OVLBI TIMEKEEPING WITH THE VLBA FORMATTER

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90 August 1

Abstract

This report discusses a procedure that will allow the VLBA formatter to be used without modification to control the recording of OVLBI data. The time recorded on the tape headers will be determined by counting the down-link data clock, so that (unlike ground telescope data) it will not accurately track UTC. Nevertheless, the UTC at which each sample was taken at the spacecraft will be known to within an additive error which remains constant during any period of continuous contact with the spacecraft. The procedure takes into account restrictions imposed by the design of the VLBA formatter.

I. The VLBA Formatter

An overall block diagram of the VLBA formatter is given in Figure 1. This digital processing machine is constructed in several VME-bus modules and includes a microcomputer for control and communication. It is driven by externally-generated clock signals at three frequencies, nominally at 1 Hz, 32 MHz, and $(r/m) \times (32\text{MHz})$. The third frequency is called the "record rate clock," and is the rate at which bits are written to each tape track, taking into account the addition of parity bits and header information; r is the ratio of the number of bits recorded to the number of signal bits received, and $m = 4$, 8, or 16, depending on the tape speed. The signal bits must be valid on every nth transition of the 32 MHz clock, where $n = 1, 2, 4, \ldots, 128$ (corresponding to sample rates from 32 to 0.25 Msamp/sec), including the 32 MHz transition which corresponds to a 1 Hz transition. The recorded data is broken into "frames" and the format of a frame is programmable; each frame can have up to 65,536 bits per tape track, most of which are usually signal samples. In particular, each frame normally includes a "time code" field containing the time-of-day of the first signal sample in the frame.

When the formatter is used at a ground radio telescope, all three clock signals are normally derived from the local stable oscillator (typically a hydrogen maser), and their frequencies correspond closely to the nominal values. The time code is obtained by counting the 32 MHz clock, and the counter can be initialized upon command at the next 1 Hz transition. Thus, if the 1 Hz transitions occur on the UTC seconds, the counter can be made to maintain an accurate measure of UTC. The 1 Hz transition is not only used for initialization, but also to implement the part of the counter corresponding to time intervals greater than 1 sec; it is therefore necessary that the 1 Hz and 32 MHz clocks be synchronous and in exactly the right frequency ratio. The record rate clock must also be synchronous, and the programmed format must produce r tape bits for each input bit; otherwise, the FIFO buffers for the signal samples will overflow or underflow. (Incidentally, the 1 Hz clock is also used for certain

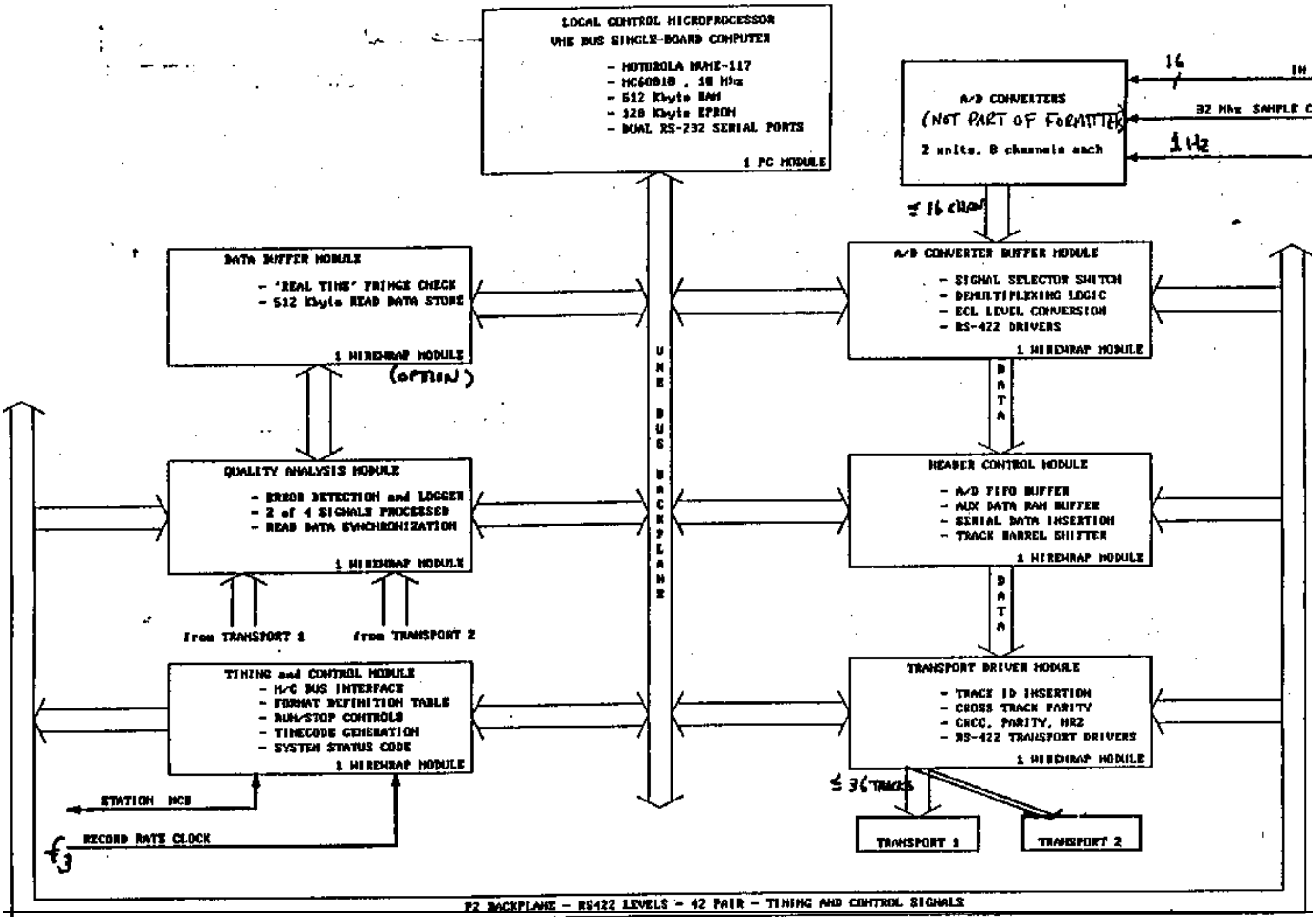

Figure 1: VLBA FORMATTER CHASSIS BLOCK DIAGRAM

internal error checks, which will fail if this clock is missing or asynchronous.)

When the telescope is in space and the signal is digitized there and downlinked to earth, the samples will be received at a variable rate due to the Doppler effect and due to variation of the sampling phase at the spacecraft. However, a clock synchronous with the received samples can be derived. This clock, if near 32 MHz, can be substituted for the 32 MHz clock to the formatter. A substitute "1 Hz" clock can then be provided by dividing the recovered data clock by 32×10^6, and the record rate clock can be synthesized from the recovered data clock using a phase locked loop. The phase of the 1 Hz clock divider must be such that a signal sample is valid on its output transition (in case the sampling rate is less than 32 Msamp/sec), but otherwise it is not restricted. The formatter will then operate normally. However, the time code will not accurately track UTC.

II. Time Setting

Figure 2 shows a block diagram of a portion of an OVLBI earth station. The important features for our purposes are these:

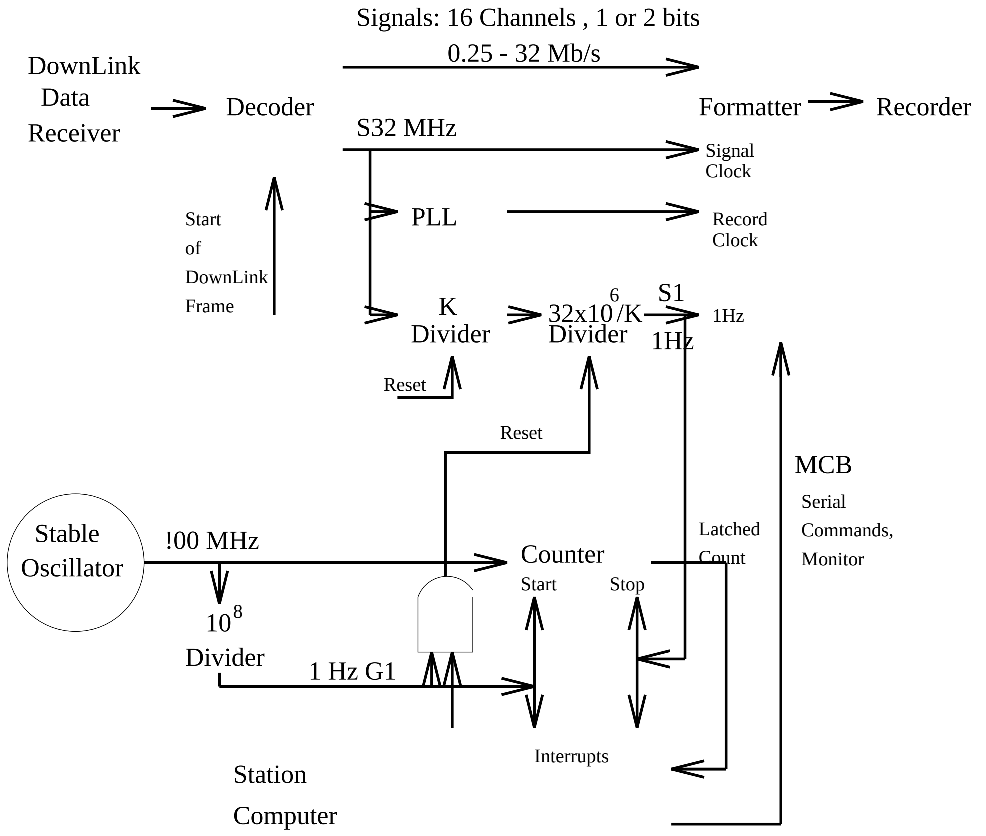

Figure 2: Block Diagram of part of the Earth Station

(1) The downlink decoder synthesizes a (nominally) 32 MHz signal from the received sample stream.

(2) The decoder also detects the start of a downlink data frame. Here we assume that the downlink data is broken into frames in a way that is independent of the formatter's frames, and that there is an integral number of each type of frame in one (nominal) second. It is then possible, and desirable for convenience, to arrange that each 1 Hz transition (call it S1) corresponds to the beginning of each type of frame. This is accomplished by separating the 32×10^6 divider into two cascaded parts, with the first part having a radix equal to the number of downlink frames per second, and ensuring that this part of the divider is zero at the start of a downlink frame.

(3) There is a stable oscillator (hydrogen maser) which provides a high frequency signal (100 MHz) and a 1 Hz signal (call it G1) with transitions on the UTC second.

(4) The station computer can cause the remaining part of the divider to be reset at a transition of G1.

(5) The station computer is interrupted at each transition of both S1 and G1.

(6) Each second, an accurate measurement is made of the time from a transition of G1 to the next transition of S1.

We then can use the following procedure to maintain knowledge of the time of each sample.

(a) For each acquisition of signal from the spacecraft, the S1 divider and the time code counter in the formatter will be initialized in accord with the timing diagram in Figure 3. The station computer selects a particular UTC second (G1 transition) on which the initialization will occur; call this the "setting epoch," t_0. Two seconds prior to t_0, just after a G1 transition, the computer commands a reset of the second part of the S1 divider; this occurs on the next G1 transition, at $t_0 - 1$ sec. Thereafter, S1 transitions will occur shortly after G1 transitions (0 to 1 downlink frame later). The computer next waits until the next G1 and S1 transitions have both occurred, and then commands the formatter to initialize the time code counter to exactly t_0. The initialization does not occur at exactly t_0, but rather at the next S1 transition, which is slightly later; this difference, the "setting error" Δt_s, is measured by a high resolution counter [item (6) above]. The computer reads this counter immediately after the next S1 transition. The values of t_0 and Δt_s are recorded for later use.

(b) In addition to the data downlink, the station maintains a two-way timing link to the spacecraft. The signal sampler on the spacecraft, from which the 32 MHz clock is ultimately derived, is driven from the uplink portion of the timing link. The uplink transmitter is phase modulated so as to keep the sampler (and other spacecraft signals) at its nominal frequency and phase, within the accuracy of the *a priori* orbit knowledge. Any residual error in this phase is monitored by the downlink portion of the timing link, which measures the difference between the *a priori* prediction of the propagation time and its actual value. Call this the "residual propagation time" $\Delta\tau(t)$. It is measured frequently (perhaps once per second) and the results are recorded for later use.

(c) At the correlator, when the tape is played back, the best estimate of the time (UTC) that the first sample of a (recorder) frame was taken is given by

$$t = t_t + \Delta t_s - \hat{\tau}(t_0) - \Delta\tau(t)$$

where t_t is the time code from the tape, and $\hat{\tau}(t_0)$ is the best *a posteriori* estimate of the propagation delay at the setting epoch. The times of other samples of the frame can be obtained by interpolation.

III. Discussion

For a more thorough discussion of the considerations in OVLBI timekeeping, see [1]. Here we consider only those issues that lead to the procedure given above.

Having the computer reset the slower bits of the S1 divider just before the time code initialization is necessary to avoid the possibility of a race between S1 and G1. The computer must take a non-zero time to respond to each interrupt, and if the relative time of the interrupts is arbitrary then there is always a possibility of making a 1 sec error in the time code initialization.

It might be noted that no information from the downlink frame header is used in this scheme. In particular, the contents of a time code counter or frame counter on the spacecraft might be transmitted, but it is ignored. For such a counter to be useful in timekeeping, it would need to be carefully initialized, and this is much more difficult

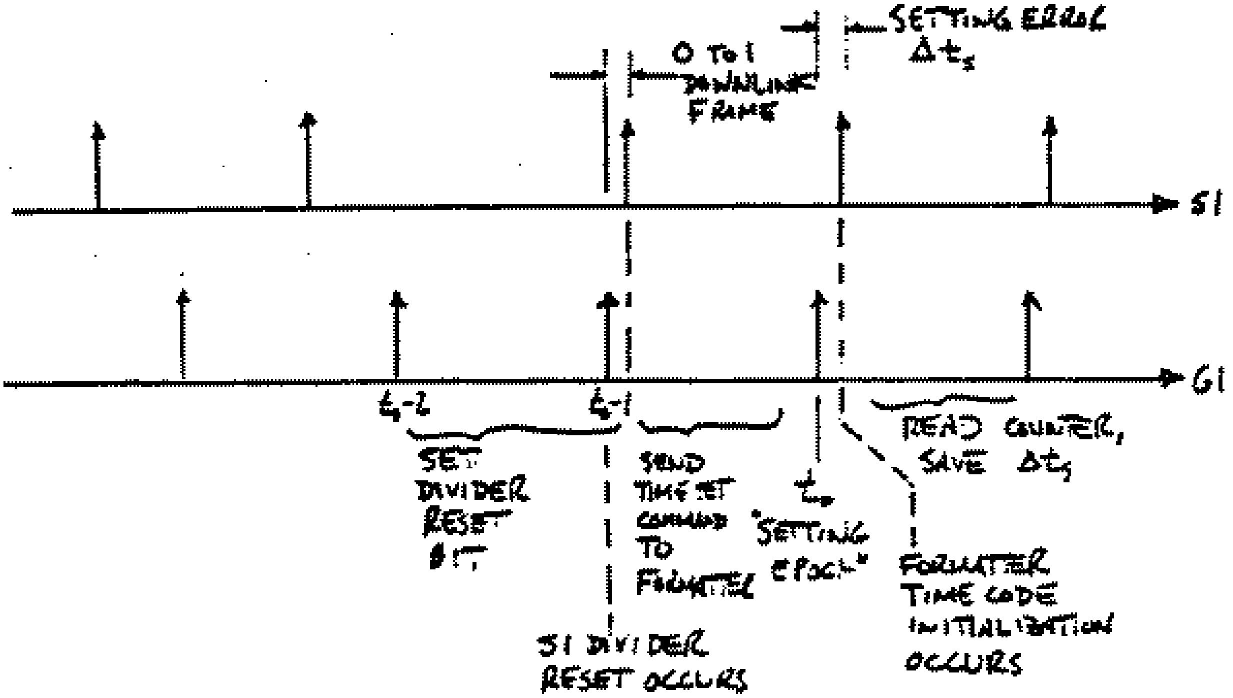

Figure 3: Timing Diagram for initialization

on the spacecraft. Besides, the VLBA formatter design prevents frequent updating of the time code or of any other data in the header, and it prevents initializing the time code to any non-integer number of seconds (although the time code counter has 1 microsecond resolution). Nevertheless, the spacecraft frame counter might be useful for error checking and for recovering from dropouts.

The "best estimate" of the time of any sample is still subject to numerous errors. First, the earth station's knowledge of UTC is not exact, nor is its "stable oscillator" perfect. More significantly, the timing link measurement of $\Delta\tau$ may be subject to large ambiguities (see [1]), as well as noise. However, all of these errors are constant or well characterized as long as continuous contact with the spacecraft is maintained. A determination of the final timing error, taking all these effects into account, must be made astronomically after correlation.

Procedures for recovering from dropouts will be discussed in a later memo. In general, a communication dropout requires repeating the initialization and re-determination of the final time error after correlation.

IV. The RADIOASTRON Case

The RADIOASTRON spacecraft design, including both the signal digitization and the downlink, are compatible with the scheme described here and with the VLBA formatter. Sampling rates are 4, 8, or 16 Msamp/sec and the downlink frame rate is 400/sec.

The downlink format overwrites signal samples with header information, creating gaps in the data. In principle we should not correlate during the gaps, but since it is difficult to synchronize a correlator in this way we propose instead to insert non-correlating data in the gaps. Pseudo random noise could be used, but another possibility (suggested by B. Clark) is to insert a portion of the data stream with a large delay.

A decoder for use at Soviet earth stations is being designed in Moscow, and much of that design may be adopted for use at the Green Bank station. It contains many of the elements shown in Figure 2, including the G1 to S1 time difference counter. It also produces a "1 Hz" output synchronous with the downlink frame. However, the present design does not include the capability of synchronizing the S1 divider to G1. If this capability is added, then very little additional equipment is needed to connect the Soviet decoder to a VLBA formatter.

References

[1] L. R. D'Addario, 1990, "Time Synchronization in Orbiting VLBI." Submitted to *IEEE Trans. on Instr. & Meas.*