

T2L2

Time Transfer by Laser Link

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Abstract

T2L2 (Time Transfer by Laser Link) is a new generation time transfer experiment based on the principles of LASSO (Laser Synchronization from Synchronous Orbit) and used with an operational procedure developed at OCA (Observatoire de la Côte d'Azur) during the active intercontinental phase of LASSO. The hardware improvements could lead to a precision better than 10 ps for time transfer (flying clock monitoring or ground based clock comparison). Such a package could fly on any spacecraft with a stable clock. It is developed in France in the frame of the PHARAO project (cooled atom clock in orbit) involving CNES and different laboratories. But T2L2 could fly on any spacecraft carrying a stable oscillator. A GPS satellite would be a good candidate, as T2L2 could allow to link the flying clock directly to ground clocks using light, aiming to important accuracy checks, both for time and for geodesy. Radioastron (a flying VLBI antenna with a H-maser) is also envisioned, waiting for a PHARAO flight. The ultimate goal of T2L2 is to be part of more ambitious missions, as SORT (Solar Orbit Relativity Test), aiming to examine aspects of the gravitation in the vicinity of the Sun.

INTRODUCTION

The development of very stable clocks, and the increasing number of applications of their use in space (see for example [1]), urges to study the possibility of linking these clocks to the ground with better and better accuracies. The techniques used for transferring time between two remote clocks using satellites can be divided in two classes. The first uses electromagnetic signals in the radio domain, as two way time transfer through telecommunication satellites, or GPS. The second class deals also with electromagnetic signal, but at light frequencies, as LASSO or a laser link through the Ajisai satellite. It is not very easy to guess which precision and accuracy could reach these techniques within the next five to ten years. However, one can try to estimate what could be the more important limitations for each of them, starting with the radio domain.

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WHICH FUTURE FOR THE RADIO-FREQUENCY TIME TRANSFER ?

The current accuracy of GPS for time transfer is slightly better than 10 ns on long baselines (6000 km). It can be improved to around 3 ns on regional comparisons. Improvements in the receivers could bring to a sub-nanosecond accuracy, let say 500 ps, assuming that the receivers used in the time transfer experiment have been carefully calibrated, and that their environment will be well monitored in order to map properly the variation of their metrology characteristics. To do better seems very difficult, mainly due to the atmospheric correction, which will probably bring the ultimate limitation at around 500 ps.

Two-way time transfer is presently achieving a precision of around 200 ps, and an accuracy of 1 to 2 ns. One could think that the new methods of calibration to be used in order to reach a better accuracy could lead to a strong improvement. Nobody can tell now what could be the best calibration achievable. However, the atmosphere will be definitely a limitation at 50 ps, and, again, the accuracy will depend on how well the calibrations can be performed. . .

PRARETIME (the PRARE positioning system modified for precise time transfer) could reach an accuracy of 100 ps if comparing directly the clocks through their 5 MHz frequency, 200 to 300 ps being the overall accuracy when the time scales, as realized by the 1 pps, are compared^[2]. Doing better seems very difficult if one wants to keep the original PRARE equipment with only slight modifications.

As a conclusion of this quick look to a mid-term evolution of the radio frequency time transfer techniques, 50 ps seems to be a reasonable limit, even assuming very careful calibrations and delay variation monitoring.

TRANSFERRING TIME WITH LIGHT

The basic principle of time transfer using T2L2 is briefly described in [2], where can be found also a general uncertainty analysis of both PRARETIME and T2L2. A complete analysis of the T2L2 precursor, LASSO, can be found in [3]. We will detail here the uncertainty analysis of the T2L2 equipment.

Short events

In contrast with the radio frequency techniques, optical time transfer is based on the timing of individual very short events with respect to a clock. We are now able to create such short events using lasers with pulse length of 20 ps or less, with enough energy to be sent in space, recorded by a flying detector, and still recorded on the ground after their reflection on a retroreflector array on the satellite. Even the geosynchronous orbit can be reached with such short pulses. The duration of the event to be timed will not be the limit of such techniques, as the uncertainty it brings will decrease by averaging measurements (typically, for 10 s, 100 events can be timed. . .). The problem now is to know how well we can time an event.

Rapid detectors

The light event needs first to be transformed into an electric signal. This will be done through a detector. This detector has to be rapid, in order to benefit from the short event. Its transit time has to be very stable, and checked by a real time calibration. A photomultiplier is no longer a good candidate, as its transit time is varying depending on where the light is arriving on its photocathode. This transit time is also very long, and varying very quickly with the environment. Avalanche photodiodes are the kind of detectors widely used now in the laser ranging measurements. Some of them exhibit very short transit times, with small detector areas minimizing the jitter. Preliminary tests made at the LLR (Lunar Laser Ranging) station at OCA on various photodiodes allows to assign 50 ps to the detector uncertainty (single measurement).

The event timer

Event-timers are rarely used in the laser ranging community, as the basic measurement is the flight time of a laser pulse to the target and back, which is a time interval. The start time itself has to be recorded with an accuracy not better than 0.1 ms. One can use a counter for an absolute timing if one measure for example the interval between the event to be timed and the next 5 MHz tick. Unfortunately, most of the counters, claiming precisions of 20 ps, are not accurate at that level, and there are no event-timers reaching a 2 ps resolution, or 10 ps accuracy... The extrapolation of the (more than 10 years old) LASSO event timer performances, using the up-to-date technology, should make possible timing with a 10 ps accuracy with respect to the reference frequency.

T2L2 uncertainty

Atmosphere and modeling

T2L2 will be made of a a detector and a timer flying on a satellite. The participating ground stations will be equipped with comparable detector and timer as the flying ones. The method is described in [2]. As we are working in a two-way mode, the only noise added by the atmosphere is the fluctuation between the way up and the way down of the troposphere. The more pessimistic value, with a very high satellite for which 250 ms will separate the start and the return of the light at the ground station, leads to a 20 ps uncertainty, with is purely random as there is no systematic in the very short term variations of the troposphere. As the stations and the satellite will be localized well enough, there is no influence of the modeling of the measurement in term of relativistic corrections which can be completed at the picosecond level.

Overall noise

On a single measurement, the noise can be written as following:

Satellite: $\sigma^2 = (50 \text{ ps})^2 + (10 \text{ ps})^2 + (20 \text{ ps})^2 = (55 \text{ ps})^2$
 detector timer laser

Ground : $\sigma^2 = (50 \text{ ps})^2 + (10 \text{ ps})^2 + (20 \text{ ps})^2 = (55 \text{ ps})^2$
with the same sources, as the equipment is basically the same

Atmosphere : $\sigma^2 = (20 \text{ ps})^2$

Overall single measurement noise : $\sigma^2 < 80 \text{ ps}$

The uncertainty for a T2L2 clock offset determination, based on 100 measurements, is then smaller than 8 ps (one sigma).

Overall accuracy ? It depends on the use of T2L2...

How well will one be able to measure the variations of the equipment delays, i.e. to calibrate the flying equipment and the ground stations? The experience acquired for the LASSO experiment^[4] clearly demonstrates how difficult it is to achieve such a calibration at the sub-nanosecond level. Depending on the goal of the mission using T2L2, we can approach the question on different manners.

Flying clock monitoring

In that case, we have a very stable clock flying, and another one on the ground. We do not care really about the absolute offset between them, as the flying clock will be switched on some time after the launch, or behave during the launch in an unpredictable way. A consequence is that we will need only to keep constant all the delays at the station, or to monitor any change in its time characteristics, without the requirement of an absolute calibration. Concerning the flying package, careful laboratory tests will have to be made in the laboratory in order to parametrize the instrumental delays with respect to the environment, and to monitor the parameters all along the experiment. LASSO demonstrated that more problems arise from the ground, as the onboard equipment is free of any changes... Such a monitoring of the ground equipment and a good parametrization of T2L2 should lead to an uncertainty of 50 ps. We could perhaps do better, but need more investigations.

In one day, T2L2 could then reach a frequency transfer between the ground and the satellite with an accuracy of 10^{-16} . Such an accuracy is promising if T2L2 is used for monitoring an ultra-stable clock (as cooled atom or trapped ion devices).

Time transfer

Now, we need an absolute calibration, in order to allow a time scale comparison. Up to now, only relative calibrations^[4] performed between the participating stations have been made. We clearly need to find another way to work, as we have to monitor all the variations which can arise after, or between, calibration campaigns. If the calibration itself could be achieved also at the 50 ps level, how to maintain it has to be explored. 100ps seems not too difficult, 10

ps is definitely a very difficult goal. It means that the time transfer accuracy will in fact be dominated by our capability to calibrate the ground equipments.

If we consider that we need to link the 1 pps of each station for a real time scale comparison, we have to add an uncertainty due to the link between the reference frequency used for timing and this 1pps. Estimated to be between 100 and 300 ps, it becomes the most important source of uncertainty. However, the meaning of the clock offset at a given time as provided by T2L2 without direct reference to a 1 pps signal has to be explored carefully.

The present status and near future of T2L2

T2L2 is entering in a phase A study within CNES. It is part of the studies made in the PHARAO project. The clear goal of T2L2 will be to provide a link between the flying cooled atom clock and the ground. T2L2 will not be the main link as it is weather dependent. But it will provide the opportunity of a link based on a completely different technology, and able of a very high accuracy. T2L2 could then be used for calibrating the (main) microwave link, and, depending on the weather, provide continuous accurate monitoring on some extended periods, and accurate measurements from time to time.

In this one year T2L2 phase A, the flying package feasibility will be carefully studied. A ground version of the event-timer should be tested at the LLR station in the beginning of 1995, and the selection of a detector suitable for T2L2 should be made. In addition, a great attention will be paid to the following points :

- hardware requirements at the laser stations
- T2L2 clock offset determination meaning (with respect to time scale link)
- calibration procedures
- station delay real-time monitoring
- operational aspects (observation strategy, network organization,...)

Various scenarios for a first test flight of T2L2 will be envisioned, waiting for a (not decided yet) PHARAO mission. After the death of the ExTRAS / Space maser on Meteor 3-M project, other opportunities exist for T2L2. Radioastron could be one, as the timeframe of the launch is compatible with a possible schedule for the fabrication of T2L2. Another possible spacecraft, which would be very interesting for both time and geodesy, could be a GPS satellite equipped with retroreflectors. It would allow a direct link through light with the satellite clock, as well as a good satellite positioning through the laser ranging measurements which are a by product of T2L2. Other future missions are under consideration.

For the T2L2 observations, the SLR (Satellite Laser Ranging) network has been approached, and many positive answers have been received from many stations in more than 10 countries around the world. Time transfer is a new application of these ground equipments mainly used for geodesy and geophysics. At a time where SLR role in these applications is not as unique as it used to be in the past two decades, thanks to GPS, the laser stations find a new field of

application, pushing the technique at its limits. In countries where permanent SLR sites are operating, the national time laboratories should approach them in order to start a cooperation on these time transfer opportunities. In the same time, they could stress the importance of GPS ranging for both time and geodesy.

Other scientific objectives of T2L2

T2L2, as well as a microwave link, and a very stable clock in orbit is rich of many applications. In an eccentric orbit around the Earth, it could provide an improvement by a factor 400 in the Vessot–Levine gravitational redshift measurement. It could give the opportunity of the still controversial East–West West–East independent measurement of the speed of light, as proposed by the first author for the TROLL project in 1991, which can be extended to a general check of the isotropy of light^[5]. In orbit around the Sun, it could allow the measurement of the so-called Shapiro effect, the delay experienced by the light in a strong gravitational field. The PPN parameter g could be determined with an accuracy of 10^{-7} . It is the SORT mission proposed to ESA^[6], where two similar satellites could also allow a simultaneous g measurement through interferometry. We are far from time transfer between ground clocks, but such dreams for a far future are driving the efforts of today...

CONCLUSION

T2L2 could be able to monitor a flying clock or to transfer time with a 10 ps precision, and an accuracy depending on the capability of calibrating and monitoring the instrumental delays, 50 ps being a reasonable guess if the necessary efforts are made, and depending also on the necessity to work with a 1 pps for linking the time scales. If the phase A to be conducted in 1995 concludes on the feasibility of T2L2, and if the funding for its fabrication is obtained, a flight model could be available in mid 1997, ready to benefit from any spacecraft carrying a stable clock...

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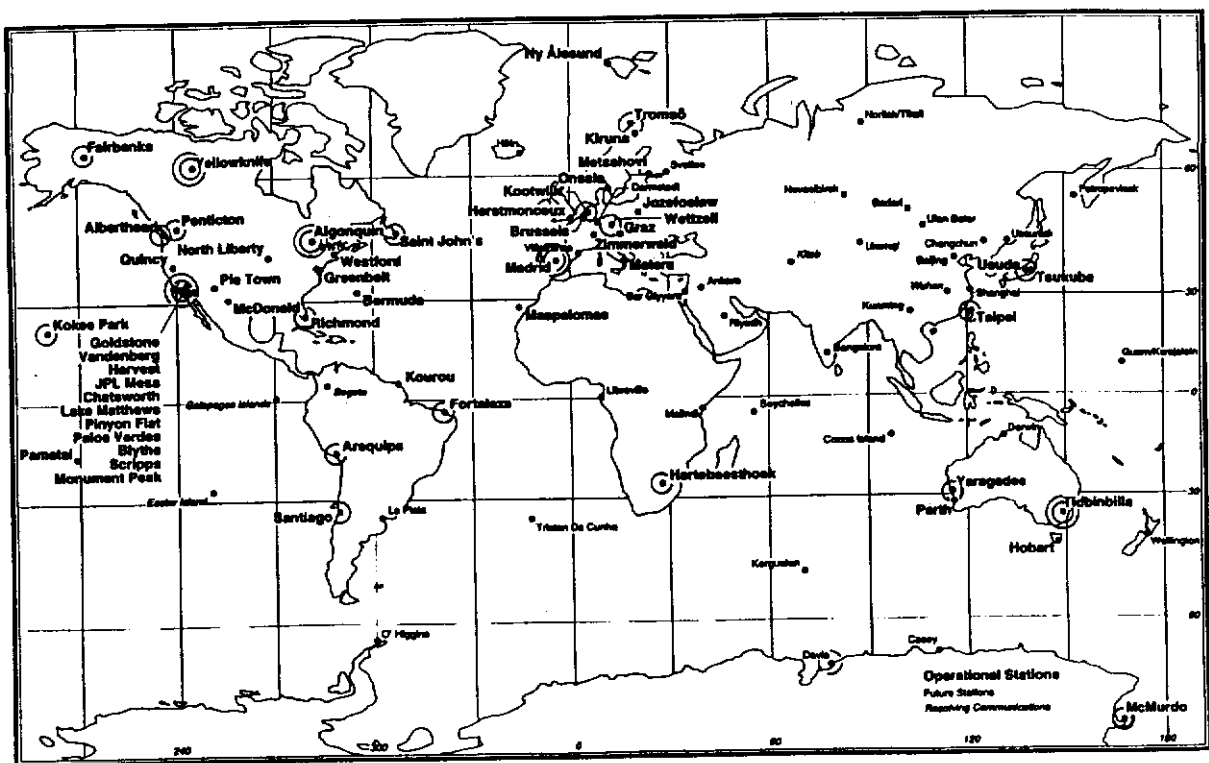


Figure 1. Map showing locations of GPS receiver stations of the International GPS Service for Geodynamics. Stations mentioned in the text have double circles. The global GPS solutions whose timing results are described in the text, use up to 24 stations - such as the set shown circled here.

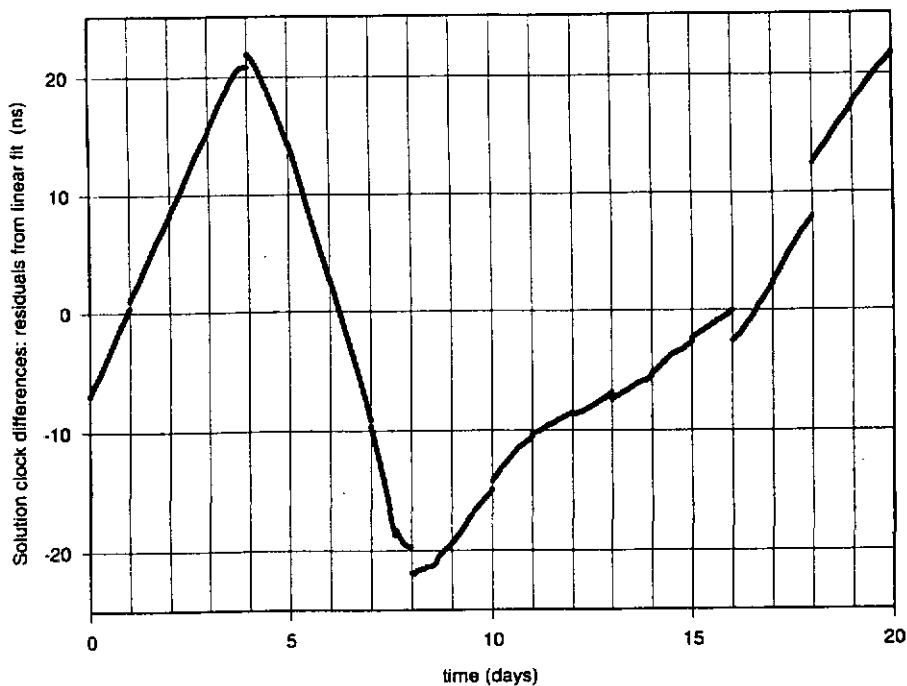


Figure 2. Maser clock differences between Algonquin and NRC, as calculated from the global solution. Each day is treated independently.

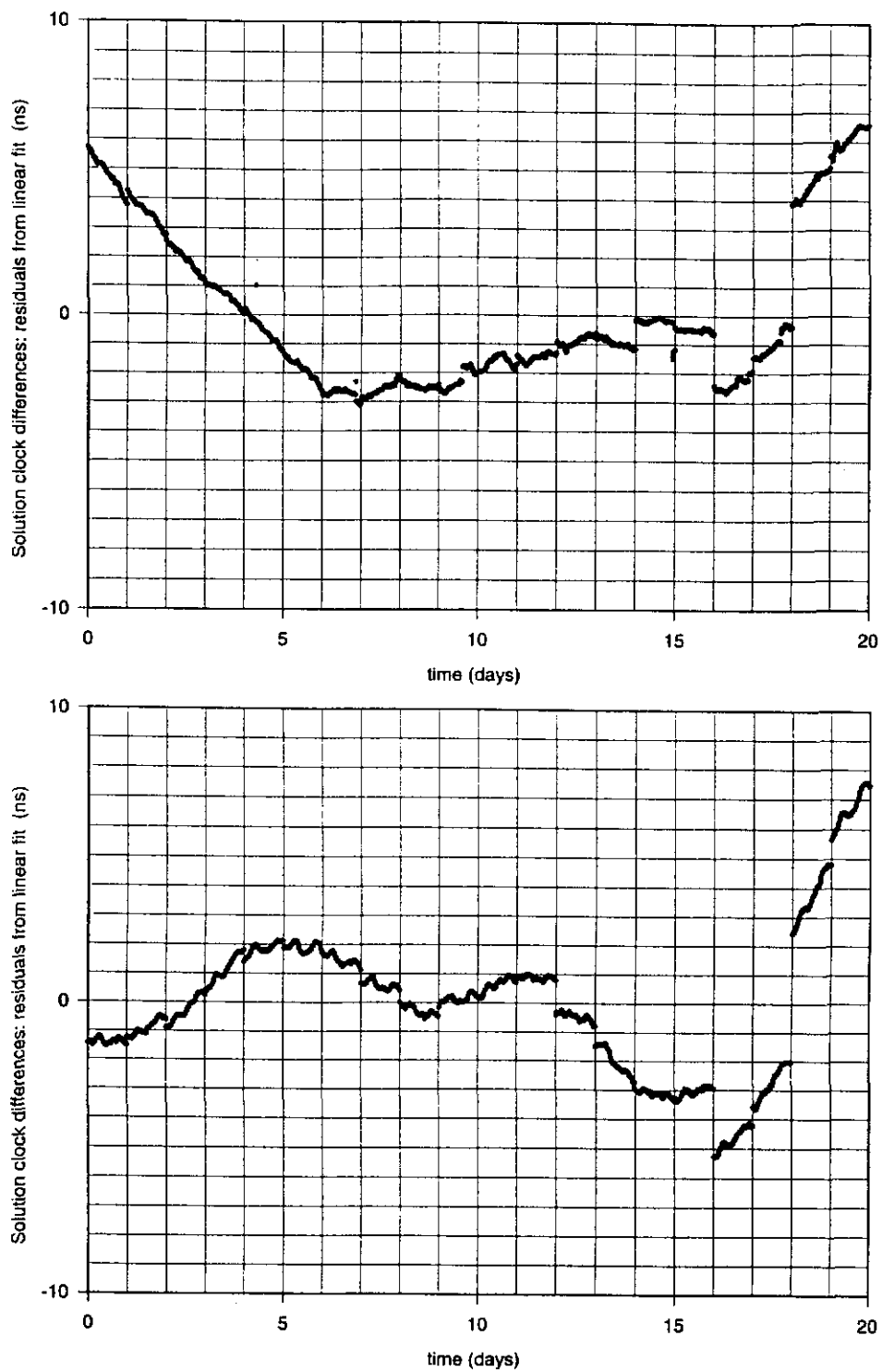


Figure 3. Maser clock differences between Goldstone and NRC, (top) and between Madrid and NRC (bottom), as calculated from the global solution. Some direct common view satellites exist for these pairs.

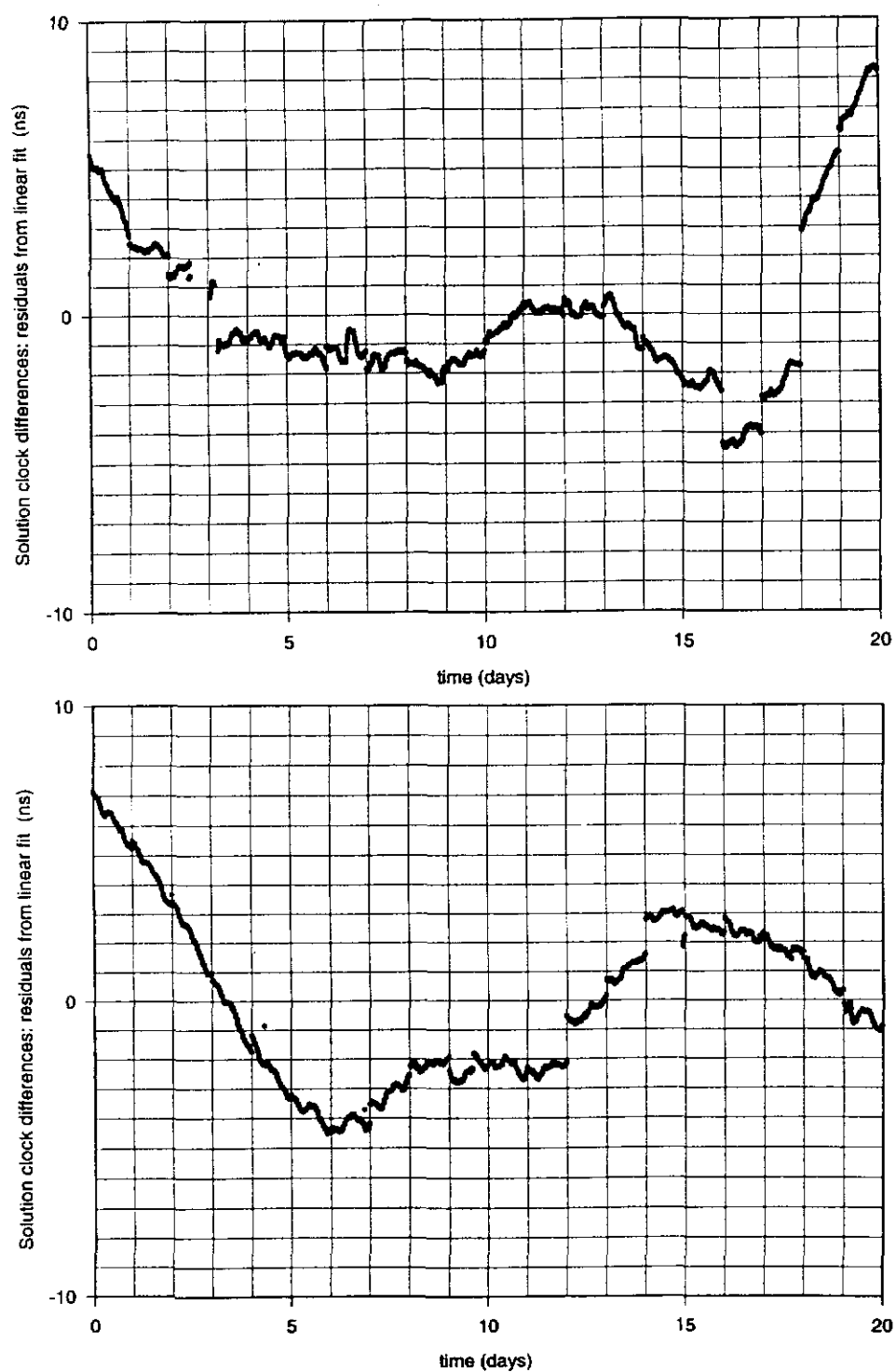


Figure 4. Maser clock differences between Tidbinbilla and NRC, (top) for which no direct common view satellites exist; and between Goldstone and Madrid (bottom), as calculated from the global solution via NRC only.

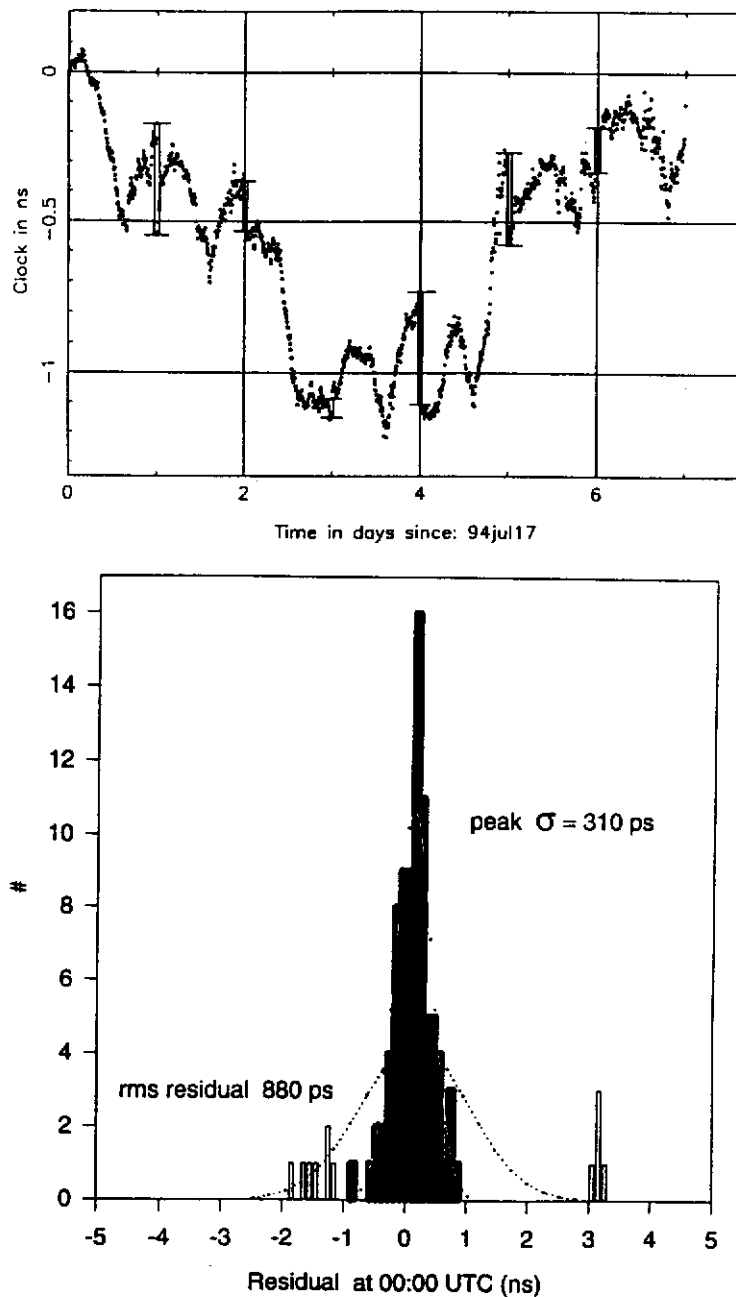


Figure 5. (Top) daily global solution discontinuities in Algonquin - NRC maser clock differences, emphasized by the "bars" at 00:00 each day. (Bottom) Histogram of daily solution discontinuities for the 19 days of Figs.2-4, between NRC and five IGS stations' masers, scaled by $1/\sqrt{2}$ to reflect the residual at the ends of the daily solutions. The open bars represent values included in the determination of the "rms" value, and excluded from the "peak σ " value.

QUESTIONS AND ANSWERS

W. LEWANDOWSKI (BIPM): I have a comment on that. There are some chances to put this equipment on GLONASS satellites. And that is interesting because GLONASS satellites are very often launched, so there is not this problem of metal, for example, on other satellites in which just one is launched. So I think that is something which should be —

CHRISTIAN VEILLET (OBSERVATOIRE DE LA CÔTE D'AZUR): You are right. Perhaps you could put this, too, on the back of GPS satellites and put the PRARE time on it. On GLONASS, yes.

I have just one more comment. It's concerning the fact that T2L2 has been announced with the satellite as a ranging network. And already at least 10 countries have expressed that they would be very happy to participate. And I think that you should approach your SLR stations in your country -- I'm not talking about the state, because you did that already. But now, SLR stations would be very happy to be used for something as geodesy and geophysics. As you know, SLR is not as important as it was in the last two decades for geodesy and geophysics, thanks to GPS. And so it means that they have nice devices, good satellites as running stations. And the need to use that -- and there is a very nice use of the stations which can be made for time.

I would so I would ask the your countries to approach these stations, because they could do a nice job for them. Thanks.