TWO-WAY SATELLITE TIME TRANSFER TO A MOVING PLATFORM

Edward Powers
U.S. Naval Observatory
Washington, DC 20392, USA
E-mail: *powers.edward@usno.navy.mil*

James Romberg, Roger Griffin
Boeing
E-mail: *james.m.romberg@boeing.com*

Angela McKinley
U.S. Naval Observatory

David Diener, Harold A. Klotz, Jr., and David Wolters
Boeing

Abstract

Precision time transfer is a key requirement for many applications. Three methods of time transfer that have typically been used are Stand-alone GPS, GPS Common View, and Two–Way Satellite Time Transfer (TWSTT). Only the Stand-alone GPS approach has been regularly been used on a moving platform and this is the least accurate of the three time transfer methods. Analyses show that the standalone method is inadequate to meet the time requirement specified for some applications.

Boeing and the US Naval Observatory (USNO) have investigated and tested a Two-Way Satellite Time Transfer (TWSTT) method that has the potential of providing adequate time transfer accuracy to aircraft in flight. This approach employs a TWSTT system that communicates via satellite with a time reference center (such as the USNO) and the aircraft to provide accurate absolute time.

Equipment used in the TWSTT test consisted of a time transfer modem and a GPS time transfer receiver furnished by the USNO, and a Boeing Connexion Ku-band aircraft transceiver and phased array antennas. The Connexion transceivers provided the satellite communication link between the moving platform and a Geostar-1 satellite that was used to relay information between USNO headquarters and the Boeing Seattle test site. Special test software, including a Kalman filter that processed raw pseudorange and pseudorange rate outputs from the GPS time transfer receiver, was also developed for the test. Data collected during the tests are presented in this paper along with an analysis of the results that have been collected to date.

The two-way link that offers the cancellation of all errors in the time transfer channel could be provided by either geostationary or lower orbit altitude satellites.

1 TIME TRANSFER METHODS OVERVIEW

The three common time transfer methods used are: (1) GPS stand-alone, (2) GPS common view, and (3) Two-Way Satellite Time Transfer (TWSTT). Time transfer refers to providing time from a source to a remote user. Time transfer involving a satellite as a relay between the time source and time user has a large earth surface coverage. The range of this coverage, between the time source and the time user as a function of satellite altitude and user horizon mask angle, is diagrammed in Figure 1.

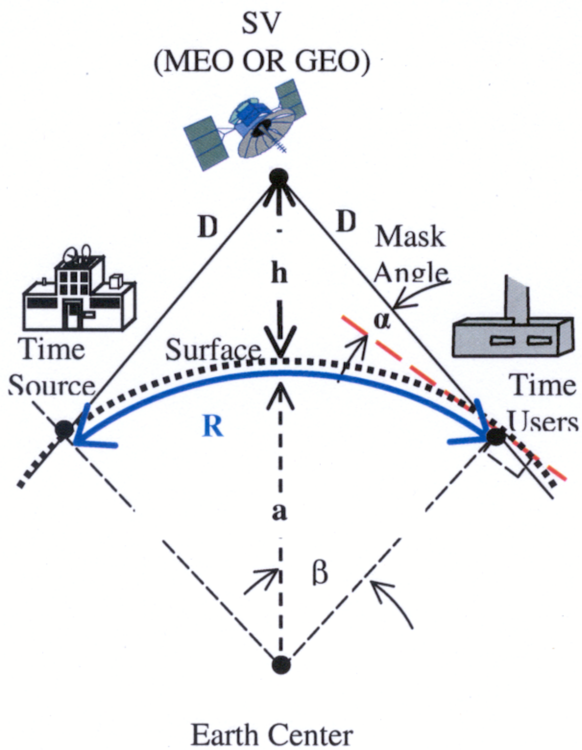

Figure 1. Time Transfer Coverage Range

$$D = \sqrt{a^2 \sin^2 \alpha + 2ah + h^2} \; - \; a \sin \alpha \tag{1}$$

$$R = 2a\beta = 2\mathrm{a} \sin^{-1}\left(\frac{D\cos\alpha}{\mathrm{a}+\mathrm{h}}\right) \tag{2}$$

where:

R	=	time transfer coverage range,
a	=	earth radius,
β	=	earth center angle between radii,
D	=	maximum distance from satellite to both the user and the time source when including mask angle,
α	=	mask angle (assume 5°), and
h	=	satellite altitude.

The range capability and general accuracy capability of the three common time transfer methods are shown in Figure 2.

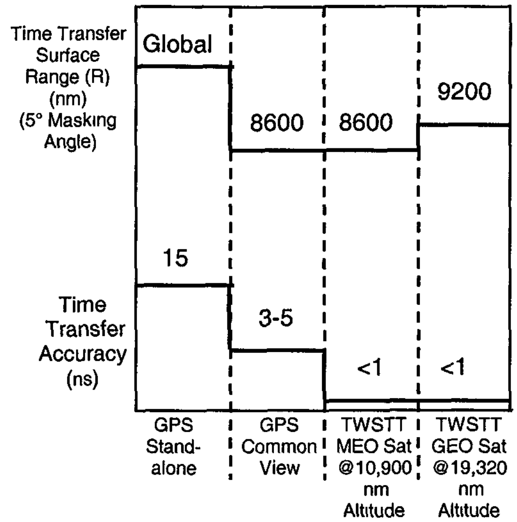

Figure 2. Time Transfer Surface Range Versus Time Transfer Accuracy

The simplest time transfer is the one-way GPS satellite vehicle (SV) stand-alone time transfer illustrated in Figure 3.

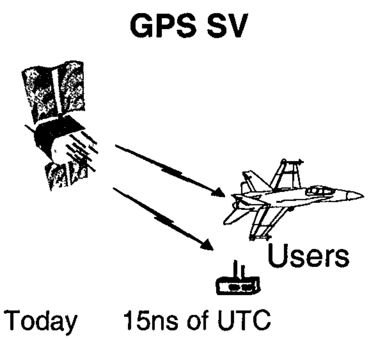

Figure 3. Stand-Alone

The stand-alone method is the normal method used for time transfer and is the time output by a GPS receiver operating in a stand-alone mode. Today, the specification is for 100 nanoseconds (ns) GPS time transfer relative to UTC (USNO). However, the normally accuracy is about 15 ns due to better than specified performance by the GPS system. This system has worldwide coverage. With GPS III these accuracies are expected to improve.

The GPS common-view time transfer method is used to transfer very accurate time over long distance inexpensively. Figure 4 illustrates the GPS common-view method.

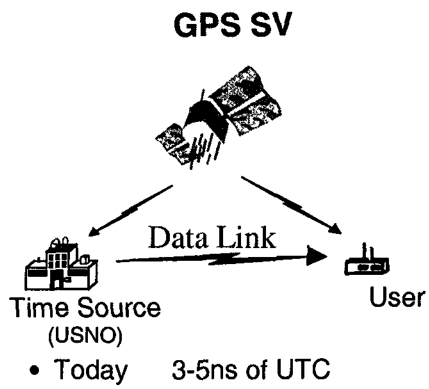

Figure 4. Common View

Common view means that the same GPS satellite(s) needs to be seen by both the time source and the user. GPS time from the satellite is used as a common time reference at the time source and at the user. Because it is common, the time errors of the satellite clock cancel out. Today, GPS common-view time transfer accuracy of 3-5 ns is achieved, which is better than the time accuracy obtained using the stand-alone method.

The data link shown for the common-view approach does not require high data rates or low latency for precise time registration. This means that near-real-time low-cost data transfer methods are acceptable, e.g. use of the Internet. The user calculates "(USNO master clock time minus GPS SV time) minus (User local time minus GPS SV time)." The data link transfers the GPS satellite vehicle(s) being tracked at the USNO and the "USNO Master Clock time minus GPS SV time." Constraints are that both the time source and the user must be viewing the same GPS satellite(s) at the same time. Advanced common-view concepts will provide for GPS all-in-view and carrier-phase operation, although a single GPS satellite and code phase have typically been used to date.

The third time transfer method available is the two-way satellite time transfer as illustrated in Figure 5. Two-way time transfer refers to the process for comparing time between a reference clock and a remote user clock and then providing the time difference information to the user. The user can then adjust his time to the reference clock. This is the most accurate method of time transfer and has not used the GPS satellite system to date. Rather, geostationary earth orbit synchronous satellites (GEOS) have been used for this method. GEOS offer longer transfer ranges than the GPS satellites, but are very expensive to users because a satellite transponder channel must be leased, whereas GPS is free.

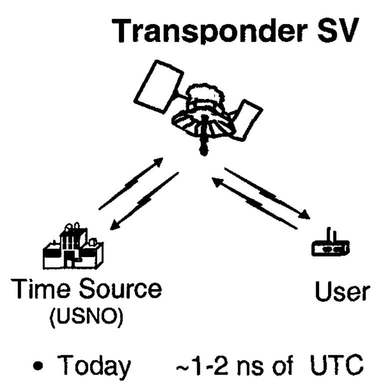

Figure 5. TWSTT

The time transfer range in equation (2) above applies. The same transponder channel and signal used for time transfer also transfers the data required for the time transfer calculations. Pseudo-random noise codes with phase shift key (PSK) modulation are used for the time transfer signal. This is the same type of signal used by the GPS satellites; therefore, the same type of correlators or the same correlators used for GPS could be used for correlation of the received two-way time transfer signal. Two-way satellite time transfer removes the satellite time errors and the RF channel time errors.

Figure 6 shows a concept in which one satellite, i.e. GPS III, could provide all of the time transfer methods, and the user then determines what time transfer method to use, depending upon what accuracy he needs and how complex/expensive the equipment is that he is willing to install.

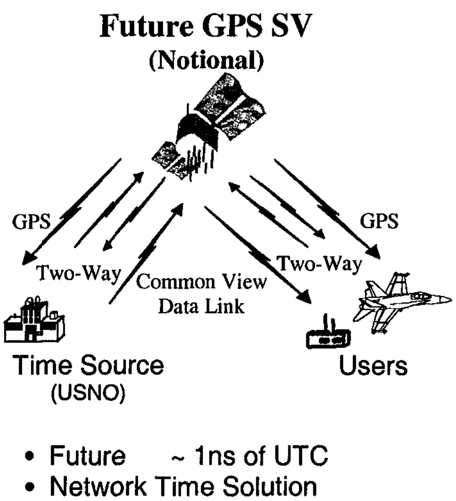

Figure 6. Multi-Time Transfer Methods

This is a full service time capability. Future GPS upgrades/constellations might provide as accurate or nearly as accurate time transfer as the common-view method. Therefore, the common-view method may not be required. This is still to be determined. However, both stand-alone and two-way time transfer are believed to be required. GPS could provide a global capability, free service, and a higher accuracy than provided with today's systems. Time transfer bandwidths of about 20 MHz are sufficient; however, less bandwidth is possible, but will provide less time transfer accuracy.

2 TWO-WAY SATELLITE TIME TRANSFER TEST

TEST PURPOSE

The TWSTT test purpose was to demonstrate that precise time measurement difference between the USNO clock and a moving platform clock was feasible using a geostationary transponder satellite link. The challenges to this test were having continuous satellite carrier track, time measurements accuracy of ±1 ns, and determining the time correction factors resulting from the satellite to moving platform communication path changes. Other factors such as ionosphere, troposphere, Doppler shift, and moving platform relativistic effects were considered negligible for this test.

TEST FACILITIES

The U.S. Naval Observatory Earth Station in their Washington, D.C. facility was the Master Clock source. Figure 7 is a picture of the USNO facility.

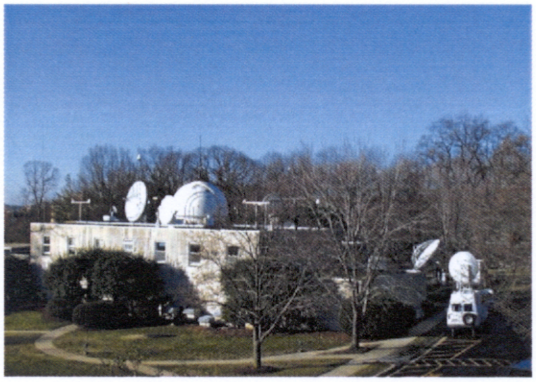

Figure 7. USNO Facility

Also, this facility provided the ground transceiver and antenna systems for satellite communications, TWSTT modem, and people to conduct the test.

The Boeing Phantom Works located at Kent, Washington provided the moving platform, platform transceiver and antenna system, test track, and support for conducting the test. The High Mobility Multipurpose Wheeled Vehicle (HMMWV) was equipped with a satellite communications system, GPS receiver, cesium-beam clock, and a Satellite Time and Ranging modem. Figure 8 is a picture of the HMMWV with the satellite transmit and receive phased-array antennas (both white in color) mounted on equipment module rooftop.

Figure 8. TWSTT Moving Platform

The HMMWV was not a licensed vehicle; this limited our movement to Boeing property. The test runs were conducted on a road approximately 1400 feet long and running north and south. Refer to Figure 11 for the on-board GPS recorded test track. The north end of the track is located at 122.25° west longitude, 47.41° north latitude and negative 47.4m altitude (WGS 84 datum).

SITE TEST EQUIPMENT

The USNO equipment at Washington, D.C. consisted of the Master Clock system; TimeTech Satellite Time and Ranging Equipment (SATRE) modem, Model Number S2CP-V4.30; and satellite communication Base Earth Stations, BEST1 and BEST2.

The HMMWV moving platform (MP) equipment consisted of Boeing's Satellite Communications System (Connexion), and the USNO-provided SATRE time transfer modem, TWSTFT-067; Allen Osborne Associates (AOA) GPS time transfer receiver, Model TTR12; GPS antenna with choke-ring; and a Hewlett-Packard 5071A high-performance cesium-beam time standard. Note: For the remainder of the paper, the moving platform (MP) will be the used to identify the HMMWV.

The transponder satellite used was the GE-1 located at 103° west longitude operating as a transponder in the Ku frequency band.

TEST EQUIPMENT FUNCTIONAL DESCRIPTION

The SATRE time modem is the interface between the USNO Master Clock for the reference time and the ground-based satellite communications hardware. The SATRE time modem has a 70 MHZ intermediate frequency (IF) input/output for a full-duplex full time continuous two-way time data flow. The time modem modulates the IF with direct sequencing pseudo-random noise spread spectrum. That is, the USNO time transmit data signal, T_{TxUSNO}, modulates the carrier with a known pseudo-noise (PN) spreading code at a rate of 2.5 Mchip/s using bipolar phase-shift keying (BPSK) to phase-modulate the signal onto the 70 MHz IF. The moving platform (MP) SATRE time modem demodulates this signal by knowing the PN spreading code. See Figure 9.

The SATRE time modem used on the moving platform was a modified version of those operated at ground installation sites. The modifications included data smoothing, data-recording software, and carrier-phase tracking loop control to operate on a moving platform. The SATRE time modem operation, without change, is for a stationary ground user installation with a 2-minute time constant for data smoothing/tracking.

The USNO satellite communications hardware consists of uplink and downlink equipment. The USNO uplink equipment consists of a RF up-converter (70 MHz to 14 GHz range), solid-state power amplifier, and a Vertex 4.5 meter KPK Company Cassegrainian antenna. The USNO downlink from the satellite uses the same Vertex 4.5 meter antenna, a low noise amplifier, and a RF down-converter (11GHz range to 70 MHz).

The MP Allen Osborne Associates TTR-12 Time Transfer Receiver is a Y-codeless GPS receiver that outputs uncorrected pseudorange and delta-pseudorange data along with the broadcast ephemerides. See Figure 10. The same cesium clock provides the time reference to both the TWSTT time modem and the GPS time receiver. Boeing developed the software to postprocess the GPS receiver outputs in order to generate a moving-platform position, velocity, and time (PVT) solution. Three PVT estimation algorithms were developed: (1) an 11-state Kalman filter; (2) a 26-state Kalman filter; and (3) a point solution.

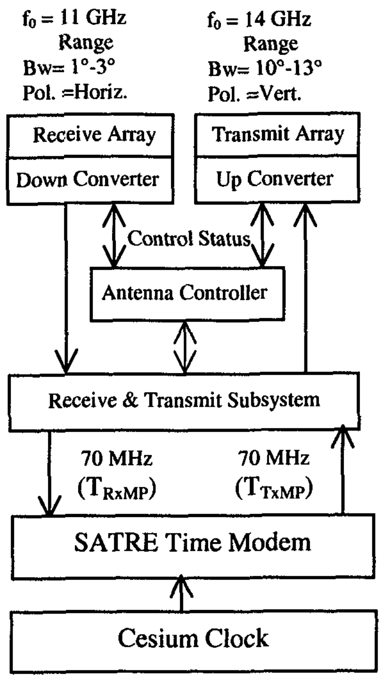

Figure 9. Moving Platform TWSTT System

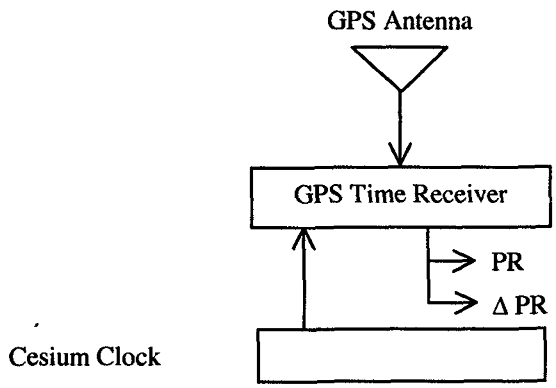

Figure 10. Moving Platform GPS System

The Boeing Satellite Communication System, Connexion, has two phased array antennas located on top of the moving platform equipment module. The basic block diagram is shown in Figure 9.

TIME PARAMETERS DEFINITION

The following definitions are used:

T_{OS} = moving Platform (MP) clock offset time (offset from receive to transmit) (unknown)

T_P = path transmission time (one-way USNO to user or user to USNO) (unknown)

T_{TxUSNO} = USNO transmit time (measured)

T_{RxMP} = MP receive time of USNO transmission (unknown)

T_{RxMP}' = MP receive time of USNO transmission at MP's clock (measured)

T_{TxMP} = MP return transmit time (unknown)

T_{TxMP}' = MP return transmit time using MP's clock (measured)

T_{RxUSNO} = USNO receive time of MP return transmission (measured)

TWSTT TEST FLOW

The TWSTT operation sends a 1 pps timing signal, T_{TxUSNO}, referenced to the USNO Master Clock (USNOMC) from the USNO via transponder satellite to the moving platform. The T_{TxUSNO} timing signal along with the moving platform local reference time, T_{TxMP}, is sent back to USNO at the 1 pps rate. The time delay for the original USNO timing signal to go the round trip represents the two-way network equipment and path delay. Dividing the total time delay by two provides one-way signal path delay. Therefore, USNO, after compensating for network total time delay and knowing the one-way time delay, T_{TxUSNO} minus T_{TxMP}, determined the moving platform clock offset from the USNO Master Clock. In an operational system, these calculations could be done at the user platform to provide real time operations. TWSTT data were recorded at USNO for post time-offset analysis. The post analysis also uses the recorded AOA GPS receiver data to correct the times offset measurement caused by the moving platform. The moving platform GPS position and velocity parameters are required to correct for the change in TWSTT communication paths, which affects the time transfer accuracy. Refer to Section 4 for the detailed analysis and time compensation equations.

TEST DATA GATHERING

Test data were recorded both at the time source and time user locations. The AOA GPS receiver recorded its data in a flash memory card contained in the unit itself. The SATRE time modem recorded the MP reference cesium clock time and the time received from USNO.

Test data were gathered on a north-south test track shown in Figure 11. Data were gathered for MP velocities of 5, 15, and 30 mph.

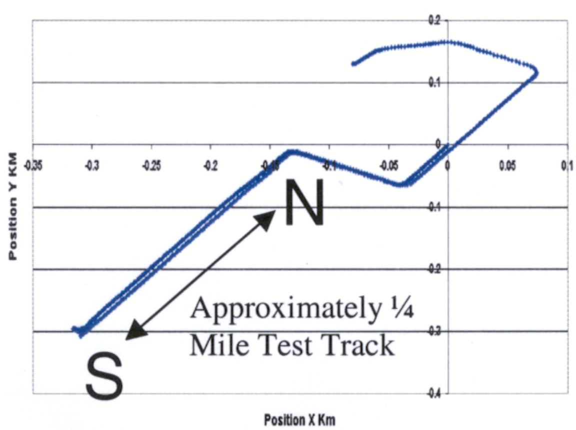

Figure 11. Moving Platform Test Track

System Calibration

The system used for this test was not calibrated for time delays. Rather, the cesium standard, HP 5071, was used as the stable user reference time standard and variations about this standard were recorded and treated as the time variations. This was done for cost and schedule purposes. The operational system would, however, need to be calibrated for time variations. The measured precision of the recorded two-way time transfer data was investigated, and from this, an accuracy was deduced based on past system calibration accuracy achieved.

3 DATA ANALYSIS

Data Analysis Flow

Figure 12 shows the data analysis flow. Data were recorded at the USNO time source and at the Boeing time user locations and processed later. The GPS pseudorange and delta-pseudorange data were also sent to JPL for postprocessing using their GIPSY program.

TWSTT Data

The raw TWSTT data shown in Figure 13 were corrected with the correction factors generated. The correction factors compensate for the user moving platform velocity and for the user TWSTT system transmit to receive antenna displacements. The data after correction is shown in Figure 14.

GPS Time Transfer Data

GPS stand-alone time transfer was also measured in addition to the two-way time transfer. Figure 15 shows the range of real time GPS time measurements for one run. These GPS measurements were post processed using the JPL GIPSY program and post processed data. A GPS time receiver was used in this test, so very accurate GPS time was also received. The results of the postprocessing shown in Figure 16 indicates approximately ± 250 picoseconds of accuracy.

The two-way real-time time transfer accuracy results, previously shown, are not quite as good as, but comparable to, the GPS postprocessed time data of Figure 16.

Kalman Filter Design

As part of this test, we developed both 11-state and 26-state Kalman filters. The purpose of the Kalman filters are to process the pseudorange and delta-pseudorange outputs of the GPS receiver to provide user platform velocity and heading for generation of time corrections.

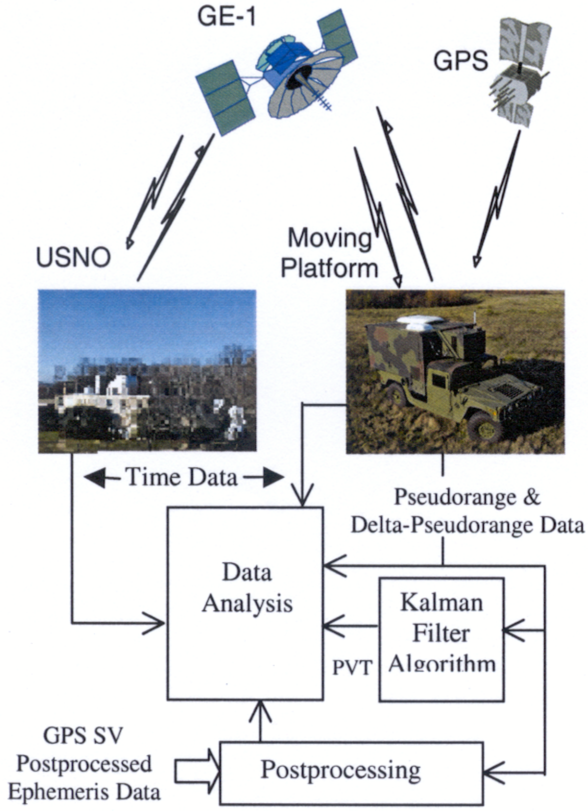

Figure 12. Test Data Flow

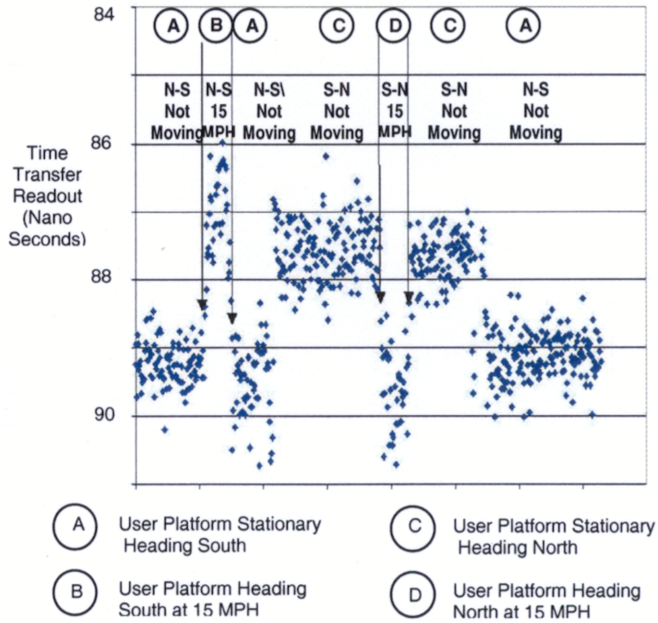

Figure 13. Raw TWSTT Data Uncorrected for MP Velocity and Antenna Displacement

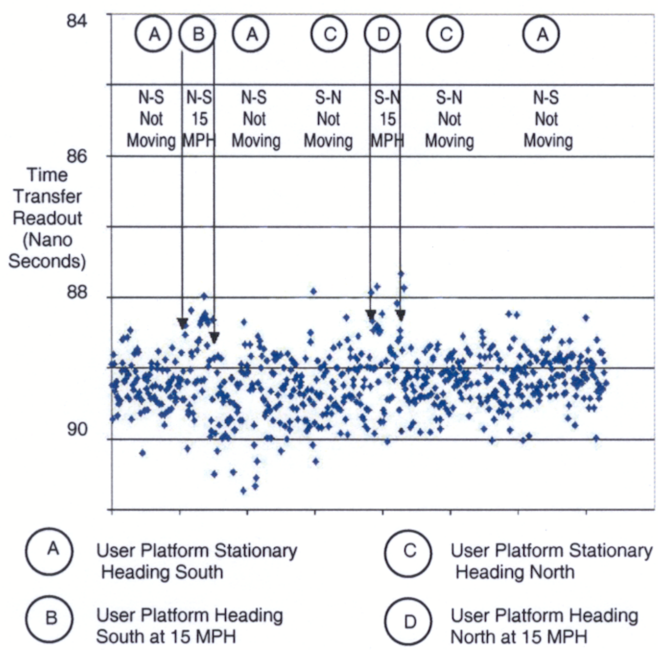

Figure 14. Raw TWSTT Data Uncorrected for MP Velocity and Antenna Displacement

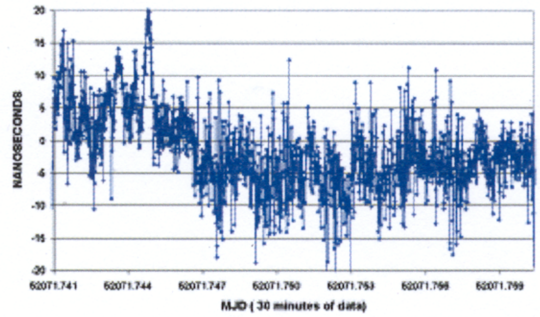

Figure 15. Kalman Filter Time Measurements

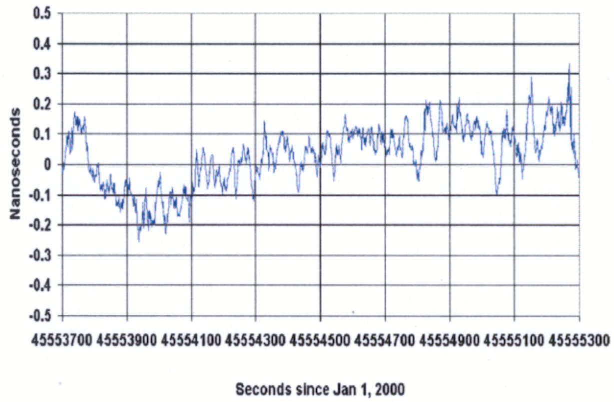

Figure 16. Postprocessed GPS Time

4 TIME COMPENSATION FOR MP TRANSMIT-RECEIVE ANTENNA DISPLACEMENT AND MP VELOCITY

This section describes the necessary two-way time transfer compensation that is required because the MP employs separate receive and transmit antennas and because the MP is moving.

Accurate calculation of the MP clock offset, T_{OS}, with two-way time transfer is based on the assumption that the forward and return RF transmission paths are the same. That is, the forward path from the USNO time source to the geosynchronous satellite to MP is the same as the return path from MP to satellite to USNO. Thus, the forward-path transmission time T_P from USNO to MP is the same as the return-path time from MP to USNO.

The time source (USNO) transmits the forward signal at time T_{TxUSNO}. The MP receives the signal at time

$$T_{RxMP} = T_{TxUSNO} + T_P,$$

but the MP measures the receive time as

$$\begin{aligned} T_{RxMP}' &= T_{RxMP} - T_{OS} \\ &= T_{TxUSNO} + T_P - T_{OS}. \end{aligned}$$

The MP transmits the return signal at time T_{TxMP}, but according to the MP's clock, the transmit time is

$$T_{TxMP}' = T_{TxMP} - T_{OS}.$$

USNO receives the return signal at time

$$T_{RxUSNO} = T_{TxMP} + T_P .$$

The MP offset is calculated from USNO forward transmit time (T_{TxUSNO}), USNO return receive time (T_{RxUSNO}), and the MP clock versions of MP forward receive time (T_{RxMP}') and MP return transmit time (T_{TxMP}'):

$$\begin{aligned} T_{OS,calc} &= [(T_{RxUSNO} - T_{TxMP}') \\ &\quad - (T_{RxMP}' - T_{TxUSNO})] / 2 \end{aligned}$$

$$\begin{aligned} T_{OS,calc} &= [\, T_{TxMP} + T_P - (T_{TxMP} - T_{OS}) \\ &\quad - (T_{TxUSNO} + T_P - T_{OS}) \\ &\quad + T_{TxUSNO}] / 2 \end{aligned}$$

$$T_{OS,calc} = T_{OS}$$

This ideal situation fails to hold when the path transmission time is different for the forward and return paths. The forward and return paths are different in the MP experiment, because the MP employs separate receive and transmit antennas and because the MP is moving. This is shown in Figure 17.

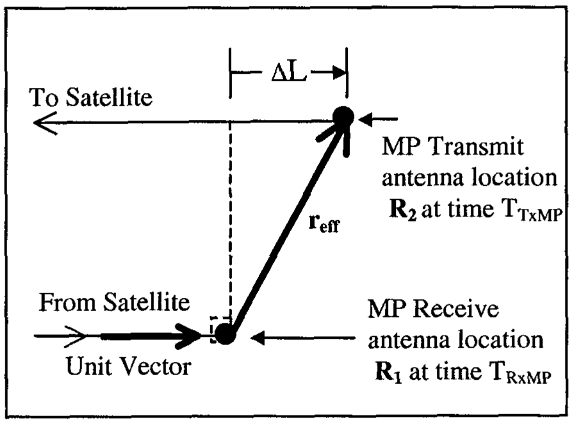

Figure 17. MP Transmission Path Geometry

If **r** is the displacement vector from MP's receive antenna to his transmit antenna and **v** is MP's velocity, then the vector displacement between the receive antenna at time T_{RxMP} (when the MP receives the forward signal) and the transmit antenna at time T_{TxMP} (when the MP transmits the return signal) is:

$$\mathbf{r}_{eff} = \mathbf{r} + (T_{TxMP} - T_{RxMP})\, \mathbf{v} .$$

This vector $\mathbf{r}_{eff}$ is the MP's effective differential displacement for the return path relative to the forward path. The user can use his own clock to measure the time delay $T_{TxMP} - T_{RxMP}$, because $T_{TxMP}' - T_{RxMP}' = T_{TxMP} - T_{RxMP}$. If the user knows his velocity, then he can calculate $\mathbf{r}_{eff}$.

The component of $\mathbf{r}_{eff}$ perpendicular to the transmission path produces a negligible change in path length, because the magnitude of $\mathbf{r}_{eff}$ is very small relative to the satellite-to-MP range. Only the component of $\mathbf{r}_{eff}$ parallel to the transmission path changes the path length.

The return path is longer than the forward path by $\Delta L = \hat{\mathbf{u}}_S \bullet \mathbf{r}_{eff}$, where $\hat{\mathbf{u}}_S$ is the unit vector from satellite to MP. If the forward-path transmission time from USNO to MP is T_P, then the return path transmission time from MP to USNO is $T_P + \Delta T_P$, where

$$\Delta T_P = \frac{\Delta L}{c} = \frac{\hat{\mathbf{u}}_S \bullet \mathbf{r}_{eff}}{c}$$

$$\Delta T_P = \frac{\hat{\mathbf{u}}_S \bullet [\mathbf{r} + (T_{TxMP} - T_{RxMP})\mathbf{v}]}{c}$$

and c is the speed of light. The time at which USNO receives the return signal is now given by:

$$T_{RxUSNO} = T_{TxMP} + T_P + \Delta T_P.$$

The calculated MP offset time becomes:

$$\begin{aligned} T_{OS,calc} &= [(T_{RxUSNO} - T_{TxMP}') \\ &\quad - (T_{RxMP}' - T_{TxUSNO})] / 2 \end{aligned}$$

$$\begin{aligned} T_{OS,calc} &= [\, T_{TxMP} + T_P + \Delta T_P \\ &\quad - (T_{TxMP} - T_{OS}) \\ &\quad - (T_{TxUSNO} + T_P - T_{OS}) \\ &\quad + T_{TxUSNO}] / 2 \end{aligned}$$

$$T_{OS,calc} = T_{OS} + \Delta T_P / 2$$

Thus, a correction factor $T_C = -\Delta T_P / 2$ must be added to the calculated MP offset time $T_{OS,calc}$ to compensate MP receive to transmit antenna displacement **r** and velocity **v**. This correction factor is as follows:

$$T_C = -\frac{\hat{\mathbf{u}}_S \bullet [\mathbf{r} + (T_{TxMP} - T_{RxMP})\mathbf{v}]}{2c} \qquad (3)$$

where:

T_C = time transfer correction,
r = antenna displacement vector $\mathbf{T_{RxMP}}$ = MP receive time of USNO transmission,
$\mathbf{T_{TxMP}}$ = MP return transmit time,
v = velocity vector,
$\hat{\mathbf{u}}_S$ = unit vector from satellite to user,
c = speed of light, and
• = dot product.

The equation (3) correction factor was applied to data in Figure 13, resulting in the data shown in Figure 14. The straight line of the corrected data shows the correction factor corrects very well.

The MP experiment was set up so that both USNO and the MP transmitted at the same time. That is, $T_{TxMP} = T_{TxUSNO}$. Since $T_{RxMP} = T_{TxUSNO} + T_P$, the time delay $T_{TxMP} - T_{RxMP}$ in the expression for T_C becomes:

$$T_{TxMP} - T_{RxMP} = T_{TxUSNO} - (T_{TxUSNO} + T_P)$$

$$T_{TxMP} - T_{RxMP} = -T_P$$

The path transmission time T_P was calculated from the USNO, satellite, and MP locations, and was found to be 0.2547 seconds.

5 TWSTT TO MOVING PLATFORM CONCLUSION

The two-way satellite time transfer test to a moving platform was successful. Less than 1 nanosecond of time transfer error is indicated after applying corrections and filtering. Scatter plots show that the precision of the time transfer readings were usually within ± 0.5 nanoseconds. A smooth time transfer capability was shown after the calculated corrections for the user velocity and the antenna placements were applied to the raw data.

The recommended next steps are:

- Generate TWSTT error budget
- Show that either a MEO or GEO satellite can be used for time transfer (implications of faster velocities)
- Reduce transmit time between receive to transmit in the user time modem
- Perform TWSTT to an aircraft in flight
- Investigate methods for data transfer between platforms using the TWSTT RF transmission links

It is expected that the two-way time transfer to a moving platform will have many users in the military and scientific communities. Uses such as multi-aircraft sensor fusion and obtaining accurate relative time at multi-locations are prime candidates. However, further development is required to make this most time accurate time transfer method available to moving platforms. Additional tests on high velocity platforms are needed.

6 TWSTT FOLLOW-ON EFFORT

USNO plans to determine the modifications needed to update the TimeTech SATRE time modem for higher velocity operation and for reduced time delay interval between receive and transmit.

Follow-on TWSTT testing is pending, based on available hardware and participants' budget availability.

7 ACKNOWLEDGMENTS

Others who contributed are Lisa Nelson, Phu Mai, Jim DeYoung, and Paul Wheeler from USNO and Mike Pounds and Richard Bowers from Boeing.

Questions and Answers

SIGFRIDO LESCHIUTTA (Politecnico di Torino and Istituto Eletrotecnico Nazionale): The phased array antenna was used just to have a local antenna, or was it used in order to have a directional beam?

ED POWERS: It is a real active phased ray antenna with multiple elements that are actively phase-shifted to steer a beam to the satellite. So it is a full beam-steered antenna. It is not just a flat-looking dish; it is a true beam-steered antenna.