PRECISE TIME DISSEMINATION THROUGH INMARSAT — PRELIMINARY RESULTS

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BIOGRAPHIES

ALISON BROWN

Alison Brown is the President of NAVSYS Corporation, which specializes in developing GPS technology. She has 15 years experience in GPS receiver design and has seven GPS related patents. She has published numerous technical papers on GPS applications and is on the editorial board for GPS World and GIS World magazines. Dr. Brown is currently the Space Representative for the ION Council and Vice Chair for the IEEE Pikes Peak Section.

DICK DAVIS

Mr. Davis recently retired after 40 years of government service and 25 years as an electronics engineer with NIST/NBS time and frequency division. He was primary design engineer on several NIST time/frequency dissemination sys-tems, including the model for a closed captioning system currently that is used for the deaf and hearing impaired, the "GOES" satellite time system, and the "ACTS" automated computer time service, a dial up modem service. The NBS/GPS common view time transfer receiver designed by Mr. Davis became the standard for international time/ frequency transfer at the 10 ns level. Over 500 receivers based on this design are currently in use for precise time transfer. Mr. Davis is currently working as a T/F consultant.

RICK WALTON

Rick Walton is Director, Service Development in COMSAT Mobile Communications Land Mobile and Special Services Group. He has 17 years experience in satellite communications systems engineering, including earth stations, design, communications equipment for both fixed and mobile applications, and satellite design, fabrication and testing. As director of COMSAT's London office, Mr. Walton worked with Inmarsat on mobile communication systems and services, including the Inmarsat-III spacecraft technical requirements. He is currently responsible for the development of technical solutions of land mobile customers' communications requirements through Inmarsat.

Mr. Walton received a BSEE from Lehigh University and an MSEE in Communications Engineering from George Washington University. He is a member of the RTCA Working Group on Wide Area DGPS and Integrity and has co-authored several papers on the Inmarsat-III navigation transponders.

ABSTRACT

INMARSAT has designed a GPS (L1) transponder that will be included in their third generation satellites. This transponder will broadcast a pseudo-GPS signal that can be used for navigation and also for disseminating integrity data and/or differential corrections for the GPS satellites. This INMARSAT Geostationary Overlay (IGO) service will be used to enhance the performance of the GPS navigation service for civil aviation and other users.

The IGO service can also be used as a method of disseminating a precise time reference. Since the IGO signal is compatible with GPS, conventional GPS timing receivers can easily be modified to utilize the proposed service. Preliminary test results taken through the IGO satellite have demon-strated a timing accuracy of 10 nanoseconds.

INTRODUCTION

The INMARSAT-III constellation of four geostationary satellites will provide redundant coverage over most of the earth, as illustrated in . In addition to the communications payload, the INMARSAT-III satellites will also carry a navigation transponder that will be used to broadcast GPS-like signals. These signals can be used for navigation and will broadcast a GPS Integrity Broadcast (GIB) generated by the Federal Aviation Administration (FAA) that provides warnings to users when the GPS service is not operating correctly.

The INMARSAT Geostationary Overlay (IGO) signal is generated at the satellite earth station and is controlled so that the IGO signal broadcast by the satellite appears to be synchronized with the GPS satellite signals. It is also possible to use this architecture to precisely synchronize the IGO signal to a time reference. Since only a single satellite signal is required for precise time dissemination at fixed installations, the four INMARSAT-III satellites can provide redundant worldwide coverage for precise time dissemination.

NAVSYS, COMSAT, and NIST have signed a cooperative research and development agreement to perform a timing experiment using the FAA's GIB Test-Bed equipment. The architecture to be employed in this experiment is illustrated in . The IGO signal generator design by NAVSYS is installed at the Southbury Earth Station operated by COMSAT. This signal generator is designed to synchronize the IGO signal to a precision time reference installed at the earth station. A monitor station installed at NIST will be used to measure the accuracy of the broadcast IGO signals. NIST will also provide time and frequency corrections to the earth station to steer the precision time reference and to calibrate for observed offsets in the system. This testing will continue through 1994. Preliminary results from the initial tests are included in this paper. In the long term, INMARSAT time could be that of UTC as generated at the Bureau Internationale de Poids et Mesures (BIPM).

INTERNATIONAL HIGH ACCURACY TIMING

The INMARSAT transponder can be used to provide an international high accuracy timing service. Usages of a service vary depending on the application and include, for example, the need for time accuracy, time stability, time predictability, frequency accuracy, and frequency stability [1]. The typical user, of course, may need high accuracy or stability at some generic site, but wishes not to have a high investment in timing equipment. At the same time, reliability and redundancy are often very important issues.

The capabilities of different time and frequency dissemination systems are summarized in . This table was prepared by the International Tele-communications Union (ITU) Radiocommunication Study Group 7A held in Geneva in April 1993 [2].

Toward the high accuracy end of time and frequency transfer systems, GPS has had a major impact on international timing. The large number of users for positioning and navigation have driven GPS receiver prices down to around a thousand dollars (US). The same is not true for GPS timing receivers, because of the smaller number of users. However, with the growing high accuracy needs within tele-communications, such as with the Synchronous Optical Network (SONET) and the Synchronous Digital Hierarchy (SDH), as well as within the power industry, the prices of receivers will decrease in natural consequence.

In response to the current and anticipated needs within the telecommunications industry, the 1993 Consultative Committee for the Definition of the Second (CCDS) wrote a recommendation encouraging the study of the technical problems associated with the goal of 100 ns worldwide synchronization. As these problems are studied, it is anticipated that many of them will have solutions within currently available resources. The resources within time and frequency have improved dramatically over the last decade, and there is good reason to believe they will continue to improve. The availability of GPS, alone, has been very significant to the telecommunications industries (telecom) as well as to the time and frequency community.

The official time and frequency reference within the US for telecommunications is UTC [3]. Yet if you ask the question of telecom leaders, "How many of you are using UTC?" the answer will almost always be no one! Everyone knows UTC is an outstanding time scale, but the problem is that it tells you what time it was several weeks after the fact, and in addition, it is not readily accessible in any direct way. Indirectly, it is accessible via GPS, which also broadcasts UTC (USNO). UTC (USNO) is now steered to within 100 ns of UTC.

GPS, being a US military system, has not been accepted by all countries as a reliable reference. In this regard, apprehensions may be greater than they need to be. An official Civil GPS Interface Service Committee (CGSIC) has been set up between the US Department of Defense and the Department of Commerce. A computer bulletin board, accessible internationally, has been set up giving current information about the status of GPS as well as a set of post-processed precise ephemerides. In addition, a Memorandum of Agreement has been signed between the Department of Defense and the Department of Transportation (effective 8 January 1993 through the year 2005) for the civil use of GPS.

The INMARSAT timing system described in this paper could provide three significant steps forward. It could provide an international civil reference time scale, which could be a real time reference to UTC. It could also provide a set of corrections providing higher accuracy usage of GPS, given the degradation caused by selective availability. In addition, as will be described in this paper, it could also provide higher accuracy at less cost and with more reliability then can be obtained with GPS.

In telecommunications, support from the time and frequency community could significantly enhance the accuracy and the rate of information flow. UTC could become their real-time, ultra-accurate reference on a global basis. Now most of the telecom servers generate their own timing, yet different servers have to communicate with each other, which often creates information flow conflicts. In practice, to avoid some of the conflicts in data flow, the servers tend to use the biggest server as a reference. Having an externally unbiased and readily available reference—always somewhat better than their needs—would mitigate many of the current problems. This external support from UTC as a real-time timing reference could significantly improve data flow efficiency. Such support may also reduce costs, since the servers would not have to use as much of their resources to supply precise timing.

INMARSAT GEOSTATIONARY OVERLAY (IGO)

INMARSAT has ordered four INMARSAT-III satellites which will include C-to-L1 transponders and C-to-C band transponders (for atmospheric corrections). Contracts for all four spacecraft launches have been signed, with the first launch scheduled for June 1995.

The INMARSAT Council took the decision to include navigation transponders, which would transmit GPS look-alike signals, on the third generation satellites in order to accomplish three major objectives:

1)to provide real-time (within 6 seconds as established by FAA and ICAO) integrity status of each of the GPS satellites and other navigation satellites such as GLONASS;

2)to provide a geostationary overlay to existing navigation satellite systems (hence the term INMARSAT Geostationary Overlay or IGO) which would augment other satellite navigation systems with an undegraded (no selective availability) navigation signal; and

3)to provide, if possible, Wide Area Differential GPS (WADGPS) corrections to enhance air traffic safety.

In addition to providing a navigation and integrity service, the transponder signal can also be used to disseminate a precise time reference. The GPS-like signals would be synchronized to a precision time reference (e.g. UTC) and would provide access to this reference over a large area.

INMARSAT has been a strong participant in the Radio Technical Commission for Aviation (RTCA) and other international forums which are responsible for the design and specification of the signal structure, data format, and operational characteristics of the Integrity/WADGPS broadcast. The RTCA Sub-committee 159 is responsible for writing the performance specifications (MOPS) for the Integrity broadcast that will eventually form the basis for a GPS-based sole means of navigation for commercial aircraft. The INMARSAT-III transponder will be an integral part of the Integrity broadcast to warn pilots when a GPS satellite is providing erroneous signals.

The navigation transponder on each INMARSAT-III consists of fully redundant (except for the antenna) C-to-L1 and C-to-C band translators as well as redundant transmit amplifiers (HPAs). A block diagram of the transponder is shown in . The transponder receives GPS-like signals on the 6.4 GHz up-link to the satellite from the earth station and retransmits these signals at L1 (1575.42 MHz) on an earth-coverage antenna. The GPS-like signals use a 1.023 Mbps C/A code from the same family of codes used for GPS. The C/A code is modulated onto the carrier with 50-500 bps data which includes the Integrity message and WADGPS data.

The data rate on normal GPS signals is 50 bps, but the Integrity and WADGPS signals require a 250 bps rate with rate ½ convolutional coding which brings the total rate to 500 bps. This data rate is required to provide timely warnings for all of the GPS (and GLONASS) satellites and to meet the accuracy requirements for non-precision approaches.

IGO SIGNAL GENERATOR

A block diagram of the IGO signal generator is included in . This has been designed by NAVSYS to provide precise synchronization of the IGO signal to an external time reference. The signal generator (SIGGEN) includes the following components:

1)a communication server which is used to receive the formatted Integrity and WADGPS message to be transmitted on the IGO signal;

2)a SIGGEN time and frequency reference to which the IGO signal is synchronized;

3)a SIGGEN controller which generates and controls the IGO IF signal output to the earth station for up-link to the satellite; and

4)a SIGGEN monitor which receives the IGO signal and provides the feedback data used in the SIGGEN control algorithms.

SIGGEN COMMUNICATION SERVER

The FAA is developing a network of ground-based reference stations which will be used to continuously monitor the status of the GPS satellites and generate differential corrections for the observed range errors. This data is processed at a central facility to generate a GPS Integrity Broadcast (GIB) message for transmission by the IGO. The function of the communication server is to continuously receive the GIB message from the FAA central facility and then pass this data to the SIGGEN controller for modulation on the IGO signal.

SIGGEN TIME AND FREQUENCY REFERENCE

The SIGGEN time and frequency reference provides the time standard to which the IGO signal is synchronized. In the initial test phase, an HP 5071A primary frequency standard has been provided on loan by Hewlett Packard. The HP 5071A includes an improved cesium beam tube design that results in an accuracy of $\pm 2\times 10^{-12}$. The HP 5071A will be operated during the test phase under remote control by NIST to adjust the reference for frequency offset and maintain it synchronized with NIST's time standard.

SIGGEN CONTROLLER

The purpose of the SIGGEN controller is to generate the IGO signal and control its timing relative to the SIGGEN precise time reference. The IGO signal is steered so that the timing of the signal (the C/A code and data epochs) appear to be synchronous with the SIGGEN time reference when they are transmitted by the INMARSAT-III satellite. In order to achieve this, the signal output by the SIGGEN controller must be advanced in time to compensate for the delays on the up-link path through the satellite transponder.

The signal output by the SIGGEN controller is characterized by the following equation.

$$S_{IF}^{XTM}(t) = D(t + \tau_C)\, C(t + \tau_C) \cos 2\pi(f_{IF}t + \delta f_C t + \theta) \quad (1)$$

where S_{IF}^{XTM} is the IF signal output by the SIGGEN
C(t) is the C/A code at time t
D(t) is the integrity data modulated on the signal
τ_C is the controller time advance
f_{IF} is the nominal frequency of the IF signal (near 70 MHz)
δf_C is the frequency offset inserted by the controller

The IF signal is mixed up to C-band by the earth station, adjusted to compensate for the satellite Doppler, and broadcast up to the satellite where it is mixed to L-band. The signal broadcast by the INMARSAT-III satellite is characterized by the following equation.

$$S_{SV}^{XTM}(t) = D(t + \tau_C - \tau_D)\, C(t + \tau_C - \tau_D) \cos 2\pi(f_{L1} t + \delta f_C t - \delta f_D t + \theta') \quad (2)$$

where S_{SV}^{XTM} is the L1 signal broadcast by the INMARSAT-III satellite
τ_D is the time delay in the signal path from the SIGGEN
f_{L1} is the GPS L1 frequency (1575.42 MHz)
δf_D is the composite frequency offsets in the signal path from the SIGGEN

In order for the IGO signal to appear as a synchronous GPS-type satellite signal, the time and frequency offsets inserted by the controller must be driven to cancel out the time delay and frequency offsets in the signal path from the controller to the satellite (i.e. $\tau_C = \tau_D$ and $\delta f_C = \delta f_D$). These offsets consist of the following composite effects.

$\tau_D = \tau_{TXES} + R/c + \tau_{TROPO} + \tau_{IONO}^C + \tau_{SV}$(3)

$\delta f_D = \delta f_{ES} - R'/c + \delta f_{SV}$(4)

whereτ_{TXES} is the group delay in the earth station path to the up-link antenna
R and R′ are the range and range rate to the satellite in meters and m/s
c is the speed of light (m/s)
τ_{TROPO} is the group delay from the tropospheric portion of the atmosphere
τ_{IONO}^C is the ionospheric group delay on the C-band up-link to the satellite
τ_{SV} is the group delay in the satellite transponder
δf_{ES} is the frequency compensation applied at the earth station
δf_{SV} is the frequency offset due to drifts in the transponder frequency reference

SIGGEN MONITOR
In order to dynamically compensate for the group delays and frequency offsets, the SIGGEN monitor is used to measure the time and frequency offsets of the received signal relative to the SIGGEN time and frequency reference. The received SIGGEN signal is described by the following equation.

$S_{ES}^{RX}(t) = D(t - \tau_R) \cos 2\pi(f_{L1}t + \delta f_R t + \theta'')$(5)

whereS_{ES}^{RX} is the L1 signal received by the SIGGEN monitor
τ_R is the measured time delay from the reference
δf_R is the measured frequency offset from the reference

The measured time offset is related to the controller signal through the following equations.

$\tau_R = \tau_D - \tau_C + R/c + \tau_{TROPO} + \tau_{IONO}^{L1}$
$+ \tau_{RXES} + n_{PR}$(6)

$\delta f_R = \delta f_D - \delta f_C - R'/c + n_{DR}$(7)

whereτ_{IONO}^{L1} is the ionospheric group delay on the L1 down-link from the satellite
τ_{RXES} is the group delay in the earth station reception path

n_{PR} is the measurement error in the SIGGEN code tracking loops
n_{DR} is the measurement error in the SIGGEN frequency tracking loops

SIGGEN CONTROL ALGORITHM
The SIGGEN control algorithm uses the measurements of the received time and frequency offsets (τ_R and δf_R) and a measurement of the controller state (τ_C) to synchronize the IGO signal with the time reference. The following steps are performed by the algorithm.

1)Estimated delays are calculated to correct the observations for the up-link and down-link atmospheric, earth station, and satellite group delays τ_{est}^U and τ_{est}^D. The ionospheric delays are observed through dual frequency observations. The tropospheric delays are modeled and the earth station and satellite group delays are removed through calibration parameters.

$\tau_{est}^U = \tau_{TXES} + \tau_{TROPO} + \tau_{IONO}^C + \tau_{SV}$(8)

$\tau_{est}^D = \tau_{RXES} + \tau_{TROPO} + \tau_{IONO}^{L1}$ (9)

2)The range and range-rate (R and R′) to the satellite are estimated through a Kalman filter using the following observable (Z_R). This is applied as an update to the filter to generate estimates of the range and range-rate.

$Z_R = \tau_R - \tau_{est}^D + \tau_C - \tau_{est}^U = 2R/c + \varepsilon_{est}^U$
$+ \varepsilon_{est}^D + n_{PR}$(10)

The accuracy of the final range and range-rate estimates (ε_R and $\varepsilon_{R'}$) is a function of the calibration errors in the up-link and down-link to the satellites (ε_{est}^U and ε_{est}^D), the noise on the receiver code measurements (n_{PR}), and the time constant of the Kalman filter. Since the satellite is in a highly predictable geostationary orbit, the range and range-rate estimates can be smoothed to reduce their residual error to a minimal level.

3)The time and frequency of the controller are adjusted to minimize the following residuals.

$Z_C = \tau_C - R/c + \tau_c^U = \varepsilon_R + \varepsilon_{est}^U$(11)

$Z_F = \delta f_C + R'/c = \varepsilon_{R'} + n_{DR}$(12)

The accuracy of the final closed loop synchronization is primarily a function of the calibration errors in the satellite up-link. The SIGGEN is designed to measure the state of the broadcast IGO signal (τ_{est}) very precisely. Because of the highly predictable nature of the satellite orbit, the range and range-rate residual error can also be reduced to a minimal level. The dominant error source then becomes the residual errors in the up-link and down-link calibration parameters (ε_{est}^U and ε_{est}^D).

PRELIMINARY TEST RESULTS

A test program is currently being performed in conjunction with NIST using the FAA GPS Integrity Broadcast Test Bed to demonstrate the timing accuracy that can be provided through the INMARSAT Geostationary Overlay. The preliminary test results included in demonstrate the accuracy of the time signal residuals using signals broadcast through the INMARSAT Atlantic Ocean Region-West satellite. These plots show the time accuracy measured on both the transmit and receive paths.

As shown in this figure, the residual error on the timing control loop was maintained within 12 nsec 1-sigma and had a mean offset of only 0.2 nsec at the transmitter and 1.5 nsec at the receiver. Modifications made to the SIGGEN controller since these tests are anticipated to improve on these preliminary results.

Testing is continuing with the IGO signal. In the next phase of the program, calibration parameters will be included to compensate for atmospheric effects. A precise ephemeris for the INMARSAT satellite will also be generated using the SIGGEN range measurements. Finally, NIST will experiment with methods of remotely steering the earth station primary time reference to maintain it synchronized in time and frequency.

CONCLUSION

The INMARSAT timing system described in this paper has three significant advantages over existing time and frequency dissemination systems. The global coverage provided by the INMARSAT satellites will allow this service to be provided as an international civil reference time scale. The ability to monitor and steer the INMARSAT time reference remotely from an establishment such as NIST provides the capability to generate a real-time reference to UTC. Finally, the accuracy and reliability of the system will be significantly improved over existing services, including GPS.

The IGO timing service will be of great benefit to GPS users. Conventional GPS receivers will be able to use the IGO signal with only minor software modification. Since the system is operated through real-time ground control, the integrity and reliability of the service will be much higher than that provided by the GPS satellite constellation. However, the GPS system can be used as a backup in the unlikely event of two IGO satellites failing, since the IGO signal is also fully compatible with GPS. In the future, the IGO signal is anticipated to become the preeminent time and frequency reference worldwide.

One of the issues still to be resolved is the time reference to be used for synchronizing the IGO signal. The alternatives are listed in . GPS time would be an obvious choice except for the difficulty in accessing the base reference, the master clock at the GPS master control station. UTC (USNO) may be more appropriate since this can be accessed directly. Another possibility would be to create a new international atomic standard (UTC-IGO) which is steered to within 10 nsec of UTC as determined by the BIPM. As shown in Table 2. This would provide the same or better navigation performance as a clock synchronized to the GPS satellite time or to UTC (USNO), and would also provide a highly accurate international UTC time standard.

REFERENCES

[1]D.W. Allan and A. Lepek, "Trends in International Timing," Proceedings of 1993 European Frequency and Time Forum.

[2]Draft New Recommendation, "Systems, Techniques and Services for Time and Frequency Transfer," available from ITU secretariat for documents, Geneva, Switzerland.

[3]D. Bodson, et al, "Time and Frequency Information in Telecommunications Systems Standardized by Federal Standard 1002A," IEEE Proceedings, Vol 79, No 7, July 1991.

[4]Civil GPS Service Interface Committee (CGSIC) has a GPS Information Center (GPSIC) bulletin board. Call (703) 866-3826 for information on how to access.