PRECISION SATELLITE TIME DETERMINATION FOR APPLICATION TO GEOS-3 DATA

F. M. Boykin
NASA - Wallops Flight Center

R. E. Dwyer
Computer Sciences Corporation

ABSTRACT

The Geodynamics Experimental Ocean Satellite (GEOS-3) was launched on April 9, 1975, to perform experiments in the geosciences discipline (e.g., solid earth physics and oceanography). The primary experimental instrument, a dual mode radar altimeter, is being applied to oceanographic objectives which include mapping the topography of the ocean surface and determining the ability of the altimeter to measure wave height. Precise time correlation of the altimetric measurements to UTC (within an accuracy of ± 600 μsec) is required in the application of the data. A special timing system is employed which is independent of the timing data recorded on analog telemetry tapes at the NASA - Spacecraft Tracking and Data Network (STDN), and ultimately serves to identify the time of each altimeter transmitted pulse to the required accuracy. The timing system begins in the GEOS-3 spacecraft where both the altimeter pulse repetition frequency and the telemetry bit rate frequency are coherently derived from a clock divider driven by an ultra - stable 5 MHz oscillator. The telemetry format is programmed to uniquely identify each major and minor telemetry frame over an unambiguous period extending more than one year. Approximately once each day, a STDN station is scheduled to detect the time of arrival (relative to station time) of a selected bit in the telemetry frame synchronization patterns over the duration of the pass. Approximately 600 data points consisting of time and major and minor frame identifications are transmitted to the GEOS-3 control center located at Goddard Space Flight Center (GSFC) along with station pre- and post-pass delay measurements. At the control center the data is processed to account for spacecraft system delay, propagation delay, ground systems delay, and discrepancies between station time and UTC. Within a matter of minutes a report is generated providing UTC time (at the spacecraft) for uniquely identified major frames of telemetry. Indications as to the quality of the data are also provided. The timing reports

are transmitted to the Wallops Flight Center, where all GEOS-3 altimeter data is processed. Using the daily timing reports and interpolating between each report, a time base is established to allow precise time tagging of each GEOS-3 frame of data. Subsequently, as telemetry data arrive at Wallops on magnetic tape, the frames of data are simply identified and appropriately time tagged. The UTC time of each altimeter measurement telemetered within a given frame is then identified by applying known time relationships between telemetry frame time and the time of the altimeter transmitted pulse(s) from which the telemetered altimetric measurement was derived.

INTRODUCTION

GEOS-3 Mission:

The Geodynamics Experimental Ocean Satellite (GEOS-3) was launched on April 9, 1975, from the Western Test Range by a two-stage Delta Vehicle, thrust augmented with four first-stage solid propellant motors. A near perfect 844 km circular orbit was obtained with an inclination of 115 degrees and a period of 101.8 minutes. These orbit parameters were chosen to provide orbit traces that cover the earth's surface in a prescribed grid work pattern.

The GEOS-C Mission Objectives in order of priority are:

To perform an in-orbit satellite altimeter experiment to: (1) determine the feasibility and utility of a space-borne radar altimeter to map the topography of the ocean surface with an absolute accuracy of ±5 meters, and with a relative accuracy of 1 to 2 meters, (2) determine the feasibility of measuring the deflection of the vertical at sea, (3) determine the feasibility of measuring wave height, and (4) contribute to the technology leading to a future operational altimeter satellite system with a 10-centimeter measurement capability.

To further support the calibration of NASA and other agencies' ground C-band radar systems by providing a space-borne coherent C-band transponder system, to assist in locating these stations in the unified earth-centered reference system, and to provide tracking coverage in support of the radar-altimeter experiment.

To perform a satellite-to-satellite experiment with the ATS-6 satellite using an S-band transponder subsystem to directly measure the short period accelerations imparted to the spacecraft by the gravity field and to determine the position of the spacecraft. The satellite-to-satellite system is also used for altimeter telemetry data relay through ATS-6.

To further support the intercomparison of new and established geodetic and geophysical measuring systems including: the radar altimeter, satellite-to-satellite, C-band, S-band, Laser, and Doppler tracking.

To investigate solid-earth dynamic phenomena such as polar motion, fault motion, earth rotation, earth tides, and continental drift theory with precision satellite tracking systems.

To further refine orbit-determination techniques, the determination of interdatum ties, and gravity models.

To support the calibration of S-band sites in the STDN to assist in positioning the network stations in the world reference system, and to assist in evaluating the system as a tool for geodesy and precise orbit determination.

GEOS-3 Spacecraft

The GEOS-3 Spacecraft, shown in Figure 1, was designed and fabricated by the Johns Hopkins University/Applied Physics Laboratory. The structure consists of a rigid box in the form of an octahedron topped by a truncated pyramid. The octahedron measures 1.37 meters across the flats. A 6.46 meter rigid boom supporting a 46.2 Kg end mass provides gravity gradient stabilization for the spacecraft. Total spacecraft weight is 345.9 Kg. The system block diagram is shown in Figure 2.

The experiment package consists of five basic instruments as follows:

1. Radar Altimeter

2. C-band Transponders

3. S-band Transponder

4. Laser Retroreflector

5. Doppler Transmitters

The basic objectives of the radar altimeter experiment are to demonstrate the feasibility of utilizing an on-board altimeter to measure the time varying behavior of the ocean's surface and the departure of the sea-surface from the geoid, as well as to investigate altimeter instrumentation technology. The basic measurement goals established for the altimeter are:

Precision: Short pulse mode 30 centimeters
Long pulse mode 60 centimeters

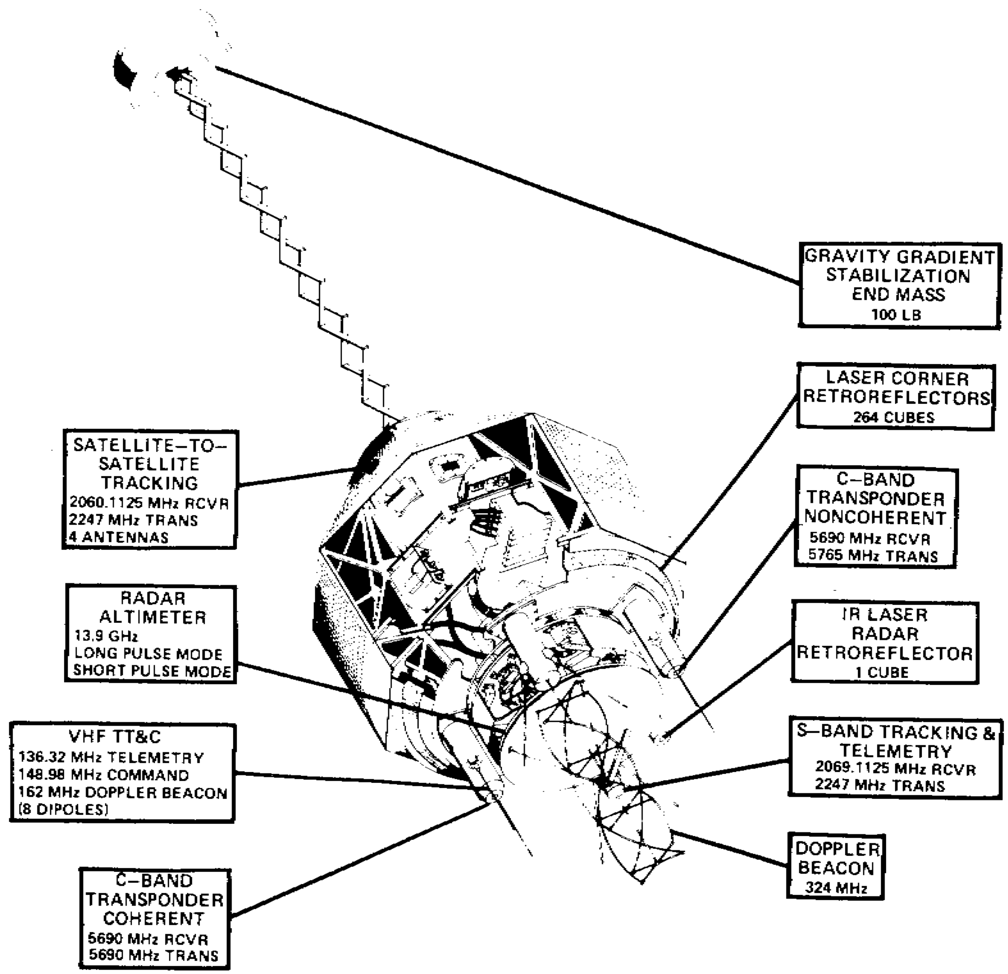


Figure 1 GEOS-3 Spacecraft Cutaway

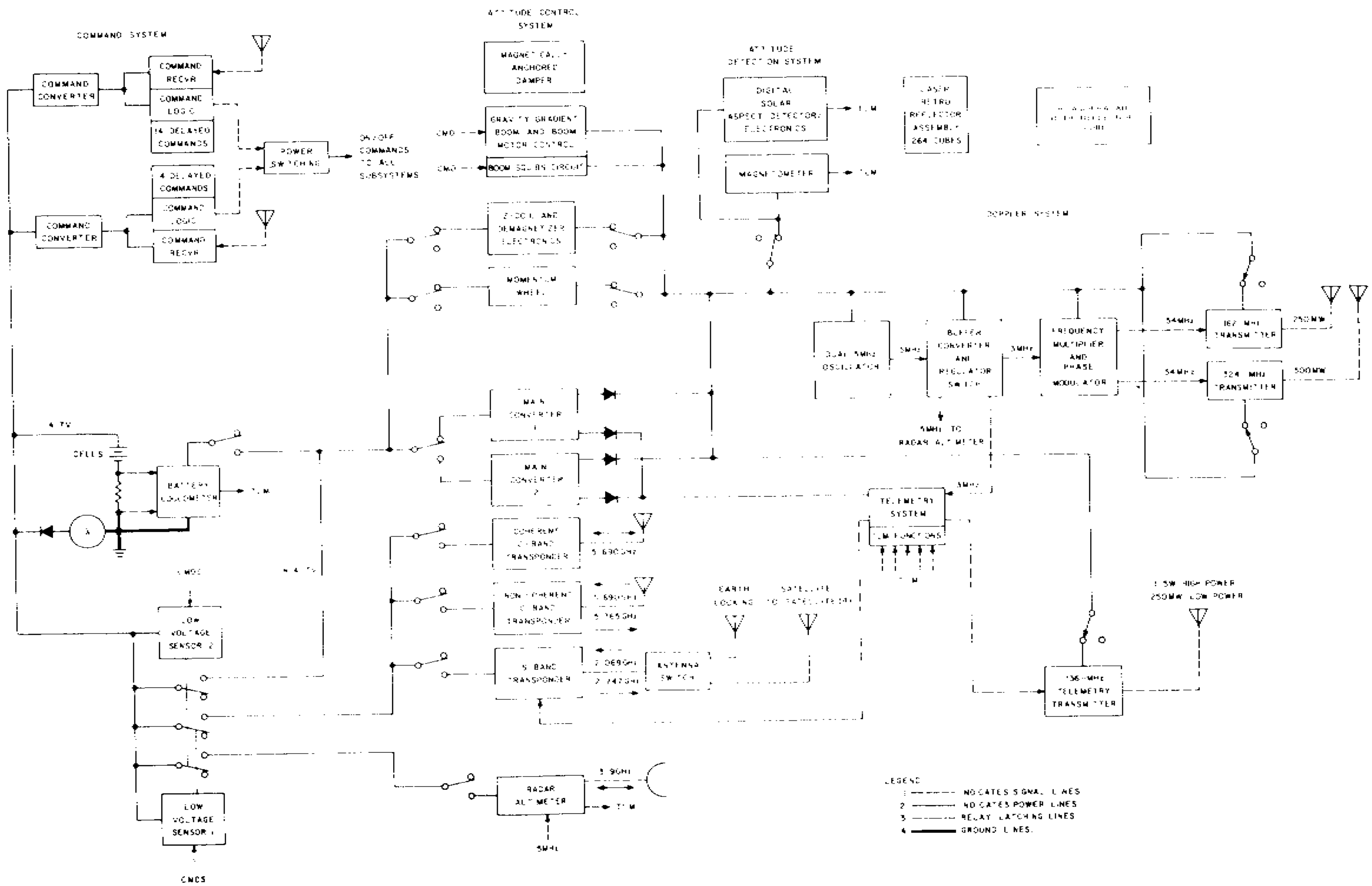


Figure 2 - GEOS-3 Spacecraft Systems Block Diagram

Geoid Recovery Accuracy: Absolute ± 5 Meters
Relative ± 2 Meters

Sea State Determination Accuracy: 25% of Significant Wave Height

Two C-band radar transponders are incorporated to support the altimeter and C-band system calibration as well as geometric, gravimetric, and other geodetic investigations. The C-band system consists of the two transponders (one coherent and one noncoherent) and the associated ground tracking C-band radars. The noncoherent transponder, operating in conjunction with existing ground radar systems, provides range and angle measurements. The coherent transponder, operating in conjunction with existing coherent ground radar systems, provides range, range rate, and angle measurements.

The laser retroreflector array consists of 264 quartz cube corner reflectors mounted on a 45° conic frustum. The retroreflector is utilized in conjunction with ground-based laser systems to obtain precise satellite ranging data.

The Doppler System consists of two space-borne transmitters and ground base doppler receiving stations. The dual frequencies (162 and 324 MHz) are coherently related and derived from the 5-MHz spacecraft oscillator, which also provides the basis for the altimeter Pulse Repetition Frequency (PRF), telemetry rates and spacecraft timing. The difference frequencies between the higher and lower received frequencies and the station oscillator are combined in the proper proportions to obtain both the first-order ionospheric refraction correction and the refraction corrected doppler frequency.

The S-band system consists of a single coherent S-band transponder and an antenna network capable of two-way communications direct to the STDN ground stations or to the ATS-6 ground stations through the geosynchronous ATS-6 satellite. In either mode of operation coherent range-rate, ranging, and GEOS-3 telemetry data can be provided.

GEOS-3 Mission Timing Requirements

The GEOS-3 Mission Timing Requirements are segmented into two categories: (1) tracking station requirements associated with the various tracking instrument types, and (2) spacecraft timing requirement associated with time tagging the data of the space-borne tracking instrument, the radar altimeter.

Tracking station time requirements are satisfied by conventional techniques and are not the topic for discussion in this paper. The tracking station timing goals are listed below:

Instrument Type	Timing Accuracy Goal
Laser	± 8 μsec
S-band:	
Direct-to-Ground	± 25 μsec
Through ATS-6	± 11 μsec
Coherent C-band	± 10 μsec
Non-Coherent C-band	± 50 μsec
Doppler	+ 100 μsec

Relative to satellite altimetry, the purpose of the ground tracking systems is to provide data for precise orbit determination in position and time. With the orbit established, the radar altimeter data must be time tagged commensurate with its ranging precision. The requirement is to time tag the range data to an accuracy of ±600 μsec. With a maximum radial range rate of 100 meters per second due to the combined effects of orbit eccentricity and geoid undulation, a 600 μsec timing error would produce a range error of six centimeters. The altimeter precision is estimated to be 50 centimeters at a measurement rate of 10 samples/second. A one-second average yields a precision of about 20 centimeters.

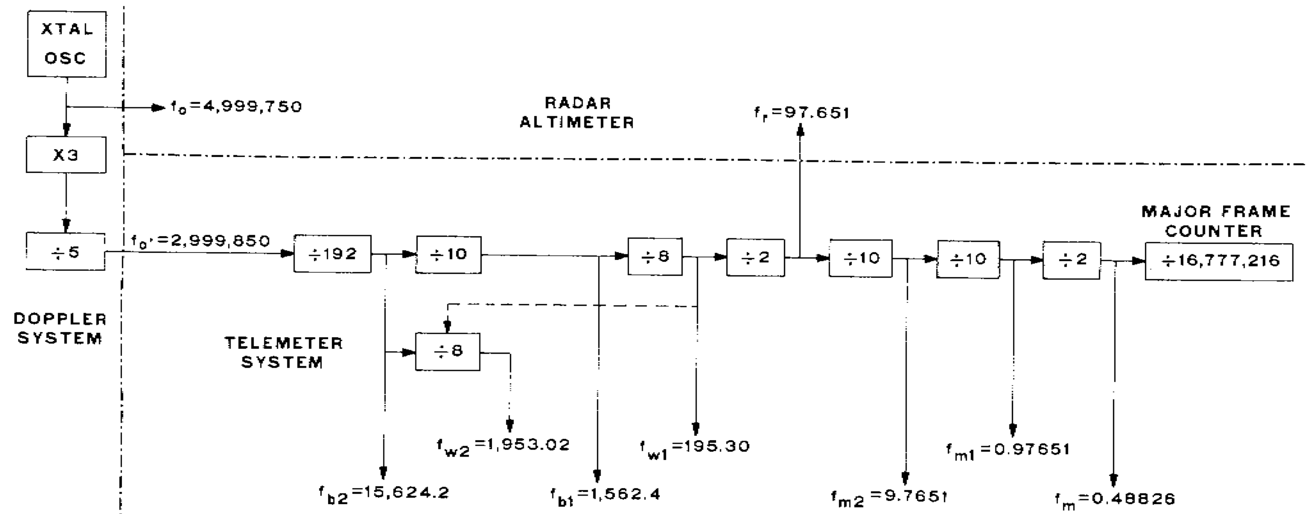
Since the altimeter is a spacecraft-borne radar with all of the associated tracking functions performed in-orbit, a means was sought to satisfy the time tagging requirement. This necessitates determining spacecraft time, and, specifically, determining the time of the radar altimeter transmitted pulse(s) that is incorporated in any given range measurement.

The system implemented to perform this task is discussed relative to the three main portions of the system. They are the satellite system, the ground station time detection system, and the data processing system. Sample results are also included.

SPACECRAFT SYSTEM

In the spacecraft, both the altimeter PRF and the telemetry bit-rate frequencies are derived from a stable crystal oscillator operating nominally at 4999,750 Hz. The timing network is given in Figure 3 and supplies the clock for (1) two telemetry bit rates detailed in Table 1, (2) the altimeter PRF, and (3) a major frame counter referred to as the Time Code Generator (TCG). The altimeter transmitted pulse time relationships are very similar for either telemetry bit rate. Therefore,

TIMING NETWORK FOR DUAL RATE TELEMETER SYSTEM



NOTES: f_b DENOTES BIT RATE
f_m DENOTES MINOR FRAM RATE
f_M DENOTES MAJOR FRAME RATE
f_o DENOTES ALTIMETER REFERENCE FREQUENCY
$f_{o'}$ DENOTES TELEMETER REFERENCE FREQUENCY
f_r DENOTES ALTIMETER REPETITION RATE
f_w DENOTES WORD RATE

ALL RATES AND FREQUENCIES IN Hz.
SECONDARY SUBSCRIPTS 1 AND 2 DENOTE LOW AND HIGH DATA RATES, RESPECTIVELY.

Figure 3

TELEMETRY PARAMETERS

• FREQUENCY	• 136.32 MHz
• TYPE	• PCM-SPLIT PHASE/PM
• INDEX	• ONE RADIAN
• BIT RATES	• 1562 Hz AND 15624 Hz
• POWER (MIN.)	• .25 WATTS AND 1.5 WATTS

FORMATS

	LOW RATE	HIGH RATE
WORD (BITS)	8	8
MINOR FRAME LENGTH (WORDS)	100	100
MAJOR FRAME LENGTH		
• MINOR FRAMES	4	64
• PERIOD (SECONDS)	2.05	3.28

Table 1

for clarity sake only the low bit rate telemetry mode (i.e., 1562 bps) is discussed in this paper.

Table 2 is a sample of a GEOS-3 minor telemetry frame in the low bit rate. As noted in Table 1, four of these minor frames constitute a major frame with each major frame identified by a specific TCG count. The TCG increments in a binary count on every major frame up to a maximum of 2^{24} and then turns over to zero and begins counting again. The four minor frames within a major frame are identified by the FFID which increments in a 2 bit field from 00 binary to 11 binary. Therefore, with the combination of TCG and FFID (See Table 2) each minor frame is unambigiously identified throughout more than one year.

The radar altimeter transmitted pulses have a known relationship to the telemetry frame. As shown in Figure 4, a transmit clock occurs one word time (5120.2 μsec) + 224 μsec = 5344.2 μsec before the beginning of the frame. The actual altimeter transmit pulse is generated 25.6 μsec after the clock (a value derived through tests). Therefore, the altimeter pulse precedes the frame start time by 5318.6 μsec. This pulse is the last included in the referenced altitude accumulation (See Figure 4) with the altitude result subsequently read-out into the telemetry stream in words 11, 13, 15, and 17 (See Table 2). The altimeter transmitted pulse time for subsequent altitude results are derived in a similar manner and are all referenced in the beginning of a telemetry frame.

The actual telemetry frame start time used as a reference in the foregoing is delayed by a constant during the process of developing the split-phase Pulse Code Modulation (PCM) waveform. Figure 5 shows this relationship. The spacecraft delay of 336 μsec is accounted for in the time correlation data processing to be discussed later in this paper.

To summarize the spacecraft system, the following has been established:

1. The time relationship of the telemetry frame and the altimeter transmitted pulses.

2. The unambigious identification of any telemetry minor frame for more than a one-year period.

3. A spacecraft delay constant to be applied in time correlation data processing.

GROUND STATION TIME DETECTION SYSTEM

Selected STDN stations detect the time of arrival of the leading edge of the first bit in the telemetry synchronization pattern with respect

MODE 1 TELEMETRY FORMAT

Word	Function	Word	Function	Word	Function	Word	Function	Word	Function
0	$SYNC_a$	20	NCSS	40	ASC0 (4 + B)	60	ASC0 (8 + B)	80	ASC0 (12 + B)
1	$SYNC_b$	21	FFID	**41**	**TCG_a**	**61**	**TCG_b**	**81**	**TCG_c**
2	$SYNC_c$	22	NCRR	42	ASC1 (4 + B)	62	ASC1 (8 + B)	82	ASC1 (12 + B)
3	**FFID**	23	CP	43	$DSAD_a$	63	$DSAD_b$	83	Spare
4	RTP	24	ASC0 (1 + B)	44	ASC0 (5 + B)	64	ASC0 (9 + B)	84	ASC0 (13 + B)
5	AS	25	AS	45	AS	65	AS	85	AS
6	ANG	26	ASC1 (1 + B)	46	ASC1 (5 + B)	66	ASC1 (9 + B)	86	ASC1 (13 + B)
7	Spare	27	DSC (A)	47	DSC (1 + A)	67	DSC (2 + A)	87	DSC (3 + A)
8	ARG	28	ASC0 (2 + B)	48	ASC0 (6 + B)	68	ASC0 (10 + B)	88	ASC0 (14 + B)
9	IPG	29	IPG	49	IPG	69	IPG	89	IPG
10	APG	30	ASC1 (2 + B)	50	ASC1 (6 + B)	70	ASC1 (10 + B)	90	ASC1 (14 + B)
11	**$CALT_d$**	31	$CALT_d$	51	$CALT_d$	71	$CALT_d$	91	$CALT_d$
12	AASG	32	ASC0 (3 + B)	52	ASC0 (7 + B)	72	ASC0 (11 + B)	92	ASC0 (15 + B)
13	**$CALT_c$**	33	$CALT_c$	53	$CALT_c$	73	$CALT_c$	93	$CALT_c$
14	CCSS	34	ASC1 (3 + B)	54	ASC1 (7 + B)	74	ASC1 (11 + B)	94	ASC1 (15 + B)
15	**$CALT_b$**	35	$CALT_b$	55	$CALT_b$	75	$CALT_b$	95	$CALT_d$
16	CCRR	36	ASC2 (A)	56	ASC2 (1 + A)	76	ASC2 (2 + A)	96	ASC2 (3 + A)
17	**$CALT_a$**	37	$CALT_a$	57	$CALT_a$	77	$CALT_a$	97	$CALT_a$
18	RAGC	38	RAGC	58	RAGC	78	RAGC	98	RAGC
19	RSE	39	RSE	59	RSE	79	RSE	99	RSE

Table 2

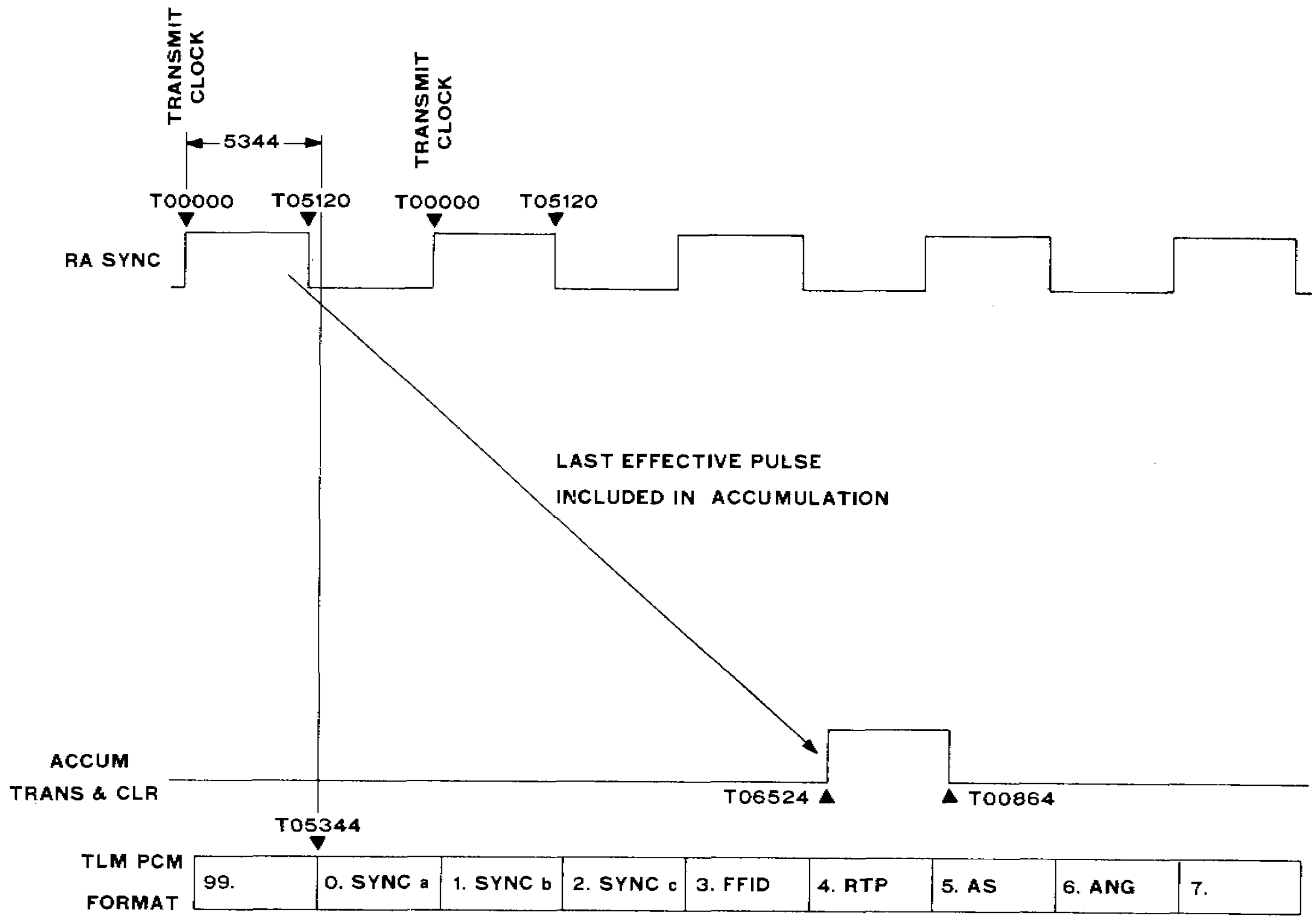


Figure 4 - GEOS-3 Timing Diagram

PCM WAVEFORMS

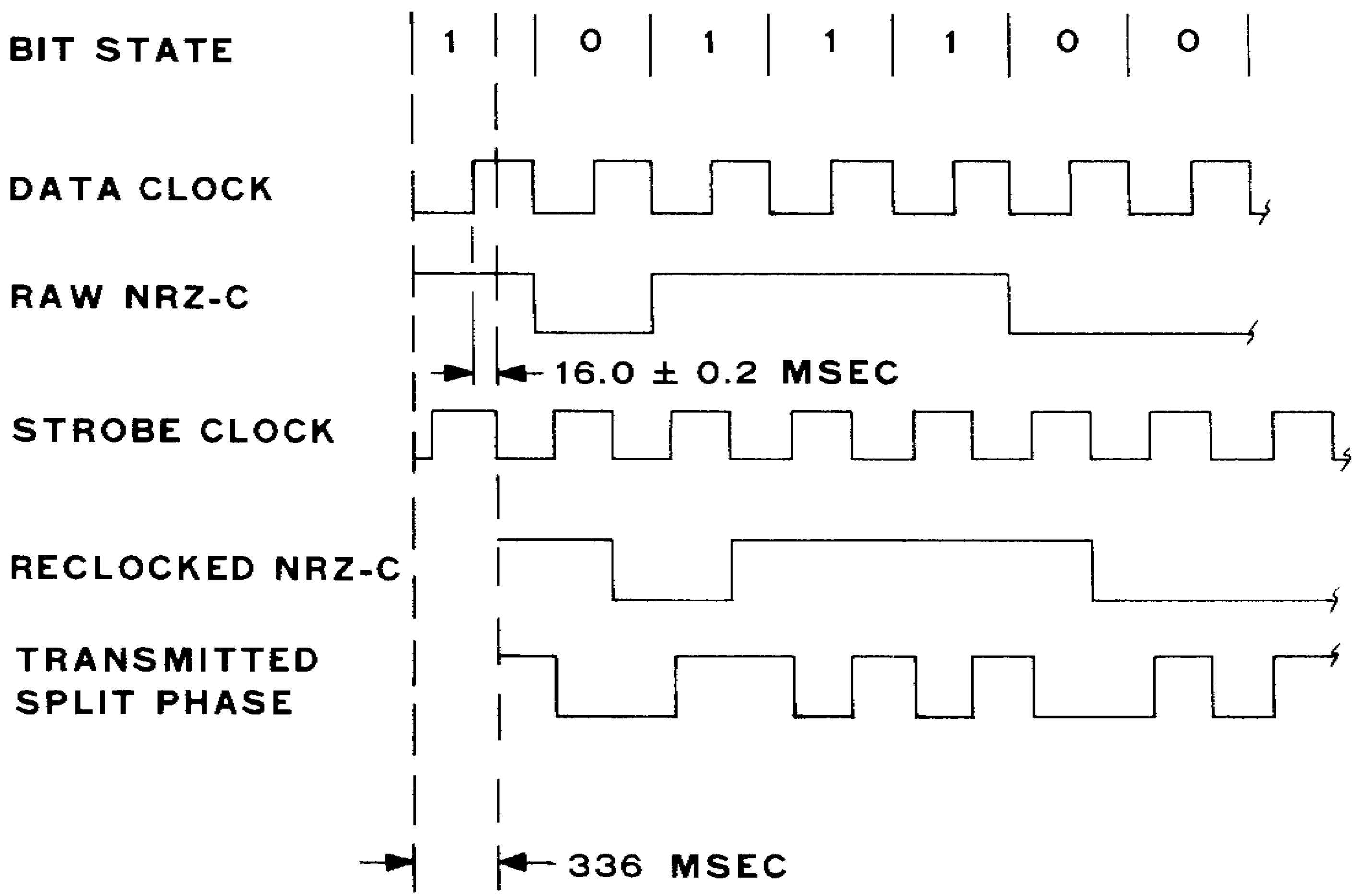


Figure 5

to station time. This is performed at a rate of once every other frame with GEOS-3 in its low data rate. A nominal ten-minute pass yields about 600 data points. Each data point contains the following information:

(1) Station hour, minute, second (major time) of the detected frame.

(2) Microsecond (minor time) of the detected frame.

(3) TCG and FFID of the detected frame.

The station equipment used is a PCM decommutation system known as the Manned Space Flight Telemetry Processor (MSFTP-3). In addition to the data points described above, pre- and post-pass delay constants are measured by generating test patterns and timing their delay through the system as shown in Figure 6. This reported ground system delay is also accounted for in time correlation data processing.

During the satellite pass at the station, the data points are stored for post-pass formatting and transmission to the GEOS-3 control center. The data are formatted as shown in Figure 7 with each 1200 bit block containing 12 data points. A maximum of 50 blocks can be stored (i.e., 600 data points) requiring slightly more than eight seconds for transmission to the control center.

DATA PROCESSING SYSTEM

For each time correlation pass, a maximum of 600 data points are transmitted to the GEOS-3 control center located at Goddard Space Flight Center. These data points are read into the control center SDS-930 computer for processing.

Initially, the data points are grouped in sets of sixteen (16) as shown in the input data set of Figure 8. This provides a set of data at a rate of approximately one data point per second over a period of approximately 16 seconds. This provides the basis for data averaging and makes it consistent with a common major frame start time in both the spacecraft low and high data rates. Each of the sixteen points is then adjusted by subtracting multiples of the nominal minor frame rate to translate each data point to the common major frame boundary.

The input data represents the time of arrival of GEOS-3 telemetry frames at the receiving station. To establish actual frame start time in the spacecraft, four correction factors are applied to each data point:

(1) Station Time Versus UTC Correction - This is a constant derived from knowledge of the difference between station clock and UTC time

TIME DELAY TEST CONFIGURATION

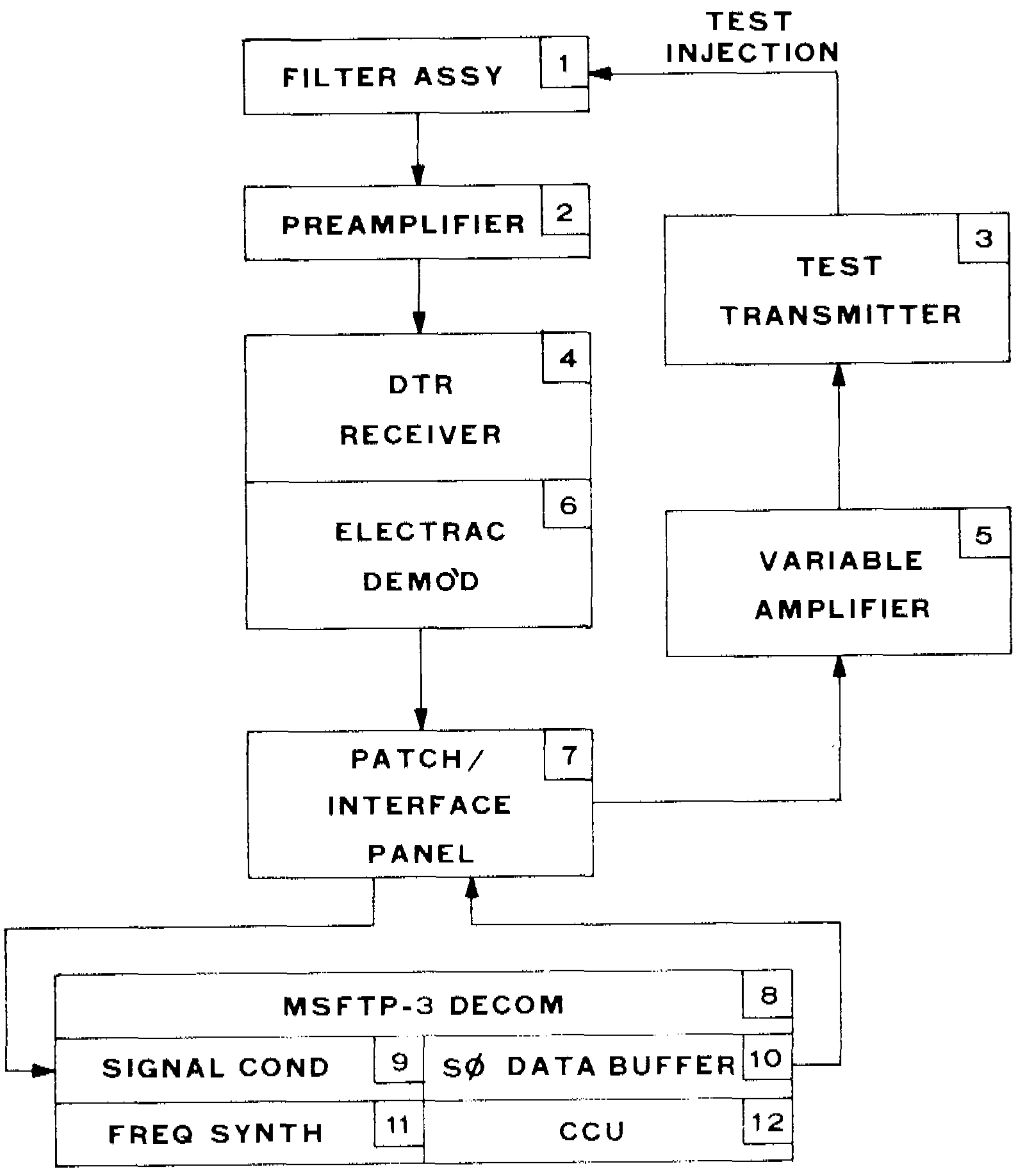
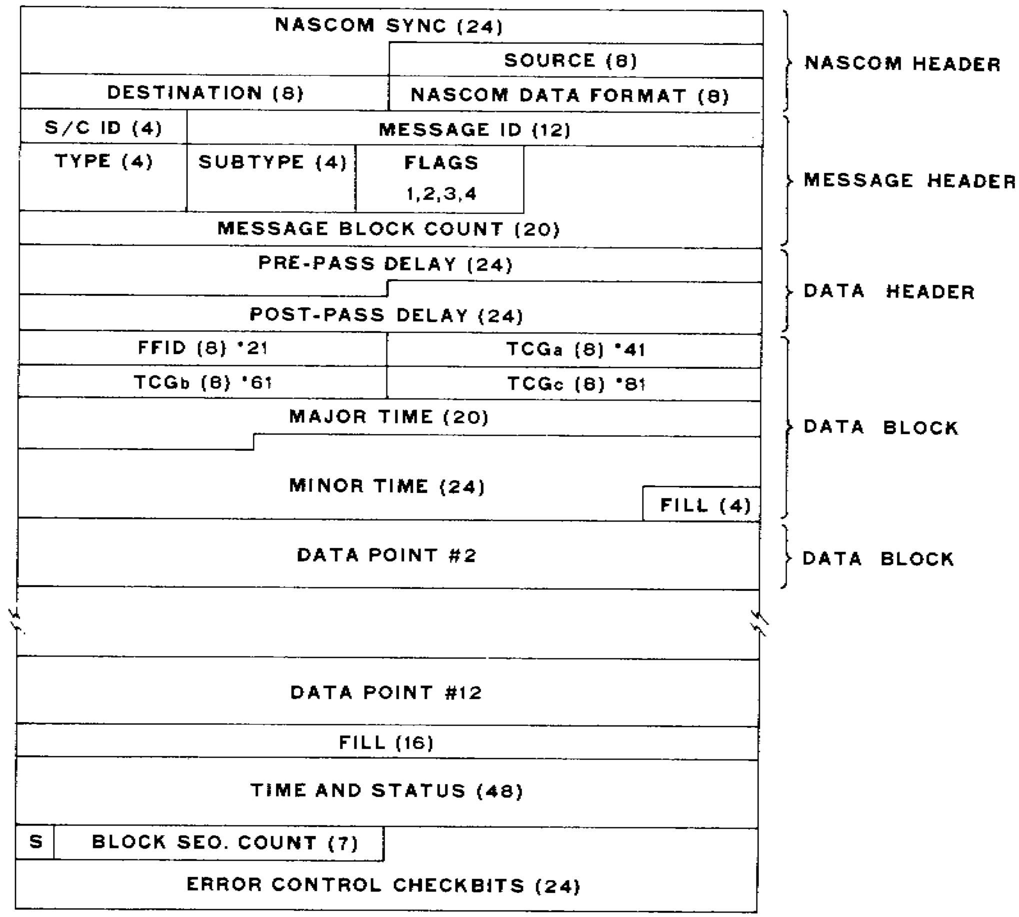


Figure 6

COMMUNICATIONS BLOCK



TOTAL STORAGE = 50 BLOCKS/3750 WORDS

BLOCK SIZE 75 - 16 BIT WORDS = 1200 BITS

Figure 7

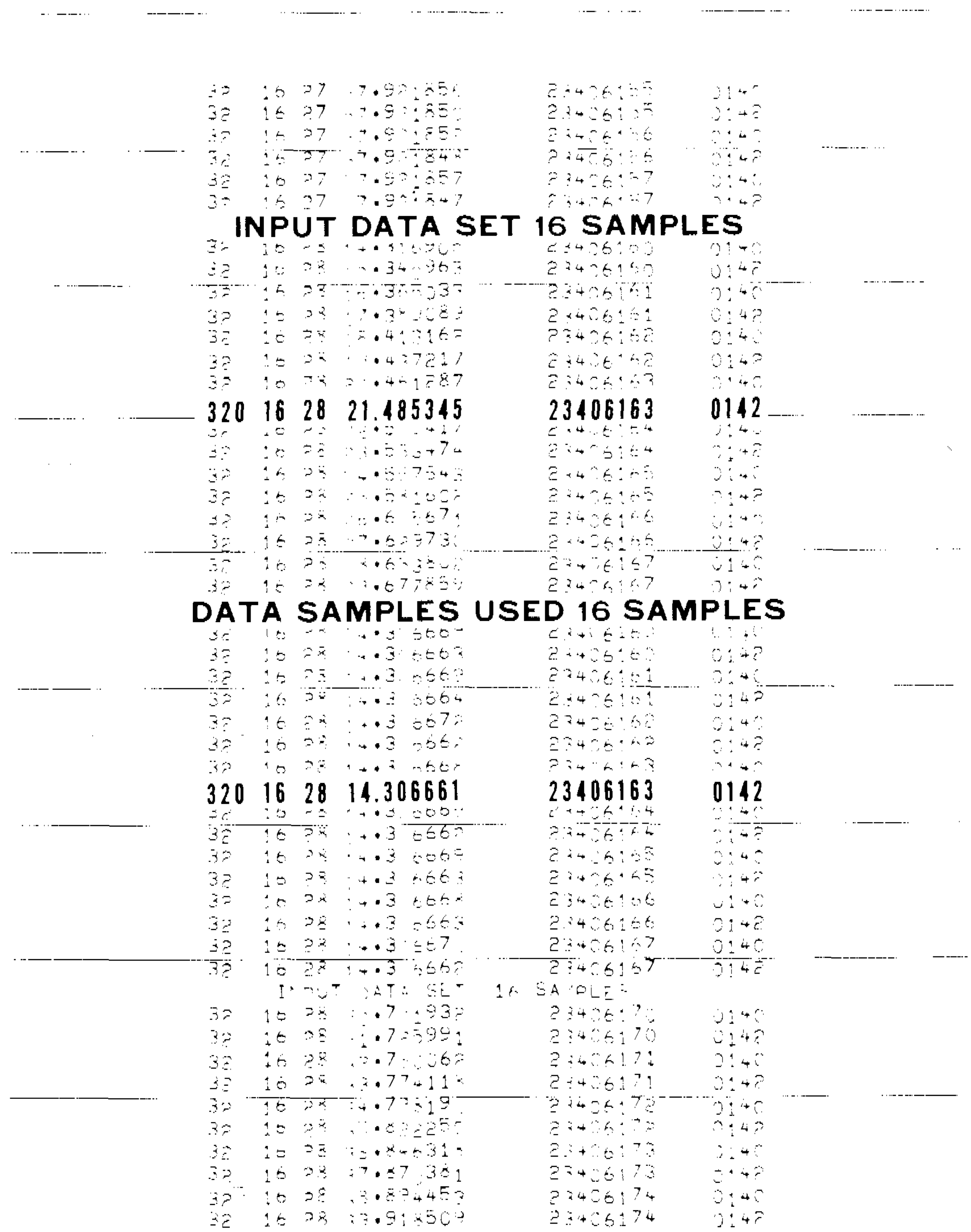

INPUT DATA SET 16 SAMPLES
320 16 28 21.485345 23406163 0142
DATA SAMPLES USED 16 SAMPLES
320 16 28 14.306661 23406163 0142

Figure [illegible]

and is applied to each data point with the proper sign to correct station time to UTC time.

(2) Ground System Delay - This is a constant for the pass being processed which is derived as the average of the reported pre- and post-pass delay calibration. This constant is subtracted from each data point. If the pre-to-post-pass delay varies more than 25 microseconds, the data is flagged.

(3) Propagation Delay - This is a variable which is derived from station to spacecraft predicted slant ranges. The predicted range is calculated at the time of each input data point and a corresponding propagation delay is subtracted from the data point.

(4) Spacecraft System Delay - This is the constant delay discussed in the spacecraft system portion of this paper and is subtracted from each data point.

The resultant data set is shown with the corrections applied in the "Data Samples Used" portion of Figure 8. All times as reported by the station are corrected to spacecraft time and the sixteen points are translated to the beginning of the common major frame. The eight octal bit TCG field and four octal bit FFID field is also displayed.

A report is then formatted as shown in Figure 9. The mean time of each data set is calculated and reported with the corresponding TCG number. Quality indicators detailing the number of samples in each data set, the number of samples used, and the standard deviation of the used samples are also reported.

The timing correlation data print is also outputted on paper tape and transmitted via teletype to Wallops Flight Center. At Wallops, the time reports are used in the altimeter data processor to establish the spacecraft telemetry frame time base from which all altimeter data time tagging is derived.

One time correlation report per day provides sufficient data to model the spacecraft oscillator drift. Linear interpolation between these daily data points provides frame time for any of the frames of interest occurring between the daily reports.

TIMING CORRELATION DATA PRINT

MEAN UTC TIME				TCG NUMBER	NUMBER OF SAMPLES	SAMPLES USED	STANDARD DEVIATION
DDD	HH	MM	SS.SSSSSS				
32	16	18	40.838371	5114712	14	14	000005
32	16	18	57.222870	5114720	16	16	000004
32	16	19	13.607574	5114728	16	16	000006
32	16	19	29.992407	5114736	16	16	000005
32	16	19	46.377218	5114744	16	16	000005
32	16	20	2.762036	5114752	16	16	000009
32	16	20	19.146855	5114760	16	16	000015
32	16	20	35.531674	5114768	16	16	000004
32	16	20	51.916501	5114776	16	16	000008
32	16	21	8.301314	5114784	16	16	000004
32	16	21	24.686127	5114792	16	16	000008
32	16	21	41.070957	5114800	16	16	000005
32	16	21	57.455770	5114808	16	16	000007
32	16	22	13.840585	5114816	16	16	000008
32	16	22	30.225404	5114824	16	16	000004
32	16	22	46.610223	5114832	16	16	000004
32	16	23	2.995047	5114840	16	16	000007
32	16	23	19.379851	5114848	16	16	000005
32	16	23	35.764676	5114856	16	16	000010
32	16	23	52.149510	5114864	16	16	000005
32	16	24	8.534306	5114872	16	16	000008
32	16	24	24.919125	5114880	16	16	000015
32	16	24	41.303959	5114888	16	16	000008
32	16	24	57.688786	5114896	16	16	000009
32	16	25	14.073585	5114904	16	16	000006
32	16	25	30.458402	5114912	16	16	000006
32	16	25	46.843256	5114920	16	16	000015
32	16	26	3.228066	5114928	16	16	000010
32	16	26	19.612867	5114936	16	16	000004
32	16	26	35.997704	5114944	16	16	000011
32	16	26	52.382562	5114952	16	16	000010
32	16	27	8.767361	5114960	16	16	000009
32	16	27	25.152174	5114968	16	16	000005
32	16	27	41.537022	5114976	16	16	000013
32	16	27	57.921858	5114984	16	16	000008
320	**16**	**28**	**14.306665**	**5114992**	**16**	**16**	**000004**
32	16	28	30.691495	5115000	16	16	000005
32	16	28	47.076323	5115008	16	16	000008

Figure 9

QUESTION AND ANSWER PERIOD

MR. RUEGER:

You have just heard one of the results of a very complicated satellite that is spewing out data by the carloads, working for seven months in orbit.

They are keeping track of every pulse of the radar in its time relationship to 600 microseconds, and cataloguing this data.

MR. DWYER:

I failed to mention that the requirement is 600 microseconds, but we feel the system is doing much better than that. It is a quantum jump from trying to correlate time on tape to data on tape. It is a quantum jump once you go to a system like this. You go down much better than the 600 microseconds. We evaluated about 50 microseconds.