COMPARISONS BETWEEN TRANSATLANTIC TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER AT KU-BAND AND X-BAND

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ABSTRACT

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is an ultra-high precision method of time transfer used principally by primary timing laboratories for intercomparison of atomic timescales. Several routine Ku-band TWSTFT links are now used by the Burea International des Poids et Mesures (BIPM) as operational links in the construction of International Atomic Time (TAI).

In March 2001 the United States Naval Observatory (USNO) shipped a portable X-band TWSTFT satellite earth station to the National Physical Laboratory (NPL) in the UK. This enabled a TWSTFT link utilising an X-band satellite to be set-up between the NPL and the USNO. This offered a unique opportunity for a study to be carried out comparing measurements at Ku- and X-band over the same transatlantic baseline link. Measurements taken by the two systems at approximately the same times over a period of six months are compared. A continuous set of Ku-band measurements spanning a period of 4-days in September 2001 were also carried out in order to compare measurements centred at the same times. Analysis of the data collected shows that both Ku- and X-band measurements exhibit diurnal variations which can be attributed to hardware temperature coefficients. We also compare plots of the Allan variance obtained for each system and comment on the levels of noise observed.

1. INTRODUCTION

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is an ultra-high precision method of time transfer which utilises telecommunications satellites [1]. It has been shown that sub-nanosecond precision time transfer is possible using this technique. TWSTFT differs from other methods of satellite time and frequency transfer in that signals are both transmitted to and received from the satellite. Many of the systematic errors present in receive-only time-transfer methods, such as common-view GPS, are either eliminated or substantially reduced. However, TWSTFT requires significantly more hardware as the method requires both transmission and reception of signals. Furthermore arrangements are required with satellite operators in order to carry out the measurements. The basic set-up of a TWSTFT link is shown in Figure 1.

TWSTFT was introduced into operational use by the Burea International des Poids et Mesures (BIPM) for the construction of International Atomic Time (TAI) for the first time in 1999. In 2000 several new links were introduced, including the transatlantic link between the National Physical Laboratory (NPL) in the UK and the United States Naval Observatory (USNO). All of these links form part of a larger network operating at Ku-band frequencies.

In March 2001 the USNO shipped a calibrated portable X-band TWSTFT satellite earth station to the NPL. It was then possible to establish a calibrated X-band TWSTFT link between the NPL and the USNO. This paper presents comparisons of the TWSTFT data sets collected using the operational Ku-band and temporary X-band links.

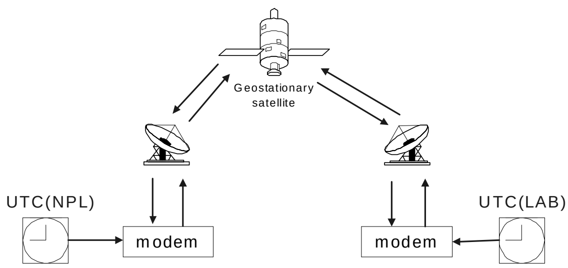

Figure 1: The basic set-up of a TWSTFT link.

2. KU-BAND DATA

The operational NPL-USNO Ku-band link was calibrated using the portable X-band station, with the calibration centred at MJD 52054. These Ku-band data have been obtained as part of the regular international time transfers which take place three times per week (on Monday, Wednesday and Friday) at times between 1400 and 1500 UTC. The sequence of data acquisition and data processing for an operational Ku-band TWSTFT link is shown in Figure 2. Presently there are four European and two US laboratories participating on a regular basis. The NPL-USNO measurements occur at times between 1443 and 1445 UTC. The signals are exchanged in each direction between Europe and the USA using two transponders on-board the INTELSAT

706 satellite at 307° East. A series of 1 pulse per second (1PPS) measurements are made over two minutes for each link. The modems used at each laboratory are Satre modems (S/N 038 and 058 for the NPL and the USNO respectively) [2] manufactured by TimeTech. After the data have been collected at each laboratory they are converted to a standard 1PPS format file [3]. These data are then reduced to an ITU format data file reporting one line per link obtained by normally carrying out a least-squares quadratic fit to the corresponding two minutes of measurements. However, in this case a linear least-squares fit has been carried out instead for consistency with the case of the X-band data processing (see Section 3). The least-squares fit is then used to obtain a single representative measurement at the midpoint of that period. The file format also allows reporting of earth station and calibration parameters as well as environmental parameters. The 1PPS and reduced ITU files are posted on FTP sites in order to exchange data between participating laboratories and also to provide access for the BIPM. This is normally achieved well within 24 hours and in the best cases the first time transfers are available within a few minutes after the completion of measurements. In principle it is possible to exchange data and obtain a time transfer in real-time.

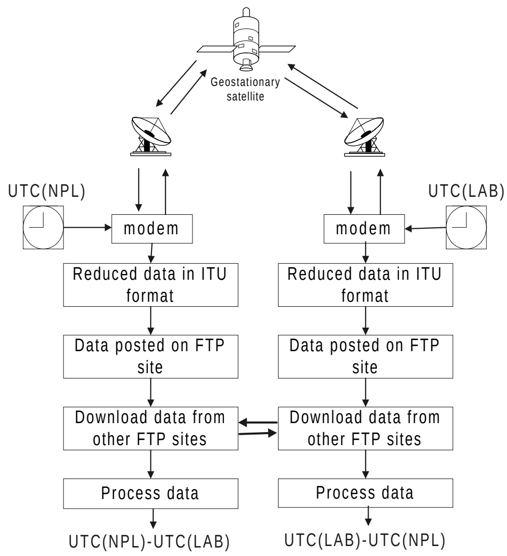

Figure 2: Data acquisition and processing used in the Ku-band TWSTFT.

3. X-BAND DATA

The X-band TWSTFT [3] data have been collected once per hour at times between 20 minutes and 40 minutes past each hour. The system uses Allen Osborne Associate TWSTFT modems (model AOA TWT-100) at each end of the link and is fully automatic. The sequence of data acquisition and data processing in this case is shown in Figure 3. Data have been collected from late March 2001 to late January 2002. Sometimes there are significant data gaps over durations ranging from between 1 hour to a few days caused by adverse weather conditions, misalignment of the dish or hardware difficulties. A series of 1PPS measurements are made over five minutes. The 1PPS measurements obtained at the NPL are transmitted to the USNO over the satellite link simultaneously during the measurements. The NPL and the USNO data-sets are then processed automatically on a regular basis at the USNO. The subsequent data processing involves a linear least-squares fit to the data. This is carried out to each complete 300 s data-set and provides a single representative measurement at the midpoint of that period. This measurement for each of the NPL and the USNO is then used to obtain a single TWSTFT time-transfer. The system allows time-transfer in real-time. The NPL was able to download the final time-transfer results from USNO on a daily basis via FTP.

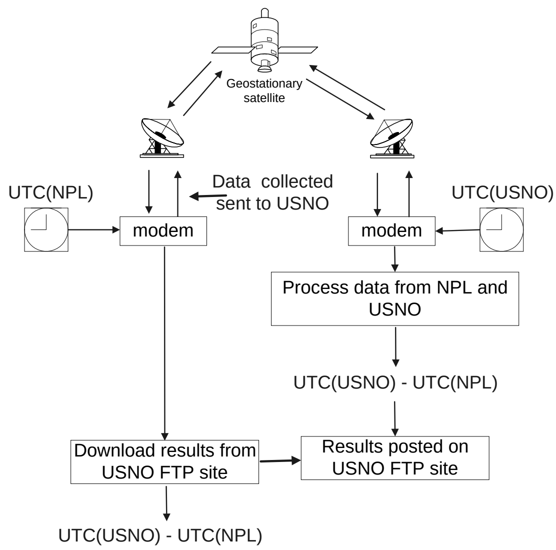

Figure 3: Data acquisition and processing used in the X-band TWSTFT.

4. COMPARISON BETWEEN X-BAND AND ROUTINE KU-BAND

X-band and routine Ku-band measurements collected over a 6 month period between 16th July 2001 (MJD 52106) and 16th January 2002 (MJD 52290) are shown in Figure 4. A plot showing X-band data (where available) collected at approximately the same times (to within 1 hour) as the Ku-band data is shown in Figure 5. The differences between the two data-sets are also plotted. Over the period of the comparison the differences show an rms scatter of 1 ns and a long-term drift of 2 ns. Analysis of temperature data suggests that the steady change in difference value is caused mainly by outdoor seasonal temperature changes at the NPL.

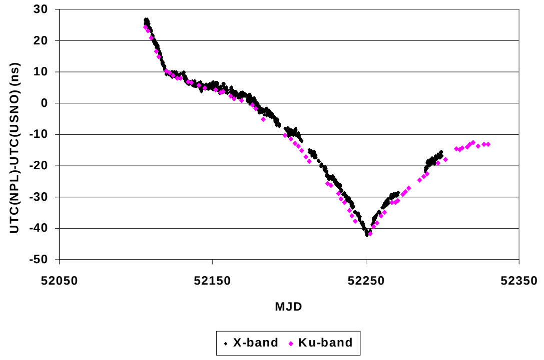

Figure 4: X-band and routine Ku-band TWSTFT measurements carried out between the NPL and theUSNO.

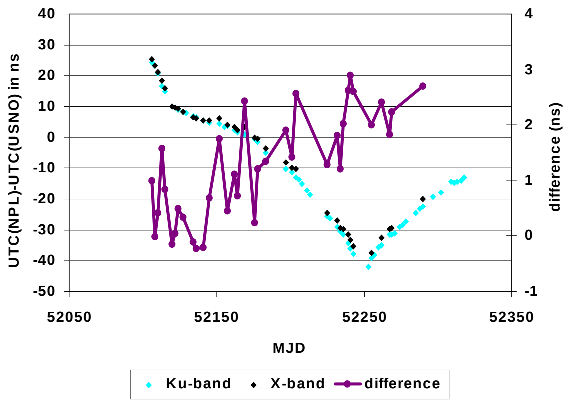

Figure 5: Plot showing X-band and routine Ku-band measurements (using left-hand y-axis scale) and differences between them (using right-hand y-axis scale).

5. COMPARISON BETWEEN X-BAND AND CONTINUOUS KU-BAND

Between 26th and 30th September 2001, the USNO and the NPL carried out continuous Ku-band measurements using the INTELSAT 706 satellite. The 1PPS data collected at NPL were processed (as in the case of the routine data) in blocks of 120 s, to achieve a single representative point which is processed with the corresponding point for data collected at USNO. This provided one measurement every two minutes. The resulting measurements are shown in Figure 6. The Ku- and X-band measurements (see Section 2 and 3 above) centred at the same times, together with their differences and temperature data are shown in Figure 7. It is clear that there are diurnal variations present in all of these measurements.

The variations in the Ku- and X-band differences correlate with NPL outdoor temperature. As the Ku-band variations are significantly smaller, this suggests that the X-band station used at NPL had a temperature coefficient of -0.15 ns/^{o} C. In the case of Ku-band, it is possible to set an upper limit of 0.07 ns/^{o} C on the temperature coefficient of each of the NPL and USNO

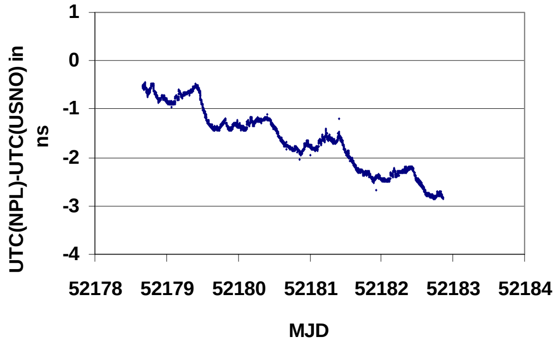

Figure 6: Plot showing processed continuous Ku-band measurements between USNO and NPL carried out over 4 days.

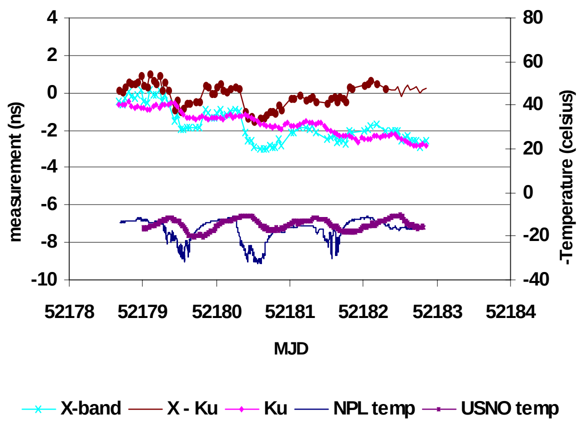

Figure 7: Plot showing data for Ku-band, X-band, Ku/X-band difference and NPL/USNO outdoor temperature.

TWSTFT systems.

6. INVESTIGATING NOISE IN KU- AND X-BAND SYSTEMS

A plot of the Allan variance, σ_y, for the Ku- and X-band data for averaging times, τ, between 1 hour and 2 days is shown in Figure 8. The X-band data show much higher levels of noise, typically by a factor of 5, for all of these averaging times. There is a minima in the noise at approximately $\tau = 1$ day, which can be explained as the reduced effect of hardware temperature variations by sampling at the same time of day.

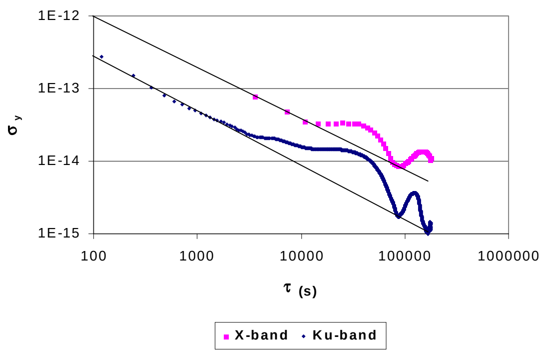

Figure 8: Allan variance plots for X-band and Ku-band data collected in the 4-day experiment.

In the case of X-band the gradient of the plot is –0.75 for values of τ < 4 hours. This is significantly different from that for greater averaging times. The line passing through these points (see Figure 8) also passes through the points for τ = 1 day, indicating that it may represent an underlying noise process that is different from the effect of hardware temperature variations. Although the origin of this is not clear, we expect a component here from the timescales at each laboratory. The gradient of -0.75 suggests that it is either a mixture of White Phase Modulation, Flicker Phase Modulation and White Frequency Modulation or a fractional noise type. The higher levels of noise above this line can be explained as being the effect of hardware temperature variations.

For the case of Ku-band there are data available for τ < 1 hour and these also show a gradient of –0.75. As in the case for X-band, this line also passes through the points for τ = 1 day (see Figure 8), indicating again that this is a different noise process from the effect of hardware temperature variations.

In both systems it is possible to divide the observed noise into two main types. Firstly, it is evident that there is a component caused by the effect of hardware temperature variations, which dominates for values of τ > hours, except for values of $\tau = n$ days, where *n* is an integer. Secondly, it is evident that there is a different underlying noise component also present which is greater by a factor of 5 in the X-band than in the case of Ku-band. Although the origin of this component is not clear, it may be due to the effect of electronic thermal noise or noise from elsewhere in the link budget. Further investigation is required to understand the cause of this.

7. CONCLUSIONS

1. Comparison of Ku- and X-band TWSTFT measurements between the NPL and the USNO over a period of 6 months show differences with an rms scatter of 1 ns and a long-term drift of 2 ns.

2. Both the Ku- and X-band measurements show diurnal variations, although these are larger in the case of X-band and found to be correlated with NPL outdoor temperature. It is evident that the X-band station used at NPL had a temperature coefficient of -0.15 ns/^{o} C. In the case of the Ku-band, it is possible to set an upper limit of 0.07 ns/^{o} C on any temperature coefficient in each of the NPL and USNO TWSTFT systems.

3. The Allan variance, σ_y, of the X-band data for averaging times, τ, between 1 hour and 2 days is found to be greater than in the case of the Ku-band by a factor of 5.

4. In the Ku- and X-band systems it is possible to divide the observed noise into two main types. Firstly, it is evident that there is a component caused by the effect of hardware temperature variations, which dominates for values of τ > hours, except for values of $\tau = n$ days, where *n* is an integer. Secondly, it is evident that there is a different underlying noise component also present which is greater by a factor of 5 in the X-band than in the case of Ku-band. Although the origin of this component is not clear, it may be due to the effect of electronic thermal noise or noise from elsewhere in the link budget.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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