Committee on GNSS Time Transfer
Progress report
and
Long Term Plans

The long-term goal of GNSS time transfer is to realize an accuracy of 0.1 ns in comparing clocks at timing laboratories over baselines of any length. This goal is very ambitious, and it may be sometime before we can realize it. An intermediate goal is to realize a *stability* of 0.1 ns RMS (white phase noise spectrum) over baselines of any length for averaging times up to about 30 days. The work of the committee is to study the factors that limit these metrics and to see if there are methods of realizing them using GNSS data. These goals are derived from a number of considerations.

1. This accuracy is needed to support the current Circular T data, which give the values of UTC – UTC(lab) with a resolution of 0.1 ns. I don't know of any current application that requires time accuracy of this order, but these applications are likely to appear in the future, and we should start to study methods of addressing the limitations now.
2. This stability will make it possible to compare the current generation of primary frequency standards, which have a frequency accuracy of somewhat better than 10^{-15}, with only a few days of averaging, and it will make it possible to compare many of the next generation of primary frequency standards with averaging times that are on the order of 1 month, which is the averaging time that is often used at present. This averaging time is too long for many of the newer optical frequency standards. This is probably the most important consideration, since the re-definition of the length of the second is already on the horizon, and developing methods for distributing the frequency of primary frequency standards without degrading their performance will be needed if the full advantages of the new standards are to be realized.
3. Two-way satellite time transfer, which is the only other generally-available technique that can support anything close to this level of stability at present, is becoming increasingly expensive, and there may come a time in the not too distant future when it is simply too expensive for many laboratories to afford. In addition, the station hardware of many two-way links are usually calibrated using GNSS data, so that the uncertainty in the GNSS time differences limit the accuracy (but not necessarily the stability) of the two-way data.
4. At present, optical-fiber links that can support this level of performance require dedicated, "dark" fibers, and are limited to a few special paths. It is unlikely that the time and frequency community will be able to afford to use dark fibers in general because they will be too expensive in general and perhaps not available generally at any price at some locations.
5. This level of performance will be particularly useful for the smaller timing laboratories, since it will allow them to realize a local version of UTC with an uncertainly of about 1 ns using a simple clock ensemble – perhaps even just a single maser or high-performance cesium device. These laboratories will probably never be able to afford the relatively high cost of two-way satellite time transfer.

The current international system of time comparison uses a mixture of several different techniques with differing levels of performance. Some timing laboratories are linked using a single-hop two-way satellite link to the PTB, which is used as the hub of the network that provides data for the computation of TAI and UTC. Other laboratories use GNSS data that is post-processed with precise ephemerides and analyzed using the all-in-view method. Some laboratories use the older single-channel C/A code receivers in common-view using the broadcast ephemeris, possibly augmented with post-processed ephemerides. This multi-level approach has historical roots, but it is not optimum as a long-term goal. There is an advantage to using a single technique for all time links, and we should consider realizing this idea as a long-term goal, even if it cannot be realized in the short term for various reasons. At a minimum, a single technique will simplify the specification of a standard configuration for all timing laboratories. This is likely to be most helpful for the smaller laboratories, which can simply copy the standard configuration.

There are a number of problems that must be solved in order to realize an accuracy of 0.1 ns:

(1) A direct measurement of the refractivity of the ionosphere rather than just using some average map or an estimate based on a model. Our first goal should be to encourage all laboratories to upgrade to dual-frequency hardware, since single-frequency L1 receivers cannot provide an estimate of the ionosphere and are no longer adequate.

(2) Receiver calibration and uncertainties in the coordinates of the antenna. This is an ongoing problem, and the uncertainty and long-term drift of the receiver calibration is a long-standing problem. We should develop protocols for calibrations and for routinely determining the coordinates of antennas that can support the accuracy goal of 0.1 ns. The current protocols are probably not adequate for this task, especially at sites where multipath is a significant problem. In addition, the use of multiple wavelengths to estimate the ionosphere will introduce additional complexity into the calibration process. The interaction between multiple wavelengths and multipath reflections may be particularly troublesome.

(3) Developing and testing analysis software. We should encourage development of carrier-phase methods of data reduction. The current techniques have sufficient resolution in the short term, but the accuracy for longer averaging times is not consistent with the short-term resolution. One of the most serious problems is the discontinuities at the analysis boundaries. These discontinuities make a significant (perhaps even the largest) contribution to the error budget of the carrier phase method. Some preliminary work shows that these discontinuities cannot be characterized as white phase noise, so that they cannot be attenuated by averaging long data sets with multiple discontinuities.

(4) The current 13-minute tracks and the algorithm used to compute them from the basic 1 s data are obsolete and the reporting process should be re-considered. Any changes would not necessarily require a change to the format of the data files, and there is an advantage to maintaining the same format for backward compatibility. Receivers that are used for carrier-phase data often use an averaging time of 30 s, and we should consider making this a standard for the future. There are already methods for converting 30 s data in the standard RINEX format to the older CGGTS format, and these conversions should be used on an interim basis and gradually phased out. The increased size of RINEX files relative to the older CGGTTS format is no longer a significant limitation given the increased bandwidth of data transmission and the large storage media that are widely available.

(5) We should encourage studies of methods for handling the refractivity of the troposphere. Current mapping functions often use the zenith delay as a

scaling factor, and there is generally no easy way of determining this parameter with an uncertainty that is consistent with our overall performance requirement. This is likely to be a difficult problem to address, since the zenith delay will be correlated with the estimate of the time difference. The estimate of the refractivity of the troposphere is particularly difficult at a site (like Boulder, Colorado), which has significant azimuthal asymmetry.

In the longer term, we recommend a transition to time transfer using carrier phase receivers and RINEX data, assuming that the problems identified above have been adequately addressed. The PPP method is a useful intermediate step in this direction, but it can be difficult to estimate ambiguities using this type of analysis, and network-based solutions may prove to be better able to do this in the long run. This is also a question for further study. It is outside of the traditional terms of reference of the CGGTTS committee, and it might be better addressed by a committee of experts on this question.

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