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TIME ASPECTS OF THE EUROPEAN COMPLEMENT TO GPS: CONTINENTAL AND TRANSATLANTIC EXPERIMENTAL PHASES

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Abstract

The CNES project of a European Complement to GPS [CE–GPS] is conceived to fullfill the needs of Civil Aviation for a non–precise approach phase with GPS as sole navigation means. This generates two missions: a monitoring mission – alarm of failure –, and a navigation mission – generating a GPS–like signal on board the geostationary satellites. The host satellites will be the Inmarsat constellation. The CE–GPS missions lead to some time requirements, mainly the accuracy of GPS time restitution and of monitoring clock synchronization.

To demonstrate that the requirements of the CE–GPS could be achieved, including the time aspects, an experiment has been scheduled over the last two years, using a part of the Inmarsat II F–2 payload and specially designed ground stations based on 10 channels GPS receivers. This paper presents a review of the results obtained during the continental phase of the CE–GPS experiment with two stations in France, along with some experimental results obtained during the transatlantic phase (three stations in France, French Guyana, and South Africa). It describes the synchronization of the monitoring clocks using the GPS Common–view or the C– to L–Band transponder of the Inmarsat satellite, with an estimated accuracy better than 10 ns (1 σ).

INTRODUCTION

The 'Centre national d'études spatiales' (CNES, France) is the French Space Agency. The CNES project of a European Complement to GPS (CE–GPS in the following) is dedicated to the needs of the Civil Aviation community to achieve the requirements of a non–precision approach phase with GPS used as sole navigation means. Many functions have to be fullfilled by such a system, for which the time requirements are reaching the state of the art of the techniques used by the Time Metrology community. The whole CE–GPS project started more than four years ago, and the experimental part more than two years ago.

At this point of the CE–GPS project, all experimental stages have been performed, with a great amount of collected data to be processed. The results presented in this paper concern only the time aspects of the experiment, the calibrations of the ground stations and the synchronization of the monitoring clocks during the continental and transatlantic phases. Both Common–view GPS and Two–way time transfer through geostationary satellite have been used, the processing of the data being carried out by the 'Laboratoire primaire du temps et des fréquences' (LPTF, France). The results obtained are compared to the requirements of the CE–GPS project.

SHORT REMINDER OF THE CE–GPS PROJECT

The concept of the CE–GPS and the experimental system were presented at the EFTF 93[1]. The CNES project of a European Complement to GPS is mainly dedicated to the needs of the Civil Aviation community. It can be considered as the first step of a French design for a Global Navigation Satellite System (GNSS). The reference mission adopted by the CNES will:

- achieve the requirements of a non–precision approach phase.
- enable GPS to be used as sole navigation means.

The functions to be fullfiled by such a system are:

- a monitoring mission: alarm of a failure on a GPS satellite within 10 seconds.
- a navigation mission: to increase the GPS availability by eliminating coverage gaps.

Following the proposals of satellite operators, it was agreed that the space segment would be provided by the Inmarsat III geostationary satellites. Because one of the system specifications is to minimize modifications on the existing GPS receivers, the signal transmitted by the geostationary payload shall be similar to a GPS signal. In addition it has to carry specific CE–GPS informations. This and other specifications have many consequences, among which only the time aspects are described in this paper.

To prove the feasability of such a Complement to GPS, and to help estimating the performances and the limits of an operational system, the CNES has organized an experiment of which main objectives are:

- to confirm the ability of transmitting a GPS–like signal from a geostationary satellite.
- to demonstrate the feasability of synchronizing with the GPS time a virtual clock on board the geostationary satellite.
- to demonstrate the capability of GPS receivers to process the CE–GPS signal.
- to evaluate the User Equivalent Range Error (UERE) [2] when using the geostationary satellite.
- to synchronize the ground stations following the requirements.

The space segment of the CE–GPS experiment, beside the GPS NAVSTAR constellation, is the Inmarsat II F2 geostationary satellite of which part of a transponder in the payload was made available free of charge to the CNES for the duration of the experiment. The ground segment is made of three specially designed ground stations based on 10 channels navigation GPS receivers, whose development has been entrusted to the IN–SNEC (Caen, France), and of a computer processing station for the collected data located at the CNES space center of Toulouse (France).

The CE–GPS experimentation was divided into three stages: a first stage in May–June 1993, with two stations located at the IN–SNEC (Caen, France) in parallel with the same clock, called the "calibration phase", a second stage from September to November 1993 with one station at the LPTF (Paris, France) and another one at the CNES space center of Toulouse (France), called the "continental phase"; a third stage from May to June 1994, with three stations located at the CNES space centers of Toulouse (France), Kourou (French Guiana) and Hartebeeshoek (South Africa), called the "transatlantic phase". The acronyms used for these three stations are TLS, KRU, and HBK, with obvious meanings.

TIME ASPECTS OF THE CE–GPS

The time requirements concerning the navigation mission to be fullfilled by the system are the synchronization with respect to GPS satellites. The standard deviation of the time difference between an event issued from the geostationary payload and an equivalent event issued from any GPS satellite should be less or equal to 120 ns with Selective Availability (S.A.) on [2]. With S.A. off, these requirements drop to 20 ns. Concerning the monitoring mission, the time requirements deal with the relative synchronization of the monitoring clocks, which should be within 10 ns (1 s) in accuracy if they are in view of the same geostationary satellite, or within 15 ns (1 s) if not.

The description of the system architecture, of the ground stations, and the discussion about time and frequency servo–control techniques, or orbitography aspects, have been made elsewhere [1,3]. Only the experimental set–up and some of the calibration results are presented here. The method for restituting the GPS time following the requirements, based on the statistical behaviour of the S.A. noise, is described in a paper presented at the EFTF 94 [4], along with some experimental results obtained with a four–channel time dedicated GPS receiver: over an averaging period of 2 h 24 min, and with the simultaneous use of the four channels, it has been demonstrated that the GPS time could be restituted on the ground with an accuracy of 14 ns (1 s). A possible method for achieving a clock synchronization is to use the results of the GPS time restitution separately calculated in remote stations [1,4].

The time aspects of the CE–GPS presented in this paper are the synchronization of the ground stations clocks, either by GPS Common–view or by Two–way satellite time transfer (TWSTT) through the geostationary payload. The well known method for the synchronization of remote atomic clocks is the GPS Common–View technique [5]. Because GPS time dedicated receivers are included in the CE–GPS ground stations, it was decided to use the Common–View technique with the BIPM schedule as the reference for clock synchronization, provided that a calibration of the remote receivers is done, and that atmospheric measurements are made available. Until now, TWSTT was performed using Eutelsat or Intelsat telecommunication system, or domestic satellites. When using MITREX Modems over short bases (800 km), an accuracy of 1.7 ns (1 s) has been estimated, and directly compared to the equivalent GPS Common-view results [6]. It was proposed to use the Inmarsat C– to L–Band transponder, and the spare C/A GPS gold pn–codes [1,2].

EXPERIMENTAL SET–UP

The description of the ground stations will be limited to the basic equipments involved and to the items and techniques related to the results presented in this paper. The complete presentation of the stations of the CE–GPS experiment can be found elsewhere [1].

Inmarsat II F2 is located -15.5 E. The Sagnac effect for all links is easy to determine with an uncertainty within 0.01 ns (1 s). All stations are identical in terms of a spatial link:

Antenna diameter C-Band: 0.6 m
Uplink frequency: 6428.475 MHz (C-Band)
Uplink S/C G/T: -14 dB/K
Antenna diameter L–Band: 1.2 m
Downlink frequency: 1533.475 MHz (L-Band)
Downlink on axis G/T: 1.3 dB/K
Maximum EIRP: 39.8 dBW

At the start of the experiment, no data were available concerning TWSTT performances when using an Inmarsat transponder, C/A gold codes, and GPS receivers as Modem. The basic sampling period of the data inside these GPS receivers is 0.6 s. It was decided to schedule four sessions per day, each lasting 15 min, to allow statistical analysis on a sufficient amount of data, and to detect any influence of atmospheric parameters on the performances. The sessions took place at 1:15, 7:15, 13:15, and 19:15 TU.

Inside each ground station (figure 1) are implemented two SERCEL NR106, which are ten–channel GPS navigation receivers. They are related, thanks to the switcher 1, either to a common GPS antenna (L1 carrier), or to the receiving antenna of the Inmarsat signal (L–Band) converted to L1 before the switcher. The GPS antenna is also connected to a GPS receiver SERCEL NRT2, which is a 4 channels time dedicated receiver. The NRT2 is directly supplied with the 1pps output of the Cesium clock of the station. This is the classical set–up for the GPS Common–view technique.

Because the navigation receivers NR106 have no input for dating external events, like the 1 pps from the Cesium clock, it was necessary to build up a so–called 'GPS signals generator', which has two functions. It generates a sequence of C/A code synchronized with the 1 pps output of the clock, which modulates a L1 carrier in order to be dated by the internal counter of both NR106. This signal is denoted '1 pps L1–C/A'. The C/A code chosen for this internal link for all CE–GPS stations is numbered 33: it is a spare for the operational GPS, not to be used until further notice. For refering any external signal to the Cesium clock of the station, the dating of this internal 1 pps L1–C/A signal has to be done simultaneously with the dating of the external signal. The other function of this 'generator' is to output the servo–controlled signal related to the 1 pps of the clock to the transmitting antenna towards Inmarsat (C–Band carrier). This is similar to the transmitting part of a Modem used for the TWSTT, like MITREX for instance. The equivalent to the receiving part of a classical TWSTT Modem are the NR106 receivers.

There are opportunities for test links, short loop, and changes of the role of each NR106 receiver. There are other possible station configurations to be considered [1], but for the time aspects of the CE–GPS, a stable configuration was chosen for the whole period of data collection. The Cesium clocks monitoring the CE–GPS stations were a HP 5071 A option 1 at the LPTF, a HP 5061 A option 4 at TLS and KRU, and an Oscilloquartz at HBK. All types have proven to remain stable enough to evaluate properly the performances of the CE–GPS stations.

Either the GPS or the C– to L–Band radiowave techniques need estimations of the atmospheric delays. Models for tropospheric delays are working reasonnably well at the nanosecond level. For ionospheric delays, ionospheric calibrators are needed. Ten channels codeless receivers (not on figure 1) were used at all CE–GPS stations for measuring the ionospheric delays on the GPS satellites signals. A polynomial mapping method was scheduled to be used to determine the ionospheric delays in the direction of the Inmarsat geostationary satellite. But many problems occured during the running of the ionospheric calibrators. Considering the small distance between both stations involved in the continental phase (800 km), it was decided to use the STANAG results as the ionospheric delays in the direction of GPS satellites, and a Bent model for the C– and L–Band ionospheric delays in the direction of the Inmarsat satellite. Because the lines of sight of the Inmarsat satellite from both TLS and LPTF stations were very close, the difference of the C–Band ionospheric delays was negligible at the nanosecond level.

For the transatlantic phase, because the ionospheric calibrators have worked well only part of the time, the LPTF proposed to compute the ionospheric delays as following:

- for each 15 s sampled measurements in the direction of GPS satellites, a VTEC (vertical total electronic content) is calculated.
- a mean value of these VTECs is estimated, and projected in the direction of the geostationary satellite.
- for each TWSTT 15 min session, a mean value of the ionospheric delays is computed.
- during the whole periods where TWSTT measurements have been made continuously an average value of the ionospheric delays in the direction of the geostationary satellite is computed, separately for the 4 daily sessions. Three periods of 5 to 7 days duration, where the CE–GPS stations have worked continuously, have been identified during the transatlantic phase of the experiment.

It was proposed to consider as an uncertainty on these values the highest standard deviation of the computed average values, which was 5.1 ns (1 s). This is of course not a state of the art value. It was also proposed to try to use some IGS (International GPS Service for geodynamics) post–processed data, but the results are not available yet.

CALIBRATIONS

All internal delays of the ground stations were either measured (cables) or estimated (electronic components) following the manufacturers data sheets with a good uncertainty. A short loop performed during the calibration stage of the experiment, along with TWSTT sessions with both stations connected to the same clock, have shown that the measured differential delays were in good agreement with the estimated values, given the estimated global uncertainty. One of the critical issues is the calibration of the 'GPS signal generators'. Examining the synchronization equations, it appears that the 1 pps signal group delay through each generator must be monitored. Frequent calibration sessions were scheduled in all stations during the whole experiment. A calibration consists roughly in measuring the time delay between the arrivals into the NRT2 of two homologous 1 pps signals: a direct 1 pps signal from the Cesium clock and the 1 pps L1–C/A signal supplied through the generator output. This procedure was possible because the NRT2 have proven to remain quite stable all over the experiment.

The results of the successive calibrations during the continental phase are presented on figure 2. The calibrations at CNES station appear more stable than the LPTF station measurements. Moreover the CNES station was switched off for a while on MJD 49266 (October 6): there are obviously two sets of data before and after this MJD, each scattered within 4 ns. On the contrary the LPTF data are much more scattered within 25 ns. It has been shown by the manufacturer of the stations that, owing to the components used for this experiment, the signal generator could exhibit stepwise varying delays, each step being a multiple of 2.44 ns. By processing in deferred time the dating of the 1 pps L1–C/A performed continuously by both NR106 of each station, those variations could be identified, summed and compared to the day to day calibrations of figure 2. With the analysis of these records, some improvements could be achieved, but a lot of discrepencies are remaining, mainly due to missing data. This is why these discontinuities in the delays are disregarded. The average values of the calibration sessions are adopted along with the relevant standard deviations as uncertainties, giving for the signal generators delays:

- at TLS (continental phase): mean value = 1007.5 ns; standard deviation = 4.8 ns.
- at LPTF: mean value = 998.5 ns; standard deviation = 7.1 ns.

A similar behaviour of the signal generators was observed during the transatlantic phase of the experiment (Figure 3). The generator of the HBK station, formerly located at the LPTF, remained the most perturbated one, compared to the generator of the KRU station, which has never been switched off during the whole experiment. The manufacturer of the stations believes that the generator of the KRU station has reached the best achievable stability, with the components used for the building of it. The average values of the calibration sessions were adopted along with the relevant standard deviations as uncertainties, as for the continental phase, giving for the signal generators delays:

- at TLS (transatlantic phase): mean value = 1009.4 ns; standard deviation = 6.3 ns.
- at HBK: mean value = 986.1 ns; standard deviation = 7.6 ns.
- at KRU: mean value = 1025.8 ns; standard deviation = 1.4 ns.

A calibration by transportation of two GPS receivers was organized during the continental phase of the experiment, so that three round–trips were performed between the LPTF and the TLS station. It has worked remarquably well, except for some local problems too long to explain here, giving the usual uncertainty of 1.5 ns (1 s) on the differences between the two time scales. An other control of the results was possible thanks to the operational GPS Common–view link between the two stations involved, used continuously for the computation of the TAF ('Temps atomique francais').

No temperature effect was noticeable on the sets of data.

CONTINENTAL EXPERIMENTAL PHASE

An analysis of the data by the Modified Allan deviation showed that white phase noise is preponderant on each 15 min session over a period long enough to allow the computation of an average value. The precision of one 0.6 s sampled CE–GPS observation is about 9 to 10 ns, as can be deduced from the Modified Allan deviation. It could be compared to the MITREX observations that are ten times better [6], but it remains consistent with the magnitude expected when using C/A code along with standard discriminators on signals affected by a measured C/No of about 40 dB(Hz).

On Figure 4 are presented the average values of the TWSTT 15 min sessions, compared to the Common–view GPS daily averages between the GPS time receivers connected to the CE–GPS stations. One can see that the TWSTT points are well distributed around the GPS curve, even though they are scattered. It appears that many sessions have suffered from the above mentionned stepwise varying delays compared to the average values of the generators delays. This is a logical consequence of the choice to use an average of the calibration measurements. The uncertainties of the generators delays are obviously the most degrading part for the accuracy of this experiment of TWSTT through Inmarsat. We propose the following uncertainty budget in nanoseconds (1 s):

Inmarsat transponder	0	[Global coverage]
Sagnac effect	0.0	
Ionospheric delays	2.0	[Differential/Bent model]
Differential delays (LPTF–CNES)	6.2	[1ppsL1–C/A generator]
UTC(LPTF)-1 pps REF	0.5	[short line]
UTC(CNES)-1 pps REF	1.0	[long line]
Two–way accuracy	6.6	[Quadratic sum]

This accuracy is given for each session averaged result, and remain well below the upper limit of the CE–GPS requirements (10 ns). It surely will drop to a more interesting value compared to the MITREX results [6] if the behaviour of the generators could be withdrawn from the measurements. The uncertainty of the comparison between GPS Common–view and TWSTT can be estimated in nanoseconds (1 s) by:

TWSTT (CE–GPS continental)	6.6	
GPS Common–view [5]	3.4	[800 km baseline]
Uncertainty of the comparison	7.5	

This uncertainty appears consistent with the data plotted on Figure 4.

TRANSATLANTIC EXPERIMENTAL PHASE

A statistical analysis of the transatlantic data showed that a white phase noise behaviour is observed, as for the continental phase. Until now, no GPS Common–view data are available to be compared to the TWSTT results, and a lot of TWSTT data are missing, due to local problems in the equipments. On figures 5, 6 and 7 are plotted the TWSTT results on each link. The regular behaviour of the two different types of atomic clocks used can yet be recognized. In a very similar way as for the continental phase, we propose the following uncertainty budgets in nanoseconds (1 s) for each link:

Ionospheric delays	5.1 [average computed from GPS measurements]		
Equipment delays	TLS - HBK	HBK - KRU	KRU - TLS
7.0	5.5	4.6	
UTC(k)-1 pps REF		1.0	[two stations]
TWSTT accuracies	8.7	7.6	6.9

These accuracies are near the upper limit of the CE–GPS requirements (10 ns). One of the possible tests of the consistency of the results, along with a check of the computation options, is to calculate the deviation from the closure between the three stations. For this purpose, daily independant TWSTT results have been built up, for two of the three TWSTT links, by interpolation between two separated measurements sessions, centered on the date of the third link result. The deviations from the closure are plotted on figure 8. Even if only few points are available, there is obviously a bias between the three different sets of data. Again the behaviour of the generators of the stations is suspected to be the most important part of this bias. The results are scattered between - 8.0 ns and 15.3 ns. These values are consistent with the estimated accuracies given above. But the weak number of computed values do not allow us to realize a more complete statistical analysis.

If one could consider that the behaviour of the 1 pps L1–C/A generator in the KRU station would be the regular behaviour of an operational CE–GPS ground station, and if the ionospheric delays could be measured with a better uncertainty, by using the IGS post–processed data for instance, one could estimate the following uncertainty budget:

Ionospheric delays	2.0
Equipment delays	1.5
UTC(k)-1 pps REF	1.0 [two stations]
TWSTT accuracy	2.7

This could be the best achievable accuracy of the method, with similar stations more than 10,000 km apart, as far as the global coverage of the satellite's antenna is realized.

CONCLUSION

It has been demonstrated that the time requirements of the CE–GPS could be fullfilled with ground stations comparable to those built up for the purpose of the experiment presented in this paper, either for a distance between the stations inferior to 1000 km, or for stations more than 10,000 km apart. Even with the calibration problems related to the signal generators as conceived for this experiment, the monitoring clock synchronization could be done by the TWSTT technique through an Inmarsat geostationary satellite, with C/A gold codes and GPS receivers, with an accuracy of 7 to 9 ns (1 s). The best achievable accuracy is estimated within 2.7 ns (1 s).

The software for computing the timing data from the pseudo–range measurements made by the NR106, which are only GPS navigation receivers, is nearly completed. It will allow in the future the computation of GPS Common–view data the same way as in GPS receivers dedicated to time measurements, making the NRT2 receivers connected to the CE–GPS stations useless. Because NR106 are 10 channels receivers, it will supply data for the restitution of GPS time with the highest number of GPS satellites available simultaneously, reducing the averaging period for a similarly reduced S.A. noise.

Beside TWSTT, other techniques are scheduled to be tested with signals transmitted by the Inmarsat transponder. Among others, the servo–control could be the most interesting due to its near real–time time transfer capability. In this case however the synchronization is less accurate than the best achievable with post–processed data.

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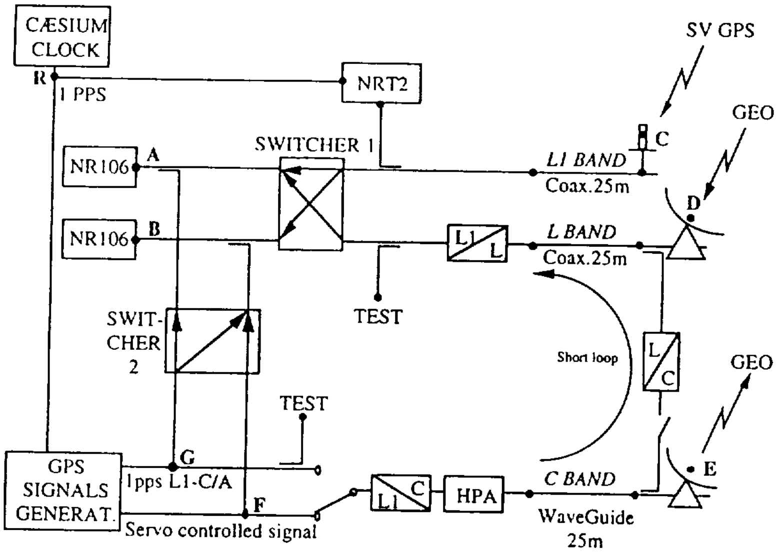

Figure 1. Diagram of a CE-GPS ground station.

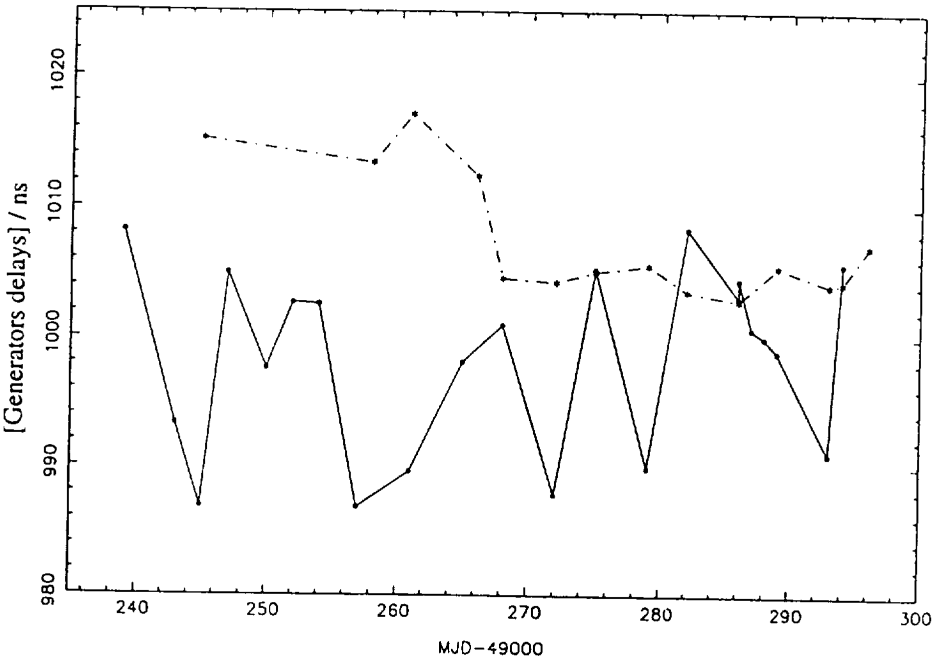

Figure 2. Calibration of the generators at the LPTF (•) and at TLS (*) during the continental phase of the experiment.

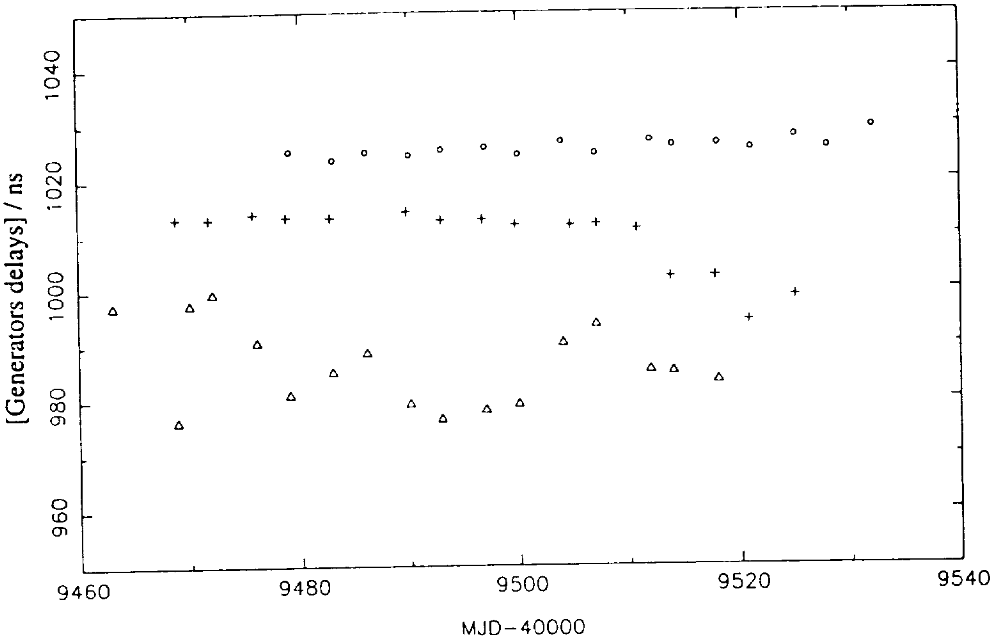

Figure 3. Calibration of the generators at the KRU (°), the TLS (+), and the HBK (Δ) stations during the transatlantic phase of the experiment.

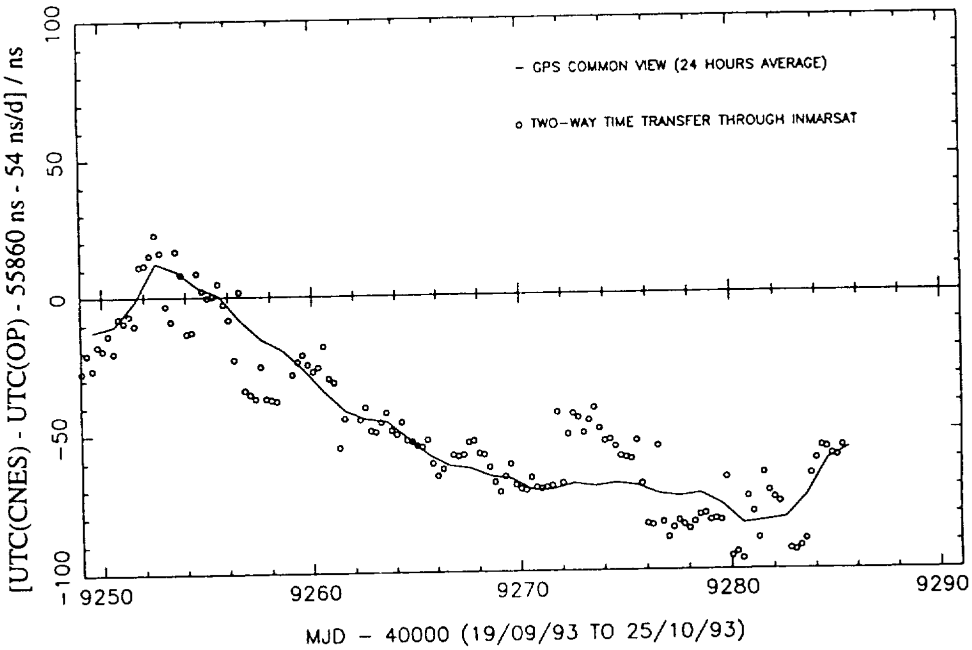

Figure 4. TWSTT 15 min averaged sessions and GPS common-view daily averages (CE-GPS continental phase).

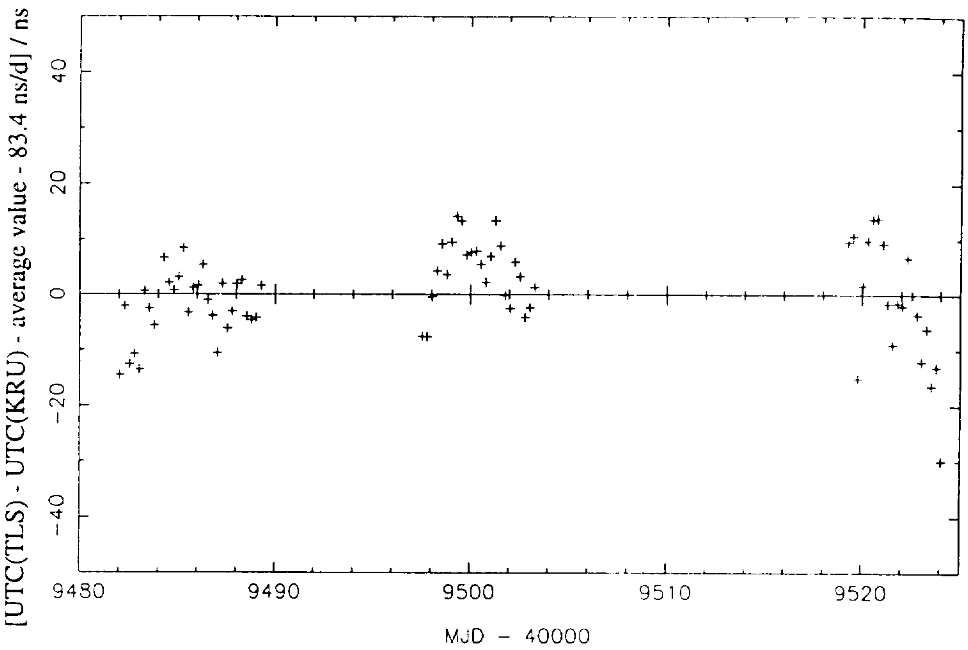

Figure 5. TWSTT 15 min averaged sessions between TLS and KRU (CE-GPS transatlantic phase).

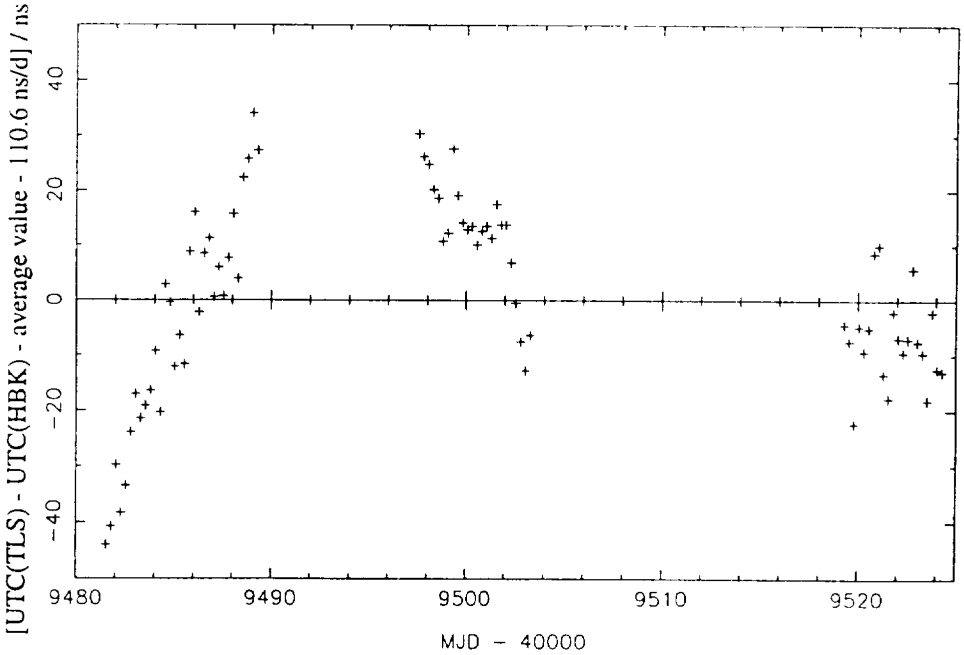

Figure 6. TWSTT 15 min averaged sessions between TLS and HBK (CE-GPS transatlantic phase).

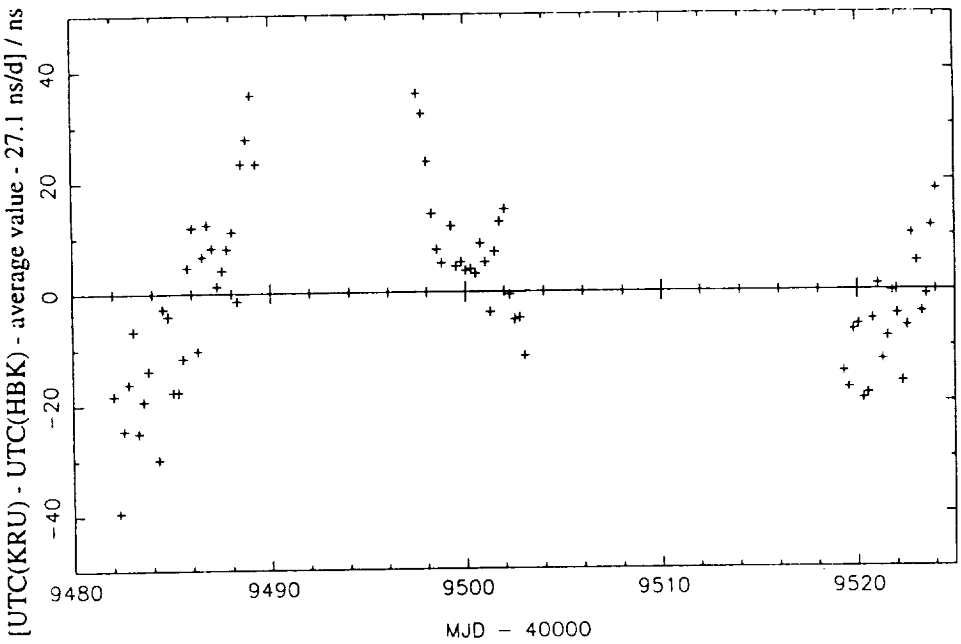

Figure 7. TWSTT 15 min averaged sessions between KRU and HBK (CE-GPS transatlantic phase).

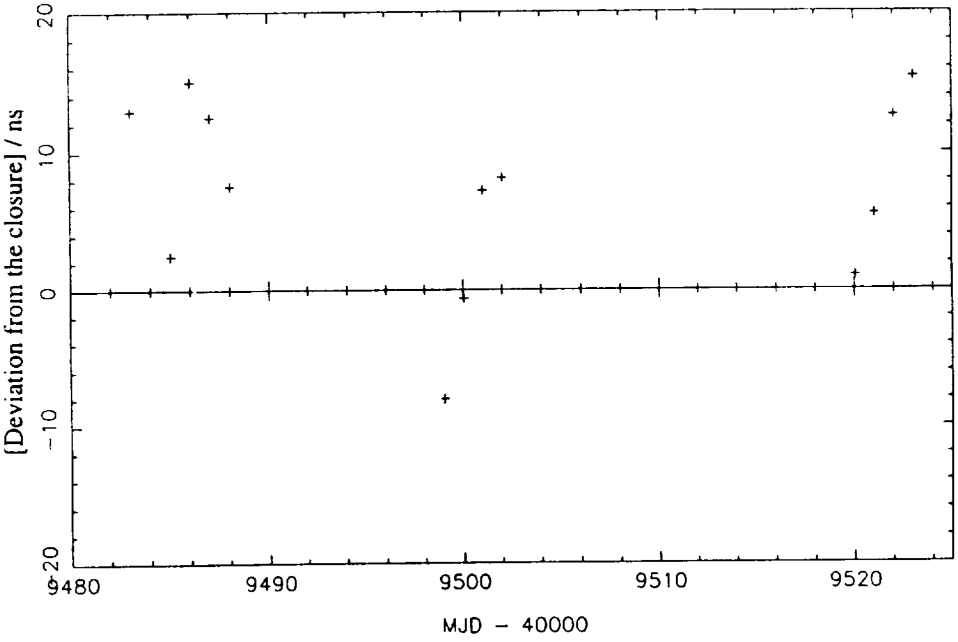

Figure 8. Deviation from the closure TLS - KRU - HBK (CE-GPS transatlantic phase).

LASSO EXPERIMENT INTERCALIBRATION TRIP FOR THE TWO LASSO RANGING STATIONS

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Abstract

In order to achieve the accuracy of the LASSO time transfer between OCA, Grasse, France and McDonald Observatory, Texas, USA, an intercalibration of the two Laser Ranging Stations was made.

At the same stations, GPS receivers were set up and the GPS to Laser epoch differences were also monitored.

In addition to the principle and the results of the measurements, the cause of the difficulties met during the campaign will be described.

INTRODUCTION

After a successful LASSO Ranging Campaign by the two Lunar Laser Ranging (LLR) Stations, University of Texas at Mc Donald and Observatoire de la Côte d'Azur in Grasse, which took place from April 1992 to January 1993, an intercalibration trip for the participating stations has been set up.

The principle of this intercalibration (Fig. 1) is to use a common vector on both sites, in order to determine the emission delay difference.The common vector is a specially designed laser ranging station, transportable and able to be set up close to each telescope. The range limit of such a station is of a few kilometers on simple ground targets (corner cube).

CONFIGURATIONS

At each site two configurations were scheduled:

- emission by the LLR local station and reception by both LLR local station and calibration station (Fig.2).
- emission by the calibration station and reception by both stations (Fig. 3). These configurations allow to write a set of redundant relations from which we can derive the difference of the emission delays. This difference is called the LASSO calibration. For the LASSO calibration to be valid, it is necessary that the delays of the calibration station and the cables for the 5 MHz and the 1 Hz remain stable. A special design of the calibration station allows to monitor any change in the internal delays and the cables being considered as part of the equipment thereof. The same set of cables will be used at every site.

Outside of the LASSO calibration, another calibration is needed in the Lasso synchronization relations. It is the ranging calibration of each LLR Station.

This is routinely surveyed by the ranging teams and could be also determined from the two way flight time of the laser beam of the calibration station.

CALIBRATION TRIP

The calibration started in April 1993 at LLR OCA Station. The transportation of the calibration station was easy since a van had been purchased for that purpose. Setting the station near the LLR telescope was quite easy, we only had to solve a Radio Frequency Interference, probably caused by the iron sheet cover of the dome of the LLR station. In June of the same year, we moved the station to the LLR station at McDonald. The transportation of the calibration station was done by air, from Nice to Houston, then by truck, from Houston to El Paso and finally by car, from El Paso to the Observatory.

At the station our equipment had to be set up outside as the shelter of the LLR station was already quite crowded. This occurred to be somewhat of a problem as the weather was unusually bad (heavy rain and wind) for such an area as Texas at that time of the year. After some hardware adjustments (laser, telescope focus) the calibration station was ready to work in less than two days in what we would call an expected nominal mode. However, because we did not have any oscilloscope that we could use, we were unable to control the level of the discriminators and actually for some reason they were not set as they were for the calibration at OCA.

We have to mention here that we encountered some problems, which are not unusual when you carry material to different countries. The ATA Carnet, for example is not commonly used in some areas as El Paso, and of course it can be of a risk to go through customs on an official Holiday.

CALIBRATION SESSIONS

- The LLR OCA station was designed with LASSO in mind, therefore outside of the Radio Frequency Interference problem, no other difficulties appeared. The data files are very stable for successive and close together sessions, but not for day to day sessions with a noise around 150 ps up to 300 ps (Fig. 4).

- The LLR McDonald station, in spite of some difficulties saved the LASSO experiment, as it was the only other station ready and in position to make LASSO sessions at that time.

The station had been designed with only the goal of ranging and later on adapted for LASSO observations.

Consequently we have encountered some limitations at McDonald station:

1. Processing the data in real time was impossible, as a preprocessing of the data at University of Texas at Austin was absolutely necessary to make the files readable. This led to the impossibility of scheduling any other session in case that something would fail. An example is that we could not discover that a range gate had been adjusted in the wrong way, rejecting the real data and recording the adjacent noise (Fig. 5).
2. The design of the equipment is such that the same interpolator is used for both the emission and the reception. Ranging the Moon or satellites is very efficient in this way, as any variation in the interpolator slope cancels. For LASSO the emission delay, relying on a single path in the interpolator, may and actually does change from day to day (estimated to up 5 ns). For calibration sessions, ranging on a close target is impossible, because the dead time of the interpolator is far too large (Fig. 6). As the system is computer driven in a synchronous mode, the LLR station is then also unable to record emissions from the calibration station (Fig. 7).

Back to OCA LLR station we discovered that the calibration equipment delay had changed during the trip, most likely during the hardware tuning at McDonald station and because we did not have a oscilloscope, we could not readjust the constant fraction discriminator at the ideal level. This adds an uncertainty of 1 ns. Taking into account the previous remarks, the data files recorded at McDonald station have the same discrepancy than the ones of OCA. The short term stability is rather good (1 to 3 hours) but the values drift from session to session.

The overall calibration is computed at 136,999 ps. It is obvious that this is meaningless due to the long term unstability of a part of the Lunar Laser Ranging station equipment at McDonald, which was not fully designed for LASSO experiment.

The estimated discrepancy could be up to ±2.5 ns.

CONCLUSION

Considering what we have learned during this first intercalibration trip, we think that the equipment as it is designed, could provide a value with an accuracy of a few hundreds picoseconds (200 to 300 ps).

It has to be noticed that the stations willing to participate in such campaigns have to be designed for time transfer and need event timers reaching at least the same accuracy.

With some changes, such as fast photodetectors, a new event timer and new discriminates, the level of 30 to 10 picoseconds could be reached.

REFERENCE

J. Gaignebet et al., *"LASSO Experiment: Intercalibration of the LASSO Ranging Stations"*, Proceedings 25th Annual Precise Time and Time Interval Applications and Planning Meeting, December 1993.

INTERCALIBRATION LASSO
CONFIGURATION GENERALE

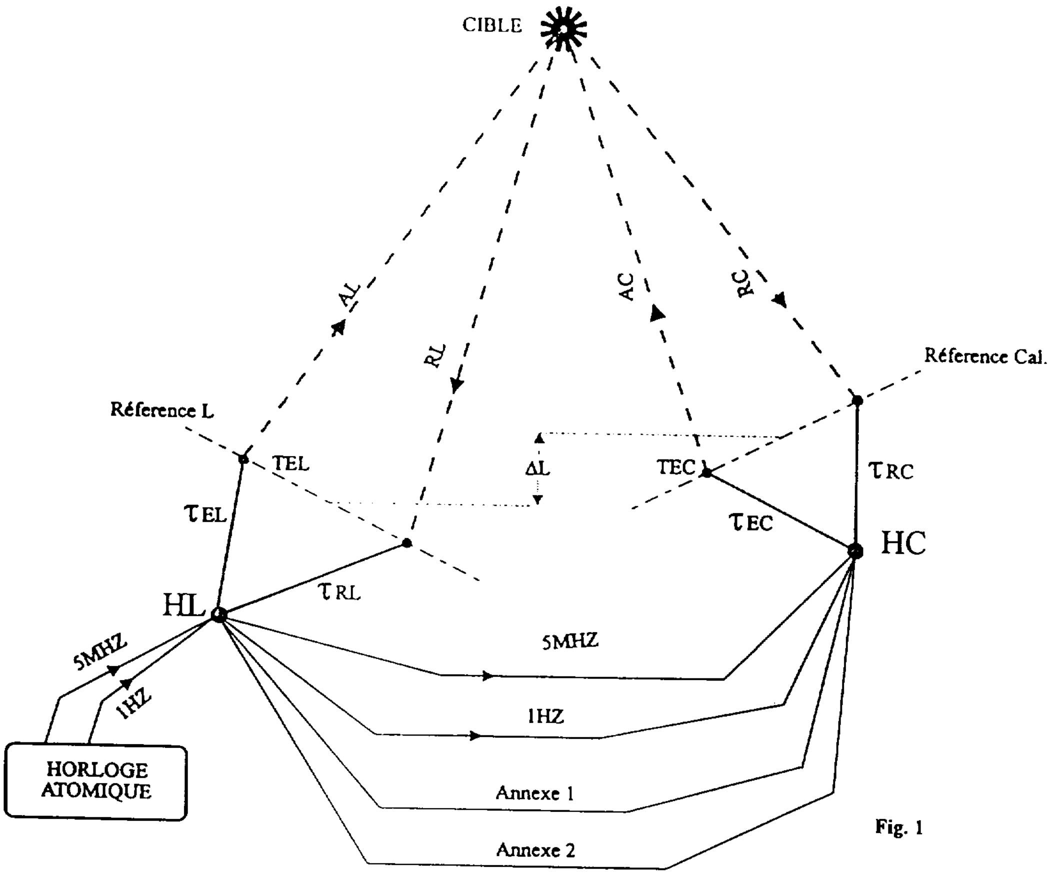

Fig. 1

STATION LASER LUNE :

HL = Dateur Laser Lune
Ref.L = Référénce station Laser Lune
TEL = Heure passage laser au point de réf.
AL = Temps aller Ref.L / cible
RL = Temps retour cible / Réf.L.
τEL = Ecart Réf.L / Dateur HL.
τRL = Ecart Dateur HL / Réf.L.
CCLL = τEL+τRL (Constante de calibration LL)
AL = RL

5MHZ,1HZ,Annexe1,Annexe2 = Cables coaxiaux

STATION DE CALIBRATION :

HC = Dateur station de calibration
Réf.Cal. = Réference stat. de Calib.
TEC = Heure au point de Réf.
AC = Temps aller Réf.Cal/cible
RC = Temps retour cible/Réf.Cal.
τEC = Dateur Réf.Cal. / Dateur HC
τRC = Ecart Dateur HC / Réf.Cal.
τEC = τRC = τC
AC = RC

INTERCALIBRATION LASSO CONFIGURATION PHASE1 GRASSE

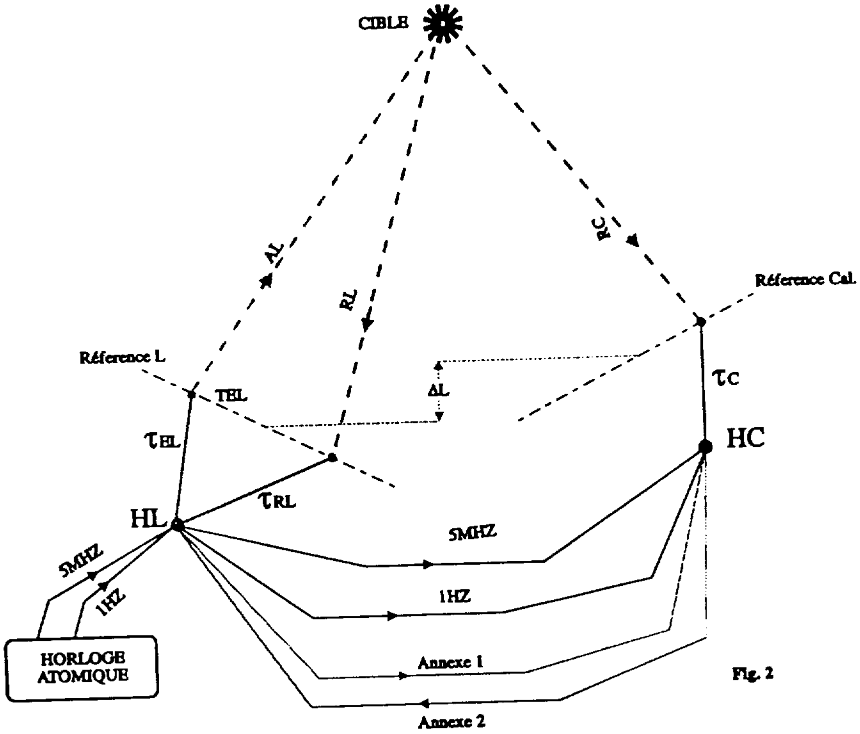

Fig. 2

INTERCALIBRATION LASSO CONFIGURATION PHASE2 GRASSE

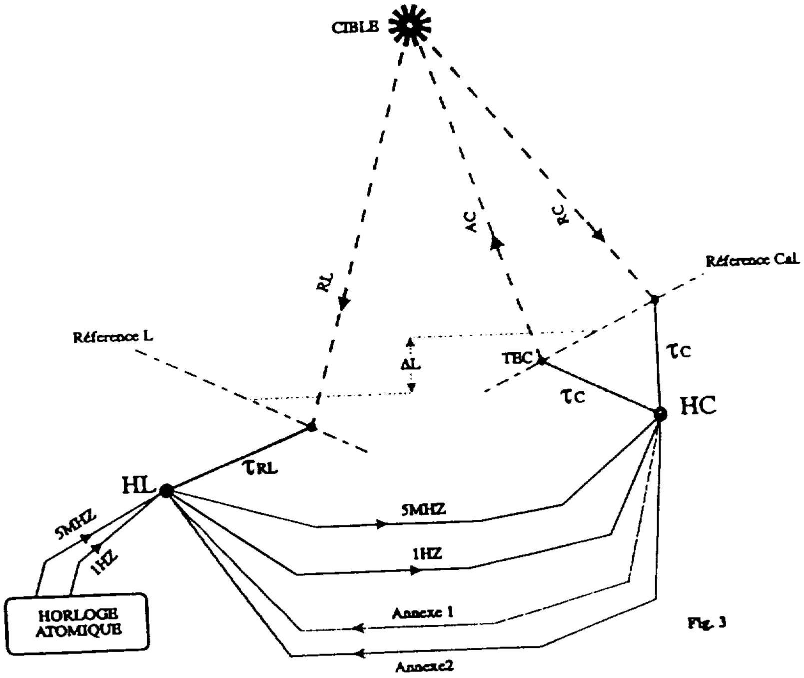

Fig. 3

LASSO INTERCALIBRATION PHASE 1 GRASSE

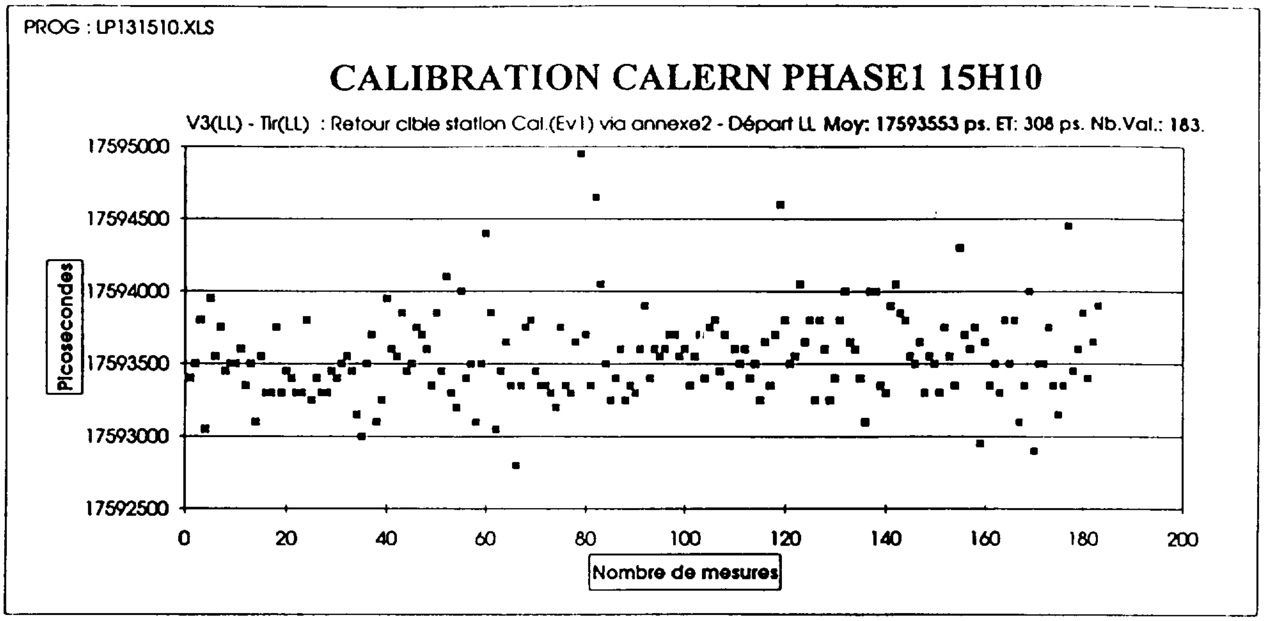

Fig. 4

LASSO INTERCALIBRATION PHASE2 TEXAS

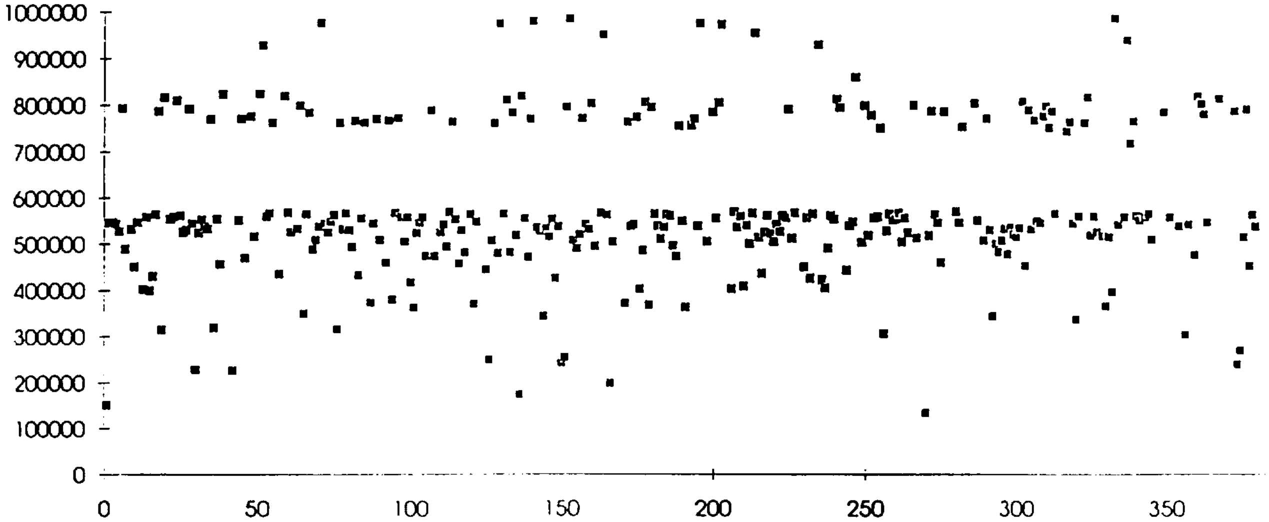

Fig. 5

INTERCALIBRATION LASSO CONFIGURATION PHASE1 TEXAS

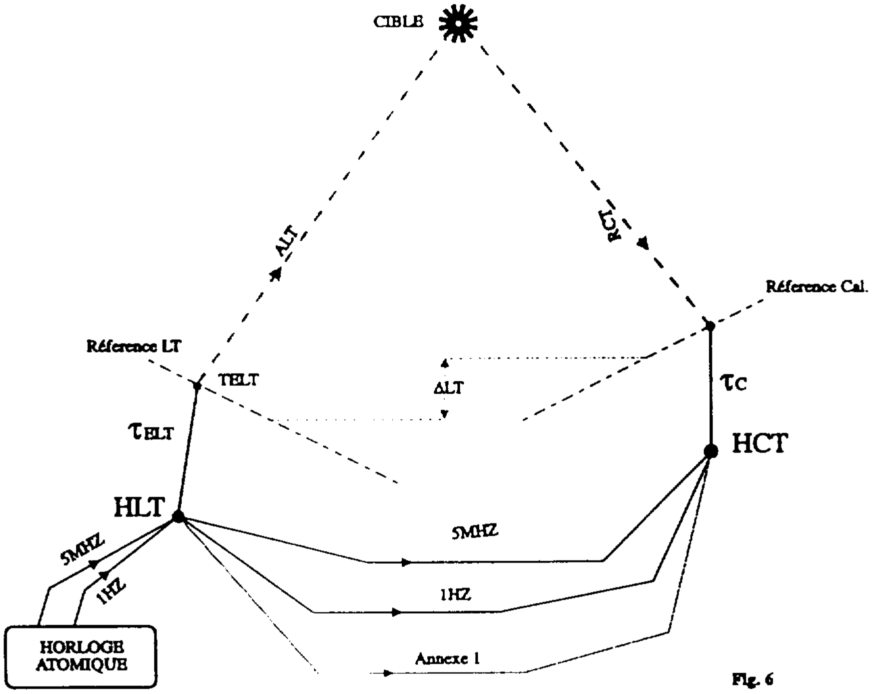

Fig. 6

INTERCALIBRATION LASSO CONFIGURATION PHASE2 TEXAS

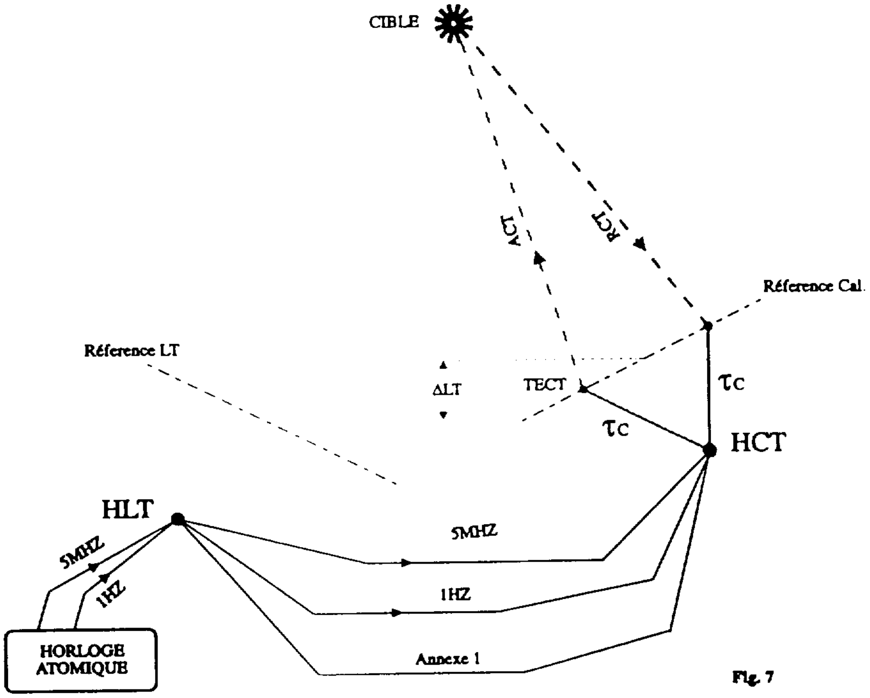

Fig. 7