace (filled triangles, solid line) indicates the noise floor of the phase-noise test set.

Figure 4.2 shows that the stabilization system produces an Allan deviation of $9.7 \times 10^{-12}$ Hz/Hz at 1 s of integration, dropping to $3.9 \times 10^{-14}$ Hz/Hz at 10$^3$ s integration time, and to $6.4 \times 10^{-15}$ Hz/Hz at 10$^4$ s integration time.
4.6 Discussion

The system achieves good suppression of noise over longer timescales, with the measured stabilities improved by an order of magnitude or more at integration times of $10^2$ s and longer.

The Allan deviation against integration time, $\tau$, of the stabilized transfer data (blue, filled circles, solid line) regresses more slowly than $\tau^{-1}$, but significantly faster than $\tau^{-1/2}$, indicating that the dominant noise source for the stabilized transmission is white phase noise, with smaller contributions from other noise types.

The frequency stability achieved in this experiment does not match the results presented in [78] and [71]. However, both [78] and [71] measured free-running transfer stabilities on their links that were more than an order of magnitude more stable than our free-running transmission (blue, open circles, dashed line), indicating that our 166 km link is subjected to higher levels of noise. The performance of the stabilized transfer system in its current state is likely limited by its sensitivity to short timescale noise. Using the process outlined in [158], the achieved stability corresponds to a loss of coherence that exceeds the SKA requirements by around two orders of magnitude.

Even so, a number of steps can be taken to improve the frequency transfer stability of the system. Frequency dividing $\nu_{\text{Mix,2}}$ by a large factor ($> 100$) before mixing with the LO to produce the electronic error signal would increase the noise suppression by increasing the period of the rapid frequency fluctuations on the link, reducing the in-loop error of the servo electronics at the expense of servo bandwidth.

While testing other transmission frequencies, we found that when the system is configured correctly, that is, optical and electronic signal levels are optimized and adequate filters are employed, the absolute frequency stabilities of the transmitted signals are very similar (within a factor of about 2) regardless of the transmission frequency. This observation has been found to hold true for the stabilized transmission of a frequency up to 50 times higher (the 8 GHz frequency transfer presented...
in [155]). Therefore, the fractional frequency stability can be improved by transmitting higher transmission frequencies.

The frequency stability achieved at the Remote Site can also be improved by installing repeater stations at intervals along the link.

The techniques employed mean that the system does not require the use of specialized fiber such as dispersion compensating fiber or polarization maintaining fiber. The use of Faraday mirrors at the ends of the MI arms ensures that the maximum signal is available at the photodetectors without the need for any initial polarization alignment or ongoing polarization control or polarization scrambling. Furthermore, the technique is compatible with data transmission on the same link, allowing the system to make use of active telecommunications links if the non-bidirectional components of the link are bypassed as in [110] and [90]. Bi-directional optical amplifiers can be used to simply extend the range of the system without the use of signal regeneration stations at certain points along the link.

4.7 Conclusion

We have described and experimentally demonstrated the function of a stabilized radio-frequency transfer technique. This technique exploits several advantages of optical phase-sensing and optical phase-actuation over other radio- and microwave-frequency transfer techniques, producing equipment that is compact in size with robust performance.

The use of AOMs for optical phase-actuation allows the Local Site transmitter units to have a more compact construction than systems using fiber stretchers or thermal spools. AOMs also provide an infinite feedback range, avoiding any potential need for integrator-reset or range-limit monitoring circuits. The rapid response of AOMs allows for better optimization of the servo gains for short links where the feedback bandwidth is limited by electronic delay rather than the light round-trip time.
This technique actively suppresses phase noise introduced in the Local Site MZI as well as the transmission link. Along with the simplicity of the remote site optical and electronic components, this makes the system very resistant to the effects of environmental perturbations (such as temperature variation or vibration) on the system hardware.

By using AOMs to generate shifts of the optical frequency at the local and remote sites, this technique avoids the need to use additional lasers at the remote sites to circumvent the effects of unwanted reflections on the transmission link. This reduces the complexity and cost of the system. In addition, on links where unwanted reflections are minimal, it is possible to remove an anti-reflection AOM from the stabilized transfer system (either the remote AOM, or the local AOM), to further reduce the cost and complexity. The local and the remote anti-reflection AOMs mitigate unwanted reflections by generating unique RF frequencies at the photodetectors. Sensible choices of AOM frequencies allow this to happen without overlapping with signals of interest.

The technique of splitting and frequency shifting the signal from a single laser source is also considerably simpler than offset-locking a master and slave laser, however, the range of possible transmission frequencies is limited to the RF domain (that is, < 1 GHz) by the practical limitations of existing AOM technology. The largest frequency shifts produced by commercially available AOMs at the time of publication are ±110 MHz. Including additional passive AOMs can further increase the transmission frequency. However, due to the optical power loss of the AOMs, it is not currently practical to achieve stabilized MW transmission (> 1 GHz) using the technique presented here. Stabilized MW transmissions using optical phase-sensing and actuation require the more extensive modifications presented in [155].

This stabilized RF transfer technique was one of two considered for selection as the phase-synchronization system for the Square Kilometre Array SKA1-LOW radio telescope [23].
5 Microwave Frequency Transfer for SKA1-MID

Foreword

As described in Chapter 4, separate frequency transfer system designs were developed for SKA1-LOW and SKA1-MID and optimized to the performance and engineering requirements of each telescope. The higher microwave frequencies required by SKA1-MID mean that the optical layout and phase detection procedure of the two systems differ substantially, as well as requiring the use of different microwave electronics. Acousto-optic modulators such as those used in Chapter 4 are not suited to generating significant microwave frequency shifts and incur high optical power losses, so a dual-parallel Mach-Zehnder modulator, such as that used in Chapter 3, was employed to generate the microwave frequency shift. However, the DP-MZM is not double-passable in the same way as an AOM and so a different optical layout was required. To accommodate the new layout and higher modulation frequencies while still suppressing phase noise arising from the Mach-Zehnder modulator as well as the fiber link, a novel frequency mixing procedure to enable phase noise detection was developed and tested.
CHAPTER 5. MICROWAVE FREQUENCY TRANSFER FOR SKA1-MID

This chapter gives a mathematical description of the innovative phase detection methods, explaining how phase noise in the transmitter-side Mach-Zehnder modulator is suppressed, while compensating the phase noise of the fiber link. The performance of the system is then experimentally verified over a 166 km fiber link, comparable in length to the longest fiber links required by SKA1-MID ($\approx 173$ km). Because the system largely makes use of components and techniques used in stabilized optical frequency transmission, the potential for optical frequency transfer infrastructure to be quickly and cheaply converted to stabilized microwave transfer for applications not suited to receiving optical frequencies is also discussed.

The results of these experiments have been published in the journal *Optics Letters*. The manuscript is reproduced here with formatting changes to make it consistent with the rest of the work in this thesis. In particular, *Optics Letters* does not clearly separate sections of the paper, and this is why the final section of this chapter is presented as a joint “Discussion and Conclusion” section. I contributed 10% of the manuscript preparation, which was completed by Dr Schediwy. I performed 80% of the experimental work, with the remainder contributed by Dr Schediwy and undergraduate research intern Simon Stobie.

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5.1. ABSTRACT

Stabilized microwave-frequency transfer using optical phase sensing and actuation

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5.1 Abstract

We present a stabilized microwave-frequency transfer technique that is based on optical phase sensing and optical phase actuation. This technique shares several attributes with optical-frequency transfer and, therefore, exhibits several advantages over other microwave-frequency transfer techniques. We demonstrated the stabilized transfer of an 8000 MHz microwave-frequency signal over a 166 km metropolitan optical fiber network, achieving a fractional frequency stability of $6.8 \times 10^{-14}$ Hz/Hz at 1 s integration and $5.0 \times 10^{-16}$ Hz/Hz at $1.6 \times 10^4$ s. This technique is being considered for use on the Square Kilometre Array SKA1-MID radio telescope.

5.2 Introduction

Stabilized frequency transfer over optical fiber is rapidly moving from experimental demonstrations, to actively supporting a broad range of real-world applications. The frequency of the transmitted signal — optical, radio, or microwave — dictates which applications can be supported with this technology. Stabilized optical-frequency transfer techniques lead this research in terms of demonstrated transfer distance [96], frequency stability performance [110], and network roll-out [31]. However, most practical applications, including radio astronomy, geodesy, finance,
navigation, defense, and aspects of fundamental physics [40, 82], require the transfer of stabilized radio- or microwave-frequency signals to directly interface with the application’s electronic systems. Optical combs can be used to translate optical frequencies into the radio or microwave domain [88], but they remain too complex, bulky, or costly for many applications. Therefore, most practical support of the aforementioned applications involves microwave-frequency transfer techniques, but these are constrained in the following ways.

The standard stabilized microwave-frequency transfer techniques [109] require group-delay actuation to compensate for the physical length changes of the fiber link. For practical deployments over long links, this usually involves implementing a combination of fiber stretcher (medium actuation speed and very limited range) in a series with a thermal spool (slow actuation speed and physically bulky). In contrast, the acousto-optic modulator (AOM) actuators used in stabilized optical-frequency transfer are capable of the faster actuation speeds, as well as having infinite feedback range. Radio-frequency phase conjugation techniques [119] have been demonstrated over longer distances [71, 123] than standard stabilized microwave-frequency transfer, but have yet to match their transfer performance.

In addition, stabilized radio- or microwave-frequency transfer techniques require the returned signal to be rebroadcast at either a different modulation frequency, optical wavelength, or fiber core, to avoid frequency overlap from unwanted reflections on the link, which can cause the servo to function improperly. These reflection mitigating methods then can bring about additional complications, including those resulting from optical polarization and chromatic dispersion which, in turn, requires further complexity. In stabilized optical-frequency transfer, strategically placed AOMs can be used to simply apply static optical-frequency shifts [85] to avoid these issues. In this Letter, we report on a stabilized microwave-frequency transfer technique that is based on optical phase sensing and actuation and which, therefore, is able to utilize many of the key advantages of stabilized optical transfer.
5.3 Theory

As shown in Figure 5.1, an optical signal with frequency $\nu_L$, generated by a laser at the Local Site, is injected into two arms of a Mach-Zehnder interferometer (MZI). A dual-parallel Mach-Zehnder modulator (DPM) is located in Arm 1 of the MZI, and a microwave frequency of $\nu_{DP}$ is applied to the DPM electronic inputs. The phase of the electronic inputs, and the DPM voltage biases, are tuned to generate single-sideband suppressed-carrier modulation, thereby producing a static microwave-frequency shift $\nu_{DP}$ on the optical signal. Arm 2 of the MZI contains an AOM, which adds the servo AOM radio frequency shift $\nu_{A-srv}$ and the servo actuation signal $\Delta \nu_{A-srv}$ to the optical signal. In addition, the optical signals in each of the two arms of the MZI pick up undesirable non-common phase noise $\Delta \dot{\phi}_{MZI,i}$ (where $i$ is the index representing the optical signals in Arm 1 and Arm 2 of the MZI).

Just as in the case of standard stabilized optical transfer techniques [110], the optical signals then enter a Michelson interferometer (MI) via an optical isolator.
(to prevent reflections returning to the laser). The Fiber Link is incorporated into the long arm of the MI, with the short arm providing the physical reference for the optical phase sensing. The optical reference signals $\nu_{\text{ref},i}$ at the photodetector are

$$\nu_{\text{ref},1} = \nu_L + \nu_{\text{DP}} + \frac{1}{2\pi} (\Delta \dot{\phi}_{M2I,1} + 2\Delta \dot{\phi}_{MI}),$$  \hspace{1cm} (5.1)$$

$$\nu_{\text{ref},2} = \nu_L + (1 + \Delta)\nu_{A-srv} + \frac{1}{2\pi} (\Delta \dot{\phi}_{M2I,2} + 2\Delta \dot{\phi}_{MI}),$$  \hspace{1cm} (5.2)$$

where $\Delta \dot{\phi}_{MI}$ is the undesirable phase noise picked up by the optical signals passing through the MI reference arm.

A local anti-reflection AOM that applies a static frequency offset of $\nu_{A-lar}$ can be incorporated into either the long arm (as shown in Figure 5.1) or the reference arm of the MI. This allows the servo electronics to distinguish $\nu_{\text{ref},i}$ from unwanted reflections on the link. (Note: the anti-reflection AOMs are not critical for the technique, but are useful for practical implementation on fiber links that may contain unwanted reflections.) With the local anti-reflection AOM placed in the long arm, the optical signals transmitted across the Fiber Link $\nu_{\text{tr},i}$ are

$$\nu_{\text{tr},1} = \nu_L + \nu_{\text{DP}} + \nu_{A-lar} + \frac{1}{2\pi} \Delta \dot{\phi}_{M2I,1},$$  \hspace{1cm} (5.3)$$

$$\nu_{\text{tr},2} = \nu_L + (1 + \Delta)\nu_{A-srv} + \nu_{A-lar} + \frac{1}{2\pi} \Delta \dot{\phi}_{M2I,2}.$$  \hspace{1cm} (5.4)$$

As these signals are transmitted across the fiber link, they pick up phase noise $\Delta \dot{\phi}_{Lk,i}$ from random optical path length changes in the link that are unique to their specific transmitted frequencies.

At the Remote Site, the two optical signals pass through a remote anti-reflection AOM with a static frequency of $\nu_{A-rar}$ to produce the following two remote signals $\nu_{\text{rm},i}$:
\[ \nu_{rm,1} = \nu_L + \nu_{DP} + \nu_{A-lar} + \nu_{A-rar} + \frac{1}{2\pi}\left(\Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{Lk,1}\right), \quad \text{and} \quad (5.5) \]

\[ \nu_{rm,2} = \nu_L + (1 + \Delta)\nu_{A-srv} + \nu_{A-lar} + \nu_{A-rar} + \frac{1}{2\pi}\left(\Delta \dot{\phi}_{MZI,2} + \Delta \dot{\phi}_{Lk,2}\right). \quad (5.6) \]

At the remote site, the signal is split into two fiber paths, with one set of signals going to a photodetector and the other to a Faraday mirror. At the photodetector, the beat between the two optical signals \( \nu_{rm,1} \) and \( \nu_{rm,2} \) is recovered as the Remote Site microwave-frequency electronic signal:

\[ \nu_{rm,MW} = (1 + \Delta)\nu_{A-srv} - \nu_{DP} + \frac{1}{2\pi}\left(\Delta \dot{\phi}_{MZI,2} - \Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{Lk,2} - \Delta \dot{\phi}_{Lk,1}\right). \quad (5.7) \]

On the other fiber path, a Faraday mirror reflects the two optical signals back to the Local Site across the Fiber Link, with each signal receiving additional optical shifts \( \nu_{A-rar} \) and \( \nu_{A-lar} \) when passing through the remote and local AOMs a second time. In addition, the two optical signals pick up another copy of \( \Delta \dot{\phi}_{Lk,i} \) from the Fiber Link. The two reflected optical signals \( \nu_{rfl,i} \) then strike the servo photodetector to produce

\[ \nu_{rfl,1} = \nu_L + \nu_{DP} + 2(\nu_{A-lar} + \nu_{A-rar}) + \frac{1}{2\pi}\left(\Delta \dot{\phi}_{MZI,1} + 2\Delta \dot{\phi}_{Lk,1}\right), \quad \text{and} \quad (5.8) \]

\[ \nu_{rfl,2} = \nu_L + (1 + \Delta)\nu_{A-srv} + 2(\nu_{A-lar} + \nu_{A-rar}) + \frac{1}{2\pi}\left(\Delta \dot{\phi}_{MZI,2} + 2\Delta \dot{\phi}_{Lk,2}\right). \quad (5.9) \]

The mixing of the two reference frequencies \( \nu_{ref,i} \) and the two reflected optical frequencies \( \nu_{rfl,i} \) results in six primary electronic mixing products \( \nu_{MW,j} \) (where \( j \) is the index 1 to 6). Of those, the two microwave-frequency signal mixing products that are crucial for this technique are
\[
\nu_{MW,1} = \nu_{ref,1} - \nu_{rf,1} \\
= \nu_{DP} - (1 + \Delta)\nu_{A-srv} - 2(\nu_{A-lar} + \nu_{A-rar}) + \frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,1} - \Delta \dot{\phi}_{MZI,2}) + \frac{1}{\pi}(\Delta \dot{\phi}_{MI} - \Delta \dot{\phi}_{Lk,2}), \text{ and}
\]

\[
\nu_{MW,2} = \nu_{ref,2} - \nu_{rf,1} \\
= \nu_{DP} - (1 + \Delta)\nu_{A-srv} - 2(\nu_{A-lar} + \nu_{A-rar}) + \frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,2} - \Delta \dot{\phi}_{MZI,1}) + \frac{1}{\pi}(\Delta \dot{\phi}_{MI} - \Delta \dot{\phi}_{Lk,1}).
\]

Given an appropriate selection of AOM frequencies, the other four mixing products (and all intermodulations) occur at different frequencies.

Once in the electronic domain, the microwave-frequency signals \(\nu_{MW,j}\) can be mixed with a copy of \(\nu_{DP}\), to produce the following two critical electronic radio-frequency signals:

\[
\nu_{RF,1} = -(1 + \Delta)\nu_{A-srv} - 2(\nu_{A-lar} + \nu_{A-rar}) + \frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,1} - \Delta \dot{\phi}_{MZI,2}) + \frac{1}{\pi}(\Delta \dot{\phi}_{MI} - \Delta \dot{\phi}_{Lk,2}), \text{ and}
\]

\[
\nu_{RF,2} = (1 + \Delta)\nu_{A-srv} - 2(\nu_{A-lar} + \nu_{A-rar}) + \frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,2} - \Delta \dot{\phi}_{MZI,1}) + \frac{1}{\pi}(\Delta \dot{\phi}_{MI} - \Delta \dot{\phi}_{Lk,1}).
\]

The electronic signal path is then split, with each path containing a bandpass filter that is centered on one of the above frequencies. These filters reject the opposing signal, as well as the other unwanted mixing products (\(\nu_{MW,3}\) to \(\nu_{MW,6}\)) and any frequency intermodulations. The signals \(\nu_{RF,1}\) and \(\nu_{RF,2}\) are then mixed to produce the lower sideband:

\[
\nu_{Mix,lsb} = \nu_{RF,2} - \nu_{RF,1} \\
= 2((1 + \Delta)\nu_{A-srv} + \frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,2} - \Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{Lk,2} - \Delta \dot{\phi}_{Lk,1})).
\]
5.4. EXPERIMENTAL SETUP

A low-pass filter is used to reject the upper sideband and other products. Finally, \(\nu_{Mix,lsb}\) is mixed with the servo local oscillator \(\nu_{LO}\) (set to \(2 \times \nu_{A-srv}\)) to produce the servo error signal:

\[
\nu_{err} = 2(\Delta \nu_{A-srv} + \frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,2} - \Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{Lk,2} - \Delta \dot{\phi}_{Lk,1})).
\] (5.15)

The servo error signal is applied to a voltage controlled oscillator (VCO) with a nominal frequency \(\nu_{A-srv}\). The VCO output goes to the servo AOM, thereby closing the servo loop. When the servo is engaged, \(\nu_{err}\) is driven to zero, so

\[
\Delta \nu_{A-srv} = -\frac{1}{2\pi}(\Delta \dot{\phi}_{MZI,2} - \Delta \dot{\phi}_{MZI,1} + \Delta \dot{\phi}_{Lk,2} - \Delta \dot{\phi}_{Lk,1}).
\] (5.16)

Substituting this into Equation 5.7 shows that the undesirable non-common phase noise picked up in the Fiber Link, as well as the phase noise from the MZI in the Local Site, is canceled out (within the light round-trip bandwidth and other practical gain limitations). This gives

\[
\nu^{*}_{rm,MW} = \nu_{A-srv} - \nu_{DP}
\] (5.17)

where \(\nu^{*}_{rm,MW}\) is the MW remote signal with the servo engaged.

5.4 Experimental Setup

We describe the experimental verification of this method using 8000 MHz transfer, with all optical elements fiberized. An NKT Photonics Koheras BASIK X15 laser (spectral linewidth <100 Hz) was used to produce an optical frequency of \(\nu_{L} = 193\) THz (corresponding to a wavelength of 1552 nm). The DPM was a Photline MXIQ-LN-40 configured to produce a down shift of the optical frequency by \(\nu_{DP} = \)
−7960 MHz. The microwave-frequency oscillator was an Agilent N5183A MXG, with all other radio-frequency signals supplied by a Liquid Instruments Moku:Lab.

The AOMs were an IntraAction FCM-series, with $\nu_{A-srv} = +40$ MHz, resulting in a frequency difference between $\nu_{tr,1}$ and $\nu_{tr,2}$ of 8000 MHz. The anti-reflection AOMs had frequencies of $\nu_{A-lar} = +50$ MHz, and $\nu_{A-rar} = +50$ MHz. For the experiment described here, the local anti-reflection AOM was located in the link arm of the MI, as shown in Figure 5.1.

Polarization-maintaining fiber was used until the MZI output to ensure that the polarization into the DPM was optimally aligned and that the MZI optical power remained maximized. The signal was transmitted through installed metropolitan optical fiber networks up to 166 km in length (2×83 km AARNet-managed fiber loops). This resulted in a two-way light round-trip time of 1.6 ms, limiting the servo bandwidth to around 600 Hz. The total optical loss of the fiber link was 47 dB. Two IDIL Fibres Optiques bi-directional optical amplifiers were used to boost signal strength, with one amplifier located after the first 83 km fiber loop, and the other located just prior to the Local Site. Discovery Semiconductors DSCR402 and DSC-R401HG photodetectors were used for the opto-electronic conversion. Faraday mirrors were used at the ends of the two arms of the MI to ensure the signals reflected back to the servo photodetector at the Local Site were aligned in polarization.

The combination of the AOM frequencies used in this experiment resulted in the following two key microwave-frequency electronic signals at the output of the servo photodetector: $\nu_{MW,1} = 8200$ MHz, and $\nu_{MW,2} = 7800$ MHz. After mixing with $\nu_{DP}$, this resulted in the following radio frequency signals: $\nu_{RF,1} = 240$ MHz and $\nu_{RF,2} = 160$ MHz. The mix of these two signals produced the lower side-band $\nu_{Mix,lsb} = 80$ MHz. The local oscillator $\nu_{LO}$ was set to 80 MHz to produce a DC error signal $\nu_{err}$ upon mixing with $\nu_{Mix,lsb}$. Both the Local Site and the Remote Site were co-located in the same laboratory, enabling an independent out-of-loop measurement of the transfer stability, with all electronic equipment referenced to an IEM-KVARZ CH1-75A active hydrogen maser. The 8000 MHz Remote
Site microwave-frequency electronic signal was mixed with $\nu_{DP}$ to produce a radio-frequency signal at $\nu_{rm,RF} = 40$ MHz that could be directly probed by an Agilent 53132A high-precision frequency counter (gate time set to 1 s). The output data were used to produce a triangle weighted estimate of the frequency stability.

5.5 Results

Figure 5.2 shows the fractional frequency stability of three 8000 MHz transfer measurements plotted as a function of integration time. The blue dashed line with open markers shows the unstabilized transfer over 166 km. Here the transfer stability is $8.4 \times 10^{-14}$ Hz/Hz at 1 s of integration, and $1.1 \times 10^{-13}$ Hz/Hz at $1.6 \times 10^4$ s. The blue solid line with solid markers represents transfer with the stabilization servo engaged. At 1 s of integration, the stability is $6.8 \times 10^{-14}$ Hz/Hz and, at $1.6 \times 10^4$ s, it is $5.0 \times 10^{-16}$ Hz/Hz; this demonstrates a suppression of fiber noise by more than two orders of magnitude. The noise floor of the transfer system, as measured by stabilized transfer over a 2 m fiber patch lead, is displayed as the red solid line with triangle markers. It starts at a value of $5.5 \times 10^{-14}$ Hz/Hz at 1 s and drops to $1.2 \times 10^{-15}$ Hz/Hz by 512 s. In addition, the 166 km stabilized frequency transfer was shown to be accurate to within 20 $\mu$Hz.

5.6 Discussion and Conclusion

We have described and experimentally demonstrated the efficacy of a stabilized microwave-frequency transfer technique that is based on optical phase sensing and optical phase actuation. While it does not achieve the same level of ultimate transfer stability performance as the world-leading results [83,109], it does exhibit several advantages over other radio- or microwave-frequency transfer techniques, as discussed in the following six paragraphs.
The use of AOMs enables the construction of compact servo systems at the Local Site by not requiring bulky fiber stretchers or thermal spools. The use of the AOMs eliminates feedback range concerns due to their infinite feedback range; therefore, the servo systems can be constructed without potentially complex integrator-reset circuits. Finally, AOMs have faster feedback than fiber stretchers or thermal spools, which allows for optimized servo gains for short links that are not limited by the light round-trip time.

The technique actively suppresses phase noise originating not just from the Fiber Link in the MI arm but also from the MZI at the Local Site. Plus, given the simplicity of components at the Remote Site, the technique is largely immune to environmental perturbations on the systems hardware. As in stabilized optical transfer, anti-reflection AOMs can be used to generate appropriate optical-frequency shifts to mitigate unwanted reflections that are present on most real-world links. Our technique therefore requires only a single laser, reducing system complexity. Further system optimization can be achieved by locating the local anti-reflection AOM in
the MI reference arm, which has the benefit of removing some unnecessary optical loss from the link arm.

The technique utilizes Faraday mirrors at the ends of the MI arms to give a maximum detected signal at the servo photodetector, as is done with stabilized optical transfer. This removes the need for any initial polarization alignment, or any ongoing polarization control or polarization scrambling. The technique can be deployed on standard fiber links alongside data transmission and does not require a specialty fiber, such as dispersion compensation or polarization-maintaining fiber, in the Fiber Link.

The microwave signal being transmitted on the Fiber Link arises from only two optical signals, not three, as is the case for standard intensity modulation commonly used in radio- or microwave-frequency transfer. Using only two optical signals ensures that the maximum signal power is available at the Remote Site, regardless of link length. This also enables the transmission frequency to be varied without the consideration of link length.

Bi-directional optical amplifiers can be deployed to extend the range of transmission and, therefore, potentially complex electronic signal re-generation systems are not required. Two optical amplifiers were used to demonstrate stabilized microwave-frequency transfer over a 166 km metropolitan optical fiber network, around twice the distance of previously published microwave-frequency (< 1 GHz) transfer [83, 109].

This stabilized microwave-frequency transfer technique is one of two being considered for selection as the phase-synchronization system for the Square Kilometre Array SKA1-MID radio telescope [23, 159]. In addition, we are exploring the technique’s role in the MeerKAT radio telescope [24] as part of a potential future X-band receiver upgrade.
Astronomical Verification

Foreword

To ensure compliance with SKA engineering requirements, the stabilized frequency transfer systems must be tested in a process of astronomical verification in which the frequency transfer system is installed at an existing radio telescope and provides the frequency reference used to conduct a set of astronomical observations. Comparison of the performance of the telescope using the system under test against conventional operation using the observatory’s own frequency distribution systems, as well as other tests, are used to determine the operational performance of the stabilized frequency transfer system in a real-world setting.

In the experiments described in this chapter, the SKA1-MID stabilized microwave frequency transfer prototype described in Chapter 5 was installed at CSIRO’s Australia Telescope Compact Array (ATCA) near Narrabri in New South Wales and used to provide a frequency reference to the telescope’s systems during a set of observations of an astronomical calibrator source. The ATCA was selected for these tests because its systems were compatible with the SKA1-MID frequency transfer prototype, and the dual-receiver architecture of the ATCA antennas enabled observations using the observatory’s standard systems, as well as the stabilized transfer system,
to be conducted simultaneously on the same physical baselines. This enabled an extremely reliable and detailed comparison of the performance of the different frequency transfer systems.

The results of these experiments have been published in *The Astronomical Journal*. The manuscript is reproduced here with formatting changes to make it consistent with the rest of the work in this thesis. I carried out 90% of the preparation of the manuscript, and performed 50% of the experimental work contributing to this paper. I have also presented this work as a poster at the SKA Engineering Meeting (Stellenbosch, September 2016), and as talks at ICRAR-con (Mandurah, September 2016), the Australian Institute of Physics WA Student Conference (Perth, October 2016), the CSIRO Pietro Baracchi Conference (Perth, November 2016), the CSIRO Bolton and Student Symposium (Perth, Dec 2016), and as a colloquium at the CSIRO Australia Telescope National Facility (Sydney, February 2017).

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Astronomical verification of a stabilized frequency reference transfer system for the Square Kilometre Array

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6.1 Abstract

In order to meet its cutting-edge scientific objectives, the Square Kilometre Array (SKA) telescope requires high-precision frequency references to be distributed to each of its antennas. The frequency references are distributed via fiber-optic links and must be actively stabilized to compensate for phase noise imposed on the signals by environmental perturbations on the links. SKA engineering requirements demand that any proposed frequency reference distribution system be proved in “astronomical verification” tests. We present results of the astronomical verification of a stabilized frequency reference transfer system proposed for SKA-MID. The dual-receiver architecture of the Australia Telescope Compact Array was exploited to subtract the phase noise of the sky signal from the data, allowing the phase noise of observations performed using a standard frequency reference, as well as the stabilized frequency reference transfer system transmitting over 77 km of fiber-optic cable, to be directly compared. Results are presented for the fractional frequency stability and phase drift of the stabilized frequency reference transfer system for celestial calibrator observations at 5 and 25 GHz. These observations plus additional laboratory results for the transferred signal stability over a 166 km metropolitan fiber-optic link are used to show that the stabilized transfer system under test exceeds all SKA phase-stability requirements within a broad range of observing condi-
tions. Furthermore, we have shown that alternative reference dissemination systems that use multiple synthesizers to supply reference signals to sub-sections of an array may limit the imaging capability of the telescope.

6.2 Introduction

The Square Kilometre Array (SKA) project [160] is an international initiative to build the largest and most capable radio telescope ever constructed. Construction of the SKA has been divided into phases, with the first phase (SKA1) accounting for the first 10% of the telescope’s receiving capacity. During SKA1, a low-frequency aperture array (SKA1-LOW) will be constructed in Western Australia, while a dish-array of 197 antennas (SKA1-MID), incorporating the 64 dishes of MeerKAT, will be constructed in South Africa.

Radio telescope arrays such as the SKA require phase-coherent frequency reference signals to be transmitted to each of the antennas in the array. In the case of the SKA, the frequency references will be generated at a central site and transmitted to the antenna sites via fiber-optic cables. Environmental influences affect the optical path length of the fiber and act to degrade the phase stability of the frequency references received at the antennas, which has the ultimate effect of reducing the fidelity and dynamic range of the data [16]. To improve the phase-coherence of the array, the SKA will employ stabilized frequency transfer systems to suppress the fiber-optic link noise [20]. Reference frequency stabilization systems have been used successfully on the Atacama Large Millimetre Array (ALMA) [16, 141], and other radio telescope arrays such as the Very Large Array [137], e-Merlin in the UK [138], and the Australia Telescope Compact Array (ATCA) [139] have employed phase measurement systems in order to apply phase corrections in the correlator. The existing SKA precursor telescopes including the Murchison Widefield Array [161, 162],
the Australian SKA Pathfinder [163,164], and MeerKAT [165] currently employ passive frequency reference dissemination systems that provide adequate phase stability over the relatively short transmission distances required by these telescopes.

There are three SKA systems requirements that apply to the phase-noise performance of the frequency transfer system [166]. The frequency transfer system must provide a maximum coherence loss of 2% over the correlator integration time (1 s) and over the in-beam calibration time (60 s) for observing frequencies up to 13.8 GHz. Of this 2% coherence loss budget, 1.9% is allocated to the stabilized frequency reference transfer system. In addition, the frequency reference must have a phase drift of less than 1 rad over a 10-min period to ensure that there is no ambiguity in the phase solution during array calibration measurements on either side of an observation of up to 10 min.

Researchers at the University of Western Australia (UWA) have led the development of a stabilized frequency transfer system proposed for SKA1-MID [155]. This has been tested extensively using standard metrology techniques in a laboratory setting, with signals transmitted over metropolitan fiber links. Laboratory and field testing of an alternative stabilized frequency transfer system for the SKA has also been reported previously [72,167] and other research groups have developed similar systems with a view to support the SKA and VLBI applications [71,123]. However, SKA technology down-select requirements demand a process of “astronomical verification” in which the proposed frequency transfer system is shown to meet the stability requirements under observing conditions on an operational radio telescope. In this paper, we present results of astronomical verification of the UWA SKA1-MID stabilized frequency transfer prototype and show that the system exceeds the SKA phase-stability requirements under a wide range of observing conditions.
6.3 Experimental design

6.3.1 Extracting the Reference Signal Phase Stability

The astronomical verification observations were performed using the ATCA. The ATCA’s dual-receiver chain architecture permitted analyses that would not have been possible to conduct using single-receiver telescope arrays. As shown in Figure 6.1, immediately following the feed horn and the first low-noise amplifier (LNA), the sky signal, for both polarizations, is split into two separate, but functionally identical, receiver chains (referred to here as ‘chain-1’ and ‘chain-2’). The sky signals are then down-converted by mixing them with separate frequency reference signals, Frequency Reference 1 and Frequency Reference 2. These are normally supplied by two separate microwave frequency synthesizers located in the observatory’s correlator room. The two frequency references are transmitted up to 4.5 km away to the antennas through parallel fiber cores in buried conduits using a pair of electronic-to-optical transmitters (E/Os). The transmitted references are detected at the antennas by optical-to-electronic (O/E) receivers (two in each antenna) that feed the signals to a pair of yttrium-iron-garnet (YIG) oscillators operating in a phase-locked loop. The YIG oscillators act as clean-up oscillators to suppress high-frequency phase noise. The down-converted sky signals are digitized by analogue-to-digital converters (ADCs) that feed to two separate correlators, one for each receiver chain, in the correlator room.

The advantage of this configuration for astronomical verification tests is that Frequency Reference 1 can be supplied by the ATCA’s conventional reference signal distribution system, while Frequency Reference 2 is supplied by the stabilized frequency reference transfer system under test (as shown in Figure 6.1). Because the two receiver chains in the antennas detect the same sky signal, any differences in the phase solution of these signals between the two receiver chains for a given telescope baseline can be attributed to non-common phase noise produced in the separate
Figure 6.1: Schematic of the reference frequency distribution setup for astronomical verification at the ATCA. Three antennas are shown for reference. Antenna 3 shows the modification made to antennas 1 and 3 to enable comparative measurements of the two frequency references to be made. Baselines with antennas 1 or 3 using correlator 2 are ‘mixed’ reference baselines. Tx is the stabilized frequency transfer system transmitter unit, Rx is the stabilized frequency transfer system receiver unit, RF shift is an IQ-mixer producing carrier-suppressed single-sideband modulation, E/O is the electronic-to-optical transmitter, O/E is the optical-to-electronic receiver, YIG is the yttrium-iron-garnet clean-up oscillator, LNA is the low-noise amplifier, Mix is the microwave signal mixer, and ADC is the analogue-to-digital converter.
frequency reference dissemination systems. For example, the phase solution for the chain-1 baseline between two antennas $i$ and $j$ ($\phi_{ij,1}(t)$) is

$$\phi_{ij,1}(t) = (\phi_{R1}(t) + \phi_{E1,i}(t) + \phi_{S1}(t))$$

$$- (\phi_{R1}(t) + \phi_{E1,j}(t) + \phi_{Sj}(t)), \quad (6.1)$$

where $\phi_{R}(t)$ is the phase of the Frequency Reference as a function of time ($t$) and $\phi_{S}(t)$ is the phase of the sky signal at a particular antenna receiver. The term $\phi_{E}(t)$ represents the phase noise contributed by components in the ATCA reference frequency distribution system, including the E/O/E systems, differential fiber-link noise, and noise from the YIG oscillator. The corresponding phase solution for the chain-2 baseline between antennas $i$ and $j$ ($\phi_{ij,2}(t)$) is

$$\phi_{ij,2}(t) = (\phi_{R2}(t) + \phi_{E2,i}(t) + \phi_{S1}(t))$$

$$- (\phi_{R2}(t) + \phi_{E2,j}(t) + \phi_{Sj}(t)). \quad (6.2)$$

In the configuration depicted in Figure 6.1, any additional phase noise contributed by the stabilized frequency transfer system (Frequency Reference 2) is common to all of the down-converted signals from the chain-2 mixer outputs. Therefore, the chain-2 baseline phase solutions do not exhibit additional phase noise compared with the simultaneous phase solution for the same physical baseline using chain-1 (as shown by Equations 6.1 and 6.2).

To remedy this, the outputs of the chain-1 mixers in antennas 1 and 3 were split using microwave power splitters in the antennas, and fed to both the chain-1 and chain-2 ADCs. This was done for both the A- and B-polarizations (for clarity, only one polarization is shown in Figure 6.1). As a result, the outputs of the chain-2 ADCs on antennas 1 and 3 did not incorporate the phase-noise contributed by the stabilized frequency transfer system and the chain-2 E/O system. The phase solution $\phi_{ij,2}(t)$ (where antenna $i$ is either antenna 1 or 3) then becomes

$$\phi_{ij,2}(t) = (\phi_{R1}(t) + \phi_{E1,i}(t) + \phi_{S1}(t))$$

$$- (\phi_{R2}(t) + \phi_{E2,j}(t) + \phi_{Sj}(t)). \quad (6.3)$$
6.3. EXPERIMENTAL DESIGN

By subtracting the chain-1 phase solution from the chain-2 phase solution, for baselines that included antennas 1 or 3, the differential phase noise between the two frequency references could be measured. Hereafter, chain-2 baselines that incorporate antenna 1 or antenna 3 will be referred to as ‘mixed’ baselines (because they operate using a ‘mix’ of two different frequency references). Baselines operating in the conventional manner will be referred to as ‘unmixed’ baselines. The resulting phase difference between the phase solutions for the unmixed and mixed baselines is then

\[
\phi_{\text{Diff}}(t) = \phi(t)_{ij,1} - \phi(t)_{ij,2} = \phi_R(t) - \phi_{R1}(t) + \phi_{E2,j}(t) - \phi_{E1,j}(t).
\]  

(6.4)

This means that not only can a direct comparison be made of the array performance under the two different frequency transfer systems, but the phase of the sky signal has been subtracted out and so the relative stability of the frequency references (with non-common phase noise contributions from some telescope systems) can be measured directly.

To avoid the contribution of the relative phase drift between two synthesizers, a single microwave synthesizer (Agilent E8257D) was used to supply both Frequency Reference 1 and the UWA stabilized frequency transfer prototype (which supplies Frequency Reference 2). So, the phase of Frequency Reference 2 is

\[
\phi_R(t) = \phi_{R1}(t) + \phi_{UWA}(t),
\]  

(6.5)

where \(\phi_{UWA}(t)\) is the phase of the UWA stabilized frequency transfer prototype. The phase difference becomes:

\[
\phi_{\text{Diff}}(t) = \phi_{UWA}(t) + \phi_{E2,j}(t) - \phi_{E1,j}(t).
\]

(6.6)

Therefore, the phase stability of the UWA stabilized frequency transfer prototype can be measured; however, there will be some contamination \((\phi_{E2,j}(t) - \phi_{E1,j}(t))\)
from the standard ATCA frequency reference distribution systems. Because the
ATCA receiver chains and frequency reference distribution systems use identical
components and the fiber links from the correlator room to the antennas run through
the same buried cables, we assume that the contributions of these components to
the phase differences are small and the differences are dominated by phase noise
contributed by the stabilized frequency transfer system.

6.3.2 Experimental Setup

The astronomical source used to make the measurement observations was a cal-
brator labeled 1057-797, at a declination of close to $-80^\circ$, which is isolated in
the sky and always above the ATCA horizon, enabling long uninterrupted array
phase measurements. The frequency reference signal was transmitted at 8.00 GHz,
this is the nominal frequency of UWA’s SKA1-MID stabilized frequency transfer
system. Given the specific design of the ATCA’s receiver architecture [168], this
enabled observations to be made across two separate frequency bands, with centre
observing frequencies of 4.96 and 25.44 GHz and a bandwidth of 2048 MHz. The
lower observing frequency is representative of SKA1-MID’s operational observing
range of 0.35–13.8 GHz [160], while the higher observing frequency demonstrates
the performance of the stabilized frequency transfer prototype under more demand-
ing observing conditions than SKA1-MID will encounter.

The transmitter unit (Tx) of the UWA SKA1-MID stabilized frequency trans-
fer prototype was installed in the ATCA correlator room. In order for Frequency
Reference 1 and Frequency Reference 2 to both supply 8.00 GHz while using only
one microwave synthesizer, the synthesizer was set to supply 7.96 GHz, which the
servo system of the stabilized frequency transfer prototype shifted up to 8.00 GHz
to supply Frequency Reference 2. An electronic IQ-mixer (Marki IQ0741LXP), set
to produce carrier-suppressed single-sideband modulation at 40 MHz, was used to
shift the synthesizer signal to 8.00 GHz to supply Frequency Reference 1. Labo-
ratory measurements of the intrinsic stability of the IQ-mixer frequency shift show
that it is better than the stability of the stabilized frequency transfer prototype by an order of magnitude, so it did not make a significant contribution to the measured phase noise.

The Tx and the receiver unit (Rx) were co-located in the correlator room, as shown in Figure 6.1. The signal transmitted by the stabilized frequency transfer prototype was sent over 52 km of buried fiber-optic cable and a further 25 km spool of fiber in the correlator room, producing a total link length of 77 km. The 52 km fiber link consisted of two 26 km fiber cores that ran off-site, under and along local roadways and a bridge (through a variety of moderate-to-high shrink-swell soil types), to a telecommunications controlled environment vault at Springbrook Creek (located along the Newell Highway, approximately 17.5 km southeast of the observatory and 16.3 km southwest of Narrabri). A short fiber patch was used to connect the two cores in the vault, creating a 52 km loop. A bi-directional erbium-doped fiber amplifier (IDIL Fibres Optiques) was required in order to compensate for the 18 dB optical power loss of the 77 km link.

Additionally, measurements were made to assess the effect of phase drift between two microwave synthesizers. One supplied the standard ATCA frequency distribution system with 8.00 GHz and the second supplied the stabilized frequency transfer prototype with 7.96 GHz. Both synthesizers were referenced to the observatory’s hydrogen masers.

Observations were performed over several days in May and June 2016 during scheduled ATCA maintenance periods. Table 6.1 summarizes the measurements that will be discussed in this paper. Due to maintenance requirements, the number of antennas available at different times varied.

The logging rate was limited by the data volume limitation of the correlator, and it was not possible to perform overnight observations with a logging period shorter than 5 s. A shorter observation of only 2 hr was performed with a logging period of 1 s in order to obtain array phase-stability measurements at shorter integration times.
**Table 6.1:** Summary of astronomical verification observing runs.

<table>
<thead>
<tr>
<th>Date</th>
<th>Centre frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>Available antennas</th>
<th>Logging rate (s)</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 May 26</td>
<td>4.96</td>
<td>2048</td>
<td>01, 02, 03, 04, 05, 06</td>
<td>12</td>
<td>12 hr overnight run, dual synthesizers</td>
</tr>
<tr>
<td>2016 Jun 20</td>
<td>4.96</td>
<td>2048</td>
<td>01, 02, 03, 04, 06</td>
<td>5</td>
<td>13 hr overnight run</td>
</tr>
<tr>
<td>2016 Jun 21</td>
<td>4.96</td>
<td>2048</td>
<td>01, 02, 03, 04, 06</td>
<td>5</td>
<td>12 hr overnight run</td>
</tr>
<tr>
<td>2016 Jun 22</td>
<td>25.44</td>
<td>2048</td>
<td>01, 02, 03, 04, 05, 06</td>
<td>1</td>
<td>12 hr daytime run</td>
</tr>
<tr>
<td>2016 Jun 22</td>
<td>25.44</td>
<td>2048</td>
<td>01, 02, 03, 04, 05, 06</td>
<td>5</td>
<td>15 hr overnight run</td>
</tr>
</tbody>
</table>
6.4. RESULTS

Figure 6.2: Phase solutions (ac) and corresponding phase differences (df) for a selection of three baselines of different lengths (a, d = 46 m; b, e = 152; c, f = 4439 m) for 4.96 GHz observations from 2016 June 21st. Blue represents unmixed baselines; green shows mixed baselines; pink (d), orange (e), and purple (f) depict phase differences for baselines (a), (b), and, (c), respectively.

6.4 Results

Phase solutions and phase differences were produced for all mixed and unmixed baselines for each of the measurements summarized in Table 6.1. An example of the phase solutions and phase differences for a single polarization for three baselines of different lengths from observations conducted on 21st June 2016 is shown in Figure 6.2. The blue traces represent the unmixed baselines (using the conventional ATCA reference distribution) while the green traces represent the same physical baselines using the mixed references. The corresponding phase differences are shown to the right of the figure.

At the commencement of the observations, the delay errors for each antenna were measured by the correlator while observing the calibrator source and corrected for (residual delay errors were typically less than 0.1 nanoseconds). We also added phase
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Figure 6.3: Example amplitude and phase bandpass solutions from 4.96 GHz overnight observation from 21st June 2016. The bandpass solutions for the X-polarization of three antennas (antennas 1, 3, and 6) are shown.

offsets to produce a zero phase for each baseline at the beginning of the observation. No further delay or phase calibration was made while the array was observing.

All post-observation data reduction was performed with the Miriad software package [169]. First, we performed a bandpass calibration with the Miriad task “mfcal”, while solving for time-varying gains every 30 s. The resultant bandpass solutions (examples of which are shown in Figure 6.3) were then subtracted from the entire dataset (we assumed that they stay constant with time). We then used the task “gpcal” to solve for time-variable complex gains every cycle, which is possible due to the brightness of the calibrator source. This was used to produce the phase solutions (like those shown in Figure 6.2) that reveal how the measured phases changed over the duration of the observation.

The phase solutions and phase differences were processed to produce plots of absolute frequency stability. Figure 6.4 shows the absolute stabilities for the three baselines used as examples in Figure 6.2 as well as the phase difference stability of an
6.4. RESULTS

Figure 6.4: Absolute frequency stability of phase solutions and phase differences for (i) 4.96 GHz overnight observation from 2016 June 21 and (ii) 25.44 GHz overnight observation from 2016 June 22. Phase solutions: blue triangles, solid line represent the unmixed 46 m baseline; green triangles, dashed line depict the mixed 46 m baseline; blue squares, solid line show the unmixed 152 m baseline; green squares, dashed line show the mixed 152 m baseline; blue circles, solid line represent the unmixed 4439 m baseline; and green circles, dashed line show the mixed 4439 m baseline. Phase differences: pink triangles, dotted line show the 46 m baseline; orange stars, dashed line represent the 152 m baseline; purple triangles, solid line represent the 4439 m baseline; and black diamonds, solid line show the 107 m baseline between antennas 1 and 3 using only the standard ATCA reference system.

unmixed (conventionally referenced) baseline for comparison. Absolute frequency stability values are obtained by multiplying the Allan deviation computed for the signal by the frequency of the signal. Values in terms of absolute frequency stability are necessary to directly compare the stability of signals of different frequencies, and this allows the noise contributions of different parts of the interferometer and frequency reference systems to be assessed more easily. Figure 6.4 shows the absolute stability plots for the traces shown in Figure 6.2, as well as for the 25 GHz measurements from 22nd June 2016 (using the same example baselines).
The process was repeated for the 1-s logged daytime run from 22nd June 2016 and the resulting absolute frequency stabilities are shown in Figure 6.5. The 1-s logging period of this measurement allows the stability values to be calculated at integration times down to 1 s but, due to the relatively short time span of the observations, stability data are limited to integration times shorter than 1,024 s.

To assess the performance of the system with respect to the 10-min phase-drift requirement, the phase drifts between the mixed and unmixed baselines for each 10-min interval in all 42 hr of stabilized observations (Table 6.1, 20th - 22nd June 2016) were measured. The compiled phase-drift values are shown in Figure 6.6. Within one standard deviation, the phase drifts are less than 0.08 rad, and no 10-min period phase drift exceeded a value of 0.56 rad.

The synthesizer comparison test (Table 6.1, 26th May 2016) exhibits large phase drifts between the mixed and unmixed baselines, an example of which is shown in Figure 6.7. This relative phase drift between the two synthesizers significantly affected the stability of the baseline phase solutions and phase differences. Figure 6.8 shows the resulting absolute frequency stabilities for three example mixed baselines plus an unmixed baseline for comparison.

6.5 Discussion

6.5.1 Stability Analysis

Each of the example stability plots in Figures 6.4 and 6.5 show three traces for the stability of the phase difference between the mixed and unmixed baselines, one each for the short (pink trace), intermediate (orange trace), and long (purple trace) baselines. As expected, the three curves lie on top of each other because they are the result of effectively subtracting out the phase of the sky signal. The remaining phase noise is due to the reference distribution systems and non-common elements of the receiver chains. The frequency transfer systems (UWA stabilized transfer system plus ATCA distribution system electronics) are the dominant source of differential
Figure 6.5: Absolute frequency stability of phase solutions and phase differences for one-second logged 4.96 GHz daytime observation from 22nd June, 2016. Phase solutions: blue triangles, solid line – unmixed 46 m baseline; green triangles, dashed line – mixed 46 m baseline; blue squares, solid line – unmixed 152 m baseline; green squares, dashed line – mixed 152 m baseline; blue circles, solid line – unmixed 4439 m baseline; and green circles, dashed line – mixed 4439 m baseline. Phase differences: pink triangles, dotted line – 46 m baseline; orange stars, dashed line – 152 m baseline; purple triangles, solid line – 4439 m baseline; and black diamonds, solid line – 107 m baseline between antennas 1 and 3 using only the standard ATCA reference system.
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Figure 6.6: Total number of phase drifts of a particular magnitude over 10 min for all observations with the stabilized frequency transfer system.

Figure 6.7: Phase solutions for a single polarization for a 76 m baseline from the dual-synthesizer observation from 26th May 2016. Blue represents the unmixed baseline and green represents the mixed baseline.
Figure 6.8: Absolute frequency stability of phase solutions and phase differences for 4.96 GHz overnight dual-synthesizer observation from 2016 May 26. Phase solutions: blue triangles, solid line show the unmixed 76 m baseline; green triangles, dashed line show the mixed 76 m baseline; blue squares, solid line represent the unmixed 138 m baseline; green squares, dashed line represent the mixed 138 m baseline; blue circles, solid line show the unmixed 3505 m baseline; and green circles, dashed line show the mixed 3505 m baseline. Phase differences: pink triangles, dotted line represent the 76m baseline; orange stars, dashed line represent the 138 m baseline; purple triangles, solid line depict the 3505 m baseline; and black diamonds, solid line depict the 413 m baseline between antennas using only the standard ATCA reference system.
Figure 6.9: Output of the ATCA seeing monitor (black line) overlaid with the phase differences for the 4439 m baseline from the 4.96 GHz overnight observation from 21st June 2016 (purple trace, copy of Fig. 6.2 panel (f)). Increases in atmospheric path length noise shown by the seeing monitor correspond to increases in the rate of phase drift.

noise and, because that noise is common to all chain-2 frequency references, the frequency stability curves for the different baselines are almost identical. Panels (d), (e) and (f) in Figure 6.2 show that the phase differences have some remaining baseline dependence, with the total phase drift increasing with increasing baseline length. This may be due to differential noise on the fiber links between the correlator room and the antennas as well as residual atmospheric effects. Figure 6.9 shows the output of the ATCA seeing monitor [170,171] for the time period corresponding to the example observations from 21st June 2016, overlaid with the phase differences for the 4439 m baseline from this observation (Figure 6.2, panel (f)). The data from the seeing monitor show that the atmospheric path length noise is greater during the periods when there is a noticeable increase in the rate of phase drift.

The difference between the stabilities of the phase differences for the mixed (pink, orange, and purple traces in Figures. 6.4 and 6.5) and unmixed baselines (black traces in Figures. 6.4 and 6.5) is due to noise contributed by both the stabilized frequency transfer prototype and parts of the ATCA frequency distribution system and receiver chains. While the stabilized frequency transfer prototype is
6.5. DISCUSSION

assumed to be the dominant source of the extra phase noise, the following analysis shows that phase noise contributed by the ATCA systems account for a significant fraction of the difference between the mixed and unmixed baseline phase difference stabilities. The mixed baseline phase difference stabilities compared to the integration time ($\tau$) follow a power law with a gradient that is close to $\tau^{-1}$ up to integration times of around 40 s. The phase difference stabilities for the baseline between antennas 1 and 3 (comparing an unmixed baseline with an unmixed baseline, black traces in Figures 6.4 and 6.5) also exhibit this power law out to longer integration times, indicating that some of this extra noise does not originate with the stabilized frequency transfer system [172]. This power law is a signature of white- and/or flicker-phase noise and is most likely due to noise introduced by amplifiers outside of the stabilized frequency transfer system [15]. Measurements of the relative phase drift between the two E/O systems, conducted separately to the main observations, indicated that the ‘bump’ feature in the phase difference stabilities between $\tau = 40$ s and $\tau = 640$ s is due to phase-noise in the E/O systems [172]. This noise is not normally obvious during conventional observations because there is no cross-correlation between signals from chain-1 and chain-2.

6.5.2 Extrapolation to SKA1

With the main contributions to the residual differences between the stability of the phase differences for mixed and unmixed baselines accounted for, the measured absolute frequency stabilities are in good agreement with values expected from laboratory measurements of the stabilized frequency transfer system [155]. This provides confidence that standard metrology measurement techniques are adequate to reliably demonstrate the stability of the stabilized frequency transfer system for SKA verification purposes. The stability of the transmission over 166 km of buried conduit fiber-optic cable around Perth, Western Australia (Figure 6.10), has been measured previously using a Microsemi 5125A Phase Noise Test Set. The Allan deviation
values for the signal stability over the 166 km link were extrapolated to obtain a prediction for the performance of the stabilized transfer system over a single 173 km span (the longest SKA1 fiber-link length). This was achieved by multiplying the measured Allan deviation values by \((L_2/L_1)^{3/2}\) [79], where \(L_1\) is the length of the test link (166 km) and \(L_2\) is the length of the link for which the prediction is being made (173 km). These predicted Allan deviation values were then multiplied by a factor of \(\sqrt{2}\) to give a prediction of the Allan deviation between two stabilization system receiver units at the ends of two separate 173 km links (assuming that deviations in the two signals are uncorrelated). By assuming that the dominant noise process of the stabilized frequency reference is white phase noise (as indicated by the approximately \(\tau^{-1}\) slope of the Allan deviation measurement), an estimate of the coherence loss can be calculated using the process described by [18] and [15].

Using this process, an upper limit was calculated for the permissible Allan deviation of the frequency transfer prototype corresponding to the 1.9% coherence loss requirement for a maximum observing frequency of 13.8 GHz. This Allan deviation is \(3.91 \times 10^{-12}/\tau\) and is shown in Figure 6.10 (pink line). The measured and predicted stability of the stabilized frequency transfer system is well below this limit at all integration times.

Applying the same coherence calculations directly to the measured Allan deviation, the coherence losses resulting from the extrapolated Allan deviation values for a maximum observing frequency of 13.8 GHz are \(7.41 \times 10^{-6}\) at 1 s integration time and \(7.96 \times 10^{-5}\) at 60 s integration time. These values exceed the 1.9% coherence loss requirement by a factor 2560 and 239, respectively.

An alternative method of estimating coherence loss from Allan deviation was used by members of the ALMA project [53–55]. Using this method, we calculate coherence losses of \(4.4 \times 10^{-6}\) at 1 s integration time and \(1.6 \times 10^{-5}\) at 60 s integration time. These values exceed the 1.9% requirement by factors of 4320 and 1190, respectively.
Figure 6.10: Allan deviation of the stabilized frequency transfer prototype over 166 km of buried conduit fiber around Perth, Western Australia (black diamonds) and extrapolated to two links of 173 km (red circles). Allan deviation limit corresponding to SKA 1 s and 60 s coherence requirements (assuming white phase noise) is represented by the pink line.
6.5.3 Dual-Synthesizer Test Analysis

The large phase drift in the results from 26th May 2016 (green trace, Figure 6.7) is dominated by the phase drift between the two synthesizers used as frequency references. In order for a synthesizer to maintain its output frequency relative to a 10 MHz reference, it must change the phase of its output signal as its internal temperature changes in response to variations in ambient temperature. The large drifts were not seen when only one synthesizer was used with the IQ-mixer frequency shift. Figure 6.8 shows that the phase noise of the two synthesizers even dominates the phase noise of the sky signals caused by the atmosphere on baselines up to around 200 m in length at observing frequencies around 5 GHz. This is not an issue in normal observations because interferometers such as the ATCA do not operate in configurations where multiple synthesizers are used to provide frequency references to different antennas or sub-arrays. However, any system that uses multiple remote synthesizers may encounter such a synthesizer phase drift issue despite the transmission frequency being successfully stabilized. This is a critical consideration for the design of stabilized time and frequency reference systems planned for the SKA.

6.6 Conclusion

We have used the dual-receiver architecture of the ATCA to perform astronomical verification tests of a prototype stabilized frequency transfer system proposed for the SKA, as well as to assess the effects of using multiple microwave frequency synthesizers to supply frequency references to different telescope antennas or sub-arrays. The results of these astronomical verification trials show that the stabilized frequency transfer prototype exceeds the SKA level-1 coherence and phase-drift requirements under a broad range of observing conditions. Extrapolating the system’s performance from laboratory measurements over a link of 166 km to SKA operating conditions predicts that, even for a worst-case scenario, this stabilized frequency
transfer system will exceed the 1 s coherence requirement by three orders of magnitude and the 60 s coherence requirement by two orders of magnitude. Over the 77 km link used in these tests, the 10-min phase drift never exceeded 0.56 rad, and all drifts within one standard deviation of the mean had a magnitude less than 0.08 rad. However, the 10-min phase drift is dependent on both systematic and random phase fluctuations, so it is not known how the magnitude of the phase drifts will scale with increasing link length. Also, unlike for the Allan deviation results, it was not possible to determine, from the data obtained, how much of the observed phase drift was due to the stabilized frequency transfer system, and how much can be attributed to other systems, such as the E/O systems. For this reason, bench tests in the laboratory are a better method for validating the stabilized transfer system against this SKA systems requirement. Despite this, these results are a strong indication that this stabilized frequency transfer system is capable of exceeding the 10-min phase-drift requirement.

These tests have also highlighted potential problems with the use of multiple synthesizers to provide phase-coherent signals to separate antennas, even when the reference frequencies to those synthesizers have been successfully phase-stabilized. Care must be taken to ensure that alternative stabilized frequency reference transfer systems being considered for the SKA do not suffer from phase drift to the extent that it is a detriment to the performance of the telescope. Synthesizer phase-drift rates such as those seen in these tests would reduce the sensitivity of the array and, under some conditions, limit the imaging capability.
Radio Frequency Transfer via Aerial Fiber

Foreword

The SKA will be built over two different continents, with SKA1-LOW being built in the Murchison region of Western Australia, and SKA1-MID being built in the Karoo region of South Africa. Both of these locations present difficulties to engineers attempting to design an optimal fiber route for the backbone of the SKA’s signal and data transport network. In particular, the geology of the Karoo region, outside of the main core of the telescope, is extremely difficult (and so, expensive) to trench fiber cable through because it comprises mostly large boulders. In an effort to reduce construction costs, the SKA fiber network infrastructure engineers proposed routing the fiber cable overhead on telecommunications poles. This would expose the fiber cable, including the stabilized frequency transfer link, to the elements, causing the cable to swing in the wind, and be subjected to large temperature fluctuations that would cause the cable to undergo much larger thermal changes than a trenched cable.

It was not known if a stabilized frequency transfer system could cope with the large noise amplitudes caused by the exposure of the cable, and meet the SKA’s synchronization requirements. To determine this, we conducted field tests at SKA South Africa’s Karoo Support Base of a prototype SKA stabilized radio frequency
CHAPTER 7. RADIO FREQUENCY TRANSFER VIA AERIAL FIBER

transfer system (based on the one described in Chapter 4) over aerial suspended fiber links up to 186 km in length. The stabilized transfer system was able to successfully and reliably stabilize the phase noise on even the longest links at levels that exceeded the SKA phase stability requirements.

This chapter presents the results and analysis of these aerial fiber tests, and extends the analysis to compare the aerial fiber links to buried links of similar length. This allows us to make predictions of the performance of the SKA1-MID stabilized frequency transfer system which, at the time of the Karoo field tests, was not ready for field deployment.

The work presented in this chapter is a reproduction of the manuscript submitted to IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control reformatted to be consistent with the rest of this thesis. My experimental contribution to this research was 70% and I prepared 90% of the manuscript, with the remaining work contributed by Dr Schediwy.

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7.1. ABSTRACT

Stabilized Modulated Photonic Signal Transfer Over 186 km of Aerial Fiber

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7.1 Abstract

Aerial suspended optical-fiber links are being considered as economical alternatives to buried links for long-distance transfer of coherent time and frequency signals. We present stability measurements of an actively stabilized 20 MHz photonic signal over aerial fiber links up to 186.2 km in length. Absolute frequency stabilities of \(2.7 \times 10^{-3}\) Hz at 1 s of integration, and \(2.5 \times 10^{-5}\) Hz at \(8 \times 10^3\) s of integration are achieved over this longest link. This stability is compared to that achieved over buried links for both radio and microwave frequencies, to enable us to make a prediction of the stability performance of higher transmission frequencies over these aerial links. The results show that aerial fiber links are a suitable alternative to buried links for a wide range of frequency transfer applications.

7.2 Introduction

Stabilized frequency transfer over long-distance fiber-optic networks has applications in science and industry ranging from radio astronomy, earth sciences, and tests of fundamental physics, to network synchronization and monitoring [40]. As stabilized frequency transfer technologies have matured in recent years, they have rapidly moved beyond the laboratory in to real-world applications [16, 28, 82, 155].
Studies of the frequency transfer stability over in-the-field optical fiber installations have focused on underground [90, 110, 125] and submarine [173] links, as well as telecommunications links incorporating dense wavelength division multiplexing (DWDM) infrastructure [90, 110, 125]. Frequency transfer stability over aerial suspended fiber cables and optical ground wires (OPGWs, [174]) has received less attention because their greater exposure to environmental perturbations means that frequency transfer stability over these links is severely degraded compared with buried links. Overhead links have been shown to exhibit orders-of-magnitude more noise than underground links of similar length [175, 176] which represents a major challenge for frequency stabilization systems. As a result, most research on overhead links has focused on characterizing polarization mode dispersion, state of polarization fluctuations, and transmission delay variations and their impact on telecommunications and network monitoring [177–181]. However, the greatly reduced cost of reticulating overhead fiber links relative to underground links, as well as the prevalence of existing overhead fiber infrastructure (usually in the form of OPGWs), means that there are situations in which it is necessary or desirable to exploit aerial fiber links for stable frequency transmission. Specifically, the tests reported in this paper were carried out in order to determine the effectiveness of disseminating stabilized frequency references over aerial fiber links that will form the backbone of the Synchronization and Timing network for the component of the Square Kilometre Array radio telescope to be constructed in the Karoo region of South Africa (SKA-MID) [20, 23].

Using a stabilized radio-frequency transfer system based on the design described in [182], we report the successful stabilization of a 20 MHz photonic signal transmitted over aerial suspended fiber links of 32.6 km, 153.6 km, and 186.2 km in length which were subject to adverse weather conditions including high wind speeds and large thermal gradients. The transferred frequency stabilities of these links are compared to the performance of transferred frequency stabilities over buried links.
of similar length. Results in terms of absolute frequency stability are used to extend the discussion of the practicality of aerial links across multiple frequency bands.

### 7.3 Experimental Design

These tests were conducted at SKA South Africa’s Karoo support base at Klerefontein. The links used in these tests comprised two cores of a 16.3 km aerial suspended fiber cable between Klerefontein and the Carnarvon point-of-presence (POP) site, and two cores of a 76.8 km aerial suspended fiber cable between Klerefontein and the SKA site. Figure 7.1 is a map depicting the relevant locations and fiber routes.

A fiber patch lead was installed at the Carnarvon POP site to produce a loop-back link of 32.6 km. Another patch was installed at the SKA site to produce a loop-back length of 153.6 km. To compensate for the large optical power loss on the 153.6 km link (31.7 dB loss), the patch at the SKA site included an IDIL Fibres Optiques bi-directional optical amplifier (with a gain of +18.7 dB and a noise figure of 7.6 dB). The fiber in the aerial cables was of standard SMF E9, according to ITU T G.652.D, with a chromatic dispersion coefficient of 18 ps/nm-km at a
CHAPTER 7. RADIO FREQUENCY TRANSFER VIA AERIAL FIBER

Figure 7.2: Schematic of the stabilized modulated photonic signal transfer system and $2 \times 76.8$ km fiber link with optical amplifier. PD, photodetector; AOM, acousto-optic modulator; FM, Faraday mirror; BPF, band-pass filter; Mix, frequency mixer; DDS, direct digital synthesizer.)

wavelength of 1550 nm. The aerial fiber cables were suspended from utility poles for the entirety of their runs and had a typical span distance of 70 m.

Figure 7.2 shows a schematic representation of the stabilized signal transfer system deployed at the Karoo support base at Klerefontein. This stabilized modulated photonic signal transmission system is based on that presented in [182] which achieves phase-noise suppression of the modulated photonic signal through optical phase-sensing and optical phase-actuation using acousto-optic modulators (AOMs). The transmitter and receiver of the stabilized transfer system were co-located in the same room at the support base to enable out-of-loop measurements of the transfer stability to be made.

In the transmitter section of the system, an NKT Photonics Koheras BASIK X15 commercial diode laser (spectral linewidth < 100 Hz) was used to provide a highly coherent optical frequency at 193 THz (1552 nm). The optical signal was split and part of the signal was reflected off a Faraday mirror (FM) and onto the
transmitter-side photodetector (PD) to provide the optical reference signal for an
imbalanced Michaelson interferometer. The other part of the optical signal from
the laser entered a Mach-Zehnder interferometer where a pair of AOMs shifted the
optical frequency by 50 MHz and 70 MHz, producing a single-sideband modulated
20 MHz signal at the output of the Mach-Zehnder. This modulated photonic signal
was injected into the aerial fiber link.

The transmitted signal made the round trip through the link and entered the
receiver section of the system. The optical signal was split with part being directed
to the measurement PD. The 20 MHz signal from the measurement PD was counted
directly by an Agilent 53132A high-precision frequency counter. This class of device
has measurement dead-times, which results in loss of information about the noise
processes present in the transmission. Other instruments, such as the Microsemi
5125A used to characterize the frequency transfer system in [182] do not suffer
from such effects, however, the Agilent counter was the only suitable instrument
available for the fieldwork and so the frequency counter data were used to calculate
an estimate of the fractional frequency stability of the transmitted signal.

The rest of the received optical signal passed through the receiver AOM which
introduced a $2 \times 50$ MHz frequency shift so that the optical signals returning to
the transmitter could be distinguished from reflections on the fiber link. The optical
signals reflected off of a FM and returned through the link to the transmitter
where they again passed through the Mach-Zehnder interferometer and entered the
transmitter-side PD where they beat against the optical reference to produce elec-
tronic signals.

The signals of interest were 200 MHz (the signal that double-passed the 50 MHz
AOM in the Mach-Zehnder) and 240 MHz (the signal that double-passed the 70 MHz
AOM). These electronic beat signals encoded information about the frequency fluc-
tuations resulting from environmental perturbations on the link. The signals were
split and filtered separately to remove the unwanted frequencies. The 200 MHz
and 240 MHz signals were then mixed, producing a 40 MHz signal that was then
mixed with a 40 MHz local oscillator to produce a DC error signal that was fed to the synthesizer supplying the 70 MHz AOM. When the control loop was closed, the DC error signal adjusted the frequency of the 70 MHz AOM to suppress frequency fluctuations on the link. (A full mathematical description of the operation of this type of stabilized modulated photonic signal transfer system is given in [182].) Measurements of stabilized transmissions were performed over links of 32.6 km (Klerefontein–Carnarvon POP–Klerefontein, 8.6 dB loss), 153.6 km (Klerefontein–SKA site–Klerefontein, 31.7 dB loss, 18.7 dB gain from optical amplifier), and 186.2 km (Klerefontein–SKA site–Klerefontein–Carnarvon POP–Klerefontein, 40.3 dB loss, 37.4 dB gain from two optical amplifiers). Optical amplifiers were used as necessary to compensate for the attenuation of the optical signal on the links. The 153.6 km link used the one amplifier installed at the SKA site, while the 186.2 km link incorporated a second amplifier at Klerefontein which served to boost the signal arriving from the SKA site before it was directed to the Carnarvon POP. Measurements of stabilized transmission over the two longest links were made for periods of 24 and 48 hours, while the transmission over the 32.6 km link was measured for one hour. The measurements of the 32.6 km link were run for a shorter period of time than for the longer links because the primary goal of the tests was to determine the ability of the frequency transfer system to stabilized the longer links. The 32.6 km link was measured only for comparison.

To assess the ability of the stabilization system to cope with adverse weather conditions, weather data, including wind speed and air temperature, coinciding with the period of the tests were collected from a weather station operated by the C-Band All Sky Survey (C-BASS) at the Klerefontein site.
7.4 Results

The frequency counter data were processed to produce a triangle-weighted estimate of the absolute frequency stability of the transmitted photonic signals. Results are presented in terms of absolute frequency stability because this more readily allows for the comparison of different transmission frequencies that is covered in the discussion section. Unlike fractional frequency stability, absolute frequency stability is independent of the value of the transmitted frequency and, as will be demonstrated in the discussion section, allows a prediction to be made of the performance of different stabilized frequency transmission systems over these aerial links. Fractional frequency stability values are readily obtained by dividing the absolute frequency stability by the transmission frequency (in this case, 20 MHz). The absolute frequency stability curves are shown in Figure 7.3 (a). Figure 7.3 (b) shows the measured absolute frequency stability of the 20 MHz transmission over ground links that were within 7% of the length of the aerial links. These ground-comparison tests were performed in the laboratory in Perth, Western Australia using the same frequency transfer system on links that comprised a mix of metropolitan networks and spooled fiber up to 144 km in length. To improve the comparison, the noise levels measured on the ground links were scaled (by up to 7%) using the procedure developed by Williams and colleagues [79] to estimate the noise level on ground links of exactly the same length as the aerial links. This was achieved by multiplying the measured absolute frequency stability of the ground link by $(L2/L1)^{3/2}$, where $L1$ is the length of the measured ground link and $L2$ is the length of the link for which the prediction is being made.

The black traces in Figure 7.3 (a) and (b) (black triangles) are ‘zero-length’ stability measurements made by connecting the transmitter and receiver with a fiber patch lead with attenuation set equal to that of the 32.6 km aerial link (8.6 dB loss). As such, these traces represent the noise floor of the transmission system. The discrepancy between the noise floor measurements for the aerial and ground links
Figure 7.3: Absolute frequency stabilities for (a) aerial and (b) ground links derived from the Agilent 53132A frequency counter. Trace styles indicate aerial and ground links of similar lengths. Traces with open markers and dashed lines indicate extrapolated data. Green, filled diamonds, solid line – (a) 32.6 km, (b) 31 km; green, open diamonds, dashed line – 31 km link extrapolated to 32.6 km; orange, filled squares, solid line – (a) 153.6 km, (b) 144 km; orange, open squares, dashed line – 144 km link extrapolated to 153.6 km; purple circles – 186.2 km; black triangles ‘zero-length’ noise floor.
7.4. RESULTS

Figure 7.4: Wind gust speed (blue line) and air temperature (red line) as recorded at the Klerefontein site for the period coinciding with the tests performed on 153.6 km and 186.2 km links. The shaded regions indicate the times when frequency transfer measurements were being performed.

is likely due to the lack of environmental shielding for the stabilization system at the Klerefontein site. The server room at Klerefontein in which the stabilization system was installed is a repurposed farm house with very poor insulation and draft exclusion. This subjected the stabilization system to a significant fraction of the large and rapid temperature fluctuations shown in Figure 7.4, impacting the profile of the measured noise floor. In contrast, the ground link tests were performed in a temperature-controlled metrology laboratory.

The 32.6 km aerial transmission (Figure 7.3 (a), green diamonds) achieved an absolute frequency stability of $4.2 \times 10^{-4}$ Hz at one second of integration time. Using the scaling equation described previously [79], the measured absolute frequency stability of the 31 km ground link (31 km of metropolitan fiber network, Figure 7.3 (b), green, filled diamonds, solid line) was extrapolated to predict the stability of an equivalent 32.6 km ground link (Figure 7.3 (b), green, open diamonds, dashed line). The predicted absolute frequency stability for this link at 1 s of integration time is
CHAPTER 7. RADIO FREQUENCY TRANSFER VIA AERIAL FIBER

$3.1 \times 10^{-4}$ Hz, slightly better than the stability of the aerial link. The stability of this predicted ground link drops to $3.1 \times 10^{-6}$ Hz at $8 \times 10^3$ s of integration time.

The aerial 153.6 km transmission (Figure 7.3 (a), orange squares) achieved an absolute stability of $1.5 \times 10^{-3}$ Hz at one second of integration time, dropping to $8.9 \times 10^{-6}$ Hz at $8 \times 10^3$ s of integration time. The longest available ground link for comparison was 144 km in length (31 km metropolitan network plus 123 km of spooled fiber). The measured frequency stability of this link (Figure 7.3 (b), orange, filled squares, solid line) was extrapolated to predict the stability of a ground link of 153.6 km in length (Figure 7.3 (b), orange, open squares, dashed line). The resulting predicted absolute stability was $1.1 \times 10^{-3}$ Hz at one second of integration time dropping to $6.2 \times 10^{-6}$ Hz at $8 \times 10^3$ s of integration time.

The 186.2 km transmission (Figure 7.3 (a), purple circles) achieved an absolute stability of $2.7 \times 10^{-3}$ Hz at one second of integration time, and $2.5 \times 10^{-5}$ Hz at $8 \times 10^3$ s of integration time. Because this 186.2 km aerial link was nearly 30% longer than the most similar length ground link (144 km), no aerial-ground comparison was made for these measurements.

The results in Figure 7.3 show that the transfer stabilities over aerial and ground links of comparable lengths are very similar, with the aerial links displaying frequency stability values that were only around 35% higher than the ground links despite the large stress loadings imposed by climatic effects.

The frequency transfer over the aerial links proved to be very robust, with the system demonstrating its ability to stabilize an aerial link subject to a wide variety of weather conditions. The measurements of the 32.6 km link were performed during stormy weather in which the speed of wind gusts exceeded 60 km/h. The period corresponding to the measurements of the 153.6 km and 186.2 km links had weather conditions that varied from thick overcast, with wind gust speeds around 50 km/h, to fine conditions with wind gusts not exceeding 28 km/h. Figure 7.4 shows wind gust speed and air temperature data from the C-BASS weather station. The time periods corresponding with frequency transfer measurements are shaded and labeled.
Figure 7.4 shows that measurements of stabilized transfer over the 153.6 km and 186.2 km links were made during periods of high winds, demonstrating that the stabilized transfer system could maintain a robust lock despite the large stresses induced on the aerial cable spans which cause large and rapid phase fluctuations that can potentially cause slower-acting stabilization servo systems to cycle slip. Due to the thick overcast, the thermal gradients on the cables during these times were relatively small compared to the days of fine weather and little overcast. Fine days produced greater thermal gradients due to the larger air-temperature range and the effects of solar heating of the aerial cables. The stabilized signal transfer system was able to operate continuously throughout these weather conditions. No cycle slips were recorded for the 24 hours of the 153.6 km link measurements or the 16 hours of the 186.2 km link measurements coinciding with the periods of higher wind speeds (see Figure 7.4). Also, no cycle slips were recorded for the 48 hours of the 153.6 km link measurement coinciding with the period of larger thermal gradients (see Figure 7.4), during which the air temperature ranged from 0°C to 15°C with a maximum thermal gradient of 1.2°C over 10 minutes.

7.5 Discussion

Figure 7.4 shows that the stabilized frequency transmission system operated through periods of adverse weather including large wind gusts and significant thermal gradients. Inspection of the recorded frequency fluctuations at the end of the tests did not produce any correlation between the magnitude of the frequency fluctuations and the wind speed or temperature gradients. As an example, Figure 7.5 shows the absolute magnitude of the recorded frequency fluctuations for the 48 hour 153.6 km link test compared with concurrent wind speed and air temperature readings. The frequency fluctuations show no relation to either the thermal gradient or the wind-loading of the cables.
The choice of transmission frequency (20 MHz) for these tests was determined mainly by the AOMs available at the time. Higher transmission frequencies would improve the fractional frequency stability performance of the system. Tests of this type of optically sensed/actuated modulated photonic signal transfer system [182] at different transmission frequencies over other fiber links have shown that, at these high levels of noise, the absolute frequency stability of the system is largely independent of the transmitted frequency. This effect is demonstrated in Figure 7.6.

### 7.6 Conclusion

We have demonstrated the stabilized transfer of a 20 MHz photonic signal over aerial suspended fiber links up to 186.3 km in length. The frequency transfer proved to be very robust, demonstrating continuous stabilized transfer throughout inclement weather conditions including high winds and large thermal gradients. The overall stability levels measured on the aerial links were comparable to ground links of similar length using the same frequency transfer system. Increasing the modulation frequency offers an immediate way to significantly improve the fractional frequency stability levels attained by this type of stabilized photonic signal transfer system [182].
7.6. CONCLUSION

Figure 7.6: Absolute frequency stability of transmissions over 166 km of buried fiber at 20 MHz (orange, open squares, dashed line), 160 MHz (red circles), and 8,000 MHz (blue triangles, data from [155], Figure 2).

Based on the overall noise levels observed for all of the transmissions, it is likely that other modulated photonic signal frequency transfer systems, such as [73], [78], and [71], will also achieve effective stabilization on aerial links to at least the levels of stability achieved here. However, the infinite feedback range provided by AOM-actuated systems offers advantages over the group-delay actuator technology of [73] and [78] over long links subjected to large thermal gradients. These results indicate that aerial fiber is a suitable medium for stabilized frequency transfer and presents an attractive alternative when underground links are unavailable or prohibitively expensive. The independence of the absolute frequency stability demonstrated in Figure 7.6 allows the performance of similar modulated photonic signal frequency transfer systems operating at different frequencies on the overhead links to be predicted. Early results from another set of tests carried out on these aerial links on behalf of the SKA [183] support our conclusion that aerial links are also suitable for
microwave frequency transfer.
Light thinks it travels faster than anything but it is wrong. No matter how fast light travels, it finds the darkness has always got there first, and is waiting for it.

— Sir Terry Pratchett

Aerial Fiber Optical Frequency Transfer Characterization

Foreword

As well as the stabilized radio frequency transfer tests over aerial fiber conducted at the SKA South Africa Karoo Support Base (described in Chapter 7), we also performed optical frequency transfer tests over the aerial links. The performance of optical frequency transfer over aerial suspended fibers is of great interest to the time and frequency transfer community because buried links are not always available, aerial fiber is more economical to install, and the extensive network of power line optical ground wires may be exploited for experimental purposes.

This chapter describes the transmission of a 193 THz optical signal over aerial suspended fiber cables, up to 154 km in length, servicing the South African SKA site. Analysis of the data showed that the dominant source of noise on the links was related to the fundamental lateral oscillation (swinging mode) of the pole-to-pole fiber spans loaded by the wind. Attempts were also made to stabilize the optical transmission, but with limited success. Only the shortest, 36 km link was successfully stabilized, and only for a period of nearly half an hour.
CHAPTER 8. AERIAL FIBER OPTICAL FREQUENCY TRANSFER CHARACTERIZATION

The results of these experiments have been published in the journal *Optics Letters*. The manuscript is reproduced here with formatting changes to make it consistent with the rest of the work in this thesis. In particular, *Optics Letters* does not use section headings as they appear here. I contributed 80% of the manuscript preparation and performed 70% of the experimental work, with the remainder contributed by Dr Schediwy.

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8.1. ABSTRACT

Characterization of optical frequency transfer over 154 km of aerial fiber

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8.1 Abstract

We present measurements of the frequency transfer stability and analysis of the noise characteristics of an optical signal propagating over aerial suspended fiber links up to 153.6 km in length. The measured frequency transfer stability over these links is on the order of $10^{-11}$ at an integration time of 1 s dropping to $10^{-12}$ for integration times longer than 100 s. We show that wind loading of the cable spans is the dominant source of short-timescale noise on the fiber links. We also report an attempt to stabilize the optical frequency transfer over these aerial links.

8.2 Introduction

Long-distance optical fiber networks are increasingly being used for the transmission of high-precision frequency and timing signals because the stability and accuracy of optical links surpass that of conventional satellite two-way time and frequency transfer by more than three orders of magnitude [184–186]. The frequency and timing signals have applications in science and industry, ranging from radio astronomy, geodesy, and tests of fundamental physics, to network synchronization and high-precision manufacturing [40].
One factor that limits the performance of long-distance frequency transfer is the phase noise imposed onto the optical signal by mechanical stresses on the fiber link. Measurements of frequency transfer stability have mostly focused on underground [90, 110, 125] and some submarine links [173]. Although aerial suspended fibers and optical ground wires (OPGWs) are subject to greater mechanical stresses due to their greater exposure, the lower cost of reticulating overhead fiber means that there are circumstances under which the timing and frequency transfer stability of transmissions employing overhead fiber links is of interest. In particular, this Letter was carried out in order to characterize the impact of synchronization signals that are to be disseminated over aerial fiber links as part of the Square Kilometre Array (SKA) radio telescope to be constructed in the Karoo region of South Africa [20].

The investigation of detrimental effects on telecommunications and network monitoring due to the impact of environmental conditions on aerial fibers and OPGWs has focused on polarization mode dispersion, the state of polarization fluctuations, and transmission delay variations [177–181]. To the best of our knowledge, only one study [175] has undertaken a characterization of frequency transfer stability on aerial fiber to date, and only at radio frequencies (10 MHz). In this Letter, we present, to the best of our knowledge, the first characterization of optical frequency transfer stabilities on aerial suspended fiber links of 32.6, 65.2, and 153.6 km lengths.

Optical frequency transfer provides the highest level of precision for the purposes of metrology and other sciences [110]; however, it is also the most sensitive to mechanical stresses on the link and is the most difficult to actively stabilize. The magnitude of the phase perturbations detected on the aerial fiber links in this Letter demonstrate the challenges for optical phase stabilization systems attempting to compensate for the noise imposed on the link.
8.3 Measurement Setup

These tests were conducted at SKA South Africa’s Karoo support base at Klerefontein near the South African SKA site. Figure 8.1 shows the physical arrangement of the relevant locations. Four cores of a 16.3 km fiber link from Klerefontein to the Carnarvon point-of-presence (POP) site, and two cores of a 76.8 km fiber link between Klerefontein and the SKA central site were used for the tests (fiber standard, SMF E9 according to ITU T G.652.D; chromatic dispersion at 1550 nm, 18 ps/nm-km). The fiber cables were suspended from power poles for the entirety of their runs. Fiber patch leads were installed at the Carnarvon POP to give two loop-back sections of 32.6 km of aerial fiber, while another patch, incorporating an IDIL Fibres Optiques bidirectional optical amplifier (with a gain of +18.7 dB and a noise figure of 7.6 dB), was installed at the SKA central site to produce a loop-back length of 153.6 km.

Figure 8.2 shows a schematic representation of the system that was installed at Klerefontein and used to characterize the fiber links. The system is fundamentally a stabilized optical frequency transmission system, based on the technology pioneered by Ma et al. [85]. Our primary aim was to characterize the noise on the fiber, but we
designed the equipment to also be capable of active stabilization of the link noise. However, in practice, we were unable to achieve continuously stabilized transmission for more than several minutes, even over the 32.6 km link, due to the magnitude of the perturbations and the design of the stabilization servo electronics.

In the transmitter section of the system, an NKT Photonics Koheras BASIK X15 commercial diode laser (spectral linewidth < 100 Hz) was used to provide a highly coherent optical frequency at 193 THz (1552 nm). A small fraction (3%) of the optical signal was split off to provide the out-of-loop optical reference for the measurement photodetector (PD). The rest of the power continued downline where it was split again, with part being reflected off a Faraday mirror (FM) at the end of a short length of fiber to become the reference signal for an imbalanced Michelson interferometer. The fiber link constituted the long arm of the Michelson interferometer. Before the optical signal was injected into the fiber link, it passed...
through the servo acousto-optic modulator (AOM) which produced a +70 MHz shift of the optical frequency.

The rest of the received signal power passed through the receiver AOM (+50 MHz frequency shift), reflected from a FM, passed through the receiver AOM again and returned through the fiber link back to the transmitter side of the system. After passing through the servo AOM, the signal from the link and the signal from the reference arm entered the input of the servo PD where they formed a 240 MHz electronic beat signal. This beat signal encoded information about the frequency fluctuations on the fiber link due to environmental perturbations. The electronic signal was divided by a factor of 24 and then mixed with a 10 MHz local oscillator. The mixer product became the servo error signal and was used to steer the 70 MHz output of the frequency synthesizer. Activating the frequency modulation closed the servo loop, and the system adjusted the frequency shift produced by the servo AOM to compensate for frequency fluctuations caused by perturbations on the fiber link.

The characterization of the noise of the fiber link was achieved with the servo loop deactivated. Links of 32.6 (2 × 16.3 km, 8.6 dB loss) and 65.2 km (4 × 16.3 km, 17.4 dB loss) between Klerefontein and Carnarvon, and 153.6 km (2 × 76.8 km, 31.7 dB loss) between Klerefontein and the SKA site, were tested during these trials.

Weather data, including wind speed and wind direction, coinciding with the period of the trials were collected from a weather station operated at Klerefontein by the C-Band All Sky Survey (C-BASS). The wind velocity data were compared with the magnitude of the coincident link frequency fluctuations.

### 8.4 Results

The data from the frequency counter were processed to produce fractional frequency stability curves for the three links studied. These curves are shown in Figure 8.3. The blue trace in Figure 8.3 (filled triangles, solid line) is a “zero-length” (a 2 m fiber
patch lead) measurement with optical attenuation set equal to that of the 32.6 km link and is, therefore, a measurement of the fiber characterization system noise floor.

Due to the magnitude of the noise on the fiber links, it was not possible to actively stabilize the optical transmission for more than a few minutes before a cycle slip occurred. The data presented here show only one stabilized transmission of 26 minutes for the 32.6 km link (green, filled triangles, solid line). The measurements for the characterization of the frequency noise on the free-running links were taken for periods of between 1 and 93 hours at all times of day and night.
8.5 Discussion

There is little difference in the overall frequency noise levels between the three different aerial link lengths (Figure 8.3). However, all three links show an extreme level of noise. The instability of the 153.6 km link (red, open triangles, dashed line) at one second integration time is approximately 260 times greater than the free-running link noise for the 1840 km buried fiber link reported by Droste and colleagues [96].

For comparison with the stabilized 32.6 km overhead fiber data (green, filled triangles, Figure 8.3), the stabilized transfer stability over a 31 km urban trench and conduit fiber link in Perth, Western Australia, has been included (green, filled circles, solid line). Figure 8.3 shows that the fractional frequency value for the stabilized transfer over the 32.6 km aerial fiber link is 124 times greater than that for the 31 km buried link at an integration time of one second, and that the value of the freerunning aerial link (green, open triangles, dashed line) is nearly 2 million times greater than the stabilized buried link at an integration time of one second.

Also shown in Figure 8.3 is the stability of a 142 km link, stabilized (red, filled circles, solid line) and free-running (red, open circles, dashed line), composed of 31 km of urban trench and conduit fiber, and 111 km of fiber spool in the laboratory in Perth. Compared to the 153.6 km Klerefontein-SKA site loopback link (8% longer), the fractional frequency stability of the aerial link is nearly three orders of magnitude greater than the 142 km free-running link at an integration time of one second.

The extreme difference in the frequency transfer stability between the aerial and buried fiber links is due to mechanical stresses on the fiber cables caused by the weather. During the testing period, the fiber cables were subjected to high and gusting winds, rain, and large thermal gradients, as the fiber went from overnight frost to direct morning sunlight. The greatest source of short-timescale perturbations was the wind.
The raw data from the frequency counter displayed a noticeable periodicity in the amplitude of the frequency fluctuations. By taking the Fourier transform, shown in Figure 8.4, of the timeseries frequency data for the 153.6 km Klerefontein-SKA site link, it can clearly be seen that there is a dominant periodicity in the frequency perturbations of $1.405 \pm 0.002$ s ($2\sigma$).

Visual inspection of typical spans of aerial fiber in the vicinity of Klerefontein (recorded on camera for later analysis) estimated the period of the fundamental lateral (swinging) mode of the spans to be $2.85 \pm 0.15$ s, giving a half-period of $1.43 \pm 0.08$ s. This overlaps, within uncertainty, with the dominant period in the frequency fluctuation data (Figure 8.4), and indicates that the swinging action of the cable is related to the periodicity of the frequency fluctuations. The swinging of the spans induces periodic stresses on the fiber, altering the optical path length and producing phase noise on the signal.

The Klerefontein-SKA aerial fiber link is composed of around 1000 span segments with a median span distance of 70 m. Because the frequency fluctuations induced
8.5. DISCUSSION

Figure 8.5: Absolute magnitude of frequency fluctuations over time (filled red area), overlayed with the projected component of the wind speed perpendicular to the weighted dominant direction of the Klerefontein-SKA site fiber link (blue line).

by the mechanical oscillations of the fiber manifest as twice the cable fundamental mode frequency, their signal magnitudes combine in quadrature, even when the oscillations of separate fiber cable spans are not coherent.

The impact of wind loading on the fiber cables can be further examined by assessing the correlation between the magnitude of the frequency fluctuations (which are dominated by the 1.405 s periodic component) and the amplitude of the swinging of the cable spans. This oscillation mode is loaded by the vector component of the wind perpendicular to the direction of the cable span. Figure 8.5 shows a plot of the absolute magnitude of the frequency fluctuations over time, overlayed with the projected component of the wind speed (determined from C-BASS weather station data) perpendicular to the weighted dominant direction of the Klerefontein-SKA site fiber link.

The data suggest that there is a causal correlation between the wind speed and the magnitude of the frequency fluctuations. The residual discrepancy is attributed
to the local variation in wind speed between the weather station site and the fiber route. The time resolution of the wind speed data also mask the effects of gusts.

8.6 Conclusion

We have measured the frequency transfer stability and characterized the noise of optical signals transmitted over aerial fiber links up to 153.6 km in length. All of the tested aerial fiber links exhibited levels of frequency noise hundreds of times greater than comparable buried links. The dominant source of noise was shown to be caused by mechanical strains imposed by the swinging of the fiber spans due to transverse loading from the wind. Only the shortest link (32.6 km) was successfully stabilized for a period of nearly half an hour without a cycle slip, and with two orders of magnitude poorer stability than the equivalent buried link. Higher-frequency division ratios in the servo error signal chain may improve the frequency locking performance of this and similar stabilization systems. In addition, repeater stations at intervals along the link will also improve the stability of the whole link. This increases the servo bandwidth and allows for greater servo gain. If the longer fiber spans can be successfully stabilized for significant periods of time, then aerial fiber may present a useful alternative for optical frequency transmission in situations where buried fiber is unavailable or cost-prohibitive. The challenges of robust signal stabilization over aerial fiber are significantly reduced at radio and microwave transfer frequencies due to the lower sensitivity of the phase of these transmissions to fiber length changes. The same aerial links tested here were successfully stabilized at radio frequencies [155], based on the technique in Ref. [182], and microwave frequencies [183].
There are no such things as applied sciences, only applications of science.
— Louis Pasteur

9

Conclusions

This thesis describes important progress on the development of stabilized radio and microwave frequency reference transfer systems for SKA1-LOW and SKA1-MID. The first half of this thesis detailed the design, theory of operation, and laboratory testing of three prototype systems, including one preliminary concept that was later redesigned. The second half of this thesis described the results of field campaigns to perform astronomical verification tests of the the frequency transfer system, and aerial fiber frequency transfer characterization tests in support of SKA design option considerations. The frequency transfer systems exceeded the SKA design requirements, and the results from the field campaigns contributed important data and understanding that have significant impacts on SKA design decisions.

9.1 Summary of Results

Chapter 3 introduced a first concept for a frequency transfer design that, with minimal modification, could support the radio frequency transfer required by SKA1-LOW as well as the microwave frequency transfer required by SKA1-MID. The chapter gives a rigorous mathematical description of the theory of operation, gives a detailed description of the physical design, and presents results for optical frequency
CHAPTER 9. CONCLUSIONS

transfer as well as the transfer of a 10.02 GHz signal over 30 km of spooled fiber in the laboratory. The systems achieved an excellent optical frequency absolute transfer stability of $1.7 \times 10^{-3}$ Hz (equivalent to a fractional frequency of $8.8 \times 10^{-18}$) over one second, but only a moderate microwave absolute frequency stability of $1.7 \times 10^{-3}$ Hz (equivalent to a fractional frequency of $1.7 \times 10^{-13}$) over one second. Optical frequency phase noise was suppressed by more than three orders of magnitude, but the system only achieved a small reduction of the microwave frequency phase noise. Longer links may have permitted a more thorough investigation of the frequency transfer performance, but, at the time, the 30 km spool was the longest available fiber link. Despite this, the achieved transfer stabilities met SKA requirements. The overall design, which mostly uses optical frequency transfer components and is compatible with optical frequency transfer may have applications in hybrid time and frequency transfer networks for scientific or commercial applications.

Field tests of the frequency transfer system presented in Chapter 3, which were not detailed in the submitted and published papers reproduced in this thesis, showed that the transmitter design was sensitive to the mechanical vibrations present in a typical observatory correlator room because the optical layout was effectively a large Mach-Zehnder interferometer. To overcome this issue, the frequency transfer system was redesigned to stabilized both the Mach-Zehnder interferometer and the link, resulting in the separate radio and microwave frequency transfer system concepts presented in Chapters 4 and 5.

Chapter 4 presented a simple stabilized radio frequency transfer system optimized to the design requirements of SKA1-LOW. The novel design offers a simple and compact stabilized radio frequency transfer solution. The chapter covered the mathematical proof of the theory of operation, gave a detailed description of the experimental setup, and presented results for the transfer of 160 MHz signal over 166 km of metropolitan fiber network (which had become available after the tests presented in Chapter 3). The achieved fractional frequency stability of $9.7 \times 10^{-12}$ over one second compares favourably with other radio frequency transfer systems.
and easily exceeds the stability required by SKA1-LOW. Possible applications of this simple radio frequency transfer design, which mostly made use of optical frequency transfer components, to scientific and commercial applications in time and frequency transfer networks were also discussed in the chapter.

Chapter 5 presented a stabilized microwave frequency transfer system optimized to the design requirements of SKA1-MID. The radio and microwave frequency designs share a general stabilization concept (stabilizing both the Mach-Zehnder interferometer and the link simultaneously), but, because of the different electronic frequencies, require different electronics and a significant rearrangement of the optical layout to accommodate the uni-directional dual-parallel Mach-Zehnder modulator. The chapter covers the mathematical and technical description of this novel and simple stabilized microwave transfer design, and presents the results of 8 GHz frequency transfer over 166 km of metropolitan fiber network. The simple stabilized transfer system achieved stabilities comparable to other microwave transfer systems, realizing a fractional frequency stability of $6.8 \times 10^{-14}$ over one second, which is well in excess of the stabilities required by SKA1-MID. The chapter also notes the advantages of the technique in terms of simplicity and compact size, and discusses potential applications in other frequency transfer networks.

Chapter 6 described astronomical verification tests of the stabilized microwave frequency transfer system presented in Chapter 5 undertaken at the Australia Telescope Compact Array (ATCA). The microwave frequency transfer system was installed in the ATCA correlator room and supplied a frequency reference, over 77 km of fiber link, to one of the receivers in a subset of the ATCA antennas. The dual-receiver architecture of the ATCA antennas was exploited to permit simultaneous astronomical observations with both the stabilized transfer system and the conventional ATCA frequency reference dissemination system. The performance of the stabilized transfer system was successfully extracted from the astronomical data and analyzed. The performance of the transfer system over a 166 km fiber link,
CHAPTER 9. CONCLUSIONS

extrapolated to the 173 km of the longest SKA1-MID links, was shown to exceed the coherence loss requirements of the SKA by two to three orders of magnitude.

Chapter 7 described field tests in which a photonic 20 MHz radio frequency signal was transmitted over aerial fiber links at the SKA South Africa site. The stabilized transfer was accomplished using a radio frequency transfer system based on the one presented in Chapter 4 and was achieved over links up to 186 km in length. The absolute frequency stability of the 20 MHz signal achieved over this longest link was $2.7 \times 10^{-3}$ over one second which was found to be very similar to that achieved over buried metropolitan links of comparable length. The weather (wind speed and temperature variations) had no obvious impact on the transfer stability, showing that the system was resilient to these disturbances and will be robust against the weather conditions the SKA is expected to endure in normal operation. The similarity between transfer stabilities achieved over aerial and buried links was extended to make a prediction of the performance of the stabilized microwave transfer system presented in Chapter 5 over the 173 km aerial links planned for SKA1-MID.

Chapter 8 is the final experiment presented in this thesis and presents results of the characterization over optical frequency transfer over the same aerial fiber links at the South African SKA tested in Chapter 7. Attempts to stabilize the optical transfer over these aerial links in high winds were only marginally successful, with only the shortest 32.6 km link being successfully continuously stabilized for a period of 26 minutes. The dominant source of noise was found to be related to the swinging of the fiber spans caused by wind loading, while some contributions from thermal effects were also identified. The results presented in both Chapters 7 and 8 contribute important information to SKA design decisions, as well as providing a useful resource to engineers and scientists designing and implementing future time and frequency transfer networks by aiding them to assess the utility of aerial fiber links and existing optical ground wire infrastructure.

Through the work presented in this thesis, simple, small, and robust radio and microwave frequency stabilized reference signal transfer systems have been developed
9.2. RESIDUAL ERROR ANALYSIS

for SKA1-LOW and SKA1-MID. Field tests have proved the robustness and efficacy of the systems in conditions that the SKA is expected to be subjected to in normal operation. The work presented here contributed to documentation presented to the SKA Organisation to support a down-select decision between competing frequency reference transfer systems. The microwave transfer system presented in Chapters 5 and 6 was chosen as the system to be implemented on SKA-MID in South Africa, while a competing system was selected for SKA-LOW. The work also appears in several SKA technical reports. The paper attached as Appendix B gives a complete overview of the SKA synchronization and timing infrastructure design, and provides details of how the stabilized frequency reference transfer systems will interface with the rest of the telescope systems, and what services the frequency references render to the SKA receivers and digitizers. The work presented in this thesis has also contributed useful information and details of novel frequency transfer solutions to the frequency transfer and metrology research community.

9.2 Residual Error Analysis

The preceding chapters did not contain a significant or detailed analysis of the processes limiting the achieved stability of the frequency transfer systems. Possible limiting effects and ways to improve the stability were suggested, but detailed analysis was not considered, usually due to the page limits or other constraints on the papers submitted for publication. An analysis of the contributions to the residual instabilities is useful and so is covered here.

A complete and rigorous analysis cannot be made due to a lack of available resources and information. Experiments and apparatus have been deconstructed for use in other experiments, some equipment is no longer available, and field trips cannot easily be repeated. Equipment to perform a spectral density analysis would be necessary to examine the contributions to the short timescale noise (noise with a
period significantly less than one second) and this equipment was not available for most of the experiments reported in this thesis. Bode analyzers, which are needed to measure the transfer functions of various apparatus, were also not available. Without the ability to conduct a spectral density or Bode analysis, the effects of the feedback bandwidth cannot be measured or modelled effectively because this effect becomes apparent in short timescale measurements. Because of this, this analysis will focus on identifying factors limiting the stability from the long timescale noise shown by plots of the fractional frequency deviation.

Figure 9.1 shows typical absolute frequency stabilties for zero-length transfer of 193 THz optical, 8 GHz microwave, and 160 MHz and 20 MHz radio frequencies using the systems presented in Chapters 4 to 8. Figure 9.1 also shows the absolute frequency stability of the frequency counter noise floor. The counter noise floor was obtained by feeding a 20 MHz signal from a frequency synthesizer straight into the frequency counter.

From Figure 9.1 it is clear that the zero-length 20 MHz transfer matches the noise floor of the counter and so the frequency stability of the reference synthesizers and counter limits our ability to resolve the noise of the zero-length 20 MHz transfer, but does not limit the analysis of the instability of the 160 MHz, 8 GHz, and optical transmissions.

Comparing this result to Figure 7.3(b) in Chapter 7 shows that the 20 MHz zero-length transfer measurement in Figure 7.3(b) is limited by the noise floor of the counter. However, the 31 km and 144 km 20 MHz transfer results in Figure 7.3(b) exhibit levels of stability that scale approximately linearly with the length of the link, L, rather than scaling as $L^{3/2}$ as expected from the results and analysis of Williams and colleagues [79]. The linear rather than $L^{3/2}$ scaling suggests that the apparent increase in noise is produced by processes within the stabilization system. Signals that are heterodyned in order to detect the link phase fluctuations and produce error signals may not be sufficiently stable over the round trip time of the transmitted signal. The prime candidate for this is the laser. However, the mathe-
9.2. RESIDUAL ERROR ANALYSIS

Figure 9.1: Analysis of residual instabilities. This figure shows absolute frequency stability results for transfer of optical, microwave, and radio frequencies over zerolength using the systems described in Chapters 4 to 8. The stability of the noise floor of the frequency counter is also shown.

A mathematical description of the operation of the radio and microwave frequency transfer systems given in Chapters 4 and 5 shows that, to first order, the transfer systems are insensitive to the frequency instability of the laser. A change in frequency of the optical signal from the laser during the signal round trip is cancelled out by the signal mixing procedure. While the laser could still be the culprit, the analysis indicates that it is due to higher order effects, which we would expect to have a very much reduced influence on the frequency transfer stability.

Another candidate for the source of this noise is the frequency mixing process used to detect the phase perturbation of the signal returning on the link and to generate the error signal. However, there is no clear pattern to this in Figure 9.1. The performance of the system is highly dependent on the performance of the frequency mixers but the 20 MHz, 160 MHz, and 8 GHz transfer systems largely use the same
radio frequency mixers, indicating that the different performance of these systems
is not due to the mixers.

Stabilized frequency transmissions systems such as the ones presented in this
thesis are highly sensitive to state of polarization change (SOPC) and polarization
mode dispersion (PMD) on the fiber links [143,187]. The Faraday mirrors installed
in the receiver units are used to solve the problem of signal fading in the heterodyne
beat of the returning signal at the transmitter, but they can still cause significant
degradation of the phase stability of a transmitted signal [143]. Referring to Fig-
ure 7.3 in Chapter 7, the results from these tests showed that the 20 MHz transfer
stability performance was very similar over aerial and buried fiber links. The aerial
links are exposed to significantly greater stresses and would be expected to have a
much higher rate of SOPC and change of PMD and this should be apparent in the
achieved stability. Because of this, the high degree of similarity between stability
of the aerial and buried links in the tests presented in Chapter 7 is unexpected and
this indicates that there is a significant limiting factor within the phase detection
and correction system, but it is dominant over polarization effects.

It is conceivable that the frequency shift applied at the remote site to tag the
returning signal and guard against the effects of spurious reflections could cause delay
errors that significantly affect the stability performance of the frequency transfer
system. The birefringence of the fiber is wavelength dependent, meaning different
wavelengths have different PMD, effectively a second-order chromatic PMD [147].
While it is not possible with the available data to directly calculate the effect of
the differential frequency propagation on the achieved fractional frequency stability,
the deviation of the dual differential propagation delay caused by the second-order
PMD, $\sigma_{PMD,2}$, can be calculated from the following [147,188]:

$$\sigma_{PMD,2} = \frac{2\pi c D^2}{\sqrt{3}} \left( \frac{1}{\lambda_1^2} - \frac{1}{\lambda_2^2} \right) \Delta \lambda L$$  (9.1)
where \( c \) is the speed of light, \( D \) is the fiber PMD parameter (typically around 0.079 ps/km\(^{1/2} \) for standard single mode fiber), \( \lambda_1 \) and \( \lambda_2 \) are the propagating optical wavelengths that generate the radio or microwave frequency carrier, \( \Delta \lambda \) is the wavelength of the remote site frequency shift, and \( L \) is the length of the fiber link in km.

Taking the parameters for the 20 MHz radio and 8 GHz microwave frequency transfer systems described in Chapters 7 and 5 respectively, we can calculate the dual differential propagation delay deviation for these systems.

\[
\sigma_{\text{PMD,20MHz}} = 7.8 \times 10^{-8} \text{fs}, \quad \text{and} \quad 9.2
\]

\[
\sigma_{\text{PMD,8GHz}} = 3.1 \times 10^{-5} \text{fs}. \quad (9.3)
\]

The delay deviation for both systems is extremely small and is unlikely to make any significant contribution to the residual instability of the stabilized frequency transfer. The remote site frequency shift does not adversely affect the performance of the system. This analysis, however, does not take into account non-reciprocity of disturbances on the link, which could still have a significant effect on the overall performance of the systems, particularly in regard to short timescale noise.

Over the long links used for most of the experiments described in Chapters 4 to 8 it was necessary to use EDFAs to compensate for the optical power loss of the links. EDFAs are known to contribute significant additive noise to the propagating signal, though their reciprocal delay is very closely matched. Figure 9.2 shows absolute frequency stability measurements for a stabilized optical transmission through a short fibre patch lead with and without an EDFA. The attenuation of the patch lead is adjusted to ensure optical and electronic signal power levels are the same with and without the EDFA.

Figure 9.2 shows that the inclusion of an EDFA in the link adds a significant level of noise, particularly at short timescales. The difference is significant enough that...
the L$^{3/2}$ scaling rule cannot be reliably used to compare links in situations where the different link lengths require a different number of EDFAs, such as the situation presented in Chapters 7 and 8.

The residual error analysis conducted above, while unable to make a rigorous and conclusive analysis due a lack of available data and resources, shows that the stabilized frequency transfer systems presented in this thesis are not limited by reference frequency stability, SOPC, PMD, or non-reciprocal link effects due to the remote site frequency shift. The achieved stabilities are likely to be limited by laser self-heterodyne noise, or an as yet unconsidered effect within the phase error detection process. Only extensive testing of individual components and complete systems with equipment that permits a Bode analysis and measurement of the short timescale noise spectral density can shed further light on the limitations of the stabilization systems.
9.3 Future Research

Within the next year, the SKA will move into its construction phase. To support the implementation of the chosen stabilized frequency reference transfer systems during this time, extensive further development, verification, and integration analysis will be performed.

Work on designs for mass manufacture archetypes of the SKA1-LOW and MID systems presented in Chapters 4 and 5 is already in an advanced stage (not covered in this thesis) with the first test units already constructed and under test, but some further work is required to complete the development and testing of these archetypes. Details of how the stand alone microwave frequency transfer system presented in this thesis will be expanded to the service the multiple links and receiver sites used in the SKA have not been covered here. Some aspects of the design of the system will need to be modified to economically service SKA-MID. In particular, items such as the laser and the dual-parallel Mach-Zehnder modulator can service hundreds of links by simply using a single high-power device and splitting the signal to each transmitter unit. A paper detailing the SKA architecture and interfaces based on the systems presented here is currently being written. Ancillary systems, such as a controller for the dual-parallel Mach-Zehnder modulator, also have not yet been designed. All of this work will be crucial the ensure the performance of the frequency transfer design leading in to the construction phase. Integration tests of the SKA1-MID system with the existing MeerKAT precursor telescope systems will need to be carried out and are planned for 2018.

Application of the microwave frequency transfer system and related optical frequency transfer system technologies are currently being investigated in relation to the ACES mission. UWA is a potential ground station for ACES, and significant increases in measurement precision can be achieved by using stabilized links to transfer frequency signals from UWA to the Yarragadee Geodetic Observatory, an approximately 480 km fiber transfer distance, where the laser ranging station will direct
precisely timed pulses at the ACES payload aboard the International Space Station. Methods for bridging a 60 km fiber gap using stabilized free-space transfer are also currently being investigated in support of this project.

This research is all planned for the next few years, but looking further towards the future, technologies and techniques related to those presented in this thesis will be investigated in relation to supporting scientific projects such as the next-generation VLA, and VLBI experiments such as the Event Horizon Telescope, as well as other related applications such as synchronization and referencing of antennas at proposed deep space communications facilities, and coherent optical communications.


[144] J.-F. Cliche, “Teraxion’s photonic contributions to the most powerful radio astronomy telescope: The atacama large millimeter wave array (alma) telescope,”


Appendices
Publications Arising from this Thesis

This thesis contains research which has been published in peer-reviewed journals. Copies of these publications are included for completeness in the following pages.
Simultaneous Transfer of Stabilized Optical and Microwave Frequencies Over Fiber

David R. Gozzard, Sascha W. Schediwy, and Keith Grainge

Abstract—We demonstrate simultaneous stabilization of optical and microwave signals on an optical-fiber link by independently stabilizing two optical signals that are separated by a nominated microwave frequency. This system can be implemented on conventional stabilized optical frequency transfer networks without degrading the stability of the optical signal, increasing the scope of applications of existing and future large-scale frequency transfer networks. For a 30 km optical-fiber link, we demonstrate a 193 THz optical carrier transfer absolute frequency stability of 4.9×10⁻⁷ Hz at 10⁻⁶ s, and a 10.02 GHz microwave signal transfer absolute frequency stability of 1.3×10⁻⁴ Hz at 10⁻⁶ s.

Index Terms—frequency stability, optical fiber networks, phase synchronization, time and frequency transfer.

I. INTRODUCTION

The push to apply the unrivalled performance of optical atomic clocks to scientific experiments including geodesy [1], radio astronomy [2], [3], and tests of fundamental physics [4], [5], has driven scientific communities to begin implementing permanent frequency transfer networks such as the European NEAT-FT [5], [6] and the Beijing Regional Time and Frequency Network [7], [8].

The NEAT-FT network and other high-precision frequency comparison experiments [6], [9], [10], have employed stabilized optical frequency transfer because of the superior fractional frequency stability of optical-frequency signals over radio-frequency (RF) and microwave (MW) signals [5], [11]. However, many applications of frequency transfer in science, commerce, and industry require RF or MW signals in order to interface with their electronic systems [12]. While optical-to-RF and optical-to-MW conversion methods using optical frequency combs are well tested [3], [13], [14], the required equipment is expensive and complex. The range of applications and experiments supported by frequency transfer networks can be improved by the direct provision of stabilized RF and MW signals. Many of the applications of RF and MW transfer will benefit even at the expense of inferior fractional frequency stability compared with optical frequency transfer.

A stabilized MW transfer technique based on optical phase-sensing and actuation has been demonstrated previously [15]. This MW transfer technique exploited the technology and techniques of stabilized optical frequency transfer to provide a stabilized MW frequency to the remote end of a link previously used for optical frequency transfer. In this paper, we present a related technique that provides a stabilized MW signal to the remote site, and without degrading the stability of the optical frequency.

II. THEORY

Other stabilized MW transfer techniques use physically bulky group delay actuators [16], or relatively complicated receiver units at the remote site [17], [18], to achieve stabilization and to mitigate unwanted reflections on the fiber link. The technique presented here uses optical phase sensing and actuation and so is able to benefit from the advantages of optical frequency transfer in terms of reduced size and complexity of the stabilization equipment.

The technique involves splitting the optical carrier signal into two physically separate paths, applying a fixed MW-frequency shift to one of the optical paths, and simply duplicating the conventional optical stabilization servo system, before recombining the two optical paths into a single fiber link. This creates two, independently stabilized optical signals that are separated by a given MW frequency. We show that the MW frequency is also stabilized and that the optical transfer stability is not degraded by the presence of a second optical frequency.

Previously, comparable stabilized MW transfer systems have used a second laser slaved to the master laser using an offset lock [19]. Any phase noise in the offset locking system is imprinted onto the MW signal received at the remote end, meaning that complex offset locking systems are required to minimize this noise contribution. Frequency shifting the optical carrier by means of Carrier-Suppressed Single Sideband (CS-SSB) modulation, as presented here, provides a simple way of generating a second optical signal with minimal phase noise.
relative to the original carrier.

Currently available commercial acousto-optic modulators (AOMs) can generate positive or negative frequency shifts of on the order of 200 MHz, and commercial dual-parallel Mach-Zehnder modulators (DP-MZMs), can generate frequency shifts up to around 20 GHz [20].

The dual-stabilization technique described only occupies one 100 GHz ITU optical fiber telecommunications channel (and also the 50 GHz and 25 GHz fiber subdivisions), so frequency references can be transmitted simultaneously with data traffic (assuming a properly configured link architecture as in [11] and [21]), and only a standard photodetector (PD) is required at the remote site to generate the received MW signal. The theory behind this dual-stabilization technique is outlined below.

The optical signal Opt, from a laser is split into the two arms of a Mach-Zehnder interferometer (MZI, see Fig. 1). A frequency shift, νM, is applied to one of the arms (designated Arm-B) while the optical signal passing through the other arm (Arm-A) is un-modified. Each signal then passes through its servo AOM (correspondingly designated AOM-A and AOM-B). The AOMs apply a frequency shift νM, centered on a nominal wavelength plus a correctional frequency shift, νC, determined by the feedback from the servo electronics. Prior to these servo AOMs, the two optical signals will have also picked up phase perturbations Δϕ1 and Δϕ2 in the arms of the MZI. The two optical signals are then recombined at the output of the MZI and inserted into the optical-fiber link, where they make a second pass through the AOMs and are received at a separate PD in each arm. The returning signals beat against the optical reference frequencies at the PD where νM + νMW + ΔϕB/2π MHz is the reference for Arm-B, and νM + ΔϕA/2π MHz is the reference for Arm-A. The transmission laser has been selected with a coherence length that is longer than the RTT of the transmitted signals and so it can be assumed that νM(0) = νL(0). Electronic band-pass filtering after the PDs is used to reject the unwanted signals resulting from the portion of the Arm-A signal returning through Arm-B and vice versa. The resulting, filtered, electronic signals are

$$v_{a,loc} = 2ν_{a,loc} + 2Δν_{a,loc} + 2Δϕ_{a,link}/2π + 2ν_{a,rem} + Δϕ_{a,link}/2π$$

$$v_{b,loc} = 2ν_{b,loc} + 2Δν_{b,loc} + 2Δϕ_{b,link}/2π + 2ν_{b,rem} + Δϕ_{b,link}/2π$$

$$v_{a,loc} = (2ν_{a,loc} + 2Δν_{a,loc} + 2Δϕ_{a,link}/2π + 2ν_{a,rem})/γ$$

$$v_{b,loc} = (2ν_{b,loc} + 2Δν_{b,loc} + 2Δϕ_{b,link}/2π + 2ν_{b,rem})/γ$$

The beat signals described by (6) and (7) are mixed with the synthesizers driving the AOMs. The control signals are

$$v_{a,loc,div} = (2ν_{a,loc} + 2Δν_{a,loc} + 2Δϕ_{a,link}/2π + 2ν_{a,rem})/γ$$

$$v_{b,loc,div} = (2ν_{b,loc} + 2Δν_{b,loc} + 2Δϕ_{b,link}/2π + 2ν_{b,rem})/γ$$

The signals described by (6) and (7) are mixed with appropriate local oscillators, νL, in this case, twice their servo AOM frequency plus twice the Re.AOM frequency, divided by the frequency division factor, γ.

$$v_{a,lo,a} = (2ν_{a,loc} + 2Δν_{a,loc} + 2Δϕ_{a,link}/2π + 2ν_{a,rem})/γ$$

$$v_{b,lo,b} = (2ν_{b,loc} + 2Δν_{b,loc} + 2Δϕ_{b,link}/2π + 2ν_{b,rem})/γ$$

This results in two error signals that contain the phase noise information of the relevant optical signal, and are used to steer the synthesizers driving the AOMs. The control signals are

$$v_{a} = 2ν_{a,loc} + 2Δϕ_{a,link}/2π$$

$$v_{b} = 2ν_{b,loc} + 2Δϕ_{b,link}/2π$$

Engaging the stabilization servos has the effect of reducing the phase noise from νL to νL and νL to 0. As a result, the magnitude of the ΔϕA,Link signals are such that they cancel the phase noise resulting from a single pass of the link (within the bandwidth defined by the RTT).

$$Δϕ_{a,link} = Δϕ_{a,link}/2π$$

Substituting these values into (3) gives

$$v_{remote} = ν_{MW} - ν_{a,rem} + ν_{a,rem} - Δϕ_{a,link}/2π + Δϕ_{b,link}/2π$$

So at the remote site, the phase noise resulting from

![Fig. 1. Schematic diagram of our dual-optical stabilization technique](attachment:image.png)

νL = 193 THz; νL,A = 11.25 MHz; νL,B = 20 MHz; νL,loc = 50 MHz; FM, Faraday mirror; AOM, acousto-optic modulator; PD, photodetector; LO, local oscillator; Mix, frequency mixer; DP-MZM, dual-parallel Mach-Zehnder modulator; C, frequency counter.
perturbations on the fiber link, is suppressed for both of the optical signals, as well as the MW signal (with some contamination from the $\Delta \phi_{A1}$ and $\Delta \phi_{B1}$ terms).

**III. EXPERIMENTAL SETUP**

This frequency transfer technique was demonstrated over 30 km of optical fiber spool in the laboratory because this was the longest single length available to us within the coherence length of our laser source. A Grade 4 RIO PLANEX diode laser (spectral line width < 3 kHz) was used to transmit a 1552 nm (193 THz) optical signal. In Arm-A the signal was frequency shifted +50 MHz by AOM-A. In Arm-B the optical signal was shifted +10.00 GHz by a DP-MZM configured to produce CS-SSB modulation, and then further shifted +70 MHz by AOM-B. This resulted in a 10.02 GHz frequency difference between the two optical signals.

The DP-MZM used in this experiment was constructed by placing two dual-drive Mach-Zehnder modulators (DD-MZMs) in parallel, with a piezoelectric fiber stretcher used to control the differential phase, essentially mimicking the functionality of a commercial DP-MZM. Electronic and optical signal phases were adjusted appropriately to produce CS-SSB modulation.

The remote site was co-located in the same laboratory as the signal source, allowing an independent measurement of the transfer stability of the three signals (the two optical signals plus the resulting MW modulation). The Re-AOM frequency was +40 MHz. Three Agilent 53132A A-type frequency counters were used to produce triangle-weighted estimates of the absolute frequency stability of the MW signal and the two optical signals. The out-of-loop fiber connections were kept as short and as thermally isolated as practicable.

The division ratios used for the local PD beat signals, as described in (6) and (7), were a factor of 16 for Arm-A and a factor of 11 for Arm-B because these were available.

**IV. RESULTS AND DISCUSSION**

Fig. 2 shows the absolute frequency stability of the optical and MW signals, as measured by the frequency counters, plotted as a function of integration time. The absolute stability of the signals is reported here because this more clearly highlights the relationship between the stabilities of the optical and MW signals. It is the absolute stability of optical signals, rather than their fractional stabilities, that govern the absolute stability of the MW signal. The fractional frequency stability can be easily obtained by dividing the absolute frequency stability by the frequency of the signal.

In this plot, dashed lines with open markers indicate the absolute frequency stability of the optical and MW signals at the remote site when the frequency dissemination was un-stabilized. Solid lines with filled markers indicate the stability of the signals with active stabilization.

The un-stabilized absolute frequency stability of the optical signals (light-green open triangles and dark-green open circles, dashed line) are 3.0 Hz at 1 s and 1.2 Hz at 10^3 s of integration, while the absolute frequency stability for the MW signal (blue, open diamonds, dashed line) is more than three orders-of-magnitude lower at 2.0x10^{-3} Hz at 1 s and 2.9x10^{-4} Hz at 10^3 s.

Although the instability of the MW is a combination of the instabilities of optical signals, much of the noise on the two optical signals will be common to both signals because the environmental noise affecting the optical link will affect the signals in similar ways. This means that large frequency fluctuations in the optical signals do not necessarily correspond to large frequency fluctuations in the MW signal.

With the stabilization servos engaged, the stability of the optical signals is improved by more than three orders-of-magnitude. The optical signals from Arm-A (dark-green, filled circles, solid line) achieves absolute frequency stabilities of 1.7x10^{-3} Hz at 1 s and 4.9x10^{-4} Hz at 10^3 s. The stability of the optical signal from Arm-B (light-green, filled triangles, solid line, which includes the DP-MZM) is 1.7x10^{-3} Hz at 1 s and 1.3x10^{-4} Hz at 10^3 s. These absolute stabilities are equivalent to fractional frequency stabilities of 8.8x10^{-18} at 1 s, placing these results amongst the best stabilized optical frequency transfer performances reported for comparable fiber link lengths [5], [6]. We attribute the poorer performance of the Arm-B optical signal at long time-scales to thermal changes in the DP-MZM, which was not actively stabilized and, being constructed from discrete components, comprised several meters of fiber, making it very sensitive to temperature changes.

The MW transfer stability (blue, filled diamonds, solid line) improves to an absolute frequency stability of 1.7x10^{-3} Hz at 1 s and 1.1x10^{-4} Hz at 10^3 s. At integration times greater than 10 s this overlaps, within the measurement uncertainty, the absolute transfer stability of the optical signal from Arm-B, showing that the MW transfer can be stabilized to the same absolute level as the optical transfer. When the stabilization systems are active, common frequency fluctuations between the
two optical signals are mostly suppressed and no longer dominate the instability of the optical signals. The stability of the MW signal is then set by the absolute stabilities of the optical signals. In situations, such as the experiment reported here, where one of the two optical signals exhibits significantly poorer stability than the other, the absolute stability of the stabilized MW signal then follows the absolute stability of the least-stable of the two optical signals. The MW transfer stability is similar to several other reported techniques (e.g. [15] and [22]), and two orders of magnitude worse that the best performing systems [16].

With AOM-B disabled, thus not allowing an optical signal to propagate from Arm-B, the system functions as a conventional optical-frequency stabilization system. The transfer stability of the optical signal from Arm-A was measured and found to remain unchanged when the signal from Arm-B was disabled. The stabilized MW transfer is achieved without degradation of the stability of the optical signals.

Because the optical transfer is unaffected by the inclusion of the MW transmission modifications, and the absolute frequency stability of the MW signal is set by the absolute frequency stability of the optical signals, the fractional frequency stability of the MW transfer can easily be increased by increasing the MW frequency. For example, doubling the value of the MW frequency will not affect the achieved absolute frequency stability, but will improve the fractional frequency stability by a factor of two.

V. CONCLUSION

We have demonstrated that by using this dual-stabilization technique, existing optical transfer networks may be modified to also disseminate stabilized MW signals without degradation of the optical transfer stability. The technique enjoys several advantages of optical phase sensing and optical phase actuation systems over other stabilized RF and MW signal transfer techniques including compact size, large bandwidth feedback, and infinite feedback range. We expect that the overall stability at longer integration times will be improved by the use of a commercial DP-MZM unit instead of the two parallel DD-MZM device used in these tests due to the reduced sensitivity to thermal changes and mechanical noise. The achieved stability and effective transmission distance can also be significantly improved by employing a laser source with a smaller line-width and longer coherence length. Better thermal isolation of the local-site systems will greatly improve the transfer stability at integration times beyond 10^5 s. The fractional frequency stability of the transferred MW signal can immediately be improved by increasing the magnitude of the MW frequency shift. A less complex RF dissemination system (not requiring a DP-MZM and associated electronics) for frequencies up to around 200 MHz can be implemented without the MW frequency shifter by simply utilizing the frequency difference between two servo AOMs. Multiple, additional RF and MW signals can be transmitted by employing an extra servo system per desired transfer frequency. The stabilized frequency transfer is compatible with active telecommunication links if the non-bi-directional components of the link are bypassed as in [12] and [21].

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Stabilized microwave-frequency transfer using optical phase sensing and actuation

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We present a stabilized microwave-frequency transfer technique that is based on optical phase sensing and optical phase actuation. This technique shares several attributes with optical-frequency transfer and, therefore, exhibits several advantages over other microwave-frequency transfer techniques. We demonstrated the stabilized transfer of an 8000 MHz microwave-frequency signal over a 166 km metropolitan optical fiber network, achieving a fractional frequency stability of $6.8 \times 10^{-14}$ Hz/Hz at 1 s integration and $5.0 \times 10^{-16}$ Hz/Hz at 1.6 $\times 10^6$ s. This technique is being considered for use on the Square Kilometre Array SKA1-mid radio telescope.

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Stabilized frequency transfer over optical fiber is rapidly moving from experimental demonstrations, to actively supporting a broad range of real-world applications. The frequency of the transmitted signal—optical, radio, or microwave—dictates which applications can be supported with this technology.

Stabilized optical-frequency transfer techniques lead this research in terms of demonstrated transfer distance [1], frequency stability performance [2], and network roll-out [3]. However, most practical applications, including radio astronomy, geodesy, finance, navigation, defense, and aspects of fundamental physics [4,5], require the transfer of stabilized radio- or microwave-frequency signals to directly interface with the application’s electronic systems. Optical combs can be used to translate optical frequencies into the radio or microwave domain [6], but they remain too complex, bulky, or costly for many applications. Therefore, most practical support of the aforementioned applications involves microwave-frequency transfer techniques, but these are constrained in the following ways.

The standard stabilized microwave-frequency transfer techniques [7] require group-delay actuation to compensate for the physical length changes of the fiber link. For practical deployments over long links, this usually involves implementing a combination of fiber stretcher (medium actuation speed and very limited range) in a series with a thermal spool (slow actuation speed and physically bulky). In contrast, the acousto-optic modulator (AOM) actuators used in stabilized optical-frequency transfer are capable of the faster actuation speeds, as well as having infinite feedback range. Radio-frequency phase conjugation techniques [8] have been demonstrated over longer distances [9,10] than standard stabilized microwave-frequency transfer, but have yet to match their transfer performance.

In addition, stabilized radio- or microwave-frequency transfer techniques require the returned signal to be rebroadcast at either a different modulation frequency, optical wavelength, or fiber core, to avoid frequency overlap from unwanted reflections on the link, which can cause the servo to function improperly. These reflection mitigating methods then can bring about additional complications, including those resulting from optical polarization and chromatic dispersion which, in turn, requires further complexity. In stabilized optical-frequency transfer, strategically placed AOMs can be used to simply apply static optical-frequency shifts [11] to avoid these issues.

As shown in Fig. 1, an optical signal with frequency $\nu_s$, generated by a laser at the Local Site, is injected into two arms of a Mach–Zehnder interferometer (MZI). A dual-parallel Mach–Zehnder modulator (DPM) is located in Arm 1 of the MZI, and a microwave frequency of $\nu_{DP}$ is applied to the DPM electronic inputs. The phase of the electronic inputs, and the DPM voltage biases, are tuned to generate single-sideband suppressed-carrier modulation, thereby producing a static microwave-frequency shift $\nu_{DP}$ on the optical signal. Arm 2 of the MZI contains an AOM, which adds the servo AOM radio-frequency shift $\nu_{AOM}$ and the servo actuation signal $\Delta \nu_{AOM}$ to the optical signal. In addition, the optical signals in each of the two arms of the MZI pick up undesirable non-common
phase noise $\Delta \phi_{\text{MZL12}}$ (where $i$ is the index representing the optical signals in Arm 1 and Arm 2 of the MZI).

Just as in the case of standard stabilized optical transfer techniques [2], the optical signals then enter a Michelson interferometer (MI) via an optical isolator (to prevent reflections returning to the laser). The Fiber Link is incorporated into the long arm of the MI, with the short arm providing the physical reference for the optical phase sensing. The optical signals $\nu_{\text{ref},i}$ at the photodetector are

$$\nu_{\text{ref},1} = \nu_L + \nu_{\text{DP}} + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL1}} + 2 \Delta \phi_{\text{MI}}), \quad (1)$$

and

$$\nu_{\text{ref},2} = \nu_L + (1 + \Delta) \nu_{\text{A-arr}} + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL2}} + 2 \Delta \phi_{\text{MI}}). \quad (2)$$

where $\Delta \phi_{\text{MI}}$ is the undesirable phase noise picked up by the optical signals passing through the MI reference arm.

A “local anti-reflection” AOM that applies a static frequency offset of $\nu_{\text{A-arr}}$ can be incorporated into either the long arm (as shown in Fig. 1) or the reference arm of the MI. This allows the servo electronics to distinguish $\nu_{\text{ref},i}$ from unwanted reflections on the link. (Note: the anti-reflection AOMs are not critical for the technique, but are useful for practical implementation on fiber links that may contain unwanted reflections.)

With the local anti-reflection AOM placed in the long arm, the optical signals transmitted across the Fiber Link $\nu_{\text{m},i}$ are

$$\nu_{\text{m},1} = \nu_L + \nu_{\text{DP}} + \nu_{\text{A-arr}} + \frac{1}{2 \pi} \Delta \phi_{\text{MZL1}}, \quad (3)$$

and

$$\nu_{\text{m},2} = \nu_L + (1 + \Delta) \nu_{\text{A-arr}} + \nu_{\text{A-arr}} + \frac{1}{2 \pi} \Delta \phi_{\text{MZL2}}. \quad (4)$$

As these signals are transmitted across the fiber link, they pick up phase noise $\Delta \phi_{\text{rar},j}$, random optical path length changes in the link that are unique to their specific transmitted frequencies.

At the Remote Site, the two optical signals pass through a remote anti-reflection AOM with a static frequency of $\nu_{\text{A-arr}}$ to produce the following two remote signals $\nu_{\text{m},i,j}$:

$$\nu_{\text{m},1,j} = \nu_L + \nu_{\text{DP}} + \nu_{\text{A-arr}} + \nu_{\text{A-arr}} + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL1}} + \Delta \phi_{\text{rar},1}), \quad (5)$$

$$\nu_{\text{m},2,j} = \nu_L + (1 + \Delta) \nu_{\text{A-arr}} + \nu_{\text{A-arr}} + \nu_{\text{A-arr}} + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL2}} + \Delta \phi_{\text{rar},2}). \quad (6)$$

At the remote site, the signal is split into two fiber paths, with one set of signals going to a photodetector and the other to a Faraday mirror. At the photodetector, the beat between the two optical signals $\nu_{\text{m},1,j}$ and $\nu_{\text{m},2,j}$ is recovered as the Remote Site microwave-frequency electronic signal:

$$\nu_{\text{m,RF}} = (1 + \Delta) \nu_{\text{A-arr}} - \nu_{\text{DP}} + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL2}} - \Delta \phi_{\text{MZL1}} + \Delta \phi_{\text{rar},2} - \Delta \phi_{\text{rar},1}). \quad (7)$$

On the other fiber path, a Faraday mirror reflects the two optical signals back to the Local Site across the Fiber Link, with each signal receiving additional optical shifts $\nu_{\text{A-arr}}$ and $\nu_{\text{A-arr}}$ when passing through the remote and local AOMs a second time. In addition, the two optical signals pick up another copy of $\Delta \phi_{\text{rar},j}$ from the Fiber Link. The two reflected optical signals $\nu_{\text{r},j}$ then strike the servo photodetector to produce

$$\nu_{\text{r},1,j} = \nu_L + \nu_{\text{DP}} + 2 (\nu_{\text{A-arr}} + \nu_{\text{A-arr}}) + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL1}} + 2 \Delta \phi_{\text{rar},1}), \quad (8)$$

and

$$\nu_{\text{r},2,j} = \nu_L + (1 + \Delta) \nu_{\text{A-arr}} + 2 (\nu_{\text{A-arr}} + \nu_{\text{A-arr}}) + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL2}} + 2 \Delta \phi_{\text{rar},2}). \quad (9)$$

The mixing of the two reference frequencies $\nu_{\text{ref},i}$ and the two reflected optical frequencies $\nu_{\text{r},j}$ results in six primary electronic mixing products $\nu_{\text{m,RF},j}$ (where $j$ is the index 1 to 6). Of those, the two microwave-frequency signal mixing products that are crucial for this technique are

$$\nu_{\text{m,RF},1} = \nu_{\text{ref},1} - \nu_{\text{ref},2} = \nu_{\text{DP}} - (1 + \Delta) \nu_{\text{A-arr}} - 2 (\nu_{\text{A-arr}} + \nu_{\text{A-arr}}) + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL1}} - \Delta \phi_{\text{MZL2}}) + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL1}} - \Delta \phi_{\text{rar},1}), \quad (10)$$

and

$$\nu_{\text{m,RF},2} = \nu_{\text{ref},2} - \nu_{\text{ref},1} = (1 + \Delta) \nu_{\text{A-arr}} - \nu_{\text{DP}} - 2 (\nu_{\text{A-arr}} + \nu_{\text{A-arr}}) + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL2}} - \Delta \phi_{\text{MZL1}}) + \frac{1}{2 \pi} (\Delta \phi_{\text{MZL2}} - \Delta \phi_{\text{rar},2}). \quad (11)$$

Given an appropriate selection of AOM frequencies, the other four mixing products (and all intermodulations) occur at different frequencies.

Once in the electronic domain, the microwave-frequency signals $\nu_{\text{m,RF},j}$ can be mixed with a copy of $\nu_{\text{DP}}$, to produce the following two critical electronic radio-frequency signals:
When the servo is engaged, 

\[ \nu_{\text{RF,1}} = -(1 + \Delta \nu_{\text{AOM}} - 2(\nu_{\text{LO}} + \nu_{\text{RF}}) + \frac{1}{2\pi} (\Delta \phi_{\text{MZL1}} - \Delta \phi_{\text{MZL2}} + \frac{1}{\pi} (\Delta \phi_{\text{RF}} - \Delta \phi_{\text{LL1}})). \]  

(12)

and

\[ \nu_{\text{RF,2}} = (1 + \Delta \nu_{\text{AOM}} - 2(\nu_{\text{LO}} + \nu_{\text{RF}}) + \frac{1}{2\pi} (\Delta \phi_{\text{MZL2}} - \Delta \phi_{\text{MZL1}} + \frac{1}{\pi} (\Delta \phi_{\text{RF}} - \Delta \phi_{\text{LL1}})). \]  

(13)

The electronic signal path is then split, with each path containing a bandpass filter that is centered on one of the above frequencies. These filters reject the opposing signal, as well as the unwanted mixing products (\(\nu_{\text{RF,1}} + \nu_{\text{RF,2}}\)) and any frequency intermodulations. The signals \(\nu_{\text{RF,1}}\) and \(\nu_{\text{RF,2}}\) are then mixed to produce the lower sideband:

\[ \nu_{\text{Mix,ll}} = \nu_{\text{RF,2}} - \nu_{\text{RF,1}} = 2((1 + \Delta \nu_{\text{AOM}} - 2(\nu_{\text{LO}} + \nu_{\text{RF}}) + \frac{1}{2\pi} (\Delta \phi_{\text{MZL2}} - \Delta \phi_{\text{MZL1}} + \frac{1}{\pi} (\Delta \phi_{\text{RF}} - \Delta \phi_{\text{LL1}}))). \]  

(14)

A low-pass filter is used to reject the upper sideband and other products. Finally, \(\nu_{\text{Mix,ll}}\) is mixed with the servo local oscillator \(\nu_{\text{LO}}\) (set to 2\(\nu_{\text{LO}}\)) to produce the servo error signal:

\[ \nu_{\text{err}} = 2(\Delta \nu_{\text{LO}} + \frac{1}{2\pi} (\Delta \phi_{\text{MZL2}} - \Delta \phi_{\text{MZL1}} + \frac{1}{\pi} (\Delta \phi_{\text{RF}} - \Delta \phi_{\text{LL1}}))). \]  

(15)

The servo error signal is applied to a voltage controlled oscillator (VCO) with a nominal frequency \(\nu_{\text{VCO}}\). The VCO output goes to the servo AOM, thereby closing the servo loop. When the servo is engaged, \(\nu_{\text{err}}\) is driven to zero, so

\[ \Delta \nu_{\text{LO}} = -\frac{1}{2\pi} (\Delta \phi_{\text{MZL2}} - \Delta \phi_{\text{MZL1}} + \frac{1}{\pi} (\Delta \phi_{\text{RF}} - \Delta \phi_{\text{LL1}})). \]  

(16)

Substituting this into Eq. (7) shows that the undesirable non-common phase noise picked up in the Fiber Link, as well as the phase noise from the MZI in the Local Site, is canceled out (within the light round-trip bandwidth and other practical gain limitations). This gives

\[ \nu_{\text{em,RF}} = \nu_{\text{RF}} - \nu_{\text{VCO}} \]  

where \(\nu_{\text{em,RF}}\) is the MW reference signal with the servo engaged.

We describe the experimental verification of this method using 8000 MHz transfer, with all optical elements fiberized. An NKT Photonics Keheras Basic X15 laser (spectral line-width <100 Hz) was used to produce an optical frequency of \(\nu_{\text{LO}} = 193\) THz (corresponding to a wavelength of 1552 nm). The DPM was a Photline MXIQ-LN-40 configured to produce a down-shift of the optical-frequency by \(\nu_{\text{DPM}} = \pm 7560\) MHz. The microwave-frequency oscillator was an Agilent N5183A MXG, with all other radio-frequency signals supplied by a Liquid Instruments MokuLab.

The AOMs were an IntraAction FCM-series, with \(\nu_{\text{VCO}} = \pm 40\) MHz, resulting in a frequency difference between \(\nu_{\text{rf,1}}\) and \(\nu_{\text{rf,2}}\) of 8000 MHz. The anti-reflection AOMs had frequencies of \(\nu_{\text{LO}} = \pm 50\) MHz, and \(\nu_{\text{LO}} = \pm 50\) MHz. For the experiment described here, the local anti-reflection AOM was located in the link arm of the MI, as shown in Fig. 1.

Polarization-maintaining fiber was used until the MZI output to ensure that the polarization into the DPM was optimally aligned and that the MZI optical power remained maximized. The signal was transmitted through installed metropolitan optical fiber networks up to 166 km in length (2 × 83 km AARNet-managed fiber loops). This resulted in a two-way light round-trip time of 1.6 ms, limiting the servo bandwidth to around 600 Hz. The total optical loss of the fiber link was 47 dB. Two IDIL Fibres Optiques bi-directional optical amplifiers were used to boost signal strength, with one amplifier located after the 83 km fiber loop, and the other located just prior to the Local Site. Discovery Semiconductors DSC-R402 and DSC-R401HG photodetectors were used for the opto-electronic conversion. Faraday mirrors were used at the ends of the two arms of the MI to ensure the signals reflected back to the servo photodetector at the Local Site were aligned in polarization.

The combination of the AOM frequencies used in this experiment resulted in the following two key microwave-frequency electronic signals at the output of the servo photodetector: \(\nu_{\text{RF,1}} = 8200\) MHz, and \(\nu_{\text{RF,2}} = 7800\) MHz. After mixing with \(\nu_{\text{LO}}\), this resulted in the following radio-frequency signals: \(\nu_{\text{RF,1}} = 240\) MHz and \(\nu_{\text{RF,2}} = 160\) MHz. The mix of these two signals produced the lower sideband \(\nu_{\text{Mix,bb}}\). The local oscillator \(\nu_{\text{LO}}\) was set to 80 MHz to produce a DC error signal \(\nu_{\text{err}}\) upon mixing with \(\nu_{\text{Mix,bb}}\).

Both the Local Site and the Remote Site were co-located in the same laboratory, enabling an independent out-of-loop measurement of the transfer stability, with all electronic equipment referenced to an IEM-KVARZ CH1-75A active hydrogen maser. The 8000 MHz Remote Site microwave-frequency electronic signal was mixed with \(\nu_{\text{LO}}\) to produce a radio-frequency signal at \(\nu_{\text{em,RF}} = 40\) MHz that could be directly probed by an Agilent 5312A high-precision frequency counter (gate time set to 1 s). The output data was used to produce a triangle weighted estimate of the frequency stability.

Figure 2 shows the fractional frequency stability of three 8000 MHz transfer measurements plotted as a function of integration time. The blue dashed line with open markers shows the unstabilized transfer over 166 km. Here the transfer stability is \(8.4 \times 10^{-14}\) Hz/Hz at 1 s of integration, and \(1.1 \times 10^{-13}\) Hz/Hz at 1.6 \(\times 10^4\) s. The blue solid line with solid markers represents transfer with the stabilization servo engaged. At 1 s of integration, the stability is \(6.8 \times 10^{-14}\) Hz/Hz and, at 1.6 \(\times 10^4\) s, it is \(5.0 \times 10^{-16}\) Hz/Hz; this demonstrates a suppression of fiber noise by more than two orders of magnitude.

The noise floor of the transfer system, as measured by stabilized transfer over a 2 m fiber patch lead, is displayed as the red solid line with triangle markers. It starts at a value of \(5.5 \times 10^{-14}\) Hz/Hz at 1 s and drops to \(1.2 \times 10^{-15}\) Hz/Hz by 512 s. In addition, the 166 km stabilized frequency transfer was shown to be accurate to within 20 MHz.

We have described and experimentally demonstrated the efficacy of a stabilized microwave-frequency transfer technique that is based on optical phase sensing and optical phase actuation. While it does not achieve the same level of ultimate transfer stability performance as the world-leading results [7,12], it does exhibit several advantages over other radio- or microwave-frequency transfer techniques, as discussed in the following six paragraphs.

The use of AOMs enables the construction of compact servo systems at the Local Site by not requiring bulky fiber stretchers or thermal spools. The use of the AOMs eliminates feedback
range concerns due to their infinite feedback range; therefore, the servo systems can be constructed without potentially complex integrator-reset circuits. Finally, AOMs have faster feedback than fiber stretchers or thermal spools, which can allows for optimized servo gains for short links that are not limited by the light round-trip time.

The technique actively suppresses phase noise originating not just from the Fiber Link in the MI arm but also from the MZI at the Local Site. Plus, given the simplicity of components at the Remote Site, the technique is largely immune to environmental perturbations on the system's hardware.

As in stabilized optical transfer, anti-reflection AOMs can be used to generate appropriate optical-frequency shifts to mitigate unwanted reflections that are present on most real-world links. Our technique therefore requires only a single laser, reducing system complexity. Further system optimization can be achieved by locating the local anti-reflection AOM in the MI reference arm, which has the benefit of removing some unnecessary optical loss from the link arm.

The technique utilizes Faraday mirrors at the ends of the MI arms to give a maximum detected signal at the servo photodetector, as is done with stabilized optical transfer. This removes the need for any initial polarization alignment, or any ongoing polarization control or polarization scrambling. The technique can be deployed on standard fiber links alongside electronic signal re-generation systems are not required. Two optical amplifiers were used to demonstrate stabilized microwave-frequency transfer over a 166 km metropolitan optical fiber network, around twice the distance of previously published microwave-frequency (>1 GHz) transfer [7,12].

This stabilized microwave-frequency transfer technique is one of two being considered for selection as the phase-synchronization system for the Square Kilometre Array (SKA) project. The SKA project is an international effort to build the world's largest radio telescope, led by the SKA Organization with the support of 10 member countries.

Bi-directional optical amplifiers can be deployed to extend the range of transmission and, therefore, potentially complex electronic signal re-generation systems are not required. Two optical amplifiers were used to demonstrate stabilized microwave-frequency transfer over a 166 km metropolitan optical fiber network, around twice the distance of previously published microwave-frequency (>1 GHz) transfer [7,12].

This stabilized microwave-frequency transfer technique is one of two being considered for selection as the phase-synchronization system for the Square Kilometre Array (SKA) project [13,14]. In addition, we are exploring the technique's role in the MeerKAT radio telescope [15] as part of a potential future X-band receiver upgrade.

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Astronomical Verification of a Stabilized Frequency Reference Transfer System for the Square Kilometer Array

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Abstract

In order to meet its cutting-edge scientific objectives, the Square Kilometre Array (SKA) telescope requires high-precision frequency references to be distributed to each of its antennas. The frequency references are distributed via fiber-optic links and must be actively stabilized to compensate for phase noise imposed on the signals by environmental perturbations on the links. SKA engineering requirements demand that any proposed frequency reference distribution system be proved in “astronomical verification” tests. We present results of the astronomical verification of a stabilized frequency reference transfer system proposed for SKA-mid. The dual-receiver architecture of the Australia Telescope Compact Array was exploited to subtract the phase noise of the sky signal from the data, allowing the phase noise of observations performed using a standard frequency reference, as well as the stabilized frequency reference transfer system transmitting over 77 km of fiber-optic cable, to be directly compared. Results are presented for the fractional frequency stability and phase drift of the stabilized frequency reference transfer system for celestial calibrator observations at 5 and 25 GHz. These observations plus additional laboratory results for the transferred signal stability over a 166 s fiber-optic link are used to show that the stabilized transfer system under test exceeds all SKA phase-stability requirements within a broad range of observing conditions. Furthermore, we have shown that alternative reference dissemination systems that use multiple synthesizers to supply reference signals to sub-sections of an array may limit the imaging capability of the telescope.

Key words: instrumentation: interferometers – methods: observational – telescopes

1. Introduction

The Square Kilometre Array (SKA) project (Dewdney 2015) is an international initiative to build the largest and most capable radio telescope ever constructed. Construction of the SKA has been divided into phases, with the first phase (SKA1) accounting for the first 10% of the telescope's receiving capacity. During SKA1, a low-frequency aperture array (SKA1-low) will be constructed in Western Australia, while a dish-array of 197 antennas (SKA1-mid), incorporating the 64 dishes of MeerKAT, will be constructed in South Africa. Radio telescope arrays such as the SKA require phase-coherent frequency reference signals to be transmitted to each of the antennas in the array. In the case of the SKA, the frequency references will be generated at a central site and transmitted to the antennas via fiber-optic cables. Environmental influences affect the optical path length of the fiber and act to degrade the phase stability of the frequency references received at the antennas, which has the ultimate effect of reducing the fidelity and dynamic range of the data (Cliche & Shillue 2006). To improve the phase-coherence of the array, the SKA will employ stabilized frequency transfer systems to suppress the fiber-optic link noise (Grainge et al. 2017). Reference frequency stabilization systems have been used successfully on the Atacama Large Millimetre Array (ALMA; Cliche & Shillue 2006; Shillue et al. 2004), and other radio telescope arrays such as the Very Large Array (Thompson et al. 1980), e-Merlin in the UK (Garrington et al. 2004), and the Australia Telescope Compact Array (ATCA; Hancock et al. 2011) have employed phase measurement systems in order to apply phase corrections in the correlator. The existing SKA precursor telescopes including the Murchison Widefield Array (Lonsdale et al. 2009; Tingay et al. 2013), the Australian SKA Pathfinder (Beresford 2008; Hotan et al. 2014), and MeerKAT (Julie & Abbott 2017) currently employ passive frequency reference dissemination systems that provide adequate phase stability over the relatively short transmission distances required by these telescopes.

There are three SKA systems requirements that apply to the phase-noise performance of the frequency transfer system (Turner 2015). The frequency transfer system must provide a maximum coherence loss of 2% over the correlator integration time (1 s) and over the in-beam calibration time (60 s) for observing frequencies up to 13.8 GHz. Of this 2% coherence loss budget, 1.9% is allocated to the stabilized frequency reference transfer system. In addition, the frequency reference must have a phase drift of less than 1 rad over a 10-min period to ensure that there is no ambiguity in the phase solution during array calibration measurements on either side of an observation of up to 10 min.

Researchers at the University of Western Australia (UWA) have led the development of a stabilized frequency transfer
system proposed for SKA1-mid (Schediwy et al. 2017). This has been tested extensively using standard metrology techniques in a laboratory setting, with signals transmitted over metropolitan fiber links. Laboratory and field testing of an alternative stabilized frequency transfer system for the SKA has also been reported previously (Wang et al. 2015; Gao et al. 2016), and other research groups have developed similar systems with a view to support the SKA and other VLBI applications (He et al. 2013; Baldwin et al. 2016). However, SKA technology down-select requirements demand a process of astronomical verification in which the proposed frequency transfer system is shown to meet the stability requirements under observing conditions on an operational radio telescope.

In this paper, we present results of astronomical verification of the UWA SKA1-mid stabilized frequency transfer prototype and show that the system exceeds the SKA phase-stability requirements under a wide range of observing conditions.

2. Experimental Design

2.1. Extracting the Reference Signal Phase Stability

The astronomical verification observations were performed using the ATCA. The ATCA’s dual-receiver chain architecture permitted analyses that would not have been possible to conduct using single-receiver telescope arrays. As shown in Figure 1, immediately following the feed horn and the first low-noise amplifier (LNA), the sky signal, for both polarizations, is split into two separate, but functionally identical, receiver chains (referred to here as “chain-1” and “chain-2”). The sky signals are then down-converted by mixing them with separate frequency reference signals, Frequency Reference 1 and Frequency Reference 2. These are normally supplied by two separate microwave frequency synthesizers located in the observatory’s correlator room. The two frequency references are transmitted up to 4.5 km away to the antennas through parallel fiber cores in buried conduits using a pair of electronic-to-optical transmitters (E/Os). The transmitted references are detected at the antennas by optical-to-electronic (O/E) receivers (two in each antenna) that feed the signals to a pair of yttrium-iron-garnet (YIG) oscillators operating in a phase-locked loop. The YIG oscillators act as clean-up oscillators to suppress high-frequency phase noise. The down-converted sky signals are digitized by analog-to-digital converters (ADCs) that feed to two separate correlators, one for each receiver chain, in the correlator room.

The advantage of this configuration for astronomical verification tests is that Frequency Reference 1 can be supplied by the ATCA’s conventional reference signal distribution system, while Frequency Reference 2 is supplied by the stabilized frequency reference transfer system under test (as shown in Figure 1). Because the two receiver chains in the antennas detect the same sky signal, any differences in the phase solution of these signals between the two receiver chains for a given telescope baseline can be attributed to non-common phase noise produced in separate frequency reference dissemination systems. For example, the phase solution for the chain-1 baseline between two antennas $i$ and $j$ ($\phi_{ij}(t)$) is

$$\phi_{ij}(t) = (\phi_{E1,i}(t) + \phi_{E2,i}(t)) + \phi_j(t) - (\phi_{E1,j}(t) + \phi_{E2,j}(t)),$$

where $\phi_j(t)$ is the phase of the Frequency Reference as a function of time ($t$) and $\phi_{E}(t)$ is the phase of the sky signal at a particular antenna receiver. The term $\phi_j(t)$ represents the phase noise contributed by components in the ATCA reference frequency distribution system, including the E/O/E systems, differential fiber-link noise, and noise from the YIG oscillator. The corresponding phase solution for the chain-2 baseline between antennas $i$ and $j$ ($\phi_{ij,2}(t)$) is

$$\phi_{ij,2}(t) = (\phi_{E2,i}(t) + \phi_{E2,j}(t)) + \phi_j(t) - (\phi_{E1,i}(t) + \phi_{E1,j}(t)) + \phi_j(t).$$

In the configuration depicted in Figure 1, any additional phase noise contributed by the stabilized frequency transfer system (Frequency Reference 2) is common to all of the down-converted signals from the chain-2 mixer outputs. Therefore, the chain-2 baseline phase solutions do not exhibit additional phase noise compared with the simultaneous phase solution for the same physical baseline using chain-1 (as shown by Equations (1) and (2)).

Figure 1. Schematic of the reference frequency distribution setup for astronomical verification at the ATCA. Three antennas are shown for reference. Antenna 3 shows the modification made to antennas 1 and 3 to enable comparative measurements of the two frequency references to be made. Baselines with antennas 1 or 3 using correlator 2 are “mixed” reference baselines. Tx is the stabilized frequency transfer system transmitter unit, Rx is the stabilized frequency transfer system receiver unit, RF shifter is an IQ mixer producing carrier-suppressed single-sideband modulation, E/O is the electronic-to-optical transmitter, O/E is the optical-to-electronic receiver, YIG is the yttrium-iron-garnet clean-up oscillator, LNA is the low-noise amplifier, Mix is the microwave signal mixer, and ADC is the analogue-to-digital converter.
To remedy this, the outputs of the chain-1 mixers in antennas 1 and 3 were split using microwave power splitters in the antennas, and fed to both the chain-1 and chain-2 ADCs. This was done for both the A- and B-polarizations (for clarity, only one polarization is shown in Figure 1). As a result, the outputs of the chain-2 ADCs on antennas 1 and 3 did not incorporate the phase noise contributed by the stabilized frequency transfer prototype and the chain-2 E/O system. The phase solution \( \phi_{ij} (t) \) (where antenna i is either antenna 1 or 3) then becomes

\[
\phi_{ij} (t) = (\phi_{i1} (t) + \phi_{i2} (t)) - (\phi_{j1} (t) + \phi_{j2} (t)).
\]

By subtracting the chain-1 phase solution from the chain-2 phase solution, for baselines that included antennas 1 or 3, the differential phase noise between the two frequency references could be measured. Hereafter, chain-2 baselines that incorporate antenna 1 or antenna 3 will be referred to as “mixed” baselines (because they operate using a “mix” of two different frequency references). Baselines operating in the conventional manner will be referred to as “unmixed” baselines. The resulting phase difference between the phase solutions for the unmixed and mixed baselines is then

\[
\phi_{\text{Diff}} (t) = \phi_{i1} (t) - \phi_{i2} (t)
\]

This means that not only can a direct comparison be made of the array performance under the two different frequency systems, but the phase of the sky signal has been subtracted out and so the relative stability of the frequency references (with non-common phase noise contributions from some telescope systems) can be measured directly.

To avoid the contribution of the relative phase drift between two synthesizers, a single microwave synthesizer (Agilent E8257D) was used to supply both Frequency Reference 1 and the UWA stabilized frequency transfer prototype (which supplies Frequency Reference 2). So, the phase of Frequency Reference 2 is

\[
\phi_{ij} (t) = \phi_{i1} (t) + \phi_{UWA} (t),
\]

where \( \phi_{UWA} (t) \) is the phase of the UWA stabilized frequency transfer prototype. The phase difference becomes:

\[
\phi_{\text{Diff}} (t) = \phi_{UWA} (t) + \phi_{E1,j} (t) - \phi_{E2,j} (t) - \phi_{E1,j} (t).
\]

Therefore, the phase stability of the UWA stabilized frequency transfer prototype can be measured; however, there will be some contamination \((\phi_{E2,j} (t) - \phi_{E2,j} (t))\) from the standard ATCA frequency reference distribution systems. Because the ATCA receiver chains and frequency reference distribution systems use identical components and the fiber links from the correlator room to the antennas run through the same buried cables, we assume that the contributions of these components to the phase differences are small and the differences are dominated by phase noise contributed by the stabilized frequency transfer system.

2.2. Experimental Setup

The astronomical source used to make the measurement observations was a calibrator labeled 1057-797, at a declination of close to –80°, which is isolated in the sky and always above the ATCA horizon, enabling long uninterrupted array phase measurements. The frequency reference signal was transmitted at 8.00 GHz, because this is the nominal frequency of UWA’s SKA1-mid stabilized frequency transfer system. Given the specific design of the ATCA’s receiver architecture (Frater et al. 2016), this enabled observations to be made across two separate frequency bands, with center observing frequencies of 4.96 and 25.44 GHz and a bandwidth of 2048 MHz. The lower observing frequency is representative of SKA1-mid’s operational observing range of 0.35–13.8 GHz (Dewdney 2015), while the higher observing frequency demonstrates the performance of the stabilized frequency transfer prototype under more demanding observing conditions than SKA1-mid will encounter.

The transmitter unit (TX) of the UWA SKA1-mid stabilized frequency transfer prototype was installed in the ATCA correlator room. In order for Frequency Reference 1 and Frequency Reference 2 to both supply 8.00 GHz while using only one microwave synthesizer, the synthesizer was set to supply 7.96 GHz, which the servo system of the stabilized frequency transfer prototype shifted up to 8.00 GHz to supply Frequency Reference 2. An electronic IQ-mixer (Marki IQ0741LXP), set to produce carrier-suppressed single-sideband modulation at 40 MHz, was used to shift the synthesizer signal to 8.00 GHz to supply Frequency Reference 1. Laboratory measurements of the intrinsic stability of the IQ-mixer frequency shift show that it is better than the stability of the stabilized frequency transfer prototype by an order of magnitude, so it did not make a significant contribution to the measured phase noise.

The Tx and the receiver unit (Rx) were co-located in the correlator room, as shown in Figure 1. The signal transmitted by the stabilized frequency transfer prototype was sent over 52 km of buried fiber-optic cable and a further 25 km spool of fiber in the correlator room, producing a total link length of 77 km. The 52 km fiber link consisted of two 26 km fiber cores that ran off-site, under and along local roadways and a bridge (through a variety of moderate-to-high shrink-swell soil types), to a telecommunications controlled environment vault at Springbrook Creek (located along the Newell Highway, approximately 17.5 km southeast of the observatory and 16.3 km southwest of Narrabri). A short fiber patch was used to connect the two cores in the vault, creating a 52 km loop. A bi-directional erbium-doped fiber amplifier (IDIL Fibres Optiques) was required in order to compensate for the optical power loss of the 77 km link.

Additionally, measurements were made to assess the effect of phase drift between two microwave synthesizers. One supplied the standard ATCA frequency distribution system with 8.00 GHz and the second supplied the stabilized frequency transfer prototype with 7.96 GHz. Both synthesizers were referenced to the observatory’s hydrogen masers.

Observations were performed over several days in 2016 May and June during scheduled ATCA maintenance periods. Table 1 summarizes the measurements that will be discussed in this paper. Due to maintenance requirements, the number of antennas available at different times varied.

The logging rate was limited by the data volume limitation of the correlator, and it was not possible to perform overnight observations with a logging period shorter than 5 s. A shorter observation of only 2 hr was performed with a logging period of 1 s in order to obtain array phase-stability measurements at shorter integration times.

3. Results

Phase solutions and phase differences were produced for all mixed and unmixed baselines for each of the measurements.
summarized in Table 1. An example of the phase solutions and phase differences for a single polarization for three baselines of different lengths from observations conducted on 2016 June 21st is shown in Figure 2. The blue traces represent the unmixed baselines (using the conventional ATCA reference distribution) while the green traces represent the same physical baselines using the mixed references. The corresponding phase differences are shown to the right of the figure.

At the commencement of the observations, the delay errors for each antenna were measured by the correlator while observing the calibrator source and corrected for (residual delay errors were typically less than 0.1 nanoseconds). We also added phase offsets to produce a zero phase for each baseline at the beginning of the observation. No further delay or phase calibration was made while the array was observing.

All post-observation data reduction was performed with the Miriad software package (Sault et al. 1995). First, we performed a bandpass calibration with the Miriad task “mfcal”, while solving for time-varying gains every 30 s. The resultant bandpass solutions (examples of which are shown in Figure 3) were then subtracted from the entire data set (we assumed that they stay constant with time). We then used the task “gpcal” to solve for time-variable complex gains every cycle, which is possible due to the brightness of the calibrator source. This was used to produce the phase solutions (like those shown in Figure 2) that reveal how the measured phases changed over the duration of the observation.

The phase solutions and phase differences were processed to produce plots of absolute frequency stability. Figure 4 shows the absolute stabilities for the three baselines used as examples in Figure 2 as well as the phase difference stability of an unmixed (conventionally referenced) baseline for comparison. Absolute frequency stability values are obtained by multiplying the Allan deviation computed for the signal by the frequency of the signal. Values in terms of absolute frequency stability are necessary to directly compare the stability of signals of different frequencies,

<table>
<thead>
<tr>
<th>Date</th>
<th>Center Observing Frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>Available Antennas</th>
<th>Logging Rate (s)</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 May 26</td>
<td>4.96</td>
<td>2048</td>
<td>01, 02, 03, 04, 05, 06</td>
<td>12</td>
<td>12 hr overnight run, dual synthesizers</td>
</tr>
<tr>
<td>2016 Jun 20</td>
<td>4.96</td>
<td>2048</td>
<td>01, 03, 04, 06</td>
<td>5</td>
<td>13 hr overnight run</td>
</tr>
<tr>
<td>2016 Jun 21</td>
<td>4.96</td>
<td>2048</td>
<td>01, 03, 04, 06</td>
<td>5</td>
<td>12 hr overnight run</td>
</tr>
<tr>
<td>2016 Jun 22</td>
<td>4.96</td>
<td>2048</td>
<td>01, 03, 04, 05, 06</td>
<td>1</td>
<td>2 hr daytime run</td>
</tr>
<tr>
<td>2016 Jun 22</td>
<td>25.44</td>
<td>2048</td>
<td>01, 03, 04, 05, 06</td>
<td>5</td>
<td>15 hr overnight run</td>
</tr>
</tbody>
</table>

Figure 2. Phase solutions (a–c) and corresponding phase differences (d–f) for a selection of three baselines of different lengths \((a, d = 46 \text{ m}; \ b, e = 152 \text{ m}; \ c, f = 4439 \text{ m})\) for 4.96 GHz observations from 2016 June 21st. Blue represents unmixed baselines; green shows mixed baselines; pink (d), orange (e), and purple (f) depict phase differences for baselines (a), (b), and (c), respectively.

and this allows the noise contributions of different parts of the interferometer and frequency reference systems to be assessed more easily. Figure 4 shows the absolute stability plots for the traces shown in Figure 2, as well as for the 25 GHz measurements from 2016 June 22 (using the same example baselines).

The process was repeated for the 1-s logged daytime run from 2016 June 22, and the resulting absolute frequency stabilities are shown in Figure 5. The 1-s logging period of this measurement allows the stability values to be calculated at integration times down to 1 s but, due to the relatively short time span of the observations, stability data are limited to integration times shorter than 1024 s.

To assess the performance of the system with respect to the 10-min phase-drift requirement, the phase drifts between the mixed and unmixed baselines for each 10-min interval in all 42 hr of stabilized observations (Table 1, 2016 June 20–22) were measured. The compiled phase-drift values are shown in Figure 6. Within one standard deviation, the phase drifts are less than 0.08 rad, and no 10-min period phase drift exceeded a value of 0.56 rad.

The synthesizer comparison test (Table 1, 2016 May 26) exhibits large phase drifts between the mixed and unmixed baselines, an example of which is shown in Figure 7. This relative phase drift between the two synthesizers significantly affected the stability of the baseline phase solutions and phase differences. Figure 8 shows the resulting absolute frequency stabilities for three example mixed baselines plus an unmixed baseline for comparison.

4. Discussion

4.1. Stability Analysis

Each of the example stability plots in Figures 4 and 5 show three traces for the stability of the phase difference between the mixed and unmixed baselines, one each for the short (pink trace), intermediate (orange trace), and long (purple trace) baselines. As expected, the three curves lie on top of each other because they are the result of effectively subtracting-out the phase of the sky signal. The remaining phase noise is due to the reference distribution systems and non-common elements of the receiver chains. The frequency transfer systems (UWA stabilized transfer system plus ATCA distribution system electronics) are the dominant source of differential noise and, because that noise is common to all chain-2 frequency references, the frequency stability curves for the different baselines are almost identical. Panels (d)–(f) in Figure 2 show that the phase differences have some remaining baseline dependence, with the total phase drift increasing with increasing baseline length. This may be due to differential noise on the fiber links between the correlator room and the antennas as well as residual atmospheric effects. Figure 9 shows the output of the ATCA seeing monitor (Middelberg et al. 2006; Indermuehle & Burton 2014) for the time period corresponding to the example observations from 2016 June 21, overlaid with the phase differences for the 4439 m baseline from this observation (Figure 2, panel (f)). The data from the seeing monitor show that the atmospheric path length noise is greater during the periods when there is a noticeable increase in the rate of phase drift.

The difference between the stabilities of the phase differences for the mixed (pink, orange, and purple traces in Figures 4 and 5) and unmixed baselines (black traces in Figures 4 and 5) is due to noise contributed by both the stabilized frequency transfer prototype and parts of the ATCA frequency distribution system and receiver chains. While the stabilized frequency transfer prototype is assumed to be the dominant source of the extra phase noise, the following analysis shows that phase noise contributed by the ATCA systems account for a significant fraction of the difference.

Figure 3. Example amplitude and phase bandpass solutions from 4.96 GHz overnight observation from 2016 June 21. The bandpass solutions for the X-polarization of three antennas (antennas 1, 3, and 6) are shown.
between the mixed and unmixed baseline phase difference stabilities. The mixed baseline phase difference stabilities compared to the integration time ($\tau$) follow a power law with a gradient that is close to $\tau^{-1}$ up to integration times of around 40 s. The phase difference stabilities for the baseline between antennas 1 and 3 (comparing an unmixed baseline with an unmixed baseline, black traces in Figures 4 and 5) also exhibit this power law out to longer integration times, indicating that some of this extra noise does not originate with the stabilized frequency transfer prototype (Schediwy & Gozzard 2016). This power law is a signature of white- and/or flicker-phase noise and is most likely due to noise introduced by amplifiers outside of the stabilized frequency transfer system (Thompson et al. 2008). Measurements of the relative phase drift between the two E/O systems, conducted separately to the main observations, indicated that the “bump” feature in the phase difference stabilities between $\tau = 40$ s and $\tau = 640$ s is due to phase noise in the E/O systems (Schediwy & Gozzard 2016). This noise is not normally obvious during conventional observations because there is no cross-correlation between signals from chain-1 and chain-2.

4.2. Extrapolation to SKA1

With the main contributions to the residual differences between the stability of the phase differences for mixed and unmixed baselines accounted for, the measured absolute frequency stabilities are in good agreement with values expected from laboratory measurements of the stabilized frequency transfer prototype (Schediwy et al. 2017). This provides confidence that standard metrology measurement techniques are adequate to reliably demonstrate the stability of the stabilized frequency transfer system for SKA verification purposes. The stability of the transmission over 166 km of buried conduit fiber-optic cable around Perth, Western Australia (Figure 10), has been measured previously using a Microsemi 5125A Phase Noise Test Set. The Allan deviation values for the signal stability over the 166 km link were extrapolated to obtain a prediction for the performance of the stabilized transfer system over a single 173 km span (the longest SKA1 fiber-link length). This was achieved by multiplying the measured Allan deviation values by $(L_2/L_1)^{1/2}$ (Williams et al. 2008), where $L_1$ is the length of the test link (166 km) and $L_2$ is the length of the link for which the prediction is being made (173 km). These predicted Allan deviation values were then multiplied by a factor of $\sqrt{2}$ to give a prediction of the Allan deviation between two stabilization system receiver units at the ends of two separate 173 km links (assuming that deviations in the two signals are uncorrelated). By assuming that the dominant noise process of the stabilized frequency reference is white phase noise (as indicated by the approximately $\tau^{-1}$ slope of the Allan deviation measurement), an estimate of the coherence loss can be calculated using the process described by
Rogers & Moran (1981) and Thompson et al. (2008). Using this process, an upper limit was calculated for the permissible Allan deviation of the frequency transfer system corresponding to the 1.9% coherence loss requirement for a maximum observing frequency of 13.8 GHz. This Allan deviation is $3.91 \times 10^{-12}/\tau$ and is shown in Figure 10 (pink line). The measured and predicted stability of the stabilized frequency transfer prototype is well below this limit at all integration times.

Applying the same coherence calculations directly to the measured Allan deviation, the coherence losses resulting from the extrapolated Allan deviation values for a maximum observing frequency of 13.8 GHz are $7.41 \times 10^{-6}$ at 1 s integration time and $7.96 \times 10^{-5}$ at 60 s integration time. These values exceed the 1.9% coherence loss requirement by a factor 2560 and 239, respectively.
Figure 10. Output of the ATCA seeing monitor (black line) overlaid with the phase differences for the 4439 m baseline from the 4.96 GHz overnight observation from 2016 June 21 (purple trace, copy of Figure 2 panel (f)). Increases in atmospheric path length noise shown by the seeing monitor correspond with increases in the rate of phase drift.

Figure 9. Output of the ATCA seeing monitor (black line) overlaid with the phase differences for the 4439 m baseline from the 4.96 GHz overnight observation from 2016 June 21 (purple trace, copy of Figure 2 panel (f)). Increases in atmospheric path length noise shown by the seeing monitor correspond with increases in the rate of phase drift.

An alternative method of estimating coherence loss from Allan deviation was used by members of the ALMA project (Kawaguchi 1983; Kiuchi 2005; Yamada et al. 2006). Using this method, we calculate coherence losses of $4.4 \times 10^{-5}$ at 1 s integration time and $1.6 \times 10^{-3}$ at 60 s integration time. These values exceed the 1.9% requirement by factors of 4320 and 1190, respectively.

4.3. Dual-synthesizer Test Analysis

The large phase drift in the results from 2016 May 26 (green trace, Figure 7) is dominated by the phase drift between the two synthesizers used as frequency references. In order for a synthesizer to maintain its output frequency relative to a 10 MHz reference, it must change the phase of its output signal as its internal temperature changes in response to variations in ambient temperature. The large drifts were not seen when only one synthesizer was used with the IQ-mixer frequency shift. Figure 8 shows that the phase noise of the two synthesizers even dominates the phase noise of the sky signals caused by the atmosphere on baselines up to around 200 m in length at observing frequencies around 5 GHz. This is not an issue in normal observations because interferometers such as the ATCA do not operate in configurations where multiple synthesizers are used to provide frequency references to different antennas or sub-arrays. However, any system that uses multiple remote synthesizers may encounter such a synthesizer phase drift issue despite the transmission frequency being successfully stabilized. This is a critical consideration for the design of stabilized time and frequency reference systems planned for the SKA.

5. Conclusions

We have used the dual-receiver architecture of the ATCA to perform astronomical verification tests of a prototype stabilized frequency transfer system proposed for the SKA, as well as to assess the effects of using multiple microwave frequency synthesizers to supply frequency references to different telescope antennas or sub-arrays. The results of these astronomical verification trials show that the stabilized frequency transfer prototype exceeds the SKA level-1 coherence and phase-drift requirements under a broad range of observing conditions. Extrapolating the system’s performance from laboratory measurements over a link of 166 km to SKA operating conditions predicts that, even for a worst-case scenario, this stabilized frequency transfer system will exceed the 1 s coherence requirement by three orders of magnitude and the 60 s coherence requirement by two orders of magnitude. Over the 77 km link used in these tests, the 10-min phase drift never exceeded 0.56 rad, and all drifts within one standard deviation of the mean had a magnitude less than 0.08 rad. However, the 10-min phase drift is dependent on both systematic and random phase fluctuations, so it is not known how the magnitude of the phase drifts will scale with increasing link length. Also, unlike for the Allan deviation results, it was not possible to determine, from the data obtained, how much of the observed phase drift was due to the stabilized frequency transfer prototype and how much can be attributed to other systems, such as the E/O systems. For this reason, bench tests in the laboratory are a better method for validating the stabilized transfer system against this SKA systems requirement. Despite this, these results are a strong indication that this stabilized frequency transfer system is capable of exceeding the 10-min phase-drift requirement.

These tests have also highlighted potential problems with the use of multiple synthesizers to provide phase-coherent signals to separate antennas, even when the reference frequencies to those synthesizers have been successfully phase-stabilized. Care must be taken to ensure that alternative stabilized frequency reference transfer systems being considered for the SKA do not suffer from phase drift to the extent that it is a
detriment to the performance of the telescope. Synthesizer phase-drift rates such as those seen in these tests would reduce the sensitivity of the array and, under some conditions, limit the imaging capability.

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Characterization of optical frequency transfer over 154 km of aerial fiber

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We present measurements of the frequency transfer stability and analysis of the noise characteristics of an optical signal propagating over aerial suspended fiber links up to 153.6 km in length. The measured frequency transfer stability over these links is on the order of $10^{-11}$ at an integration time of 1 s dropping to $10^{-12}$ for integration times longer than 100 s. We show that wind-loading of the cable spans is the dominant source of short-timescale noise on the fiber links. We also report an attempt to stabilize the optical frequency transfer over these aerial links. © 2017 Optical Society of America

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Long-distance optical fiber networks are increasingly being used for the transmission of high-precision frequency and timing signals because the stability and accuracy of optical links surpass that of conventional satellite two-way time and frequency transfer by more than three orders of magnitude [1–3]. The frequency and timing signals have applications in science and industry, ranging from radio astronomy, geodesy, and tests of fundamental physics, to network synchronization and high-precision manufacturing [4].

One factor that limits the performance of long-distance frequency transfer is the phase noise imposed onto the optical signal by mechanical stresses on the fiber link. Measurements of frequency transfer stability have mostly focused on underground [5–7] and some submarine links [8]. Although aerial suspended fibers and optical ground wires (OPGWs) are subject to greater mechanical stresses due to their greater exposure, the lower cost of reticulating overhead fiber means that there are circumstances under which the timing and frequency transfer stability of transmissions employing overhead fiber links is of interest. In particular, this Letter was carried out in order to characterize the impact of synchronization signals that are to be disseminated over aerial fiber links as part of the Square Kilometre Array (SKA) radio telescope to be constructed in the Karoo region of South Africa [9].

The investigation of detrimental effects on telecommunications and network monitoring due to the impact of environmental conditions on aerial fibers and OPGWs has focused on polarization mode dispersion, the state of polarization fluctuations and network monitoring due to the impact of environmental conditions on aerial fibers and OPGWs has focused on polarization mode dispersion, the state of polarization fluctuations, and transmission delay variations [10–14]. To the best of our knowledge, only one study [15] has undertaken a characterization of frequency transfer stability on aerial fiber to date, and only at radio frequencies (10 MHz). In this Letter, we present, to the best of our knowledge, the first characterization of optical frequency transfer stabilities on aerial suspended fiber links of 32.6, 65.2, and 153.6 km lengths.

Optical frequency transfer provides the highest level of precision for the purposes of metrology and other sciences [7]; however, it is also the most sensitive to mechanical stresses on the link and is the most difficult to actively stabilize. The magnitude of the phase perturbations detected on the aerial fiber links in this Letter demonstrate the challenges for optical phase stabilization systems attempting to compensate for the noise imposed on the link.

These tests were conducted at SKA South Africa’s Karoo support base at Klerefontein near the South African SKA site. Figure 1 shows the physical arrangement of the relevant locations. Four cores of a 16.3 km fiber link from Klerefontein to the Carnarvon point-of-presence (POP) site, and two cores of a 76.8 km fiber link between Klerefontein and the SKA central site were used for the tests (fiber standard, SMF E9 according to ITU-T G.652.D; chromatic dispersion at 1550 nm, 18 ps/nm/km). The fiber cables were suspended from power poles for the entirety of their runs. Fiber patch leads were installed at the Carnarvon POP to give two "loop-back" sections of 32.6 km of aerial fiber, while another patch, incorporating an IDNL Fibres Optiques bidirectional optical amplifier (with a gain of +18.7 dB and a noise figure of 7.6 dB), was installed at the SKA central site to produce a loop-back length of 153.6 km.
Figure 2 shows a schematic representation of the system that was installed at Klerefontein and used to characterize the fiber links. The system is fundamentally a stabilized optical frequency transmission system, based on the technology pioneered by Ma et al. [16]. Our primary aim was to characterize the noise on the fiber, but we designed the equipment to also be capable of active stabilization of the link noise. However, in practice, we were unable to achieve continuously stabilized transmission for more than several minutes, even over the 32.6 km link, due to the magnitude of the perturbations and the design of the stabilization servo electronics.

In the transmitter section of the system, an NKT Photonics Koheras BASIK X15 commercial diode laser (spectral linewidth <100 Hz) was used to provide a highly coherent optical frequency at 193 THz (1552 nm). A small fraction (3%) of the optical signal was split off to provide the out-of-loop optical reference for the measurement photodetector (PD). The rest of the power continued downline where it was split again, with part being reflected off a Faraday mirror (FM) at the end of a short length of fiber to become the reference signal for an imbalanced Michelson interferometer. The fiber link constituted the long arm of the Michelson interferometer. Before the optical signal was injected into the fiber link, it passed through the servo acousto-optic modulator (AOM) which produced a ±70 MHz shift of the optical frequency.

The transmitted signal made the round-trip through the fiber link and entered the receiver side of the system. The optical signal passed through a polarization controller (Pol) and was split, part of the power being directed to the measurement PD where it beat against the optical reference to produce a 70 MHz electronic signal, the stability of which and, thus, the noise on the fiber link, was measured using a frequency counter (Agilent 53132A) which produced a triangle-weighted estimate of the fractional frequency stability. The polarization controller was used to align the polarization of the received signal with the polarization of the optical reference.

The rest of the received signal power passed through the receiver AOM (+50 MHz frequency shift), reflected from a FM, passed through the receiver AOM again and returned through the fiber link back to the transmitter side of the system. After passing through the servo AOM, the signal from the link and the signal from the reference arm entered the input of the servo PD where they formed a 240 MHz electronic beat signal. This beat signal encoded information about the frequency fluctuations on the fiber link due to environmental perturbations. The electronic signal was divided by a factor of 24 and then mixed with a 10 MHz local oscillator. The mixer product became the servo error signal and was used to steer the 70 MHz output of the frequency synthesizer. Activating the frequency modulation closed the servo loop, and the system adjusted the frequency shift produced by the servo AOM to compensate for frequency fluctuations caused by perturbations on the fiber link. The characterization of the noise of the fiber link was achieved with the servo loop deactivated. Links of 32.6 km (2 × 16.3 km, 8.6 dB loss) and 65.2 km (4 × 16.3 km, 17.4 dB loss) between Klerefontein and Carnarvon, and 153.6 km (2 × 76.8 km, 31.7 dB loss) between Klerefontein and the SKA site, were tested during these trials.

Weather data, including wind speed and wind direction, coinciding with the period of the trials were collected from a weather station operated at Klerefontein by the C-Band All Sky Survey (C-BASS). The wind velocity data were compared with the magnitude of the coincident link frequency fluctuations.

The data from the frequency counter were processed to produce fractional frequency stability curves for the three links studied. These curves are shown in Fig. 3. The blue trace in Fig. 3 (filled triangles, solid line) is a “zero-length” (a 2 m fiber patch lead) measurement with optical attenuation set equal to that of the 32.6 km link and is, therefore, a measurement of the fiber characterization system noise floor.

Due to the magnitude of the noise on the fiber links, it was not possible to actively stabilize the optical transmission for more than a few minutes before a cycle slip occurred. The data presented here show only one stabilized transmission of 26 minutes for the 32.6 km link (green, filled triangles, solid line). The measurements for the characterization of the frequency noise on the free-running links were taken for periods of between 1 and 93 h at all times of day and night.
There is little difference in the overall frequency noise levels between the three different aerial link lengths (Fig. 3). However, all three links show an extreme level of noise. The instability of the 153.6 km link (red, open triangles, dashed line) at one second integration time is approximately 260 times greater than the free-running link noise for the 1840 km buried fiber link reported by Droste and colleagues [17].

For comparison with the stabilized 32.6 km overhead fiber data (green, filled triangles, Fig. 3), the stabilized transfer stability over a 31 km urban trench and conduit fiber link in Perth, Western Australia, has been included (green, filled circles, solid line). Figure 3 shows that the fractional frequency value for the stabilized transfer over the 32.6 km aerial fiber link is 124 times greater than that for the 31 km buried link at an integration time of one second, and that the value of the free-running aerial link (green, open triangles, dashed line) is nearly 2 million times greater than the stabilized buried link at an integration time of one second.

Also shown in Fig. 3 is the stability of a 142 km link, stabilized (red, filled circles, solid line) and free-running (red, open circles, dashed line), composed of 31 km of urban trench and conduit fiber, and 111 km of fiber spool in the laboratory in Perth. Compared to the 153.6 km Klerefontein-SKA site loopback link (8% longer), the fractional frequency stability of the aerial link is nearly three orders of magnitude greater than the 142 km free-running link at an integration time of one second.

The extreme difference in the frequency transfer stability between the aerial and buried fiber links is due to mechanical stresses on the fiber cables caused by the weather. During the testing period, the fiber cables were subjected to high and gusting winds, rain, and large thermal gradients, as the fiber went from overnight frost to direct morning sunlight. The greatest source of short-timescale perturbations was the wind.

The raw data from the frequency counter displayed a noticeable periodicity in the amplitude of the frequency fluctuations. By taking the Fourier transform, shown in Fig. 4, of the time-series frequency data for the 153.6 km Klerefontein-SKA site link, it can clearly be seen that there is a dominant periodicity in the frequency perturbations of $1.405 \pm 0.002$ s ($2\pi$).

Visual inspection of typical spans of aerial fiber in the vicinity of Klerefontein (recorded on camera for later analysis) estimated the period of the fundamental lateral (swinging) mode of the spans to be $2.85 \pm 0.15$ s, giving a half-period of $1.43 \pm 0.08$ s. This overlaps, within uncertainty, with the dominant period in the frequency fluctuation data (Fig. 4), and indicates that the swinging action of the cable is related to the periodicity of the frequency fluctuations. The swinging of the spans induces periodic stresses on the fiber, altering the optical path length and producing phase noise on the signal.

The Klerefontein-SKA aerial fiber link is composed of around 1000 span segments with a median span distance of 70 m. Because the frequency fluctuations induced by the mechanical oscillations of the fiber manifest as twice the cable fundamental mode frequency, their signal magnitude combine in quadrature, even when the oscillations of separate fiber cable spans are not coherent.

The impact of wind-loading on the fiber cables can be further examined by assessing the correlation between the magnitude of the frequency fluctuations (which are dominated by the $1.405$ s periodic component) and the amplitude of the swinging of the cable spans. This oscillation mode is loaded by the vector component of the wind perpendicular to the direction of the cable span. Figure 5 shows a plot of the absolute magnitude of the frequency fluctuations over time, overlaid with the projected component of the wind speed (determined from C-BASS weather station data) perpendicular to the weighted dominant direction of the Klerefontein-SKA site fiber link.

The data suggest that there is a causal correlation between the wind speed and the magnitude of the frequency fluctuations.
The residual discrepancy is attributed to the local variation in wind speed between the weather station site and the fiber route. The time resolution of the wind speed data also mask the effects of gusts.

We have measured the frequency transfer stability and characterized the noise of optical signals transmitted over aerial fiber links up to 153.6 km in length. All of the tested aerial fiber links exhibited levels of frequency noise hundreds of times greater than comparable buried links. The dominant source of noise was shown to be caused by mechanical strains imposed by the swinging of the fiber spans due to transverse loading from the wind. Only the shortest link (32.6 km) was successfully stabilized for a period of nearly half an hour without a cycle slip, and with two orders of magnitude poorer stability than the equivalent buried link. Higher-frequency division ratios in the servo error signal chain may improve the frequency locking performance of this and similar stabilization systems. In addition, repeater stations at intervals along the link will also improve the stability of the whole link. This increases the servo bandwidth and allows for greater servo gain. If the longer fiber spans can be successfully stabilized for significant periods of time, then aerial fiber may present a useful alternative for optical frequency transmission in situations where buried fiber is unavailable or cost-prohibitive. The challenges of robust signal stabilization over aerial fiber are significantly reduced at radio and microwave transfer frequencies due to the lower sensitivity of the phase of these transmissions to fiber length changes. The same aerial links tested here were successfully stabilized at radio frequencies [18], based on the technique in Ref. [19], and microwave frequencies [20].

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**REFERENCES**

This is a copy of an SKA Signal and Data Transport Consortium paper published in *Astronomy Reports*. The paper gives an overview of the Consortium’s design. Work presented in this thesis contributed to the publication. The paper is included to give a complete record of published work arising from the research presented in this thesis.
Square Kilometre Array: The Radio Telescope of the XXI Century


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Abstract—The Square Kilometre Array (SKA) will be the world's largest and most sensitive radio telescope. It will address fundamental unanswered questions about our Universe including how the first stars and galaxies formed after the Big Bang, how dark energy is accelerating the expansion of the Universe, the role of magnetism in the cosmos, the nature of gravity, and the search for life beyond Earth. This project envisages the construction of 133 15-m antennas in South Africa and 131072 log-periodic antennas in Australia, together with the associated infrastructure in the two desert sites. In addition, the SKA is an exemplar Big Data project, with data rates of over 10 Tbps being transported from the telescope to HPC/HTC facilities.

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1. INTRODUCTION

The Square Kilometre Array (SKA) is an international project to build a next generation radio telescope. The telescope will be built in two phases, with even the Phase 1 instrument having a survey speed around 100 times faster than the current state-of-the-art. The SKA will be the world’s largest astronomical instrument and will join such instruments as ALMA, JWST, and E-ELT as one of the world’s great observatories. It will be the next transformational step in radio astronomy, and will shape its future for many decades. The detailed design for Phase 1 of the telescope is currently underway, with Preliminary Design Reviews passed by all the telescope elements and Critical Design Review on schedule for late 2017. Construction of the SKA will start in 2018 and it will be built over a 5 year period by international industry within a cost cap set in 2013 of €650M.

The SKA comprises two separate interferometric arrays on two different continents. The SKA-low telescope will operate between frequencies of 30–350 MHz and will be deployed at the Murchison Radio Astronomy Observatory, Australia. It will incorporate a total of 131 072 log-periodic antennas, which are grouped into 512 stations of 256 antennas each. 296 of these stations will be configured into a central core area, with the remaining 216 deployed along three spiral arms to give a maximum baseline of 65 km. The SKA-mid telescope will operate between frequencies of 1.35–13.8 GHz and will be located in the Karoo desert in South Africa. It will be made up of 133 offset Gregorian antennas with 15-m diameter, and will additionally incorporate 64 antennas of 13.5-m diameter being built for the MeerKAT telescope. Again, there will be a central core of antennas and three spiral arms allowing a maximum baseline of 150 km.

In this paper we will briefly discuss the key science drivers for the SKA and one of the dominant challenges for this project, the vast amount of data that will be produced, transported and processed. We will then focus into one of the design areas required for tackling this exemplar Big Data problem, namely that of the networking required for the SKA.

2. SCOPE OF SKA SCIENCE

The original ideas for the SKA arose in the 1980s and were then developed in the 1990s. Central to these ideas was the goal of imaging neutral hydrogen through its redshifted 1.4 GHz emission line, and it was realized that the sensitivity required to image typical galaxies out to redshift 2 at better than arcsecond resolution would require a telescope with a collecting area of around 1 km² and baselines of around 100 km. While neutral hydrogen imaging is still one of the key drivers for the telescope, the science goals of the SKA are now much broader. The SKA science case is captured in “Advancing Astrophysics with the Square Kilometre Array” [1] and contains 135 chapters written by 1213 contributors. The book spans many diverse areas of astrophysics, with transformational discoveries possible in the following areas.

- **Strong-field tests of gravity with pulsars and black holes** [2]. The surveying capabilities of the SKA will be sufficient to increase the number of normal and millisecond pulsars by more than 10-fold. Through extremely accurate timing measurements of these pulsars, the SKA will be able to search for gravitational wave by effectively using the whole our Galaxy as a detector. In addition, pulsar systems are exquisite laboratories for studying physics in very strong gravitational fields and will allow testing of the predictions of General Relativity.

- **Cosmic dawn and the epoch of reionization** [3]. The first stars in the Universe were born around 100 million years after the Big Bang.Very little is known about this era of Cosmic Dawn, and the most promising avenue for exploration comes through observations of highly redshifted neutral hydrogen. These first stars and AGN began to heat and then ionize the matter in the Universe during the Epoch of Reionization (EoR). Measurements of neutral hydrogen will allow us to directly image these EoR structures.

- **The transient radio sky** [4]. In recent years a new phenomenon of Fast Radio Bursts (FRBs) has been discovered. These FRBs are believed to be due to extremely violent explosions in galaxies at cosmological distances. FRBs are interesting in their own right, but also offer the possibility of allowing detection of the missing baryons in the Universe. Monitoring the behavior of other transient objects will allow astronomers to study the disruption of stars by super-massive black holes.

- **Cosmology & dark energy** [5]. A number of techniques will allow the SKA to investigate cosmology, including strong and weak gravitational lensing; neutral hydrogen intensity mapping; radio galaxy surveys out to high redshift;
and HI galaxy redshift surveys. Through these we hope to learn about the nature of Dark Energy, modified gravity, and primordial non-Gaussianity.

• The origin and evolution of cosmic magnetism [6]. Radio measurements of Faraday rotation offer a unique method for exploring magnetic fields. These are known to be of vital importance in galaxy formation and to the evolution of galaxy clusters. In addition we will also be able to explore the origin of cosmic magnetic fields.

• Galaxy evolution probed by neutral hydrogen [7]. The SKA will have the sensitivity to allow the imaging of substantial number of high-redshift galaxies in HI at resolutions of <1? for the first time, vastly improving our understanding of the formation, growth and evolution of galaxies.

• The cradle of life & astrobiology [8]. One of the key unresolved issues in the understanding of planetary formation is the mechanism by which small pebbles in the disk around a young star are able to coalesce to form boulders, which then go on to form planets. The SKA’s wavelength range is well matched to that of these pebbles and so it will be able to observe this phase of planetary evolution.

• Galaxy and cluster evolution probed in the radio continuum [9]. The process of star formation reached a peak of activity about 3 billion years after the Big Bang and since then the rate has dropped. The mode of star formation at this epoch seems to have a different character to that at the present day and further study will require high sensitivity radio continuum observations allowed by the SKA in order to be able to penetrate the obscuring matter round these sites.

3. BIG DATA AND THE SKA

The volumes of data that the SKA will generate are vast. Each of the 197 antennas of the SKA-mid will generate around 90 Gbits/s of digitized payload data, giving a total of 17.7 Tbl/s to be transported from the geographically distributed antennas back to a Central Processing Facility (CPF). Here the data are processed, with interferometric visibilities being formed by correlation of the signals between antenna pairs and in addition a search being formed for pulsar candidates. The processing required by these steps is around 50 Plops and the hardware and firmware is being designed by the Central Signal Processor (CSP) consortium. These intermediate data are then passed to the Science Data Processor (SDP) for further analysis, requiring around 250 Plops of additional computing power.

For the SKA-low the volumes are even larger. The signals from each of the log-periodic antennas are transmitted on RF-over-fiber to a bunker where each polarization is Nyquist sampled at 8 bits, generating around 1.490 Tbl/s. The data are beamformed and then, in a similar fashion to SKA-mid, passed to first CSP and then SDP for processing.

These data volumes and processing requirements make the SKA an exemplar Big Data challenge. The design of the CSP and SDP are beyond the scope of this paper, and in the next section we concentrate on the challenges posed by the data transport requirements of the SKA.

4. NETWORKING FOR THE SKA

The SKA Signal and Data Transport (SADT) Consortium is comprised of 15 different institutes from 8 countries, and is led by the University of Manchester. The SADT Consortium has been allocated responsibility by the SKA Organization for design of the various networks that connect the other elements of the telescope.

4.1. Overview of SKA Networking

The scope of the Signal and Data Transport (SADT) element is to provide 3 logically distinct networks for both of the telescopes that comprise the SKA.

1. The astronomical data network. This is itself split into 3 sub-systems which have very different requirements.
   (a) The Digital Data Backhaul (DDBH) network transports signals from the receptors to the CSP.
   (b) The CSP–SDP network transports data products from the CSP to the SDP.
   (c). The SDP network distributes data from the SDP to the regional SKA Regional Data Centers.

2. The Synchronization and Timing (SAT) network. This provides frequency and clock signals from a central clock ensemble to all elements of the system to maintain phase information to the required accuracy for all receptors, and timing signals for data identification and time critical activities at the receptors, the CSP and SDP.

3. The Non-Science Data Network (NSDN). This connects all locations of the telescope system.
Fig. 1. Schematic of the SADT networks. The three astronomical data networks are shown in red and the data flows are unidirectional. The network that distributes time, frequency and phase is shown in blue. The non-science data network is shown in green. An instance of the above diagram will be required for each of the two telescopes. In the case of SKA-low the DDBH and Station Time and Frequency Reference (STFR) networks will only be provided to the outer stations/antennas as part of the SADT Element.

and transports the monitoring and control information that is the responsibility of the Telescope Manager (TM) element, and the general communications traffic.

4. The Network Manager (NMGR) sub-system provides the local monitoring and management of the DDBH and CSP-SDP science data networks, the NSDN and the associated networking equipment. Local monitoring and control for the SAT is provided separately by the SAT LMC sub-system. SADT is also responsible for the local infrastructure (LIN-FRA) requirements specific to SADT and outside the scope of the INFRA consortium, for example optical fiber reticulation design and SADT repeater shelter buildings.

The scope of the SADT networking connectivity is summarized in Fig. 1. In the following sections we give some more details about the various SADT sub-systems appropriate to a snapshot in time corresponding to the Preliminary Design Review (PDR).

4.2. Astronomical Data Transport Networks

4.2.1. DDBH network. The Digital Data Back-Haul (DDBH) network will be a fully managed, self-contained, COTS solution with short reach Ethernet client interfaces that are completely vendor agnostic. From a cost driven point of view, it will use simple layer 1 or layer 2 switching technologies. Wherever possible the same technology has been used for both telescopes allowing for greater efficiencies in operational costs across the SKA1 deployment. The equipment will support a rich feature-set of management, monitoring and remote access protocols. Figure 2 shows the logical network diagrams for the two telescopes.

SKA-mid telescope. For the SKA-mid telescope, there will be two different implementations of the DDBH system dependent on the fiber distance of the antenna from the Central Processing Facility (CPF) building. There are approximately 95 inner array dishes that fall within a distance of less than 10 km. These will have “pizza box” equipment deployed at the Dish sites and present a single 100 G short reach optical client interface compliant with the IEEE 802.3 Ethernet standard, 100GBASE-SR4. At the CSP side of the link the proposal is to aggregate the 95 dishes into a larger chassis based equipment using standard LR-4 transceivers on the line side and presenting 100GBASE-SR4 short reach interfaces to the CSP client. The remaining 38 outer array dishes (>10 km) will use long reach DWDM transmission equipment, but with the same 100GBASE-SR4 client interface.

SKA1-low telescope. For the SKA1-LOW telescope, the DDBH network needs to support a client data capacity of 40GE from each of the stations outside the core area. There are 36 SKA-low clusters of 6 stations each located in Remote Processing Facilities (RPFs) less than 80 km from the CPF building. The optical client interface in the COTS design will comply with IEEE 802.3 Ethernet standards with 6x40GBASE-SR4 capacity per RPF location. The line side interface will be provided by optical DWDM equipment using coherent modulation formats. All switches will be non-blocking to maintain transparency.

4.2.2. CSP–SDP network. The SKA CSP–SDP Network provides long distance high bandwidth connectivity between the Central Signal Processor (CSP) locations, and the Science Data Processor (SDP) complex for each of the telescopes. It will carry the science data traffic from the CSP to SDP facilities.
as well as non-science data such as monitoring and control from TM and other auxiliary site traffic. These services will be separated at the optical layer. Figure 3 shows a schematic of the CSP–SDP connecting the CSP, the SDP and the Engineering Operations Centre (EOC) locations.

Due to the data rates and distances required, 7.4 Tbit/s over a distance of ~910 km for the observatory in South Africa and 5.8 Tbit/s over a distance of ~820 km for the observatory in Australia, the equipment choice is constrained to standard long-haul coherent transmission equipment used by telecommunications carriers. Based on the current road maps, the line or transmission side technology will use an encoding technique similar to Dual Polarization Quadrature Phase-Shift Keying modulation (DP-QPSK) with Coherent Detection (CD) and Dense Wavelength Division Multiplexing (DWDM). No regeneration is required over these distances, but optical amplification will be needed approximately every 70 to 100 km. COTS equipment and fiber will be used and will support 120 channels each running at 200 Gbps. Ethernet with support for Jumbo frames that carry an IP MTU 9000 bytes will be used.

4.3. Synchronization and Timing

There are multiple different, but related, requirements for Synchronization and Timing for the SKA.

1. Ensuring that the whole synthesis array is phase coherent. A maximum permitted coherence loss of 2% equates to 0.2 radians of phase error, which, at a maximum observing frequency of 20 GHz, corresponds to accuracies of ~1 ps.

2. Providing high precision long-term timing, for astrophysical phenomena such as pulsars and transients. In particular, pulsar monitoring experiments require timing accuracies of 10 ns over time periods of 10 years.
3. Providing absolute time for system management, antenna pointing, beam steering, time stamping of data and producing regular timing ticks.

4. Providing frequency standards for Local Oscillators (LOs), digitizer clocks, low frequency square waves or Walsh functions for phase switches and noise diode.

5. For VLBI operations, in which some, or all, of the phased SKA core will be combined with other telescopes around the world, the requirements of (1) apply, possibly with some degree of relaxation relative to the other, independent telescopes.

A block diagram of how these requirements are met by the SKA Synchronization and Timing element is shown in Fig. 4 and its sub-systems are discussed below.

4.3.1. SAT timescale. The design of the reference timescales for the SKA telescopes assumes that near-identical timescales will be constructed for each of the Mid telescope in South Africa and for the Low telescope in Australia. The timescales will use Coordinated Universal Time (UTC) as their time and frequency reference. A robust design is proposed for each timescale, based on the use of an ensemble of three active hydrogen masers as the reference clocks. The first two of these masers each produces a physical realization of the SKA Timescale. One of these will act as the master realization and the other as back-up. Physical switching (triggered by the appropriate software command) between master and back-up timescale should enable continued operation following individual hardware failures and enable the SKA timescales to meet their operational requirements. The third maser allows for a “Three Cornered Hat” arrangement to allow identification of which of the two timescale realizations is the source of an anomaly should they disagree.

A key requirement of the SKA Timescales is an accurate knowledge of their time offsets with respect to UTC. This is required for pulsar timing and other applications. Global Navigation Satellite System (GNSS) time transfer will be used as the primary time transfer method. Each SKA Timescale will operate three GNSS receivers, which will be regularly calibrated using portable calibrating GNSS receivers. Direct traceability to UTC will be achieved by the SKA Timescales becoming UTC(k) facilities, and the time transfers being computed by the Bureau International des Poids et Mesures (BIPM).

A steering mechanism is required to keep the time and frequency of the SKA Timescale close to that of UTC. Timescale signals are generated from the outputs of the active hydrogen masers, which are then adjusted by applying small frequency changes. This process both enables the resulting SKA master and back-up timescales to be aligned to UTC and leaves the free running active hydrogen masers unperturbed. The steering process may be achieved using either manual or automatically generated frequency steers. A steering algorithm will be provided to offer the possibility of automating the SKA Timescale steering process. In all cases it will be ensured that the magnitude of the steers will be below the stochastic noise level to avoid perturbing the underlying timescale stability and astronomical timing measurements.
Monitoring the performance of the SKA Timescales is key to their successful operation. Automatic measurements and analysis of many of the components of the SKA Timescales will be included in the design, along with anomaly detection. This process will be supported by operator observations which may be undertaken on a weekly basis. An annual program of calibration, performance evaluation and servicing will form part of the operations of the SKA Timescales.

4.3.2. System for timing and frequency reference. The SAT.STFR (Synchronization and Timing, Station Time, and Frequency Reference) carries out the function of delivering standard frequency references and timing signals derived from the SKA frequency and timescale reference to the receptors and other locations. The reference signals need to be delivered with sufficient precision to enable each of the telescopes to be phase-coherent, and to support the demanding requirements on absolute time for scientific observations such as pulsar timing on timescales of decades.

These signals will be transported by optical fiber. Environmental influences, such as temperature changes or mechanical vibrations, affect the optical path length of the optical fiber links, thereby degrading the stability of the delivered reference signals. The designed solutions all measure this effect by sending a signal out and back again over the same fiber. As the signal travels both ways over the same fiber, the actual delay or phase variation at the destination will be half of the measured value and can be compensated.

For the distribution of the reference frequency, we have two designs, one concept developed by Tsinghua University, and the other by the University of Western Australia. Both systems deliver not only a reference frequency, but include a means of synthesizing all the required frequencies for driving samplers at the receptors, where required.

The UTC time reference makes use of a publically available hardware and software designs from a collaborative project called ‘White Rabbit’ which delivers sub-ns accuracy using mostly COTS components and sub-systems.

4.3.3. SAT local monitoring and control. The SAT.LMC will provide monitor and control function-
ality to the Clocks and STFR sub-systems of the SAT system. The SAT.LMC primary role will be to receive monitor data from all of the SAT sub-systems and relay this information on to the overall SKA Telescope Manager (TM). In addition the SAT.LMC will provide fault diagnostic support and provide alarm management support to the TM.

4.4. Non-Science Data Network

The Non-Science Data Network (NSDN) consists of an access layer, distribution switches and IP/MPLS Core routers, with a presence across the entire observatory. It is designed as a converged network to carry multiple services that support the operation of the telescopes. It is primarily responsible for transporting monitoring and control information between the Telescope Manager (TM) and the Local Monitoring and Control (LMC) interfaces of all sub-systems, but it also transports general data communication services such as internet connectivity, voice and infrastructure services.

The NSDN architecture is highly resilient and scalable, and consists of a core network, a distribution layer (where required) and an access layer. The NSDN will be deployed at the CPF and observatory campus locations such as accommodation and support facilities, the receptor pedestals or repeater shelters, the Science Processing Facility (SPF), the Engineering Operations Centre (EOC) and the Science Operations Centre (SOC). This network will either interface to, or incorporate, the current precursor site Operations Centre (SOC). This network will either relay this information on to the overall SKA Telescope Manager (TM). In addition the SAT.LMC will provide fault diagnostic support and provide alarm management support to the TM.

4.5. Network Manager

The SADT.NMGR sub element is responsible for monitoring the DDBH, NSDN, CSP–SDP networks and the associated infrastructure. The SADT.NMGR element comprises a Network Management System (NMS), and interacts with external systems, particularly the Telescope Manager. The NMS may consist of a single COTS solution or a combination of COTS systems from multiple vendors.

The NMS will be presented to the users in the form of a dashboard that gives a single view of the overall network health and availability, as well as generating alarms and sending alerts in case of any errors detected. Users will be able to zero-in on specific portions of the network topology to analyze and pinpoint the causes of any deviations from normal operation of the network.

4.6. Network Architecture

As described above, the SADT system consists of several different networks. The simplest approach for the architecture of these systems would be to have separate systems without any overlap. However, to obtain the lowest possible OPEX and CAPEX costs, the hardware in these subsystems needs to be shared as much as possible. To determine the overall SADT architecture separate networks are assessed with respect to their functionalities and requirements. On the basis of this assessment a single architecture for the four systems is determined.

4.7. Local Infrastructure

The fiber optic network is the physical layer across which all of the SKA1 telescope networks operate. The design and successful implementation of the fiber network is paramount to the successful operation of the SKA1 telescopes, providing both flexibility to accommodate changing requirements as network technologies develop and additional requirements identified. The challenge is to achieve these results in the most technically acceptable, economic manner to achieve the maximum utilization and life expectancy of the fiber network installation.

To this end the fiber network will use standards-based, single mode fiber types in multi-core cables as commonly used by the major telecommunication equipment manufacturers. The cable must be installed under controlled conditions and expert supervision, utilizing installation technologies that complement the natural terrain conditions, to ensure that lifetime expectancies of the fiber network are met with minimal maintenance and/or repair requirements during the operational period of the telescope. The fiber network will be optimized in the future in conjunction with the power and road network development to share trenches wherever possible, and to align with the infrastructure construction schedules to benefit from these activities wherever possible and to minimize duplication of effort and disruption to both parties in order to contain costs.

5. CONCLUSION

The SKA telescope will be the largest scientific project on the Earth. The range of science that the SKA will explore is vast and it offers to make truly transformational discoveries in the fields of understanding of the earliest stages of the Universe, gravitational waves, General Relativity and clues as to the
With a design operational lifespan of 50 years, the SKA will be the world’s leading radio observatory for much of the 21st century. Its construction will be beyond the capabilities of universities and research institutes and will require the industrialization of radio astronomy. Resolving the Big Data challenges posed by the SKA will generate and develop novel solutions that will have impact beyond radio astronomy. One of these challenges is provision of the networks to carry the huge volumes of data that will be generated. These networks are the backbone of the telescope, without which the telescope is inoperable and unable to produce the scientific results for which it has been developed.

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REFERENCES