LUNAR RECONNAISSANCE ORBITER PROJECT
CONFIGURATION CHANGE REQUEST

CCR: 431-CCR-000129	**DATE INITIATED**: 2/6/2006	**CCR REV.:**	**CCR REV DATE**: ___________
CCB SECRETARY: DEB YODER	**PROPRIETARY?** ☐ Yes ☒ No	**ITAR SENSTIVE?** ☐ Yes ☒ No	**CCR DUE DATE**: 3/20/2006

CCR TITLE (Brief Description): RELEASE BASELINE VERSION OF LUNAR RECONNAISSANCE ORBITER TIMING SPECIFICATION

ORIGINATOR NAME: Stephen Andrews **E-MAIL: Stephen.Andrews@nasa.gov**	**CODE/ORG.:** 595/GSFC **PHONE:** 301-286-3143
SPONSOR NAME: Philip Luers **E-MAIL:** PHILIP.LUERS@NASA.GOV	**CODE/ORG.:** 561/GSFC **PHONE:** 301-286-5151
EXTERNAL ORGANIZATION CCR#:	**EXTERNAL ORGANIZATION:**

DOCUMENT (INCLUDE THE DOC. # AND TITLE), CONTRACT, SOFTWARE AFFECTED:

431-SPEC-000212 LUNAR RECONNAISSANCE ORBITER TIMING SPECIFICATION

EFFECTIVITY: ☐ ALL ☐ ACS ☐ ACS ANALYSIS ☒ C&DH ☐ COMMUNICATIONS ☒ ELECT. HARNESS ☐ FLT DYNAMICS ☐ GN&C ☒ I&T ☐ LAUNCH VEHICLE ☐ MECHANICAL ☐ MECH. ANALYSIS ☐ EGSE ☐ MGSE ☒ SPACECRAFT ☐ THERMAL ☐ MASS ☒ PAYLOAD/INSTR. ☐ POWER ☐ PROPULSION ☒ SOFTWARE ☒ FLIGHT OPS ☐ WGHT ☒ GND SYS ☐ OTHER ______________

Change Class	**Criticality**	COST? ☒ **NO** ☐ **YES**	**If yes, select one basis for estimate:**			
☒ Class I ☐ Class II	☐ Emergency ☐ Urgent ☒ Routine	☐ **In-House**	☐ **Actuals**	☐ **ROM**	☐ **Historical Averages**	☐ **Other****
		** If "Other" is chosen for the Basis of Estimate, please explain in Proposed Solution box below:				

PROBLEM:

The draft baseline version of the Lunar Reconnaissance Orbiter Timing Specification (431-SPEC-000212) requires baselining by the Level 3 (LRO) CCB.

PROPOSED SOLUTION:

Release the baseline version of the Lunar Reconnaissance Orbiter Timing Specification (431-SPEC-000212) by the Level 3 (LRO) CCB. Future changes will be initiated by submittal of CCRs. The LRO CMO/Code 431 shall maintain this document.

TYPE OF CHANGE: ☐ Schedule ☐ Interface ☒ Document ☐ Waiver ☐ Deviation ☐ Contract ☐ Other ______________

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BOARD ACTION: ☐ APPROVED ☐ APPROVED WITH CHANGE ☐ DISAPPROVED ☐ WITHDRAWN ☐ DEFERRED

Comments

CCB APPROVAL LEVEL REQUIRED [Check appropriate box(es)]:

☐	LEVEL 1 NASA HQ	**Signature:**	**Date:**
☐	LEVEL 2 RLEP -Ames	**Signature:**	**Date:**
☒	LEVEL 3 LRO - GSFC	**Signature:**	**Date:**

431-SPEC-000212
Revision -
Effective Date: To be added upon Release
Expiration Date: To be added upon Release

DRAFT

Lunar Reconnaissance Orbiter Project

Timing Specification

February 14, 2006

Goddard Space Flight Center
Greenbelt, Maryland

National Aeronautics and Space Administration

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CM FOREWORD

This document is a Lunar Reconnaissance Orbiter (LRO) Project Configuration Management (CM)-controlled document. Changes to this document require prior approval of the applicable Configuration Control Board (CCB) Chairperson or designee. Proposed changes shall be submitted to the LRO CM Office (CMO), along with supportive material justifying the proposed change. Changes to this document will be made by complete revision.

Questions or comments concerning this document should be addressed to:

LRO Configuration Management Office
Mail Stop 431
Goddard Space Flight Center
Greenbelt, Maryland 20771

Signature Page

Prepared by:

______________________________ __________

Stephen Andrews Date
LRO System Engineer
GSFC/NASA, Code 595

Reviewed by:

______________________________ __________

Dave Everett Date
LRO Mission Systems Engineer
GSFC/NASA, Code 599

Approved by:

______________________________ __________

Craig Tooley Date
LRO Project Manager
GSFC/NASA, Code 431

LUNAR RECONNAISSANCE ORBITER PROJECT

DOCUMENT CHANGE RECORD

Sheet: 1 of 1

REV LEVEL	DESCRIPTION OF CHANGE	APPROVED BY	DATE APPROVED
Rev-			

List of TBDs/TBRs

Item No.	Location	Summary	Ind./Org.	Due Date
1	3.5.2	TBR: MET Register Read Interval	M. Blau/ GSFC	10/01/2006
2	1.2, 2.2.1	TBD: LOLA Timing Requirements Document Number	X. Sun/ GSFC	10/01/2006

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1.0 INTRODUCTION

This specification was written to document all aspects of timekeeping on the Lunar Reconnaissance Orbiter (LRO). The Command and Data Handling (C&DH) system will act as the spacecraft (SC) "master clock keeper" and has the responsibility of distributing the correct time to all other instruments and subsystems.

1.1 SCOPE

The purpose of this document is to explain the requirements on the SC and ground systems, and also to describe a chosen implementation that will be used on LRO.

1.2 DOCUMENTS

1.2.1 Applicable Documents

431-RQMT-000004	Lunar Reconnaissance Orbiter Mission Requirements Document
431-SPEC-000008	Lunar Reconnaissance Orbiter Electrical System Specification

1.2.2 Reference Documents

431-REF-000505	Solar Dynamics Observatory (SDO) Project Spacecraft Timing Interface Control Document (464-CDH-ICD-0057)
431-REF-000506	ST-5 Timekeeping A description of the timekeeping requirements and the Systems that are proposed for use on ST-5 (ST5-495-132)
TBD	Time Keeping and Clock Oscillator Performance Requirement for the Lunar Orbiter Laser Altimeter (LOLA)

1.3 TERMINOLOGY

UTC	Coordinated Universal Time, ground time maintained by the U.S. Naval Observatory (USNO).
SC UT	SC time, formulated from hardware counters and software values.
Clock Correlation	Procedure used to generate knowledge of difference between SC UT and UTC.
MET	Mission Elapsed Time. A SC hardware counter composed of a seconds portion and a sub seconds portion.
STCF	Spacecraft Time Correction Factor. STCF is a parameter that is updated and uplinked as needed to reduce the difference between SC UT and UTC.
Leap Seconds	Seconds added to UTC to keep it within 0.9 seconds of astronomical time.

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Frequency Drift	Change in frequency of the SC C&DH oscillator.
Clock Drift	Change in difference between SC UT and UTC.

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2.0 TIMING REQUIREMENTS

This section describes the Level 2 timing requirements, and shows their rationale.

2.1 PERFORMANCE REQUIREMENTS

Two requirements, MRD-42 and MRD-43 (Refer to Lunar Reconnaissance Orbiter Mission Requirements Document (431-RQMT-000004), define the timing performance for LRO. The post-processed timing knowledge requirement is 3 ms relative to UTC, and the maximum real-time timing accuracy requirement is 100 ms relative to UTC.

A graphical representation of these requirements is shown in Figure 2-1 as a plot of SC time and TC. If the onboard clock is perfect, SC time and UTC will always be the same, and the plot of SC time vs. UTC would be a straight line at a 45-degree angle. The two dashed lines at a 45-degree angle represent the maximum allowed drift at any given time. The expanded part of the plot shows that the knowledge error represents the difference between where the onboard clock really was and where the (linear) correlation thought it was. The vertical lines on the plot represent the effect of the time correction performed from the ground. At each correction, the SC time is adjusted to match UTC.

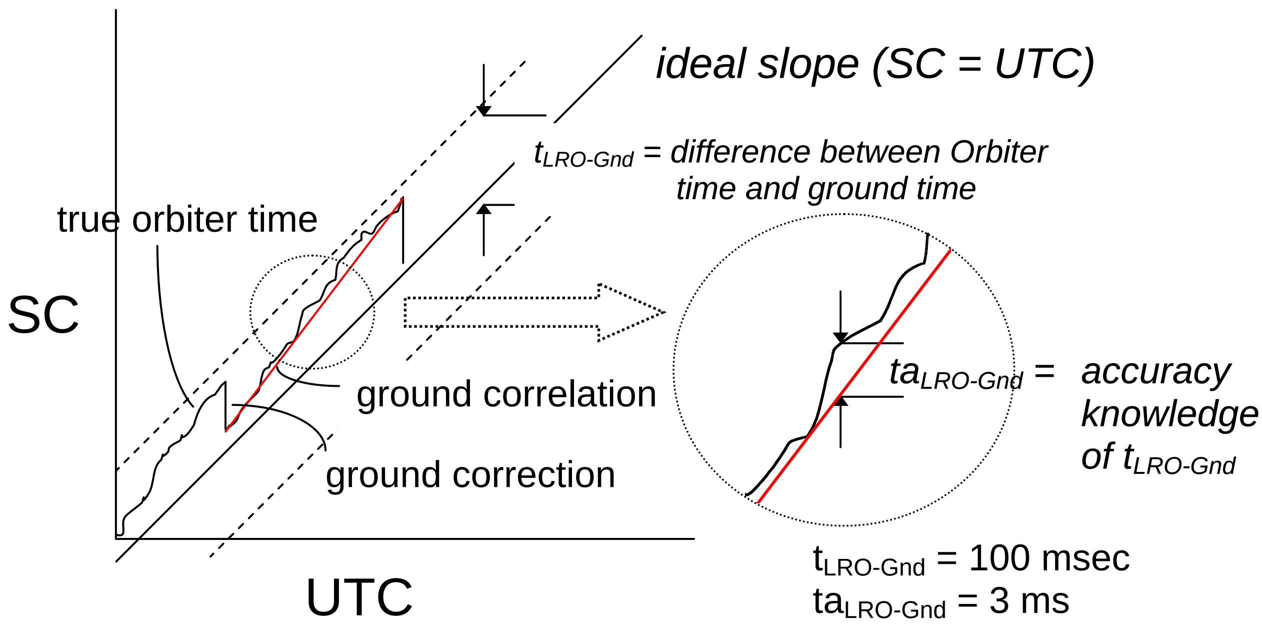

Figure 2-1. Illustrated Timing Requirements

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2.2 SCIENCE RATIONALE

2.2.1 Knowledge Rationale

See the Time Keeping and Clock Oscillator Performance Requirement for the Lunar Orbiter Laser Altimeter (LOLA) (Document # TBD) for a more complete description of the Lunar Orbiter Laser Altimeter (LOLA) timing requirements. LOLA has to time stamp its laser pulse emission time to an accuracy of 3 ms so that the uncertainty in the laser spot location is less than the size of the footprint (5 m diameter). This requirement is equivalent to the product of the timing error and the SC ground speed being less than the laser footprint size. A pictorial representation of this requirement for one pulse of LOLA is shown in Figure 2-2. The black circles are the true footprints, and the red footprints show reconstructed footprints that meet the accuracy required by the reconstruction.

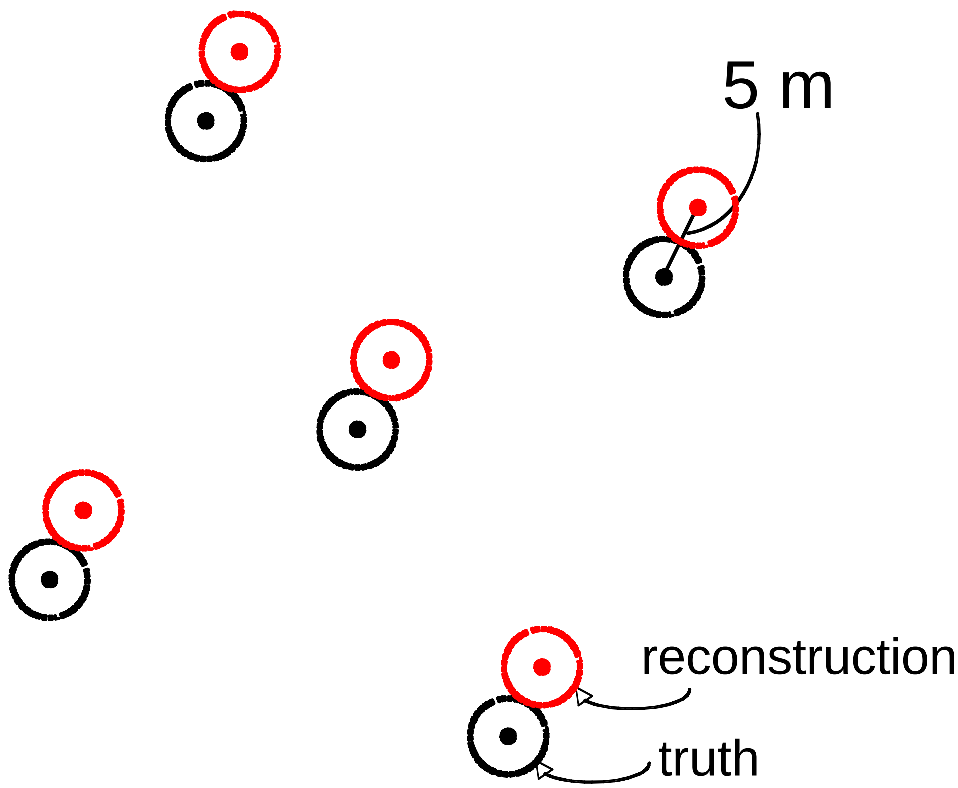

Figure 2-2. LOLA Footprint Reconstruction Accuracy

In its simplest terms, the error in timing has to allow for 5 m of ground track error. Given a nominal ground speed of 1610 m/s at 50 km altitude, the allowable timing error is 3.1 ms, which is rounded down to 3 ms, relative to UTC. This is all derivable after the fact.

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2.2.2 Drift Rationale

If the SC clock is allowed to drift no more than 100 ms from UTC, then the absolute and relative time command sequences one-second intervals will be accurate to 100 ms. Specifically, the Lunar Reconnaissance Orbiter Camera (LROC) wants the time of the rising edge of the SpaceWire TickOut signal to be accurately reported by a corresponding time message to +/- 100 milliseconds of UTC. This reduces predictive orbital position errors, which affects LROC's ability to successfully target the NAC at sites of interest. At 1.6 km/s orbital velocity, this timing drift will result in a maximum ground track error of 160 m.

In addition, since LROC is limited in the number of images per orbit it can take by buffer readout, sometimes LROC will take numerous smaller images (in terms of # of lines) rather than the full ~50,000 line images. For instance, LROC will take a 5000 line image then wait a few seconds and get a 10,000 line image, then wait 20 seconds and get a 5000 line image. Timing knowledge of 100 msec is line knowledge of +/- 300 lines, and allows more precise knowledge and control of image location within the camera.

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3.0 IMPLEMENTATION

3.1 SPACECRAFT OSCILLATOR IMPLEMENTATION

If the clock frequency drift is estimated every day, the accuracy of each estimate is 3ms/(24hr*3600sec/hr) = 3.5e-8, which would satisfy the LOLA altimetry requirement (<1e-7; see Ref. 3). In addition, the clock needs to be stable to << 3.5e-8/day (parts per billion stability) over the expected environmental temperature ranges. The drift and stability requirements require the use of an ultra-stable oscillator (USO). One type of USO is a design called an oven controlled crystal oscillator (OCXO), shown in Figure 3-1. An "oven" that keeps the crystal at a near constant temperature surrounds the oscillator.

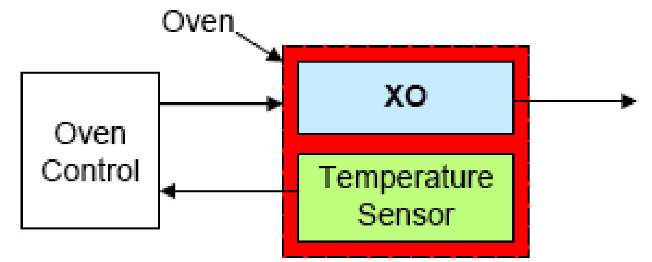

Figure 3-1. Oven Controlled Crystal Oscillator

Another type of USO is a design called a double oven controlled crystal oscillator (DOCXO), shown in Figure 3-2. Two "ovens" that keep the crystal at a near constant temperature surround the oscillator.

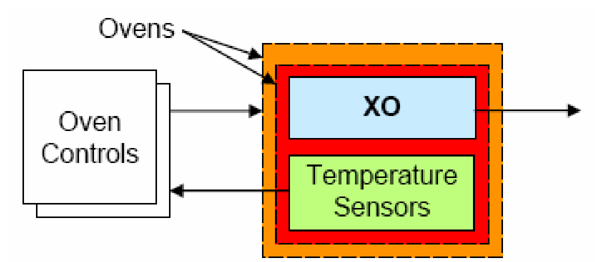

Figure 3-2. Double Oven Controlled Crystal Oscillator

For reliability purposes, there will be two USOs in the C&DH (one of each kind), each with two outputs, operating at 20 MHz. The outputs drive the C&DH (Mission Elapsed Time [MET] and 1 pulse per second [PPS]) and LOLA timing. Since the C&DH will power and control the USOs, there are no USOs in the LOLA instrument. Two coaxial harnesses will be used to send the signals to drive LOLA. The redundant units prevent a single failure from ending the mission or ending the use of LOLA, or both.

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This system, illustrated in simplified form in

Figure 3-3, increases the reliability for the C&DH and LOLA for a simpler LOLA design: there no additional synchronization necessary between the 1 pps and the LOLA 28 Hertz (Hz) laser firing. One of the oscillators will be used as a cold backup.

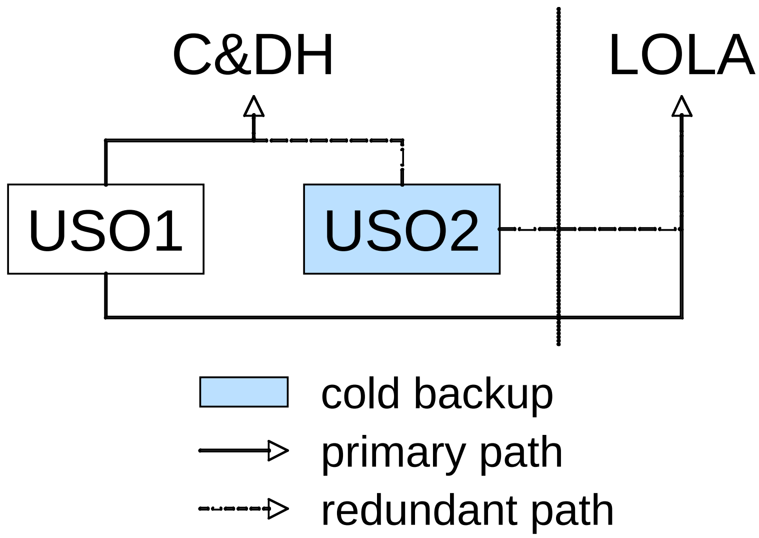

Figure 3-3. Simplified Oscillator Block Diagram

For context, the complete timekeeping architecture is shown in Figure 3-4.

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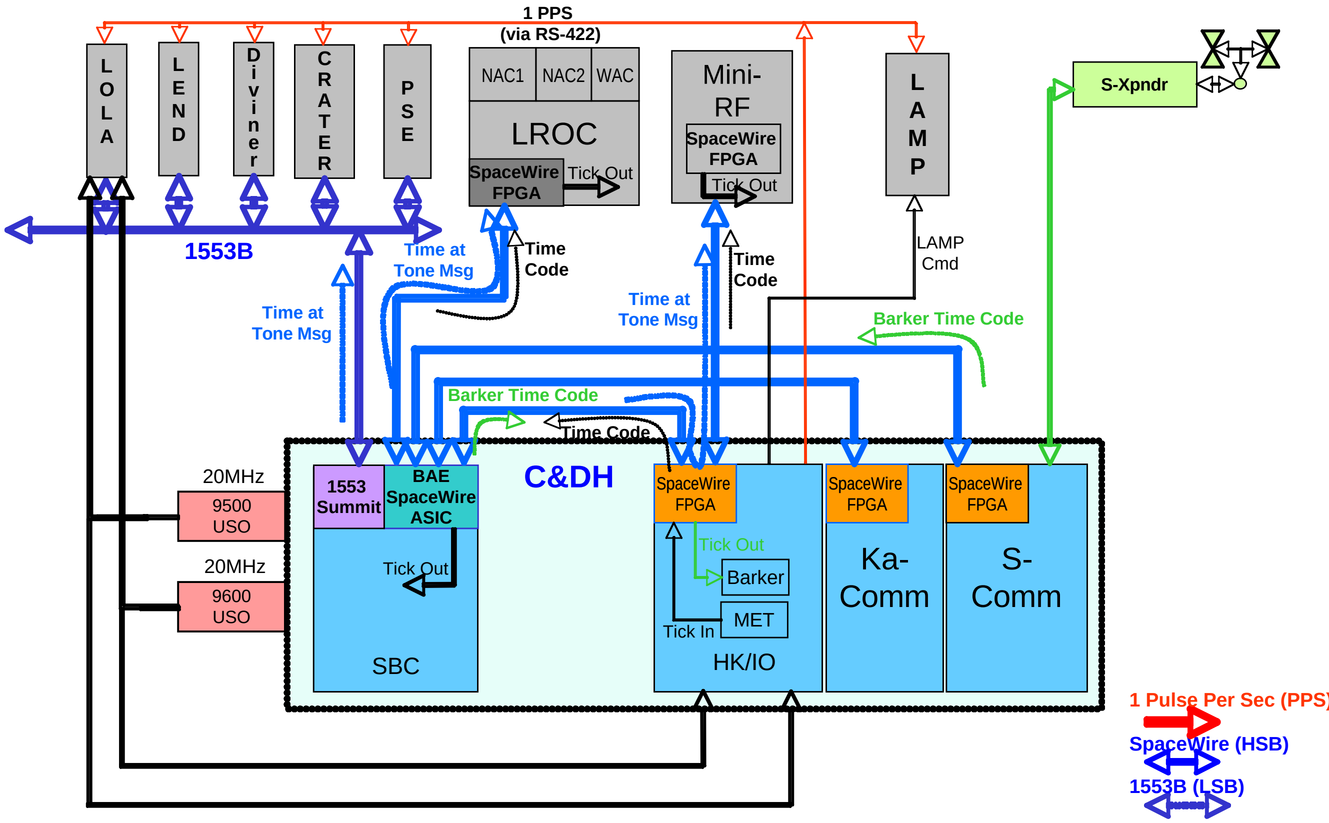

Figure 3-4. LRO Timekeeping Architecture Block Diagram

3.2 TIME DISTRIBUTION

SC master time distribution will be done over the 1553 low speed data bus and the SpaceWire high speed data bus. This will be accomplished using the USO in the C&DH as the SC Master Clock Keeper. The Housekeeping card is responsible for the 1 PPS signal distribution and for maintaining the MET time (second and subseconds). The SBC is responsible for distributing the SC time message corresponding to the 1 PPS. The time tone and time message concept discussed in the next sections is illustrated in Figure 3-5.

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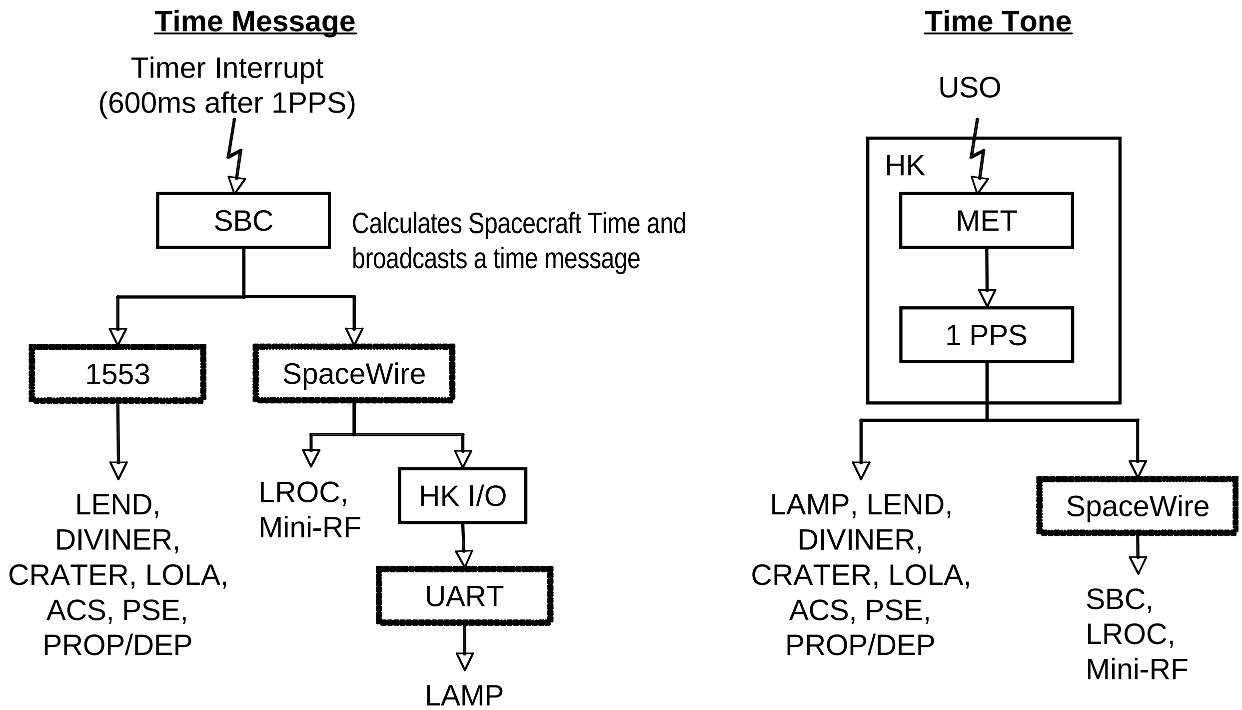

Figure 3-5. C&DH System Architecture Time Marking Concept

3.2.1 Mission Elapsed Timer

Upon power up of LRO, the C&DH will track the time of the mission with a Mission Elapsed Timer on the Housekeeping (HK) board that will not rollover for more than 136 years. There is a 32-bit counter for seconds resolution, and a 16-bit counter for subseconds. The subseconds counter will roll over every second. The seconds and subseconds counters will be registered simultaneously, and will be accessible to flight software via the SpaceWire interface as a register read.

3.2.2 Pulse Per Second

The HK assembly will generate a 1 PPS signal derived from the USO. This 1 PPS will provide timing synchronization to LAMP, LEND, Diviner, CRaTER, and LOLA on the Orbiter. Flight software will send a command to the instruments via the 1553 bus that will be a time that will be accepted at the next rising edge of the 1 PPS signal. In essence, the command will be interpreted by the instruments as "at the tone (1PPS or SpaceWire TimeCode) the time will be x". Tone refers to the rising edge of the 1 PPS. The 1 PPS will be distributed via RS-422 per the Electrical Systems Specification (431-SPEC-000008).

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3.2.3 SpaceWire Time Code

The SpaceWire time code generation feature will be used to provide timing synchronization to LROC and Mini-RF. The 1PPS generated on the HK assembly will be connected to TickIn input pin of the SpaceWire core on the HK assembly. This will cause a time code packet to be sent across the SpaceWire network. The result is a pulse that is generated on the TickOut pin on the SpaceWire router cores of the assemblies that require timing synchronization. Flight software will send a SpaceWire command to the required instruments. The contents of that command will be a time that will be accepted by the instruments at the next TickOut. In essence, the command packet will be interpreted by the instruments as “at the tone the time will be x”. Tone refers to the rising edge of the TickOut signal at the output of the instrument’s SpaceWire router core.

3.3 GROUND SYSTEM IMPLEMENTATION

Time on the ground, and SC time displayed on the ground, is usually in YY-DDD-hh:mm:ss format; times in this format can be attached to SC commands in an Absolute Time Sequence (ATS) input file to the ATS load generator. The ATS load generator is a piece of software in the MOC that takes those inputs and converts them to the format that the SC expects to see.

3.4 FLIGHT SOFTWARE IMPLEMENTATION

Flight software calculates SC time from the hardware MET seconds and the main processor subseconds counter. The hardware MET comes across SpaceWire, and the subseconds counter exists on the RAD750 processor where the flight software resides. The MET seconds are added to the processor subseconds to create a current time. The STCF, both seconds and subseconds, is then added to the current time to compute the current SC time that is used onboard. When the time correlation is performed (discussed in the next section), the MET seconds and subseconds is added to the STCF, both seconds and subseconds, to create the Barker time, which is the time the last command was received by the SC. The differences detected in the correlation are used to update the STCF onboard the SC. This is graphically illustrated in Figure 3-6.

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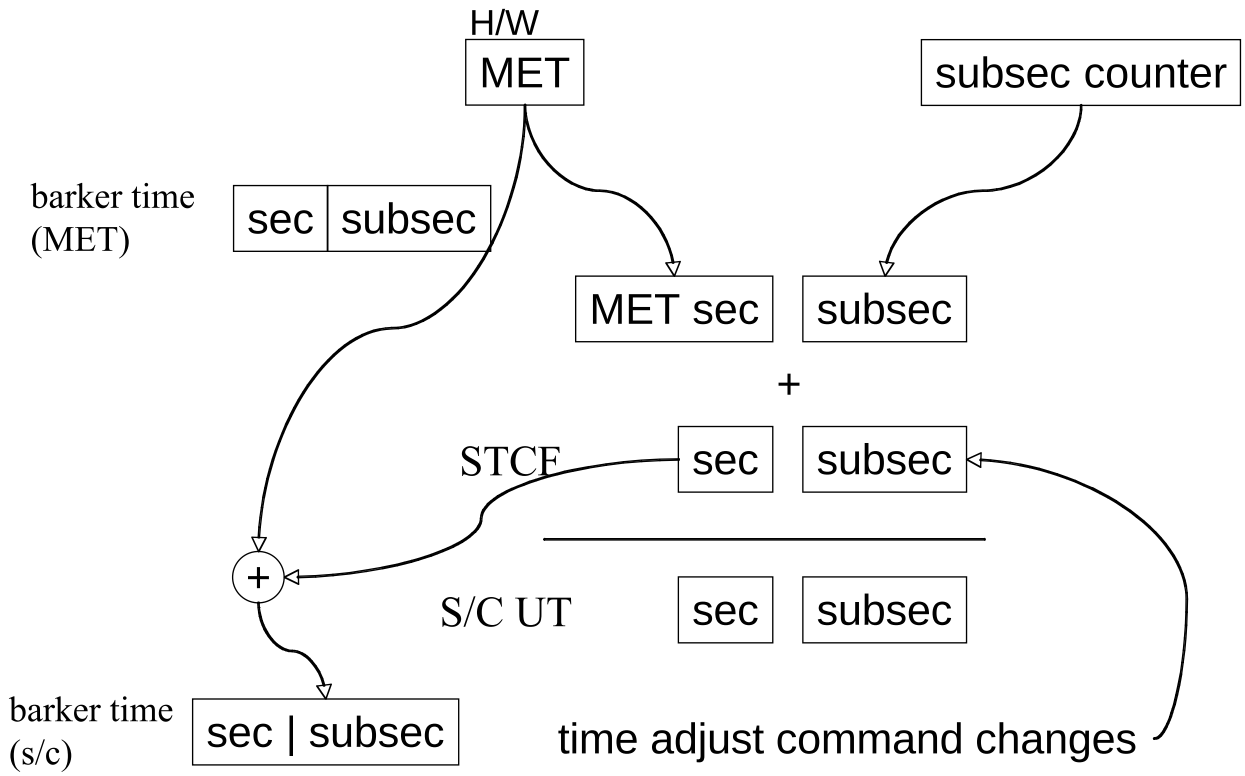

Figure 3-6. Flight Software Time Calculations

3.5 TIME CORRELATION

Time correlation is the measure of the difference between ground time and SC time. The LRO SC maintains time in a combination of both hardware and software. The flight software uses the hardware counters, the MET, and the Spacecraft Time Correction Factor (STCF) (which includes leap seconds) to represent one single value, the SC UT. The SC time will drift because the clock oscillator frequency is not stable due to changing temperature and aging of the oscillator. Using an ultra-stable oscillator (USO) will minimize these effects. In addition, if any leap seconds are added during the mission, the FOT will schedule a time adjustment command of one second to occur at midnight on the day the leap second gets added. Mechanisms exist to adjust the SC UT to reduce SC UT drift with respect to UTC. The hardware supports the SC UT to UTC correlation method that will meet the overall mission time accuracy requirements.

3.5.1 <u>Time Correlation Overview</u>

The SC clock correlation is performed by taking the difference between the time stamps of when a command left the ground station and when the SC receives the command. The ground station has an accurate clock it uses as the time standard. Using the value of the clock and the delays in

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the system, the ground system can figure out the time, relative to the ground time, that the SC command was received.

Every command in the uplink stream is time-tagged on the ground, and the SC telemeters the time associated with the receipt of the last ground command. Comparing these two times, while taking into account delays through hardware and the actual transmission time, will indicate how far ahead or behind UTC the LRO SC clock is.

The formula the operations team will use is listed below:

$$\Delta Time = GrndCmdTime - scCmdTime - xferTime - errorfactor$$

where

GrndCmdTime	command time stamp, supplied by ground
scCmdTime	spacecraft time stamp of the latest ground command received
xferTime	time associated with transmission of command to spacecraft
errorfactor	other known sources of error (or delays)

Reducing the error in ΔTime to 3 ms requires reducing the errors in the entire system, which will be discussed in the next few sections.

3.5.2 Time Correlation Details

The S-Band Comm Card provides time correlation by detecting the start sequence of a received command codeblock (0xEB90). The command decoder on the S-Band Comm Card will then generate a digital pulse to the SpaceWire chip, called TickIn. The SpaceWire chip, in turn, generates a timecode message across the SpaceWire links via a TickOut pulse on the TickOut pin of the SpaceWire core on the Housekeeping I/O assembly. The timecode is a SpaceWire specific feature. All devices on the SpaceWire network will receive the timecode message and decode it. The TickIn signal is asserted on the HK card because the SpaceWire chip on that board will see and decode the timecode message. This in turn will cause the HK hardware to register the current contents of the MET to a status register. The flight software will then have an opportunity to read out the saved value of the MET seconds and subseconds and use it for a correlation algorithm. The flight software will routinely gather the contents of the MET register every 8 or 16 seconds (**TBR**). The ground system (MOC) must wait those 8 or 16 seconds before sending another command to make a valid measurement. A simplified block diagram is shown in Figure 3-7.

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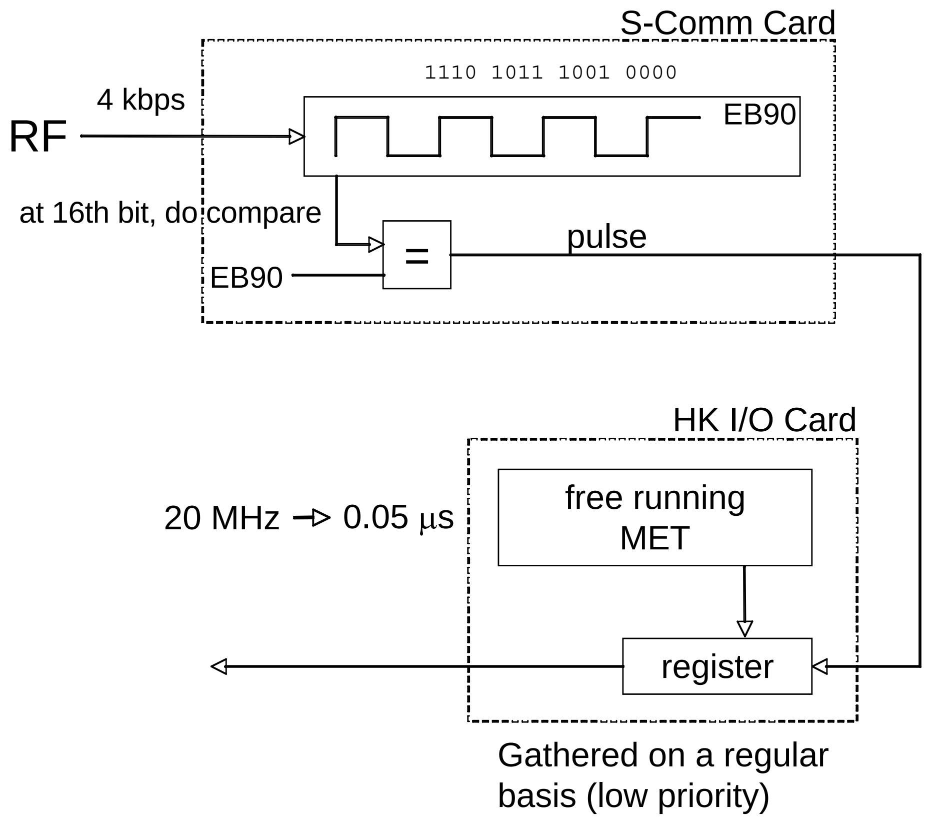

Figure 3-7. Time Correlation Spacecraft Block Diagram

3.5.3 <u>Error Factors</u>

The error factors are divided between the ground system, the SC, and the transmission between the two. The time correlation is only as good as the knowledge of the errors in each part of the correlation process. Summarized results are shown in Table 3-1.

3.5.3.1 Spacecraft Delays

There is some delay between the moment the Orbiter receives the radio frequency (RF) signal containing the command and the latching of the MET time in the HK Card. It can be broken down like this:

- 0xEB90 serial pattern detect - 16 clock periods of the uplink command rate (4 milliseconds for a 4 Kbps clock, uncertainty = 0.25 ms)
- Assert the TickIn signal to the SpaceWire chip - less than 1 microsecond
- SpaceWire chip broadcasts timecode signal across network - 1 microsecond
  Time to assert TickOut on HK card - less than 1 microsecond.
- Time to latch MET time into storage register - less than 1 microsecond.

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This is a how long it takes the command detect to propagate to the MET time latch. All values, with the exception of the TickIn assert, are all reasonably fixed and can be safely subtracted from a correlation computation. The only issue with the TickIn assert is that the time it takes for the SpaceWire chip to inject a timecode onto the network largely depends on when it actually gets to transmitting the actual timecode while the network is busy (e.g. the transmit link is already busy doing something else, so the timecode insertion will have to wait until the transmit path is clear again).

3.5.3.2 Transmission Delays

The time-of-flight of the packet from the ground to the SC and back must be taken into account. The Flight Dynamics Facility will provide predictions of the range from the LRO to the ground station during each pass in the form of a Range File. The errors in this file are dominated by orbit determination errors, and will be larger in real-time than they will be in post-processing. The definitive OD requirement of 1500 m (3σ) is equivalent to a timing error of about 5 μs.

3.5.3.3 Ground System Delays

At the selected ground station, when a command is sent to the SC, the command system must get a timetag for the command header from a timing source. Errors in this part of the system may be 50 – 100 μs. There are additional smaller error factors that could add another 100 μs delay into the system.

Table 3-1. Time Correlation Error Budget

Budget Item	Allocation (msec)	CBE (msec)	Comment
Spacecraft Errors			
Detect 0xEB90		0.2500	1-bit at 4Kbps
SpaceWire broadcast		0.0075	S-Comm to SBC to HK I/O
Sample MET		0.0153	MET subsecond resolution
1PPS TimeCode Broadcast		0.0050	HK I/O to SBC to LROC
	1.0000	*0.2778*	*Total Spacecraft*
Ground System Errors			
GrndCmdTime		0.1000	timetag error in ground system
errorfactor		0.1000	other known sources of delays in ground system
	1.0000	*0.2000*	*Total Ground System*
Other Errors			
xferTime		0.0050	from range error; assumes correlation is done soon after onboard ephemeris update
	1.0000	*0.0050*	*Total Other*
Total	**3.0000**	**0.4828**	**Total Timing Error**

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Appendix A. Abbreviations and Acronyms

Abbreviation/ Acronym	DEFINITION
ACS	Attitude Control System
ASIC	Application-Specific Integrated Circuit
C&DH	Command & Data Handling
CBE	Current Best Estimate
CCB	Configuration Control Board
CM	Configuration Management
CMO	Configuration Management Office
DOCXO	Double Oven Controlled Crystal Oscillator
FPGA	Field Programmable Gate Array
HK	Housekeeping
HSB	High Speed Bus (SpaceWire)
Hz	Hertz
ICD	Interface Control Document
km/s	kilometer per second
LAMP	Lyman Alpha Mapping Project
LEND	Lunar Exploration Neutron Detector
LOLA	Lunar Orbiter Laser Altimeter
LRO	Lunar Reconnaissance Orbiter
LROC	Lunar Reconnaissance Orbiter Camera
LSB	Low Speed Bus (1553)
m	meter
m/s	meter per second
MET	Mission Elapsed Time, Mission Elapsed Timer
MHz	megahertz
MRD	Mission Requirements Document
ms	millisecond
NAC	Narrow Angle Camera
OCXO	Oven Controlled Crystal Oscillator
PPS	Pulse Per Second
PSE	Power Switching Electronics
RF	Radio Frequency
RLEP	Robotic Lunar Exploration Program
SC	spacecraft
SBC	Single Board Computer
SDO	Solar Dynamics Observatory
ST-5	Space Technology – 5
STCF	Spacecraft Time Correction Factor
UART	Universal Asynchronous Receiver Transmitter

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Abbreviation/ Acronym	**DEFINITION**
USNO	United States Naval Observatory
USO	Ultra-Stable oscillator
UTC	Universal Time Coordinated

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