ANTICIPATED UNCERTAINTY BUDGETS OF PRARETIME AND T2L2 TECHNIQUES AS APPLIED TO ExTRAS

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Abstract

The Experiment on Timing Ranging and Atmospheric Soundings, ExTRAS, was conceived jointly by the European Space Agency, ESA, and the Russian Space Agency, RSA. It is also designated the 'Hydrogen–maser in Space/Meteor–3M project'. The launch of the satellite is scheduled for early 1997. The package, to be flown on board a Russian meteorological satellite includes ultra–stable frequency and time sources, namely two active and auto–tuned hydrogen masers. Communication between the on–board hydrogen masers and the ground station clocks is effected by means of a microwave link using the modified version for time transfer of the Precise Range And Range–rate Equipment, PRARETIME, technique, and an optical link which uses the Time Transfer by Laser Link, T2L2, method. Both the PRARETIME and T2L2 techniques operate in a two–directional mode, which makes it possible to carry out accurate transmissions without precise knowledge of the satellite and station positions.

Due to the exceptional quality of the on–board clocks and to the high performance of the communication techniques with the satellite, satellite clock monitoring and ground clocks synchronization are anticipated to be performed with uncertainties below 0.5 ns (1 σ). Uncertainty budgets and related comments are presented.

INTRODUCTION

The Experiment on Timing Ranging and Atmospheric Sounding, ExTRAS, was conceived jointly by the European Space Agency, ESA, and the Russian Space Agency, RSA. It is also designated the "Hydrogen–Maser in Space/Meteor–3M project", and is scheduled for early 1997. The experiment calls for ultra–stable frequency and time sources, two active and auto–tuned hydrogen masers, to be flown on board a Russian meteorological satellite, Meteor–3M.

Communication between the on–board hydrogen masers and the ground stations is effected by a microwave link using the Precise Range And Range–Rate Equipment modified for time transfer, PRARETIME, technique, and an optical link which uses the Time Transfer by Laser Link, T2L2, method. The combination of ultra–stable time and frequency sources with precise and accurate tracking equipment should help to solve a number of scientific and applied problems in the fields of navigation, geodesy, geodynamics and Earth atmosphere physics. It should also allow timing measurements with accuracies never reached before.

ON–BOARD HYDROGEN MASERS

Compared with other atomic frequency standards, passive hydrogen masers offer improved short–term stability[1]. They are generally used as short–term references in timing laboratories, but cannot serve as time–keepers because of the huge drift they generate over averaging times longer than several hours. However, recent developments of active hydrogen masers operating according to specific auto–tuning modes for the cavity reduce frequency drift while causing a negligible degradation of the short–term stability[2]. This type of hydrogen maser already contributes, on the ground, to short–term internal time comparisons and to long–term time keeping in national timing centres concerned with time metrology.

Rubidium and cæsium clocks are currently used in navigation systems, for example in the Global Positioning System, GPS, where all Block II satellites are equipped with cæsium standards. To date, no hydrogen maser has ever been flown with the exception of a hydrogen maser belonging to the Smithsonian Astrophysics Observatory which was sent into parabolic flight in 1976[3]. Space hydrogen masers are also planned as future on–board clocks for the Russian GLObal NAvigation Satellite System, GLONASS, in order to improve the short–term stability of the flying standards.

The active auto–tuned hydrogen masers scheduled for flight on Meteor–3M are a Russian-designed hydrogen maser, proposed by the Institute of Metrology for Time and Space, VNI-IFTRII, Mendeleevo (Russia), and a Swiss Space Hydrogen Maser, SHM, proposed by the Observatoire de Neuchâtel, ON, Neuchâtel (Switzerland). These two units are of a weight ($\leq$ 50 kg), volume ($\leq$ 0.1 m^3) and power consumption ($\leq$ 60 W) compatible with an on–board installation. In addition they will be compared continuously and are interchangeable. Their short–term stability is characterized by the Allan deviation given in Table 1.

Averaging time	Allan Deviation
τ/s	$\sigma_y(\tau)$
1	1.5×10^{-13}
10	2.1×10^{-14}
100	5.1×10^{-15}
1000	2.1×10^{-15}
10000	1.5×10^{-15}
100000	$\leq 1 \times 10^{-14}$

Table 1: Allan deviation $\sigma_y(\tau)$, versus the averaging time τ, of the Space Hydrogen Maser (SHM) developed by the Observatoire de Neuchâtel, ON, Neuchâtel (Switzerland), for flying on board Meteor–3M. Numbers are provided by Dr G. Busca, of the ON, in his proposal for ExTRAS (1993).

The first consequence is that the comparison of ground clocks with the on–board hydrogen maser ensures access to a stable and slowly drifting time scale for synchronization of local time scales used for real–time dating of events on the Earth. In a complementary process, the time scale to be delivered by the on–board clock can be closely steered in real–time on any reference time scale, such as a local representation of UTC, UTC(k), kept by laboratory k: for this purpose, it is sufficient to distribute, in the satellite message, a time correction between the on–board and ground time scales. The experiment ExTRAS thus serves all the functions of time dissemination.

The specifications of Table 1 have another impact on time metrology when flying such hydrogen masers on Meteor–3M. This is linked to particular features of the satellite orbit: its polar orbit and its altitude, of order 1000 km, lead to a period of revolution around the Earth of order T = 100 min, and to possible observation of the satellite at least four times a day from any location on the Earth. The total error (1 σ) accumulated by the on–board hydrogen maser during one revolution can be estimated as[4]:

$$\sigma \approx \sigma_y(\tau) \cdot T, \tag{1}$$

which leads to the value 12 ps. If two observations are distant by 3 hours, the error (1 σ) accumulates to less than 50 ps.

It follows that comparisons between remote clocks on the Earth can be performed by differential observation of the time scale provided by the on–board hydrogen maser when it is visible from the stations. This is the clock transportation method, and there is no need to organize common views, as is done with GPS and GLONASS, the uncertainty caused by the on–board clock during its flight between the two stations being typically of order 50 ps.

To conclude, ExTRAS provides a means of time transfer based upon the transportation, via satellite, of an ultra–stable clock able to keep its time very precisely throughout the period of transportation. This time transfer method, the simplest imaginable, is thus of major interest to the timing community. Full advantage of the qualities of hydrogen masers on board Meteor–3M can be taken only if very accurate methods are used to ensure the connection between observing stations on the ground and the spacecraft. Specific features of two–direction links, such as via PRARETIME and T2L2 are discussed in the following sections.

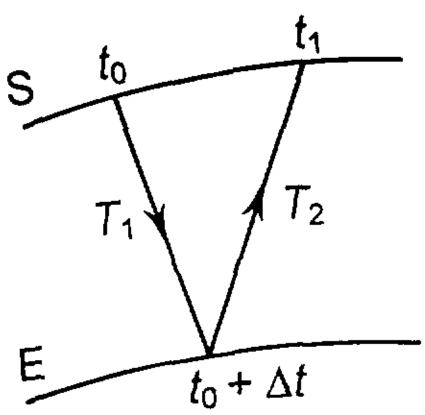
PRARETIME: PRECISE RANGE AND RANGE–RATE EQUIPMENT, MODIFIED VERSION FOR TIME TRANSFER

The Precise Range And Range–Rate Equipment, PRARE, is a high precision and fully automated facility for microwave link between clocks on board a satellite and ground stations. Its primary function consists of range and range–rate measurements, but a modified version of PRARE devoted to time transfer, PRARETIME, has also been developped. The modification concerns some hardware details and an additional time interval measurement at the ground station site. The PRARE equipment operates with a down–and–up link in the X–band (8489 GHz for down–link and 7225 GHz for up–link) between the ground and the satellite, together with a down–link in the S–band (2248 GHz)[5, 6, 7]. The PRARE X–band up–link exists only if the ground station is equipped with a ground transponder and its 60 cm parabolic dish. In this case, the only one considered in this paper, the PRARE system operates in a two–way mode, which can be used for timing purposes such as:

- time comparisons between one ground clock and the on–board clock: this is known as satellite clock monitoring, and
- time comparisons between two ground clocks through transportation of the on–board clock: this is known as ground clock synchronization.

Timing applications through ExTRAS via PRARETIME

Satellite clock monitoring



A signal is emitted by the satellite S and retransmitted immediately by the Earth station E. The time interval t_{SE} between emission and reception on board the satellite, $t_{SE} = t_1 - t_0$, is recorded. The time difference between the clocks Δt is given by[8]:

$$\Delta t = t_{SE}/2 + \delta. \tag{2}$$

With T_1 and T_2 the individual transmission times for the down–link and the up–link, the time correction δ is written as:

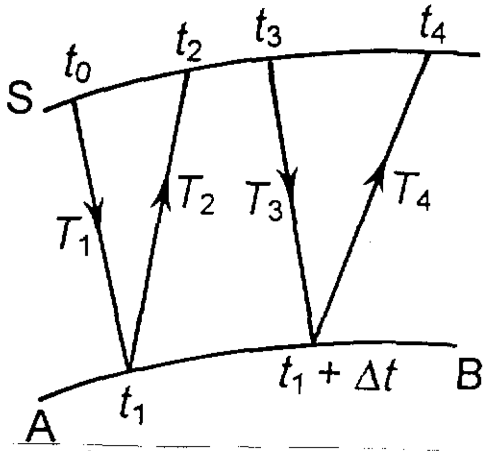
$$\delta = (T_1 - T_2)/2, \tag{3}$$

which may be expressed as[8]:

$$\delta = [\delta_{e,d} - \delta_{e,u} + \delta_{i,d} - \delta_{i,u}]/2 - \mathbf{v}_S(t_o) \cdot \mathbf{R}_{ES}(t_0)c^{-2} + \mathbf{O}(c^{-3}), \tag{4}$$

where δ_e and δ_i are external (ionospheric and tropospheric) and internal (cables, ...etc) delays respectively, subscripts 'd' and 'u' refer to the down– and up–links, $\mathbf{R}_{ES}(t_0)$ is the station to satellite vector at date t_0, $\mathbf{v}_S$ is the satellite velocity in a geocentric inertial frame and c is the speed of light in vacuum.

Ground clock synchronization



The satellite S emits signals to each ground station A and B which are immediately retransmitted to the satellite. Three time intervals are recorded by the satellite:

- $t_S = t_3 - t_0$, the time elapsed between the emission of the two signals,
- $t_{SA} = t_2 - t_0$ and $t_{SB} = t_4 - t_3$, the times elapsed between the emission and reception on-board the satellite of the signals received in stations A and B.

The time difference between the ground clocks Δt is given by[8]:

$$\Delta t = (t_{SB} - t_{SA})/2 + t_S + \delta. \tag{5}$$

The time correction δ is written as:

$$\delta = [(T_3 - T_4) - (T_1 - T_2)]/2, \tag{6}$$

where T_1, T_2, T_3, and T_4 are the individual transmission times for the down–links and the up–links.

Using (4), δ is expressed as:

$$\begin{aligned} \delta \;=\; & [\delta_{e,d} - \delta_{e,u} + \delta_{i,d} - \delta_{i,u}]_B/2 - [\delta_{e,d} - \delta_{e,u} + \delta_{i,d} - \delta_{i,u}]_A/2 - \\ & \mathbf{v}_S(t_3) \cdot \mathbf{R}_{BS}(t_3)c^{-2} + \mathbf{v}_S(t_0) \cdot \mathbf{R}_{AS}(t_0)c^{-2} + \mathbf{O}(c^{-3}), \end{aligned} \tag{7}$$

in a notation following that of (4).

In (4) and (7) no range estimations are involved in terms of order c^{-1}, which is typical of a two–way method. Terms of order c^{-2} can amount to 300 ns and can be calculated at the picosecond level even with a poor knowledge of satellite ephemerides and velocity (accuracies of these quantities should be of order 12 m and 0.02 m/s respectively). Terms in c^{-3} contribute a few picoseconds.

It follows that the time comparison value between the ground clock and the on–board clock, or between the two ground clocks, can be deduced from measurements of time intervals on–board the satellite, and from the estimations of differential delays in the up– and down–paths. No accurate estimation of the range between the satellite and the station is needed.

It is important to note that tropospheric delays totally cancel in the up– and down–paths because the troposphere is a non–dispersive medium which yields the same delay for the PRARE up and down carrier frequencies. In contrast, the ionosphere is a dispersive medium and the corresponding differential delays do not cancel in (4) and (7). The up- and down-links from the stations to the satellite do not necessarily pass through the same internal electronic circuits and cables, so internal differential delays remain in (4) and (7).

Sources of uncertainties for timing applications through ExTRAS via PRARETIME

The uncertainties affecting timing observations come from the on-board hydrogen-maser, signal transmission through the atmosphere, and the equipment which is used to emit and transmit the signals. All the uncertainties given in the following are 1 σ estimations: they are summarized in Table 2.

Uncertainty due to the on-board hydrogen maser

The uncertainty brought by the on-board hydrogen maser is deduced from its stability. This is negligible for the quantities t_{SE}, t_{SA}, andt_{SB} and thus has no impact on satellite clock monitoring. It must be taken into account, however, for the quantity t_S since this depends on the time duration which separates the observations of the satellite from the two stations being compared. A conservative estimate is of order 50 ps (1 σ).

Uncertainty on the atmospheric delay of the signal

The frequency separation between the S-band and X-band PRARE down-links makes it possible to measure the ionospheric delay of the signal. One expects a very low level of uncertainty, of order 20 ps (1 σ), for the measurement of the difference between down and up ionospheric delays. For ground clock synchronization, this uncertainty appears twice (in quadratic).

Uncertainty on the calibration of equipment

The on-board payload, the Earth stations, and the PRARETIME modems and counters must be very carefully calibrated before launch. One expects an uncertainty in the calibration of order 50 ps (1 σ) for each of these elements. These uncertainties appear twice (in quadratic) for ground clock synchronization. However, the on-board payload is known to remain very stable between adjacent observations. It follows that the corresponding uncertainty partly disappears for ground clock synchronization. One estimates a total residual uncertainty of 20 ps (1 σ) for this particular case.

The uncertainty associated with PRARETIME modems and counters arises from error sources such as instrumental delays (temperature, calibration of electronic components, C/N_o influence, ...etc), timer resolution, multipath transmission, and problems related to the antenna phase centre. It may not be possible to separate this uncertainty from those coming from the on-board payload and the Earth station calibrations.

Uncertainty due to the links to local 1 pps signals

The PRARETIME technique only uses the high frequency (5 MHz) signals from the on–board and ground clocks. Time transfer, however, usually takes place between time scales which take the form of a series of local signals at 1 pulse per second, 1 pps. It is thus necessary to take into account uncertainties arising in the links to the local 1 pps signal. Passing from 5 MHz signals to 1 pps signals requires cables and electronic circuits for frequency division and pulse formation. It generates uncertainties which are generally estimated to be of order 300 ps (1 σ). In the PRARETIME system, no 1 pps signal is physically available on board the satellite, so this class of uncertainty arises only in the timing circuitry of the ground stations.

Anticipated uncertainty budgets for timing applications through ExTRAS via PRARETIME

The anticipated uncertainty budgets for satellite clock monitoring and ground clock synchronization are given in Table 2. Those parts of uncertainty arising from the method itself and from the links to the local 1 pps signal are shown separately. The uncertainty of the method itself amounts to 89 ps (1 σ) for satellite clock monitoring, and 117 ps (1 σ) for ground clock synchronization. The total uncertainties of 313 ps and 440 ps (1 σ), largely dominated by uncertainties due to local links to the 1 pps signals in the ground stations, are well below 0.5 ns (1 σ), which represents a major improvement for time metrology. In addition, the PRARETIME instrument makes it possible to disseminate any time scale maintained on the ground thanks to additional information contained in the S–band downward signal. The achievable uncertainty of this particular timing mode is to be further investigated.

T2L2: TIME TRANSFER BY LASER LINK

The Time Transfer by Laser Link, T2L2, technique provides an optical time link between the on–board hydrogen masers and ground clocks. It may be seen as a continuation of the LAser Synchronization from Satellite Orbit (LASSO) technique, which was successfully carried out between the McDonald Observatory in Texas, USA, and the Observatoire de la Côte d'Azur, France, in 1992, through the geostationary satellite Meteosat–P2. Very few LASSO time comparison points were obtained during this experiment[9, 10]. They show a precision of order 200 ps, which is a major improvement over other methods, but, unfortunately no accuracy evaluation has been made so far now. The LASSO experiment also showed the possibility of monitoring the on–board clock with a precision of order 50 ps. This could serve time dissemination purposes, but again the corresponding uncertainty has not yet been evaluated.

The specific and principal difficulties of the LASSO experiment are:

- the rather poor stability of the oscillator on board Meteosat–P2. The consequence is that the stations to be synchronized must both shoot the laser onto the satellite within a time window equivalent of common–view conditions.
- the weather conditions must be excellent to avoid excessive light dissipation which prevents the ground observer from counting an adequate number of return photons.

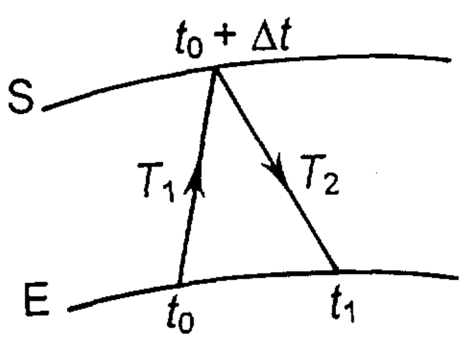
Problems with on–board oscillators should largely be resolved using T2L2, because ultra–stable sources are used. In addition, as the Meteor–3M satellite orbit is far lower altitude than that of the geostationary Meteosat–P2 satellite, the effects of weather conditions should be less severe.

The T2L2 equipment can easily be installed on board the satellite. The princial elements in this equipment are a light detector linked to an event timer, and an Optical Retroreflector Array (ORA). The Earth sites concerned with this experiment require to have at their disposal facilities for high–power pulsed–laser shooting, together with a telescope. Very few sites meet these requirements and it may be necessary to increase the number of laser stations to take full advantage of the ExTRAS experiment.

Timing applications through ExTRAS via T2L2

The T2L2 time transfer system can serve satellite clock monitoring and remote ground clock synchronization according to schemes symmetrical to those already presented for the PRARETIME technique.

Satellite clock monitoring



A signal is emitted by the Earth station E With T_1 and and reflected immediately by the satellite S. The time interval $t--ES$ between emission and reception at the station, $t_{ES} = t_1 - t_0$, is recorded. The time difference between the clocks Δt is given by[8]:

$$\Delta t = t_{ES}/2 + \delta. \qquad (8)$$

T_2 the individual transmission times for the up–link and the down–link, the time correction δ is written as:

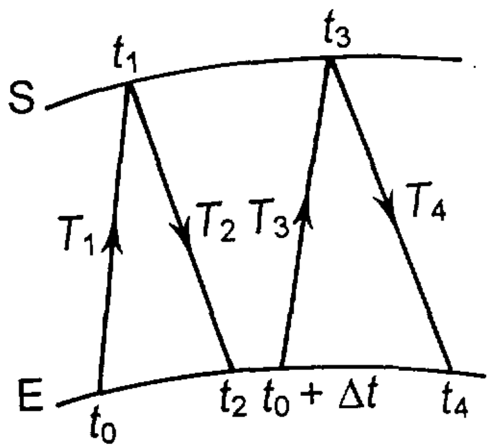
$$\delta = (T_1 - T_2)/2. \qquad (9)$$

Using (4), this is expressed as:

$$\delta = [\delta_{i,u} - \delta_{i,d}]/2 + \mathbf{v}_E(t_0) \cdot \mathbf{R}_{ES}(t_0)c^{-2} + \mathbf{O}(c^{-3}), \qquad (10)$$

with notations similar to that of (4).

Ground clock synchronization



Laser pulses are emitted from the ground stations A and B, and reflected by the satellite S. Three time intervals are recorded:

- $t_S = t_3 - t_1$, the time elapsed between the reflection of the two signals (recorded on the satellite),
- $t_{AS} = t_2 - t_0$ and $t_{BS} = t_4 - t_0 - \Delta t$, the times elapsed between the emission and reception (recorded in stations A and B).

The time difference between the ground clocks Δt is given by[8]:

$$\Delta t = (t_{AS} - t_{BS})/2 + t_s + \delta. \quad (11)$$

The time correction δ is written as:

$$\delta = [(T_1 - T_2) - (T_3 - T_4)]/2, \quad (12)$$

where T_1, T_2, T_3, and T_4 are the individual transmission times for the up-links and the down-links.

Using (10), this is expressed, with a notation similar to that of (4), as:

$$\delta = [\delta_{i,u} - \delta_{i,d}]_A/2 - [\delta_{i,u} - \delta_{i,d}]_B/2 + \mathbf{v}_A(t_0)\cdot\mathbf{R}_{AS}(t_0)c^{-2} - \mathbf{v}_B(t_0+\Delta t)\cdot\mathbf{R}_{BS}(t_0+\Delta t)c^{-2} + \mathbf{O}(c^{-3}). \quad (13)$$

In (10) and (13) no range estimations are involved in terms of order c^{-1}, which is again typical of a two-way method. Terms of order c^{-2} may amount to 20 ns and can be calculated at the picosecond level even with a poor knowledge of satellite-station ranges and station velocities in an inertial frame (accuracies in these quantities should be of order 100 m and 0.02 m/s respectively). Terms in c^{-3} contribute a few picoseconds.

It follows that the time comparison value between the ground clock and the on-board clock, or between the two ground clocks, can be deduced from measurements of time intervals on-board the satellite and in the ground stations, and from the estimations of differential delays in the up- and down-paths. No accurate estimation of the range between the satellite and the station is needed.

It is important to note that atmospheric delays totally cancel in (10) and (13) since the T2L2 up and down frequencies are equal. The up- and down-links from the stations to the satellite do not necessarily pass by the same internal electronic circuits and cables, so internal differential delays remain in (10) and (13).

Sources of uncertainties for timing applications through ExTRAS via T2L2

The uncertainties affecting timing observations come from the on–board hydrogen–maser, and from the different equipment which is used for emitting and reflecting the optical pulses. Similar comments apply to the estimation of uncertainties as were given for PRARETIME, but two points should be noted:

- no uncertainties are to be taken into account for atmospheric delays, and
- only counters, and no modems, are used in the T2L2 technique, which reduces the corresponding uncertainty to 10 ps (1 σ).

Anticipated uncertainty budgets for timing applications through ExTRAS via T2L2

The anticipated uncertainty budgets are given in Table 3 for satellite clock monitoring and ground clock synchronization through ExTRAS via T2L2. Again, the parts of the uncertainty coming from the method itself and from the links to the local 1 pps signals are separated. One obtains an uncertainty for the method of 71 ps (1 σ) for satellite clock monitoring, and 90 ps (1 σ) for ground clock synchronization. The total uncertainties of 308 ps and 434 ps (1 σ) are again largely dominated by terms arising from the local links to the 1 pps signals in the ground stations.

To conclude, the estimates of the T2L2 anticipated uncertainty budgets are very close to those obtained with PRARETIME: the main uncertainty is not due to the method itself, and the overall accuracy of time transfer is characterized by an uncertainty well below 0.5 ns (1 σ). In terms of the method itself, T2L2 is slightly more accurate than PRARETIME and may be considered as the reference technique. In addition, studies about the calibration of the on–board payload are being carried out, which may show that the tentative estimate of the corresponding uncertainty, which is given in Table 3, is too pessimistic. Unfortunately, however, T2L2 depends on clear weather and on specific laser equipment of a kind not available in many time laboratories.

CONCLUSIONS

The ExTRAS experiment could provide a time transfer method based on satellite transportation of ultra–stable hydrogen masers. Two–way connections with the satellite are ensured by two techniques, PRARETIME and T2L2, both potentially accurate at a level about 300 ps (1 σ) and both able to provide satellite clock monitoring and ground clocks synchronization. This could represent a very interesting improvement in the accuracy of time transfer methods when compared to GPS common views, achieved with an uncertainty of order 2 ns (1 σ) over short distances ($\leq$ 1000 km) and 5 ns (1 σ) over long distances ($\geq$ 5000 km), and to Two–Way Satellite Time Transfer via geostationary satellite, for which the best accuracy achieved is at present 1.7 ns (1 σ). This would be of major interest for time metrology, in particular for comparison of future clocks designed for frequency uncertainties of some parts in 10^{16}.

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Table 2: Anticipated uncertainty budgets for satellite clock monitoring and ground clock synchronization through ExTRAS via PRARETIME. All uncertainties are in picoseconds and correspond to a 1 sigma statistical analysis. No uncertainties on time comparison arise from range estimation.

Uncertainty source	Satellite clock	Ground clocks
	monitoring	synchronization
Range	0	0
Hydrogen maser	0	50
Atmospheric delay	20	$20\sqrt{2}$
On–board payload	50	20
Earth station	50	$50\sqrt{2}$
Modems & counters	50	$50\sqrt{2}$
Method accuracy	89	117
Ground link to 1 pps	300	$300\sqrt{2}$
Total accuracy	313	440

Table 3: Anticipated uncertainty budgets for satellite clock monitoring and ground clocks synchronization through ExTRAS via T2L2. All uncertainties are in picoseconds and correspond to a 1 sigma statistical analysis. No uncertainties on time comparison arise from range estimation and atmospheric delays.

Uncertainty source	Satellite clock	Ground clocks
	monitoring	synchronization
Range	0	0
Hydrogen maser	0	50
Atmospheric delay	0	0
On–board payload	50	20
Earth station	50	$50\sqrt{2}$
Counters	10	$10\sqrt{2}$
Method accuracy	71	90
Ground link to 1 pps	300	$300\sqrt{2}$
Total accuracy	308	434

QUESTIONS AND ANSWERS

SIGFRIDO M. LESCHIUTTA: I was saying that we shall aim to the 10 ps resolution. So, this experiment is aiming to 300 ps.

CLAUDINE THOMAS (BIPM): Maybe I must add that funding is not yet voted for this experiment. So, I'm not so sure it will happen, but let's hope.