HETE TELEMETRY RANGING SUBSYSTEM

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Abstract

The HETE (High Energy Transient Experiment) satellite, a joint project between MIT Center for Space Research and AeroAstro, is a high energy gamma ray burst/X-ray/UV observatory platform. In order to provide accurate time stamping of gamma ray burst events, a clock accurate to within 100 µs of Universal Time (UT) is required on the satellite.

This paper presents a clock setting/ranging subsystem that is incorporated into the HETE telemetry system at no additional weight or power consumption. This method makes use of augmenting the data scrambler with a PN ranging code with unique words which allows accurate ranging and clock setting on the spacecraft to within 3 µs or better of UT. This system operates at baseband and is thus independent of the modulation type or carrier frequency used on the uplink and downlink. It also does not require that the uplink and downlink frequencies bear any particular relationship to each other. Clock setting and ranging measurements are performed on command from the ground station. The clock setting/ranging mode duration is approximately 3 to 5 seconds and is terminated automatically through a satellite-ground station handshake.

The HETE Spacecraft and telemetry overview

The HETE satellite is scheduled to be launched in December 1994 aboard a Pegasus rocket into a circular orbit of 550 Km altitude with an inclination of 37.7°. Three ground stations, located in Miyazaki Japan, Kitt Peak Arizona, and Sicily Italy, will provide approximately 120 minutes of contact time with the satellite per day with gaps between contacts with the satellite anywhere from 20 to 100 minutes.

The mission requires that the payload science data be time stamped on the satellite to within ±100 µs of Universal time (UT) and that events separated by up to 1000 seconds be time stamped to a relative accuracy of ±10 µs. In order to meet this specification, an on board real time clock (RTC) of sufficient accuracy is needed along with a method of referencing or setting it to an Earth based time standard. In an effort to keep the on board RTC as small, low power and as inexpensive as possible, a high quality ovenized crystal oscillator (OCXO) was chosen. This oscillator has the following specifications:

Temperature stability:	$\pm 5 \times 10^{-9}$ from -55°C to +71°C
frequency aging:	$\pm 5 \times 10^{-10}$ per day
	$\pm 5 \times 10^{-8}$ per year

Thus, neglecting aging, the maximum time uncertainty over a 100 minute period would be ±30 μs. If we assume that the clock is referenced at the beginning and end of the 100 minute time period, it can be shown that the maximum error occurs at the midpoint and is only ±15μs (half of ±30 μs). Typically, however, the error will be much less. The aging effects contribute a very small error. Assuming a linear aging rate of $\pm 5 \times 10^{-10}$ / day, the worst case error contribution is given by

$$\text{aging error} = \int_0^{3000} \frac{(5 \times 10^{-10})\, t\, dt}{(24)(60)(60)} = 26.04 \text{ ns} \qquad (1)$$

Typically, frequency aging error rates tend to be fairly constant and therefore the actually error contribution will be much smaller than the worst case.

Telemetry ranging subsystem

A block diagram of the HETE spacecraft telemetry system and the ground station telemetry system is shown in figures 1 and 2. Both uplink and downlink data clocks are phase synchronous to Universal Time (UT) via a 1 MHz reference clock output from a ground station based GPS receiver. The uplink data clock is generated by dividing the reference clock by 32. On the spacecraft, the downlink clock is generated from a x8 phase locked version of the uplink data clock, which is recovered by a synchronous data clock recovery unit on the spacecraft. A 15 stage data scrambler and descrambler are used for both the uplink and downlink to randomize the data. These data scramblers and descramblers are also used as PN code generators for ranging. The two operational modes of the telemetry system are described below.

Data mode

In the data mode, data to be uplinked to the spacecraft are clocked into a data scrambler at 31.25 KHz. The scrambled data are then modulated and amplified in the transmitter and uplinked to the spacecraft. The spacecraft receives the data, demodulates and descrambles the data before passing them on to the spacecraft CPU. In a similar way, data on the spacecraft to be downlinked are clocked into a data scrambler at 250 KHz. The data are then scrambled and convolutionally encoded before being modulated, amplified and transmitted to the ground station. In this mode, the data scramblers provide randomization of the data which aids in the demodulation process.

Ranging mode

In the ranging mode, the input data to both ground station and spacecraft data scramblers are turned OFF and the data scramblers are set to a know starting state. In this mode, each data scrambler generates a maximal length PN code of 2^{15}-1 bits[1]. The all 1's state is decoded on the ground station and used to synchronize an identical PN code generator running at 8x the rate (i.e. 250 KHz). This pulse train is then timed stamped using the GPS time output to establish a reference. The spacecraft detects the all 1's state of the uplinked PN sequence and synchronizes the downlink PN code (running at 8x this rate or 250 KHz) to it. This PN code is received at the ground station and the all 1's state is decoded. The resulting pulse train is time stamped using the GPS time output. Thus, the time difference between the uplink pulses (TxP) and the downlink pulse train (RxP) represents the round trip time delay of the transmitted signals plus the bulk delays of the ground station and spacecraft digital and RF sections. Since the digital delays are integer multiples of the clock periods, they can be subtracted out without loss of accuracy. The RF delays are relatively constant and therefore can be measured and subtracted out also. Since the RF delays are relatively small (on the order on one bit time) compared to the round trip propagation delay of the RF signals, small variations as a percentage of the total RF delay will result in even smaller variations as a percentage in the overall round trip delay.

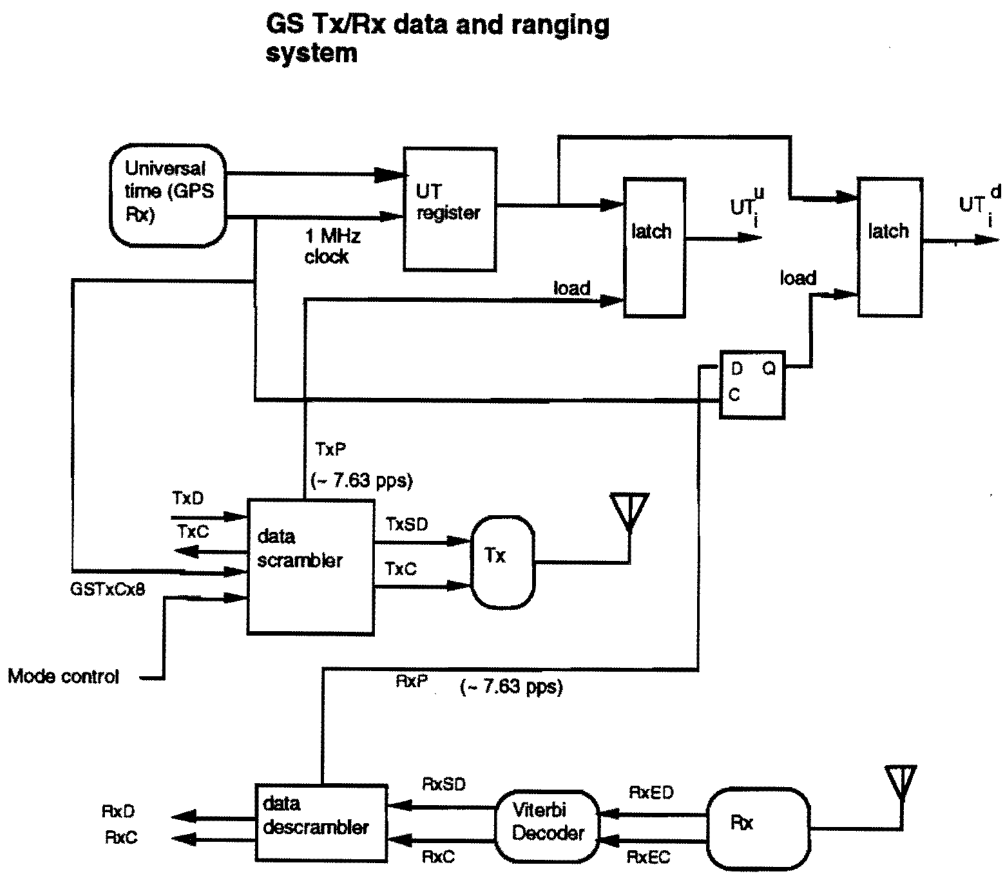

figure 1.

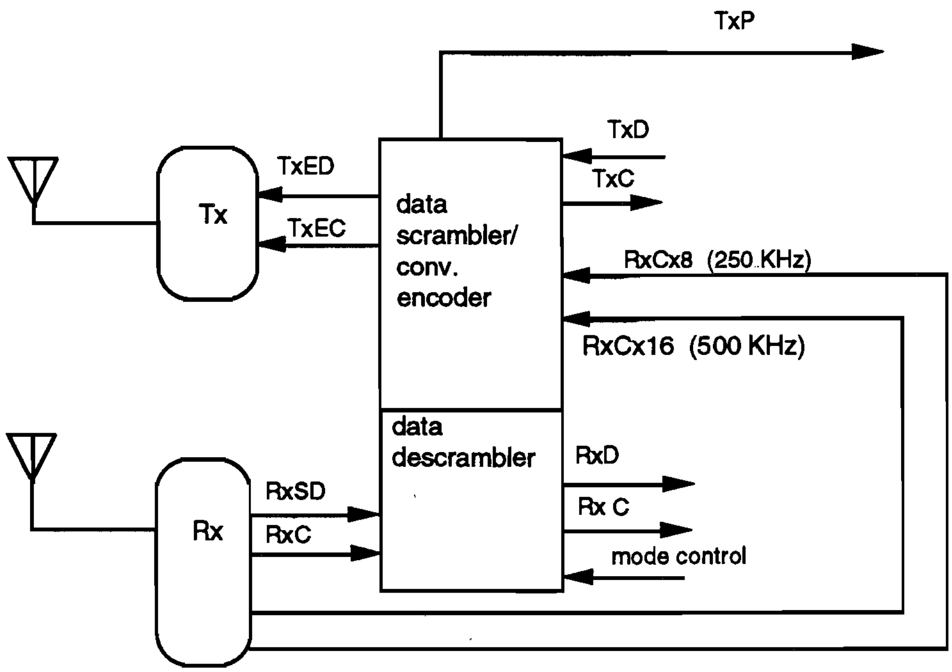

figure 2.

Data scrambler/descrambler description

A block diagram of the ground station data scrambler/descrambler is shown in figure 3 and a block diagram of the spacecraft scrambler/descrambler is shown in figure 4. The ranging mode is initiated by a ground station command to the spacecraft. The spacecraft sets the data scrambler/descrambler into the ranging mode immediately after acknowledging the ranging mode command. Once the ground station receives the acknowledgement, it sets it's data scrambler/descrambler into the ranging mode. In the ranging mode, the ground station data scrambler is initialized with 15 one's followed by a unique word of 17 bits. This sequence is uplinked to the spacecraft where it is recognized and used to load the same bit pattern of 15 one's followed by the 17 bit unique word into the downlink data scrambler and to gate the time pulses to the spacecraft CPU for time stamping. After receiving the unique word followed by the 15 one's, the ground station begins time stamping its locally generated pulse train, which is clocked at 250 KHz, and also time stamping the received downlink time pulses. Once several ranging pulse sets are time stamped, the ground station ends the ranging mode by uplinking another unique word followed by 15 one's. The spacecraft, after recognizing this pattern, echoes the pattern back to the ground station and re-enters the data mode. Likewise, after receiving the unique word followed by 15 one's, the ground station enters the data mode.

After the ranging sequence is completed, the ground station computes the time difference between the uplink and downlink pulses (RxP - TxP) and subtracts out the bulk digital and RF delays. These values are then averaged and the result is divided by 2 to yield the average RF propagation delay time from the ground station to the spacecraft. The ground station then computes the UT times corresponding to the spacecraft RTC time stamped pulses by subtracting out the RF propagation time and the spacecraft delay time from the RF input to the ranging pulse output from the received pulse times (RxP). These corresponding UT times are then uplinked to the spacecraft. The spacecraft averages the time differences between the ground station's corresponding UT time stamps and the RTC time stamps. This time offset is stored in memory and downlinked to the other ground stations to be used for RTC drift calculations.

Ground Station data scrambler/descrambler

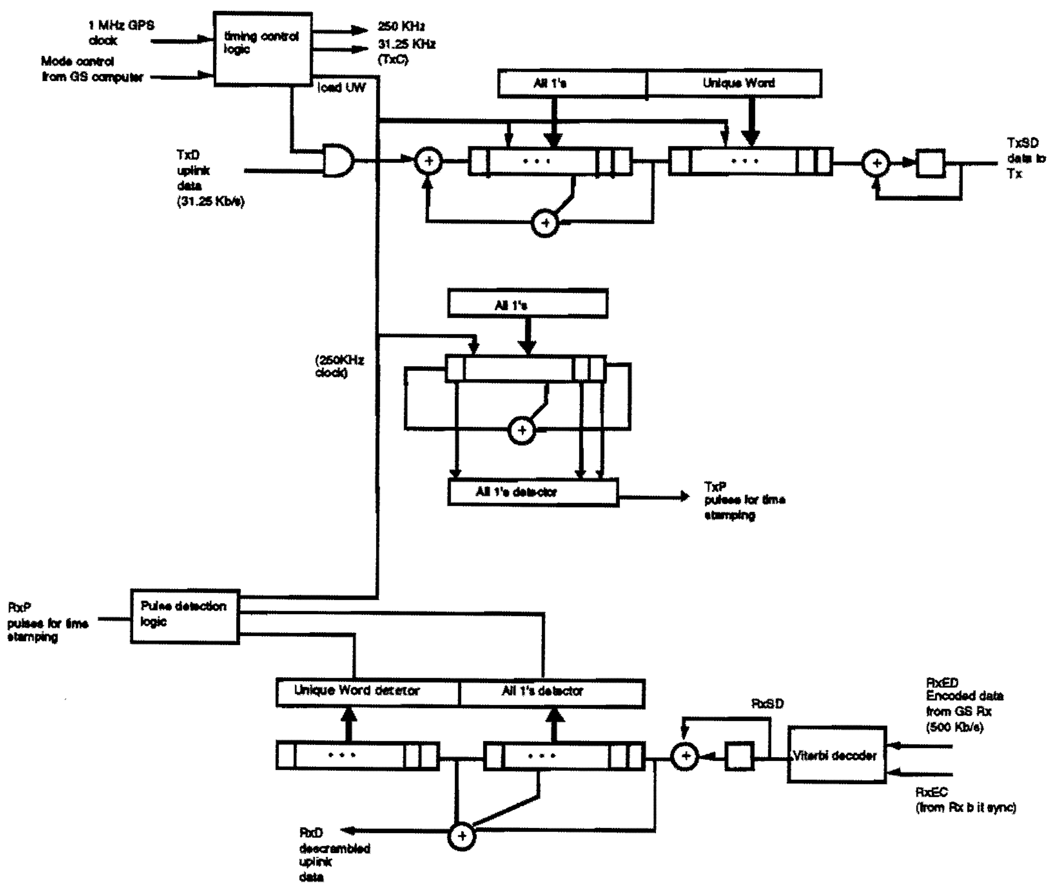

figure 3.

Spacecraft data scrambler/descrambler

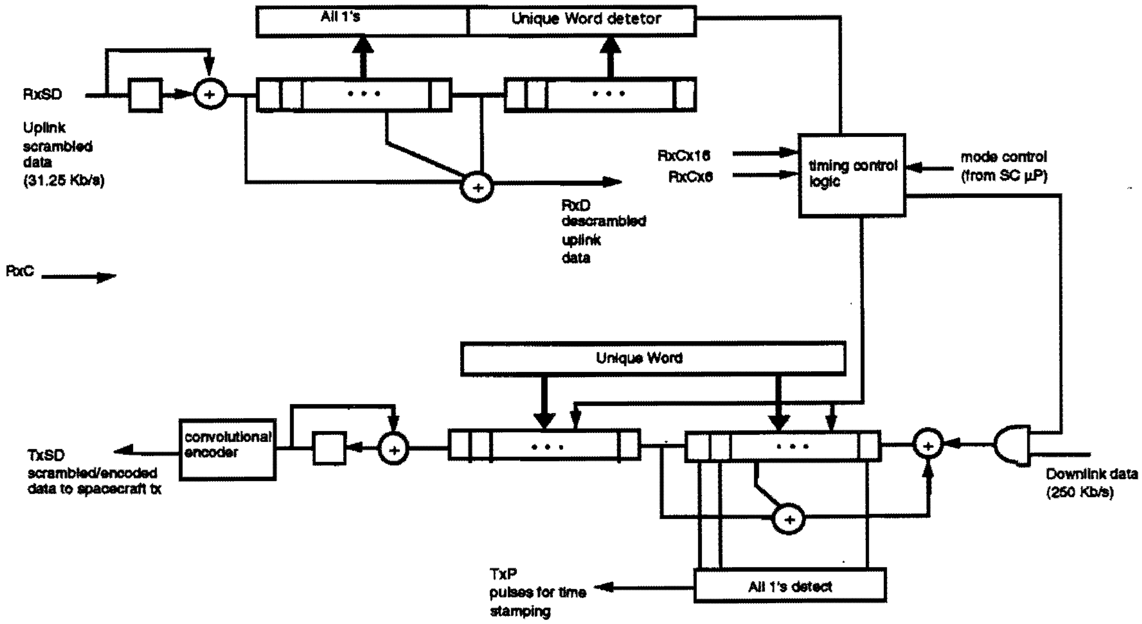

figure 4.

A list of the steps in the ranging process is given below.

1) Uplink ranging command to spacecraft (SC).

2) SC acknowledges ranging command and sets mode to ranging.

3) After ground station (GS) receives acknowledgement, GS sets mode to ranging and uplinks Unique Word (UW)

4) SC receives UW and loads UW for downlinking. SC begins time stamping pulses.

5) GS receives UW and begins time stamping transmitted and received pulses.

6) After several time pulses are received, GS ends ranging mode by uplinking UW. SC echoes UW and enters data mode. GS receives UW and also enters data mode.

7) GS computes time delay (range) to SC by subtracting SC and GS hardware delays from the difference between received and uplinked pulse times and dividing the result by 2.

8) GS computes UT values for SC time stamped pulses and uplinks values.

9) SC references RTC to UT by averaging over number of pulses received.

Note: To prevent the SC from getting stuck in the ranging mode, a time-out period is used. After the time out period has elapsed, the SC will enter the data mode and indicate an error occurred to the GS.

Clock setting and ranging accuracy

Several sources can contribute to the ranging (or time) error of the ranging system. Component variations in the RF front ends due to temperature variation and aging result in hardware time delay variations. These tend to be slow and may be relatively constant during a satellite pass. Quantization error in the ground station time stamping process results in a uniformly distributed error from -500 ns to +500 ns. The standard deviation of this error (σ_q) is 289 ns. Another source of error is thermal noise. This error is dependent on the signal to noise ratio of the received signal, the bandwidth of the symbol clock tracking loop, and the data rate. The time error due to noise for a single pulse (either uplink or downlink) is given by[2]

$$\sigma_t = \frac{T_b\sqrt{3}}{2\pi\sqrt{\frac{SNR}{T_b B_l}}} \qquad (2)$$

where σ_t is the standard deviation of the received time for a single ranging pulse, T_b is the bit time, SNR is the signal to noise ratio of the received data in the signal bandwidth, and B_l is the loop bandwidth of the symbol clock recovery circuit. For a signal to noise ratio of 10 dB, equation (2) reduces to,

$$\sigma_t = \frac{(0.3)\,T_b^{3/2}\sqrt{B_l}}{2\pi} \qquad (3)$$

Assuming a loop bandwidth of 0.1% of the data rate, the standard deviation for an uplink pulse is 48.3 ns (B_l = 31.25 Hz). For the downlink, the standard deviation is 1/8 this value or 6.0 ns (B_l = 250 Hz).

For loop bandwidths greater than the ranging pulse repetition rate (7.63 Hz), the time error for each pulse is independent from the others. The time stamping quantization errors are independent from the ranging errors and from each other. Therefore, the average ranging error is given by

$$\sigma_{t_{range}} = \frac{\sqrt{\sigma_{t_{up}}^2 + \sigma_{t_{down}}^2 + \sigma_q^2}}{2\sqrt{N}} \qquad (4)$$

Averaging 10 pulses would then result in one standard deviation equal to 46.3 ns.

This error combined with the time error of the GPS receiver, which is ±100 ns, is on the order of only 1% of the RTC maximum time error due to thermal drift and aging. Thus, the requirement of a ±100 µs time reference to UT on the spacecraft is easily met.

Conclusion

The HETE time referencing/ranging system was chosen to meet the mission requirements while minimizing the impact on the satellite hardware. This method of making ranging measurements at the baseband signal level does not require special RF hardware beyond a standard telemetry system with coherent symbol clock recovery. The digital hardware required to implement both the ranging and data scrambling functions is only slightly more complex than that of the scrambling function alone and does not increase either the power or parts count of the digital system. Other systems, such as direct sequence spread spectrum, while providing both continuous ranging information during data transfer and offering higher levels of accuracy in ranging, also require significant additional RF and digital hardware.

References

1. R.E. Ziemer, R.L. Peterson, Digital Communications and Spread Spectrum Systems, Macmillan Publishing Company, New York, Ch. 8, 1985.

2. F. M. Gardner, Phaselock Techniques , John Wiley & Sons, Inc., New York, Ch. 3, 1966.