

SOURCES OF ERROR IN TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFERS

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ABSTRACT

A study of the systematic errors occurring in Two-Way Satellite Time and Frequency Transfer (TWSTFT) experiments is reported. A small Ku-band TWSTFT earth station has been constructed at the National Physical Laboratory (NPL). Measurements have been performed to determine the delay stability of the earth station instrumentation. These delay stabilities are directly related to the time and frequency transfer capabilities of the TWSTFT system. TWSTFT instrumentation may also be used to determine the position and movement of a near geostationary satellite. The determination of the satellite's position enables TWSTFT instrumentation to be used to perform receive-only time transfers. Error budgets are provided for time transfers using both two-way and receive-only configurations.

1) INTRODUCTION

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is being developed as a method of ultra high precision time and frequency transfer. The ultimate aim is to achieve sub-nanosecond accuracy time transfers. Recent international experiments using Intelsat satellites at 30°E, have demonstrated the usefulness of the TWSTFT method for performing regular time transfers between primary timing laboratories [1]. TWSTFT may be used as an alternative to the common view of signals from Global Positioning System (GPS) satellites for the routine intercomparison of clocks contributing to international atomic time (TAI). TWSTFT relies for its operation on the use of commercially available geostationary satellites, where the signals are provided for civilian time transfer rather than military navigation. A future application of TWSTFT may be in the intercomparison of the next generation of ultra-stable frequency standards where uncertainties of 1×10^{-15} are required with averaging times as short as one day.

2) TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER METHOD

The TWSTFT method has been described previously [2] (Figure 1). Timing signals are simultaneously transmitted from earth stations A and B to the other station via a geostationary satellite. These signals are both referenced to the clock at the transmitting station, and compared against the clock at the receiving station. Small Ku-band commercial transit/receive V-SAT type antennas are used for the TWSTFT work, these are located as close as possible to the timing laboratories. The transmissions consist of Pseudo Noise (PN) coded signals spread over a bandwidth of 3.5 MHz. The use of orthogonal codes permits Code Division Multiple Access (CDMA) operation. TWSTFT has significant advantages over receive only time transfer methods, due to the increased symmetry in the method. The free space path delays cancel, eliminating the requirement to accurately determine the positions of both the earth stations and satellite.

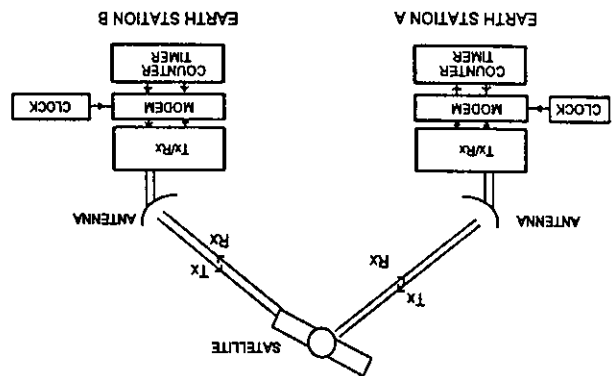
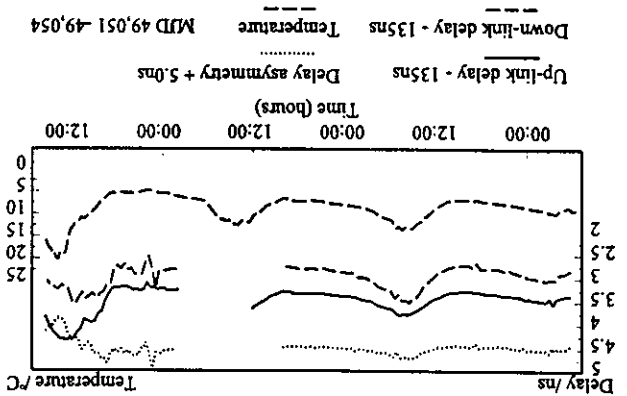


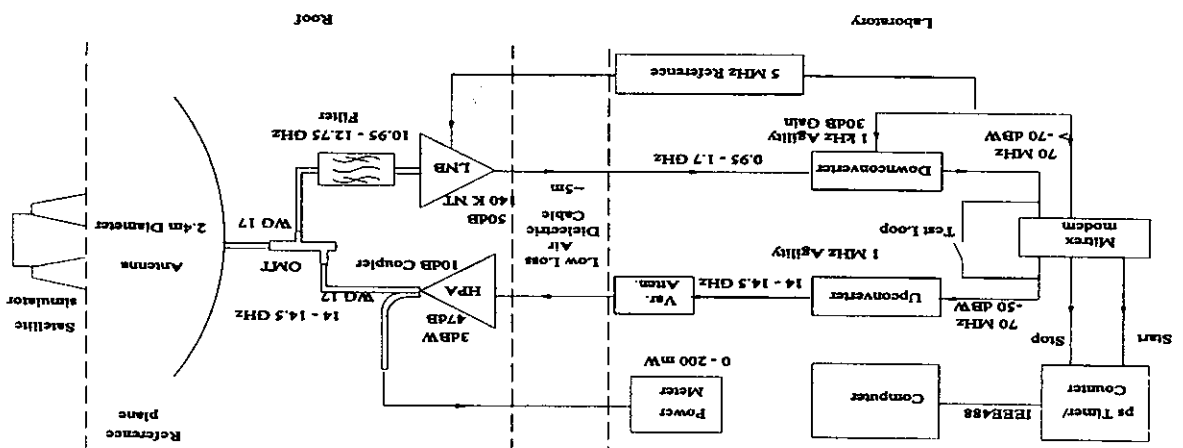
Figure 1
Two-Way Satellite Time and Frequency Transfer

A limitation to the accuracy obtainable from TWSTFT systems lies in the delay stability and measurement noise originating in the earth station instrumentation. Work has been performed at NPL to determine the delay stability of the instrumentation. Using a satellite simulator the earth station uplink (τ_x) and downlink (τ_d) delay have been determined, along with the delay asymmetry ($\tau_x - \tau_d$) [3]. Plots of the delay stability are shown in Figure 3. The maximum delay variation amounts to one nanosecond.



A schematic diagram of the NPL TWSTFT earth station is shown in Figure 2. The majority of the instrumentation consists of commercially available satellite communications equipment. A new TWSTFT installation may be constructed for between £40,000 and £50,000. Permission to use the satellite must be obtained from the operators. This may entail specific tests on the earth station, these requirements are now being relaxed for small low power earth stations. Clearance must also be obtained from the relevant regulatory authority. In the UK this is the DTI Radiocommunications Agency.

Figure 2 NPL TWSTFT Earth Station



Estimates of the errors for both TWSTFT and receive-only common-view operation are given in Table 1. Estimates are made for the uncertainty in both the time transfer and also the delay instability, the origin of frequency transfer uncertainties. An optimum system assumes a maximum possible elevation angle for a geostationary satellite and the application of both

7) ERROR BUDGET

Closing errors have been found to be due to the application of an incomplete theory when determining the time transfers. The delays in the receive chain of the earth station instrumentation, have a slight dependence on the choice of transmitting station. With improved analytical treatment closing errors may be eliminated [5].

6.7) CLOSING ERRORS

relevant propagation delays may be determined to within a few nanoseconds. The positions of the both the earth station and satellite have to be accurately determined for receive only but not for TWSTFT. Earth station locations may be determined to 30 cm. The

6.6) EARTH STATIONS AND SATELLITE POSITIONS

The TWSTFT and receive-only delay asymmetries are given by $0.5[(\tau_{ATx} - \tau_{ARx}) - (\tau_{BTx} - \tau_{BRx})]$ and $(\tau_{ARx} - \tau_{BRx})$ respectively. These are usually calibrated using a portable earth station as a transfer standard. In the case of receive only instrumentation the relative positions of the reference plane of both antennas must be determined. The delay instabilities in existing instrumentation prevent this asymmetry being calibrated to better than ± 1 nanosecond.

6.5) EARTH STATION DELAYS

Ionosphere delays are proportional to $1/f^2$ where f is the propagation frequency. For TWSTFT the uplink and downlink propagation delays partly cancel. For time transfers over short baselines, the presence of a common ionosphere will reduce the ionospheric delay errors. The use of a high elevation angle satellite, and application of an ionospheric correction, will reduce this error.

6.4) IONOSPHERE DELAYS

Troposphere delay changes depend on the length of the signal path through the troposphere and hence the elevation angle of the satellite. The delays are frequency independent, and cancel in the case of TWSTFT. For receive-only operation troposphere delays may be minimised by modelling the troposphere using atmospheric data collected at the earth station and also by choosing a geostationary satellite with a relatively high elevation angle.

6.3) TROPOSPHERE DELAYS

The Sagnac effect occurs due to the relativistic effects of the earth's rotation. A correction is determined from the locations of both the earth stations and the satellite. Errors in determining this correction are not significant.

6.2) SAGNAC CORRECTION

Sources of errors in both TWSTFT and in the receive-only operation of TWSTFT instrumentation are examined. It is assumed that the receive-only system is used for time dissemination over relatively short links when compared to the spacing of the calibration stations. This may correspond to a UK time dissemination service operating within a Europe-wide TWSTFT system.

6.1) INTRODUCTION

6) SOURCES OF ERROR

A simpler method of calculating time transfers using a receive-only system is by forming linear combinations of ranging data, common-view and one-way links. Similar techniques have been used to calculate time transfers using direct broadcasting satellites [4].

troposphere and where appropriate ionosphere delay corrections, along with the best delay stability results obtained to-date.

TABLE 1

Source of Error	TWSTFT		Receive-only common-view	
	Existing System	Optimum System	System based on existing hardware	Optimum System
Troposphere Delay	Error (ps)	Error (ps)	Error (ps)	Error (ps)
	±1500	±2000	±1500	±1000
Ionosphere Delay	Station Delay	Station Delay	Station Delay	Station Delay
	±200	±200	±200	±200
Sagnac Delay	Station Delays	Station Delays	Station Delays	Station Delays
	±1500	±1000	±500	±200
Station Position	Station Position	Station Position	Station Position	Station Position
	±1000	±2000	±1000	±1000
Satellite Position	Satellite Position	Satellite Position	Satellite Position	Satellite Position
	±500	±1000	±500	±500
Closing Errors	Closing Errors	Closing Errors	Closing Errors	Closing Errors
	±1500	±1000	±500	±600
Total	±1500	±1000	±500	±600

8) CONCLUSIONS

An overview has been given of the development of a TWSTFT earth station at NPL along with the study of earth station delay asymmetries. Sources of error in using TWSTFT instrumentation in both two-way and receive-only configurations have been examined.

ACKNOWLEDGEMENTS

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