W. W. Hansen Experimental Physics Laboratory

STANFORD UNIVERSITY

STANFORD, CALIFORNIA 94305 - 4085

Gravity Probe B Relativity Mission

S0307 Rev. B

GRAVITY PROBE B TIMING SYSTEM

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Date

George "Mac" Keiser
Chief Scientist

04/02/2004

Date

Jie Li
Research Scientist

04/02/04

Date

Paul Shestople
Research Scientist

4/5/04

Date

Sei Chun
Systems Engineer

4.5.04

Date

Tom Langenstein
ITAR Assessment Performed

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Revision Status

The description and analysis of the Gravity Probe B Timing System in this document Revision A have been changed completely compared to the same document Revision -, mostly based on the results of the GP-B Timing Tests Part A and Part B.

The following changes have been made in this document Revision B:

(1) S0876, S0916 and S0922 are added in the reference documents on page 3;

(2) The 0.1 second difference between the vehicle time of CCCA and the timestamp given by Aft SRE timing monitors is explained in detail on pages 24 and 25 ;

(3) Dependence of sampling time of ECU monitors on the ECU sample tables is discussed on page 40.

Abstract

In this document the timing system of the Gravity Probe B spacecraft is analyzed and algorithms are derived to determine the effective collection time of GP-B science data.

Reference Documents

[1] "GSS Timing", GPB-S0876, Rev.A, October 2003.
[2] "GPB Timing System, MSS/Payload Science Data Tenth Second Difference", GPB-S0916, Rev.A, April 2, 2004.
[3] "ECU Sample Tables", GPB-S0922, Rev.-, September 1, 2003.

Contents

1. Introduction

In this document the timing system of the Gravity Probe B spacecraft is analyzed and algorithms are derived to determine the effective collection time of GP-B science data.

GP-B's primary clock is located and derived within the Aft SQUID Readout Electronics (Aft SRE). A crystal oscillator produces the 16.368000 MHz (+/- 100 Hz) master frequency, and is called the 16 f-naught (f_0) clock. There are two Aft SRE units, only the active Aft SRE provides the $16f_0$ primary clock. An internal back-up clock resides within the Payload Processor (PP), which is a micro-processor board contained in the Aft SRE. Field Programmable Gate Array (FPGA) circuitry selects the master clock frequency, the $16f_0$ clock, and provides a clock signal to all spacecraft and payload components. (Fig.1-1)

The $16f_0$ clock flows to three basic paths. One path delivers the $16f_0$ signal directly to the Experiment Control Unit (ECU) and Gyro Suspension System (GSS). The second path is divided down to the 10 Hz strobe, which is supplied as a timing reference to the payload and spacecraft components, as well as providing a 10 Hz time stamp for data synchronization. The third path continuously counts the $16f_0$ clock signal in a 31-bit counter which rolls over every 131.2 seconds.

The Global Positioning System (GPS) receiver provides a known timing source to aid ground processing, in such a way, that the time at which each payload signal was sampled can be determined relative to the GPS time. The GPS Pulse-Per-Second (PPS) signal and the associated GPS time from the corresponding GPS solution shall be the standard for absolute time for the Payload. The timing system in the Aft SRE accepts the GPS PPS signal, and time stamps the PPS by sampling the output of the 31-bit rollover counter. The 10 Hz strobe is also time-stamped by independently sampling the output of the 31-bit rollover counter. The resultant PPS time stamp and 10 Hz time stamp are placed in a buffer within the SRE payload processor waiting to be called by external software program control via the 1553 data bus.

The 1553 data bus is the basis for the synchronization of all data gathering between the payload and the spacecraft components. The timing throughout the GP-B system is propagated via the $16f_0$ clock and the 10Hz strobe signal (Fig.1-2). The 1553 data bus connectivity is between the SRE's, ECU's, and GSS's on the payload side and the CCCA, ACE, and the star trackers on the spacecraft side. Distribution of the $16f_0$ clock signal is to the two ECU's and the four GSS's. Distribution of the 10Hz strobe is to the Aft GSS's, aft ECU's, to the spacecraft via the Command and Telemetry Unit (CTU), and internally to the Fwd SRE/TRE, GSS and ECU's. The payload derives all of its frequencies from the $16f_0$ clock, and all the derived frequencies are re-synchronized by the 10 Hz strobe.

The distribution of the 10 Hz strobe on the spacecraft (Fig.1-3) represents the numerous input/output processes used for data management processing, and provides the interfacing for the payload and space vehicle. The 10 Hz strobe acts either as an interrupt, a requestor, initializer, a read, or an operate flag. The 10 Hz strobe facilitates the communication to provide the required hardware and software data exchanges. The Attitude and Translation Control (ATC) logic within the Attitude Reference Platform (ARP) data is also referenced to the 10 Hz strobe signal.

Besides the PPS and the 10 Hz strobe signal, a third time stamp is the vehicle time update. It is the result of a software routine running within the CCCA. The software routine is known as the Vehicle Time Update (Fig.1-4). It counts the 10 Hz strobe signal, and for each 10 Hz strobe, outputs a vehicle time stamp label. This vehicle time stamp label is sent to the payload processor in the SRE and GSS, to multiple data packets, and is placed onto the header of each telemetry minor frame.

The Vehicle Time application maintains the internal flight software Vehicle Time word. The Vehicle Time word is a 40-bit fixed point number in CCSDS format with units of seconds. The upper 32 bits are the integral number of seconds and the lower 8 bits are the fractional part with a resolution of 1/256 second. The values are the closest binary approximation to the decimal fractions 0.0, 0.1, 0.2, ... 0.9 (corresponding to 10 Hz strobes).

In conclusion, the CCCA counts the 10 Hz strobe signal, and for each 10 Hz strobe, outputs a vehicle time stamp label. The CCCA interfaces with the CDHS via a High Speed Serial (HSS) duplex line, which includes two interrupts into the CCCA. The system as a whole uses an internal and external interrupt for communication and synchronization. In review, the 10 Hz strobe signal is derived from the 16 f_0 (16.368000 MHz) master frequency, the main timing reference. Interrupts are executed or called from within the CCCA. Interrupts are propagated (executed) throughout the spacecraft and payload upon reception of a 10 Hz strobe signal. At 10 Hz, the CCCA also provides communicates to the CDHS, IU, the spacecraft, the payload and payload processors, the SSR, and the CDHS which initiates the gathering and buffering of data at each 10 Hz strobe. This process uses the external and internal interrupts, which originated in the CDHS and were sent to the CCCA.

The science data of GP-B are transmitted to the ground station through the programmable telemetry within the CCCA, and the attached vehicle time is the time at which the data is placed into the minor frame of the telemetry format table. However, for the purpose of science data analyses and processing, the time of the data collection is required. The time latency between the data collection and the time stamp depends on how the data are collected and processed, how they are transferred to CCCA and how they are written to the telemetry format table. In the following of this document, the timing system of each component of GP-B will be discussed in detail and algorithms are given to determine the effective vehicle time of the collection of each science data.

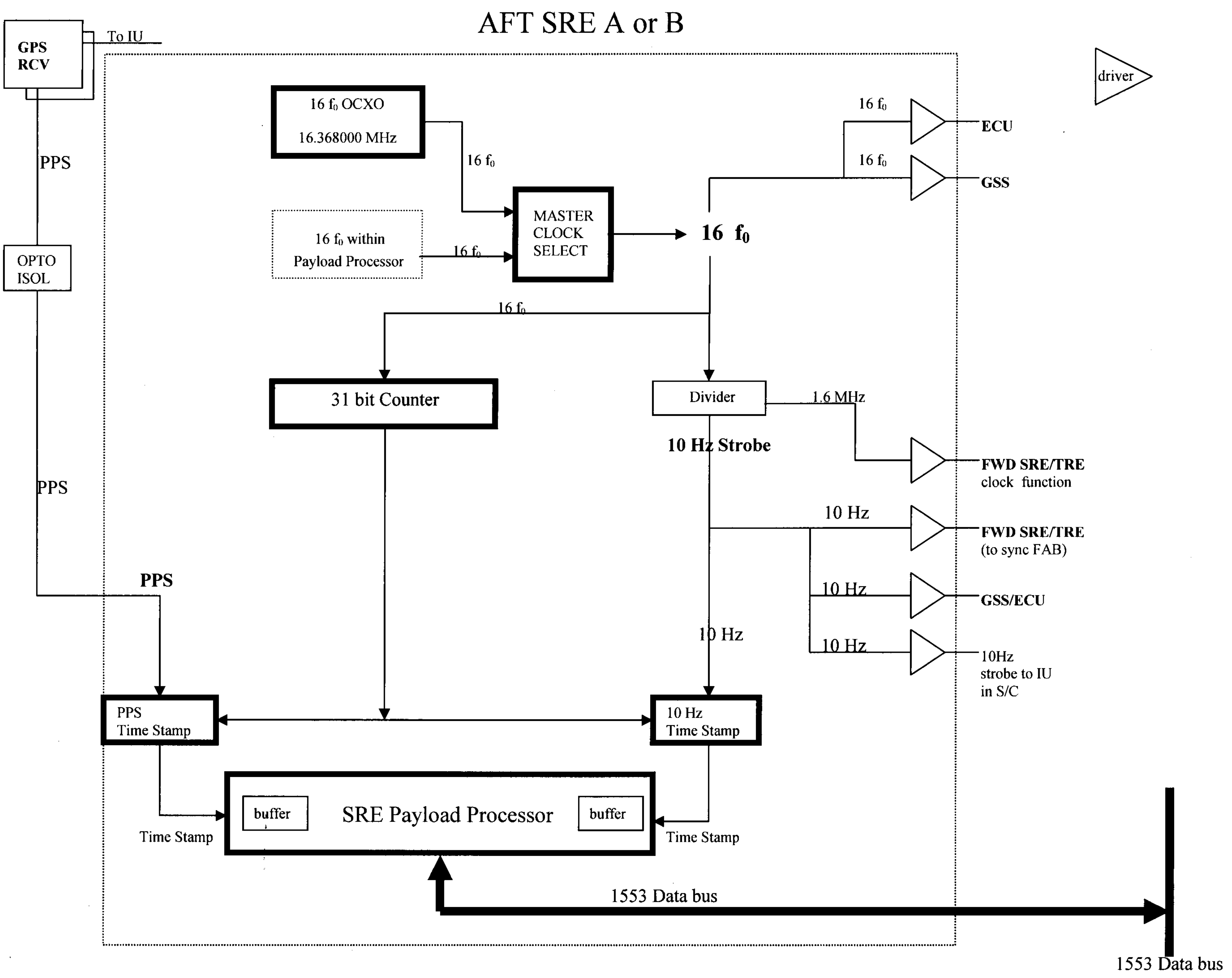


Fig. 1-1 Timing System of Aft SRE

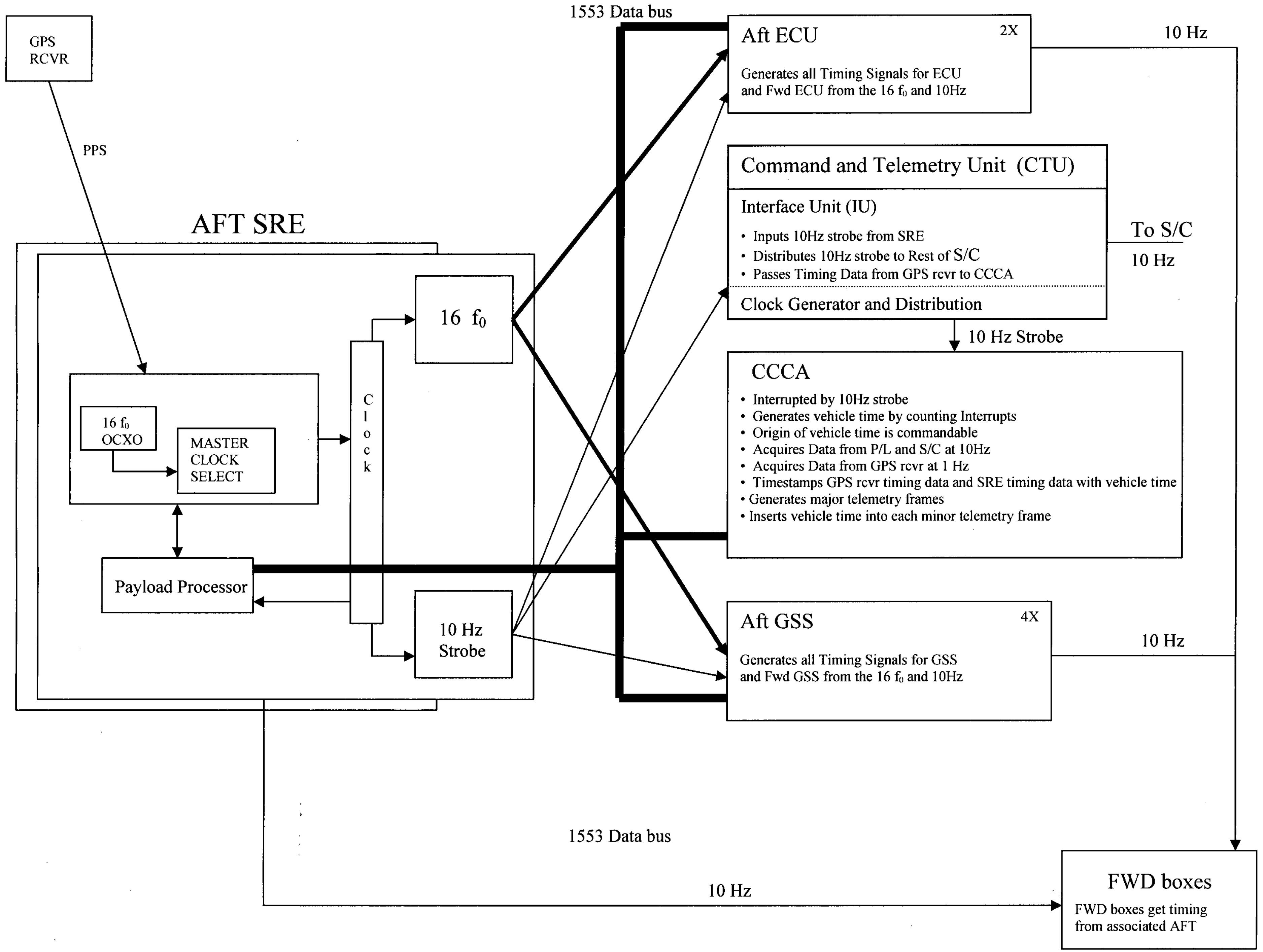


Fig. 1-2 Distribution of the 16fo clock and the 10Hz Strobe

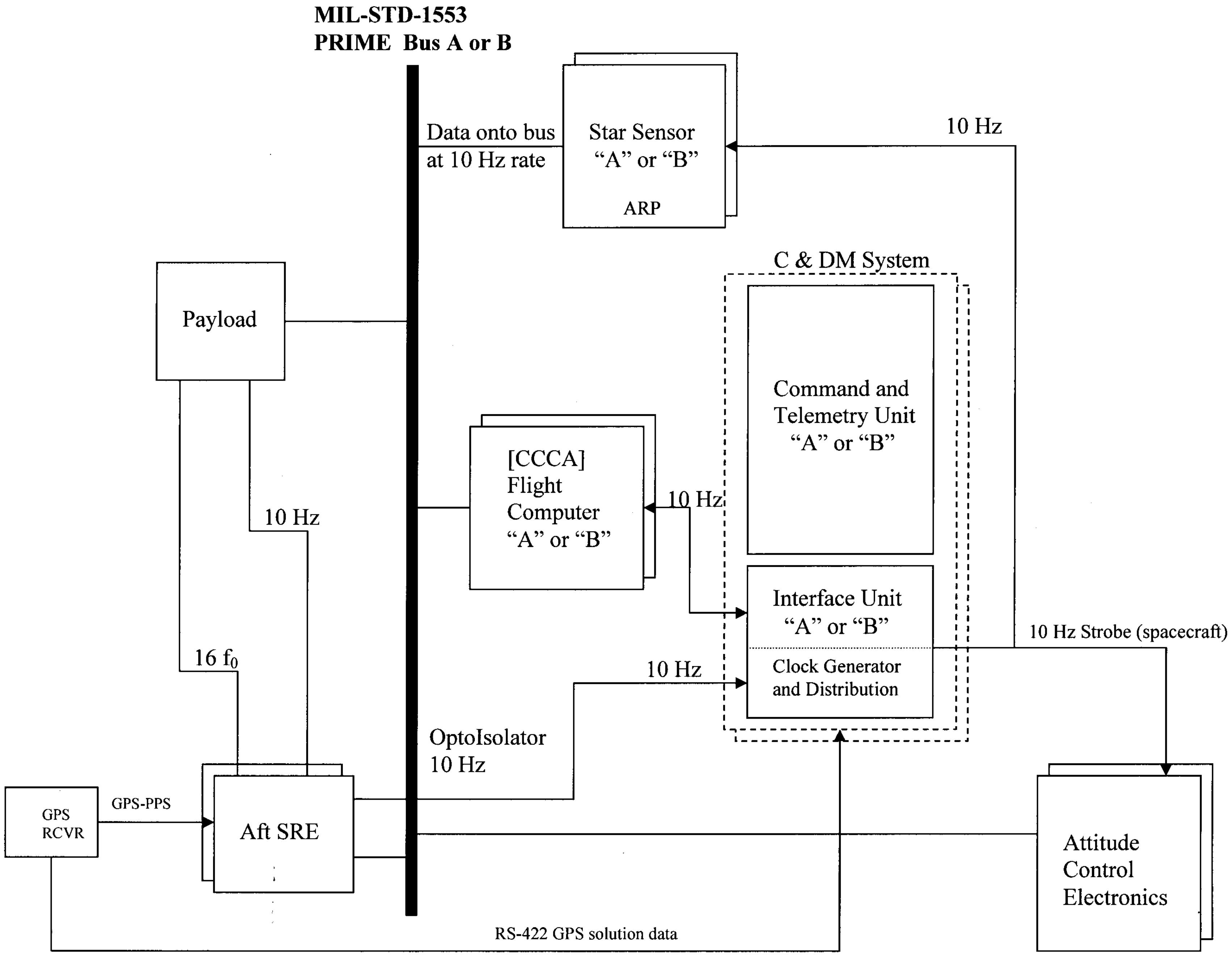


Fig.1-3 Payload-Spacecraft Interface

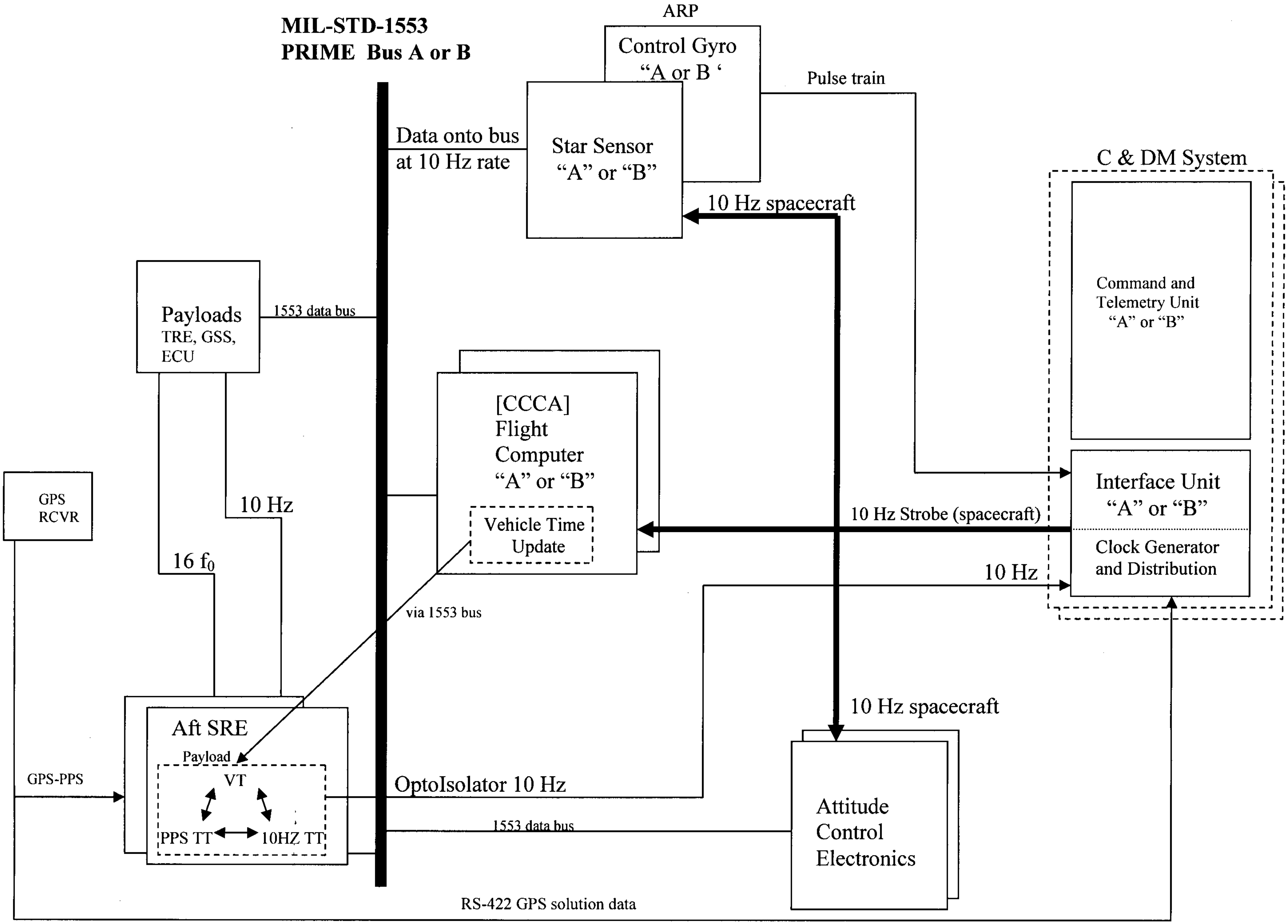


Fig. 1-4 Vehicle Time Label Interface

2. Timeline of CCCA

The CCCA has an interface to the GPS Receiver through the HSS and has interfaces to the SQUIDs, Science Telescope and Gyro Suspension System, etc. through the MIL-STD-1553 Data Bus.

The 1553 bus data transfer includes

— Minor Cycle 1
- Read SQUID/ST ATC data
- Read GSS ATC data

— Minor Cycle 2
- Read ACE data
- Read ECU data

— Minor Cycle 3
- Send ACE command
- Read Star Sensor data
- Read SQUID/ST 10Hz science data
- Read 2 SQUID/ST PITs
- Read 2 GSS PITs

The CCCA data processing includes the following main events:

— Sequence 01
- Vehicle time update
- Star Sensor processing
- ECU processing

— Sequence 02
- SRE PIT distribution
- ST processing
- Control gyro processing
- Attitude control law

— Sequence 03
- GSS PIT distribution
- Translation control law
- Thruster command generation
- SQUID processing

After Sequence 03 of CCCA processing, the CCCA will write the processed results into the telemetry format table.

Figure 2-1 illustrates the CCCA Input/Output timeline.

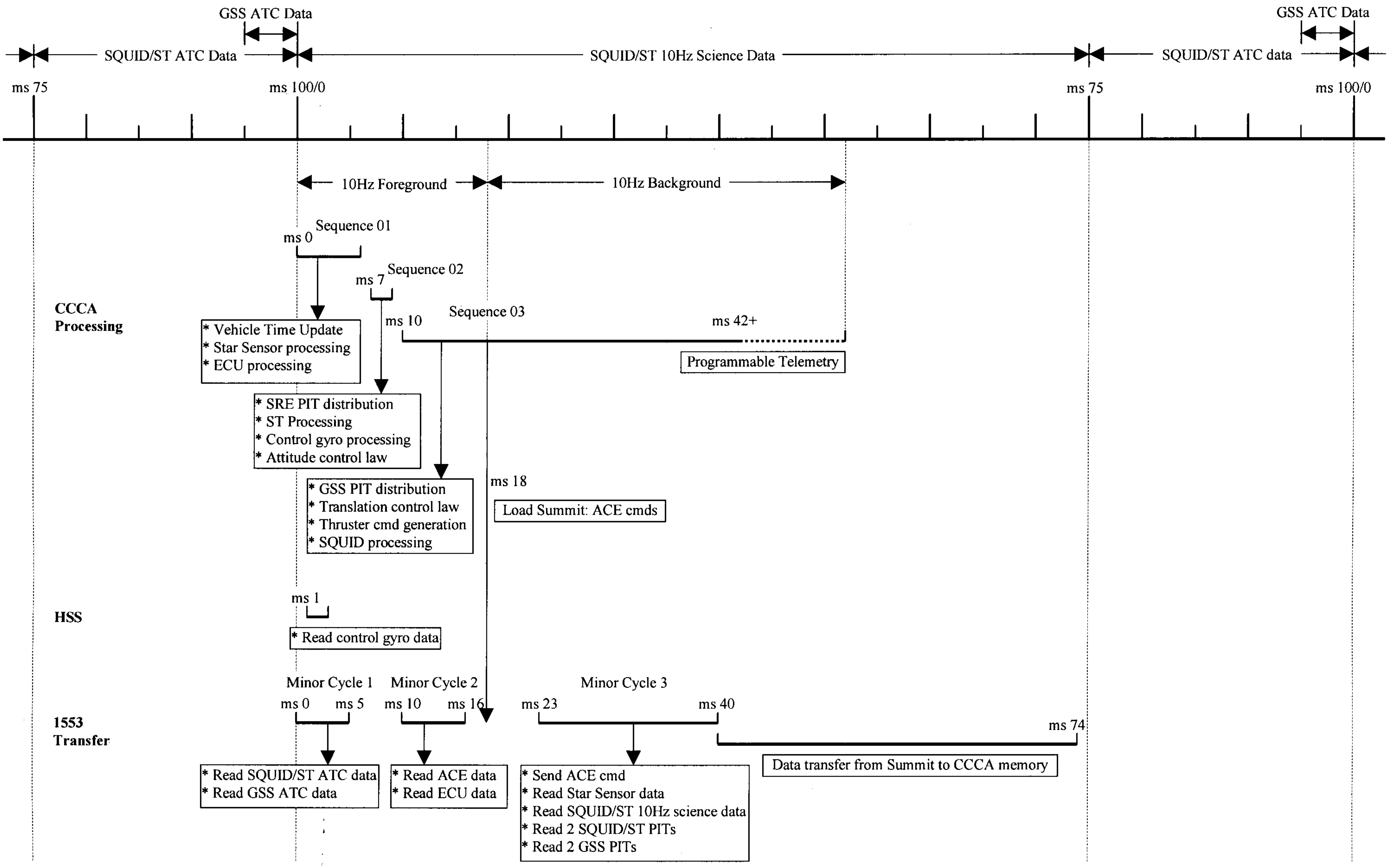


Table 2-1 CCCA Input/Output Timeline

3. Global Positioning System (GPS) Receiver

The GPS receiver provides the position and velocity of GP-B in an ECEF frame time-tagged with the GPS time. The GPS data packets are send to CCCA through HSS. One of the data packets output by the GPS receiver also provides the GPS time when the data packet is being transmitted (called time-of-transmission), and this time is accurate to 0.3s. The CCCA records the Vehicle Time of the reception of the data packet. The following GPS data are transmitted to the ground station through the telemetry:

Sybase Mnemonic	**Description**
SP_GPS_WeekNum1	GPS week number at position fix
SP_GPSTimeWeek1	GPS time of the week (units: seconds) at position fix
RP_ECEFPosX	ECEF position X (units: meters)
RP_ECEFPosY	ECEF position Y (units: meters)
RP_ECEFPosZ	ECEF position Z (units: meters)
RP_ECEFVelX	ECEF velocity Xdot (units: meters/second)
RP_ECEFVelY	ECEF velocity Ydot (units: meters/second)
RP_ECEFVelZ	ECEF velocity Zdot (units: meters/second)
SP_Time_Trans	GPS time of the week (units: seconds) of transmission of GPS data packet
SP_GPS_Digit_B	Integer part of vehicle time of reception of GPS data packet (LSB=1s)
SP_GPS_Fract	Fractional part of vehicle time of reception of GPS data packet (LSB=2^{-8}s)
SP_RecvrMode1	Receiver mode (Search Mode: 45; Normal Operation Mode: 50; Degraded Operation Mode: 51)

Table 3-1 Telemetry Monitors of the GPS Receiver

In addition, the GPS receiver provides the PPS signal to the Aft SRE, which will be time-stamped with the 31-bit rollover counter and be used to synchronize the Vehicle Time and the GPS time. The PPS is within 100 microseconds of the GPS second whenever the receiver is computing position.

4. Forward SQUID Readout Electronics (Fwd SRE)

4.1 Fwd SRE Data Acquisition

All clocks used to control the Fwd SRE data acquisition are synchronized to the 10 Hz Data Strobe. An Interval between two 10 Hz Data Strobes is 0.1 seconds or 10,000 micro-seconds. Each Interval is divided into 220 Fields, which are numbered from 0 to 219. An Field is 454.545454 micro-seconds. Each Field is divided into 31 Sectors, which are numbered from 0 to 30. A Sector is 14.662757 micro-seconds. Each Sector contains 24 Cycles of the 1.6368 MHz clock. A Cycle of the 1.6368 MHz clock is 0.610948 micro-seconds. All Analog-to-Digital conversions start one Cycle after the start of a Sector. Fig. 4-1 illustrates the relationship of the Intervals, Fields, Sectors and Cycles.

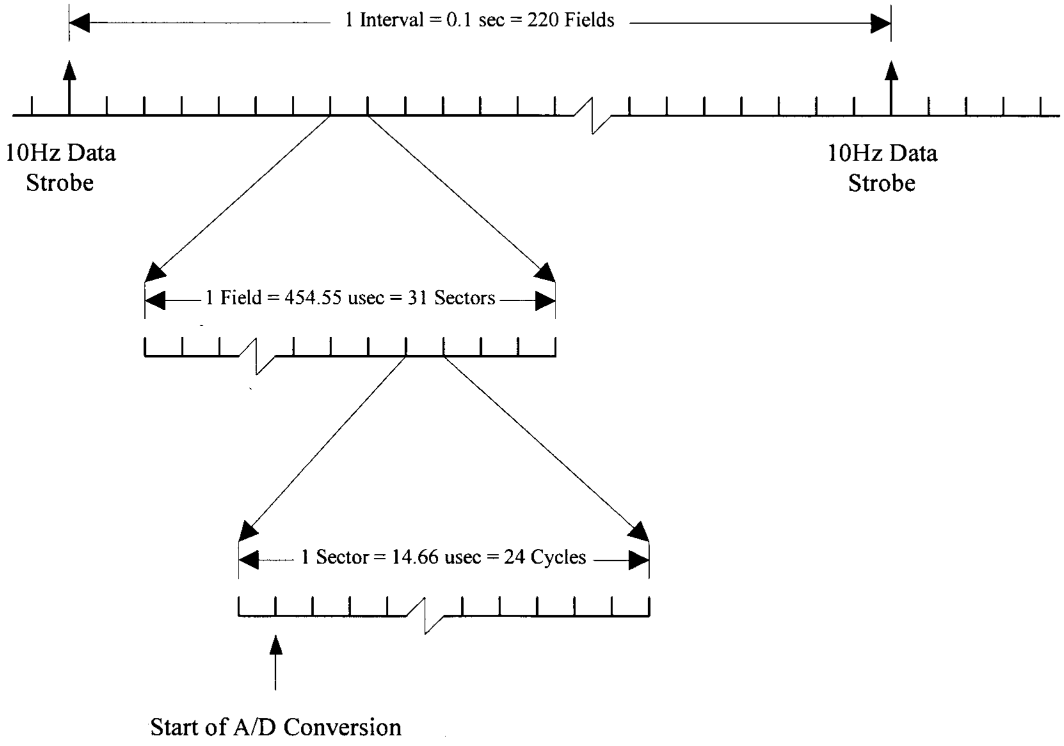


Fig. 4-1 Relationship of the Intervals, Fields, Sectors and Cycles

There are two Fwd SRE boxes, labeled as Fwd SRE-A and Fwd SRE-B respectively. Fwd SRE-A reads SQUID 1 and 3 data and the channel A data of the telescope, and Fwd SRE-B reads the SQUID 2 and 4 data and the channel B data of the telescope. Both Fwd SRE-A and Fwd SRE-B have two A/D converters, labeled as A/D 1 and A/D 2. A/D 1 and 2 read the SQUID data and the telescope data separately or altogether in different data gathering modes preset to the Fwd SRE box. Table 4-1 shows the data acquisition function at different modes for both Fwd SRE boxes. (Note: Based on PCB #446, the interleaved modes, Mode 0 and 1, won't be used in the Fwd SRE data acquisition. The new default mode is Mode 2.)

Mode	A/D 1	A/D 2
0	SQUID	Telescope
1	Telescope	SQUID
2	SQUID + Telescope	N/A
3	N/A	SQUID + Telescope

Table 4-1 Data Acquisition Function at Different Modes

The data gathering mode of the Fwd SRE can be changed with a Data Acquisition System (DAS) control command, and this command is read back from the SRE engineering data in the telemetry. The telemetry monitor of the SRE data gathering mode is included in the 1Hz SRE/TRE Processor Interface Table (PIT) #11, as listed in the following table:

PIT #	**Word**	**Bit**	**Sybase Mnemonic**	**Description**	**Rate**
11	4	4-5	PQ_DAS_SciMoCdA PQ_DAS_SciMoCdB	SRE-d, DAS Control — Science Data Gathering Mode Command 00 = DAS 1 – SQUID Data DAS 2 – ST Data 01 = DAS 1 – ST Data DAS 2 – SQUID Data 10 = DAS 1 – SQUID&ST Data DAS 2 – Null 11 = DAS 1 – Null DAS 2 – SQUID&ST Data	0.5Hz

Table 4-2 Telemetry Monitor of the SRE Data Gathering Mode

In the telemetry format table, the 1-bit monitor "PQ_DAS_SciMoCdA" is included in the 16-bit parent monitor "CD_DASCtrlCmd_A", and the 1-bit monitor "PQ_DAS_SciMoCdB" is included in the 16-bit parent monitor "CD_DASCtrlCmd_B".

The SQUID data and the telescope data are read once a Field, at the frequency of 2200 Hz. Different channels of data are designed to be read at different Sectors of the Field. Tables 4-3 to 4-10 show the details of the data acquisition timing of Fwd SRE-A and Fwd SRE-B at different modes, where the last column of the tables show the time of the start of the A/D conversion of the corresponding data from the start of the Field.

Sector Number	A/D 1	A/D 2	Time From Start of A Field (micro-seconds)
11	Echo: CMD Address	N/A	161.901
12	Echo: CMD Data	N/A	176.564
13	SQUID 1 20Hz	TRE A +X	191.227
14	SQUID 3 20Hz	TRE A –X	205.890
15	SQUID 1 1kHz	TRE A +Y	220.552
16	SQUID 3 1kHz	TRE A –Y	235.215
17	N/A	N/A	N/A
18	N/A	N/A	N/A
19	N/A	N/A	N/A
20	N/A	N/A	N/A
21	SQUID 1 Cal	N/A	308.529
22	SQUID 3 Cal	N/A	323.192
23	SQUID Test/Spare	N/A	337.854
24	Housekeeping Data	N/A	352.517
25	Status/Frame Count	N/A	367.180
26	Frame Count from Aft	N/A	381.843

Table 4-3 Data Acquisition Timing of Fwd SRE-A at Mode 0

Sector Number	A/D 1	A/D 2	Time From Start of A Field (micro-seconds)
11	N/A	Echo: CMD Address	161.901
12	N/A	Echo: CMD Data	176.564
13	TRE A +X	SQUID 1 20Hz	191.227
14	TRE A –X	SQUID 3 20Hz	205.890
15	TRE A +Y	SQUID 1 1kHz	220.552
16	TRE A –Y	SQUID 3 1kHz	235.215
17	N/A	N/A	N/A
18	N/A	N/A	N/A
19	N/A	N/A	N/A
20	N/A	N/A	N/A
21	N/A	SQUID 1 Cal	308.529
22	N/A	SQUID 3 Cal	323.192
23	N/A	SQUID Test/Spare	337.854
24	N/A	Housekeeping Data	352.517
25	N/A	Status/Frame Count	367.180
26	N/A	Frame Count from Aft	381.843

Table 4-4 Data Acquisition Timing of Fwd SRE-A at Mode 1

Sector Number	A/D 1	A/D 2	Time From Start of A Field (micro-seconds)
11	Echo: CMD Address	N/A	161.901
12	Echo: CMD Data	N/A	176.564
13	SQUID 1 20Hz	N/A	191.227
14	SQUID 3 20Hz	N/A	205.890
15	SQUID 1 1kHz	N/A	220.552
16	SQUID 3 1kHz	N/A	235.215
17	TRE A +X	N/A	249.878
18	TRE A –X	N/A	264.541
19	TRE A +Y	N/A	279.203
20	TRE A –Y	N/A	293.866
21	SQUID 1 Cal	N/A	308.529
22	SQUID 3 Cal	N/A	323.192
23	SQUID Test/Spare	N/A	337.854
24	Housekeeping Data	N/A	352.517
25	Status/Frame Count	N/A	367.180
26	Frame Count from Aft	N/A	381.843

Table 4-5 Data Acquisition Timing of Fwd SRE-A at Mode 2(default mode)

Sector Number	A/D 1	A/D 2	Time From Start of A Field (micro-seconds)
11	N/A	Echo: CMD Address	161.901
12	N/A	Echo: CMD Data	176.564
13	N/A	SQUID 1 20Hz	191.227
14	N/A	SQUID 3 20Hz	205.890
15	N/A	SQUID 1 1kHz	220.552
16	N/A	SQUID 3 1kHz	235.215
17	N/A	TRE A +X	249.878
18	N/A	TRE A –X	264.541
19	N/A	TRE A +Y	279.203
20	N/A	TRE A –Y	293.866
21	N/A	SQUID 1 Cal	308.529
22	N/A	SQUID 3 Cal	323.192
23	N/A	SQUID Test/Spare	337.854
24	N/A	Housekeeping Data	352.517
25	N/A	Status/Frame Count	367.180
26	N/A	Frame Count from Aft	381.843

Table 4-6 Data Acquisition Timing of Fwd SRE-A at Mode 3

Sector Number	A/D 1	A/D 2	Time From Start of A Field (micro-seconds)
11	Echo: CMD Address	N/A	161.901
12	Echo: CMD Data	N/A	176.564
13	SQUID 2 20Hz	TRE B +X	191.227
14	SQUID 4 20Hz	TRE B –X	205.890
15	SQUID 2 1kHz	TRE B +Y	220.552
16	SQUID 4 1kHz	TRE B –Y	235.215
17	N/A	N/A	N/A
18	N/A	N/A	N/A
19	N/A	N/A	N/A
20	N/A	N/A	N/A
21	SQUID 2 Cal	N/A	308.529
22	SQUID 4 Cal	N/A	323.192
23	SQUID Test/Spare	N/A	337.854
24	Housekeeping Data	N/A	352.517
25	Status/Frame Count	N/A	367.180
26	Frame Count from Aft	N/A	381.843

Table 4-7 Data Acquisition Timing of Fwd SRE-B at Mode 0

Sector Number	A/D 1	A/D 2	Time From Start of A Field (micro-seconds)
11	N/A	Echo: CMD Address	161.901
12	N/A	Echo: CMD Data	176.564
13	TRE B +X	SQUID 2 20Hz	191.227
14	TRE B –X	SQUID 4 20Hz	205.890
15	TRE B +Y	SQUID 2 1kHz	220.552
16	TRE B –Y	SQUID 4 1kHz	235.215
17	N/A	N/A	N/A
18	N/A	N/A	N/A
19	N/A	N/A	N/A
20	N/A	N/A	N/A
21	N/A	SQUID 2 Cal	308.529
22	N/A	SQUID 4 Cal	323.192
23	N/A	SQUID Test/Spare	337.854
24	N/A	Housekeeping Data	352.517
25	N/A	Status/Frame Count	367.180
26	N/A	Frame Count from Aft	381.843

Table 4-8 Data Acquisition Timing of Fwd SRE-B at Mode 1

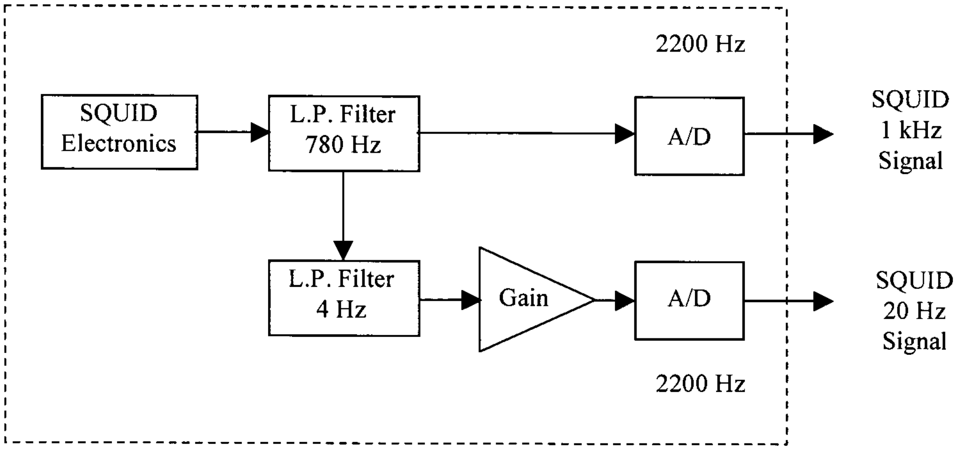
Sector Number	A/D 1	A/D 2	Time From Start of A Field (micro-seconds)
11	Echo: CMD Address	N/A	161.901
12	Echo: CMD Data	N/A	176.564
13	SQUID 2 20Hz	N/A	191.227
14	SQUID 4 20Hz	N/A	205.890
15	SQUID 2 1kHz	N/A	220.552
16	SQUID 4 1kHz	N/A	235.215
17	TRE B +X	N/A	249.878
18	TRE B –X	N/A	264.541
19	TRE B +Y	N/A	279.203
20	TRE B –Y	N/A	293.866
21	SQUID 2 Cal	N/A	308.529
22	SQUID 4 Cal	N/A	323.192
23	SQUID Test/Spare	N/A	337.854
24	Housekeeping Data	N/A	352.517
25	Status/Frame Count	N/A	367.180
26	Frame Count from Aft	N/A	381.843

Table 4-9 Data Acquisition Timing of Fwd SRE-B at Mode 2(default mode)

Sector Number	A/D 1	A/D 2	Time From Start of A Field (micro-seconds)
11	N/A	Echo: CMD Address	161.901
12	N/A	Echo: CMD Data	176.564
13	N/A	SQUID 2 20Hz	191.227
14	N/A	SQUID 4 20Hz	205.890
15	N/A	SQUID 2 1kHz	220.552
16	N/A	SQUID 4 1kHz	235.215
17	N/A	TRE B +X	249.878
18	N/A	TRE B –X	264.541
19	N/A	TRE B +Y	279.203
20	N/A	TRE B –Y	293.866
21	N/A	SQUID 2 Cal	308.529
22	N/A	SQUID 4 Cal	323.192
23	N/A	SQUID Test/Spare	337.854
24	N/A	Housekeeping Data	352.517
25	N/A	Status/Frame Count	367.180
26	N/A	Frame Count from Aft	381.843

Table 4-10 Data Acquisition Timing of Fwd SRE-B at Mode 3

4.2 Analog Filters for SQUID Signals



Forward SQUID Readout Electronics

Fig. 4-2 Analog Filters for SQUID Signals

As shown in Fig.4-2, before they are sampled by the A/D converters of the Fwd SRE, the SQUID 1 kHz signal goes through a lowpass filter with the cut off frequency of 780 Hz, and the SQUID 20 Hz signal goes through two lowpass filters with the cut off frequencies at 780 Hz and 4Hz, respectively.

The transfer function of the lowpass filter for the SQUID 1 kHz signal is

$$\left(\frac{1}{10^{-4}S+1}\right)\left(\frac{5.92x10^{7}}{S^{2}+13333S+5.92x10^{7}}\right)$$

and the transfer function of the lowpass filter for the SQUID 20Hz signal is

$$\left(\frac{1}{10^{-4}S+1}\right)\left(\frac{5.92x10^{7}}{S^{2}+13333S+5.92x10^{7}}\right)\left(\frac{4132}{S^{2}+181.8S+4132}\right)$$

The lowpass filters result in a time delay of the SQUID signal. The main component of the SQUID signal is a sinusoid signal at the roll frequency. While the roll period varies from 1 to 10 minutes, the roll frequency ranges from 0.01047 to 0.1047 rad/sec. Therefore, there is a time delay of 0.000325 seconds for the roll frequency component of the SQUID 1 kHz signal and a time delay of 0.044323 seconds for the roll frequency component of the SQUID 20 Hz signal. Considering the RC components of the filters may deviate from their nominal values by 1-2%, the uncertainties of the time delay can be as much as 4% of the estimated values. The uncertainties of the time delays of the SQUID 1kHz signal and the SQUID 20Hz signal are approximately 0.01 milliseconds and 2 milliseconds, respectively.

5. Aft SQUID Readout Electronics (Aft SRE)

5.1 Introduction

The SQUID/ST Software (SSW) supports both the SQUID and Science Telescope (ST) and resides in the Aft SRE GP-B Payload Processors (GPBPP). These processors have interfaces to the Fwd SRE through Forward-Aft Bus (FAB), and to the Command Control Computer Assembly (CCCA) as remote terminals through the MIL-STD-1553. There are two Aft SREs (side A or B) for redundancy; only one is active at any one time.

The Aft SRE provides the 10Hz clock to each payload box and to the GP-B spacecraft. The 10Hz clock is used by the payloads to synchronize data collections. The SRE increments a 31-bit rollover counter based on the $16f_0$ timing signal which operates at 16.368MHz. The SRE also time stamps the 10Hz Strobe and GPS receiver provided PPS signal. This is performed whenever the SRE receives the 10Hz Strobe or PPS; it freezes the current $16f_0$ time into a buffer available to the GPBPP on the expansion bus. There are separate 32 bit registers for the 10Hz and PPS timing signals. Finally, the AFT SRE collects the raw SQUID and ST data from the Fwd SRE, processes it and transfers it to the CCCA in a sequences of Processor Interface Tables (PITs).

5.2 SSW Tasks

The SSW processing consists of several tasks, as shown in Table 5-1.

Task	Rate	Controlled by	Description
Data Acquisition Strobe Task	10Hz	Data acquisition strobe interrupt	Trigger 10Hz ATC Task
System Clock Task	10Hz	System clock interrupt	Update counters, trigger 10Hz Science and 1Hz Science tasks
10Hz ATC Task	10Hz	Data Acquisition Strobe Task	ATC applications
10Hz Science Task	10Hz	System Clock Task	Packet transfers, command router, science applications
1Hz Science Task	1Hz	System Clock Task	Science applications

Table 5-1 SSW Tasks

The two primary tasks are the Data Acquisition Strobe Task and the System Clock Task; these are tied to the 10Hz data acquisition strobe interrupts and 10Hz system clock interrupts, respectively. Each task operates at a 10Hz rate as controlled by their respective interrupts (i.e., every 100 milliseconds). The data acquisition strobe interrupt occurs at about millisecond 75 in every 100 millisecond cycle; the system clock interrupt occurs at millisecond 100 (or 0 of the next cycle).

The primary responsibilities of the Data Acquisition Strobe Task and the System Clock Task are to update various scheduler counters and flags, and to initiate the ATC and science tasks. The Data Acquisition Strobe Task controls the 10Hz ATC Task; the System Clock Task controls the 10Hz Science Task and 1Hz Science Task.

The 10 Hz ATC Task is initiated by the Data Acquisition Strobe Task upon every data acquisition strobe interrupt. It performs high-rate ATC applications.

The 10Hz Science Task is initiated by the System Clock Task upon every system clock interrupt. It performs 1553 packet transfers, command router processing, and high-rate science applications.

The 1Hz Science Task is initiated by the System Clock Task at the beginning of each 1Hz cycle, as determined by the 0 to 9 Counter. It performs low-rate science applications.

The SSW has two important status indicators: the 0 to 9 Counter and the Tick/Tock.

The 0 to 9 Counter is a counter of 10Hz cycles grouped into 1 second intervals such that one full sequence of the counter from 0 to 9 is one second. This counter is used to coordinate data collection between the 10Hz Science Task and the 1Hz Science Task. This counter is synchronized such that 0 coincides with the start of the 1Hz Science Task.

The Tick/Tock signal is used to synchronize processing which must occur every other second. It toggles during the first 10Hz cycle of a new second.

5.3 Data Collection Applications

5.3.1 Fwd SRE Data Collection

The "Fwd_SRE" application is a 10Hz process which collects SQUID, ST and engineering data samples for use by the SSW applications.

The data consists of 220 samples from Fwd SRE-A and 220 samples from Fwd SRE-B interleaved into the RAM buffer. Each sample contains SQUID and ST data, as well as engineering data. At the time of the 10Hz system clock interrupt, the electronics is synchronized to start loading A/B packets into the start of External RAM and proceeding down. Following the collection of the 165th packet set, the Aft SRE issues the data acquisition strobe interrupt which signifies that the first 165 A/B packets are ready to be collected. Receipt of the 10Hz system clock interrupt is notification to the software that

A/B packets 166 through 220 are ready for collection. The data is moved over the Expansion Bus Interface (EBI) from the External RAM into a data structure in the computer memory.

The last four words of the External RAM consist of the PPS time stamp and the 10Hz time stamp. These are read by I/O processing and made available to other applications.

The application maintains the science data 10Hz and vehicle times. These are set to the current 10Hz and vehicle time whenever the PPS time changes.

The "Fwd_SRE" application is always performed (i.e., never disabled).

5.3.2 SQUID Science Data Collection

The "SQUID_Science_Data" application is a 10Hz process which collects 20Hz and 1kHz SQUID data for use by science applications (specifically the FFTs and the SQUID snapshots). For each SQUID signal, 4096 samples are collected. Data may be collected in normal mode, which takes about 2 seconds, or in decimated mode, which takes about 22 seconds.

In normal mode, "two seconds" of data is collected for each SQUID. Actually, it is slightly less than two seconds, which would be 4400 samples. The first 152 samples are skipped, and the last 152 samples, to yield a total of 4096 samples. The "SQUID_Science_Data" application handles this internally, so the science applications don't have to worry about skipping the first 152 samples, etc.

The data collection for the four SQUIDs is staggered, so that SQUID 1 starts at second 1, SQUID 2 at second 2, SQUID 3 at second 3 and SQUID 4 at second 4. No SQUID starts at second 5, but SQUID 4 finishes its collection during this second.

In decimated mode, the data is decimated at an 11:1 ratio; i.e., every eleventh sample is used. In each 10Hz cycle, the following samples are used: 6, 17, 28, 39, 50, 61, 72, 83, 94, 105, 116, 127, 138, 149, 160, 171, 182, 193, 204, 215. This is a total of 20 samples per 10Hz cycle (vs. all 220 samples in normal mode). *After* the decimation is accounted for, then the first 152 samples in each collection period are skipped (just like normal mode). So this means no data is collected during the first 7 cycles of the collection period; the first collected data is sample 138 of cycle 8. (Again, the "SQUID_Science_Data" application handles all this internally.) The total data collection period extends over 22 seconds in decimated mode.

In decimated mode, the data collection period for each SQUID starts at the next second that it would start in normal mode.

When collecting data, the application uses separate read and write buffers (ping/pong). Science applications requesting the data will use the read buffer, while collected data is saved in the write buffer. This ensures that the science application will get the most recent consistent set of data, even if data is currently being collected for that SQUID.

The "Time_10Hz" and "Vehicle_Time" services of the "SQUID_Science_Data" application provide timestamps for the midpoint of the collected data. This corresponds to the 10Hz cycle during which sample 2049 is collected (in normal mode this will be the beginning of cycle 11).

The "SQUID_Science_Data" application is always performed (i.e., never disabled).

5.4 Timing Data Collection

The following timing data are transferred from Aft SRE to CCCA through the 10Hz ATC Data Packet and the 10Hz Science Data Packet:

Data Packet	Word	Bit	Sybase Mnemonic	Description
10Hz ATC Data Packet	31-32	0-31	SQ_PPSv16F_Time	Current PPS/16fo timestamp MSB-LSBs (31 bit rollover counter)
10 Hz Science Data Packet	27-28	0-31	SQ_Sci10HzTime	Science 10Hz/16fo timestamp MSB-LSBs (31 bit rollover counter), which is only updated whenever the PPS/16fo time changes
	29-30	0-31	SQ_SciVehTime32	Integer part of science vehicle timestamp (LSB=1s), which is updated whenever the PPS/16fo time changes
	7	0-7	SQ_SciVehTime8	Fractional part of science vehicle timestamp (LSB=2^{-8}s), which is updated whenever the PPS/16fo time changes

Table 5-2 Telemetry Monitors of the Timing Data

As described below, the timestamp given by the Aft SRE timing monitors "SQ_SciVehTime32" and "SQ_SciVehTime8" is 0.1s smaller than the vehicle time of CCCA due to the data transmission delay.

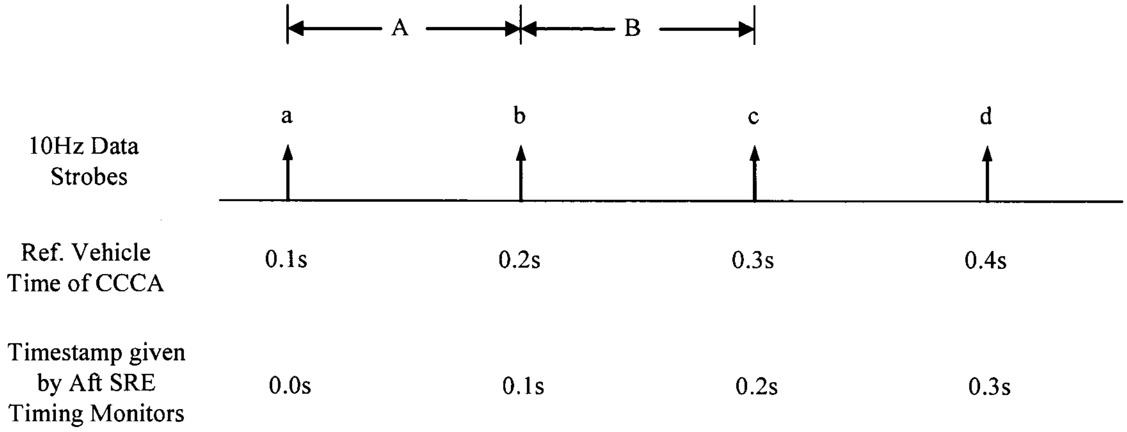


Fig. 5-1 Timeline of Data Transmission Between CCCA and Aft SRE

As illustrated in Fig.5-1, the timeline of data transmission between CCCA and Aft SRE consists of the following two phases:

Phase A (reference vehicle time of CCCA: 0.1s to 0.2s,)

- Reference vehicle time of CCCA is increased to 0.1s;
- The 10Hz Command Packet, in which the vehicle time (0.1s) is included, is written by CCCA and ready to be read by SSW.

Phase B (reference vehicle time of CCCA: 0.2s to 0.3s)

- Reference vehicle time of CCCA is increased to 0.2s;
- SSW reads the 10Hz Command Packet written by CCCA in Phase A through MIL-STD-1553 and updates the vehicle timestamp (to 0.1s);
- If $16f_0$ timestamp of PPS changes, SSW updates the timing monitors "SQ_Sci10HzTime", "SQ_SciVehTime32" and "SQ_SciVehTime8" in the 10Hz Science Data Packet with the $16f_0$ timestamp and the current vehicle timestamp (0.1s) corresponding to the 10Hz Data Strobe b.

From the above descriptions it is clear that the timestamp given by Aft SRE timing monitors is 0.1s smaller than the vehicle time of CCCA. The 10th second difference between Aft SRE timing monitors and the vehicle time of CCCA is also discussed in the reference document S0916 "GPB Timing System, MSS/Payload Science Data Tenth Second Difference".

In the telemetry format table, the 32-bit monitor "SQ_SciVehTime32" is abbreviated to the 8-bit monitor "SQ_SciVehTimByt", which is the 8 LSBs of the integer part of science vehicle timestamp (LSB=1s) and is only updated whenever the PPS/$16f_0$ time changes.

5.5 SSW 10Hz Timeline

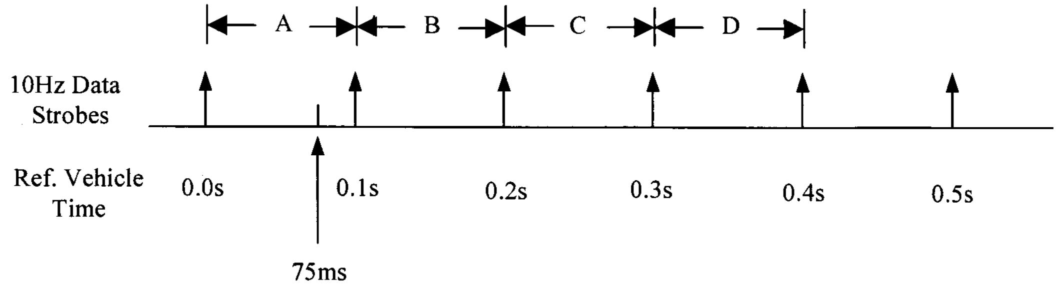


Fig. 5-2 SSW 10Hz Timeline

Fig.5-2 shows the SSW 10Hz timeline. In the figure a 10Hz Data Strobe is selected as the reference point and stamped with the reference vehicle time 0.0s, and the 10Hz data collection and processing consists of 4 phases starting from the reference point, denoted as Phase A, B, C and D, respectively. Each phase is synchronized with the 10Hz Data Strobes.

Phase A (reference vehicle time: 0.0s to 0.1s)

— Fwd SRE samples 220 SQUID/ST science data points;
— SSW collects Fwd SRE data points 1 to 165 at 75ms through the application "Fwd_SRE".

Phase B (reference vehicle time: 0.1s to 0.2s)

— SSW collects Fwd SRE data points 166 to 220 at 100ms through the application "Fwd_SRE";
— SSW collects SQUID science data points through the application "SQUID_Science_Data";
— SSW runs 10Hz Science applications;
— SSW updates the 10Hz Science Data Packet.

Phase C (reference vehicle time: 0.2s to 0.3s)

— SSW transfers the 10Hz Science Data Packet to CCCA through MIL-STD-1553;
— CCCA reads the 10Hz Science Data Packet.

Phase D (reference vehicle time: 0.3s to 0.4s)

— CCCA distributes the outputs of 10Hz Science applications into telemetry monitors, stamped with the current reference vehicle time (0.3s).

For simplicity, we will ignore the two steps of data collection at 75ms and 100ms and describe them as one process of data collection in the following part of the document.

5.6 Effective Sampling Time of the ST Science Slope Estimation

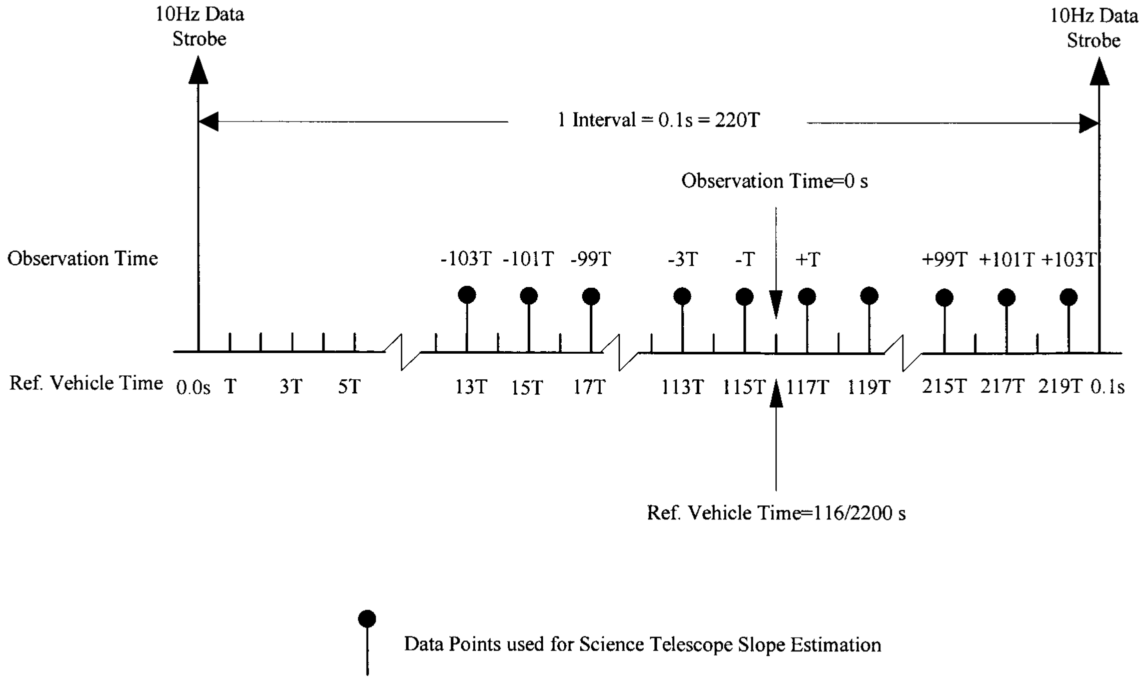


Fig. 5-3 Timeline of Telescope Slope Estimation

Input data to the telescope slope estimation algorithm is 8 channels of 220 points each, at a frequency of 10Hz. The channels are designated PX_A, MX_A, PY_A, MY_A, PX_B, MX_B, PY_B, MY_B, where PX_A for Plus X at A side and MX_A for Minus X at A side, etc.

Fig.5-3 shows the timeline of the telescope slope estimation. In the figure a 10Hz Data Strobe is selected as the reference point and stamped with the reference vehicle time 0.0s. Therefore, the reference vehicle time of the 220 points are 0s, T, ... 219T, plus a delay due to the Fwd SRE sampling, where T=1/2200 s. The Fwd SRE sampling delays are different for 8 channels and listed as follows

0.000250 s	for PX_A and PX_B channels
0.000265 s	for MX_A and MX_B channels
0.000279 s	for PY_A and PY_B channels
0.000294 s	for MY_A and MY_B channels

As illustrated in Fig.5-3, the first 13 points are discarded because of reset transients. The remained data points are decimated and only every other point is processed. Therefore, the data points used for the slope estimation are sampled at the reference vehicle time 13T, 15T, ... 219T, a total of 104 values. In the estimation algorithm, the 104 points are stamped with observation time -103T, -101T, ... -T, T, ...101T, 103T, respectively. It is obvious that the observation time 0s corresponds to the reference vehicle time 116T=0.052727s.

Given the parameters of the telescope slope estimation algorithm, it is calculated that the effective sampling time of the telescope slope, in the sense of the observation time and ignoring the Fwd SRE sampling delay, are

-0.000426 s	for PX_A channel
-0.000359 s	for MX_A channel
-0.000305 s	for PY_A channel
-0.000260 s	for MY_A channel
-0.000222 s	for PX_B channel
-0.000191 s	for MX_B channel
-0.000165 s	for PY_B channel
-0.000143 s	for MY_B channel

The above observation time corresponds to the following reference vehicle time

0.052301 s	for PX_A channel
0.052368 s	for MX_A channel
0.052423 s	for PY_A channel
0.052468 s	for MY_A channel
0.052505 s	for PX_B channel
0.052536 s	for MX_B channel
0.052562 s	for PY_B channel
0.052584 s	for MY_B channel

Considering the Fwd SRE sampling delay, the effective sampling time of the telescope slope, in the sense of the reference vehicle time, are determined as follows:

0.052551 s	for PX_A channel
0.052633 s	for MX_A channel
0.052702 s	for PY_A channel
0.052762 s	for MY_A channel
0.052755 s	for PX_B channel
0.052800 s	for MX_B channel
0.052841 s	for PY_B channel
0.052878 s	for MY_B channel

5.7 Time Latency of the ST Science Slope Estimation

The "Science_Slope" application is a 10Hz process which computes estimates of the slope and intercept of the photodiode charging that is used to point the telescope to the guide star and provide a reference to measure frame dragging.

The model of the linear charging process assumes a straight line with colored noise, and a filter estimates a correction to the slope and intercept based on the colored noise model. This component is called the Markov estimate and is part of the telemetry. The slope and intercept are updated at 10Hz while the Markov estimate is updated at 0.5Hz.

The timeline of ST Science Slope Estimation is the same as Fig.5-1, with 4 phases as follow:

Phase A (reference vehicle time: 0.0s to 0.1s)

— Fwd SRE samples 220 ST data points;

Phase B (reference vehicle time: 0.1s to 0.2s)

— SSW completes to collect 220 ST data points sampled from 0.0s to 0.1s, with the effective sampling time approximately at 0.05s (the exact values are given in the previous section) ;
— SSW runs “Science_Slope” to estimate the ST slope, intercept and Markov;
— SSW updates the 10Hz Science Data Packet, which includes the data as follows:

Word	Bit	Sybase Mnemonic	Description
11	0-15	ST_SciSlopePX_A	TRE-A X+ Science Slope, 2’s complement
12	0-15	ST_SciSlopePY_A	TRE-A Y+ Science Slope, 2’s complement
13	0-15	ST_SciSlopeMX_A	TRE-A X- Science Slope, 2’s complement
14	0-15	ST_SciSlopeMY_A	TRE-A Y- Science Slope, 2’s complement
15	0-15	ST_SciSlopePX_B	TRE-B X+ Science Slope, 2’s complement
16	0-15	ST_SciSlopePY_B	TRE-B Y+ Science Slope, 2’s complement
17	0-15	ST_SciSlopeMX_B	TRE-B X- Science Slope, 2’s complement
18	0-15	ST_SciSlopeMY_B	TRE-B Y- Science Slope, 2’s complement
19	0-15	ST_SciXceptPX_A	TRE-A X+ Science Intercept, 2’s complement
20	0-15	ST_SciXceptPY_A	TRE-A Y+ Science Intercept, 2’s complement
21	0-15	ST_SciXceptMX_A	TRE-A X- Science Intercept, 2’s complement
22	0-15	ST_SciXceptMY_A	TRE-A Y- Science Intercept, 2’s complement
23	0-15	ST_SciXceptPX_B	TRE-B X+ Science Intercept, 2’s complement
24	0-15	ST_SciXceptPY_B	TRE-B Y+ Science Intercept, 2’s complement
25	0-15	ST_SciXceptMX_B	TRE-B X- Science Intercept, 2’s complement
26	0-15	ST_SciXceptMY_B	TRE-B Y- Science Intercept, 2’s complement

Table 5-3 Telemetry Monitors of the ST Slopes and Intercepts

Phase C (reference vehicle time: 0.2s to 0.3s)

— SSW transfers the 10Hz Science Data Packet to CCCA through MIL-STD-1553;
— CCCA reads the 10Hz Science Data Packet.

Phase D (reference vehicle time: 0.3s to 0.4s)

— CCCA distributes the ST slope and intercept into telemetry monitors, stamped with the current reference vehicle time (0.3s).

It is also noted that there is an analog filter with the cut off frequency at 500 Hz in the TRE electronics before the Fwd SRE data acquisition. The analog filter, whose transfer function is $\left(\frac{9869604.4}{S^2 + 4442.88S + 9869604.4}\right)$, results in a time delay of 0.000450 seconds for the signal at the roll frequency ranging from 0.01047 to 0.1047 rad/sec. Considering the RC components of the filter may deviate from its nominal values by 1-2%, the uncertainty of the time delay can be as much as 4% of the estimated value. Therefore, the uncertainty of the time delay of the ST science slope and intercept is approximately 0.02 milliseconds.

Considering the delays due to the analog filter and the Fwd SRE data acquisition, the effective data collection time of Science Telescope slope and intercept is determined with the vehicle time stamp of the minor frame of the telemetry monitor by the following algorithms:

$$\begin{aligned} &vehtime(\,ST\_SciSlopePX\_A\,) \\ &= vehtime\_MinorFrame - (\,0.3s - 0.052551s\,) - 0.000450s \\ &= vehtime\_MinorFrame - 0.247899s \end{aligned}$$

$$\begin{aligned} &vehtime(\,ST\_SciXceptPX\_A\,) \\ &= vehtime\_MinorFrame - 0.247899s \end{aligned}$$

$$\begin{aligned} &vehtime(\,ST\_SciSlopeMX\_A\,) \\ &= vehtime\_MinorFrame - (\,0.3s - 0.052633s\,) - 0.000450s \\ &= vehtime\_MinorFrame - 0.247817s \end{aligned}$$

$$\begin{aligned} &vehtime(\,ST\_SciXceptMX\_A\,) \\ &= vehtime\_MinorFrame - 0.247817s \end{aligned}$$

$$\begin{aligned} &vehtime(\,ST\_SciSlopePY\_A\,) \\ &= vehtime\_MinorFrame - (\,0.3s - 0.052702s\,) - 0.000450s \\ &= vehtime\_MinorFrame - 0.247748s \end{aligned}$$

$$\begin{aligned} &vehtime(\,ST\_SciXceptPY\_A\,) \\ &= vehtime\_MinorFrame - 0.247748s \end{aligned}$$

$$\begin{aligned} &vehtime(\,ST\_SciSlopeMY\_A\,) \\ &= vehtime\_MinorFrame - (\,0.3s - 0.052762s\,) - 0.000450s \\ &= vehtime\_MinorFrame - 0.247688s \end{aligned}$$

$$\begin{aligned} &vehtime(\,ST\_SciXceptMY\_A\,) \\ &= vehtime\_MinorFrame - 0.247688s \end{aligned}$$

$$\begin{aligned} &vehtime(\,ST\_SciSlopePX\_B\,) \\ &= vehtime\_MinorFrame - (\,0.3s - 0.052755s\,) - 0.000450s \\ &= vehtime\_MinorFrame - 0.247695s \end{aligned}$$

$$
\begin{aligned}
&vehtime(ST\_SciXceptPX\_B)\\
&= vehtime\_MinorFrame - 0.247695s
\end{aligned}
$$

$$
\begin{aligned}
&vehtime(ST\_SciSlopeMX\_B)\\
&= vehtime\_MinorFrame - (0.3s - 0.052800s) - 0.000450s\\
&= vehtime\_MinorFrame - 0.247650s
\end{aligned}
$$

$$
\begin{aligned}
&vehtime(ST\_SciXceptMX\_B)\\
&= vehtime\_MinorFrame - 0.247650s
\end{aligned}
$$

$$
\begin{aligned}
&vehtime(ST\_SciSlopePY\_B)\\
&= vehtime\_MinorFrame - (0.3s - 0.052841s) - 0.000450s\\
&= vehtime\_MinorFrame - 0.247609s
\end{aligned}
$$

$$
\begin{aligned}
&vehtime(ST\_SciXceptPY\_B)\\
&= vehtime\_MinorFrame - 0.247609s
\end{aligned}
$$

$$
\begin{aligned}
&vehtime(ST\_SciSlopeMY\_B)\\
&= vehtime\_MinorFrame - (0.3s - 0.052878s) - 0.000450s\\
&= vehtime\_MinorFrame - 0.247572s
\end{aligned}
$$

$$
\begin{aligned}
&vehtime(ST\_SciXceptMY\_B)\\
&= vehtime\_MinorFrame - 0.247572s
\end{aligned}
$$

where *vehtime(.)*" is the effective data collection vehicle time of the midpoint of the sampled data for the corresponding telemetry monitor of the ST Science Slope Estimation, and "*vehtime_MinorFrame*" is the vehicle time stamp of the minor frame of the telemetry monitor.

The Markov estimates are included in the 1Hz Science PIT Data Packets, as listed in the following table. Since they vary slowly, the time latency of the Markov estimates of the Science Telescope can be ignored.

PIT #	Word	Bit	Sybase Mnemonic	Description	Rate
12	3	0-15	ST_SciMarkPX_A ST_SciMarkPX_B	TRE-d, X+ Science Markov, 2's complement	0.5Hz
12	4	0-15	ST_SciMarkPY_A ST_SciMarkPY_B	TRE-d, Y+ Science Markov, 2's complement	0.5Hz
12	5	0-15	ST_SciMarkMX_A ST_SciMarkMX_B	TRE-d, X- Science Markov, 2's complement	0.5Hz
12	6	0-15	ST_SciMarkMY_A ST_SciMarkMY_B	TRE-d, Y- Science Markov, 2's complement	0.5Hz

Table 5-4 Telemetry Monitors of the ST Markov Estimates

5.8 Time Latency of the SQUID Science Lowpass Filter

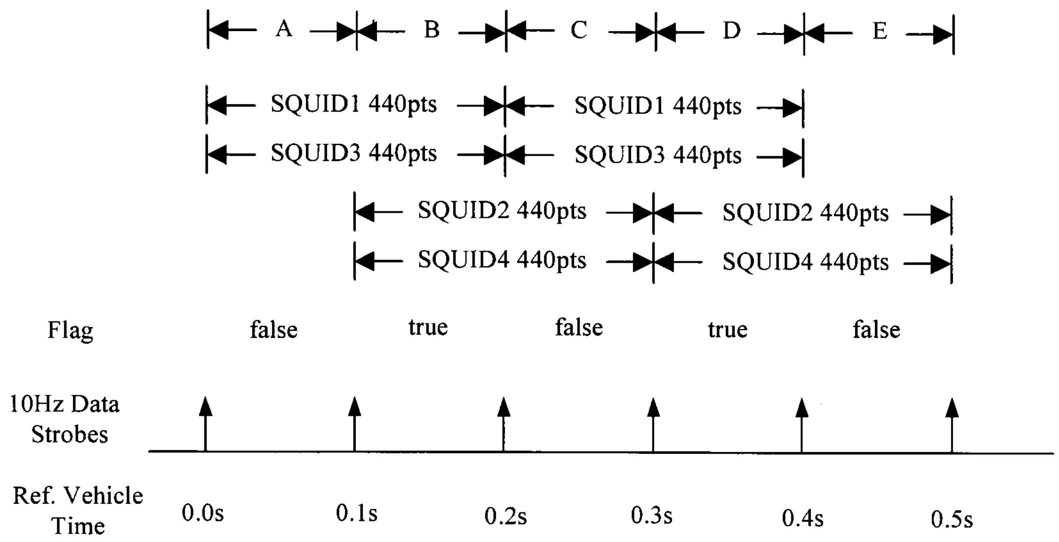


Fig. 5-4 Timeline of the SQUID Science Lowpass Filter

The “Science_Lowpass_Filter” application is a 10Hz process which performs the digital lowpass filtering of SQUID data. The data input consists of 2200Hz SQUID data after it has been analog lowpass filtered not to contain significant frequency content above 20Hz. Every 0.1 second 220 new points from each of the four SQUID data streams is collected, converted and pushed into one of four buffers of length 2200, moving the previous data further along the buffer and pushing out the 220 points representing the oldest data in the buffer. After 440 points have been collected, converted and pushed into the appropriate buffer, a window of length 2200 is applied to the buffer to produce one filtered output value. Thus the filtered output for each SQUID is at 5Hz and represents a weighted average of 2200 points containing 1760 old points and 440 new ones.

In order to distribute processor load more evenly the computations are staggered. During one 10Hz period two of the SQUIDs only collect data while the other two collect and window the data to get filtered output. In particular, the sequence is shown in Fig.5-2, Timeline of SQUID Science Lowpass Filter. When the flag is false(0), SQUID1 and SQUID3 collect data while SQUID2 and SQUID4 collect and process data. When the flag is true(1), SQUID1 and SQUID3 collect and process data while SQUID2 and SQUID4 collect data.

As illustrated in Fig.5-4, the timeline of the SQUID Science Lowpass Filter consists of the following 4 phases:

Phase A (reference vehicle time: 0.0s to 0.1s)

— Fwd SRE samples 220 data points of SQUID1, SQUID2, SQUID3 and SQUID4, respectively;

- SSW completes to collect 220 data points of SQUID1, SQUID2, SQUID3 and SQUID4, respectively, sampled from –0.1s to 0.0s;
- SSW updates the flag to "false(0)";
- SSW processes data of SQUID2 and SQUID4.

Phase B (reference vehicle time: 0.1s to 0.2s)

- SSW completes to collect 220 data points of SQUID1, SQUID2, SQUID3 and SQUID4, respectively, sampled from 0.0s to 0.1s;
- SSW updates the flag to "true(1)".
- SSW runs "Science_Lowpass_Filter" to compute a weighted average of 2200 points of SQUID1 and SQUID3 data, containing 1760 old points and 440 new ones. The 440 new points collected in Phase A and B are sampled from –0.1s to 0.1s. Therefore, the 2200 points of SQUID1 and SQUID3 data are sampled from –0.9s to 0.1s, with the midpoint approximately at –0.4s.
- SSW updates the 10Hz Science Data Packet, which includes the data as follows:

Word	**Bit**	**Sybase Mnemonic**	**Description**
3-4	0-31	SQ_SciLPasFilt1	SQUID 1 Science Digital Low Pass Filter MSB-LSBs
5-6	0-31	SQ_SciLPasFilt2	SQUID 2 Science Digital Low Pass Filter MSB-LSBs
7-8	0-31	SQ_SciLPasFilt3	SQUID 3 Science Digital Low Pass Filter MSB-LSBs
9-10	0-31	SQ_SciLPasFilt4	SQUID 4 Science Digital Low Pass Filter MSB-LSBs
31	8	PQ_SciData_Side	Beginning of 5Hz output computation from data of FWD SRE A or B side(0=Fwd SRE-A, 1=Fwd SRE-B)

Table 5-5 Telemetry Monitors of the SQUID Science Lowpass Filter

Phase C (reference vehicle time: 0.2s to 0.3s)

- SSW transfers the 10Hz Science Data Packet to CCCA through MIL-STD-1553;
- CCCA reads the 10Hz Science Data Packet.

Phase D (reference vehicle time: 0.3s to 0.4s) and
Phase E (reference vehicle time: 0.4s to 0.5s)

- Since the telemetry monitors "*SQ_SciLPasFilt1*" and "*SQ_SciLPasFilt3*" are updated at 5Hz, there are two possible ways to write them into the telemetry format table: one way is to write "*SQ_SciLPasFilt1*", "*SQ_SciLPasFilt3*" and "*PQ_SciData_Side*" into the minor frame of telemetry format table in Phase D, stamped with the reference vehicle time (0.3s), with the monitor "*PQ_SciData_Side*" to be "true(1)"; the other way is to write "*SQ_SciLPasFilt1*", "*SQ_SciLPasFilt3*" and "*PQ_SciData_Side*" into the minor frame of telemetry format table in Phase E, stamped with the reference vehicle time (0.4s), with the monitor "*PQ_SciData_Side*" to be "false(0)";.

Considering the different delays due to the analog filters and the Fwd SRE data acquisition, the effective data collection time of the midpoint of the sampled data for the SQUID Lowpass Filter is determined with the vehicle time stamp of the minor frame of the telemetry monitor by the following algorithms:

In case of telemetry monitors "*SQ_SciLPasFilt1*" and "*SQ_SciLPasFilt3*" attached with "*PQ_SciData_Side*" to be "true(1)", or telemetry monitors "*SQ_SciLPasFilt2*" and "*SQ_SciLPasFilt4*" attached with "*PQ_SciData_Side*" to be "false(0)",

$$\begin{aligned}
&\mathit{vehtime}(\,\mathit{SQ\_SciLPasFilt1}(2)\,)\\
&= \mathit{vehtime\_MinorFrame} - \{\,0.3s - [\,(-0.9s + 0.1s - 0.1s/220)*0.5 + 0.000191s\,]\,\}\\
&\qquad\qquad\qquad\qquad - 0.044323s\\
&= \mathit{vehtime\_MinorFrame} - \ 0.744359s
\end{aligned}$$

$$\begin{aligned}
&\mathit{vehtime}(\,\mathit{SQ\_SciLPasFilt3}(4)\,)\\
&= \mathit{vehtime\_MinorFrame} - \{\,0.3s - [\,(-0.9s + 0.1s - 0.1s/220)*0.5 + 0.000206s\,]\,\}\\
&\qquad\qquad\qquad\qquad - 0.044323s\\
&= \mathit{vehtime\_MinorFrame} - \ 0.744344s
\end{aligned}$$

In case of telemetry monitors "*SQ_SciLPasFilt1*" and "*SQ_SciLPasFilt3*" attached with "*PQ_SciData_Side*" to be "false(0)", or telemetry monitors "*SQ_SciLPasFilt2*" and "*SQ_SciLPasFilt4*" attached with "*PQ_SciData_Side*" to be "true(1)",

$$\begin{aligned}
&\mathit{vehtime}(\,\mathit{SQ\_SciLPasFilt1}(2)\,)\\
&= \mathit{vehtime\_MinorFrame} - \{\,0.4s - [\,(-0.9s + 0.1s - 0.1s/220)*0.5 + 0.000191s\,]\,\}\\
&\qquad\qquad\qquad\qquad - 0.044323s\\
&= \mathit{vehtime\_MinorFrame} - \ 0.844359s
\end{aligned}$$

$$\begin{aligned}
&\mathit{vehtime}(\,\mathit{SQ\_SciLPasFilt3}(4)\,)\\
&= \mathit{vehtime\_MinorFrame} - \{\,0.4s - [\,(-0.9s + 0.1s - 0.1s/220)*0.5 + 0.000206s\,]\,\}\\
&\qquad\qquad\qquad\qquad - 0.044323s\\
&= \mathit{vehtime\_MinorFrame} - \ 0.844344s
\end{aligned}$$

where "*vehtime(.)*" is the effective data collection vehicle time of the midpoint of the sampled data for the corresponding telemetry monitor of the SQUID Lowpass Filter, and "*vehtime_MinorFrame*" is the vehicle time stamp of the minor frame of the telemetry monitor.

5.9 Time Latency of the SQUID FFT Processing

The "FFTn" (n=1, 2, 3, 4) application is a 1Hz process which calculates the SQUID FFT in normal and decimated modes. The input data of the SQUID FFT processing is retrieved from the "SQUID_Science_Data" application.

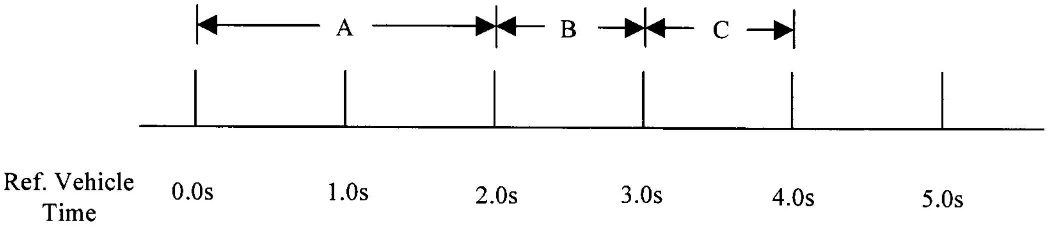


Fig.5-5 Timeline of the SQUID FFT Processing

As illustrated in Fig.5-5, the timeline of the SQUID FFT Processing consists of the following 3 phases:

Phase A (reference vehicle time: 0.0s to 2.0s)

- SSW collects science data points of SQUIDn (n=1, 2, 3, 4) through the application "SQUID_Science_Data";

Phase B (reference vehicle time: 2.0s to 3.0s)

- SSW completes to collect 4096 data points of the SQUIDn sampled from 0.0s to 2.0s, with the midpoint approximately at 1.0s;
- SSW runs "FFTn" to compute FFT of the SQUIDn;
- SSW updates the 1Hz Science PIT Data Packets. Besides the harmonics of the SQUIDn, the 1Hz Science PIT Data Packets also include the data as follows:

PIT #	**Word**	**Bit**	**Sybase Mnemonic**	**Description**
2	29-30	0-31	SQ_FFT_32VT_1 SQ_FFT_32VT_3	SQUID n (n=1, 3) FFT sample vehicle time, bit 31-0
2	31	0-7	SQ_FFT_8VT_1 SQ_FFT_8VT_3	SQUID n (n=1, 3) FFT sample vehicle time, bit 39-32
5	29-30	0-31	SQ_FFT_32VT_2 SQ_FFT_32VT_4	SQUID n (n=2, 4) FFT sample vehicle time, bit 31-0
5	31	0-7	SQ_FFT_8VT_2 SQ_FFT_8VT_4	SQUID n (n=2, 4) FFT sample vehicle time, bit 39-32

Table 5-6 Telemetry Monitors of the SQUID FFT Sample Time

In the telemetry format table, the 32-bit monitors "SQ_FFT_32VT_*n*" (*n*=1, 2, 3, 4) are abbreviated to the 8-bit monitors "SQ_FFT_VtmByt_*n*", which are the 8 LSBs of the integer part of the FFT sample vehicle time of SQUID *n*.

Phase C (reference vehicle time: 3.0s to 4.0s)

- SSW transfers the 1Hz Science PIT Data Packets to CCCA through MIL-STD-1553;
- CCCA reads the 1Hz Science PIT Data Packets.
- CCCA distributes the SQUIDn FFT harmonics and the sample vehicle time into telemetry monitors.

Considering the different delays due to the analog filters and the Fwd SRE data acquisition, the effective data collection time of the midpoint of the SQUID FFT data samples is determined with the corresponding telemetry monitor of the FFT sample vehicle time by the following algorithms:

$$
\begin{aligned}
&\mathit{Vehtime\_SQUIDFFT\_1(2)}\\
&= \mathit{SQ\_FFT\_32VT\_1(2)} + \mathit{SQ\_FFT\_8VT\_1(2)} - 0.000325s\\
&\qquad + \{\,[152*0.1s/220+(152+4096-1)*0.1s/220]*0.5 + 0.000221s - 1.0s\}\\
&= \mathit{SQ\_FFT\_32VT\_1(2)} + \mathit{SQ\_FFT\_8VT\_1(2)} - 0.000331s
\end{aligned}
$$

$$
\begin{aligned}
&\mathit{vehtime\_SQUIDFFT\_3(4)}\\
&= \mathit{SQ\_FFT\_32VT\_3(4)} + \mathit{SQ\_FFT\_8VT\_3(4)} - 0.000325s\\
&\qquad + \{\,[152*0.1s/220+(152+4096-1)*0.1s/220]*0.5 + 0.000235s - 1.0s\}\\
&= \mathit{SQ\_FFT\_32VT\_3(4)} + \mathit{SQ\_FFT\_8VT\_3(4)} + 0.000333s
\end{aligned}
$$

where "*vehtime_SQUIDFFT_n*" is the effective data collection vehicle time of the midpoint of the sampled SQUIDn FFT data.

6. Gyro Suspension System (GSS)

The Gyro Suspension System (GSS) timing is discussed in the reference document S0876 “GSS Timing”.

7. Star Sensor

The telemetry monitors of the star sensors consists of two parts: one part is the processed results of the Attitude and Translation Control (ATC) system, which are updated at 10Hz and include the telemetry monitors of the vehicle timestamp, command roll angle, roll reference, attitude error estimate, rate filter output, etc., the other part is the filtered star sensor data, which are updated every 10 seconds and include the vehicle timestamp, centroid time tag, centroid horizontal component, centroid vertical component, star magnitude, etc.

The timing of the telemetry monitors of the ATC system will be discussed in other documents. In the following of this document we will focus on the timing of the filtered star sensor data.

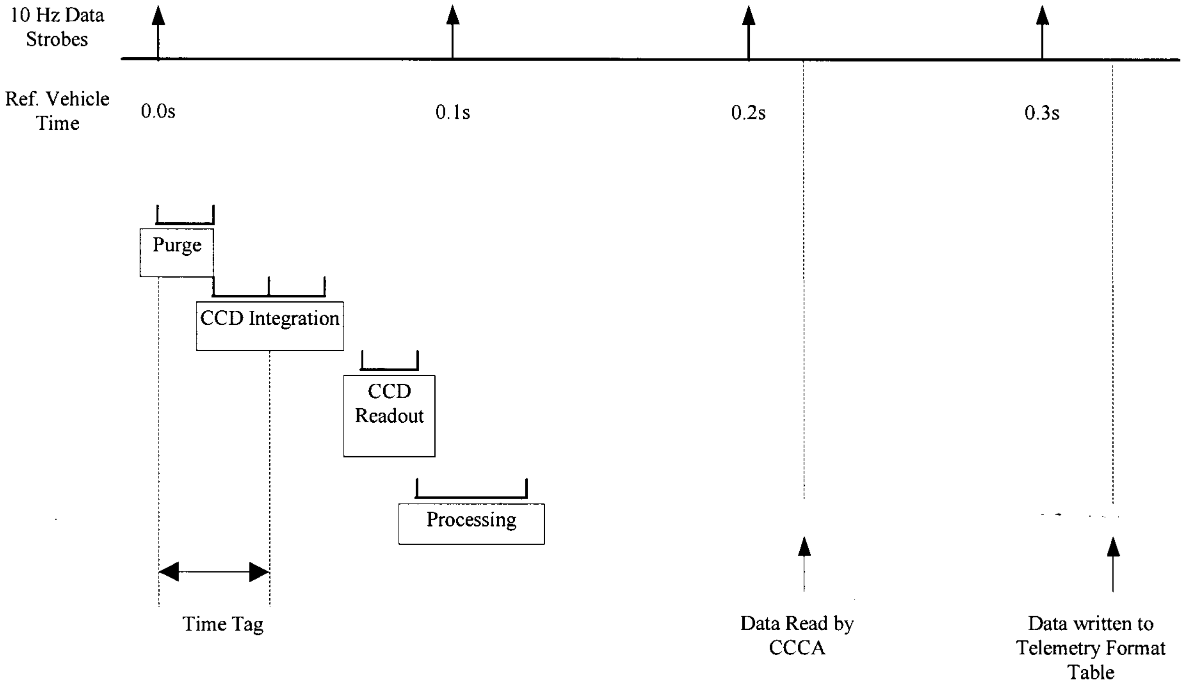


Fig.7-1 Star Sensor Data Processing Timeline

Fig.7-1 shows the diagram of the star sensor data processing timeline. As shown in the figure, a time tag provided in the filtered star sensor data identifies the time at the center of integration of the reported centroid data referenced from the leading edge of the external synch signal, i.e., the 10 Hz Data Strobe. This time-tag has a resolution of 20 microseconds and an accuracy of +/-40 microseconds.

Therefore, the effective data collection time of the Star Sensor is determined with the vehicle time stamp of the minor frame of the telemetry monitors as follows:

$$\begin{aligned} & vehtime\_StarSensor \\ &= vehtime\_MinorFrame - \{0.3s - TimeTag*0.00002s\} \\ &= vehtime\_MinorFrame - 0.3s + TimeTag*0.00002s \end{aligned}$$

where "*vehtime_StarSensor*" is the effective Star Sensor data collection vehicle time, "*vehtime_MinorFrame*" is the vehicle time stamp of the minor frame of the telemetry monitor, and "*TimeTag*" is the time-tag in decimal.

The telemetry monitors of the filtered star sensor data will be determined later.

8. Experiment Control Unit (ECU)

The Experiment Control Unit (ECU) interface operates at 10Hz. The A/D converters are sampled on every 10Hz strobe. The data is nominally sampled based on a telemetry sampling table for each ADC. ADC 1A/1B, 2A/2B and 3A/3B have sampling tables with lengths of 50 parameters, 50 parameters, and 100 parameters, respectively. Each individual data parameter is read once for each entry in the sampling table and in the order listed. The multiplexer reset rates for ADC 1A/1B, 2A/2B and 3A/3B are 2 seconds, 0.1 seconds and 0.1 seconds, respectively.

In the flight software of GP-B, the vehicle time is expressed as a 40-bit fixed point number, the upper 32 bits (LSB=1s) give the integer part of the vehicle time, and the lower 8 bits give the fractional part (LSB=2^{-8}s) of the vehicle time. In order to save the telemetry, only 16 bits of the sampling vehicle time of the first parameter of each sampling table is transmitted to the ground through the science telemetry format table, which include the 8 least significant bits of the integer part and 8 bits of fractional part of the vehicle time. The full sampling vehicle time of the first parameter of the sampling table can be recovered with the algorithm described below.

After data pre-processing on the ground, the following derived telemetry monitors are available for the sampling vehicle time of the first parameter of the sampling tables of ECU:

Sybase Mnemonic	**Description**
PE_VehTime_LSB1	8 LSBs of integer part of sampling vehicle time of the first parameter of the sampling table for ADC 1A/1B (ranging from 0 to 255)
PE_VehTimeFrac1	Fractional part of sampling vehicle time of the first parameter of the sampling table for ADC 1A/1B (taking values from { 0, 26, 51, ... 230 })
PE_VehTime_LSB2	8 LSBs of integer part of sampling vehicle time of the first parameter of the sampling table for ADC 2A/2B (ranging from 0 to 255)
PE_VehTimeFrac2	Fractional part of sampling vehicle time of the first parameter of the sampling table for ADC 2A/2B (taking values from { 0, 26, 51, ... 230 })
PE_VehTime_LSB3	8 LSBs of integer part of sampling vehicle time of the first parameter of the sampling table for ADC 3A/3B (ranging from 0 to 255)
PE_VehTimeFrac3	Fractional part of sampling vehicle time of the first parameter of the sampling table for ADC 3A/3B (taking values from { 0, 26, 51, ... 230 })

Table 8-1 Derived Telemetry Monitors of the Sampling Vehicle Time of ECU

In the telemetry format table, the 8-bit monitors "PE_VehTime_LSB*n*" and the 8-bit monitors "PE_VehTimeFrac*n*" are combined into the 16-bit parent monitors "SE_VehTime_ADC*n*" (*n*=1, 2, 3).

Let "*vehtime_MinorFrame_n*" (*n*=1, 2, 3) be the vehicle time stamp of the minor frame of the 16 bit telemetry monitor of the sampling vehicle time, then the full sampling vehicle time of the first parameter of the *n*-th sampling table "*vehtime_Para_n_1*" is given by the following codes:

```
vehtime_buf_n = floor(vehtime_MinorFrame_n/256)*256 +
                PE_VehTime_LSBn + floor(PE_VehTimeFracn*10/256+0.5)*0.1;
if ( vehtime_buf_n > vehtime_MinorFrame_n )
        vehtime_Para_n_1 = vehtime_buf_n – 256;
else
        vehtime_Para_n_1 = vehtime_buf_n;
end
```

where $floor\{\cdot\}$ is a function which rounds a real number to the nearest integer towards minus infinity.

Therefore, the vehicle time of data collection of the *i*-th parameter of the *n*-th sampling table is

$$vehtime\_Para\_n\_i = vehtime\_Para\_n\_1 + (i-1)*UpdatePeriod\_n + 0.1s$$

where

$n = 1, 2, 3$
$UpdatePeriod\_1 = 2.0s$
$UpdatePeriod\_2 = 0.1s$
$UpdatePeriod\_3 = 0.1s$

It should be noted that the sampling time of the ECU monitors depends on the ECU sample table used. ECU sample tables, e.g., science sample table, IOC sample table, flux reduction sample table, LTB sample table, etc., are discussed in the reference document S0922 "ECU Sample Tables".

Note:

There is an analog lowpass filter with the transfer function $\left(\frac{1}{0.014S^2+0.12S+1}\right)$ in the sampling channels of monitors "TE_QBS_a__GT10P" and "TE_QBS_b__GT11P", which causes a time delay of 0.120 seconds for the signal at the period of 180 seconds. There is an analog lowpass filter with the transfer function $\left(\frac{1}{0.00846S^2+0.094S+1}\right)$ in the sampling channels of all other GRT monitors, which causes a time delay of 0.094 seconds for the signal at the period of 180 seconds. Considering the RC components of the filters may deviate from their nominal values by 1-2%, the uncertainties of the time delay can be as much as 4% of the estimated values. Therefore, the uncertainties of the time delays of the sampling channels of monitors "TE_QBS_a__GT10P" and "TE_QBS_b__GT11P" and the sampling channels of all other GRT monitors are approximately 5 milliseconds and 4 milliseconds, respectively.

9. Conclusions

The science data of GP-B transmitted to the ground station through the programmable telemetry are stamped with the vehicle time at which the data is placed into the minor frame of the telemetry format table. However, for the purpose of science data analyses and processing, the time of the data collection is required. The time latency between the data collection and the time stamp depends on how the data are collected and processed, how they are transferred to CCCA and how they are written to the telemetry format table. In this document, the timing system of each component of GP-B is discussed in detail and algorithms are given to determine the effective vehicle time of the collection of each science data.

Acronym List

ACE	Attitude Control Electronics
A/D	Analog/Digital
ADC	Analog/Digital Converter
AMT	Aft Monitor and Timing
ARP	Attitude Reference Platform
ATC	Attitude and Translation Control
CCCA	Command/Control Computer Assembly
CCSDS	Consultant Committee for Space Data Systems
CDHS	Command and Data Handling System
CEF	Control Effort Filter
CMD	Command
CTU	Command and Telemetry Unit
D/A	Digital/Analog
DAS	Data Acquisition System
EBI	Expansion Bus Interface
ECEF	Earth-Centered Earth-Fixed
ECU	Experiment Control Unit
EVF	Electrode Voltage Filter
FAB	Forward-Aft Bus
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
FPGA	Field Programmable Gate Array
FWD	Forward
GP-B	Gravity Probe B
GPS	Global Positioning System
GSS	Gyro Suspension System
GSW	GSS Software
HSS	High Speed Serial
I/O	Input/Output
IOC	Initial Orbit Checkout
IU	Interface Unit
LSB	Least Significant Bit
LSW	Least Significant Word
LTB	Low Temperature Bakeout
MSB	Most Significant Bit
MSW	Most Significant Word
PIT	Processor Interface Table
P/L	Payload
PLL	Phase Loop Locked
PP	Payload Processor
PPS	Pulse Per Second

PSF	Gyro Position Filter
RAM	Random Access Memory
RTD	Read Trigger Delay
S/C	Spacecraft
SM	Science Mission
SQUID	Superconducting Quantum Interference Device
SRE	SQUID Readout Electronics
SRS	Sample Rate Select
SSR	Solid State Recorder
SSW	SQUID/ST Software
ST	Science Telescope
TRE	Telescope Readout Electronics
VT	Vehicle Time