# STATUS REPORT ON A SYNCHRONIZATION EXPERIMENT BETWEEN EUROPEAN TIME SCALES USING ECS GEOSTATIONARY SATELLITE

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**Abstract**

To test the capabilities of a synchronization system based on the use of the passive television method applied to the signals broadcasted by a geostationary satellite, namely ECS telecommunication satellites, a time synchronization experiment between the time scales of the Istituto Elettrotecnico Nazionale (IEN) and other European laboratories (URE - Czechoslovakia, TUG - Austria, AOS - Poland, ASMW - Democratic Rep. of Germany, VSL - Netherlands, STA - Sweden), was started in July 1988 and is still in progress.

The results obtained in the first year of comparisons are presented and possible solutions to the satellite position determination problem are considered together with the measurement results of the receiving station delay performed at IEN.

## 1.- Introduction

The synchronization of time scales by means of the television passive method using the ground TV networks, has been experienced during the last twenty years by most of the laboratories involved in time and frequency metrology. It is known that, within the view of a common TV transmitter, this simple and inexpensive method can yield a timing precision of about 10 ns (1σ). Over extended geographical areas, where different transmitters interconnected by microwave links have to be used, the precision is lowered by at least one order |1| due mainly to the differential propagation delay variations between the measuring sites. Nowadays there seems to be a chance to overcome these problems by using the TV method with the signal received from geostationary telecommunication satellites that covers nearly continental areas with different TV programs.

Some synchronization experiments between time scales using this kind of technique were already performed in some countries |2,3,4,5,6|, but no attempt has been made to elaborate the method, both technically and organizationally, to a degree that it could serve on a routine basis to various users.

This paper will give a status report about a synchronization experiment, which started in July 1988 and is still continuing, between some European laboratories, aiming to establish a system based on the reception of television signals from a geostationary satellite which would allow for high precision time and frequency comparisons at moderate costs all over Europe.

## 2.- Estimation of Timing Accuracy

The use of the television signals broadcasted by a geostationary satellite for the synchronization of clocks has some advantages but also one major drawback. If it is evident in fact that the measurements are performed on signals coming from a unique source and that the propagation effects on their carrier frequency (11 GHz) are negligible, the key question that has to be solved is how to determine the satellite istantaneous position to evaluate the differential delays with sufficient accuracy. Obviously, the differential delay error will be equal to the timing error. The problem is that the satellite in the geostationary orbit is not fixed with respect to its observers; due to the natural forces it is in a permanent motion maintained within a so called "parking box" by occasional corrective manoeuvres initiated by the control tracking center on the Earth. Generally the satellite position may not deviate by more than 0.1° from its nominal position, both in longitude and latitude |7|. Though small the deviation seems, it may still cause unacceptable changes of the differential delay depending, for a given satellite, on the position of the observers.

The geostationary satellites chosen for this synchronization experiment belong to the family of European Communication Satellites (ECS) of the European Space Agency (ESA). In the followings we will deal in particular with ECS 5 satellite, that is positioned at 10 degrees East to estimate the time synchronization error that one can expect over the European continent if the satellite coordinates are affected by unpredictable variations. The zone covered by the ECS satellites is shown in Fig. 1 where is outlined also the area served by the spotbeam west that has been used in our experiment.

Let us consider two receiving sites A and B and a geostationary satellite S, whose positions relative to a rotating equatorial geocentric reference frame can be expressed with the following vectors:

$$\begin{aligned} \vec{r}_A &= \vec{r}_A(\theta_A, \lambda_A, r_A) \\ \vec{r}_B &= \vec{r}_B(\theta_B, \lambda_B, r_B) \\ \vec{S} &= \vec{S}(\theta_S, \lambda_S, r_S) \end{aligned} \qquad (1)$$

where: $\theta_{A,B,S}$ is the geodetic latitude
$\lambda_{A,B,S}$ is the longidue referred to Greenwich
$r_{A,B,S}$ is the distance from the center of the Earth

The differential propagation delay of the signals transmitted by the satellite and received at stations A and B, can be expressed as:

$$t_p = \frac{1}{c}\left[|\vec{S}-\vec{r}_A| - |\vec{S}-\vec{r}_B|\right] = \frac{1}{c}\left[\rho_A-\rho_B\right] \qquad (2)$$

where $\rho_A$ and $\rho_B$ are the distances of the receiving stations from the satellite and c is the mean value of the speed of light along the propagation path.

To compute the variation of the differential propagation delay $t_p$, between the two stations, that affect the synchronization results, we have considered the satellite movements both in longitude $\Delta\lambda_S$ and latitude $\Delta\theta_S$ neglecting any change in its range. This assumption is justified as a first approximation because in our case, as can be verified in the followings, the variation in range is nearly one fifth compared with the variations in latitude and longitude.

Differentiating the term $(\rho_A^2 - \rho_B^2)$ versus $\Delta\theta_S$ and $\Delta\lambda_S$, assuming that the variations of $(\rho_A + \rho_B)$ due to the satellite motion are negligible with respect to those of the term $(\rho_A - \rho_B)$ and, being the latitude of the satellite $\theta_S$ very close to 0 degrees, we can write the approximate expression:

$$\Delta(\rho_A-\rho_B) = \frac{2Sr_A}{\rho_A+\rho_B}\left[\cos\theta_A \sin(\lambda_S-\lambda_A)\Delta\lambda_S - \sin\theta_A \Delta\theta_S\right] - \frac{2Sr_B}{\rho_A+\rho_B}\left[\cos\theta_B \sin(\lambda_S-\lambda_B)\Delta\lambda_S - \sin\theta_B \Delta\theta_S\right] \qquad (3)$$

Solving this equation for different "B" sites in Europe after having fixed station A at IEN - Torino, several values of $\Delta t_p = \Delta(\rho_A - \rho_B)/c$ have been found assuming the worst case of 0.1° of variation both in latitude $(\Delta\theta_S)$ and longitude $(\Delta\lambda_S)$ of ECS 5. In Fig. 2 are reported the contours of the time errors that can affect the synchronization values as obtained from equation (3).

## 3.- Experiment Description

To test the potentiality of a synchronization system based on a geostationary satellite using the passive television method, four European laboratories began on July 1988 an experiment that is still in progress and were joined later on by other three in the frame of a Euromet project. The participating laboratories at November 1989 are the following ones:

- Astronomical Latitude Observatory (AOS) - Borowiec, Poland
- Amt für Standardisierung, Messwesen und Warenprüfung (ASMW) - Berlin, Dem. Rep. of Germany
- Istituto Elettrotecnico Nazionale (IEN) - Torino, Italy
- Ústav Radiotechniky a Elektroniky (ÚRE) - Praha, Czechoslovakia
- Swedish Telecommunications Administration (STA) - Stockholm, Sweden
- Technische Universität (TUG) - Graz, Austria
- Van Swinden Laboratorium (VSL) - Delft, Netherlands

In Table 1 are reported the baselines between the laboratories involved in the experiment.

**Table 1 - Baselines between the laboratories**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| IEN | | | | | | | |
| AOS | 1064 | | | | | | |
| ASMW | 937 | 236 | | | | | |
| STA | 1726 | 769 | 797 | | | | |
| URE | 765 | 301 | 266 | 1033 | | | |
| TUG | 649 | 590 | 614 | 1356 | 348 | | |
| VSL | 813 | 869 | 634 | 635 | 736 | 525 | |
| | IEN | AOS | ASMW | STA | URE | TUG | VSL |

ECS satellites of Eutelsat and in particular, since mid-October 1988, ECS-5 placed in a geostationary orbit at 10° East longitude, were chosen for the experiment.

Among the television channels available from these satellites, RAI UNO program broadcasted at 11.009 GHz in horizontal polarization by a 20 W transponder has been used. At each site was arranged a measurement setup of the kind shown in Fig. 3. Some technical details about the receiving stations are reported in Table 2 together with the antennas coordinates.

**Table 2 - Ground stations specifications**

| Laboratory | PARAMETER | | | | | | |
|---|---|---|---|---|---|---|---|
| | Latitude | Longitude | Height | Antenna Ø | LNA | IF BWT | Time ref. |
| AOS | 52°16'37.0" N | 17°04'23.7" E | 129 m | 2 m | 1.4 dB | 40 MHz | UTC(AOS) |
| ASMW | 52°27'14" N | 13°37'01" E | 50 m | 0.9 m | 1.4 dB | 30 MHz | UTC(ASMW) |
| IEN | 45°00'53.6" N | 07°38'20.1" E | 297 m | 3 m | 1.9 dB | 40 MHz | UTC(IEN) |
| URE(TP) | 50°07'53" N | 14°27'09" E | 300 m | 3 m | 2 dB | - | UTC(TP) |
| TUG | 47°04'01.5" N | 15°29'35.5" E | 534 m | 1.5 m | 1.4 dB | 30 MHz | UTC(TUG) |
| VSL | 51°59'58.9" N | 04°22'50.7" E | 60 m | 3 m | 4.5 dB | 40 MHz | UTC(VSL) |
| STA | 59°09'54.2" N | 18°08'13.5" E | 109 m | - | - | - | UTC(STA) |

Every day two sets of 20 time interval measurements between the local 1 PPS reference and the trailing edge of the first field synchronizing pulse of the RAI UNO video signal were measured starting at 08:15:01 UTC and 20:15:01 UTC in each laboratory.

In two sites, namely IEN and TUG, time differences between the local 1 PPS and the satellite TV signal were also measured every ten minutes from November 1988 to March 1989 to get information about the satellite movement.

All the participating laboratories collaborate to the international atomic time scale and are linked to BIPM using either the GPS time link (IEN, TUG, VSL, STA) or the television link (AOS, ASMW, TP).

Satellite position data for Novemoer and December 1988 have been supplied by the ESA satellite control station at Redu (Belgium) that is charged of ECS satellites tracking. These data have been used to investigate the satellite movement and to correct the synchronization data.

## 4.- Measurement results

The evaluation of the results obtained in the ECS synchronization experiment, has been focused on the period for which ESA-Redu orbital elements data were available. From these data, the variations of ECS 5 in latitude, longitude and range from the origin of the rotating reference frame have been computed and reported in Figure 4 where it can be seen that the variations around their mean values are within $\pm 16$ km (range), $\pm 0.07°$ (long.), $\pm 0.08°$ (lat.). Some discontinuities due to orbital manoeuvres can also be observed.

In Fig. 5 are reported the differences between the ECS measurements performed every ten minutes at IEN and TUG relative to the beginning of November 1988 where the diurnal variations due to the satellite movement are clearly recognizable. Each point in this figure represents in microseconds, with a constant value subtracted, the difference of the distances of the satellite from IEN - Torino and from TUG - Graz versus time. The interruptions in the curve are due to the lack of TV transmissions.

For all the computations performed on the measured data whose results are reported in all the next graphs, the linear regression parameters, computed at every laboratory for each series of 20 time interval readings, were used. This solution was chosen to reduce the amount of information to be exchanged among the laboratories. Together with the linear fit parameters, the standard deviation of the residuals was computed after the rejection of the outliers by means of a statistical filter.

In Fig. 6 have been reported the time differences between UTC(IEN) and UTC(TP) obtained from ECS 4 and ECS 5 (*) synchronization measurements from

(*) The following ECS satellites were used in the course of this experiment:
ECS 4 from mid-Sep. 88 to mid-Oct. 88 (10°E)
ECS 5 from mid-Oct. 88 onward (10°E)

mid-September 1988 up to June 1989. Two curves have been traced to distinguish the two daily sets of measurements (08:15 and 20:15 UTC). The peak-to-peak variation of each curve, if the mean rate between the two time scales is removed, is of the order of 5 microseconds that is well within the time error estimated previously and reported in Fig. 2.

The results of the time comparisons performed between IEN and the other metrological laboratories (AOS, ASMW, TP-URE by means of ECS 5 in November-December 1988 together with those corrected for the ESA satellite position data and the BIPM data, from Circular-T, have been plotted in Fig. 7.

From these graphs it can be seen that the peak-to-peak time excursions are reduced to some hundreds of nanoseconds, if one corrects for the differential propagation delay variations, and that the mean rates of the time scales compared are in good agreement with those obtained from BIPM data. As regards to the uncertainty of these comparisons, worst-case residuals at the microsecond level have been found.

As a sample of the dipendence of the peak-to-peak fluctuations from the baselines between the laboratories, in Fig. 8-a are reported the differences between UTC(TP) and UTC(ASMW) having a baseline of 266 km, and in Fig. 8-b those obtained in the case of UTC(IEN) and UTC(STA) that have a baseline of 1726 km. The time step of the order of 1 us that can be noticed in the graphs of UTC (ASMW) is probably due to instrumental changes in the ECS measurement system of this laboratory.

The differences between the synchronization results obtained with ECS 5 and the BIPM data are mainly due to the following factors: the uncertainties in the satellite position data supplied by ESA, of the order of 0.004° in latitude (~3 km in the North-South direction), 0.007° in longitude (~5 km in the East-West direction), in the receiving antennas coordinates that were given in different reference systems and the differential delays of the receiving stations which have not been entirely accounted for.

In the case of the time comparisons between IEN and TUG, reported in Fig. 9, the curves obtained from ECS 5 (corrected for the satellite position) and the BIPM data are in closer agreement because the antenna coordinates are expressed in the same reference system with a better uncertainty. The differential propagation delays corrections, about 1 ns in the case of the ionosphere and about 5 ns in that of the troposphere, have been neglected. Viceversa the relativistic correction due to Earth rotation (Sagnac effect), amounting to about 20 ns, has been applied to the IEN/TUG results.

In Fig. 10 are reported the residuals of UTC(IEN)-UTC(TUG) obtained subtracting the ECS synchronization data from the GPS ones; the mean value of the differences is 180 ns and the standard deviation is 44 ns. In this particular case, if we compute the error budget due to the uncertainties of the satellite position and stations coordinates we obtain as a result about 160 ns. Considering that in the computation of the synchronization results, the differential delay of the equipment set up has been taken into account, apart from that of the satellite receivers, we can estimate that the above mentioned residuals are comparable with the error budget.

## 5.- Correction of the ECS synchronization results using GPS measurements

To substitute the ESA position data to correct the synchronization results, it has been studied and tested a correction procedure that uses both the ECS and GPS measurements performed in two stations.

If we assume that the variation of the differential delay between two stations due to the satellite motion follows a sinusoidal law of period T equal to a sidereal day, as a first approximation and for short observation times, the mean value of the differential delay computed at T/2 intervals is constant. Therefore performing ECS synchronizations at T/2 intervals and computing the mean between two adjacent values it is possible to remove the diurnal variation. Nevertheless, this procedure cannot compensate for the drift of longitude that yields to a long term variation in the mean differential delay which is left superimposed on the time differences between the reference clocks.

In the case of two laboratories performing also GPS time comparisons, the difference between the reference clocks can be subtracted and the residuals used to correct the averaged synchronization data of the laboratories performing only ECS comparisons.

This procedure has been tested using the ECS and GPS data of TEN and TUG to correct the synchronization results of TEN vs. TP and TEN vs. ASMW. The curves obtained are reported in Fig. 11 where, if one removes the mean rates, peak fluctuations of the order of 0.4 us can be observed and the differences between the time scales, compared with those computed by BIPM, can range from 0.5 us to 1.5 us. Comparing these results with those of Fig. 7, it is evident that this approach improves the precision of the ECS synchronization results, as do the ESA data, but is not satisfactory as regards to the measurement uncertainty.

Further tests using this method will concern the use of ECS synchronization measurements taken at exactly half-sideral day (up to October 1989 it has been used a half solar day interval), and the determination of the longitude variation corrections by means of a polinomial fit over several days instead of computing the correction for each couple of consecutive data.

## 6.- Delay measurement of the satellite receiving station at IEN

In the computation of the time difference between two laboratories also the differential time delay of the stations must be taken into account. If the same transmitting equipment is used to perform the measurement of the delay at each station, the systematic uncertainty affecting the single test will be deleted. To this purpose, a microwave transmitter, named "satellite simulator", has been built and tested.

## 6.1.- Satellite simulator description

The satellite simulator is a microwave generator (Gunn oscillator), tuned at f = 10.945 GHz, with an output signal level of 0 dBm, which can be frequency modulated by a standard video signal.

The test setup used to perform the satellite simulator delay measurement is shown in Fig. 12. A pulse generator with a 5 ns risetime, instead of a video signal generator, was used to modulate the satellite simulator. The simulator output frequency was down converted to about 100 MHz by means of a microwave generator, used as local oscillator, and a diode mixer.

The measurement was performed evaluating on an oscilloscope the delay between the leading edge of the modulation pulse and the output signal from the mixer taking as a reference the point where an abrupt frequency change was evident. The simulator delay was estimated to be 10 $\pm$ 5 ns, the delays introduced by the coaxial cables on both oscilloscope channels being equivalent.

## 6.2.- Receiving station delay measurement procedure

The block diagram of the equipment used is shown in Fig. 13. A horn antenna, connected to the satellite simulator by means of a coaxial cable 4 m long, is placed in front of the parabolic antenna in such a way that the beam length, from the transmitting antenna to the illuminator, is about 2 m. The satellite simulator is modulated by a test video signal in order to measure the overall delay of the station, pulse extractor included. The frequency f = 10.945 GHz was chosen because free from any other emission.

To obtain the station delay $T_r$, from the illuminator input to the STOP input of the counter, the following measurements were performed:

- the total delay $T_t$, from the START to the STOP inputs;
- the delay $T_g$, from the START to the simulator video input, using a calibrated cable to connect this last to the STOP.

The following results were obtained:

$$T_t = 1090 \text{ ns}, \ T_g = 198 \text{ ns}$$

$$T_r \quad T_t - T_g - T_a = 851 \text{ ns}$$

where $T_a$ = 41 ns is the delay of the satellite simulator with the addition of the delays of a 4 m cable to the horn antenna and a 2 m free-space beam to the illuminator input. During the measurement of $T_g$ the trigger level of the counter STOP input was regulated to a value equal to 50% of the synchronization pulse amplitude, the same value of the pulse extractor threshold. The uncertainty of the measurement of $T_r$ was evaluated to be 30 ns ($1\sigma$), having taken into account that the rise time of the television synchronization pulses is about 200 ns.

To determine the long-term stability of the station delay, it is planned to perform a series of measurements lasting some months, after having controlled in temperature the satellite simulator to eliminate frequency variations already observed in the Gunn oscillator.

## 7.- Conclusions

The results obtained in the synchronization experiment between some European laboratories, based on the television signals received from ECS5 geostationary satellite, have shown that an uncertainty ranging from some hundreds of nanoseconds up to one microsecond is achievable over a very large area, provided that the measurements are corrected for the satellite position parameters as determined by an ESA tracking station.

As a first attempt to reduce the diurnal effects on the time comparisons, since November 1989 a new measurement schedule, that allows to compute the synchronization results at a half-sideral day, was adopted.

Future developments will concern the satellite position determination investigated both with four laboratories performing ECS and GPS measurements and establishing a range measurement equipment at the Fucino ground station of Telespazio, where the television signals are transmitted to the satellite. Furthermore, the station delay measurements, actually performed at IEN, could be extended to the other laboratories to improve the accuracy of the time synchronization.

## 8.- Acknowledgments

The authors would like to thank all the participating laboratories, and particularly O. Buzek and J. Čermák of ÚRE, and B. Demelenne and G. Desiderio of ESA - Redu for the indispensable cooperation.

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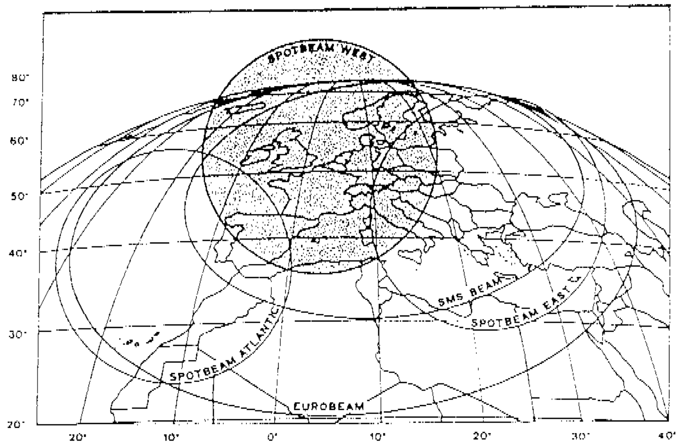



Fig. 1 - ECS satellite coverages.

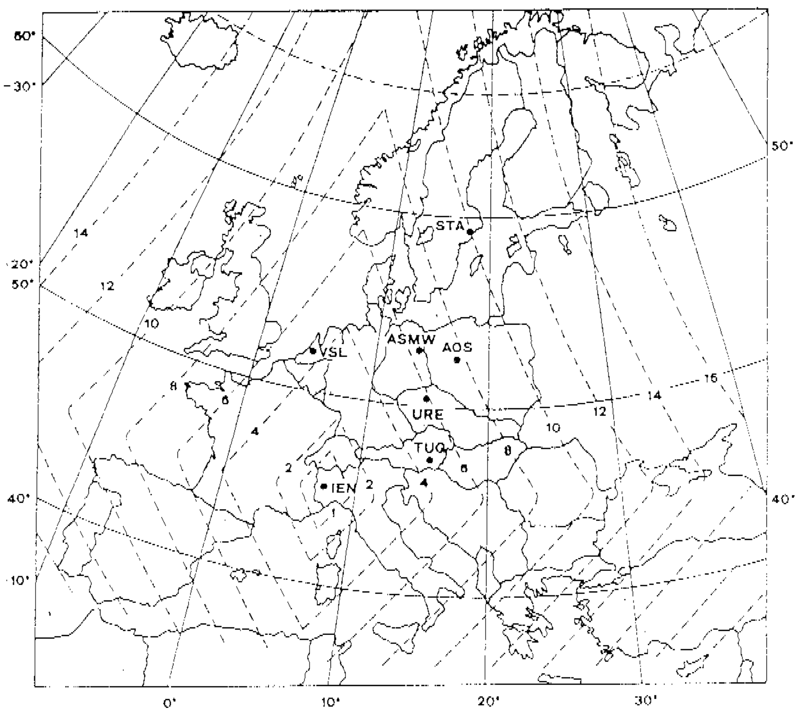



Fig. 2 - Map of the time error contours (in microseconds).

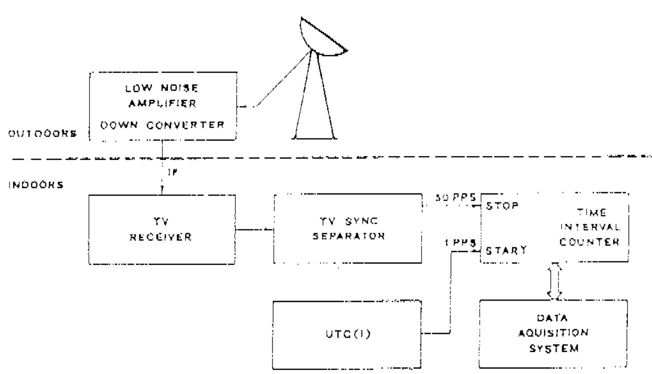



Fig. 3 - Measurement setup.

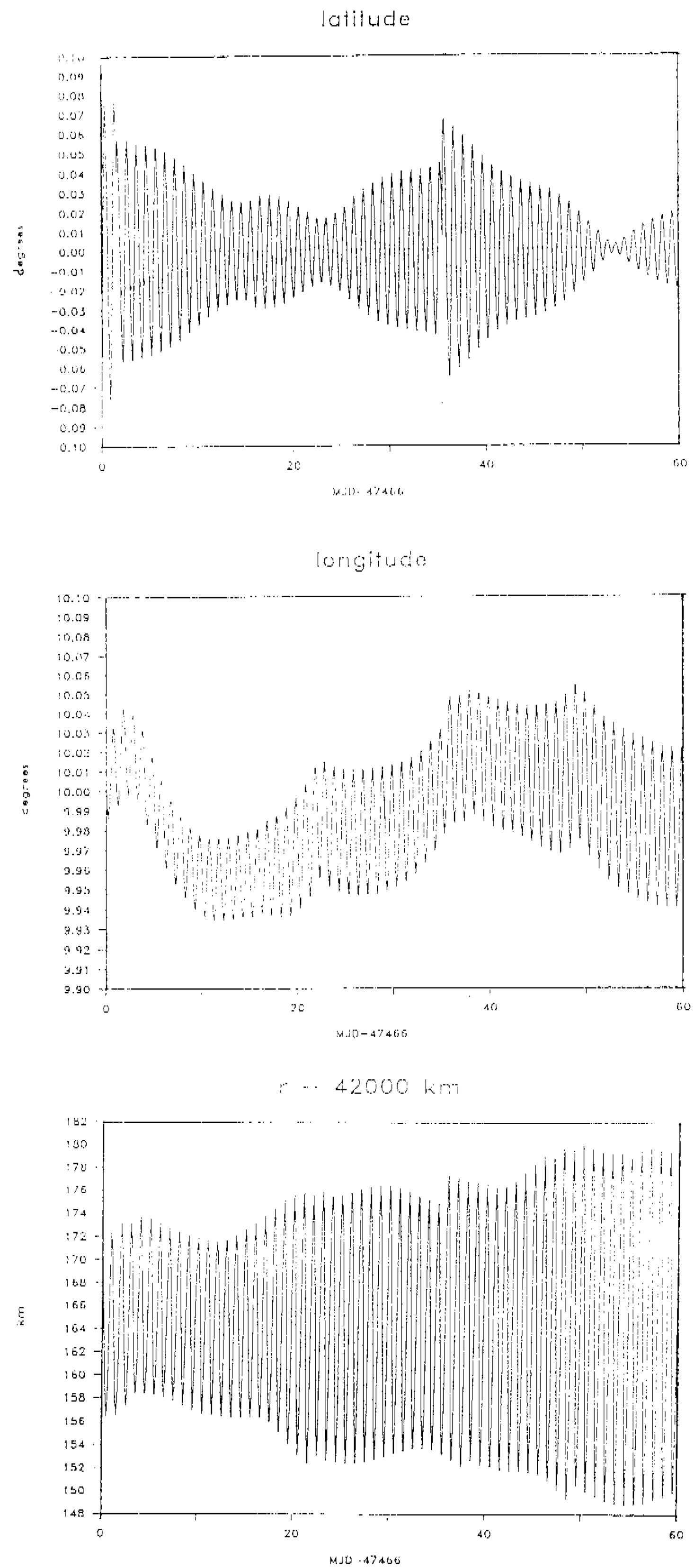



Fig. 4 - ECS 5 position from ESA-Redu data (November-December 1988).

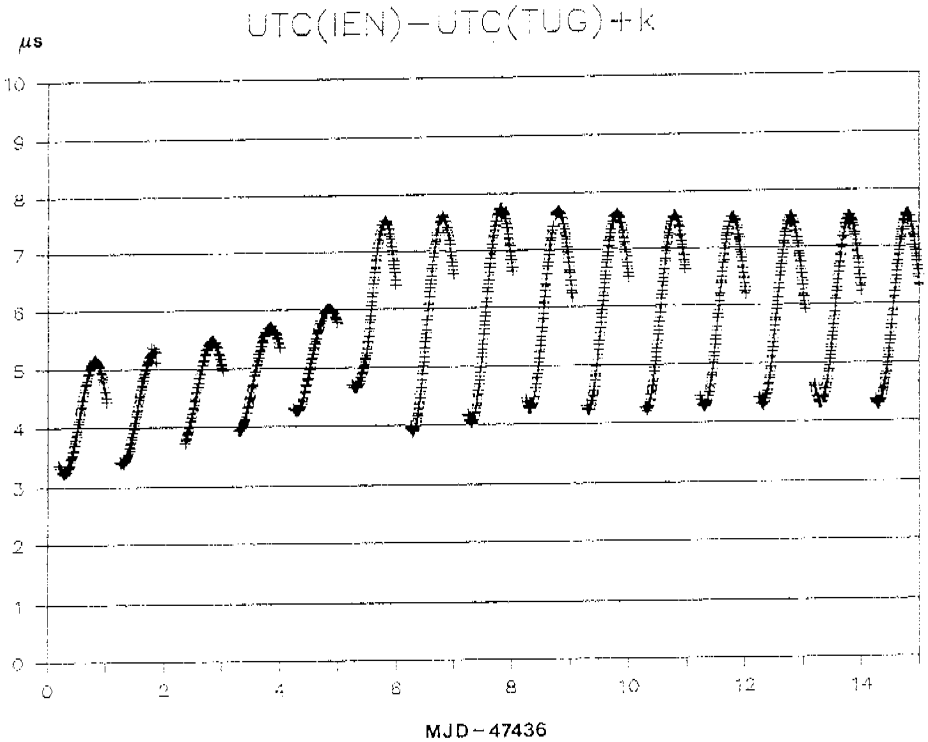



Fig. 5 - Ten minutes time differences between IEN and TUG via ECS TV signal.

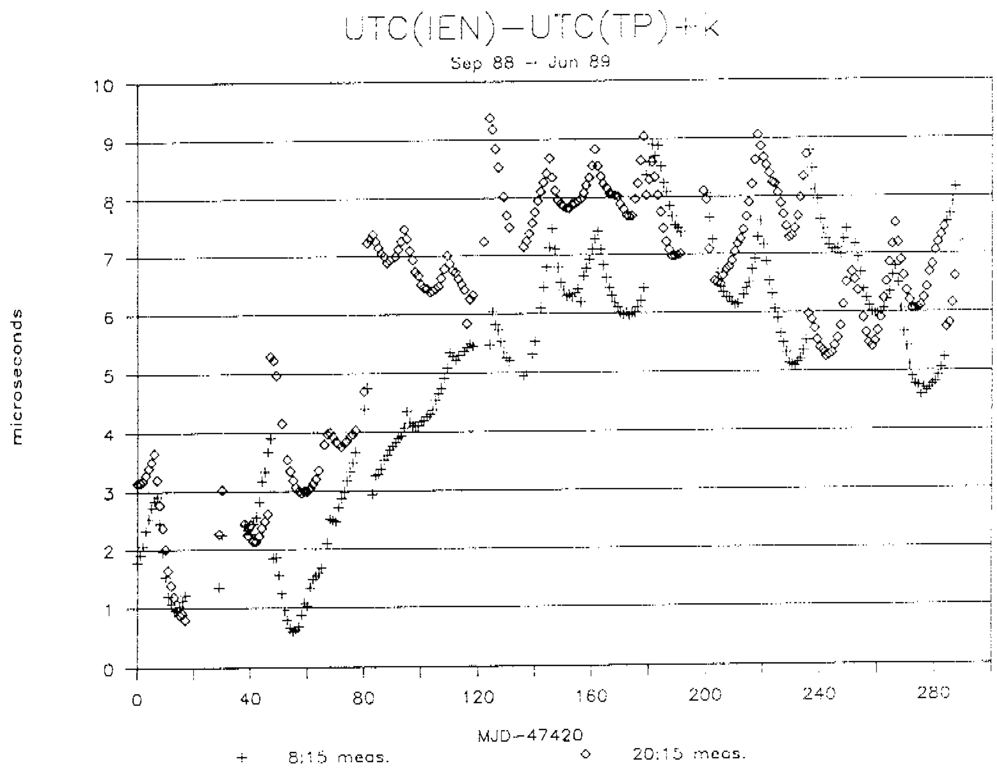



Fig. 6 - Time differences between IEN and URE from ECS 5 satellite.

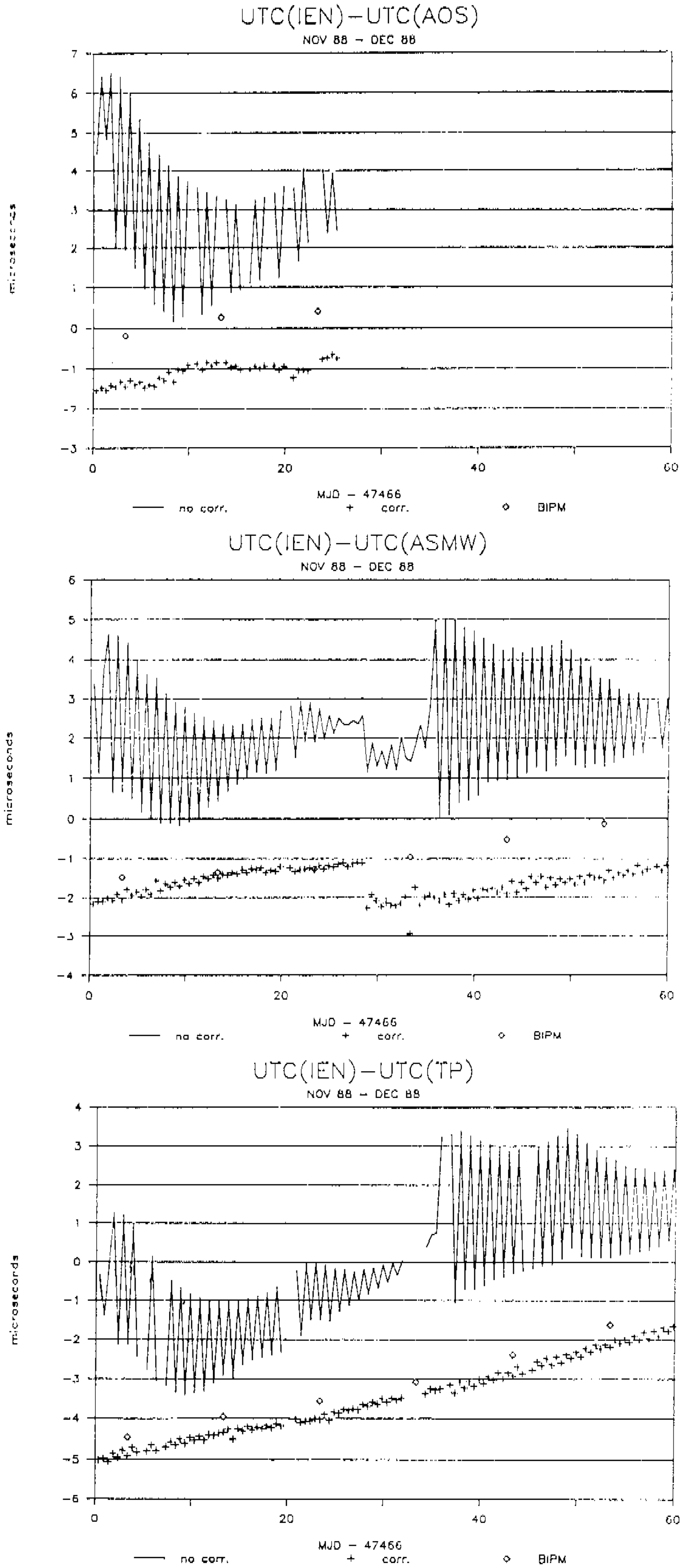
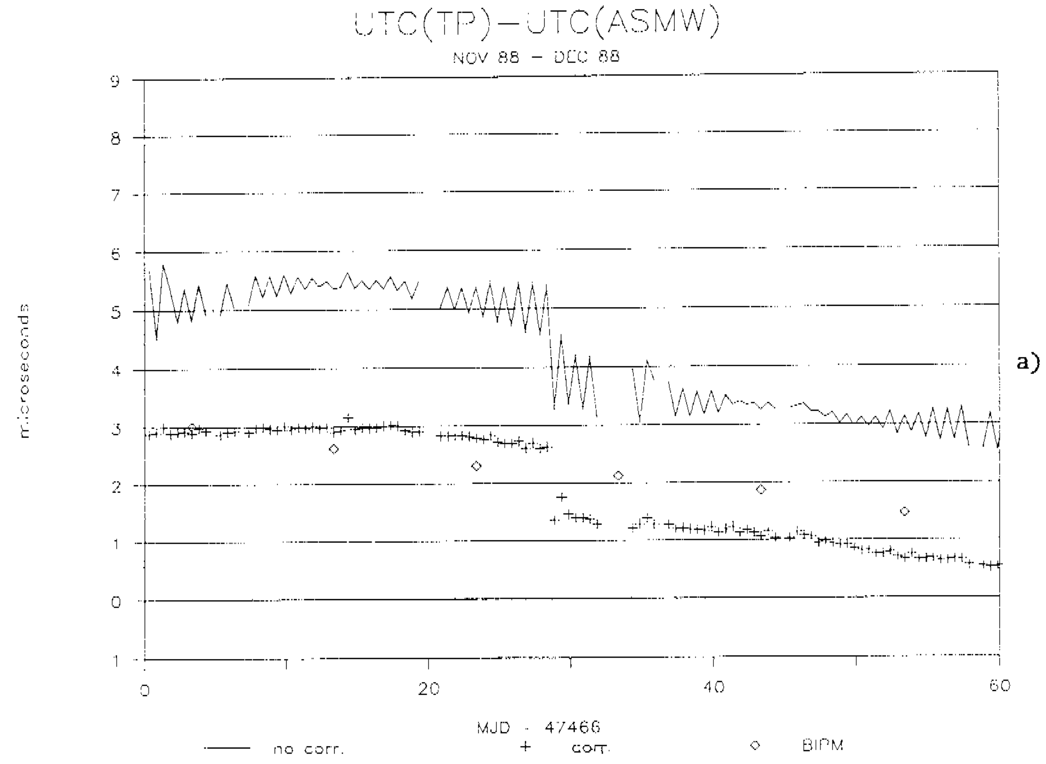



Fig. 7 - Time scales comparisons by means of ECS 5 satellite and BIPM Circular T.



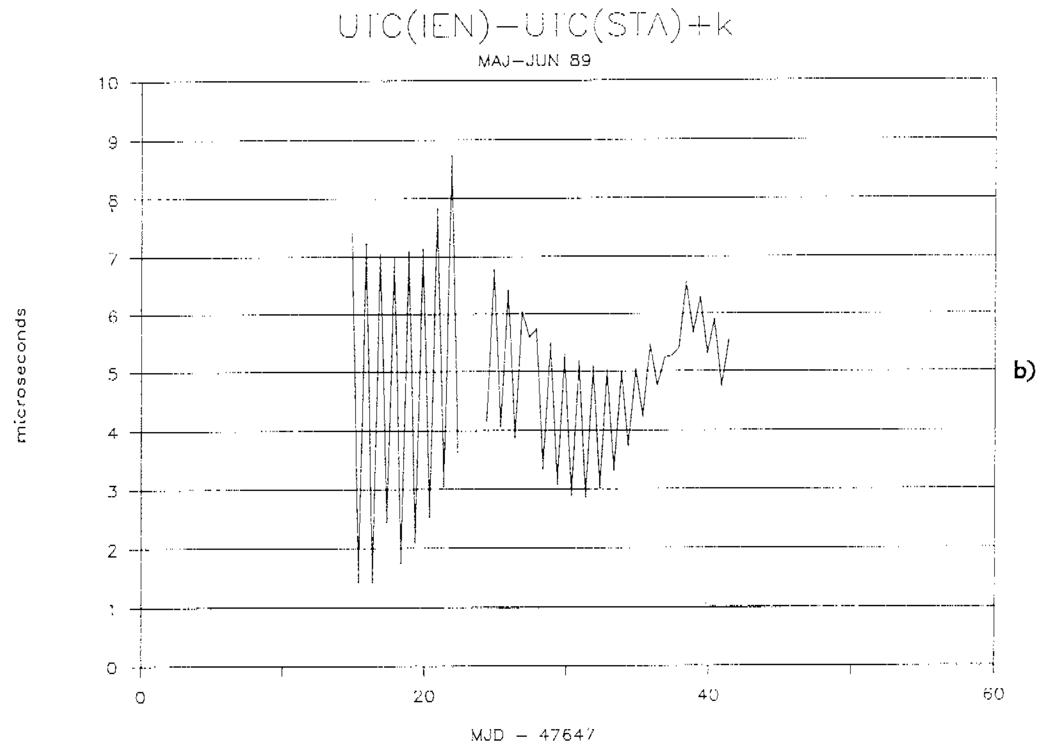




Fig. 8 - Time scales comparisons by means of ECS 5 satellite.

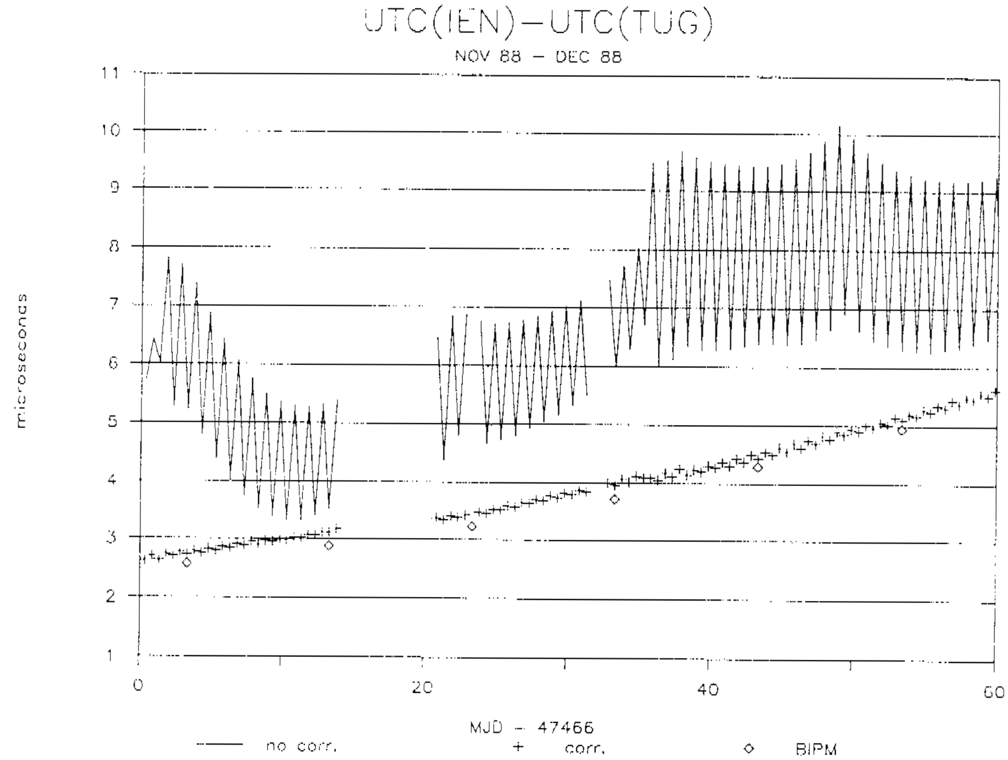



Fig. 9 - UTC(IEN vs. UTC(TUG) from ECS 5 and BIPM Circular T
(TUG time scale step compensated).

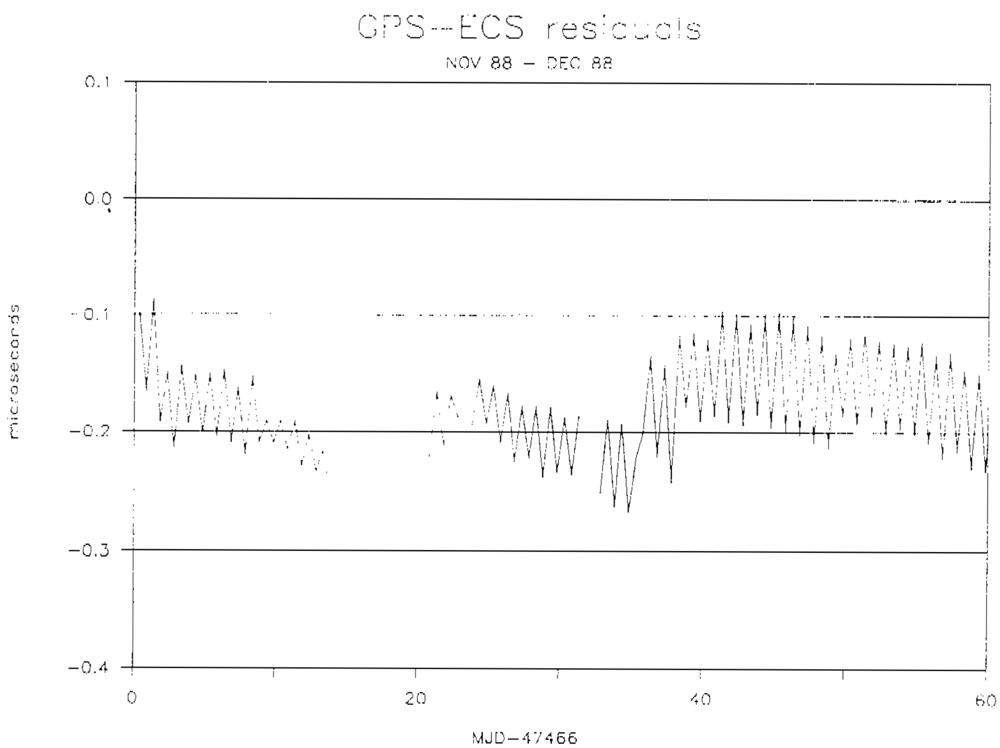



Fig. 10 - Residuals of UTC(IEN) - UTC(TUG) via GPS and ECS.

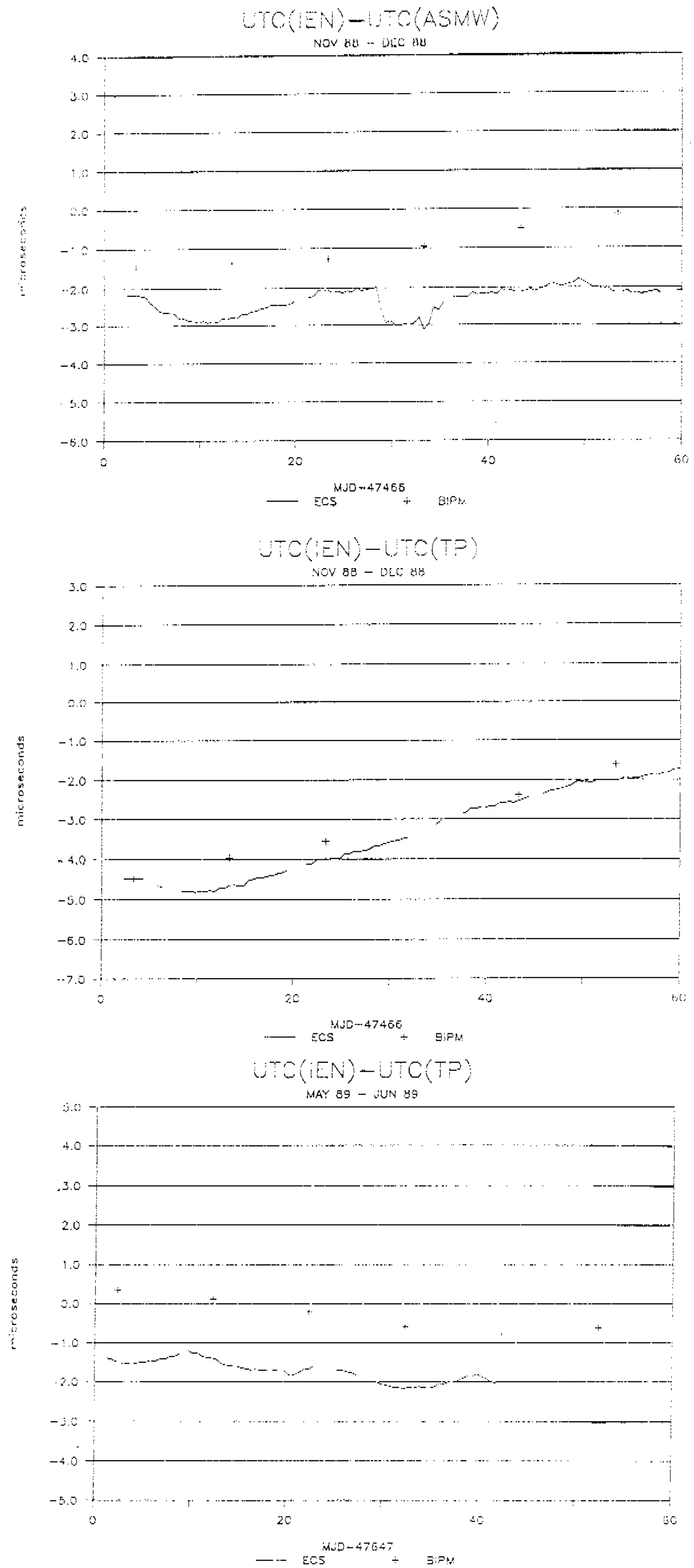



Fig. 11 - ECS 5 time scale comparisons corrected with IEN-TUG GPS data.

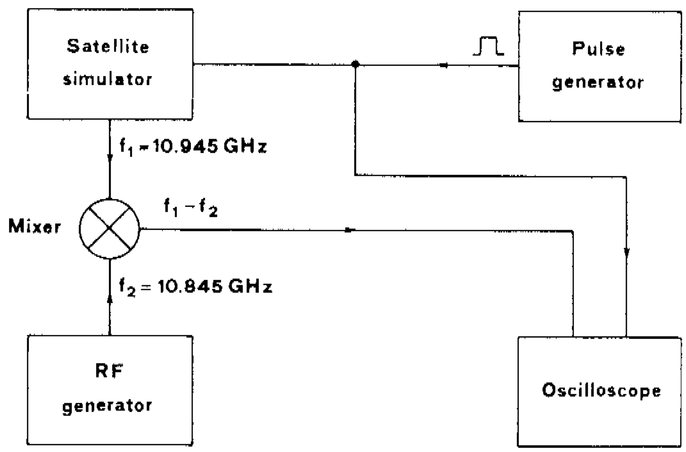



Fig. 12 - Block diagram of satellite simulator delay measurement.

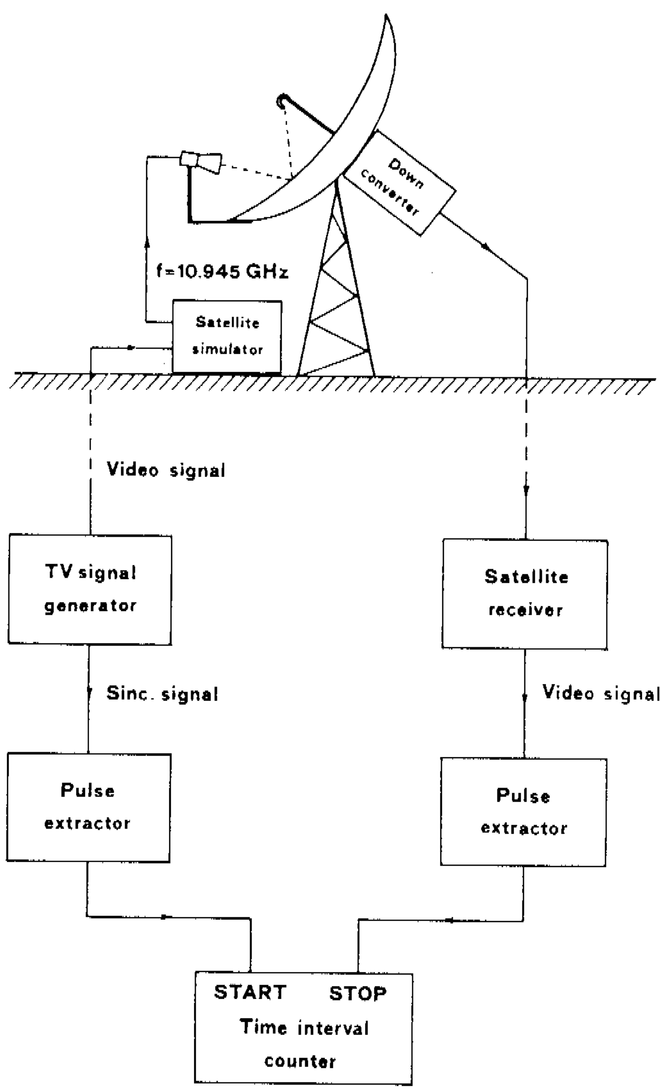



Fig. 13 - Receiving station delay measurement setup.

## QUESTIONS AND ANSWERS

**GERNOT WINKLER, USNO:** In one of your view graphs you could see a very significant break in the daily variation to a much more regular performance. Is that due to a station-keeping change in the satellite, or what happened at that moment?

**MR. PETTITI:** It was about the satellite position information. Unfortunately, it is not easy to get information from the tracking station about what is happening. This is why we are trying to eliminate this input. It was certainly due to something in the satellite control, because in the corrected data there is no sign of this behavior. It is not, however, easy to determine *a priori* what they are doing there.