TIME LINKS FOR THE CONSTRUCTION OF TAI

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Abstract

The American Global Positioning System (GPS) has served the principal needs of national timing laboratories for regular comparisons of remote atomic clocks for the last two decades. Single-channel GPS C/A-code common-view time transfer is, however, barely sufficient for comparison of today's atomic clocks within a few days, and certainly not sufficient for comparison of clocks currently being designed. For this reason the timing community is engaged in the development of new approaches to time and frequency comparisons, including techniques based on multi-channel GPS and the Russian Global Navigation Satellite System (GLONASS) C/A-code measurements, GLONASS P-code measurements, GPS carrier-phase measurements, temperature-stabilized antennas, standardization of receiver software, and two-way satellite time and frequency transfer through telecommunication satellites. This paper describes how the above-mentioned techniques can be used to meet TAI needs. Some of the techniques are already operational, and the others are expected to be introduced to meet the requirements of future higher accuracy clocks.

INTRODUCTION

The American Global Positioning System (GPS) has served the principal needs of national timing laboratories for regular comparisons of remote atomic clocks for the last two decades [1]. In the pre-GPS era the technology of atomic clocks was always ahead of that of time transfer. The uncertainties of long-distance time comparisons, carried out using the LORAN-C system, were some hundreds of nanoseconds and large areas of the Earth were not covered. This resulted in an annual term in International Atomic Time (TAI). The introduction of GPS has led to a major improvement of world-wide time metrology in precision, accuracy, and coverage. With GPS operated in single-channel common-view C/A-code mode, time comparisons can be performed with an uncertainty of a few nanoseconds, which corresponding to 1 part in 10^{14} for averaging times of a few days. For periods of about one month, the stability of TAI after removal of GPS noise is currently about 2 parts in 10^{15}. Single-channel GPS C/A-code common-view time transfer is, however, barely sufficient for comparison of today's atomic clocks within a few days, and certainly not sufficient for comparison of clocks currently being designed. For this reason the timing community is engaged in the development of new approaches to time and frequency comparisons, including techniques based on multi-channel GPS and the Russian Global Navigation Satellite System (GLONASS) C/A-code measurements, GLONASS P-code measurements, GPS carrier-phase measurements, temperature-stabilized antennas (TSAs), standardization of receiver software, and two-way satellite time and frequency transfer (TWSTFT) through telecommunication satellites.

The performances of various methods of time transfer are illustrated in Figure 1. It has been shown that the stability of time and frequency transfer is improved by a factor of about 3 when GPS common-view time transfer is carried out in multi-channel mode. The use of GLONASS P-code shows a reduction in noise level by a factor of 5 in comparison with GPS C/A-code. It is now well documented that satellite-receiving equipment is subject to significant systematic effects due to environmental conditions; the use of TSA antennas and better cables reduces these effects and improves the accuracy of time transfer. The GPS carrier-phase technique allows frequency comparisons at a level of 1 part in 10^{15} and should soon be a useful tool for the comparison of primary frequency standards. Difficulties in calibration of GPS carrier-phase equipment remain unresolved, however, and this technique can not yet be used for operational time transfer. The TWSTFT technique, which has a similar performance to that of carrier phase, is already operational and used in TAI for several time links.

This paper reviews the above-mentioned techniques and assesses their potential impact on TAI.

EVOLUTION OF CLOCKS AND TIME LINKS CONTRIBUTING TO TAI

The international time scales computed at the Bureau International des Poids et Mesures (BIPM) – TAI and UTC – are based on data from some 220 atomic clocks located in about 50 time laboratories around the world. The number of clocks fluctuates a little, but remains roughly constant. The quality of the clocks, however, has been improving dramatically. In 1992 the first HP* 5071A caesium clocks with high-performance tubes were introduced into the TAI computation (see Figure 2), and the number of hydrogen masers has also been increasing steadily. In 1999 about 65 % of the participating clocks were HP 5071A with a high-performance tube and about 17 % were hydrogen masers [2]. Other commercial cesium clocks (including HP 5071A clocks with a low-performance tube, and continuously operating primary frequency standards) account for only 18 %. This progress has of course contributed to a significant improvement in the stability of TAI.

The quality of the clocks, although an important issue, is not the only factor contributing to the stability of TAI. Another important factor is the quality of the time links used to compare the clocks. Prior to 1981 only LORAN-C and TV links were used to compare clocks contributing to TAI. In 1981 the first GPS common-view single-channel C/A-code links were introduced. These allowed, for the first time, comparison of the stability of remote atomic clocks within an averaging time of several days. The proportion of GPS common-view links has increased steadily over the years and reached almost 100% in 1999 (see Figure 3). A new technique was then entered into TAI: that of Two-Way Satellite Time and Frequency Transfer (TWSTFT). As of June 2000 five TWSTFT links are used for TAI, and several others are in preparation.

* Acronyms are listed and defined at the end of the article.

To illustrate the impact of the improved quality of the time links on the frequency stability of TAI, we have analysed the period mid-1986-1993, during which the number of GPS links steadily increase, but there was no dramatic change in the nature of the participating clocks. The frequency stability of EAL (the échelle atomic libre) against the primary frequency standard PTB CS2 is indicated in Figure 4 for the three periods mid-1986-mid-1988, 1988-1989 and 1992-1993. EAL is the free atomic time scale from which TAI is derived using steering corrections. We observe a significant improvement in the frequency stability of EAL for each consecutive period for averaging times up to a few tens of days (for these averaging times the white phase noise due to the time-transfer methods by which EAL was affected is drastically reduced). The evaluation of the frequency stability of EAL is here limited by the frequency stability of PTB CS2.

A more recent evaluation of the stability of the frequency of EAL is illustrated in Figure 5. This time, the *N*-cornered-hat method was employed using the best independent atomic time scales (maintained at the OP, the NIST, the PTB, and the USNO).

ORGANIZATION OF TAI LINKS

Until recently the TAI GPS common-view time links were organized in three major stars centered on the CRL, the NIST and the OP. Only two very long-baseline links, NIST/OP and OP/CRL, were corrected for IGS precise ephemerides [3] and ionospheric measurements [4] (see Figure 6). Since the first use of IGS ionospheric maps for international time transfer in July 1999 [5], these corrections are now applied to all TAI GPS common-view links.

In July 1999 the first TWSTFT link, PTB/TUG, was introduced into the computation of TAI. In January 2000 other TWSTFT links followed. At the time of writing there are three TWSTFT links directly used for TAI: USNO/NPL, VSL/PTB, and NPL/PTB (see Figure 7). These three links are backed-up by GPS common-view data. Further TWSTFT links are expected to be introduced in 2001. There is also a backup TWSTFT link used to check the GPS common-view NIST/PTB link. The AMC/USNO TWSTFT link is an internal link between the USNO headquarters in Washington DC and their Alternate Master Clock (AMC) in Colorado Springs.

Two transatlantic links are being used for the first time for the construction of TAI. In addition each of these links is performed by two independent techniques. This very new situation increases the robustness of the construction of TAI, which no longer relies on a single technique. These changes modify the shape of the TAI network in Europe, with TWSTFT links acting as main shore and new pivots. The first three GPS multi-channel GPS common-view links were introduced into TAI at the beginning of 2000, with NPL as pivot.

CALIBRATION OF TAI LINKS

Differential calibration of remote GPS time equipment is the basic technique for the calibration of TAI GPS common-view time links. The stated uncertainty of such a differential calibration is about 3 ns under ideal conditions.

Over the last fifteen years a number of differential calibrations have been performed by the BIPM [5], including about half of the TAI GPS links. The GPS time equipment located at the NIST in Boulder, Colorado, and the Paris Observatory (OP) have been compared about 10 times; differential time corrections determined during these calibrations differ by no more than a few nanoseconds. This gives an indication of the reproducibility that can be obtained when calibrations are performed under ideal conditions in laboratories where the GPS time equipment, including cables, is carefully maintained. It also gives some idea of the long-term stability of GPS time equipment.

Consistency between repeated calibrations is not found for all sites, however. Where discrepancies of 10 ns are found, these may be attributed to different responses of the receivers being compared, to seasonal changes of temperature, or to an unrecognized multipath effect. Other repeated calibrations have shown large discrepancies, sometimes of tens of nanoseconds; such changes probably arise from unrecorded changes, intended or not, in the GPS receiving hardware.

All TWSTFT links currently used for TAI have been calibrated: the PTB/TUG link by a portable TWSTFT station, all the others by *Circular T* (in other words, by GPS). Future GPS calibration trips will improve the calibration of the TWSTFT links. However, only repeated calibrations by portable TWSTFT equipment will allow the TWSTFT technique to be exploited to the full extent. In May 2000 the USNO undertook the calibration of the PTB/USNO TWSTFT link using a portable station. The NPL/USNO link will be calibrated by the same very shortly. These calibrations are of particular interest, because they use a geostationary satellite with a footprint covering the Eastern United States, South America, and large parts of Europe and Africa. This allows the use of the same transponder for transatlantic links and, consequently, the differential calibration of transatlantic TWSTFT links.

NEW TIME-TRANSFER TECHNIQUES

In this section we briefly review latest developments in time-transfer techniques. These are already benefitting TAI, or expected to do so in the near future.

GPS and GLONASS Multi-Channel Observations and TSA

In a field trial of time transfer over a baseline of several hundred kilometers the number of daily standard 13-minute common views increased from 40 for GPS single-channel observations to 585 for GPS+GLONASS multi-channel observations [7]. In the case of white phase noise, the corresponding gain in stability is predicted to be $(585/40)^{1/2} = 3.8$, and a value close to this was observed. Additional systematic effects were observed for averaging times of about 1 day; these are probably linked to the environmental sensitivity of the antennas and receivers.

In a one-site comparison (two separate antennas on a single site), a similar systematic effect was observed until both antennas were temperature-stabilized (TSA). Full advantage could then be taken of the improved stability offered by multi-channel time transfer [7].

There are currently about 15 TSA antennas operating at time laboratories contributing to TAI, and there are three multi-channel GPS common-view links used for TAI.

GLONASS P-Code Common View

Unlike GPS, GLONASS P-code signal is available to civil users as it is not subject to Anti-Spoofing (AS) or other encryption. GLONASS P-code has two main advantages for precise time synchronization. First, its chip-length is one-tenth that of GLONASS C/A-code and about one-fifth that of GPS C/A-code. Thus GLONASS P-code pseudo-range measurements are considerably more precise than comparable GPS or GLONASS C/A-code measurements [8]. Second, GLONASS P-code is transmitted on both L1 and L2 frequencies, so it allows high-precision measurements to be made of ionospheric delays.

GPS Carrier Phase

Locking on the carrier phase reduces multipath effects. With the multi-channel receivers now available and using the common-view double-differencing techniques typical in geodesy, two sites may well be able to maintain a common carrier phase. If measured ionospheric delays were used in combination with nominally compensated tropospheric corrections, a frequency stability of 1 part in 10^{15} might be attainable with integration times of about 1 day [10]. This performance is about what is required for the comparison of current primary frequency standards. Continuous measurements, rather than measurements taken once a day, are necessary to achieve this performance. Several trials have already demonstrated the advantages of using carrier-phase measurements for time and frequency comparisons [11].

Time metrologists have recently joined forces with geodesists in an important initiative known as the "IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons Using GPS Carrier Phase and Code Measurements". An important issue is the calibration of carrier-phase timing equipment, which limits the performance of the technique.

It is important to note that carrier phase is also affected by hardware delay instabilities. Here also, to take full advantage of this promising technology, the delays of various parts of the receiving equipment must be stabilized and measured.

In the near future the carrier-phase technique is likely to be used for frequency comparisons of primary standards.

Two-Way Satellite Time and Frequency Transfer

TWSTFT is a technique that utilizes geostationary telecommunications satellites to provide time transfer with a theoretical precision of several hundred picoseconds [12]. At present the TWSTFT technique is operational in eight European, three US and two Japanese time laboratories. Some other laboratories have reached pre-operational status. The technique has been contributed to TAI since July 1999, following recommendations of the Consultative Committee for Time and Frequency (CCTF). The number of such links used for TAI is likely to increase from the present five.

In May 1999 the BIPM started publishing Monthly TWSTFT Reports. Some selected TWSTFT links through INTELSAT 307° E are computed and compared with GPS at the time of preparation of *Circular T*. An example of such a comparison is given in Figure 8.

Modified Allan variance analysis of TWSTFT and GPS links shows better behavior of TWSTFT for all analysed links up to 10 days. This is particularly striking for the USNO/NPL link where TWSTFT is showing the behavior of clocks already for averaging time of 5 days (see Figure 9). Using a GPS link we have to wait 20 days to smooth out white-phase noise due to time transfer.

SUMMARY

The construction of TAI requires time-transfer techniques that allow participating clocks to be compared at their full level of performance for intervals at which TAI is computed. In the pre-GPS era this was impossible because the technology of atomic clocks was always ahead of that of time transfer. This resulted in an annual term in TAI. The replacement of LORAN-C links by GPS C/A-code common-view links during the years 1981-1998 has progressively reduced the impact of white phase noise on TAI, improving its stability up to about 80 days. During the 1980s, GPS allowed for the first time the comparison of remote atomic clocks at their full level of performance for averaging times of just a few days, fully satisfying needs of TAI, computed at this epoch at intervals of 10 days.

However, with the improvements in clock technology made during the 1980s and the resulting dramatic increase in the quality of the clocks contributing to TAI in the 1990s, intercontinental GPS C/A-code common-view measurements now need to be averaged over up to 20 days in order to smooth out measurement noise. This is no longer sufficient for TAI, computed at 5-day intervals from 1 January 1996.

The first analysis of the performance of TWSTFT, which is now in use for several TAI links, shows that clocks located on different continents can be compared by this technique at 5-day intervals at their full level of performance, without being affected by time-transfer measurement noise. Thus, if TWSTFT were used for all TAI links, the stability of TAI would be improved for periods of up to 20 days.

The introduction of TWSTFT into TAI has brought about another important change for the better; TAI is not longer reliant on a single technique, because TWSTFT links are backed up by GPS links and vice versa. Also, for the first time, two transatlantic links are used for its construction, and each of these links is performed by two independent techniques. This very new situation increases the robustness of TAI construction.

Another important issue is the accuracy of TAI time links. These determine the accuracy with which laboratories have access to UTC. Significant proportion of GPS links were never calibrated and their accuracy is limited to several tens of nanoseconds. The other GPS links and all but one of the TWSTFT links have been calibrated by a differential technique using a portable GPS receiver. The uncertainty of such a calibration is limited to several nanoseconds, mainly due to the environmental instability of GPS time-receiving equipment. This could be reduced by using TSAs, keeping receivers in air-conditioned rooms, and, if possible, using GLONASS P-code observations.

One TWSTFT link, PTB/TUG, has been calibrated by a portable TWSTFT station. The uncertainty of this calibration is believed to be 1 ns or better. Other TWSTFT calibrations are planned, and it is expected that use of TWSTFT will bring a substantial improvement to the accuracy of TAI time links.

For better monitoring of the accuracy of time links, repeated calibrations are required, either by GPS or by TWSTFT.

ACRONYMS

AMC – Alternate Master Clock
BIPM – Bureau International des Poids et Mesures
CCTF – Consultative Committee for Time and Frequency
CRL – Communications Research Laboratory
CV – Common View
EAL – Echelle atomic libre
GLONASS – Global Navigation Satellite System
GPS – Global Positioning System
HP – Hewlett-Packard
IGS – International GPS Service
IGEX – International GLONASS Experiment
IGLOS-PP – International GLONASS Service Pilot Project
MJD – Modified Julian Day
NIST – National Institute of Standards and Technology
NPL – National Physical Laboratory
OP – Observatoire de Paris
PTB – Physikalisch-Technische Bundesanstalt
TAI – Temps atomic international
TUG - Technical University of Graz
TWSTFT – Two-Way Satellite Time and Frequency Transfer
USNO – United States Naval observatory
UTC - Coordinated Universal Time

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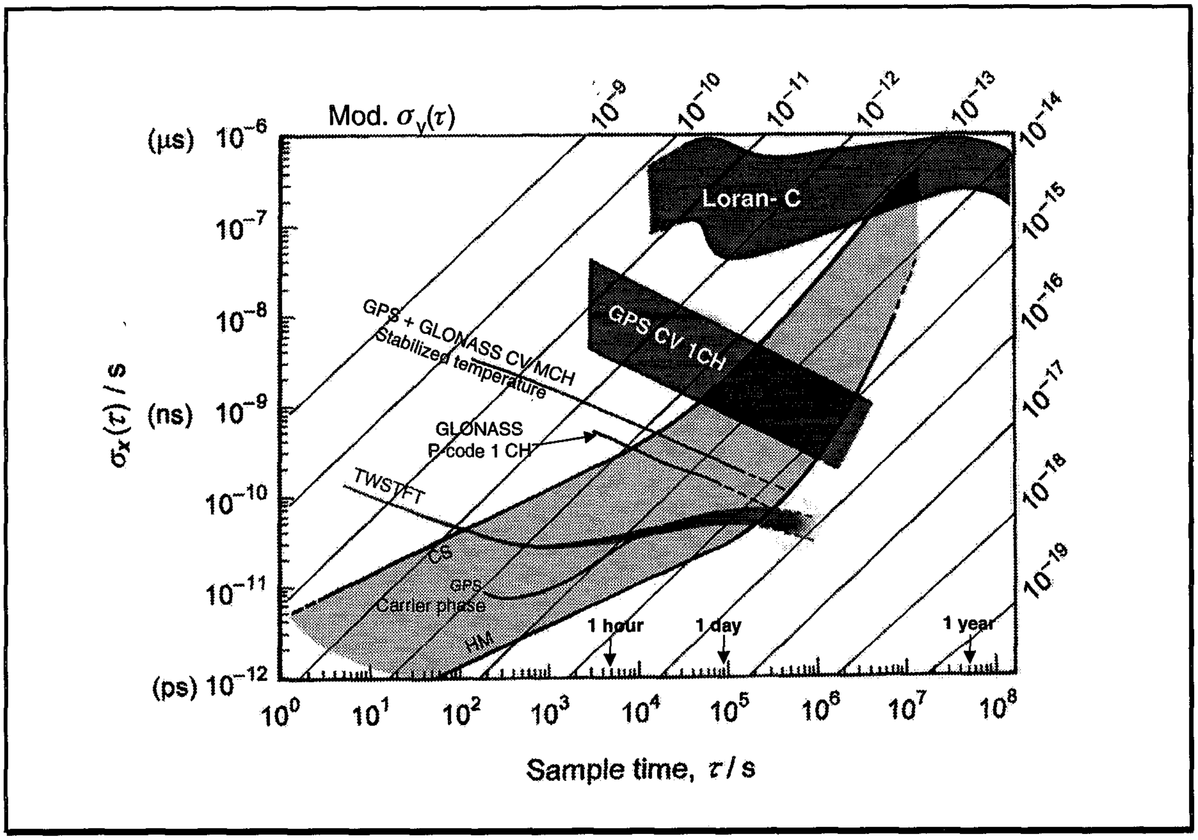

Figure 1. Comparison of some newer techniques with classical GPS single-channel common-view time transfer. Also indicated are typical clock performances.

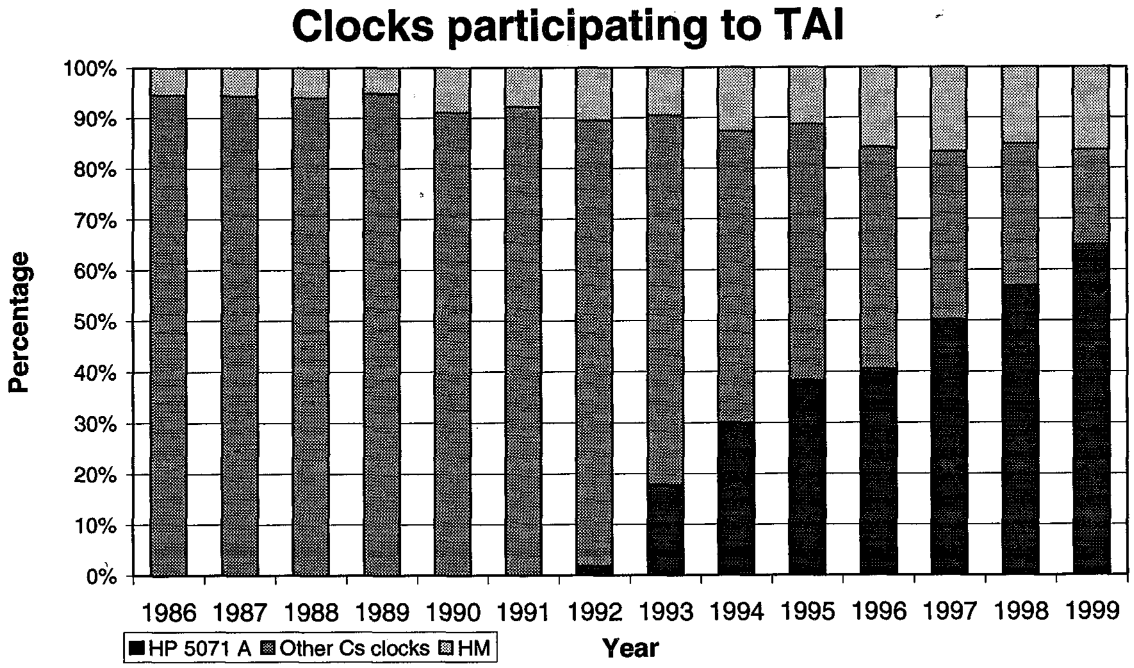

Figure 2. Clocks participating in TAI.

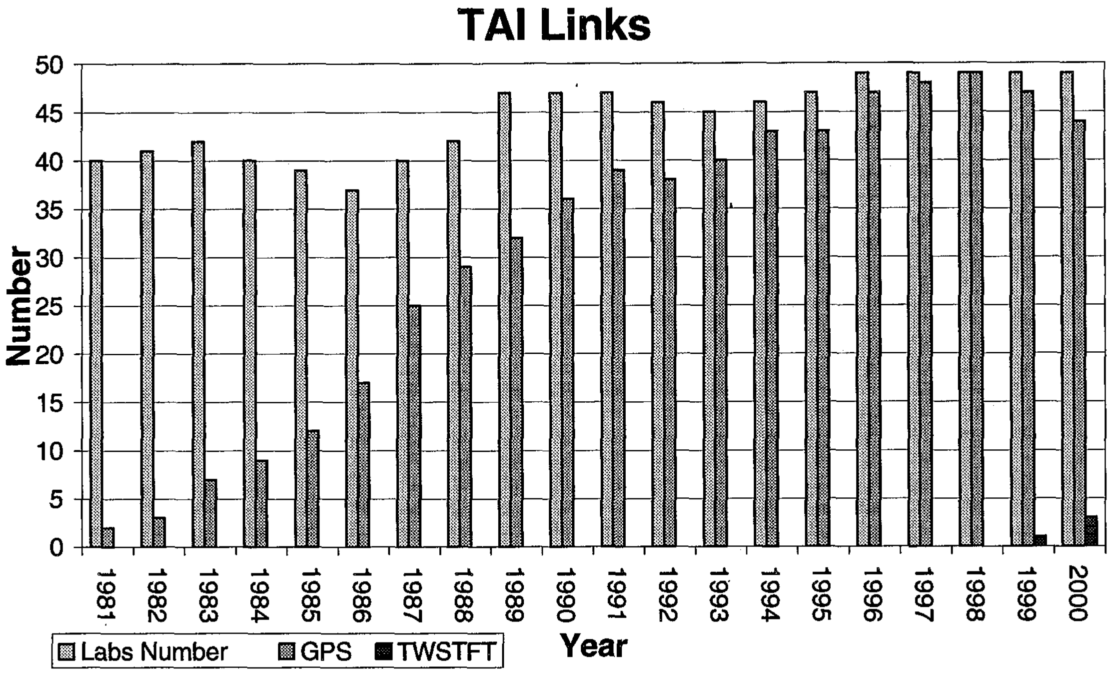

Figure 3. TAI time links.

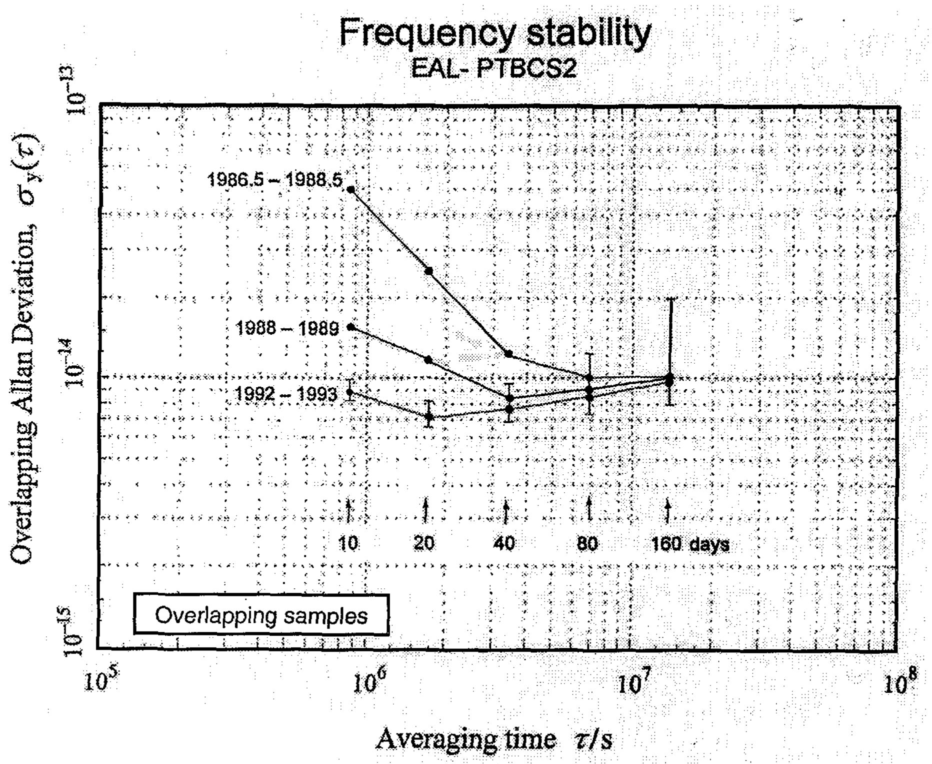

Figure 4. Frequency stability of *[EAL – PTB Cs2]*.

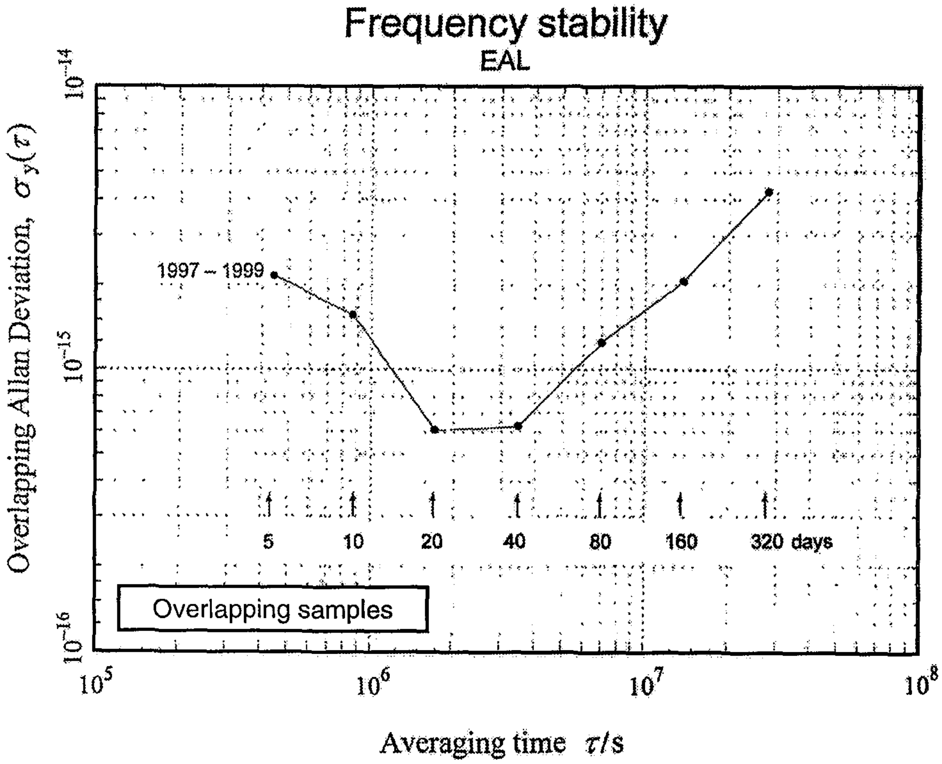

Figure 5. Frequency stability of EAL obtained by *N*-cornered-hat method using independent atomic time scales maintained at the OP, the NIST, the PTB and the USNO.

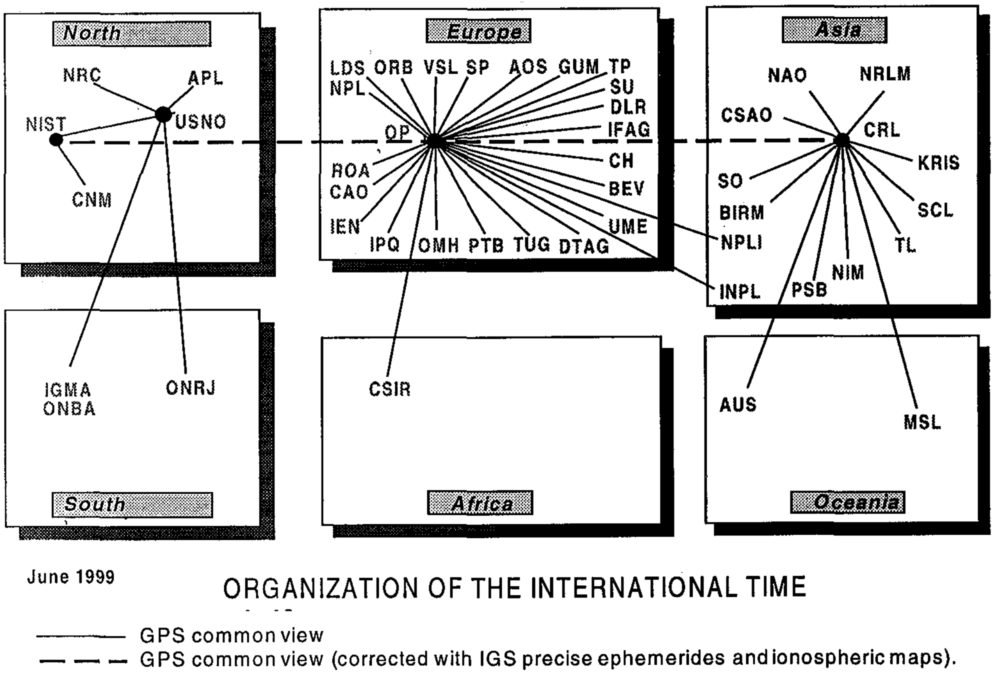

Figure 6. Organization of international time links in June 1999.

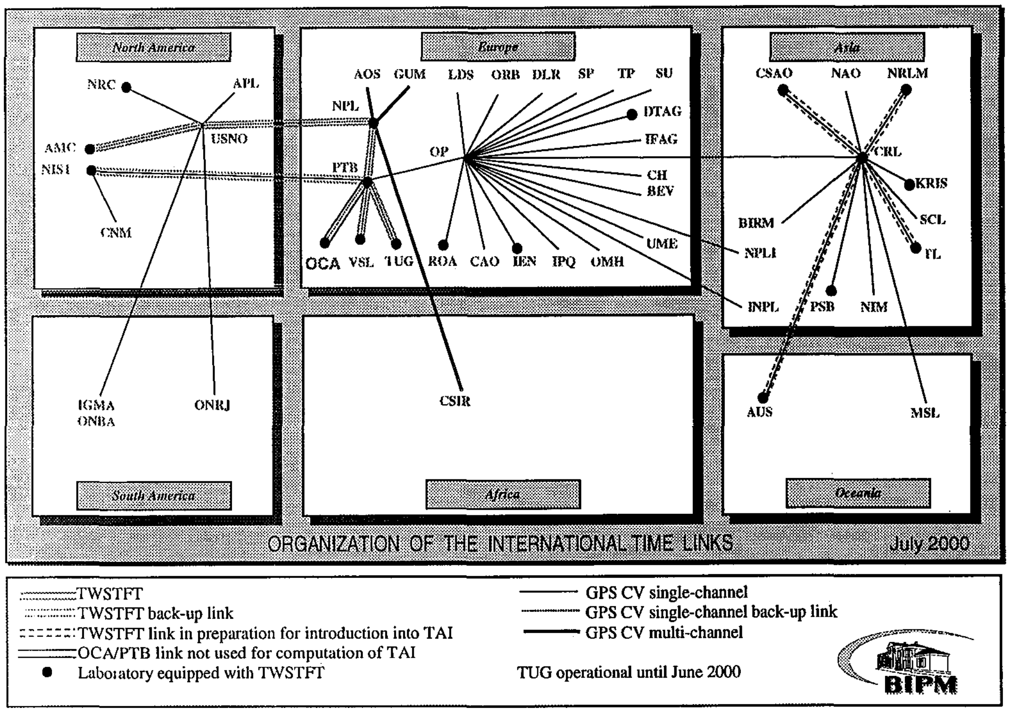

Figure 7. Organization of international time links in November 2000.

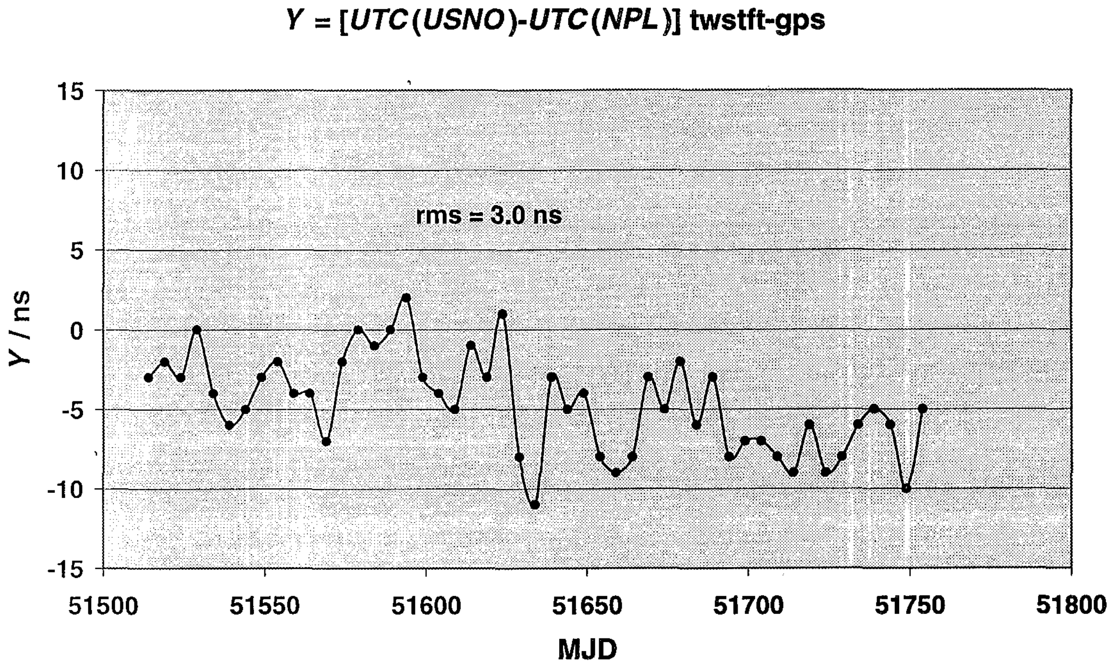

Figure 8. Differences between TWSTFT and GPS common-view for USNO/NPL link.

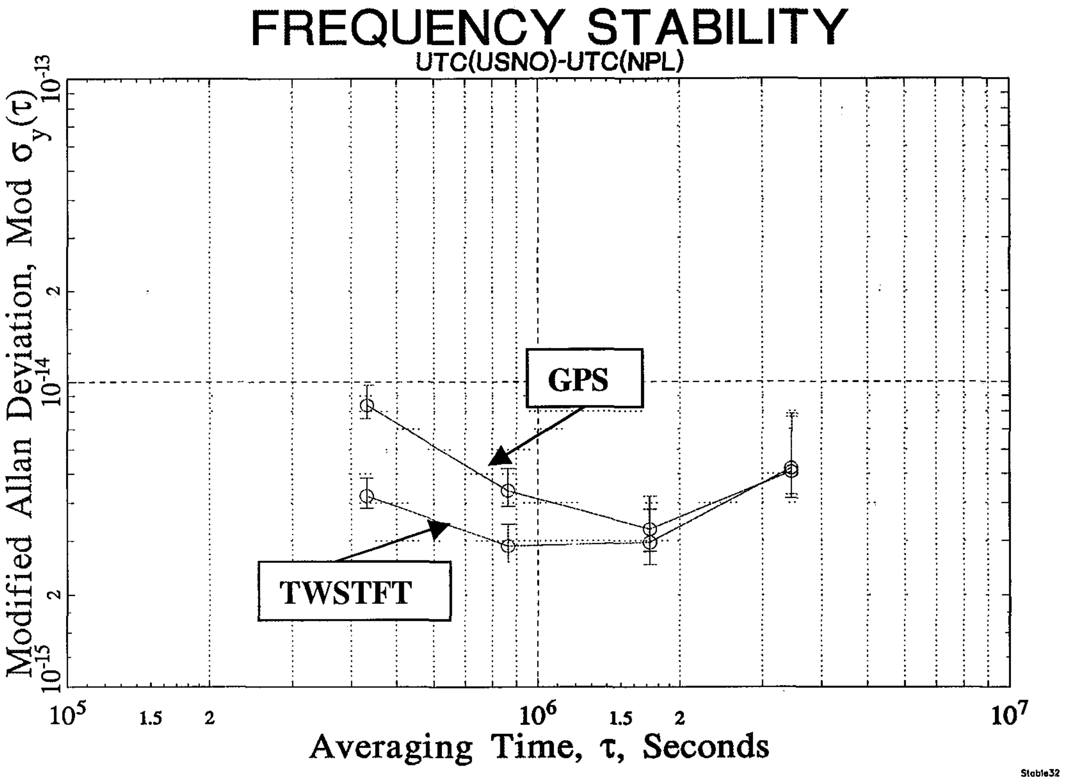

Figure 9. Frequency stability of [*UTC*(*USNO*) – *UTC*(*NPL*)] by GPS and by TWSTFT.

Questions and Answers

DEMETRIOS MATSAKIS (USNO): Let me ask a loaded question. Is there any activity going on to look at the difference between northern and southern hemispheres to find any kind of seasonal variations that way?

WLODZIMIERZ LEWANDOWSKI: You mean in time links?

MATSAKIS: Time or frequency.

LEWANDOWSKI: Well, in Japan there were some studies about the correlation between clocks. Right now, I don't see any studies done. It could be that we should provide something. For example, for the seasonal changes between two-way and GPS common-view, where we have a seasonal change, we would look in the hemisphere. But, we do not have two-way links. We may have a link between Tokyo and Australia and in the future we could be looking at that.