A Proposed Time Transfer Experiment Between the USA and the South Pacific

John Luck
Australian Surveying and Land Information Group
Canberra, ACT Australia

John Dunkley
Defence Science and Technology Organisation
Salisbury, SA Australia

Tim Armstrong
Department of Scientific and Industrial Research
Lower Hutt, New Zealand

Al Gifford, Paul Landis, Scott Rasmussen and Paul Wheeler
Department of Defense
Washington, DC USA

Tom Bartholomew
The Analytic Sciences Corporation (TASC)
Linthicum, MD USA

Sam Stein
Timing Solutions Corporation
Boulder, CO USA

Abstract

This paper describes the concept, architecture and preliminary details of an experiment directed towards providing continuous Ultra High Precision (UHP) time transfer between Washington, DC; Salisbury, SA Australia; Orroral Valley, ACT Australia; and Lower Hutt, New Zealand. It further describes a proposed method of distributing UTC(USNO) at a high level of precision to passive users over a broad area of the South Pacific.

The concept is based on active two-way satellite time transfer from the United States Naval Observatory (USNO) to the proposed USNO Master Clock West (MCW) in Wahiwa, HI USA at the 1 nanosecond level using active satellite two-way time transfer augmented by Precise Positioning Service (PPS) of the Global Positioning System (GPS). MCW would act as an intermediate transfer/reference station, again linked to Salisbury at the 1 nanosecond level using active satellite two-way time transfer augmented by PPS GPS. From this point, time would be distributed within the region by two methods. The first is an existing TV line sync system using an Australian communications satellite (AUSSAT K1) which is useful to the 20 nanosecond level. The second approach is RF ranging and multilateration between Salisbury, Orroral Observatory, Lower Hutt and the AUSSAT B1 and B2 to be launched in 1992. Orroral Observatory will provide precise laser ranging to the AUSSAT B1/B2 retro reflectors which will reduce ephemeris related time transfer errors to below 1 nanosecond. The corrected position will be transmitted by both the time transfer modem and the existing TV line sync dissemination process. Multilateration has the advantage of being an all weather approach and when used with the laser ranging technique will provide a precise measurement of the propagation path delays. This will result in time transfer performance levels on the order of 10 nanoseconds to passive users in both Australia and New Zealand.

Introduction

The motivation for the proposed time transfer experiment between the USA and the South Pacific is rooted in the Geographic Dependence and Latitude Effects Study (GDLE)[1]. The GDLE Study was conducted over a 12 month period to: 1) investigate and verify the existence of reported anomalies, the so-called "bowing effect", in GPS time recovery; 2) analyze the potential causes; and 3) determine procedures to maximize overall time transfer performance in the geographic area of interest. Based on the preliminary results of the GDLE we have concluded that the major GPS time transfer anomalies result from uncompensated clock and ephemeris errors in the daily GPS uploads. In addition we see evidence of a long term effect which may be seasonal in nature.

As further motivation, the Australian Government has a requirement to coordinate their national time scale to UTC and to disseminate this time nationally and regionally to a high level of accuracy. Their specific aim is to guarantee the general availability of UTC(AUS) at an accuracy approaching 1 nanosecond (1σ) through a low cost operational service. As part of that process they are interested in evaluating alternative methods of acquiring and distributing time. With the advent of SA/AS it has become important to explore independent techniques which can be used to augment GPS.

The proposed experiment is therefore designed to support the participants interests by: 1) providing long term monitoring of GPS one-way time recovery using Standard Positioning Service (SPS) and PPS receivers; 2) implementing a high precision, GPS independent, time transfer linkage between UTC(USNO) and Salisbury Australia; and 3) testing an improved regional TV line synch time dissemination method.

It is believed that the proposed experiment would, in conjunction with the previously described GDLE, eliminate or confirm the presence of long term variations in GPS time transfer to Australia. It would also establish a mechanism for nanosecond level time transfer to Australia and exercise an improved regional precise time distribution methodology.

Concept

Refering to Figure 1, the concept is based on active two-way Ku-band satellite time transfer, using the Satellite Business Systems SBS-5, from the United States Naval Observatory (USNO) in Washington, DC (Figure 2) to the proposed USNO Master Clock West (MCW) in Wahiwa, HI USA (Figure 3). This technique has been used operationally at the sub-nanosecond level and is expected here to be usable to 1 nanosecond. MCW would operate as an intermediate transfer/reference station, again linked to Salisbury at the 1 nanosecond level using active two-way X-band satellite time transfer modems, via the Defense Satellite Communications System (DSCS) Western Pacific Satellites, augmented by SPS and PPS GPS.

From Salisbury (Figure 4), time would be distributed within the region by two methods. The first is an existing TV line sync system using an Australian communications satellite (AUSSAT K1) (Figure 5). With after-the- fact ephemeris correction, this is useful to the 20 nanosecond level. The second approach is an improvement to be implemented with the AUSSAT B1/B2 satellites to be launched in 1992. These satellites will be fitted with retro reflectors. Laser ranging from the Orroral Observatory and RF ranging (clock difference measurements) from Salisbury, Hobart, and Sydney along with ionospheric corrections will ultimately reduce ephemeris related time transfer errors to the 1 nanosecond level. The corrected position will be transmitted by the existing TV line sync dissemination process and the time transfer modem.

As a future enhancement, multilateration (RF ranging) from Salisbury, Orroral Valley and Lower Hutt offers the advantage of all weather operations and when used with he laser ranging technique will provide a higher precision measurement of the propagation path delays. This will result in time transfer performance levels on the order of 10 nanoseconds to passive users in both Australia and New Zealand.

Elements of the Experiment

1. ENSEMBLE

The requirements for time-keeping and frequency control at both MCW and Salisbury will be supported by a system known as ENSEMBLE. It is a multi-clock time system capable of keeping stable time and frequency linked to UTC(USNO) based on the use of the Precise Positioning Service (PPS) of the Global Positioning System (GPS).

ENSEMBLE (see Figure 6) will monitor, weight and combine the outputs of up to 8 clocks in a Kalman filter algorithm known as Kalman Aiding Sources Version 2 (KAS-2), similar to the one in use at the GPS Master Control Station (MCS)[2]. KAS-2 is used to create a paper clock within a controlling computer that is the best estimate of the correct time. The frequencies of 2 of the contributing cesium clocks will be steered long-term to UTC-USNO using highly filtered continuous comparisons with GPS. The short term performance of ENSEMBLE is based on the inherent stability of the cesium clocks. For periods of 24 hours or longer the frequency of the clock ensemble is steered to the GPS constellation with the ENSEMBLE software. The steering correction is integrated over several days to eliminate short term upsets.

To insure reliability there are 3 levels of backup which include: 1) system level redundancy in clocks, receivers, computers and time code generators; 2) manual override and operation of ENSEMBLE; and 3) finally the ability to support the entire system with a single stand-alone clock. ENSEMBLE will provide for performance monitoring and fault detection through a set of outputs which will be remotely interfaced to the USNO.

Using PPS GPS, as it is currently operating, ENSEMBLE will provide an absolute time accuracy of <30 nanoseconds (RMS), not-to-exceed 150 nanoseconds (5σ) with respect to UTC(USNO). The frequency stability at one day will be less than $2x10^{-14}$, at ten days less than $1x10^{-14}$, and less than $5x10^{-15}$ at thirty days.

2. Satellite Two-Way Time Transfer Modem

Two way time transfer uses Very Small Aperture Terminals (VSAT) and communication satellites to link time transfer modems at each location. A pulse is transmitted from each end every second and its time of arrival is measured at the other end relative to the local clock (Figure 7). The measurement is equal to the difference between the two clocks plus the delays of the path and hardware. Typical errors in the process, when care is taken to calibrate the equipment and cables, are about a nanosecond.

$$Measurement_{locationA} = Time_A - Time_B + DELAY_{BtoA}$$

$$Measurement_{locationB} = Time_B - Time_A + DELAY_{AtoB}$$

$$Measurement_A - Measurement_B = 2(Time_A - Time_B)$$

If the delays and hardware are equal the difference in clocks A and B can be found by taking half the difference in the two measurements. In practice the two delays are not equal. They differ because of hardware, ionospheric path delays and earth rotation. The hardware differences can be measured by comparing systems before deployment. Path differences caused by the Sagnac effect can be calculated with approximate knowledge of the equipment and satellite locations. The differences in the ionosphere are under 100 picoseconds at the $12 - 14ghz$ operating frequency and the 2 ghz offset between the transmitting and receiving frequencies.

Typically the two way operation is accomplished with a master site and several slave sites (Figure 8). The slave sites will only respond upon command of the master site. Data measurements are exchanged between the two location over the same link that is transmitting the pulse.

The advantages of the two way technique over GPS time transfer include 1) two way does not need accurate information on antenna or satellite locations, 2) tropospheric effects cancel; and 3) ionospheric path delay errors are less than 100 picoseconds. These result in a more accurate time transfer.

The 100 picosecond number for ionospheric path delay is for Ku-band operation. At X-band the delay in each path is higher due to the inverse frequency effect but the difference between transmission and receiving frequency is less. The projected ionosphere errors at X-band are therefore about 150 picoseconds.

To perform two way time transfers between some locations it is necessary to a use an intermediate relay point. The relay point may be equipped with zero, one or two modems. With zero modems the two terminals are cabled together causing the total link noise to be the sum of the two parts. This saves equipment but does not provide time transfers at the relay point. With one modem, sequential time transfer may be done by using the local clock to flywheel between transfers. With two modems, simultaneous transfers may be done thus eliminating any small errors in the relay clock.

3. Orroral Observatory/AUSSAT Time Dissemination

The Australian national system of precise time comparisons embodied in UTC(AUS) is accomplished by measurement of TV signals from AUSSAT supported by orbit information supplied by AUSSAT Belrose and by time measurements from the GPS which provide the relationship of UTC(AUS) to International Atomic Time (IAT) and UTC(BIPM). Precision and accuracy are currently estimated to be on the order of 50 nanoseconds. Precision improves to about 10 nanoseconds when AUSSAT's orbit is improved using GPS results (Figures 5 and 9). The Orroral Laser Ranging System is being upgraded for ranging to retroreflectors on the AUSSAT B spacecraft with 5 cm precision and accuracy for much better orbits. Locally generated GPS orbits, precise base station location and ionospheric calibration, already planned for a national 'zero-order' geodetic network tied to VLBI and laser ranging sites, will add strength and reliability to the TV method.

ABC TV signals transmitted from AUSSAT K1 provide times of arrival (TOA) of arbitrary but well defined sync pulses. These are measured with respect to local clocks at participating stations as shown in Figure 5. The measurement equipment typically includes a 1.5 meter dish, LNA, B-MAC decoder and sync pulse selector, and an ordinary TV set as shown in Figure 9.

If t_0 is the time of transmission, x_i the measured time of reception, T_i the clock error, d_i the receiver delay, e_i the unmodelled random and systematic error such as ionospheric and relativistic effects, and p_i the propagation delay from satellite to station i, then:

$$x_i = t_0 + T_i + d_i + p_i + e_i$$

whence:

$$x_i - x_j = (T_i - T_j) + (d_i - d_j) + (p_i - p_j) + (e_i - e_j)$$

The relative clock error $T_i - T_j$ is readily determined when the relative propagation delay $p_i - p_j$ has been calculated from supplied orbital and receiver location data, provided the relative receiver delay $d_i - d_j$ has been calibrated. Results for the clock differences between the hydrogen masers at Mount Pleasant Observatory in Hobart and the National Measurements Laboratory (NML) in Sydney show a precision of 70 nanoseconds, which includes error contributions from the clocks, the measurements, the ionosphere and the orbit.

Alternatively, when the relative clock error is already known from independent GPS time comparisons at several 'Master' stations, the relative propagation delays $p_i - p_j$ can be calculated and used as pseudo-range differences to improve the spacecraft's orbit which is then applied to the corrections for 'Remote' stations. For this purpose, measurements are taken hourly. The results, when GPS time results from 'Master' stations at NML, Orroral, Telecom Research Laboratories in Melbourne and Yarragadee SLR have been added to solve for semi-major axis, eccentricity, inclination and relative receiver delays (station biases) show a precision of 13 nanoseconds for a 2-day fit after editing some outliers.

AUSSAT orbital positions measured by radar tracking from the Earth Station at Belrose are accurate to 30 metres. The improvement brought about by combining GPS time measurements with the TV measurements is geometrically weak for perigee, node and anomaly solutions, and under threat from the policy of 'Selective Availability'.

The next generation of AUSSAT's, B1 and B2, will be launched in 1992 and will each carry an array of 14 38 mm diameter retroreflectors (James, Steel and Evans, 1990). The range error from the upgraded Orroral laser will be less than 5 cm with a pointing error of 2-3". It would be highly desirable to upgrade the Yarragadee SLR station as well, to add strength to the solution for in-orbit longitude.

The geodetic positions of the AUSSAT and GPS antennas need to be known to better than 30 centimeters to achieve the 1 nanosecond time transfer goal. All participating locations must be located to that accuracy on a common geodetic datum.

Australian fiducial stations located at Orroral, Yarragadee, Tidbinbilla, Alice Springs, Gnangara, and Towns-ville will become the basis for the "zero-order" national network. This network will be integrated with the timing network and will provide the capability for producing accurate coordinates for time transfer, ionospheric corrections for GPS, and a regional GPS orbit determination service.

4. Salisbury/DMA Installation

The installation at Salisbury will be as shown in Figure 4. The time/frequency reference will consist of a truncated version of ENSEMBLE with a single computer, one measurement system, one GPS PPS time recovery receiver, and a minimum of 3 cesium beam frequency standards, at least one of which will be steerable. The ENSEMBLE computer will be directly interfaced to the NRL satellite time transfer modem which will provide regular time transfers from MCW via the DSCS. This is expected to maintain the local ENSEMBLE estimate of UTC(USNO) to within 2 nanoseconds (RMS). The calibrated ENSEMBLE UHP 1 PPS and 5 Mhz outputs will be buffered and supplied to the AUSSAT TV time dissemination system.

The existing DMA monitor station at Salisbury consists of 2 T14100A receivers, an HP5061 cesium frequency standard, an HP5065A rubidium frequency standard, a LORAN C receiver, a computer and a phone modem. It is expected that the DMA system will be upgraded in 1992.

Data Collection and Analysis

The participants have planned to put the elements of the experiment in place over the next 9-12 months. Operation of MCW will begin in the September 1992 time frame with the remaining segments coming on line as equipment and resources become available. It is hoped that data collection can be maintained over a minimum period of 12 months.

Data collection will be designed to build the following data sets:

- Salisbury
  - UTC(USNO) versus local clock
    - via two-way satellite time transfer modem
    - via GPS one-way broadcast
      - real-time using local ENSEMBLE PPS system
      - real-time using local DMA SPS system
      - post-time using both of the above with post-fit DMA GPS ephemerides
  - UTC (AUS) versus local clock
    - via AUSSAT K1
    - via AUSSAT B1/B2 with ephemeris corrections (when available)
- Hawaii
  - UTC(USNO) versus MCW
    - via two-way satellite time transfer modem
    - via GPS one-way broadcast
      - real-time using local ENSEMBLE SPS system
      - real-time using local ENSEMBLE PPS system
      - post-time using local ENSEMBLE PPS system and DMA post-fit GPS ephemerides
    - via common view with USNO (PPS and SPS)

Preliminary plans for data analysis include:

- Difference and compare Salisbury and MCW data sets
  - $UTC(USNO)_{viaPPS/GPS} - UTC(USNO)_{viaTwoway}$
  - $UTC(USNO)_{viaSPS/GPS} - UTC(USNO)_{viaTwoway}$
  - $UTC(USNO)_{viaPPS/GPS} - UTC(USNO)_{viaSPS/GPS}$
  - $UTC(USNO)_{viaAUSSATK1} - UTC(USNO)_{viaPPS/GPS}$
  - $UTC(USNO)_{viaAUSSATK1} - UTC(USNO)_{viaSPS/GPS}$
- Compare two-way time transfer configurations
  - pass-through method in Hawaii
  - direct retransmission in Hawaii
  - sequential transmissions in Hawaii
- Compare time transfer modem ranging performance to existing ranging systems.

References

[1] Beard, R.,Gifford, A., Stebbins, S., Rasmussen S.,and Bartholomew T. "Interim Report on the Geographic Dependency and Latitude Effects Study," Proceedings of the 45th Annual Symposium on Frequency Control, 29-31 May, 1991, Los Angeles, CA, pp. 608-625.

[2] Stein, S. R., "Kalman Ensembling Algorithm: Aiding sources Approach," Proceedings of the Third International Time Scale Algorithm Symposium, 12-13 september, 1988, turin, Italy, pp. 345-357.

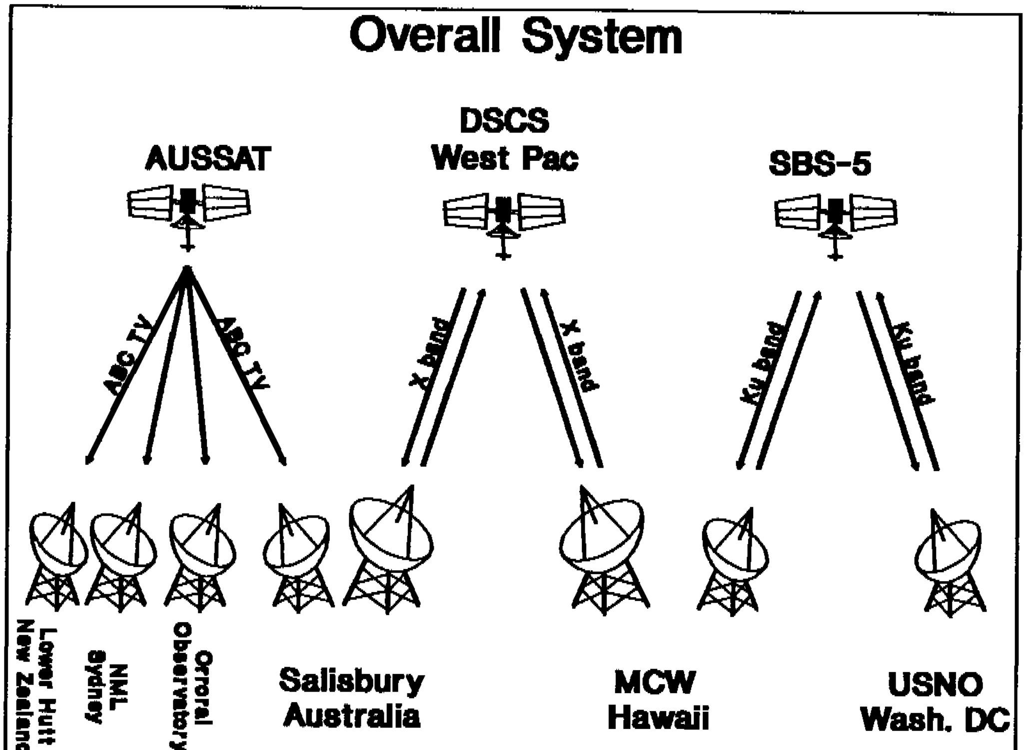


Figure 1

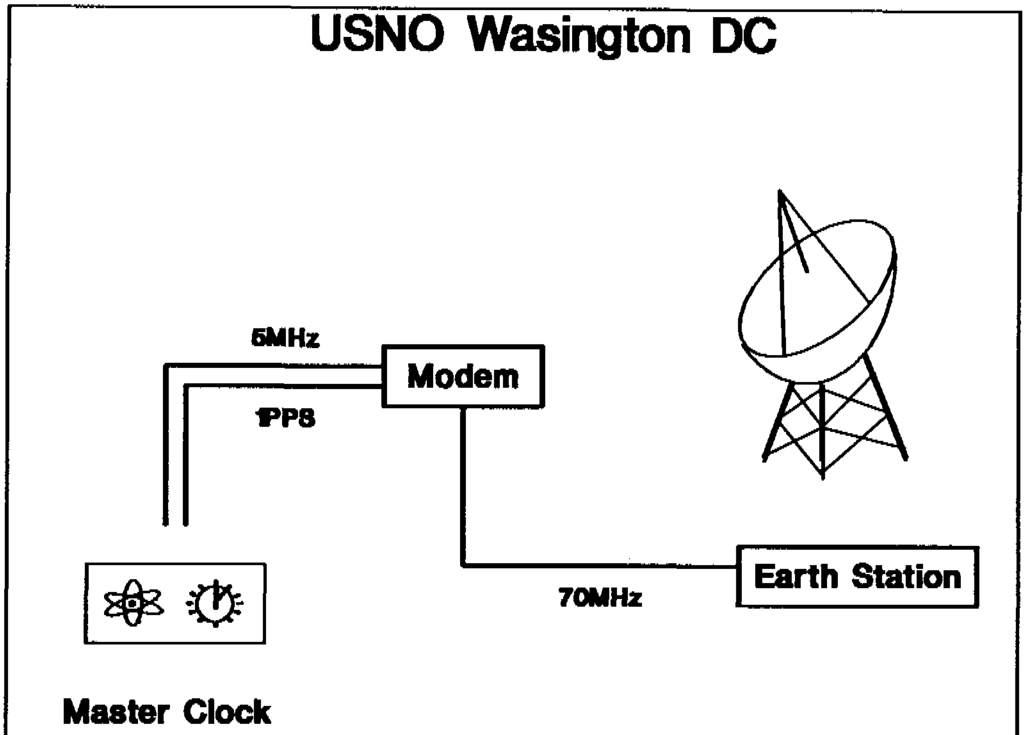


Figure 2

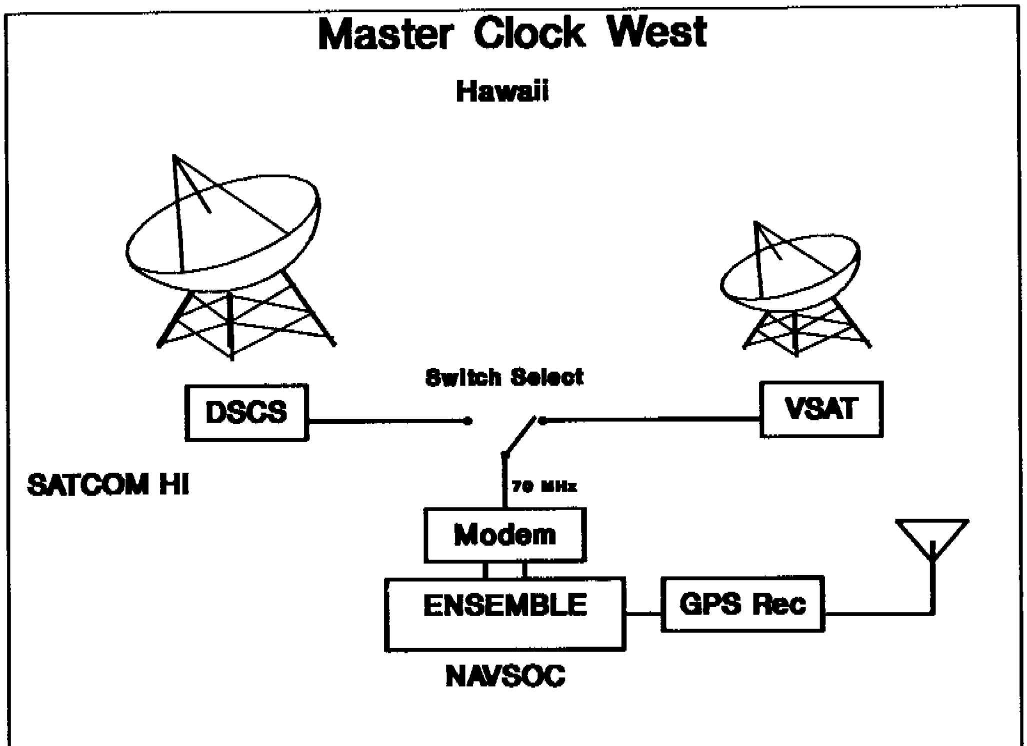


Figure 3

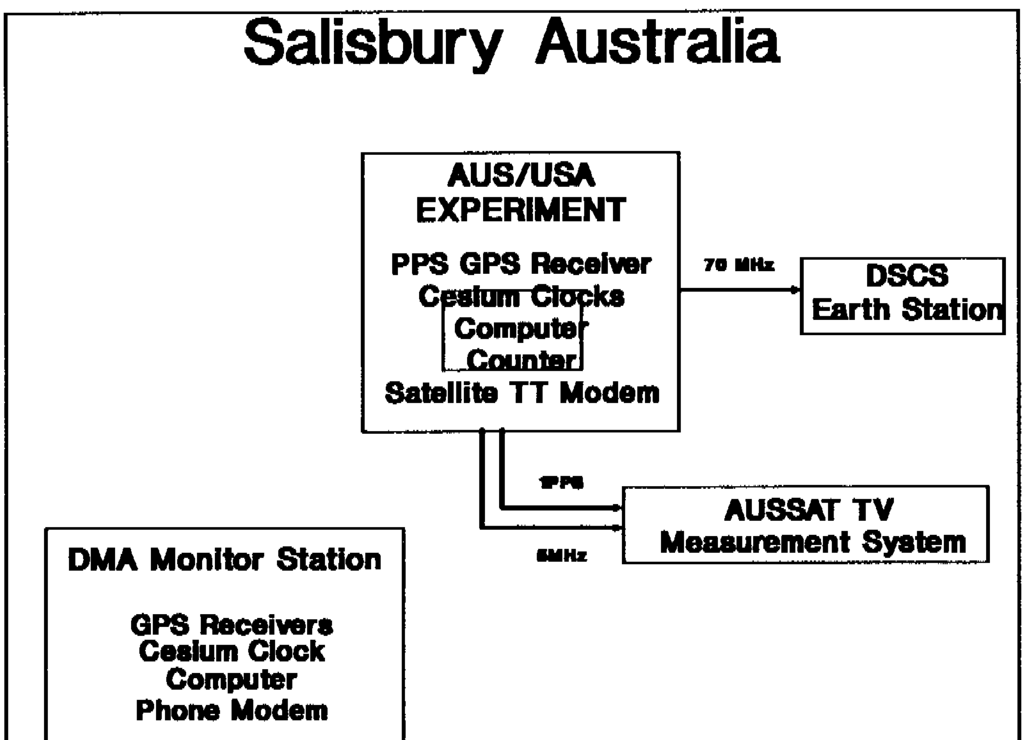
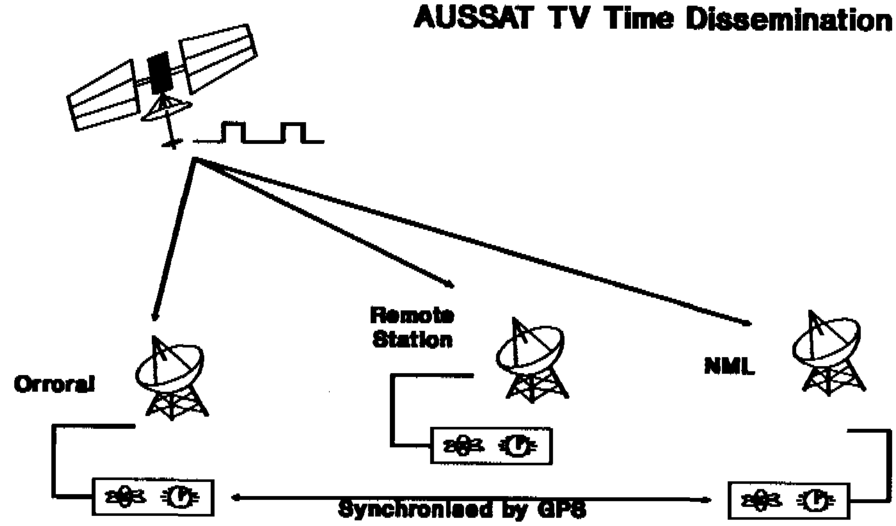


Figure 4

AUSSAT TV Time Dissemination



Clock comparisons using ABC TV signals from AUSSAT K1. Master stations are connected by GPS, allowing orbit improvement for better service to remote stations. AUSSAT B1/2 orbits will be enhanced by laser ranging.

Figure 5

ENSEMBLE

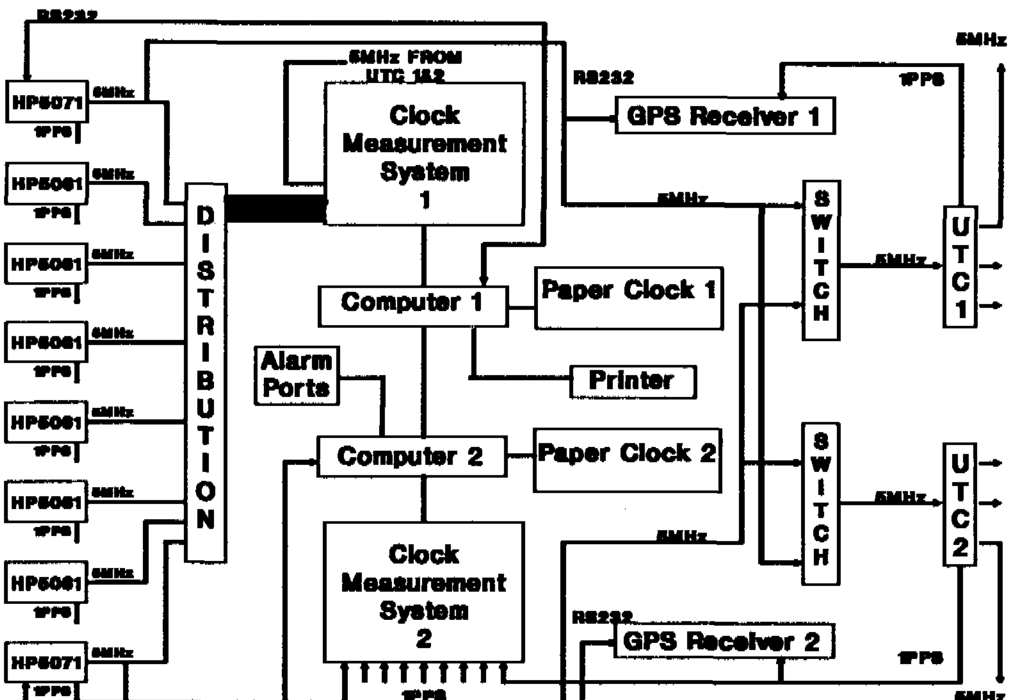


Figure 6

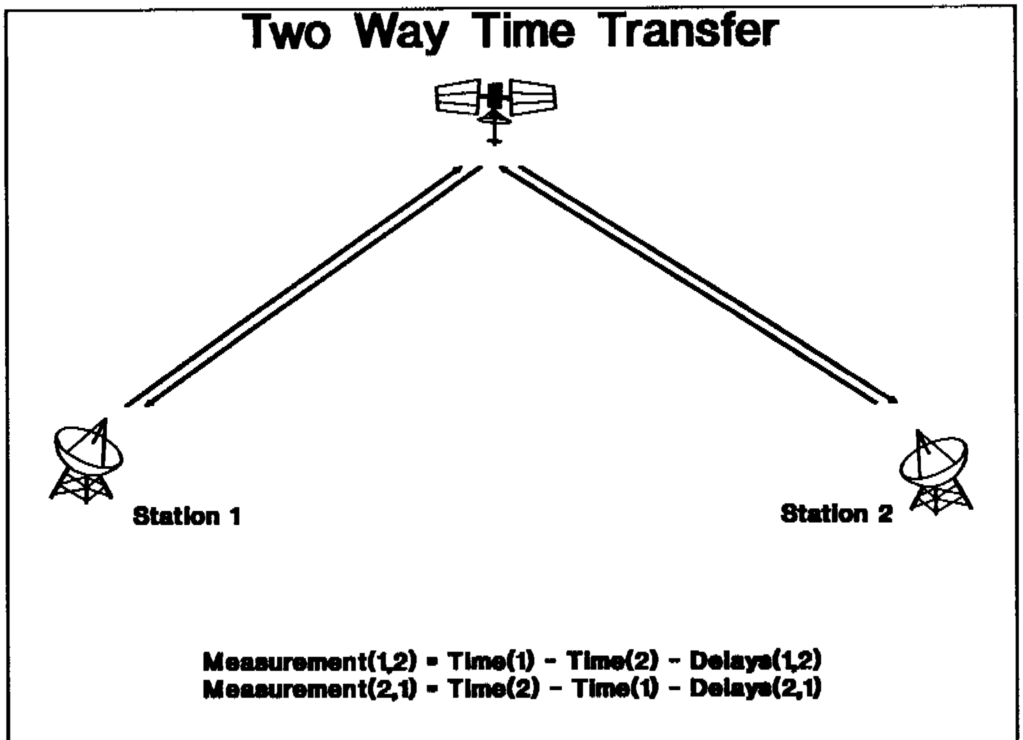


Figure 7

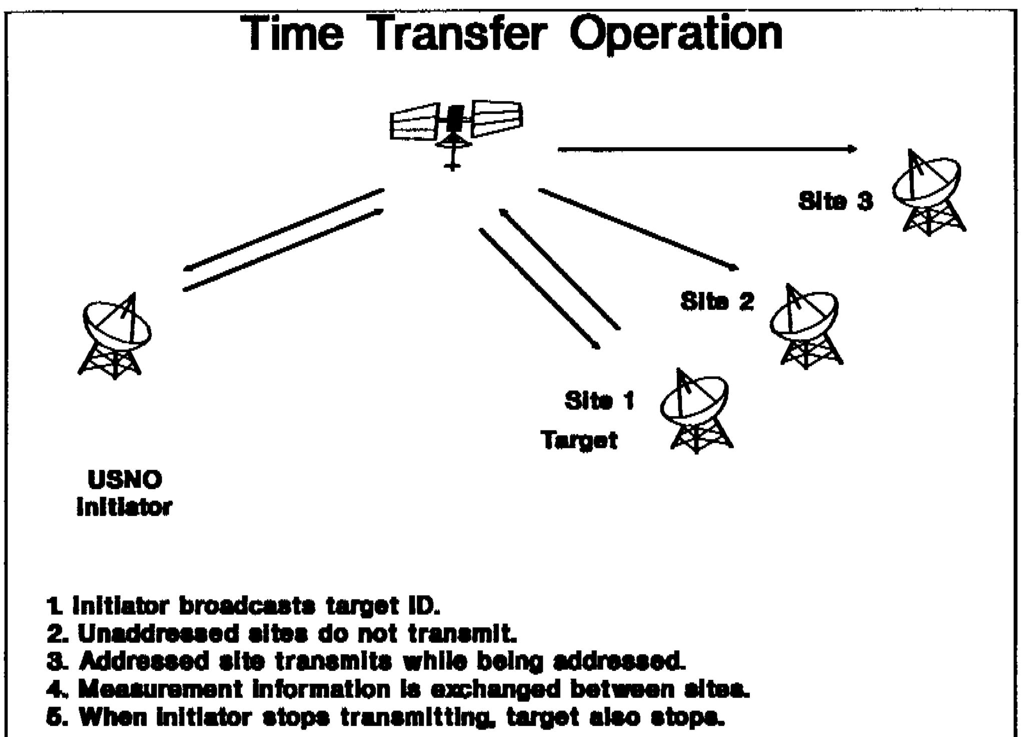
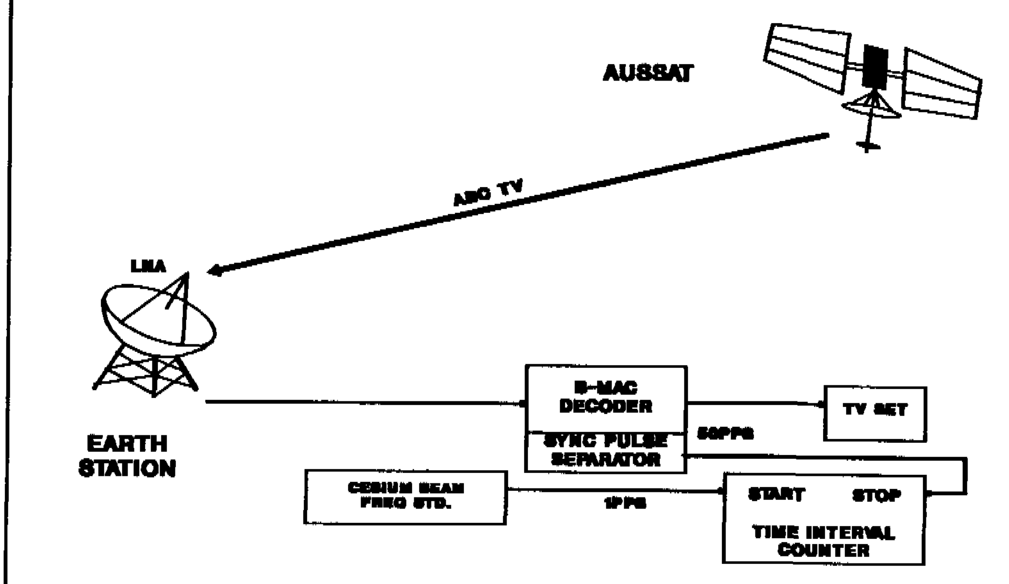


Figure 8



AUSSAT TV Measurement System

Figure 9

QUESTIONS AND ANSWERS

Dr. Claudine Thomas, BIPM: The BIPM is very interested in this experiment because of the difficulty of obtaining a good time transfer link between Australia, New Zealand and America.

Dr. Robert Vessot SAO: Will the modem that you have at NRL, the two-way time transfer modem, operate two-way with more than one station at the same time?

Mr. Gifford: No, not at the same time. It can communicate to a number of stations, but only does time transfer to one at a time.

G. Petit, BIPM: How do you get the precise ephemeris? You need at least three stations to obtain the data. Are there only two stations as shown on your slide?

Mr. Gifford: I only showed two on the slide, but NASA has about five stations in the grid.