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SPACE BORNE EVENT TIMER

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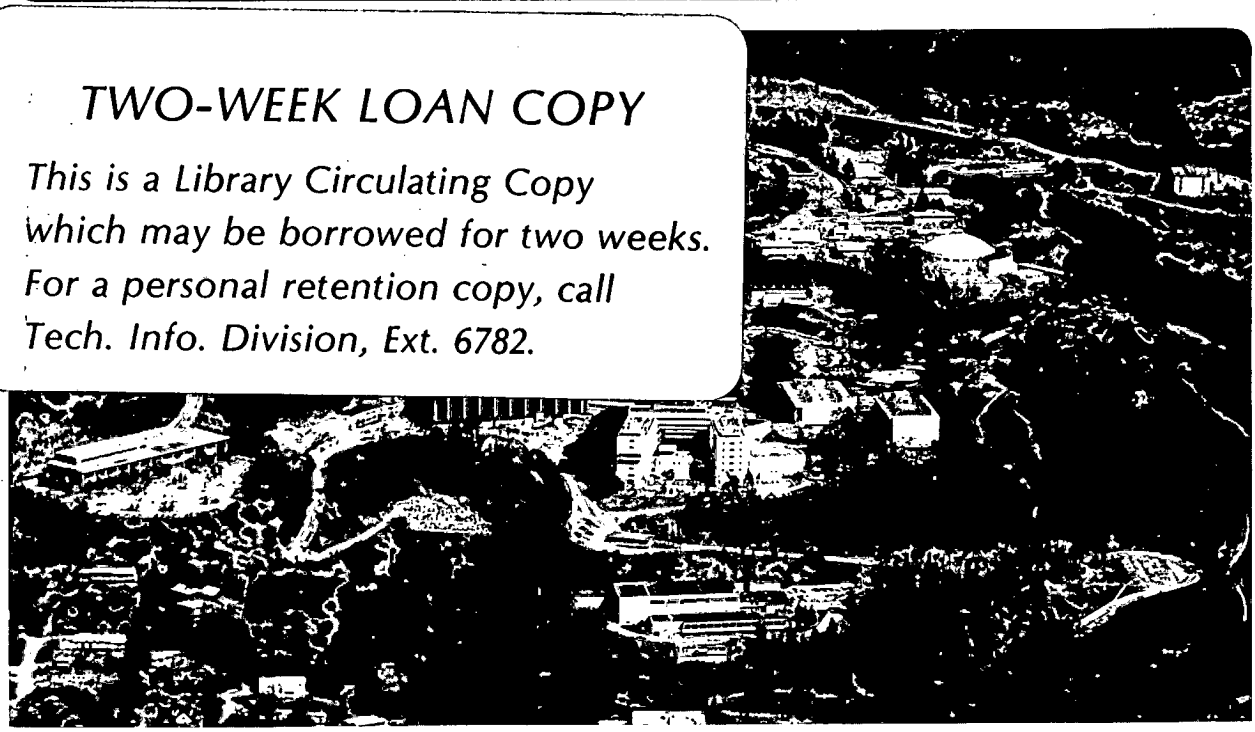

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SPACE BORNE EVENT TIMER

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Abstract

The Space Borne Event Timer is a part of the NASA laser ranging system that is intended to operate aboard the Space Shuttle orbiting over California. The object is to measure, by laser ranging, the earth movement along the San Andreas fault and possibly forecast future earthquakes. A number of cube reflector targets will be placed along both sides of the fault. The ranging system aboard the Space Shuttle will fire a burst of laser pulses at each target and detect the reflected light. Time differences between pulses from the two sides of the fault will indicate earth displacements. The Space Borne Event Timer is a CAMAC compatible system that provides extremely accurate timing data and controls the operation of the ranging system. For each event the time is given in 19.53 increments from the instant of firing the laser to the instant the reflected light is received back, within a range of 130 days.

Introduction

Laser ranging systems have been in use since the early 1960's. The National Aeronautic and Space Administration (NASA) has been using the ranging satellites for a variety of measurements such as orbit determination, polar motion, gravity field studies, earth tides and tectonic-plate motion.[1,7-9,11-12]

A typical satellite ground ranging system requires a pulsed laser, an optical timing receiver (which includes a time interval digitizer), and a satellite which is placed into a well defined orbit. For instance, the NASA Laser Geodetical Satellite (LAGEOS) is a small, heavy sphere fitted with 426 optical cube corners. Each laser pulse, fired at the satellite, also starts the time interval digitizer. The satellite reflects the light pulse back to the optical receiver in the ground station, producing the stop signal for the digitizer. From the digitized start-stop interval, the exact position of the satellite is then calculated.

The ground station is then moved to another location and its position in relation to the satellite, measured. The distance between the original and the new ground station location is then calculated by triangulation. The procedure is obviously tedious and expensive.

A different approach has been proposed by NASA: if the laser, and the optical timing receiver were spaceborne, many reflecting targets could be placed at various points on the earth's surface underneath the orbital path. The proposed measurement of the relative movement of the continental tectonic plates along the San Andreas Fault in California is outlined in Fig. 1.

A total of 42 relatively inexpensive reflecting targets are to be placed on the area covering 400 x 200 km. The spaceborne laser ranging station will start firing at the first target at a 20° elevation, switching to the next one after 25 shots. All subsequent targets will be covered within 5 minutes. The orbit is completed after about 80 minutes, followed by a new burst of ranging pulses. The ranging continues in such bursts for a typical mission period of 10 days. A number of missions are planned, for a period of several years, with the objective of evaluating the technique of measuring the strain accumulation in the covered area. An array of reflectors spaced 25 km apart serve as a ground-truth area for the calibration of the ranging. Taking into account all sources of error, it is expected that the relative positions of the targets in the array will be recovered within ± 2 cm.

General Considerations

The Space Borne Event Timer described in this paper is the time interval measuring part of the optical receiver in the laser ranging system (Fig. 2). Also, the Event Timer serves as a central clock controlling the timing of the entire laser ranging system. In order to meet the project requirements, the following characteristics of the Event Timer were especially considered.

Range and Resolution

The Event Timer is started at the beginning of a mission and can run continually for 130 days, measuring time in 19.53 ps increments. The accuracy and stability of the readout is directly related to the characteristics of the externally supplied 50 MHz frequency standard. An accurate internal clock serves for the testing of the system and the ranging of shorter distances.

Also, the Event Timer provides several frequencies, all accurately phase related to the start of the mission, for the synchronization of various components of the ranging system.

Time Interval Measurement

An event is defined by a start and a stop pulse. The start pulse is picked off when the laser is fired, and the stop pulse is generated by the optical receiver when the light pulse is returned from the ground target.

The accepted start pulse causes a conversion process in the Event Timer. The result is the time difference between the start pulse and the original mission start pulse given in 19.53 ps increments. The Event Timer is then ready to accept the stop pulse, but only after a fixed dead time of 5.3 µs. During the dead-time the start data is transferred into a buffer register. The Event Timer then resumes the counting of the mission time as though no interruption took place.

The acceptance of the stop pulse causes a new conversion in the Event Timer. Again, the stop event is digitized with respect to the mission start and the data stored in a register. The difference between the stop data and the start data is equal to the measured time range. This calculation is to be performed by an external processor.

Digital Aperture

Each laser firing will occur at exactly determined

points in the orbital path. The approximate time range for any event is therefore known. This information can be stored into the Event Timer's range register by a remote control. When the laser is fired, the Event Timer is started counting the range time in 20 ns increments. During this counting the Event Timer cannot accept stop pulses, such as those generated by spurious reflections from the earth. The stop input will be automatically enabled for a period of time at the point when the range time reaches a previously defined time period. This "time aperture" can be changed in 20 ns increments by loading the Event Timer's enable register by a remote command prior to the laser firing. Maximum range time and aperture width are 330 ms and 1.3 ms respectively.

Clock

The absolute accuracy of the Event Timer is directly related to the 50 MHz reference frequency source. A built-in oscillator is sufficiently accurate for the testing of the Event Timer and ranging of shorter distances. For greater accuracy, either the clock's stability must be compared against the external frequency standard and the data corrected, or the entire Event Timer run on the externally supplied frequency standard. Provisions for both are made.

Frequency Divider

The operation of the laser ranging subsystems must be properly timed and synchronized with the Space Borne Event Timer throughout the mission. Upon the remote mission start command, the Event Timer starts generating a number of frequencies from 5 MHz to 1 Hz. All of them are derived from the Event Timer's 50 MHz reference and are accurately phase related to the mission start. Exact position of the space orbiting station can thus be determined for any given mission time and the necessary parameters can be set prior to each laser shot to the ground target.

Calibrator

The Laboratory testing of the Event Timer requires a very accurate time marker generator for a simulation of the typical ranging functions. A built-in calibrator unit provides precise, jitter-free marker pulses, that can be used either for the mission start or the start-stop ranging simulation. The Event Timer's 50 MHz reference can be used to drive the Calibrator to produce phase-locked marker pulse rates from 80 ns to 85.89 s. Control of the Calibrator with an external frequency source will provide a test source uncorrelated to the Event Timer, as it is the case under real ranging conditions.

Buffer Register

The Event Timer presents each digitized event as a 59-bit binary word. The conversion time is fixed to 5.3 μs. The Event Timer has a buffer register for the immediate storage of the digitized event. If the digitized event is the start of a measured interval, the stop then can be accepted as soon as 5.3 μs thereafter. In addition to the 59 time bits, one more bit is used to tag each stop event. The data is also front panel displayed for manual readout.

Remote Control

In operation, all functions of the Event Timer must be able to be completely controlled from the ground. The system should be CAMAC compatible and easily tested and evaluated in a standard CAMAC crate and interfaced via an appropriate crate controller.

Circuits

The main parts of the Event Timer system are shown in the general block diagram (Fig. 3). The circuits are distributed into three modules according to their functions.

1. Clock Module. This module contains a 50 MHz frequency reference that controls all other modules. Also, it includes the CAMAC controlled frequency divider for the external synchronization of the laser ranging subsystems, and the calibrator for the alignment and check-up of the Event Timer.

2. Tandem Interpolator. An analog module serves to increase the digitizing clock frequency to the equivalent of 50 GHz. The full power of 5.2 W when in operation can be reduced to 0.2 W upon the receipt of a CAMAC stand-by command, without affecting the mission time counting of the Event Timer. This is a substantial power saving since the ranging takes less than 10% of the orbiting time.

3. Logic Module. This module contains the counters, registers and arithmetic and control circuits. The control circuits recognize up to 34 CAMAC commands that make all the Event Timer's functions fully remote controlled.

Power Consumption

Full power, about 12 W, is required only during the ranging, which is only 7 percent of the mission time. Most of the time the Event Timer can be switched into the stand-by mode by a command (consuming about 7 W), without losing any vital charactertistics of the mission time clock.

Operating Principle of the Space Borne Event Timer

In order to digitize time intervals with incremental resolution of 20 ps by merely counting high frequency clock pulses, a counting technique in the 50 GHz range would be required. However, various interpolation techniques can be used where the equivalent of count frequencies of up to 100 Ghz have been obtained[5-10]. Interpolation techniques can reduce the real counting frequencies to well below 50 MHz, eliminating the need for power consuming high speed circuits. The penalty is that the processing time per each event is increased. In normal laser ranging, the rate of events is generally low, being limited by the laser pulse rate, and processing times of 50 to 100 μs are generally acceptable. Two identical interpolation circuits are needed, one for the start and the other for the stop event[2,7]. Since the interpolation circuits are basically analog-to-digital converters, the two interpolators must be identical and perfectly matched for thermal tracking in order to minimize the timing error.

The Event Timer described here uses a new interpolation technique that leads to a tenfold reduction of the processing time, yet offers the same incremental resolution as a 50 GHz clock[10]. At the 50 MHz reference frequency, the Event Timer takes less than 5.3 μs to digitize each event in 19.53 ns increments. The same interpolator circuits can be used in succession for both the start and the stop event. Therefore, 5.3 μs is the shortest time interval that can be digitized. That interval corresponds to a minimum one-way

target distance of less than 0.5 miles, making possible on-site ground ranging tests. The common interpolator allows for a single optical receiver to accomodate both the start and stop events, making the Event Timer System virtually self-tracking. Thermal drift also becomes negligible even for the largest time ranges.

The principle of dual interpolation is shown in Fig. 4. Mission Start and Event Start pulse (line B) define the time interval T_{ak} to be digitized. The points a and k at which the two events occur are uncorrelated with the Event Timer's clock pulses (line A). Upon the acceptance of the Mission Start pulse, the Event Busy signal (line C) is generated by the Interpolator. No other event can be accepted until the end of this signal.

Pulse T_1 (line F) is internally generated at the point b, which is coincident with the second clock pulse following the mission start. A second pulse, T_1, will be generated at point 1, coincident with the second clock pulse following the Event Start signal. Three intervals are thus defined, so that

$$T_{ak} = T_{ab} + T_{b1} - T_{k1} \qquad (1)$$

T_{b1} is synchronized with the clock and thus can be expressed as a multiple of clock period T_o. In order to reduce the conversion time, T_{ab} is first made shorter by a fixed delay $T_o/2$. The rest is then expanded K_c times in the "Coarse" Time Stretcher (line D) so that

$$T_{ab} - T_o/2 = (T_{be} - T_{cd})/K_c \qquad (2)$$

where K_c is a constant and T_{cd} is a residual time fraction between the end of the "Coarse" conversion and the second following clock pulse. T_{be} is thus in synchronization with the clock and can be expressed as a multiple of clock periods T_o. The excess fraction T_{cd}, decreased by $T_o/2$ is then expanded once again K_f times in the "Fine" Time Stretcher (line G).

$$T_{cd} - T_o/2 = T_{ef}/K_f \qquad (3)$$

By substituting (3) into (2) we obtain

$$T_{ab} = (1-1/K_c)T_o/2 + T_{be}/K_c - T_{ef}/K_cK_f \qquad (4)$$

Similar procedure is followed for the Event Start pulse:

$$T_{k1} = (1-1/K_c)T_o/2 + T_{1o}/K_c - T_{op}/K_cK_f \qquad (5)$$

and (1) becomes

$$T_{ak} = T_{b1} + (T_{be}-T_{1o})/K_c-(T_{ef}-T_{op})/K_cK_f \qquad (6)$$

It can easily be shown[10] that the minimum conversion time is required when $K_c = K_f = \sqrt{K}$, where the total time expansion factor K is the ratio of clock period T_o and the desired incremtnal resolution T_{oi}. In this case K = 1024 was selected, giving the optimum "coarse" and "fine" interpolation ratio of $K_c = K_f = 32$. The longest conversion time for either the "coarse" or "fine" stretcher takes about 48 clock pulses or 0.96 μs. Less than 2 μs is thus sufficient to complete the conversion of an event to obtain an incremental time resolution of $T_o/K=20/1024=19.53$ps.

Each event is thus defined only by the pulses T_1, T_2, and T_3 (lines F, K and H in Fig. 3) that are precisely correlated to the clock frequency. These pulses are digitized by the clock pulses in the Control Logic (See also Fig. 3), where the coincidence of T_1 and T_2 gives the "coarse" counter gate (line L) and the coincidence of T_2 and T_3 gives that for the "fine" counter (line M). N_{be} and N_{ef} clock pulses are thus counted in the "coarse" and "fine" counters, respectively (lines T and U). N_{be} and N_{ef} are constants that define the initial phase between the start of the mission and the clock frequency. They remain stored for the rest of the mission in the "Coarse" and "Fine" Registers for computing of (6) (Fig. 3).

Upon the laser firing, an Event Start pulse is generated (Fig. 4, line B) initiating the Event Start conversion. A new set of T_1, T_2 and T_3 defines another pair of "coarse" and "fine" counter gate pulses (line M and L). N_{1o} clock pulses are passed to the "Coarse" Counter and N_{op} clock pulses to the "Fine" Counter (lines T and U).

In the meantime, the main time interval T_{b1} (1) is also digitized. The first 256 clock pulses following an event are counted by the Auxiliary Counter (lines N and P). At the point g the counting was switched to the Mission Counter (lines R and S). N_{g1} counts were counted up to the point 1 where the mission counting was again turned to the Auxiliary Counter at the beginning of the event start conversion. The numerical equivalent of N_{bg} counts has been added to the Mission Counter before the point g is reached so that at 1 the total of mission counts is $N_{b1}=N_{bg}+N_{g1}$. The Mission Counter temporarily does not advance after the point b, acting as a register. It contains the number N_{b1}, which is temporarily presented to the Adder for the computing of (1) (Fig. 3). By dividing Eq. 6 with T_o we obtain

$$T_{ak}/T_o = N_{b1} + (N_{be}- N_{1o})/K-(N_{ef}-N_{op})/K^2 \qquad (7)$$

which can be transformed into

$$T_{ak}/T_o = N_{b1} + (\overline{N_{be}+N_{1o}})/K + (\overline{N}_{ef}+N_{op})/K^2-C \qquad (8)$$

$$C = 2 + 1/K-1/K^2$$

Where $\overline{N}_{be}$ and $\overline{N}_{ef}$ are the complements of binary numbers N_{be} and N_{ef} and C is a constant. Eq. 8 gives the normalized time difference between the Event Start and Mission Start. Only summing operations are needed to compute the right hand side of (8). In this manner most of the computing is done by simple counting. The same counters are thus used for the counting, arithmetic operations and data storage. Considerable saving in components and power requirements results.

At the point g (line V) the conversion of the event is completed, and the data transformed into the Buffer Register (Fig. 1). The mission time counting continues without any consequence of the interruption. The interpolator and the relevant circuits are then enabled for the acceptance of a new event. Any subsequent event is digitized in the same way. All are referred to the original Mission Start in 59-bit long binary words. The stop events are also tagged by an additional bit. The time difference between any two

recorded events has to be computed externally.

Test Results

Two almost identical Space-Borne Event Timers have been completed and tested. The results confirm the expectation of inherent thermal stability, resolution and linearity of time measurement. A built-in Calibrator proved to be a very useful tool for the evaluation of the Digitizer's performance as well as for a quick visual inspection and check-up of many functions, that would otherwise require lengthy computer programming.

When driven by the same internal clock reference, the Calibrator generates accurately separated time markers that are phase locked with the internal function of the Event Timer. Very small thermal and other drifts attributal to the time interpolation can thus be observed and measured. In Fig. 5 the calibrator was set to divide the 50 MHz clock frequency by 256, generating continuous marker pulses separated by 5.12 μs. The mission was started by one of the marker pulses, and each subsequent marker pulse is then accepted and digitized as a valid event. Each event is immediately sorted out into a 256-channel section of an external digital memory and the Event Timer cleared for another event. The Event Busy output monitors the event processing time of about 5.3 μs. In Fig. 5 the event pulses appear each 5.12 μs. Therefore, only every second pulse is accepted as a valid event.

Only the 8 least significant bits of each event are stored in the 256-channel memory. Although the events are actually separated by 10.24 μs, they overlap because the higher order bits are ignored. The resulting distribution is shown in Fig. 6. The symmetrical peak shows that the total phase jitter of all the recorded events in respect to the mission start is less than 0.1 channel (2 ps).

Measurements in Fig. 7 were made with externally supplied continuous calibrating marker pulses separated by 32.768 μs. They were uncorrelated with the Event Timer's internal clock. The Event Timer was initialized after every second event. Every second marker pulse made a new mission start, followed by one event exactly 32.768 μs apart. Both the mission start and the event were stored in a 2048 channel digital memory. The starts were evenly distributed over 1024 channels, which is equivalent to one 20 ns reference clock period. All events, however, were sorted into one single peak, because the time difference between each mission start, and the event that follows, is 32.768 μs.

The number of the events in the peak (Fig. 8) equals the sum of all the mission starts distributed over 1024 channels. The area shown is an expanded peak portion of the figure 7. The two adjacent channels next to the peak contain about a third of events each, indicating a total time jitter of about 10 ps.

Temperature change has negligible effect in time ranges of several seconds. Assuming that the Event Timer's 50 MHz reference clock is ideal, i.e. has zero frequency drift regardless of the temperature and aging, the timing error throughout the mission can then be attributed to the interpolator drift only. Such a condition is closely met when the Event Timer is tested by the Calibrator using the common internal clock reference. The Event Timer was set up under the same conditions used for obtaining Fig. 5. The mission was started and run continually for 22 days. Mission time and crate temperature were taken several times a day. The results are plotted in Fig. 9. A consistent thermal coefficient of about ± 10 ps/°C is measured as the room temperature was measured throughout the each day.

During the first half of the mission, a positive, aging like, drift of several channels occured. However, after about 20 mission days, the drift reversed to return eventually to the initial point. Since other parameters (line voltage, power regulator voltages, etc.) were not taken, the drift was not well understood. Since the total 22-day drift cycle amounted to about 120 ps, the subject was not further considered.

Acknowledgments

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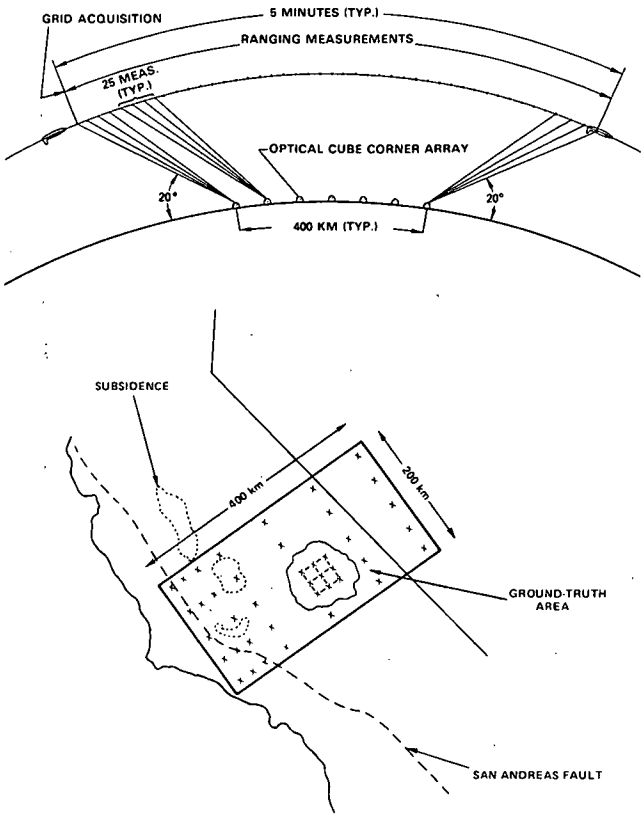

Fig. 1 Proposed measurement of the tectonic motion along the San Andreas Fault by a space-borne laser ranging system (courtesy of NASA).

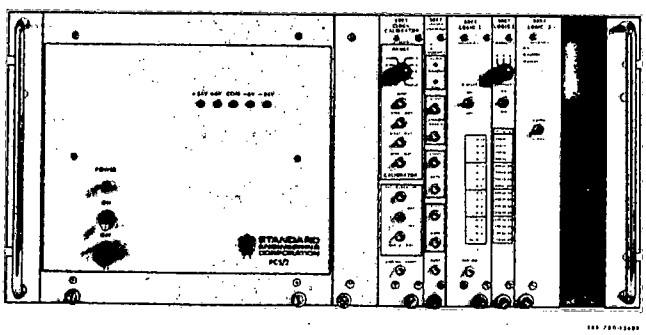

Fig. 2 Space Borne Event Timer, housed in a CAMAC minicrate for testing.

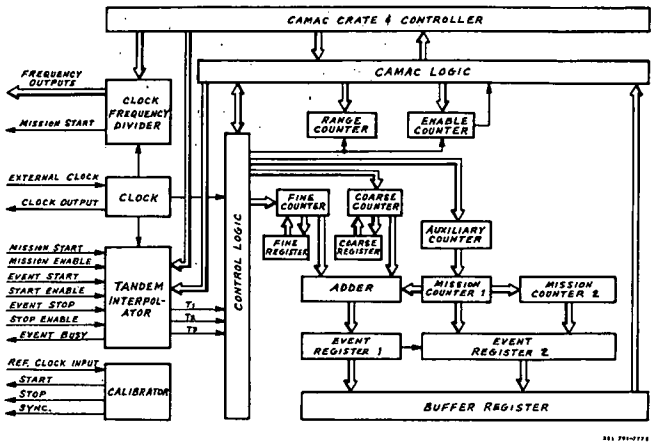

Fig. 3 General block diagram.

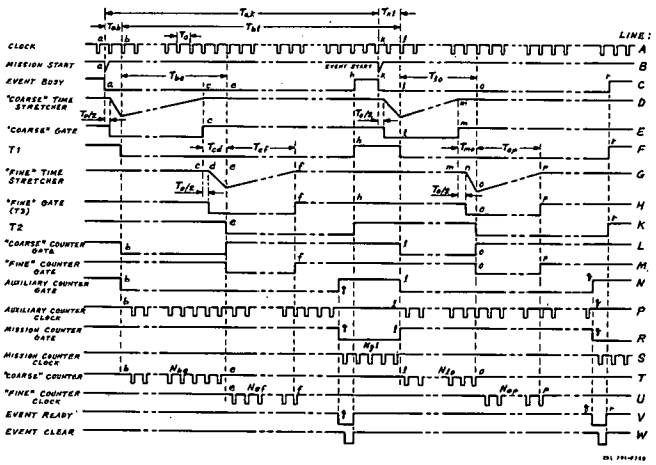

Fig. 4 Basic timing diagram of dual interpolation.

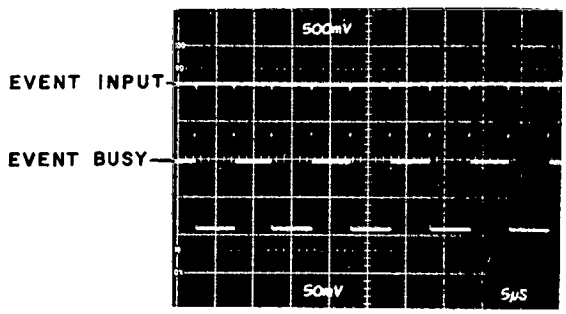

Fig. 5 Section of mission time showing a continuous event rate of 5.12 μs. Every second event is digitized because of 5.3 μs deadtime.

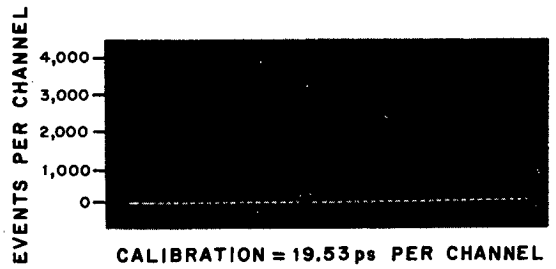

Fig. 6 Distribution of overlapped events from Fig. 5. Each event in the peak is actually 10.24 μs apart.

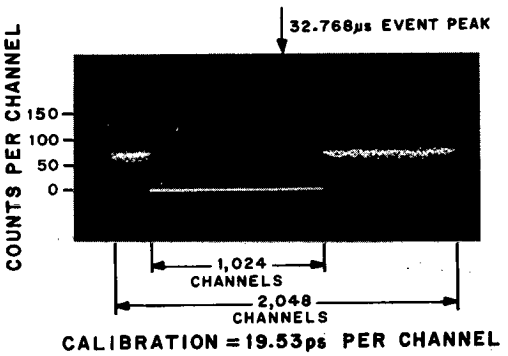

Fig. 7 Phase distribution of mission starts followed by stop events 32.768 μs apart.

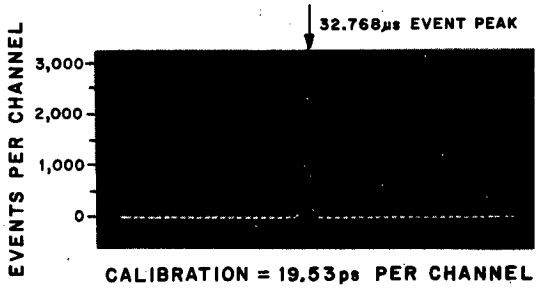

Fig. 8 Expanded peak area of Fig. 7 showing distribution of random 32.768 μs intervals.

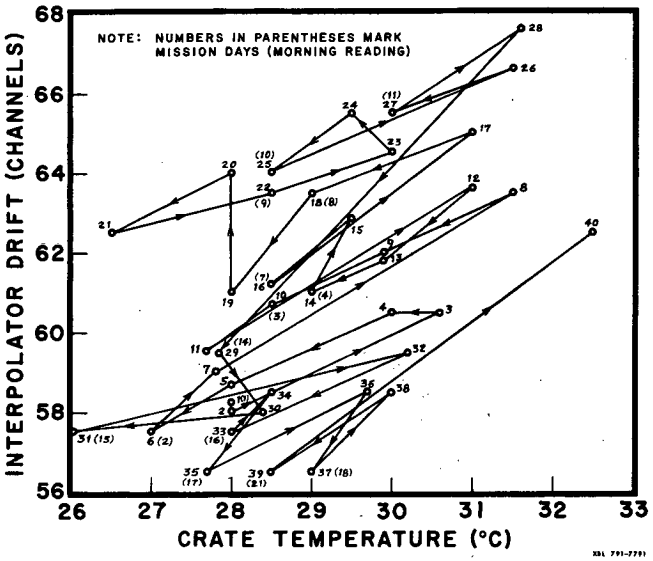

Fig. 9 Interpolator drift (referred to the mission start) vs ambient temperature for a mission time of 20 days.

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