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EFFECTS OF EARTH STATION CLOCK ERROR ON CORRELATOR TIME CORRECTIONS

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It is the role of OVLBI earth stations to determine corrections to the time stamps written onto the wideband data tape, and to supply these corrections as a time series to the appropriate correlator. Adding the corrections to the times on the tape should yield the UTC at the orbiting telescope when the corresponding data sample was taken. The format for supplying the corrections is given in a specification [1], along with some details of how they should be determined. The corrections cannot be perfect, and some of the errors involved were considered in [2].

In the present note, I elaborate on the effects of an error in the UTC clock at the earth station. This discussion is somewhat specific to the implementation of the NRAO station at Green Bank, but I believe that it is fully applicable to the other existing implementations (NASA DSN stations and ISAS Usuda station). The discussion covers the effects on correlator time corrections and not on Doppler tracking for orbit determination; the latter is closely related, but sufficiently different to require a separate treatment.

Timing at the earth station is driven by a single oscillator, normally a hydrogen maser, so that all locally-generated signals are synchronous. In that case, every such signal (even microwave oscillators) may be regarded as having a *nominal* relationship to the reading on a fictitious clock that maintains true coordinate-time UTC. To the extent that the signal's actual relationship to UTC differs from nominal, we say that the signal contains a "clock error." We are concerned here with four such signals, since they affect directly the correlator time corrections: (a) the uplink reference signal transmitted to the spacecraft; (b) the predicted downlink signal whose timing is being compared to that of the actual downlink signal from the spacecraft; (c) the sampling signal that determines the times of discrete measurements of the time difference (or phase difference) between the predicted and actual downlink signals; and (d) the reading of a counter driven by the master oscillator and used as the station's real-time approximation to UTC.

The uplink signal (a) and downlink prediction (b) are continuously adjusted according to the predicted orbit, so their nominal timings depend on the predicted spacecraft and earth station positions at each instant, and perhaps also on estimates of delays in the intervening medium. We are not concerned here with whether these predictions and estimates are accurate (see [2] for such issues), but rather with whether the signals actually generated at the earth station differ from what they should be, given the predictions. In practice, the signals are derived from several subsidiary signals such as downconverter and upconverter local oscillators and synthesizers of various types; we consider only the net results, so that clock errors of all constituent signals are included.

The counter reading (d) is a "clock" in the traditional sense. However, it is used only at one epoch of each "tracking pass," namely when the tape time generator is initialized. We call this the "clock setting epoch." Thereafter, the time stamps on the tape are derived from the downlink signal, and the reading of the local counter is ignored. Here a tracking pass means a continuous interval during which wideband data is recorded and time corrections are to be generated; if the tape time generator must be re-initialized for any reason, a new tracking pass is considered to have started.

1. Initialization

At the clock setting epoch, the correlator time correction is given by

$$\Delta t_0 = t - t_{\rm fmtr} - \hat{T}_d \qquad (1)$$

where t is the true coordinate-time UTC at that epoch, $t_{\rm fmtr}$ is the value to which the tape time generator is then set, and $\hat{T}_d$ is the estimated downlink delay (from the taking of the data sample labeled by this value of the tape time generator to t, thus including the propagation delay from the spacecraft and any processing delay within the earth station).

But t is not known exactly, so in practice the counter reading $t_{\rm clk}$ may be substituted. If the counter is carefully maintained and monitored, this might be sufficiently accurate. Note that the resulting error $t - t_{\rm clk}$

is a constant for the whole tracking pass, regardless of any variations in the clock error after the clock setting epoch. Normally the counter reading is the best available real-time estimate of UTC, so it is recorded; but the time corrections are not needed until later, so the estimate of t used in evaluating (1) need not be the counter reading alone. Any post-pass information about the clock error may be used. The specification [1] requires earth stations to use the best known value.

What accuracy is required? The objective is to minimize the need for fringe searching, and to eliminate the need for pre-correlation fringe searching. Practical considerations at the VLBA correlator then seem to require that the total error in Δt_0 be less than a few microseconds. The error in the downlink delay $\hat{T}_d$ will be of this order, and will be dominated by the error in the spacecraft position, especially if only the predicted orbit is used. If the reconstructed orbit is used, this term might be the order of 1 microsecond. It is therefore desirable to keep the clock error much smaller — a few hundred nanoseconds or less. This is well within the state of the art, so it is expected to be achieved at all stations (either in real time or in post-pass calculations).

2. Sampling Times

The specification [1] requires that, after the clock setting epoch, time correction values be supplied at intervals of 0.1 sec. Each correction value must be given an effective time stamp equal to the UTC at the earth station when the corresponding spacecraft signal was received.

The earth station hardware includes a sampling signal generator with a 0.1 sec period. Let the nominal time of the ith sample be $t_{\text{samp}}[i]$ and let the actual (true UTC) time be $t[i]$. We then have a sampling clock error $t[i] - t_{\text{samp}}[i]$, possibly time varying. At each sampling time, a measurement of the downlink signal timing is made, and these measurements are later used to derive the time correction series. The derivation of time correction values from the raw measurements is not considered here. However, the time stamp associated with the ith time correction is nominally

$$t_c[i] = t[i] - T_{\text{proc}}$$

where T_{proc} is the signal processing delay in the station (between signal reception and raw measurement sampling). It was shown in [3] that these time stamps must be accurate to about 7 microseconds. This is not very stringent; it should be easy to keep the sampling clock error much smaller. The net error in t_c is likely to be dominated by knowledge of T_{proc} rather than by the sampling clock error. To much higher precision (a few nsec), both the clock error and the processing delay are expected to be constant throughout a tracking pass.

3. Uplink And Downlink Signal Generation

The nominal link signals for VSOP and RadioAstron are sinusoidal. The actual uplink signal is the nominal signal advanced in time by the predicted uplink delay, and the predicted downlink signal is the nominal signal delayed by the predicted downlink delay. So the desired signals are, respectively,

$$\begin{aligned} s_{\text{up}}(t) &= \cos \omega_u (t + \hat{T}_u(t)) \\ s_{\text{dn}}(t) &= \cos \omega_d (t - \hat{T}_d(t)). \end{aligned} \tag{3}$$

The predicted delays are calculated in a complicated way, depending not only on the predicted orbit but also on the motion of the earth station and possibly on medium effects; all these may be estimated to various levels of accuracy which we do not consider here. We assume that the desired signals are generated as in (3), except that clock errors cause the signals generated at t to be the ones that should have been generated at $t - \delta t_u$ and $t - \delta t_d$, respectively. Note that a positive clock error is equivalent to an increase in the estimated uplink delay and a decrease in the estimated downlink delay. The measured residual delay is normally (in the absence of clock errors)

$$\tau_{\text{ideal}} = (T_u - \hat{T}_u) + (T_d - \hat{T}_d) \tag{4}$$

so it now becomes

$$\begin{aligned} \tau &= (T_u - \hat{T}_u - \delta t_u) + (T_d - \hat{T}_d + \delta t_d) \\ &= \tau_{\text{ideal}} - (\delta t_u - \delta t_d). \end{aligned} \tag{5}$$

Here terms involving derivatives of $\hat{T}_u$ and $\hat{T}_d$ have been neglected; these are much smaller than those in (5), but are not necessarily negligible. It can be seen that if the two clock errors are equal then there will be no effect on the measured residual delay. Yet the error in the uplink does produce an equal error in the time on the spacecraft; this error is not corrected. More generally, remember that the measured residual τ contributes a term $\tau/2$ to the time correction Δt (see [2]). So we obtain

$$\begin{aligned} \Delta t &= \Delta t_0 + \tau/2 \\ &= \Delta t_0 + \tau_{\text{ideal}}/2 - (\delta t_u - \delta t_d)/2. \end{aligned} \tag{6}$$

whereas the correct value is

$$\Delta t = \Delta t_0 + \tau_{\text{ideal}}/2 - \delta t_u \tag{7}$$

producing an error

$$-(\delta t_u + \delta t_d)/2. \tag{8}$$

That is, *unknown or uncorrected clock errors in generating the uplink and downlink signals do not cancel, but rather add.*

However, if these clock errors are constant throughout a tracking pass, and if they are small compared with the initialization errors, they may be insignificant. Consider first the absolute size of the clock errors, as if they are constant. The net error (8) should be a few hundred nsec or less (cf. section 1 above). To achieve this, the earth station must account for any processing delay between the calculation of an updated value of $\hat{T}_u$ or $\hat{T}_d$ and the effective generation of the corresponding signal in the hardware. This accounting can be done in the real time system, or an appropriate correction can be applied during the derivation of Δt.

Next consider any variation of the clock errors over a tracking pass. Here the requirements are much more stringent than for the initialization clock (which is used at only one epoch, so the issue of variation does not arise) or for the sampling clock (which operates on measurements of residuals only). Clock errors δt_u and δt_d on the link signal generators go directly into the corrected spacecraft time, which controls the processing of signals at the observing frequency (to 22 GHz). Thus, errors at the level of a few psec are significant; uncorrected variations over a correlator integrating interval (typically 10 to 1000 sec) will cause loss of coherence.

4. Summary

As shown in section 1, each earth station should compute the clock setting error (i.e., the time correction at the initialization epoch) using the best possible value of UTC for that epoch. Any known error in the real-time clock should be included.

As shown in [3] and discussed in section 2, the time stamps on the time correction values should be have an absolute accuracy of a few microseconds or better. This is expected to be achievable in real time, but larger clock errors that are determined after a tracking pass can be corrected during the post-pass data processing.

As shown in section 3, picosecond-level variations in clock errors during a tracking pass can lead to significant errors in the final timing. Variations should be held to smaller levels by design, or else they should be monitored to this accuracy and corrected in post-pass processing. (At the NRAO Green Bank station, clock variations of ~ 20 psec/hour sometimes occur due to delay changes in the 2 km optical fiber that links the hydrogen maser to the station. These are measured to ~ 0.2 psec accuracy and used in post-pass corrections.)

REFERENCES

[1] L. D'Addario and G. Langston, "Time corrections file interface." NRAO Specification 34300N004E, 1995 April 19.
[2] L. D'Addario, "Post-pass processing of two-way timing measurements." OVLBI-ES Memo #64, 8 July 1996.
[3] L. D'Addario, "Correlating orbiting radiotelescope data with time corrections." OVLBI-ES Memo #55, 22 March 1995.