On Optimizing the Configuration of Time-Transfer Links Used to Generate TAI

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ABSTRACT

This is the report of Study Group II of the Working Group on TAI, which was formed to study two of the three proposals in the BIPM Technical Memo 132, circulated in December, 2004. It is recommended that TAI be generated through combinations of Two Way Satellite Time and Frequency Transfer (TWSTFT) links and GPS links. It is assumed that Study Group I will not oppose acceptance of the first proposal, which is that GPS links will be converted from Common View (CV) to All in View (AV). In that case, we find benefits to the use of AV in order to optimize the link configurations, and also recommend in principle the acceptance of the second of the proposals, which was to adapt a single pivot. We specify the optimal requirements for the site selection and site maintenance, but we note that the lack of low-noise connectivity between the Asian and American-European TWSTFT links may require two pivot sites instead of one. We recommend against the third proposal, which is the introduction of a virtual pivot. We do not recommend averaging time-transfer techniques over TAI-generating links until the possibilities are further studied, and recommend that the BIPM staff give priority to developing carrier phase GNSS links over developing the averaging of redundant links.

I. INTRODUCTION

Time transfer for the generation of International Atomic Time (TAI) is achieved by a variety of techniques, including single-channel and multi-channel GPS Common View (CV), dual-frequency P-Code GPS data from geodetic receivers (P3), Ku-band Two Way Satellite Time and Frequency Transfer (TWSTFT), and X-band TWSTFT [1]. In order to improve TAI-generation, the BIPM Time Section asked the CCTF to study certain proposals.

This paper summarizes the findings of Study Group II of the Working Group on TAI, whose charter is to analyze possible means of combining the set of available time-transfer links in order to reduce the uncertainties in and increase the robustness of the creation of TAI. The existing theory of expressing the uncertainties is recalled, the utility of using redundant links is discussed, and the importance of monitoring hardware at crossover sites is developed. In the course of its work, Study Group II met both privately and publicly at PTTI-05 in Vancouver, Canada and the EFTF-06 at Braunschweig, Germany. This report includes all the scientific material published in the Proceedings of EFTF-06 in a paper with the same authors and title.

Study Group I's charter is to report on the proposal replace CV time transfer by GPS All-in-View (AV) [2-4] time transfer. In the course of its work, this study group has confirmed some of the basic findings reported in TM132. The difference is minimal on short links. Long-distance links would benefit through the greater number of observations and the more equal distribution of satellite observation angles, at the price of sensitivity to the corrected time of the satellites.

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II. THEORY OF TIME TRANSFER UNCERTAINTIES

A theory has recently been developed for numerical computation of the uncertainty of the difference [*UTC-UTC*(*k*)] between Coordinated Universal Time (UTC) and its realization by any laboratory k, UTC(k) [5-7]. UTC is generated by adding leap seconds to TAI. TAI is generated by steering the Free Atomic Timescale (Echelle Atomique Libre, EAL) to a weighted average of the frequencies of primary frequency standards so that the TAI second will realize the SI second. EAL is created by averaging clock data from participating laboratories, whose times are differenced via the several time-transfer links. TAI and EAL are currently created using the minimum necessary number of time transfer links between laboratories. One significant element in the uncertainty analysis is the distinction between link-based uncertainties and site-based uncertainties (Figure 1). Site-based uncertainties depend only on the site and contribute equally to all links involving the site. Link-based uncertainties are a property of the pair of sites that make up the link. They cannot be estimated from separately-computed uncertainties of each site. The total uncertainty of any link is assumed to be the quadratic sum of the link-based uncertainty and the two laboratories' site-based uncertainties.

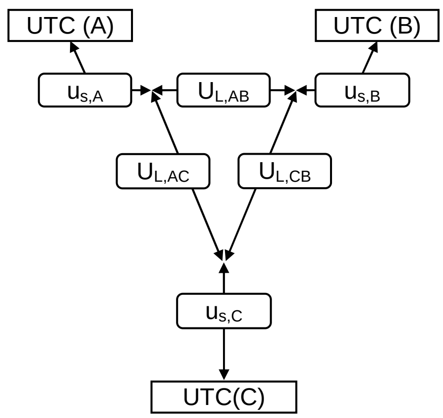

Figure 1. Site-based uncertainties ($U_{s,X}$) and link-based uncertainties ($U_{sL,XY}$).

In a network dominated by site-based noise, it makes no difference which links are used to create the non-redundant set. In the example shown in Figure 1, the time transfer between any two sites or clocks A and B is written A-B. Time transfer between A and B achieved by links with C would be written as (A-C) + (C-B). If all uncertainties associated with C are site-based, then A-B is independent of C. Also, the closure of the three signed pair-differences between any three systems, (A-C)+(C-B)+(B-A), is zero. Hence, averaging redundant links would have no effect and TAI would be independent of the topology of any network dominated by site-based noise.

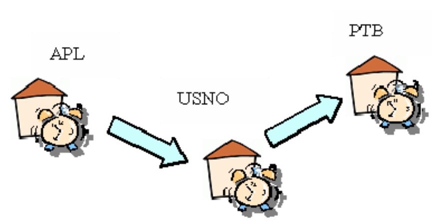

Figure 2. Example in which the USNO is a crossover site if the APL-USNO link is via GPS and the USNO-PTB link is via TWSTFT.

In contrast, link-based noise contributes to the uncertainties between all pairs of laboratories that include the link in the chain of timing links between them. If link-based noise is significant compared to site-based noise, the numerical computation of EAL would be topology-dependent. The weight of the primary standards used to measure the frequency difference between TAI and the SI second would also be topology-dependent. Numerical computations show that a system dominated by an equal amount of site-based noise in all links has 50% smaller uncertainties than one dominated by an equal amount of noise per link, but which is link-based [7]. The effects of link-based noise would be reduced by averaging redundant links, and this is investigated below.

The uncertainties of GPS observations are largely site-based because antenna, receiver, and signal-path delays depend only on the satellite in view, the laboratory receiver system, and their geometric relationship. In CV, however, link-based uncertainties are generated through link-dependent sampling in time and observation direction. In unfiltered AV link-based noise is nonexistent because the time and satellite direction samplings do not depend on the link. TAI-generation would be completely independent of topology if all links were by GPS AV. Link- based noise can exist in filtered AV, if the BIPM applies Vondrak smoothing after generating AV differences between two sites. This can be observed through nonzero closures [8].

The uncertainties of TWSTFT are largely site-based and typically attributed to uncalibrated long-term delay variations in the full signal path. However, some link-dependent effects come into play. They are due to the slightly different frequencies used in some links, the slightly different spread-spectrum codes in the links, the link-dependent character of the calibrations, and multiplicative bandpass effects. The latter is due to the overall instrumental delay being the average of the delays at each frequency, weighted by the product of the amplitudes of the two system band-passes. Link-dependent noise is also introduced from equipment and timescale instabilities between observations.

Of particular interest for TAI generation are “crossover sites”, which are pivot sites that couple links using different techniques or different equipment. Because the uncertainties in TWSTFT and GPS are completely uncorrelated, at crossover sites even a system dominated by site-based uncertainties acts as if the uncertainties were link-based. In a hybrid situation in which a TWSTFT link is calibrated by GPS, the crossover properties would apply only to the uncertainties that do not involve the calibration.

The topologies used by the BIPM involve a minimum number of pivots, all of which are currently crossover sites. Numerical simulations using the tools developed for references [5-7] have confirmed that such topologies can minimize the overall effect of link-based noise. For example, assume that all TWSTFT observations have link-based uncertainties of 400 ps. In this case the USNO-PTB TWSTFT link could be replaced by a USNO-NPL TWSTFT link, which would act in conjunction with the NPL-PTB TWSTFT link already in use. But this would add the NPL-PTB link's 400 ps uncertainty to every link between the USNO and the European, Asian, Australian, and American laboratories linked to the USNO via NPL. This includes almost every other laboratory, and would raise the uncertainty of [*UTC-UTC*(*USNO*)] due to statistical (type A) errors by 25%, and those of other laboratories by 5-10%.

III. THE CROSSOVER SITES

Although interesting studies of the benefits of averaging different modes of time transfer data are underway [9], in practice the BIPM has followed a strategy of shifting from GPS links to more precise and accurate TWSTFT links. Should the BIPM switch to the GPS AV methodology, link-based noise will virtually disappear from all GPS links. At the crossover sites, however, all site-based GPS and TWSTFT uncertainties, noise, and uncalibrated delay variations will act as if link-based. For this reason the ideal crossover site would have at least two TWSTFT and GPS systems so that instrumental effects can be identified and removed. Traceability to a site maser would be needed so as to have the ability to relate observations made at different times should it be necessary. The environmental effect on observations should be minimized through environmentally insensitive components, with minimal exposure to exterior or even room temperature variations. Temperature sensitivity can be estimated through diurnal variations in timing data or, in the case of geodetic GPS data, in code timing residuals [10] or through the magnitude of the day-boundary discontinuities. Multipath due to reflections from exterior structures and to reflections within cables should be minimized. It is noted that the IGS provides numerical measures of the observed code multipath for the geodetic GPS receivers in its networks below http://igscb.jpl.nasa.gov/network/complete.html. All key components should be monitored electronically and through human oversight. An automated warning system should allow rapid correction of problems, while a post processed analysis will ensure data quality. Both BIPM and the pivot site staff should monitor the data for both quality and continuity, with a view to software-shifting TAI generation to an alternate pivot site in the absence of a continuous set of state-of-the art time transfer data.

The current configuration of time links used for TAI (Figure 3) includes four crossover sites: NICT, NIST, PTB, and USNO, with most of the links going to PTB or NICT. To optimize the precision and accuracy of the configuration, it is best to minimize the number of crossover sites, because each one contributes link-based errors that affect all time transfer between laboratories on one side of the site and those on the other side. If one were to measure the overall sensitivity to biases at crossover sites by the product of the weighted number of clocks on each side and the sensitivity of their UTC-measurement to a bias at the crossover site, then one can show that it is almost always better to have fewer crossover sites. It is better to have multiple GPS receivers at any crossover site, if an average bias can be determined by zero baseline CV between the GPS receivers.

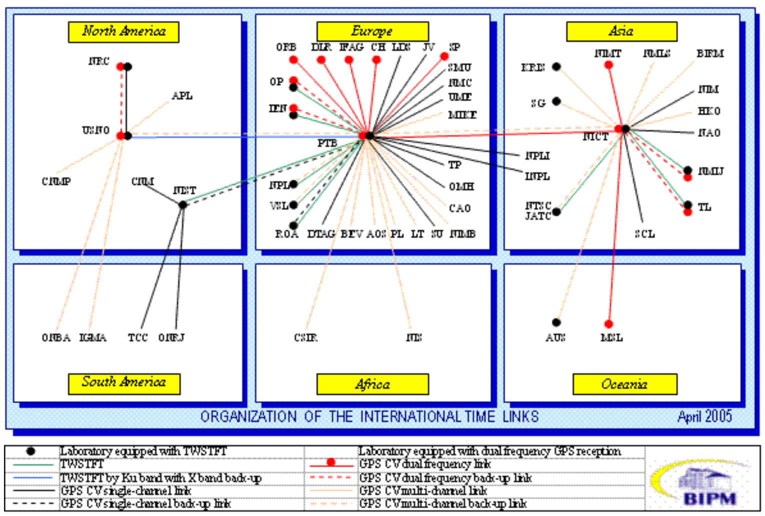

Figure 3. Links used in April, 2005 by the BIPM to generate EAL, and with it TAI and UTC.

In the case of GPS time-transfer via AV the concept of averaging collocated receivers at crossover sites can be extended to a global average over all or most sites that have operational TWSTFT and GPS systems. This averaging can be realized in the form of a least-squares fit to determine one bias parameter per crossover site, with an overall average bias constrained to be zero. The solution to that fit yields extra link calibrations for input into the BIPM's software package used to generate EAL and therefore TAI. Alternately, this fit can be used to monitor the delay variations at the crossover site. A simulation assuming TWSTFT data have 300 ps of link-based noise and that GPS has 100 ps of link-based noise plus 1.0 ns of site-based noise at five TWSTFT and GPS-enabled sites indicated that any bias variation at the crossover site can be identified to within 80 ps. The magnitude of the fitted bias is decreased by the contribution of the crossover site's simulated bias change to the average bias. We note that minimizing the number of crossover sites both improves performance and reduces complexity, while the averaging described here improves performance still more, but at the price of increased complexity.

IV. USE OF REDUNDANT TWSTFT LINKS

It may be possible to improve TWSTFT time transfer through use of redundant links [11-12]. In order to study this, a trial least-squares fit was made using TWSTFT data, taken every 2 hours, from European and North American laboratories (Figures 4 and 5). The first step was to create a software calibration of all links not involving the reference laboratory, so that they would be consistent with the links between each laboratory and a reference laboratory. Once the calibrations were made consistent, the fits used as reference laboratory either the PTB, the current pivot used by the BIPM, whose time reference is the primary clock CS2 [13] or NPL whose time reference is a maser. These fits determined the time of each laboratory's master clock relative to the reference laboratory, weighting all links equally. No significant statistical reduction in the scatter of the master clock differences was noted between observations, even in the 2-hour intervals. The RMS difference between the actual link between each lab and the PTB differed from the fitted master clock difference between 100 and 400 ps. From this we conclude that no significant precision improvements can be expected from the simplest method of averaging redundant TWSTFT links.

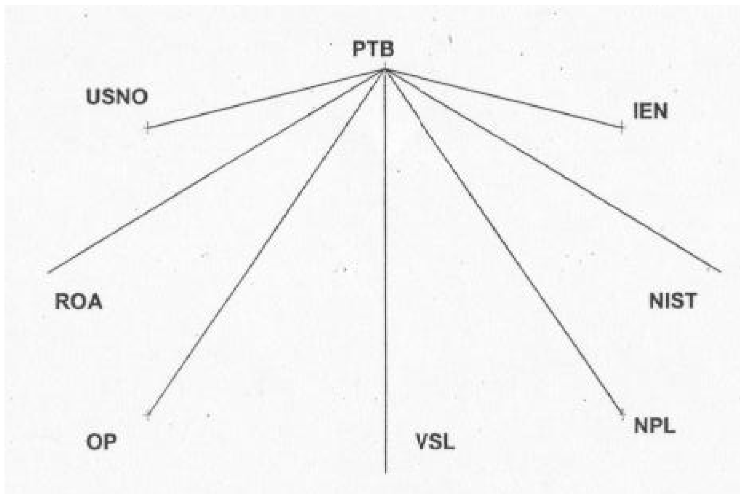

Figure 4. Non-redundant configuration of TWSTFT links in which PTB is the pivot.

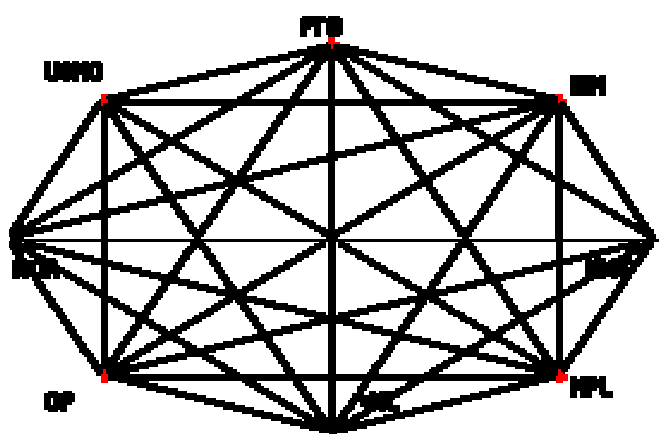

Figure 5. Complete set of European and American TWSTFT links available from sites contributing to previous figure.

The robustness of the system would be improved through averaging, but only if the data inspection and integrity checking procedures were improved commensurately with the increased complexity. Figure 6 shows histograms of the difference between using the direct link to determine [*UTC*(*PTB*)-*UTC*(*k*)] and using the fit, for 7.5 months of data from 8 European and N. American laboratories. Figure 7 shows the closure about all possible triplets of North American and European laboratories in 2005. The results are consistent with an overall link-based uncertainty of 300-400 ps for TWSTFT.

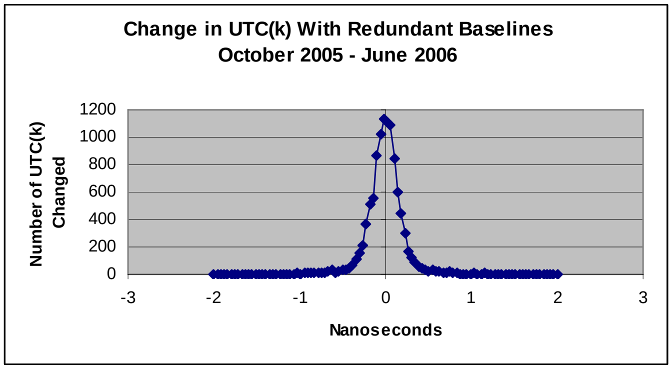

Figure 6. Histogram of differences in UTC(k) generated by including redundant links to TAI-generation. For 8 laboratories, using actual TWSTFT data, [*UTC*(*k*)-*UTC*(*PTB*)] was computed for each observing session using redundant links, and differenced with direct measurements.

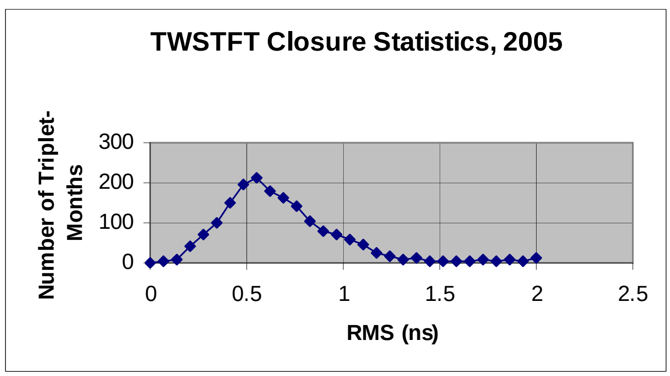

Figure 7. Histogram of hourly closures over all available triplets of Northern American and European laboratories. RMS was computed from algebraic sum of timing differences for each triplet and month, and is thus a measure of the link-based noise over the three links.

V. USE OF REDUNDANT GPS LINKS

Because unfiltered AV has no link-based noise, no improvement could be expected from averaging redundant AV links. In order to study possible benefits from averaging redundant CV differences, ionosphere and orbit-corrected GPS time transfer data made publicly available by the BIPM were analyzed for the year 2005. Figures 8 and 9 show the biases and RMS differences between AV and CV for all pairs of laboratories, wherein the largest differences are observed for single-channel receivers and long baselines. Figures 10 and 11 show analogous histograms of the CV closures among all triplets of laboratories.

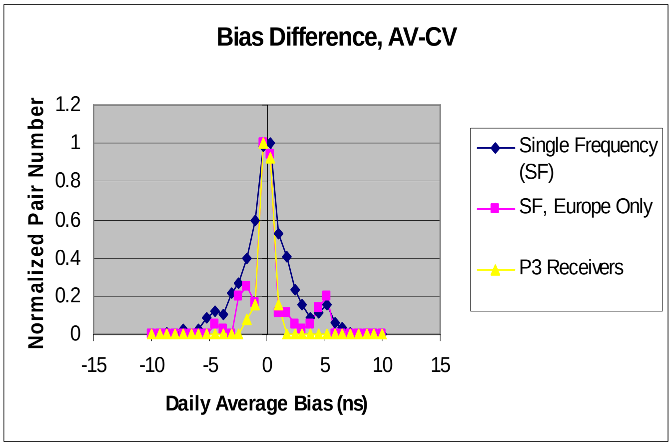

Figure 8. Histogram of daily bias between CV and AV techniques, over all laboratory pairs. Differences reflect link-based effects with CV that are not present in AV.

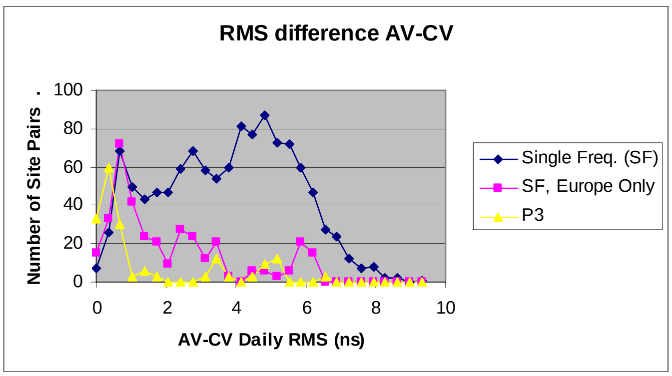

Figure 9. Histogram of RMS of daily difference between AV and CV techniques, over all laboratory pairs.

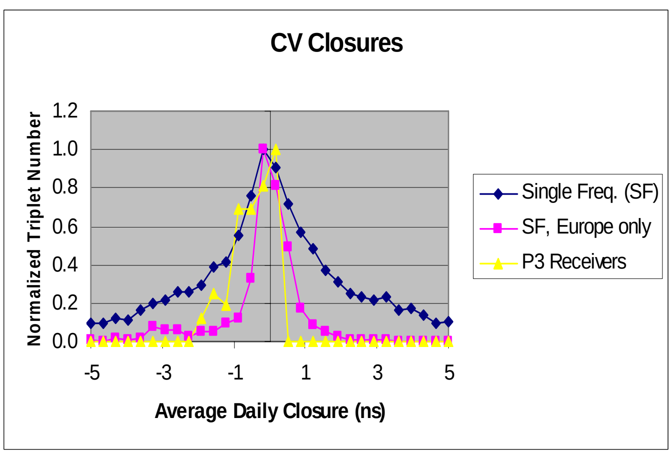

Figure 10. Histogram of bias of closure of daily CV reductions over all laboratory triplets. Plots are normalized for display.

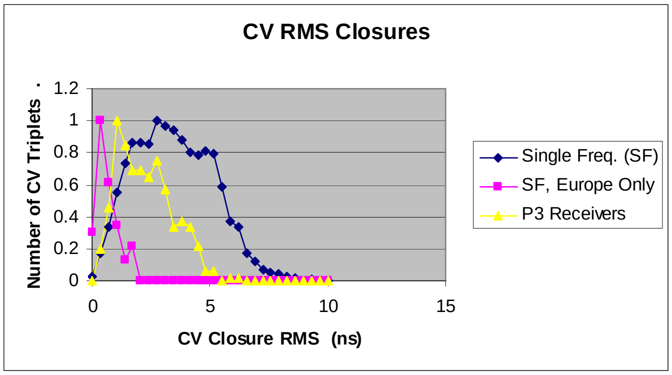

Figure 11. Histogram of RMS of closures of daily CV reductions over all laboratory triplets. Plots are normalized for display.

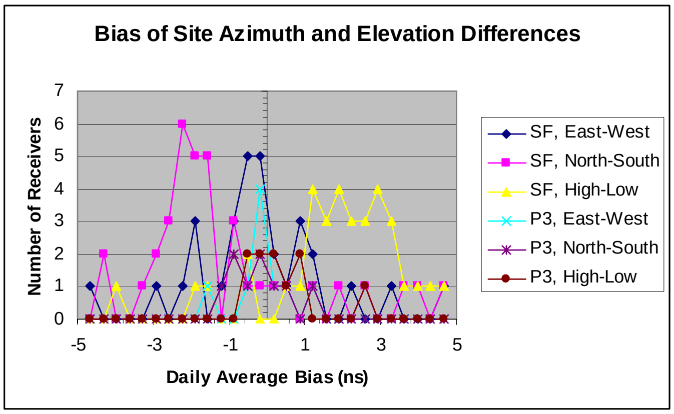

Figure 12. Histogram of difference between daily averages of all GPS observations at different elevations or opposing cardinal directions, for all laboratories.

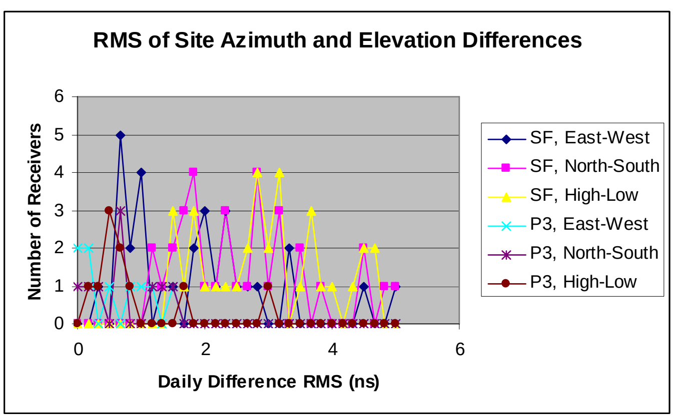

Figure 13. Histogram of RMS of daily difference between averages of all GPS observations at different elevations or opposing cardinal directions, for all sites.

Figures 12 and 13 show the average and RMS differences between daily averages of all GPS data taken towards one hemisphere at the site (east or north) and those data taken towards the opposite hemisphere (west or south). Also shown are the differences between all data taken above 30 degrees elevation and between 10 and 30 degrees elevation. These differences cause link-based effects in CV that are not present in AV. Note that northern observations tend to be low-elevation at higher latitudes.

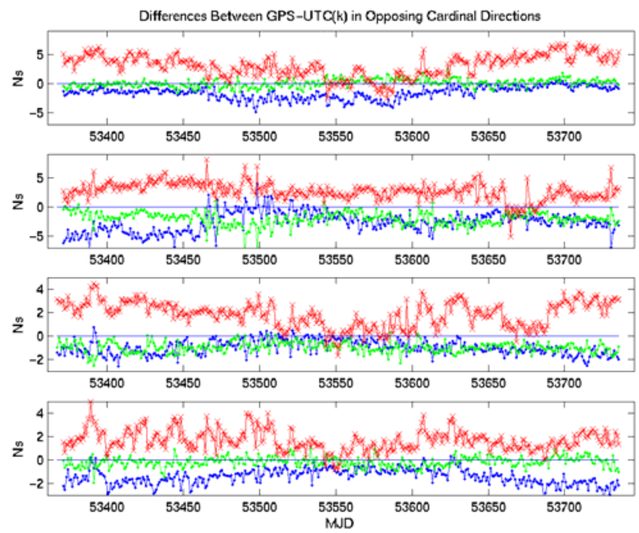

Figure 14. Differences between ionosphere and orbit-corrected single-frequency GPS observations at different elevations or in opposing cardinal directions, from the four crossover sites. Sites from top down are NICT, NIST, PTB, and USNO. North-south differences are shown by a blue dot, east-west differences by a green +, and hi-low elevation differences by a red x. Seasonal effects are apparent, and these are likely elevation-dependent. Plots are not to same vertical scale.

Figure 15. Hemispheric differences of orbit-corrected P3 data from three crossover sites. Sites from top down are NICT, PTB, and USNO, and otherwise as in previous figure.

Since the crossover sites are of particular concern, their hemisphere differences are plotted in the Figures 14 and 15. Seasonal effects are apparent, as is the higher quality of the P3 data. Increased multipath and troposphere modeling error at low elevations are likely the cause of the north/south and hi/low differences, and these same effects may be contributing strongly to the weaker east/west differences as well.

Since GPS receiver calibrations are carried out with AV, the Circular T computations should subtract the average baseline-dependent AV-CV difference as a calibration of any CV links employed, and the uncertainties of each CV link should be increased through convolution with its RMS AV-CV difference. However, the numerical differences are never large and almost always negligible.

For completeness, we also show how the receiver instrumental delay at the L1 frequency has varied between two receivers at each of the three crossover sites contributing to the P3 program.

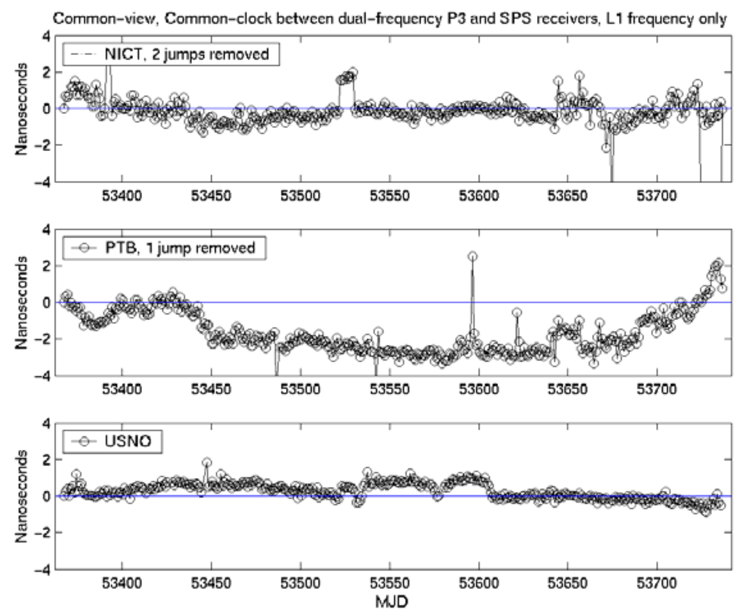

Figure 16. Differential delay variations between the single-frequency and the P3 receivers at 3 crossover sites. Data are common clock and show the variation at the L1 frequency only.

Figures 9-16 show a consistent pattern that CV results in calibration biases and daily scatters at the level of a few ns in single frequency receivers. Inter-European CV data are of higher quality because CV link-based noise increases in long baselines. In general, P3 data show less bias and RMS scatter than the single frequency (SF) receivers; this is likely due to better multipath rejection. However, the geodetic receivers used in the P3 experiment can show sudden calibration jumps at the ns level [14].

Should the BIPM continue using CV, redundant GPS links could be averaged and still conform to the current practice of giving 100% weight to all operational TWSTFT links. The TWSTFT links would be assumed valid, and all the associated UTC(k) differences would be fixed relative to any one of them. Having fixed those UTC(k) and links, a fit using all GPS links would determine the bias of the GPS systems at the crossover sites along with the values of UTC(k) for the sites that are not connected by TWSTFT. Because the bias parameters would be underdetermined, one must add the constraint that the average bias parameter is zero. Although a fitting to redundant GPS links would reduce link-based errors, the much larger site-based errors, such as those due to equipment calibration and environmental sensitivity, would be unaffected and would remain common to both AV and CV.

Whether GPS time transfer is achieved by AV or CV, fits that average GPS with TWSTFT are possible. Such averages would also help detect outliers and identify calibration variations. Use of CV alone would in general be a better tool for diagnosing multipath and other problems, and this can be done independently of TAI-generation.

VI. All in View vs. Common View for TAI Generation

It is beyond the scope of this study group's charter to make a complete recommendation on the proposal that AV be used instead of CV. However, we can recommend switching to AV from the point of view of interfacing with TWSTFT links because our simulations have shown that eliminating even a modest amount of link-based noise in the GPS links (such as 400 ps) can reduce the uncertainties in [UTC-UTC(k)] (typically 10%). While AV involving daily averaging has the drawback of sensitivity to the reference timescale of the GPS observations, we note that AV based upon differencing approximately 15-minute averages is independent of the temporal instabilities of the reference. We would therefore recommend this form of AV from the point of view of reducing the uncertainties and increasing the robustness of the link configuration. Another reason to support AV stems from the fact that BIPM-sponsored calibrations of GPS receivers are essentially AV, therefore the type B uncertainties derived from those calibrations would need to be increased for CV.

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VII. The Virtual Pivot

In the ALGOS software, it is possible to insert a pivot site that has zero weight. Such an insertion has no effect on the final results if all time-transfer links to a virtual pivot site are completely free of link-based uncertainties. However, any link-based uncertainties related to the virtual pivot links would contribute to the overall uncertainty. One source of link-based uncertainties would be the application of Vondrak smoothing after pairwise differencing, as is current practice in the generation of TAI. The use of a virtual pivot would in certain extreme situations result in numerical computation of time transfer values between two sites that have no simultaneous data; in such a situation it would be preferable to use an alternate topology that avoids this situation. Even though use of a virtual pivot would in most cases have negligible effect, we recommend against virtual pivots because we can find no scenario in which it would improve TAI .

VIII. Carrier Phase GPS

The capabilities of Carrier-Phase (CP) techniques in GNSS data processing have long been recognized, and have been shown to have unparalleled short-term precision. Their accuracy is theoretically similar to TWSTFT, although at least one widely-used receiver model appears to be susceptible to ns-level variations in its instrumental delay. CP data reductions provide improved troposphere, ionosphere, and positional corrections, but remain limited by the noise in the pseudo-range data, which is usually non-Gaussian. In most software this noise is evident in the magnitude of the day-boundary discontinuities. Reduction algorithms and associated software that are free of noticeable day-boundary discontinuities have been developed, some which are routinely used in real-time networks [15, and references therein]. All of the time-transfer uncertainties can be expected to decrease as new frequencies and Galileo become operational.

The operational costs of CP are considerably less than TWSTFT, and the latest generation of geodetic GPS receivers promises to improve the stability and calibrateability of the technique. The IGS routinely produces high-quality time transfer from several laboratories contributing to TAI. In addition, two institutions have offered to reduce CP data for the BIPM at little or no cost. We recommend that the BIPM commit some of its scarce resources to adapt this technique to TAI-generation.

IX. CONCLUSIONS

The time-transfer links used to generate TAI could be improved through reduction of the number of pivot sites, the careful selection of a pivot site (Appendix I), and the continuous monitoring and analysis of the TWSTFT and GPS equipment at crossover sites. Combining different techniques could lead to improvements, but the theory is not ready for operations. Use of virtual pivots is not recommended. According to our analysis, use of redundant TWSTFT or AV links would make minimal difference to precision or robustness. Use of these redundant links is, therefore, not recommended. Instead, emphasis should be placed on applying carrier phase analysis to GNSS data.

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APPENDIX I. CHARACTERISTICS OF THE IDEAL PIVOT SITE

1. The site should maintain multiple TWSTFT and GPS systems so that instrumental effects can be identified and removed. Single frequency GPS receivers should be given the same ionosphere corrections resolved at each frequency observed. In the case of C/A code receivers, the signals at the L1 frequency can be compared to the L1 frequency of the dual-frequency receivers. While the L2-L1 difference of geodetic receivers can be compared to IGS ionosphere maps, the existence of biases must be accounted for [16, Appendix II].

2. So as to have the ability to relate observations made at different times, the site should use an active hydrogen maser as the source of reference signals connecting the time transfer equipment to the local realization of UTC. The delay differences between the time transfer system references should be measurable at the level of 200 ps.

3. The site's time transfer systems should consist of environmentally insensitive components, with minimal exposure to the exterior or to room temperature variations.

4. The systems should be installed in such a way that minimal multipath due to reflections from exterior structures happens and that reflections within cables due to impedance mismatch are avoided. The reports of the IGS should be analyzed to verify the success of all measures.

5. Each system's key components should be monitored as complete as technically possible, electronically, and with human oversight. An automated warning system should be established to allow rapid correction of problems. Analysis in post-processing will further ensure data quality.

APPENDIX II. Timing Group Delay (TGD) and Single-Frequency Receiver Biases

Many receivers used for TAI generation are based only upon a single GPS frequency, and such receivers cannot measure the ionosphere delay in order to correct their data. This problem should eventually be minimized in the future because since September 2005 GPS satellites are being launched with C/A code on two frequencies accessible to all worldwide. Later generations of GPS satellites will have three universally accessible frequencies. All Galileo satellites will provide signals at two frequencies in its Open Service.

The BIPM currently corrects single-frequency receiver data with corrections based upon IGS ionosphere products, but the Timing Group Delay (TGD) corrections, which are also broadcast by GPS signals, are automatically applied by the receiver software to recover GPS Time. The TGD corrections remove biases between each satellite's L1 and L2 transmission, and also allow for the fact that the GPS Master Control Station's Kalman Filter (MCSKF) applies no corrections for the L1 and L2 frequency biases in the GPS monitor receivers. Those bias corrections are absorbed by the MCSKF into a constant offset in each clock's time, which in the absence of USNO monitor data would be absorbed into GPS Time. However, in the end the GPS clocks provide frequency only to the GPS MCSKF. Time is provided to GPS by referencing to UTC(USNO) with the time-monitor receivers maintained at the USNO, whose calibrations are measured and periodically updated. The appropriate corrections to recover GPS Time and GPS's delivered prediction of UTC(USNO) from single-frequency data would include the sum of the ionosphere delay plus the sum of any calibration differences relative to the USNO receivers, along with the differential biases between the satellite L1 and L2 transmissions. This satellite-dependent bias is the TGD correction, and it can be studied by fitting to a constant offset in the dependence of the measured ionosphere correction on elevation.

The TGD value for each satellite is broadcast with the GPS signal, and applied automatically by the GPS receiver software. It is provided to GPS by the Jet Propulsion Laboratories (JPL), and derived from a grid of receivers reporting to the IGS. This grid has an average calibration that is apparently inconsistent with the USNO's calibrations by about 6 ns, which appears when the TGDs and ionosphere corrections are applied to GPS Time. The USNO's single-frequency and dual-frequency receivers, although consistently calibrated at the L1 frequency, show this bias in the differences when the TGD corrections are applied to the single-frequency receivers. The resulting mismatch is reflected in the Circular T, where the long-term average value of UTC-GPS is about 6 ns. The non-zero mean is inconsistent with the fact that UTC-UTC(USNO) and UTC(USNO)-GPS are in the long term zero mean, when GPS is measured by the USNO dual frequency receivers. Reference [12] describes efforts being made to remove this discrepancy by making the calibration of the dual-frequency receivers used by JPL consistent with those of the USNO.

So long as the biases are inconsistently modeled, single-frequency users with GPS receivers calibrated consistently with the BIPM (and USNO) would measure GPS Time incorrectly, but consistently with the Circular T. AV and CV between single frequency receivers would be unaffected, but biases would appear in AV and CV between single-frequency receivers calibrated consistently with the BIPM calibrations, and dual-frequency receivers calibrated inconsistently with the dual-frequency receivers used by JPL to measure the TGDs.