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PRELIMINARY COMPARISON OF TIME TRANSFERS VIA LASSO, GPS AND TWO-WAY SATELLITE.

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Abstract.

Presently, the three primary techniques for achieving nanosecond time transfer are Common-View GPS, Two-Way Satellite Time Transfer and the Laser Ranging Technique of the LASSO Experiment. Common-View GPS offers an economical way to achieve near-nanosecond time transfer accuracy using signals from the satellites not affected by Selective Availability. Two-Way Satellite Time Transfers are capable of 100 ps precision and can be calibrated to the nanosecond level to remove systematic errors. The laser ranging technique promises to be the most intrinsically accurate technique because systematic delays can be accurately measured by means of terrestrial target and differential delays between stations can be measured by a transportable calibration station.

Trough the cooperative efforts of several international laboratories, all the three methods were implemented at two stations within Europe, CERGA and TUG. At each of these two stations, a common reference clock to all three systems allows the direct intercomparison of these three state-of-the-art techniques. This paper will discuss the operations at these two stations, present the available data and an intercomparison of it.

Introduction.

The loan of an US portable Two-Way Satellite Time Transfer station to a European laboratory was discussed for the first time during a meeting held in Delft (Holland) in June 1989. After the administrative problems had been solved, and an authorization to transmit a radio signal from France has been obtained, it was finally decided to set this station up at Observatoire de la Côte d'Azur (OCA, Grasse, France). There was a unique chance to compare the three state of the art techniques connected to the same remote atomic clocks: Common-view GPS, Two-Way Time Transfer (MITREX) and the Laser Ranging Technique of the LASSO experiment. The only other European station equiped for these three techniques was Observatory Lustbühel (Graz, Austria). The joint experiment started June 22 1990.

This paper is the following of the paper presented at the last PTTI meeting [1]. It emphasizes the MITREX technique and results between OCA and GRAZ. MITREX data are compared with data obtained from other techniques.

I.General remarks on Two-way Time Transfer.

I.1. Two-way time transfer technique.

Two-way satellite time transfer uses a telecommunication satellite for the comparison of the clocks. Ground stations able to transmit and receive radio signals are needed near the clocks to be compared. Preliminary experiments have showed it has nanosecond level capabilities.

The technique is described on **figure 1**. The two stations transmit simultaneously a coded signal which is referred to their clock 1 Hz signals. This 1 Hz signal starts a time interval counter (TIC). The satellite transponder receives the transmitted signals, and retransmits them to the opposite station. Each station receives the coded signal from the other one, from which the clock signal is extracted to stop the TIC.

The clock offset $H_A - H_B$ is given by [2]:

$$H_A - H_B = 1/2 \{ I(A) - I(B) + (D_{TA} - D_{RA}) - (D_{TB} - D_{RB}) + (D_{AS} - D_{SA}) - (D_{BS} - D_{SB}) + D_{ASB} - D_{BSA} \} + C$$

where

$I(A)$ and $I(B)$ are the results of the TIC measurements,
D_{TA} and D_{RA} are Uplink and Downlink delays in ground station A,
D_{TB} and D_{RB} are Uplink and Downlink delays in ground station B,
D_{AS} and D_{SA} are propagation delays between ground station A and satellite,
D_{BS} and D_{SB} are propagation delays between ground station B and satellite,
D_{ASB} and D_{BSA} are delays in the satellite transponder,
and C is an additionnal delay due to the earth rotation (Sagnac effect).

TIC of picosecond precision (20 ps in the case of this experiment) are needed. The ionospheric delays are negligible for ns clock comparisons, if the frequencies of the signals carriers are high enough [3]. In the case of an experiment with Eutelsat, the carrier frequencies are in the Ku-band (11 - 14 GHz), so the propagation delays cancel (Intelsat uses Ku-band or C-band). The Sagnac effect can be calculated with a sufficient accuracy, even without knowing the exact position of the satellite nor the ground stations [2].

For short distance clocks comparisons, the same transponder is used by both signals, so the delays in the satellite transponder cancel. For long distance, there could be a systematic offset if two different transponders, or two different carriers, are used on board the satellite.

Accuracy also depends on the measurements of internal delays in the ground stations. Two different techniques could be used for that. First one is global calibration of both stations with the use of a third one [2]. This portable station C is used first in parallel with the station A, with the same reference clock, and the delay (A - C) is obtained. Then the portable station C is used the same way in station B, providing (B - C) delay. It is then easy to get the global delay calibration (A - B), but only for a given date. The second technique is an absolute calibration of the delays in the complete ground station [4]. Both techniques are not very simple to use. Untill now, we don't know about the long term stability of the internal delays of ground stations.

1.2. MITREX modem.

The modems used on the link between Grasse and Graz are of the MITREX 25000 type [5], conceived by Prof. Hartl (University of Stuttgart). This device is the only one available for nanosecond Two-way Time Transfer. It needs the 1 pps (pulse per second) and 5 or 10 MHz clock frequencies as input. A 1 pps signal is generated in the modem, which is transformed by spread-spectrum techniques into a binary sequence (2.5 MHz chip rate), and coded as a pseudo-random noise signal up to 8 orthogonal codes. It is then put on a 70 MHz carrier, which is usual for links with telecommunication satellite terminals. On the receive channel, the pseudo-random noise coded signal from the remote station is correlated with the proper code to rebuild a 1 pps signal to compare with the signal coming from the clock.

2. The three techniques between OCA and GRAZ.

2.1. LASSO technique.

The technique has been described in a previous paper [1]. There has been no more LASSO results since the common sessions obtained in November 90.

2.2. GPS technique.

The Common-View GPS time transfer is a well known technique [6]. Therefore only the specifications of the OCA/GRAZ GPS time comparisons will be briefly discussed here.

The receivers are both of the classical NBS type (one channel, C/A code, L1 carrier, calculated ionospheric delays), except that the software used at OCA was partly of a different type than in GRAZ concerning the use of Bloc II satellites. This is no longer the case since last December. Both stations are following the BIPM Common-View schedule implemented every six months, but during the first part of the experiment only the Bloc I satellites have been used, to avoid any influence of the Selective Availability (SA). The Time section of the BIPM has calculated a specific schedule for the OCA/GRAZ link, in order to get a minimum of one track every half hour. In this way, the involved GPS receivers cover the Two-way and the LASSO sessions. The schedule was implemented on MJD 48244, December 19. Since then, all available satellites (including Bloc II without SA) have been used.

The coordinates of both antennas are very well known. They have been calculated by BIPM from laser geodetic points not far from receiver's antennas. This means that the coordinates' unaccuracy for the OCA/GRAZ link is less than 10 cm, and that its influence on the accuracy of the time comparisons is negligible.

2.3. Two-way MITREX link.

2.3.1. OCA earth station.

The transmit and receive terminal at OCA is of the VSAT type (Very Small Aperture Terminal). The diameter of the antenna is 1.8 m. Its approximate position is: 06° 55' N, 43° 45' E. The OCA earth station is described in **figure 2**, including the link between the atomic clock giving UTC to the GPS receiver. The main telecommunication characteristics of this station are G/T = 21 dB/K and EIRP = 49.2 dBW , when the power is set to achieve a C/N_0 (Carrier to Noise) of 55 dB/Hz (clear sky conditions).

2.3.2. GRAZ earth station.

The GRAZ earth station is described on **figure 3**. The steerable antenna of the earth station, dedicated to satellite telecommunication experiments, has a diameter of 3 m. The characteristics are G/T = 24 dB/K and, according to Eutelsat link budget calculations, EIRP = 52 dBW to obtain a C/N0 of 55 dBHz (maximun EIRP of this station is 72 dBW). The configuration of the different devices is slightly different from that of the OCA MITREX earth station. One can see that there is a synchronization device providing the 10 MHz frequency to the Modem.

The approximate position of the earth station is 15° 30' E, 47° 04' N.

On January 14 1991 (MJD 48270), a change of the reference clock was necessary at GRAZ station. The running clock was a HP option 04, the new one is a normal tube clock.

2.3.3. Eutelsat satellite.

The SMS (Satellite Multi-Service) transponder 14 of the satellite Eutelsat I-F2 was used during the first part of the experiment. A change of satellite (switch of SMS service between I-F2 and new satellite I-F4) occured October 16, because I-F2 was too high regarding the nominal position, and was too old for repositionning. The nominal position of both satellites was 7° East ± 0.1°. No operation on the ground stations has been needed. The common transmission (Tx) and reception (Rx) carrier frequencies of both stations were:

$$F_{Tx} = 14022.000 \text{ MHz}$$
$$F_{Rx} = 12522.000 \text{ MHz}$$

The choice of the channels on the satellite transponder was limited because of the inability of fine adjustments to the frequency of the VSAT station. The on-board oscillator of the satellite has proven to be very stable during our experiment, which was very important for the use of a VSAT station [7]. But this oscillator was steered by a Eutelsat ground station. This will no more be the case in the next future with the Eutelsat II generation which will have a free on-board oscillator [8].

2.3.4. Procedure.

The regular MITREX clocks comparisons started the 22nd of June 1990. They were interrupted from October 12 until November 9, because there was some water in the filter of the receiving part of the OCA antenna. It will probably stop at the end of March 1991.

We have used a regular tracking schedule of 3 sessions a week (Monday, Wednesday, and Friday). Each of these satellite sessions started at 12:00 UTC, and ended at 12:30 UTC. The MITREX measurement sessions were 2 min long [9], one point every second, except at the start of the experiment where 4 min sessions were scheduled. This has been organized to be sure to get a 2 min long usable session. After a while, the MITREX clocks comparison proved to be working well and only 2 min sessions have been scheduled. At the end of August, the three sessions of one week were scheduled to last 20 min. A look at the results (see next chapter) proves that the choice of 2 min long sessions was enough for the OCA/GRAZ MITREX link.

During the first part of the experiment, before interruption at OCA, two MITREX sessions were scheduled at 12:15 and 12:20 UTC, with the OCA 1 pps reference used to start the TIC. After the interruption at OCA, a third MITREX session has been added at 12:27 UTC, with a 1 pps reference issued by the Modem, called 1 pps Tx.

3. Results.

The whole campaign of MITREX and GPS measurements can be seen on **figure 4**. The long term drift of the clocks difference (118 ns/day) has been removed. When considering the events that occured during this period of time, it has been decided to split the results in three different parts:

Part I. Before OCA MITREX intermission (June 22 to October 10).

Part II. After OCA intermission (November 9 to January 14).

Part III. After change of the reference clock at GRAZ (until February 22).

No calibration has been made on the two-way MITREX link between OCA and GRAZ.

The distance between OCA and GRAZ is about 800 km. The GPS precision between these two stations is usually around 2 ns. The GPS accuracy is estimated to be more or less 2.5 ns [6].

The precision obtained for LASSO sessions in November 1990 is around 1 ns. There has been no calibration for the LASSO experiment. Because there has been only a few measured LASSO points attached together no LASSO result can be seen on the common results diagram (figure 4). See [1] for more details.

3.1. Two-way Precision.

For the precision plots, selection of raw data points within a window of ± 5 ns was done. Very few points have been dropped.

The plot of the precision values of the 12:15 UTC and 12:20 UTC sessions can be seen on **figure 5** for the Part I of the experiment. The mean values of the precisions obtained are:

$<sigma_{12:15}>=<sigma_{12:20}>= 0.83$ ns.

Nearly all points are below 1 ns, except for one noticeable point named A. Raw data of the MITREX session for point A are on **figure 6**. One can see that something occured right in the center of the session.

For Part II and III of the experiment, **figure 7** shows the precision of the values, for the 12:15 UTC, the 12:20 UTC and the 12:27 UTC sessions. One can see the influence of the presence of an unknown clean carrier (measured at 12523.667 MHz) in the MITREX bandwidth on December 10: precision data are degraded up until nearly 1.5 ns.

The pps_{Tx} remained very stable compared to the OCA pps_{Ref}, and its influence can be seen on this figure. For Part II of the experiment, the mean values of the precision were:

$<sigma_{12:15}>=<sigma_{12:20}>= 0.85$ ns, $<sigma_{12:27}>= 0.78$ ns.

Some points of Part III of the precision data seem to be greatly degraded. Because of the strong relationship between the two MITREX stations in the measured data, it is not easy to separate effects coming from one location or the other. These points represent MITREX sessions that are globaly degraded, giving some sigma values over 1.4 ns. It could come from MITREX links that were for some reason bad during these sessions.

Mean values of the precision for Part III are:

$<sigma_{12:15}>= 0.90$ ns, $<sigma_{12:20}>= 1.01$ ns,

$<sigma_{12:27}>= 0.89$ ns

What appears to be a small global degradation, could come from the change of the GRAZ clock.

3.2. Accuracy.

Figure 8 shows the plots of three 20 min sessions on MJD 48123 - 125 - 127. When looking carefully at the data, one can see how MITREX comparisons follow the 120 ns/day offset, giving an offset of nearly 1.7 ns/20mn, due to the long term drift of the clocks. For 2 min sessions, this offset is around 170 ps, and so remains negligible compared to the noise of the MITREX link.

The calibration Ref-Tx data are ploted on **figure 9**. This is the only easy available Modem calibration, and its use is necessary when Two-way is compared with other techniques: it has to be refered to the same clock signal. These data have been measured just before the 12:15 UTC sessions. They have been obtained by using the pps_{Tx} output of the Modem to stop the TIC. The standard deviations of the calibration data over the whole measurement period are:

Sigma $_{Ref-Tx\ OCA}$ = 1.9 ns, Sigma $_{Ref-Tx\ GRAZ}$ = 0.4 ns.

These calibration data have been used for the computation of the GPS-MITREX data.

Figure 10 shows the plot of GPS-MITREX data. A simple mean over the 2 min sessions has given the MITREX points. Vondrak smoothing has been applied to the GPS data to interpolate the GPS points to the middle of the appropriate Two-way sessions. The goal of the Vondrak smoothing is to minimize the noise coming from the method of comparison, in order to get only the noise of the clocks. The smoothed values are interpolated for the desired time using Lagrange's interpolation formula. Vondrak smoothing acts as a low-pass filter. For Part I and Part II of the experiment, a Vondrak cut-off period of about 1.5 days has been used. After the change of the GRAZ clock, a Vondrak cut-off period of 0.5 day has been applied. Three points have been excluded, because there were only few GPS traks during these days, and the results of the smoothing and interpolation were not reliable. The mean values of GPS-MITREX data and their standard deviations have been computed:

$<GPS\text{-}MITREX>_{Part\ I} = -205.8$ ns, Std $Dev._{Part\ I} = 2.6$ ns,

$<GPS\text{-}MITREX>_{Part\ II} = -210.5$ ns, Std $Dev._{Part\ II} = 3.1$ ns,

$<GPS\text{-}MITREX>_{Part\ III} = -207.3$ ns, Std $Dev._{Part\ III} = 3.6$ ns.

The value of around -200 ns comes from the difference of all the delays at both stations, including the delays of MITREX ground stations which have not been measured.

There is an offset of about 5 ns between the mean values GPS - MITREX before and after the interruption at OCA. This can not be a consequence of the change of satellite at this time, because delays in the transponder of the satellite cancel. The transmit and receive electronics of the OCA antenna were dried. This operation can not explain all the 5 ns offset. It could also have arisen from a change in the delays at one (or both) station(s), either MITREX ground stations, or GPS receivers.

Another explanation could be the slow daily variation (4 min) of the sidereal period of the GPS satellites. At the start of the experiment, there was a group of satellites that was scheduled to be observed around the time of the MITREX measurements (**figure 11.1**). As time went by, the tracks slowly moved away (**figure 11.2**). After OCA intermission, there were no more satellites available for GPS measurements around the time of the MITREX sessions (**figure 11.3**), until the new schedule was implemented on December 19, for which BIPM has computed a specific schedule between OCA and GRAZ, including nearly one tracking every half of an hour (**figure 11.4**).

Conclusions.

The results obtained with MITREX on a 800 km basis with one of the stations being a VSAT are very promising. The precision achieved for normal sessions is generaly around 0.8 - 0.9 ns. Accuracy variations of the difference GPS-MITREX reach 10 ns for a 9 months experiment. If the 5 ns offset before and after the OCA interruption is considered as a change in the delays at one location, which could be some way measured, then the MITREX/GPS comparison on the OCA/GRAZ link gives an uncertainty of one sigma of around 3 ns, which scarcely exceeds the uncertainty of GPS accuracy alone.

The question of the delay calibration in ground stations, and their possible changes with time, remains an essential problem to be solved for nanosecond time transfer with Two-way technique. But other points are of particular importance: stability of the station frequency distribution, relationships with UTC(lab), all other delays involved, TIC reliability, trigger levels,...

One of the goals of future Two-way experiments should be an attempt to look at the influence of mixing several pseudo-random noise coded signals into one satellite transponder. To share a transponder with other users at the same time, could simplify administrative problems and reduce prices for operational regular Two-way links.

Acknowledgements.

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"Preliminary comparison between GPS and Two-way Satellite Time Transfer."
42nd An. Symp. on Freq. Control, 1988.

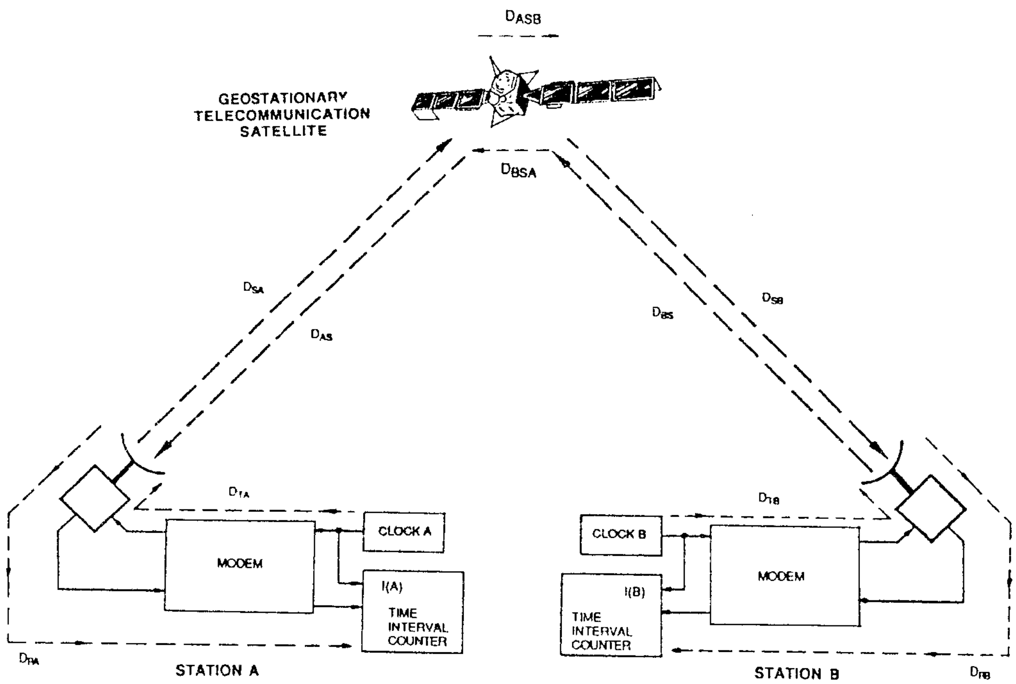


Figure 1. Two-way time transfer technique.

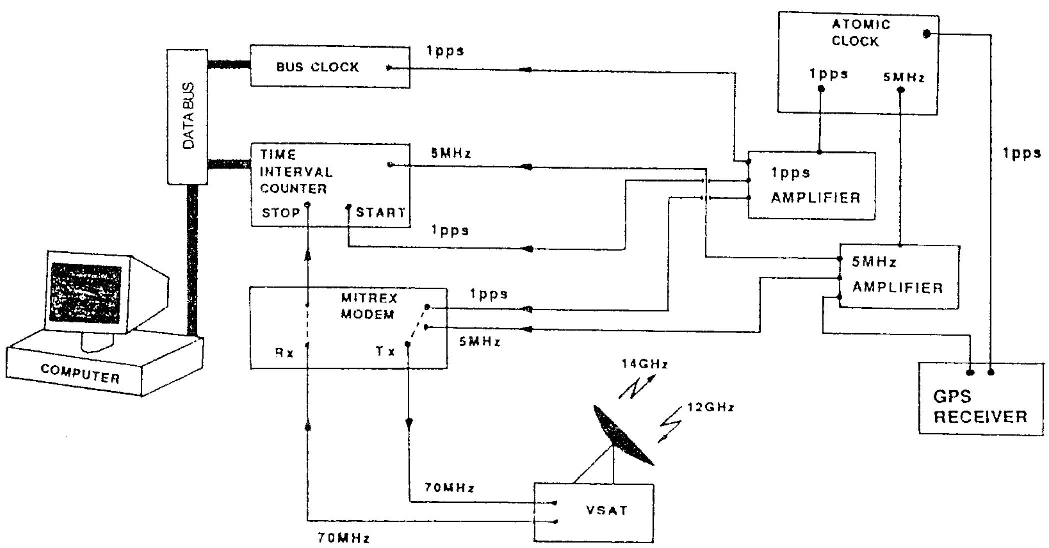
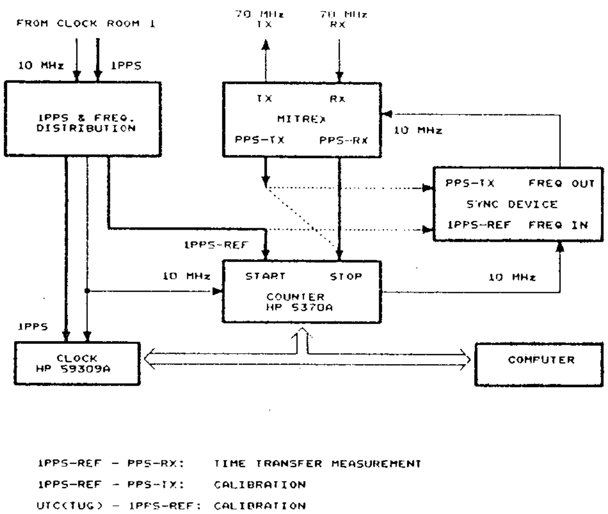


Figure 2. OCA earth station.



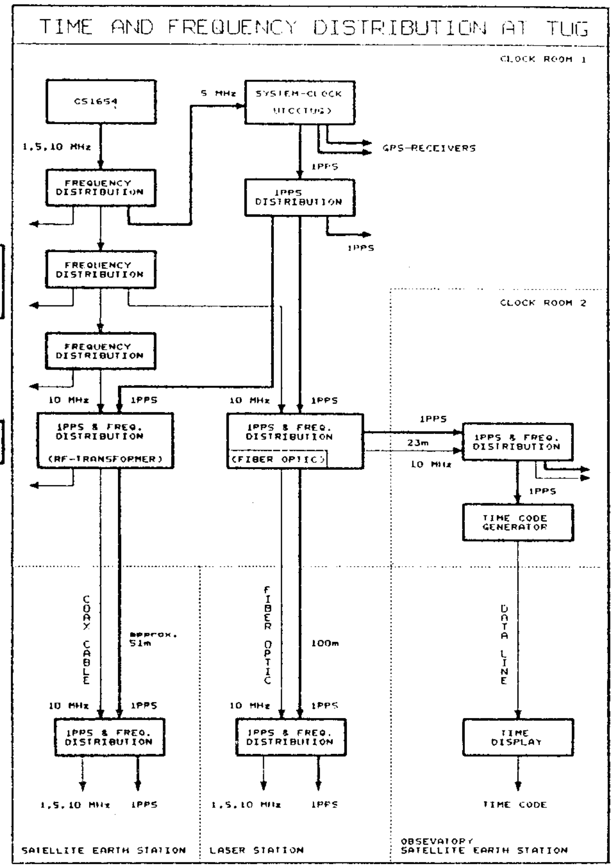


Figure 3. GRAZ earth station.

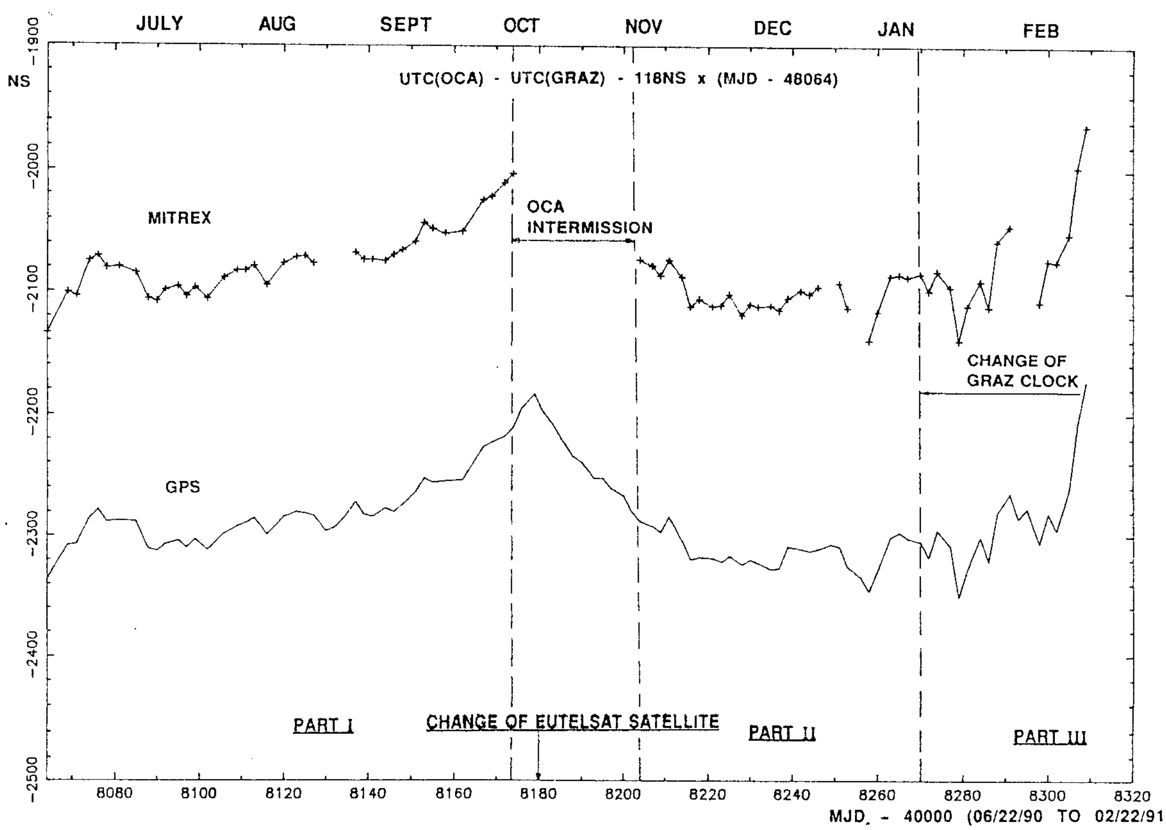


Figure 4. Experimental MITREX and GPS results.

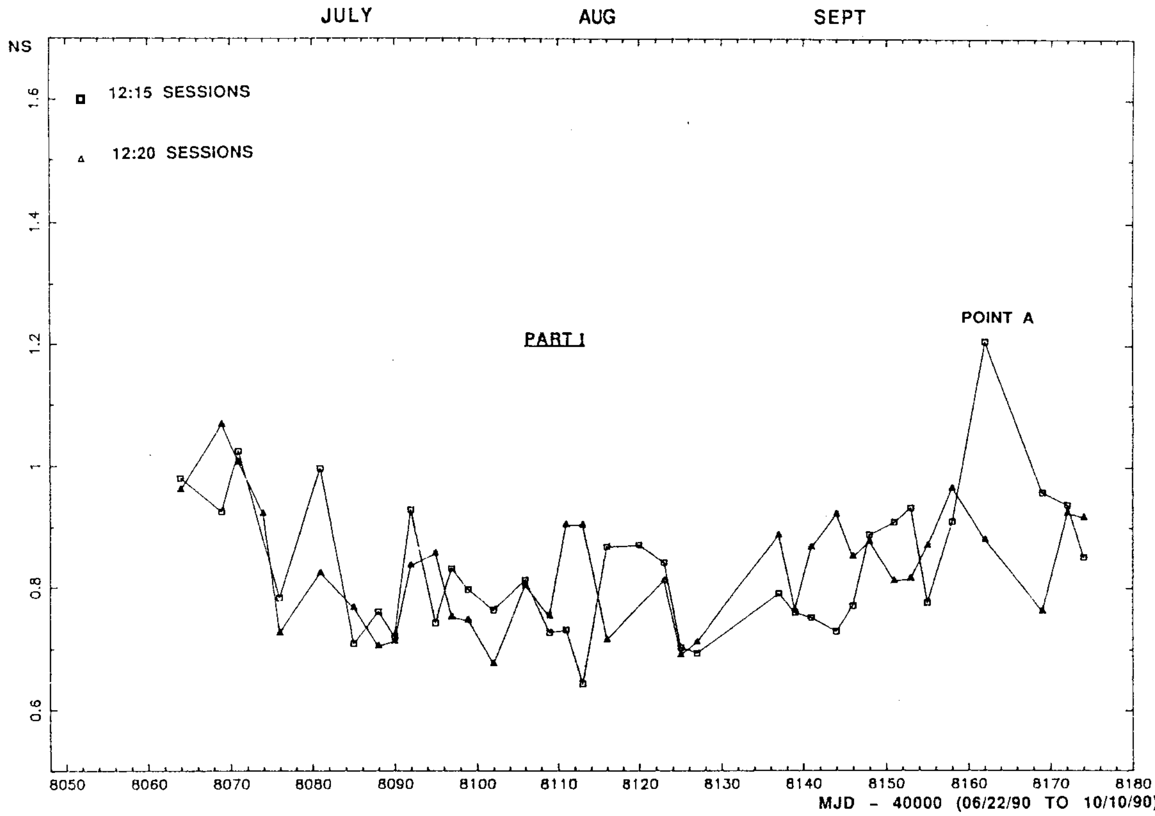


Figure 5. MITREX precision Part I.

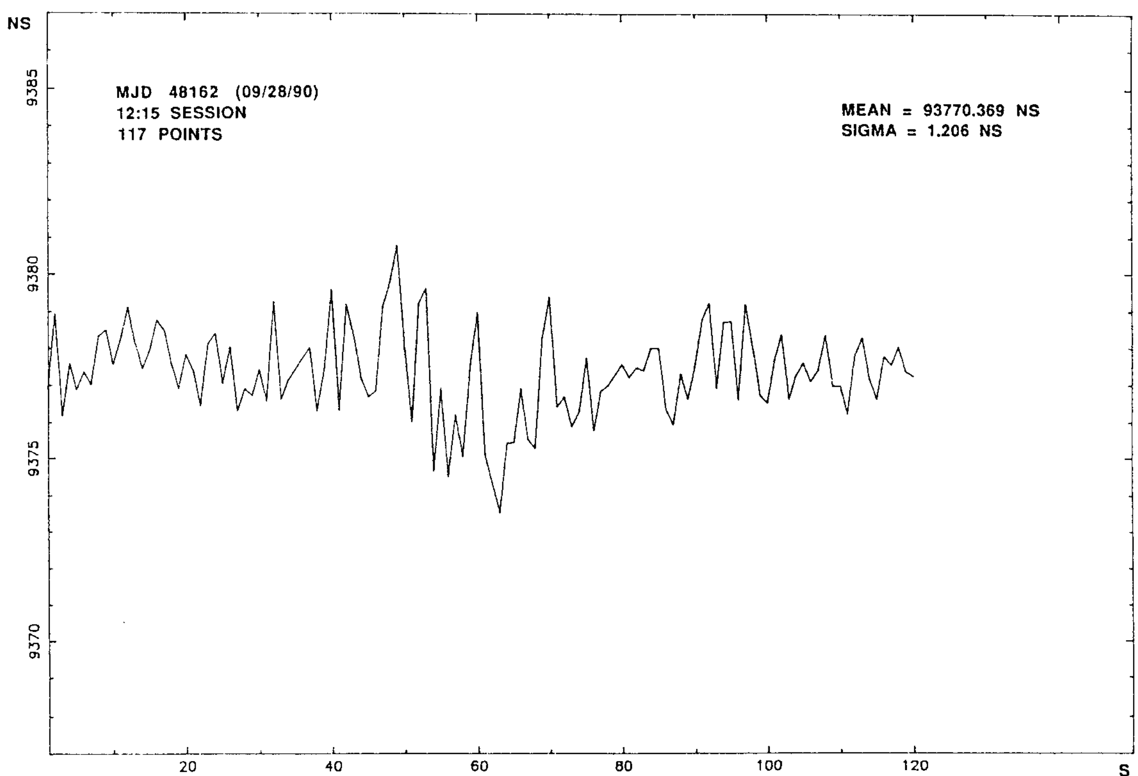


Figure 6. Raw MITREX data of point A of figure 5.

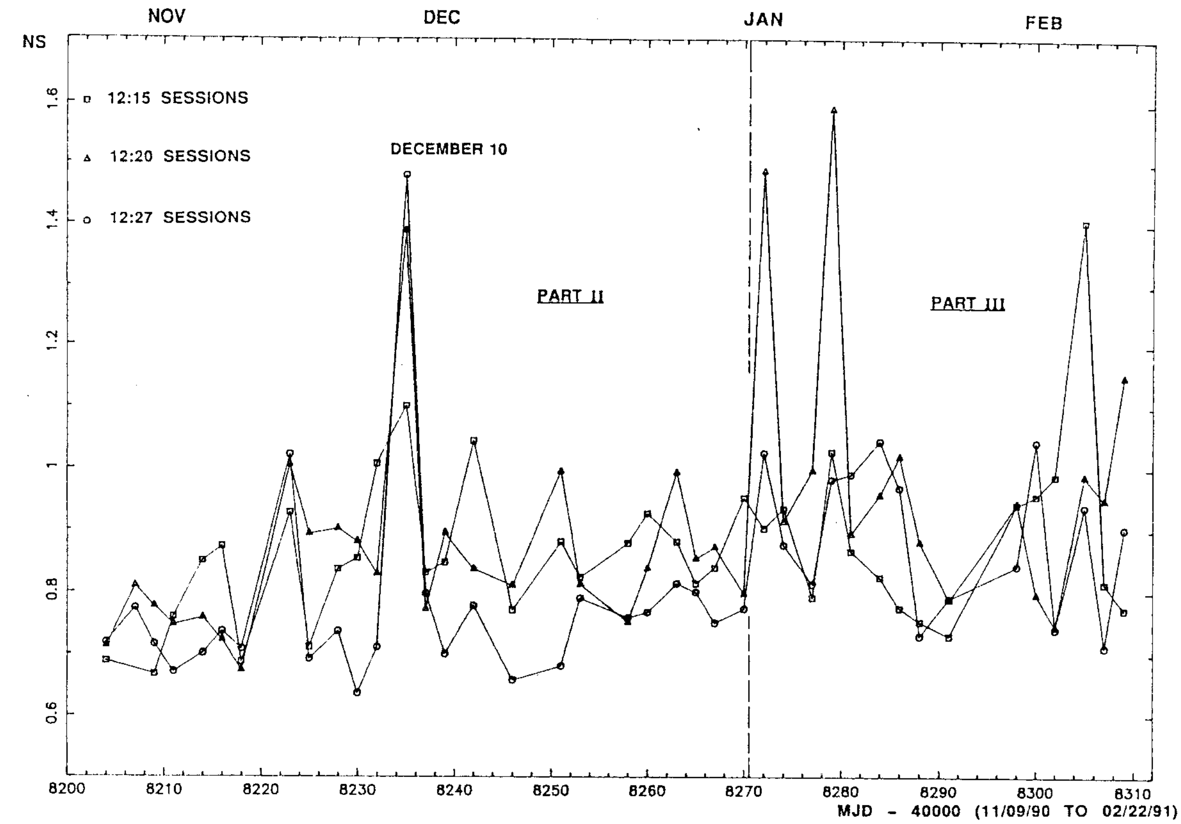


Figure 7. MITREX precision Part II and Part III.

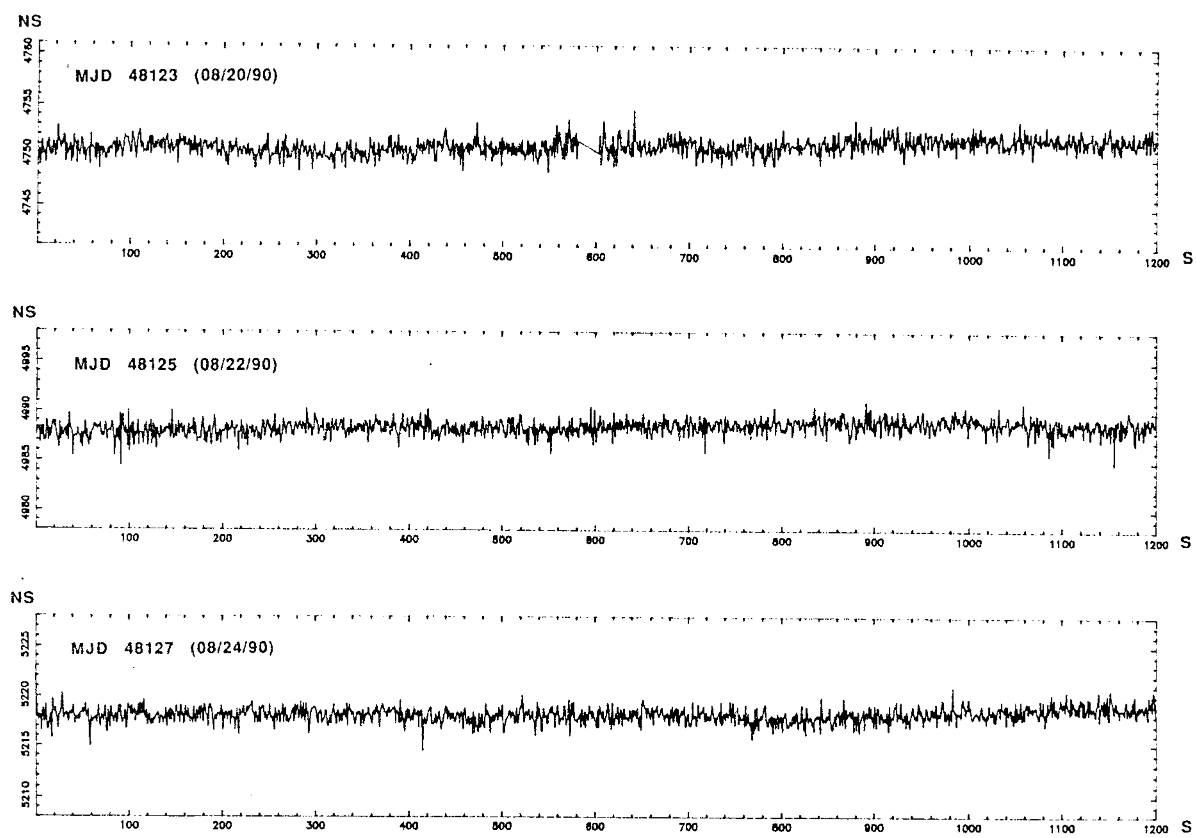


Figure 8. Plots of 20 mn sessions.

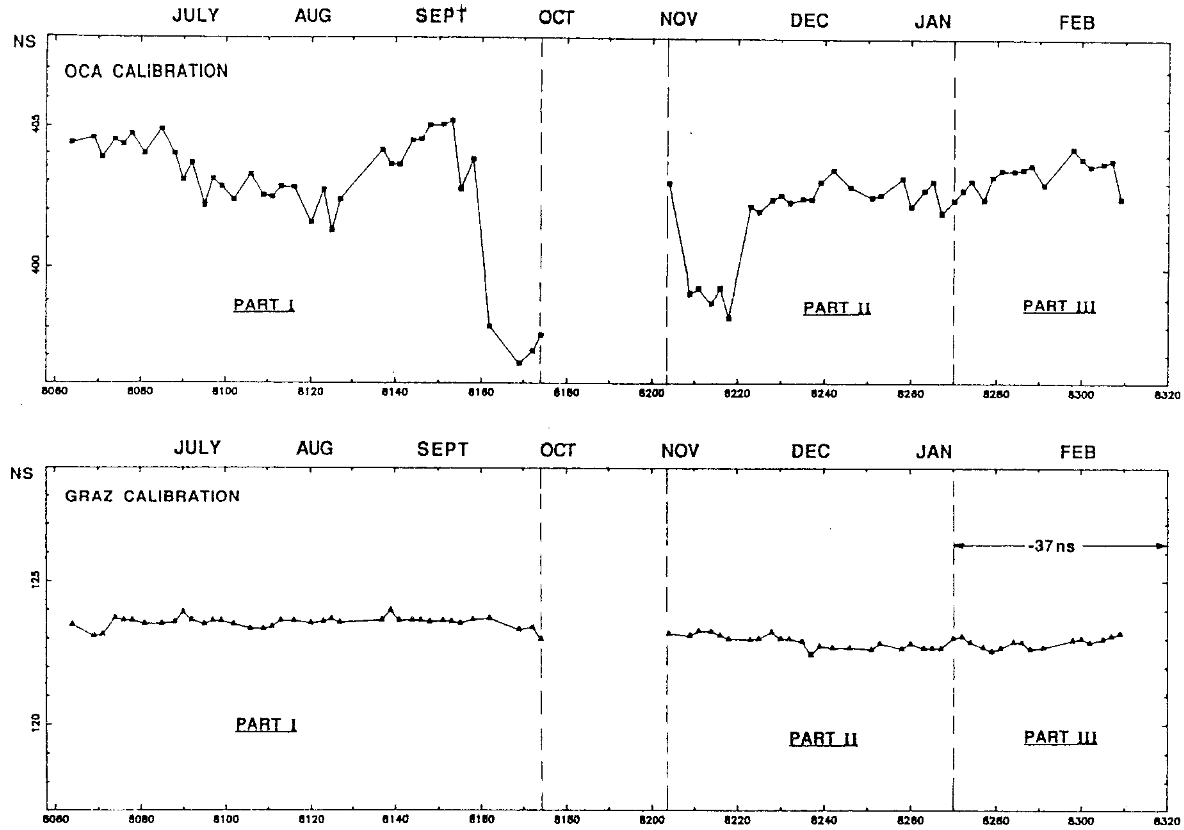


Figure 9. Ref-Tx calibrations.

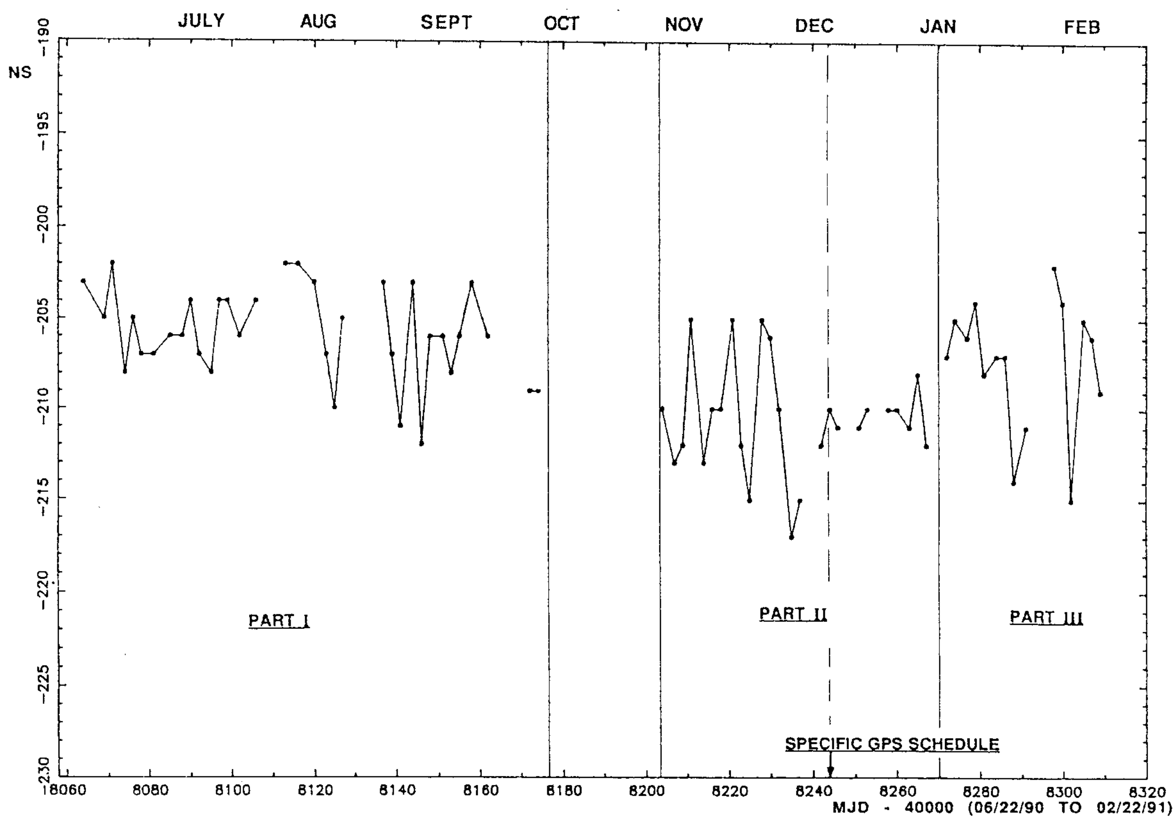
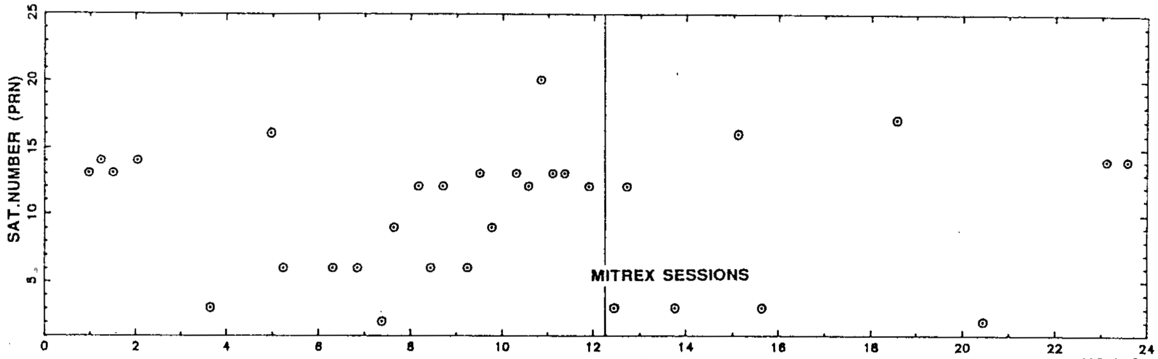
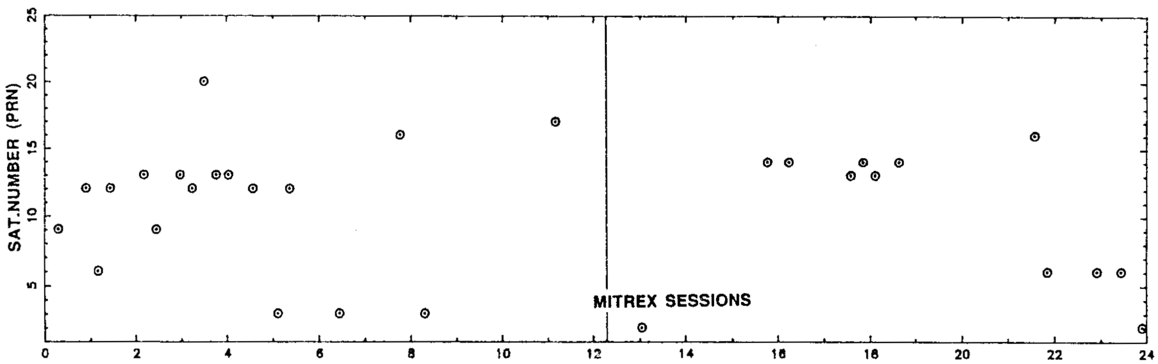


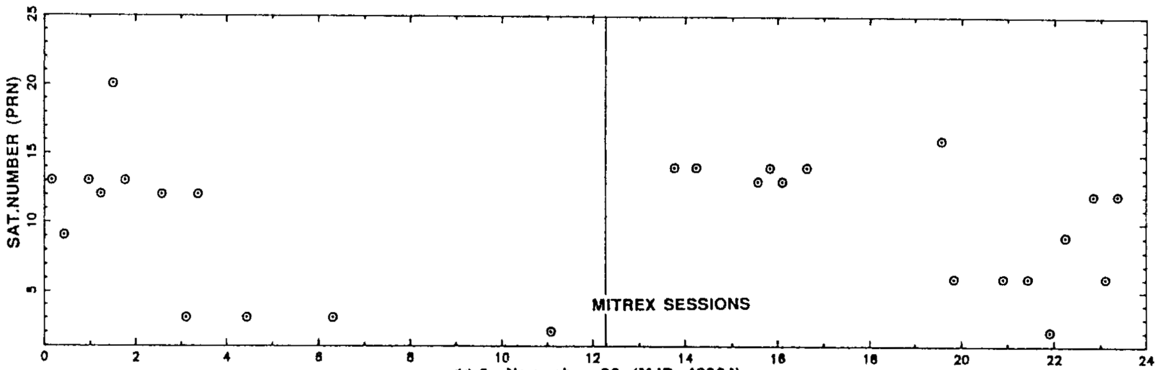
Figure 10. GPS - MITREX.



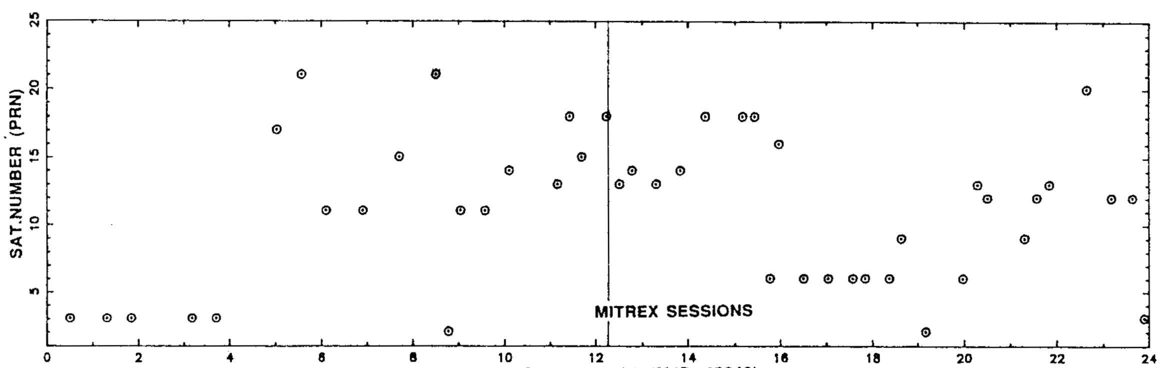
11.1. June 22 (MJD 48064).



11.2. October 10 (MJD 48174).



11.3. November 09 (MJD 48204).



11.4. December 24 (MJD 48249).

Figure 11. GPS traking schedules.