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Lunar Reconnaissance Orbiter Project

Pointing and Alignment Specification

LRO GSFC CMO

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RELEASED

Goddard Space Flight Center
Greenbelt, Maryland

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CM FOREWORD

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LUNAR RECONNAISSANCE ORBITER PROJECT

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1.0 INTRODUCTION

The Lunar Reconnaissance Orbiter mission is focused on obtaining new data that will facilitate returning humans safely to the Moon. This mission will launch late in 2008 and will acquire measurements of the Moon for at least one year.

LRO has seven instruments to perform its exploration measurements: Cosmic Ray Telescope for the Effects of Radiation (CRaTER), Diviner Lunar Radiometer Experiment (DLRE), Lyman-Alpha Mapping Project (LAMP), Lunar Exploration Neutron Detector (LEND), Lunar Orbiter Laser Altimeter (LOLA), the Lunar Reconnaissance Orbiter Camera (LROC), and the Mini-RF. LRO also has two deployable structures the High Gain Antenna and the Solar Array.

1.1 SCOPE

The purpose of this document is to define the pointing requirements and allocations for each of the LRO Instruments, the Solar Array and the High Gain Antenna.

1.2 APPLICABLE DOCUMENTS

431-RQMT-00004	LRO Mission Requirements Document
431-PLAN-000100	LRO Integration and Test Plan
431-SPEC-000162	LRO GN&C ACS Specifications Document
431-PLAN-000111	LRO Alignment Plan

1.3 UNITS

All pointing budgets will be shown in both arc-seconds and micro-radians. All budgets are 3 sigma or worst case allocations. They are also half cone or +/- budgets.

2.0 COORDINATE SYSTEM

The reference coordinate system for the LRO is show in figure 2.1. The origin for this coordinate system is at a center of the spacecraft/Launch Vehicle interface. The X axis is pointed in the main thrust direction of the orbiter. The X axis is always aligned with the velocity vector although half of the year the velocity vector is in the –X direction. The Z axis is pointed in the nadir, instrument aperture, direction and the Y axis completes the right handed coordinate system. All allocations are requirements are defined in this coordinate system.

The primary star tracker reference frame is the reference frame to which the attitude, rate and star position data are referenced to.

Assuming small angle approximations (applicable within the spacecraft pointing accuracy of +/-60 arc sec per axis), the spacecraft x axis attitude error is the roll angle about the velocity vector, the spacecraft y axis attitude error is the pitch angle measured with respect to the velocity vector and the z axis attitude error is the yaw angle measured with respect to the velocity vector.

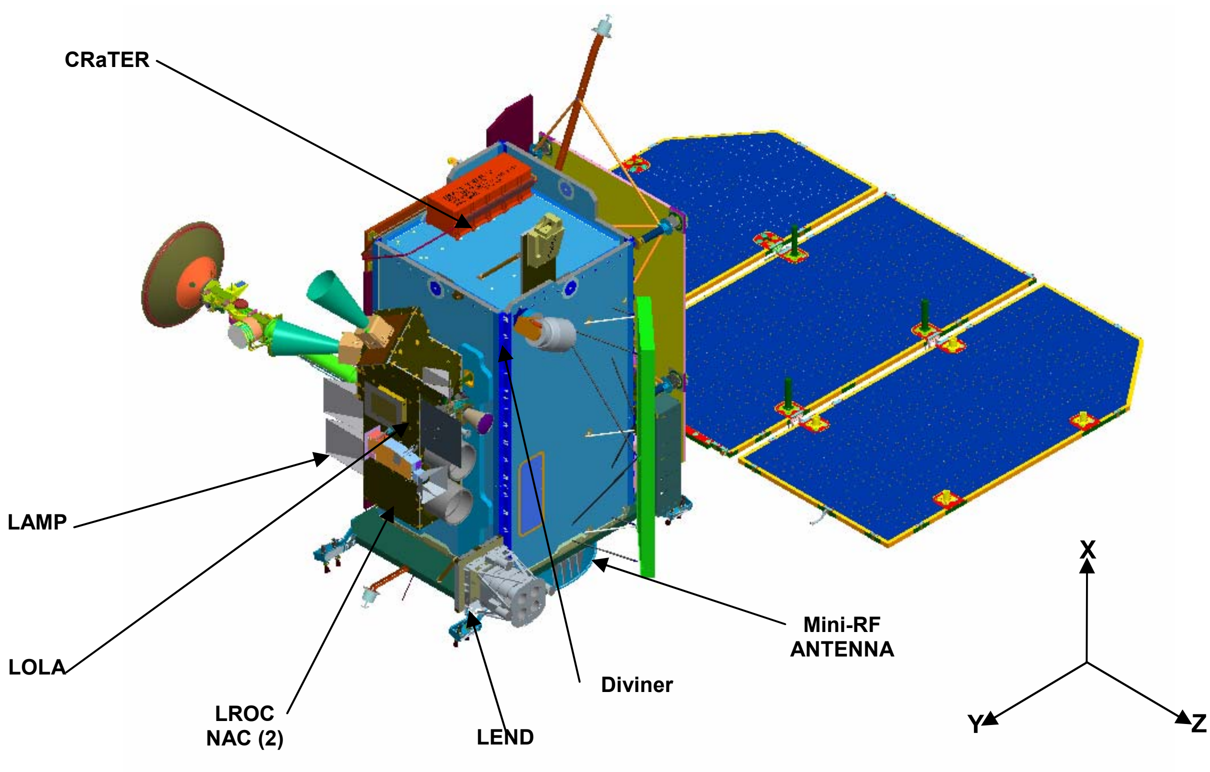

Figure 2-1: LRO Coordinate System

3.0 MAPPING AND POINTING DEFINITIONS

3.1 SOURCES OF MAPPING ERRORS

To produce a global lunar map, the principal investigator for each instrument needs to know where on the Moon the data from their instrument was collected. Before a map of lunar data can be constructed, the principal investigators and the spacecraft developers need to understand the sources of error in the map of each data set. To simplify this task, the problem is to be broken down into smaller parts. This makes it easier to distinguish, track and control each source of error. This mapping problem can be broken down in several ways.

The first way to break down the problem is to distinguish between mapping accuracy and mapping knowledge. ***Mapping accuracy*** is the ability of the spacecraft and instrument to collect a piece of data from a particular location on the Moon. Mapping accuracy is the ability to control and predict where the instrument boresight will be pointed before and during the collection of a particular piece of data. In other words, mapping accuracy is how well the instrument-spacecraft system can take a picture of a particular target. Mapping accuracy affects how the instrument-spacecraft system is operated. ***Mapping knowledge*** is the ability to determine where the instrument boresight was pointed when a particular piece of data was collected. Mapping knowledge affects the quality of the data product produced by an instrument team.

A second way to break down the mapping problem is to distinguish between spacecraft trajectory and spacecraft pointing. The ***trajectory*** portion of the mapping problem refers to the ability to determine, control and predict the location of the spacecraft center of mass relative to the surface of the Moon when a particular piece of data is collected. Spacecraft trajectory is the linear portion of the mapping problem. Errors in estimating spacecraft trajectory result in errors in spacecraft position. ***Pointing*** is the portion of the mapping problem that refers to the ability to determine and control the direction of a particular axis of the spacecraft, namely the direction of an instrument's boresight. Pointing is the angular portion of the mapping problem. Errors in pointing affect the direction of an instruments boresight. Figure 3-1 illustrates the difference between errors in spacecraft trajectory and spacecraft pointing.

The ***trajectory*** portion of the mapping problem has several components; orbit determination, spacecraft ephemeris, and timing. ***Orbit determination*** is calculating the trajectory of the spacecraft center of mass after tracking data has been collected. *Orbit determination errors* are the difference between the true trajectory of the spacecraft center of mass and the estimated trajectory of the center of mass. Spacecraft ***ephemeris*** is predicting where the trajectory of the spacecraft center of mass will be at some point in the future. Because figuring out where the spacecraft center of mass will be starts with where the spacecraft center of mass was, spacecraft ephemeris can never be more accurate than spacecraft trajectory estimated through orbit determination. ***Ephemeris errors*** are the difference between where the spacecraft center of mass is predicted to be and where the spacecraft center of mass actually goes. Spacecraft ephemeris predictions are periodically updated with new orbit determination data. Between updates, spacecraft ephemeris errors grow. This is especially true in the direction of the spacecraft velocity vector. Figure 3-2 illustrates orbit determination and spacecraft ephemeris errors.

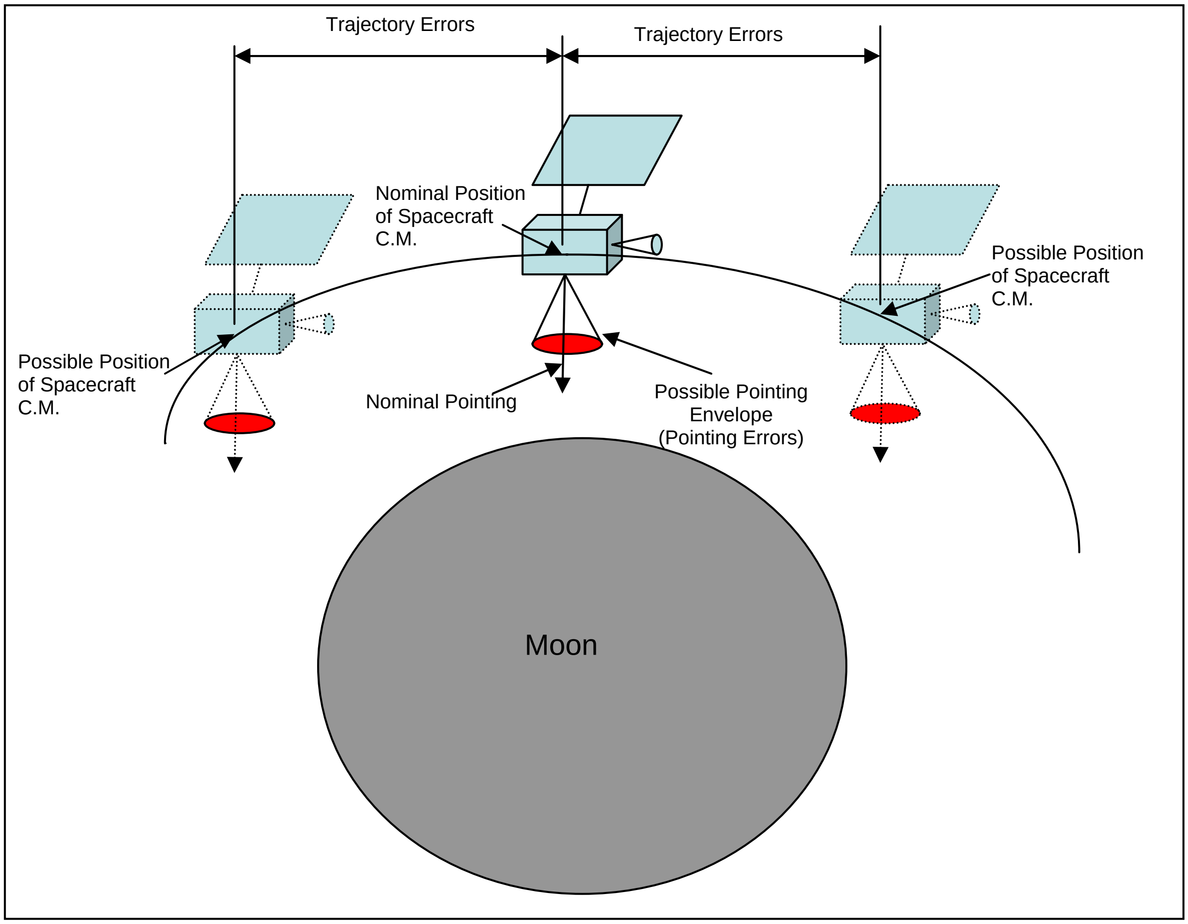

Figure 3-1: Spacecraft Trajectory and Pointing

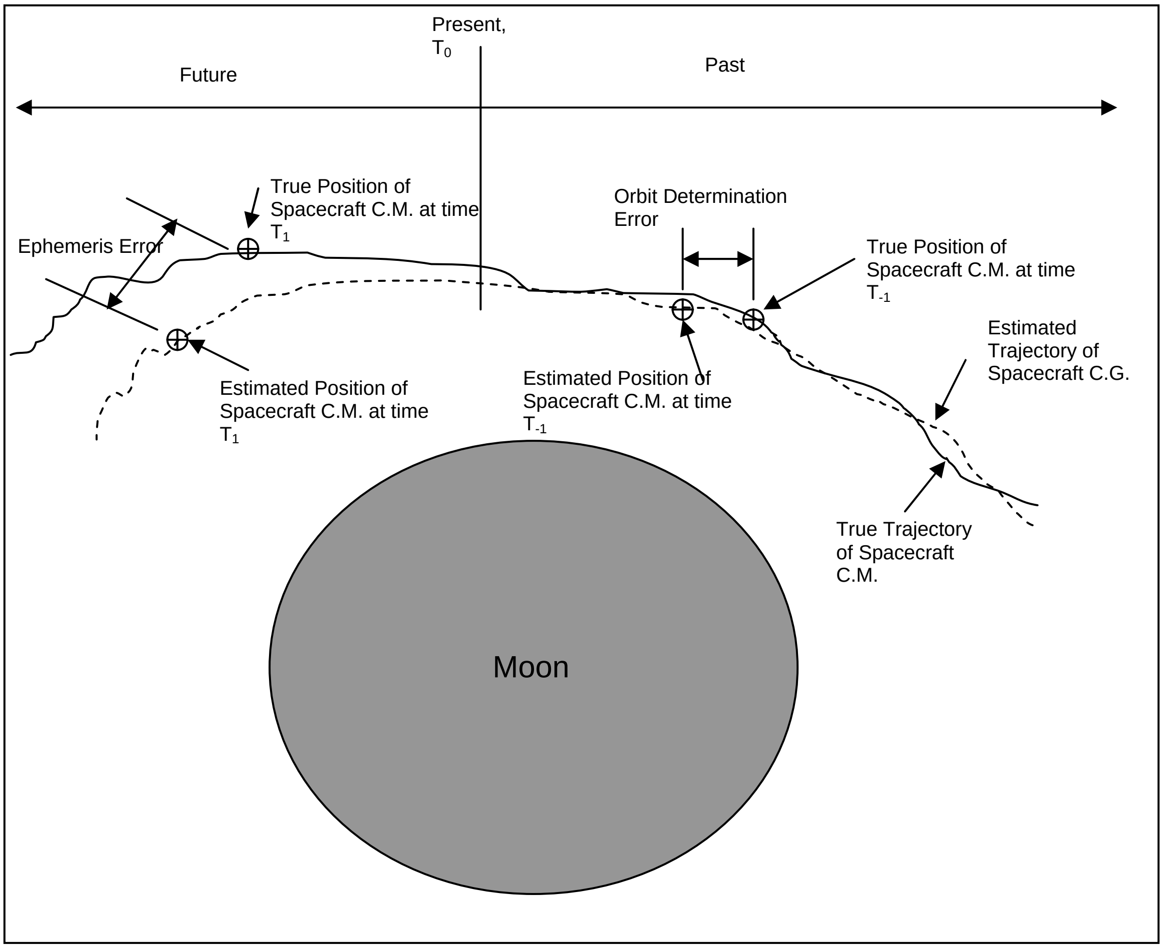

Figure 3-2: Spacecraft Orbit Determination and Ephemeris

Timing errors also affect the knowledge of spacecraft trajectory. The biggest contributor to such errors is due to the fact that clocks at the ground stations used to track the spacecraft and the clock on the spacecraft do not exactly match each other. This mismatch results in a small difference between the time stamp of a particular observation and the time stamp on the spacecraft trajectory. Timing errors cause trajectory errors mostly in the direction of the spacecraft velocity vector. Figure 3-3 illustrates the effect of timing error.

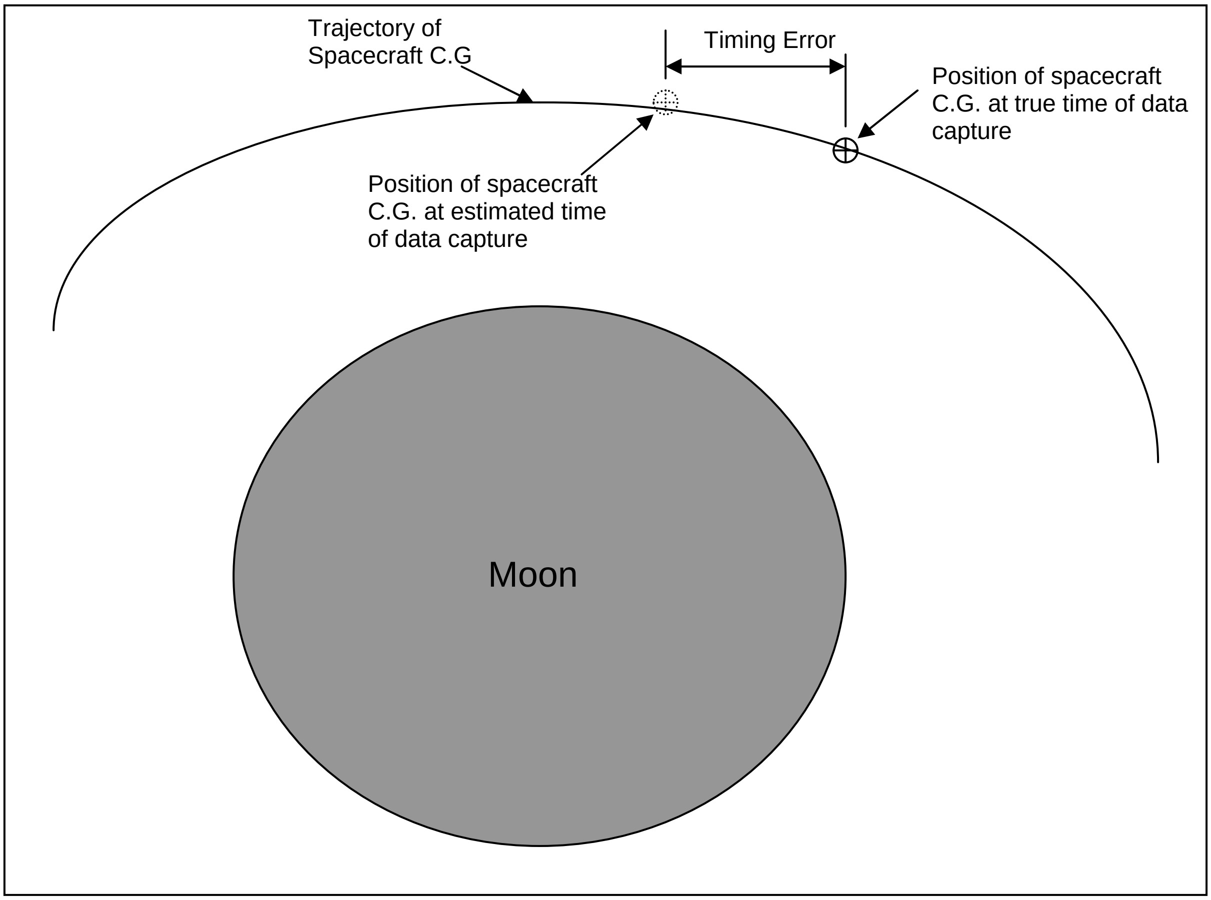

Figure 3-3: Spacecraft Timing Error Effects

The other major piece of the mapping problem is pointing. There are two major components to pointing. They are spacecraft Attitude Control System (ACS) pointing and alignment. ***ACS pointing*** is defined as how well LRO's attitude control system can control the spacecraft reference frame relative to inertial space. The ACS controls the rigid body rotations of the spacecraft. ***Alignment*** is defined as how well the boresight of a particular instrument is aligned with the spacecraft reference frame. Alignment errors are caused by the construction and deflections of the spacecraft and instrument structures. In normal mapping mode, the LRO spacecraft will point the Z axis of the spacecraft toward the center on the Moon. Figure 3-4 illustrates the difference between ACS pointing and spacecraft/instrument alignment errors.

ACS pointing accuracy is the difference between the actual pointing of the spacecraft and the true location of the target. ACS pointing accuracy is affected by two things, ACS knowledge and ACS control. ***ACS knowledge*** is how well the spacecraft ACS can determine the orientation of the spacecraft reference frame in inertial space. ***ACS control*** is how well the ACS system can control the orientation of the spacecraft reference frame relative to a desired target in inertial space. The Attitude Control System can only estimate the location of the desired target in inertial space. Therefore ACS accuracy, the difference between the actual pointing of the spacecraft and the true location of the target, includes both the errors in ACS control and ACS knowledge.

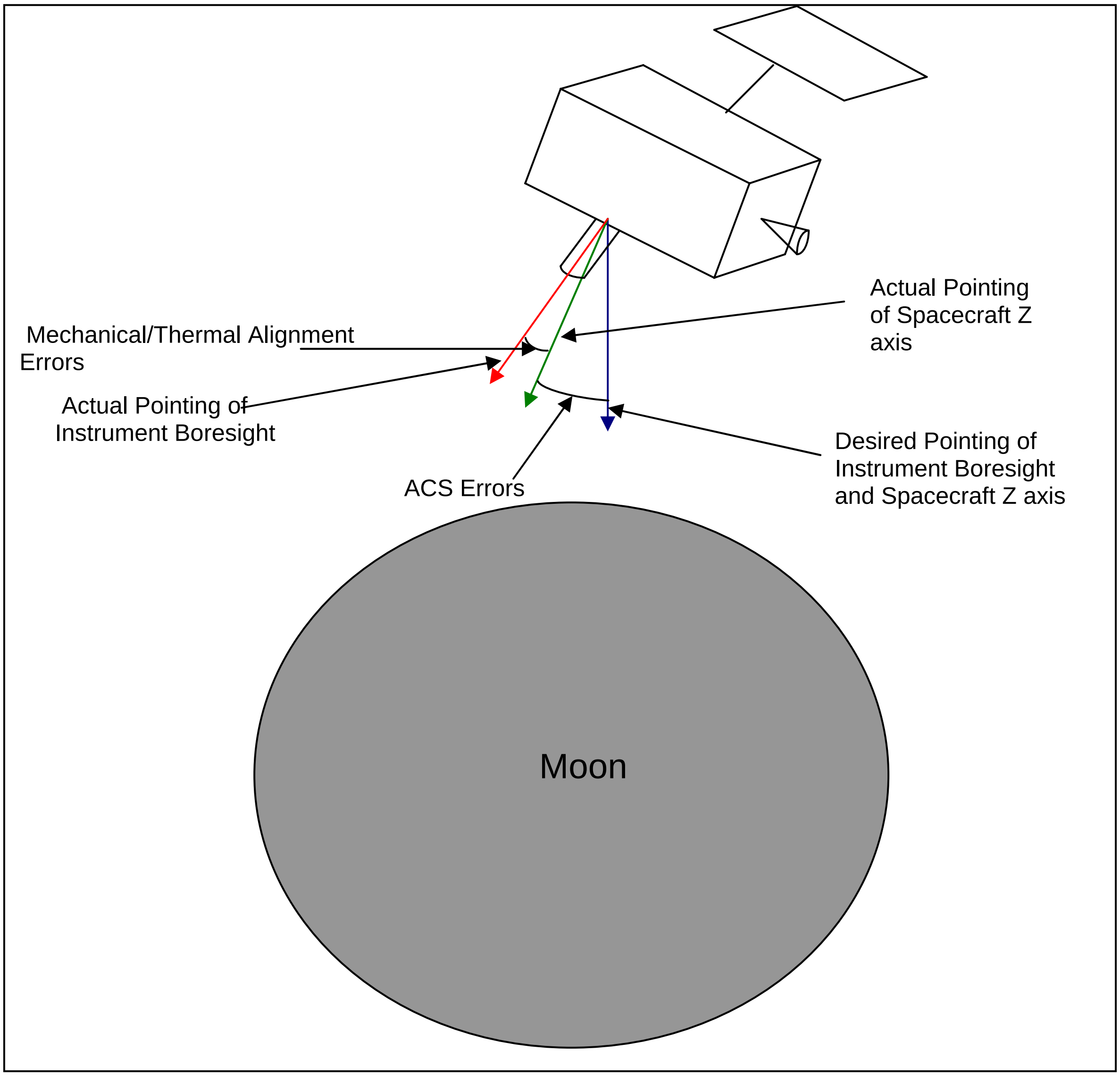

Figure 3- 4: ACS and Spacecraft Pointing and Alignment

Spacecraft/instrument alignment errors are the last piece of the mapping problem. These errors are broken down into several categories. The first division of these errors is between the spacecraft and instrument. The instruments and the LRO spacecraft are being designed, built and tested by different organizations. Therefore it is convenient to divide sources of error between instruments and the spacecraft. ***Spacecraft alignment*** errors are all sources of error between the spacecraft reference (the primary star tracker for LRO) and the spacecraft to instrument interface plane. ***Instrument alignment errors*** are all errors between the spacecraft to instrument interface plane and the instrument boresight. Instrument errors are the responsibility of each instrument team to define and track. Only the total instrument alignment error will be budgeted and tracked in this document, LRO Pointing and Alignment Specification, 431-SPEC-000113. (Instrument sources of error are specific to each type of instrument and will not be discussed here.)

There are several sources of spacecraft alignment errors. The main sources are jitter, thermal distortion and static alignment. ***Jitter*** is the dynamic response of the spacecraft due to dynamic input. Typical sources of jitter include: reaction wheel motion, solar array and high gain antenna gimbals, and such. Jitter includes all motion of the spacecraft that is beyond the control bandwidth of the ACS system. Dynamic response of the spacecraft within the bandwidth of the ACS system is called **pointing stability**.

Thermal distortion describes alignment errors caused by various thermal conditions on the spacecraft structure in space. The spacecraft is built at room temperature, but it is operated in various temperature ranges in space. The various materials that the structure is made of expand and contract as the temperature of the material is changed. This expansion and contraction of the structure as it changes temperature causes the structure to distort. This distortion changes the alignment of the instrument to the spacecraft reference.

The final group of spacecraft alignment errors is static alignment errors or static bias. ***Static alignment errors, static biases***, are all sources of alignment error that do not change once the spacecraft is on-orbit. There are three main sources of static alignment errors; ground alignment, launch shift and 1-g release. ***Ground alignment*** is how well the instrument has been placed on (aligned to) the spacecraft relative to the spacecraft reference frame during constructions of the orbiter. The source of these errors is the machining and fabrication tolerances of the mechanical hardware. Instrument alignment can be defined in terms of alignment accuracy and knowledge. ***Ground alignment accuracy*** error is the amount the instrument reference frame is off from the spacecraft reference frame. ***Ground alignment knowledge*** error is the error in the knowledge of where the instrument reference frame is relative to the spacecraft reference frame.

Launch shift is the error in instrument alignment due to structural shifting during launch. The bolt holes in the structure are slightly larger than the bolts that go through them. When the structure is vibrated during launch the bolts can move slightly in their holes. This motion causes the structure to shift slightly from its original position. After launch the spacecraft does have any sources of severe vibration thus instruments cannot shift in this way again. Thus the error caused by launch shift is static once the spacecraft is on its way to the Moon.

The third kind of alignment error is ***1-g release***. All measurements of alignment are made while the structure is under a 1-g load, but the structure operates in a zero g environment. The structure will sag slightly in a 1-g environment. When the structure is no longer under a 1 g load, the structure shifts slightly.

Some instrument developers can obtain an estimate of the instrument boresight alignment to the primary star tracker while on-orbit. Knowledge of the instrument boresight alignment to the primary star tracker is not exact, such ambiguity is called ***calibration error***. Calibration error takes the place of static biases in the pointing and alignment knowledge budget for both the spacecraft and the instrument. This is because the alignment of the instrument boresight to the star tracker is estimated. The division at the spacecraft to instrument interface plane no longer makes sense for this estimate. (this paragraph seems a little fuzzy to me)

3.2 DEFINITION OF POINTING PERFORMANCE

Pointing performance is is defined as the deviation of an instrument boresight from its commanded pointing within a given amount of time. Usually the amount of time that is of interest is the amount of time it takes for one observation. In general, the contributors to pointing performance are the ACS control, ACS knowledge and spacecraft jitter. If the time of interest is of a long duration, it may also include thermal distortion. Although the spacecraft may meet its absolute pointing and alignment accuracy and knowledge requirements, it still may not meet its pointing performance requirement. For example, the spacecraft may move enough during the capture of a picture to blur the image. Some instruments place additional constraints on the spacecraft beyond their pointing and alignment accuracy and knowledge requirements. These requirements are captured under performance requirements. Figure 3-5 illustrates the concept of pointing performance.

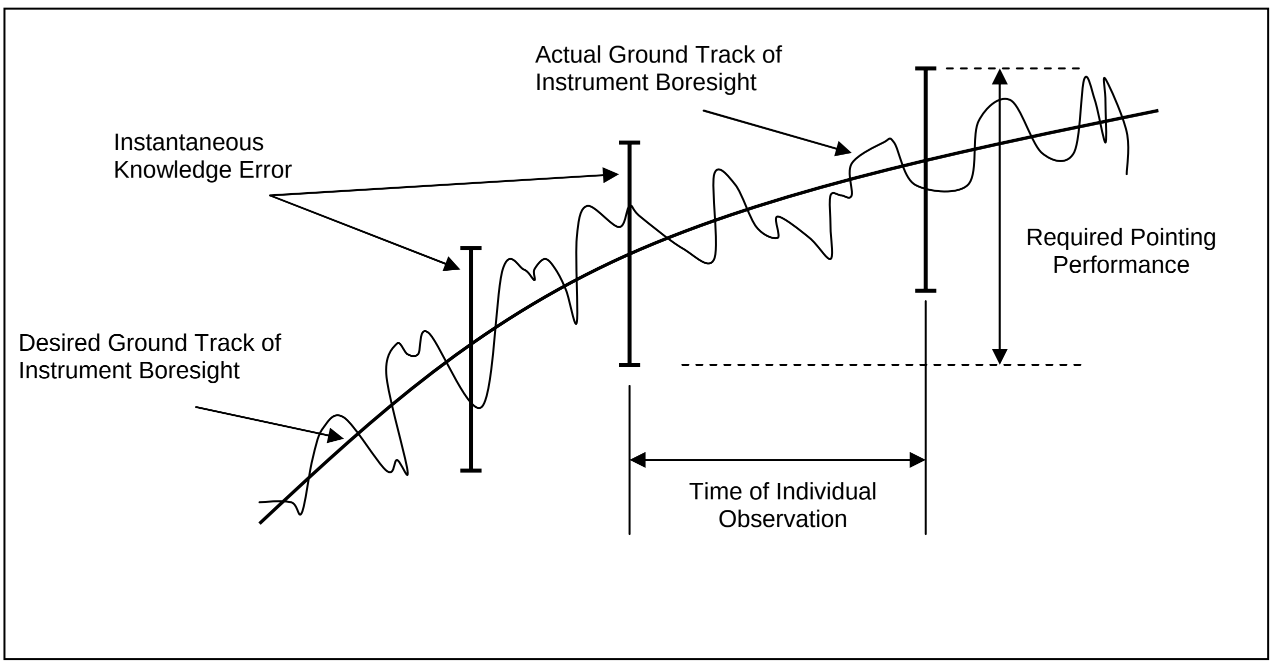

Figure 3-1: Pointing Performance

3.3 LOCATION OF MAPPING REQUIREMENTS/ ALLOCATIONS

The level two allocations for pointing and alignment for the LRO spacecraft are contained within this document, the LRO Pointing and Alignment Specification (431-SPEC-000113). Trajectory and ephemeris requirements and allocations are documented in Flight Dynamics Specification (431-SPEC-000184). Timing requirements and allocations for the LRO spacecraft are kept in the LRO Timing Specification (431-SPEC-000212). Instrument pointing, alignment and timing budgets are kept by the individual instrument teams.

3.4 COMBINATION OF THE PIECES OF THE MAPPING BUDGET

All sources of pointing and alignment errors must be combined in some fashion. In general similar source of error are root sum squared and non similar sources of error are added together. In the LRO pointing and alignment budget all static errors are root sum squared, and all other errors are added together.

4.0 CRATER POINTING AND ALIGNMENT ALLOCATIONS

The Cosmic Ray Telescope for the Effects of Radiation (CRaTER) will characterize the global lunar radiation environment and its biological impacts. The CRaTER instrument requires only that its nadir field of view look completely at the lunar surface.

CRaTER will not have an alignment cube or fudicial to add in its alignment to the spacecraft reference. It also does not have any way to calibrate out any static errors in its alignment while on orbit.

4.1 CRATER POINTING ACCURACY

The CRaTER instrument needs a pointing accuracy of +/- 35 degrees. The angle formed by the lunar surface to LRO will be approximately 150 degrees. The CRaTER nadir field of view will be no more than 80 degrees. A pointing accuracy of +/- 35 degrees insures that the CRaTER nadir field of view is always facing the lunar surface.

The LRO Allocations for CRaTER result in a pointing accuracy of approximately 6 degrees with 5 degrees allocated to the CRaTER instrument. Table 4-1 shows the allocations for the CRaTER pointing accuracy.

Table 4-1. CRaTER Pointing Accuracy Allocation

			Arc-Sec		micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
	ACS Controller	15	15	15	73	73	73
Jitter	Jitter	50	50	50	242	242	242
Thermal	Thermal Distortion	500	500	500	2423	2423	2423
Static Bias	1-g Release	200	200	200	969	969	969
	Launch Shift	50	50	50	242	242	242
	Ground Alignment accuracy	500	500	500	2423	2423	2423
Static Bias RSS		541	541	541	2621	2621	2621
Instrument		18000	18000	18000	87222	87222	87222
	Total	**19151**	**19151**	**19151**	**92799**	**92799**	**92799**
	Requirement	**126000**	**126000**	**126000**	**610556**	**610556**	**610556**
	Unallocated margin	**106849**	**106849**	**106849**	**517757**	**517757**	**517757**

4.2 CRATER POINTING KNOWLEDGE

CRaTER will examine the possibility of directionality of the primary radiation. This could be due to alignment of solar energetic particles with the local magnetic field or obscuration of incident particles by favorable Earth geometry. A pointing knowledge of 10 degrees or better insures that this is possible.

The LRO Allocations for CRaTER result in a pointing knowledge of approximately 6 degrees with exactly 5 degree pointing knowledge allocated to the CRaTER instrument. Table 4-2 shows the allocations for the CRaTER pointing accuracy.

Table 4-2. CRaTER Pointing Knowledge Allocation

		Arc-sec			micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
Jitter	Jitter	50	50	50	242	242	242
Thermal	Thermal Distortion	500	500	500	2423	2423	2423
Static Bias	1-g Release	200	200	200	969	969	969
	Launch Shift	50	50	50	242	242	242
	Ground Alignment knowledge	500	500	500	2423	2423	2423
Static Bias RSS		541	541	541	2621	2621	2621
Instrument		18000	18000	18000	87222	87222	87222
	Total	**19121**	**19121**	**19121**	**92653**	**92653**	**92653**
	Requirement	**36000**	**36000**	**36000**	**174444**	**174444**	**174444**
	Unallocated margin	**16879**	**16879**	**16879**	**81791**	**81791**	**81791**

4.3 CRATER POINTING PERFORMANCE

The CRaTER instrument does not have any pointing stability requirements.

4.4 OTHER POINTING AND ALIGNMENT REQUIREMENTS

4.4.1 Alignment to Spacecraft Reference

CRaTER will be aligned to the spacecraft reference to within 500 arc-seconds (2423 micro-radians) per axis.

4.4.2 Co-Alignment

CRaTER does not need to be aligned or require knowledge of alignment with any other instruments.

5.0 DIVINER POINTING AND ALIGNMENT ALLOCATIONS

The Diviner Lunar Radiometer Experiment is a multi-channel solar reflectance and infrared filter radiometer. Diviner will map the surface temperatures of the Moon. Diviner operates continuously while LRO is in measurement mode. The driving requirement for Diviner is the post-processed knowledge of where the data was taken. Diviner will not be targeting specific sites on the Moon.

The Diviner instrument has the ability to calibrate out static biases between its detector and the spacecraft star tracker. This will reduce static bias down to 124 arc-seconds (600 micro-radians).

Diviner will have an optical cube for alignment reference.

5.1 DIVINER POINTING ACCURACY

The Diviner instrument requires a pointing accuracy of +/- 1238 arc-seconds (6000 micro-radians). Table 5-1 shows the current allocations for DLRE pointing accuracy.

Table 5-1. Diviner Pointing Accuracy Allocation

		Arc-Sec			micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
	ACS Controller	15	15	15	73	73	73
Jitter	Jitter	50	50	50	242	242	242
Thermal	Thermal Distortion	200	200	200	969	969	969
Static Bias	1-g Release	150	150	150	727	727	727
	Launch Shift	30	30	30	145	145	145
	Ground Alignment Accuracy	500	500	500	2423	2423	2423
Static Bias RSS		523	523	523	2534	2534	2534
Instrument		413	413	413	2000	2000	2000
	Total	**1231**	**1231**	**1231**	**5963**	**5963**	**5963**
	Requirement	**1238**	**1238**	**1238**	**6000**	**6000**	**6000**
	Unallocated margin	**8**	**8**	**8**	**37**	**37**	**37**

5.2 DIVINER POINTING KNOWLEDGE

The Diviner instrument requires a pointing knowledge of +/- 619 arc-seconds (3000 micro-radians). Table 5-2 shows the pointing knowledge allocations for Diviner.

Table 5-2. Diviner Pointing Knowledge Allocation

		Arc-Sec			micro-radian		
		Rx	**Ry**	**Rz**	**Rx**	**Ry**	**Rz**
ACS	ACS Knowledge	30	30	30	145	145	145
Jitter	Jitter	50	50	50	242	242	242
Thermal	Thermal Distortion	200	200	200	969	969	969
Calibration Error		124	124	124	600	600	600
Instrument		124	124	124	600	600	600
	Total	**528**	**528**	**528**	**2557**	**2557**	**2557**
	Requirement	**619**	**619**	**619**	**3000**	**3000**	**3000**
	Unallocated margin	**91**	**91**	**91**	**443**	**443**	**443**

5.3 DIVINER POINTING PERFORMANCE

The Diviner instrument has a pointing performance requirement of 1.5 milli-radians over 0.128 seconds.

5.4 OTHER POINTING AND ALIGNMENT REQUIREMENTS

5.4.1 Alignment to Spacecraft Reference

Diviner will be aligned to the spacecraft reference to within 500 arc-seconds (2423 micro-radians) per axis.

5.4.2 Co-Alignment

Diviner has no co-alignment requirement.

6.0 LAMP POINTING AND ALIGNMENT ALLOCATIONS

The Lyman-Alpha Mapping Project (LAMP) instrument will observe the lunar surface in the far ultraviolet spectrum. LAMP will search for surface ices and frosts in the pole regions and provide spectral images of the permanently shadowed regions illuminated only by starlight and the interplanetary medium hydrogen Lyman-alpha sky glow. LAMP will operate continuously non-illuminated portions of the Moon. Post processed knowledge of where the LAMP data was taken is the driving requirement. LAMP will not be targeting specific locations on the Moon.

LAMP has the ability to calibrate static biases out of its alignment while on orbit by looking at UV bright stars.

The LAMP instrument will have an alignment cube.

6.1 LAMP POINTING ACCURACY

LAMP requires a pointing accuracy of +/- 0.22 degrees three sigma. This is 792 arc-sec or 3840 micro radians. Table 6-1 shows the allocations for LAMP pointing accuracy.

Table 6-1. LAMP Pointing Accuracy Allocation

		Arc-Sec			micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
	ACS Controller	15	15	15	73	73	73
Jitter	Jitter	30	30	30	145	145	145
Thermal	Thermal Distortion	90	90	90	436	436	436
Static Bias	1-g Release	50	50	50	242	242	242
	Launch Shift	500	500	500	2423	2423	2423
	Ground Alignment Accuracy	300	300	300	1454	1454	1454
Static Bias RSS		585	585	585	2836	2836	2836
Instrument		30	30	30	145	145	145
	Total	**780**	**780**	**780**	**3781**	**3781**	**3781**
	Requirement	**792**	**792**	**792**	**3840**	**3840**	**3840**
	Unallocated margin	**12**	**12**	**12**	**59**	**59**	**59**

6.2 LAMP POINTING KNOWLEDGE

LAMP requires pointing knowledge to a fifth of a pixel at the three sigma level, or +/-0.06 degrees. (216 arc-sec or 1047 micro radians) The allocations shown for LAMP pointing knowledge are shown in Table 6-2.

Table 6-2. LAMP Pointing Knowledge Allocation

		Arc-Sec			micro-radian		
		Rx	**Ry**	**Rz**	**Rx**	**Ry**	**Rz**
ACS	ACS Knowledge	30	30	30	145	145	145
Jitter	Jitter	30	30	30	145	145	145
Thermal	Thermal Distortion	90	90	90	436	436	436
Static Bias	Calibration Error	30	30	30	145	145	145
Instrument		30	30	30	145	145	145
	Total	**210**	**210**	**210**	**1018**	**1018**	**1018**
	Requirement	**216**	**216**	**216**	**1047**	**1047**	**1047**
	Unallocated margin	**6**	**6**	**6**	**29**	**29**	**29**

6.3 LAMP POINTING PERFORMANCE

The LRO spacecraft shall provide the LAMP instrument of a pointing performance of +/- 0.05 degrees three sigma in 1.0 seconds.

6.4 OTHER POINTING AND ALIGNMENT REQUIREMENTS

6.4.1 Alignment to Spacecraft Reference

LAMP will be aligned to the spacecraft reference to within 300 arc-seconds (1450 micro-radians) per axis. LAMP will have alignment knowledge to within 30 arc-seconds (145 micro-radians) per axis

6.4.2 Co-Alignment

LRO shall measure the alignment between the LAMP optical reference cube and the LROC-Narrow Angle Camera's (NAC's) optical alignment cubes to an accuracy of 30 arc-seconds.

7.0 LEND POINTING AND ALIGNMENT ALLOCATIONS

The Lunar Exploration Neutron Detector (LEND) will provide high spatial resolution maps of neutron emission at the lunar surface. LEND measurements will be used to create high resolution Hydrogen distribution maps, characterize surface distribution and column density of possible near-surface water ice deposits, and create a global model of the neutron component of space radiation from thermal energies up to 15 Mega Electron Volts (MeV).

Pointing knowledge is more important to LEND measurements than pointing accuracy although towards the end of the LRO mission LEND may want to target specific sites on the Lunar surface.

The LEND instrument does not have any way to calibrate out static biases between the LEND detectors and the LRO star trackers while on-orbit.

7.1 LEND POINTING ACCURACY

The LEND instrument requires a pointing accuracy of +/- 950 arc-seconds. The LEND pointing allocations are shown in Table 7-1.

Table 7-1. LEND Pointing Accuracy Allocation

			Arc-Sec			micro-radian	
		Rx	**Ry**	**Rz**	**Rx**	**Ry**	**Rz**
ACS	ACS Knowledge	30	30	30	145	145	145
	ACS Controller	15	15	15	73	73	73
Jitter	Jitter	50	50	50	242	242	242
Thermal	Thermal Distortion	300	300	300	1454	1454	1454
Static Bias	1-g Release	65	65	65	315	315	315
	Launch Shift	30	30	30	145	145	145
	Ground Alignment accuracy	500	500	500	2423	2423	2423
Static Bias RSS		505	505	505	2448	2448	2448
Instrument		50	50	50	242	242	242
	Total	**950**	**950**	**950**	**4604**	**4604**	**4604**
	Requirement	**950**	**950**	**950**	**4603**	**4603**	**4603**
	Unallocated margin	**0**	**0**	**0**	**0**	**0**	**0**

7.2 LEND POINTING KNOWLEDGE

The desired pointing knowledge for LEND is also 935 arc-seconds. This desired pointing knowledge can be met by the allocations shown in Table 7-2.

Table 7-2. LEND Pointing Knowledge Allocation

		Arc-Sec			micro-radian		
		Rx	**Ry**	**Rz**	**Rx**	**Ry**	**Rz**
ACS	ACS Knowledge	30	30	30	145	145	145
Jitter	Jitter	50	50	50	242	242	242
Thermal	Thermal Distortion	300	300	300	1454	1454	1454
Static Bias	1-g Release	65	65	65	315	315	315
	Launch Shift	30	30	30	145	145	145
	Ground Alignment knowledge	500	500	500	2423	2423	2423
Static Bias RSS		505	505	505	2448	2448	2448
Instrument		50	50	50	242	242	242
	Total	**935**	**935**	**935**	**4531**	**4531**	**4531**
	Requirement	**935**	**935**	**935**	**4531**	**4531**	**4531**
	Unallocated margin	**0**	**0**	**0**	**0**	**0**	**0**

7.3 LEND POINTING PERFORMANCE

LEND does not have any specific pointing performance requirements.

7.4 OTHER POINTING AND ALIGNMENT REQUIREMENTS

7.4.1 Alignment to Spacecraft Reference

The Doppler filter should be pointed to the direction of flight to an accuracy of 3 degrees. This results in a requirement for pointing about the Z axis to be within 3 degrees.

The pointing accuracy for the LEND instrument is 950 arc-seconds and the alignment to the spacecraft reference is 500 arc-seconds. This means that if the Doppler filter is aligned with the LEND reference to within 10,149 arc-seconds (2.8 degrees), the pointing accuracy requirement for the Doppler filter will be met.

7.4.2 Co-Alignment

LEND does not require alignment knowledge to any other instrument.

8.0 LOLA POINTING AND ALIGNMENT ALLOCATIONS

The Lunar Orbiter Laser Altimeter (LOLA) will produce global geodetic lunar topography, characterize polar region illumination, image permanently shadowed regions, assess meter scale features for landing site selection, and identify near-surface water ice. The LOLA instrument pulses a single laser through a diffractive optical element to produce five beams that will illuminate the lunar surface. For each beam, LOLA measures the time of flight (range), pulse spreading (surface roughness) and transmit/return energy (surface reflectance). LOLA will produce topographic profiles of the Moon which can be processed into continuous topographic maps.

LOLA runs continuously while LRO is in measurement mode. LOLA will not target specific sites on the Moon. The driving requirement for LOLA is post-processed pointing knowledge.

LOLA will have an optical cube for alignment reference.

8.1 LOLA POINTING ACCURACY

The LOLA five spot pattern shall be aligned within 26 deg +/- 1 deg to the LRO velocity vector or a pointing accuracy of +/- 3600 arc-seconds. The allocations for LOLA pointing accuracy meet this requirement and are shown in Table 8-1.

Table 8-1. LOLA Pointing Accuracy Allocation

		Arc-Sec			micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
	ACS Controller	15	15	15	73	73	73
Jitter	Jitter	30	30	30	145	145	145
Thermal	Thermal Distortion	75	75	75	363	363	363
Static Bias	1-g Release	75	75	75	363	363	363
	Launch Shift	30	30	30	145	145	145
	Alignment accuracy	300	300	300	1454	1454	1454
Static Bias RSS		311	311	311	1505	1505	1505
Instrument		1032	1032	1032	5000	5000	5000
	Total	**1493**	**1493**	**1493**	**7232**	**7232**	**7232**
	Requirement	**3600**	**3600**	**3600**	**17444**	**17444**	**17444**
	Unallocated margin	**2107**	**2107**	**2107**	**10212**	**10212**	**10212**

8.2 LOLA POINTING KNOWLEDGE

The allocations for LOLA pointing knowledge are shown in Table 8-2.

Table 8-2. LOLA Pointing Knowledge Allocation

		Arc-Sec			micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
Jitter	Jitter	30	30	30	145	145	145
Thermal	Thermal Distortion	75	75	75	363	363	363
Static Bias	Calibration Error	22	22	22	105	105	105
Instrument		31	31	31	150	150	150
	Total	**188**	**188**	**188**	**909**	**909**	**909**
	Requirement	**206**	**206**	**206**	**1000**	**1000**	**1000**
	Unallocated margin	**19**	**19**	**19**	**91**	**91**	**91**

8.3 LOLA POINTING PERFORMANCE

LOLA does not have specific pointing performance requirements because the laser time of flight and pulse width are extremely short.

8.4 OTHER POINTING AND ALIGNMENT REQUIREMENTS

8.4.1 Alignment to Spacecraft Reference

LOLA will be aligned to the spacecraft reference to within 300 arc-seconds (1454 micro-radians) per axis.

8.4.2 Co-Alignment

LOLA is required to be aligned to be 1.4 degrees within a NAC FOV. Table 8-3 is the allocation for the co-alignment budget. The elements have been added (most conservative case).

Table 8-3. LOLA-NAC Co-Alignment Allocation

		Arc-Sec			micro-radia	
		Rx	Ry	Rz	Rx	Ry
Jitter	Jitter	45	45	45	218	218
Thermal	Thermal Distortion	100	100	100	485	485
Static Bias	1-g Release	100	100	100	485	485
	Launch Shift	40	40	40	194	194
	Ground Alignment accuracy	425	425	425	2059	2059
Static Bias RSS		438	438	438	2125	2125
LOLA		1032	1032	1032	5000	5000
NAC		21	21	21	100	100
	Total	**1636**	**1636**	**1636**	**7927**	**7927**
	Requirement	**5040**	**5040**	**5040**	**24422**	**24422**
	Unallocated margin	**3404**	**3404**	**3404**	**16495**	**16495**

9.0 LROC-NAC POINTING AND ALIGNMENT ALLOCATIONS

The Lunar Reconnaissance Orbiter Camera (LROC) takes images of the lunar surface to help with landing site certification and polar illumination. LROC Narrow Angle Cameras (NACs) will take images of approximately meter scale to identify hazards near landing sites.

LROC has two NACs that have a combined FOV of 0.10 radian. The LROC NACs need to target specific sites on the lunar surface. Pointing accuracy is the most important alignment requirement for the NACs. Pointing knowledge is also important for the LROC NACs as it affects the quality of the uncontrolled polar mosaics.

The LROC NACs will each have an alignment cube for alignment reference.

9.1 LROC-NAC POINTING ACCURACY

The requirement for LROC-NAC pointing accuracy is +/- 2500 micro-radians. LROC-NAC pointing accuracy allocations are shown in Table 9-1.

Table 9-1. LROC-NAC Pointing Accuracy Allocation

		Arc-Sec			micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
	ACS Controller	15	15	15	73	73	73
Jitter	Jitter	30	30	30	145	145	145
Thermal	Thermal Distortion	50	50	50	242	242	242
Static Bias	1-g Release	75	75	75	363	363	363
	Launch Shift	20	20	20	97	97	97
	Ground Alignment accuracy	300	300	300	1454	1454	1454
Static Bias RSS		310	310	310	1502	1502	1502
Instrument		21	21	21	100	100	100
	Total	**456**	**456**	**456**	**2207**	**2207**	**2207**
	Requirement	**516**	**516**	**516**	**2500**	**2500**	**2500**
	Unallocated margin	**60**	**60**	**60**	**293**	**293**	**293**

9.2 LROC-NAC POINTING KNOWLEDGE

The requirement for LROC-NAC pointing knowledge is 1000 micro-radians. LROC-NAC pointing knowledge allocations are shown in Table 9-2.

Table 9-2. LROC-NAC Pointing Knowledge Allocation

		Arc-Sec			micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
Jitter	Jitter	30	30	30	145	145	145
Thermal	Thermal Distortion	50	50	50	242	242	242
Static Bias	Calibration Error	5	5	5	24	24	24
Instrument		21	21	21	100	100	100
	Total	**136**	**136**	**136**	**657**	**657**	**657**
	Requirement	**206**	**206**	**206**	**1000**	**1000**	**1000**
	Unallocated margin	**71**	**71**	**71**	**343**	**343**	**343**

9.3 LROC-NAC POINTING PERFORMANCE

The LROC-NACs have a pointing performance requirement of 5 micro-radians peak-to-peak in 0.3 milliseconds.

9.4 OTHER POINTING AND ALIGNMENT REQUIREMENTS

9.4.1 Alignment to Spacecraft Reference

LROC-NAC will be aligned to the spacecraft reference to within 300 arc-seconds (1454 micro-radians) per axis.

9.4.2 Co-Alignment

LROC-NAC's do not need to be aligned with any other instruments on LRO. The LROC-NACs need to be aligned with each other to within 0.5 milli-radians. This requirement can be met with the allocations shown in Table 9-3.

Table 9-3. NAC Co-Alignment Allocation

		Arc-Sec		micro-radian	
		Rx cross track	**Ry long track**	**Rx cross**	**Ry long track**
ACS	ACS	N/A	N/A	N/A	N/A
Jitter	Jitter	20	20	97	97
Thermal	Thermal Distortion	20	20	97	97
Static Bias	Alignment Accuracy	21	21	100	100
	1-g Release	15	15	73	73
	NAC-R Cube Knowledge	10	10	48	48
	NAC-L Cube Knowledge	10	10	48	48
	Cube to Cube Knowledge	15	15	73	73
Static Bias RSS		33	33	159	159
Instrument	NAC-R	21	21	100	100
	NAC-L	21	21	100	100
Instrument RSS		29	29	141	141
	Total	**102**	**102**	**494**	**494**
	Requirement	**103**	**103**	**500**	**500**
	Unallocated margin	**1**	**1**	**6**	**6**

10.0 LROC-WAC POINTING AND ALIGNMENT ALLOCATIONS

The Lunar Reconnaissance Orbiter Camera (LROC) takes images of the lunar surface for landing site certification and polar illumination. The LROC-WAC will acquire synoptic 100 m/pixel images of the poles during most orbits throughout the year to identify permanently shadowed and near permanently illuminated regions and characterize color differences within the regolith in seven UV and visible bands.

The LROC-WAC will not have an alignment cube, but it will perform on-orbit calibrations to remove static bias.

10.1 LROC-WAC POINTING ACCURACY

The LROC-WAC has a pointing accuracy requirement of +/- 3000 micro-radians. Table 10-1 shows the pointing accuracy allocations for the LROC-WAC.

Table 10-1. LROC-WAC Pointing Accuracy Allocation

			Arc-Sec		micro-radi	
		Rx	**Ry**	**Rz**	**Rx**	**Ry**
ACS	ACS Knowledge	30	30	30	145	145
	ACS Controller	15	15	15	73	73
Jitter	Jitter	20	20	20	97	97
Thermal	Thermal Distortion	50	50	50	242	242
Static Bias	1-g Release	100	100	100	485	485
	Launch Shift	200	200	200	969	969
	Alignment accuracy	300	300	300	1454	1454
Static Bias RSS		374	374	374	1813	1813
Instrument		52	52	52	250	250
	Total	**556**	**556**	**556**	**2693**	**2693**
	Requirement	**619**	**619**	**619**	**3000**	**3000**
	Unallocated margin	**63**	**63**	**63**	**307**	**307**

10.2 LROC-WAC POINTING KNOWLEDGE

The LROC-WAC has a pointing knowledge requirement of +/- 1000 micro-radians. Table 10-2 shows the pointing knowledge allocations for the LROC-WAC.

Table 10-2. LROC-WAC Pointing Knowledge Allocation

		Arc-Sec			micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
Jitter	Jitter	20	20	20	97	97	97
Thermal	Thermal Distortion	50	50	50	242	242	242
Calibration Error		52	52	52	250	250	250
Instrument		52	52	52	250	250	250
	Total	**203**	**203**	**203**	**985**	**985**	**985**
	Requirement	**206**	**206**	**206**	**1000**	**1000**	**1000**
	Unallocated margin	**3**	**3**	**3**	**15**	**15**	**15**

10.3 LROC-WAC POINTING PERFORMANCE

The pointing performance requirement for the LROC WAC is +/- 500 micro-radians over one second.

10.4 OTHER POINTING AND ALIGNMENT REQUIREMENTS

10.4.1 Alignment to Spacecraft Reference

LROC-WAC will be aligned to the spacecraft reference to within 300 arc-seconds (1454 micro-radians) per axis.

10.4.2 Co-Alignment

The LROC-WAC does not need to be aligned with any other instruments on LRO.

11.0 MINI-RF POINTING AND ALIGNMENT ALLOCATIONS

The Mini-RF is a technology demonstration.

11.1 MINI-RF POINTING ACCURACY

The pointing accuracy allocations for the mini-RF are shown in Table 11-1.

Table 11-1. Mini-RF Pointing Accuracy Allocation

		Arc-Sec			micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
	ACS Controller	15	15	15	73	73	73
Jitter	Jitter	50	50	50	242	242	242
Thermal	Thermal Distortion	500	500	500	2423	2423	2423
Static Bias	1-g Release	200	200	200	969	969	969
	Launch Shift	500	500	500	2423	2423	2423
	Alignment accuracy	750	750	750	3634	3634	3634
Static Bias RSS		923	923	923	4474	4474	4474
Instrument		500	500	500	2423	2423	2423
	Total	**2033**	**2033**	**2033**	**9853**	**9853**	**9853**
	Requirement	**2160**	**2160**	**2160**	**10467**	**10467**	**10467**
	Unallocated margin	**127**	**127**	**127**	**614**	**614**	**614**

MINI-RF POINTING KNOWLEDGE

The pointing knowledge requirements for the Mini-RF are shown in Table 11-2.

Table 11-2. Mini-RF Pointing Knowledge Allocation

		Arc-Sec			micro-radian		
		Rx	Ry	Rz	Rx	Ry	Rz
ACS	ACS Knowledge	30	30	30	145	145	145
Jitter	Jitter	50	50	50	242	242	242
Thermal	Thermal Distortion	500	500	500	2423	2423	2423
Static Bias	1-g Release	100	100	100	485	485	485
	Launch Shift	500	500	500	2423	2423	2423
	Alignment knowledge	30	30	30	145	145	145
Static Bias RSS		511	511	511	2475	2475	2475
Instrument		500	500	500	2423	2423	2423
	Total	**1591**	**1591**	**1591**	**7708**	**7708**	**7708**
	Requirement	**2160**	**2160**	**2160**	**10467**	**10467**	**10467**
	Unallocated margin	**569**	**569**	**569**	**2758**	**2758**	**2758**

11.2 MINI-RF POINTING PERFORMANCE

The Mini-RF does not have any pointing performance requirements.

11.3 OTHER POINTING AND ALIGNMENT REQUIREMENTS

11.3.1 Alignment to Spacecraft Reference

Mini-RF will be aligned to the spacecraft reference to within 750 arc-seconds (3634 micro-radians) per axis.

11.3.2 Co-Alignment

The Mini-RF does not need to be aligned with any other instruments on LRO.

12.0 LASER RANGING CO-ALIGNMENT

The Laser Ranging optic is mounted on the HGA bracket. The Laser Ranging optic will be outfitted with an optical cube. The Laser Ranging system requires a total contact time with the ground of 407 hours in 12 months. To achieve this, the LRO system needs its total pointing budget to be 0.55 degrees or less. The pointing of the HGAS system is 0.3 degrees. To meet the total pointing requirement for LR of 0.55 degrees, the co-alignment between the RF beam and the LR telescope must be 0.25 degrees or less. Table 12-1 represents the Laser Ranging Telescope to RF beam alignment budget and table 12-2 represents the Laser Ranging Telescope to Spacecraft reference alignment budget.

Table 12-1. Laser Ranging-RF Beam Co-Alignment Allocations

Total Alignment Allocations between the RF Beam and LR Telescope

Item	Allocation	
	Deg	mrad
Assembly / Alignment Errors		
RF Beam Pointing Resolution at HGA Delivery	0.029	0.500
LRT Boresight Alignment Capability at Installation	0.010	0.175
HGA 1g gravity distortion	0.030	0.524
Launch Shift Errors		
LRT Boresight Movement from Max Tolerance Shift	0.029	0.500
HGA Beam Movement from Max Tolerance Shift [1]	0.030	0.524
Performance Errors		
Mounting Plate Bending Due to On-Orbit Thermal / Mechanical Distortions	0.011	0.200
LRT Boresight Shift Due to On-Orbit Thermal / Mechanical Distortions	0.00001	0.000175
Total (SUM)	0.139	2.423

Table 12-2. Laser Ranging Telescope to Spacecraft Reference Allocations

Total Pointing Allocations Between Spacecraft Reference and LRT Boresight

Item	Allocation	
	Deg	mrad
LRT Mis-Alignment (See Alignment Budget)	0.139	2.426
HGAS Pointing Capability (See HGAS Pointing Budget)	0.300	5.236
Total (SUM)	0.439	7.662

13.0 HIGH GAIN ANTENNA POINTING BUDGET

The LRO High Gain Antenna System operates at two frequencies, S-band and Ka-band. The S-band system has a pointing accuracy requirement of 2°. The Ka-band system has a pointing accuracy requirement of 0.30 deg. 3σ. The Ka-band system will be used after the HGA system is calibrated. Table 13-1 shows the post calibration budget. The S-band system will be used both before and after the HGAS is calibrated on –orbit. Table 13-2 shows the pre-calibration budget. All ACS/GN&C error have been Rss'd together along with gimbal errors.

Table 13-1. LRO High Gain Antenna Pointing Post-Calibration Budget

	LRO High Gain Antenna System			
	POINTING ERROR BUDGET +/- 1080 arcsec (+/- 0.3 deg)	**3σ**		
	After On-orbit Calibration	(asec)	Random (asec)	
	ACS/GN&C Knowledge/Command Errors			
1	ACS pointing knowledge		30	
2	Ephemeris accuracy		10	
3	Algorithm accuracy (accuracy of pointing solution)		30	
4	RF Comm On-orbit Calibration Accuracy	400		
5	**Gimbal Actuator Axes Pointing Error Total (Culminates from Gimbal hardware alignment errors. Can be used to update software with a matrix of pointing corrections.)**	50		
	Dynamic Pointing Errors			
6	Jitter (analyzed at end of HGA)		100	
7	Gimbal Actuator Tracking Resolution		288	
	Thermal Distortion			
8	S/C ref to HGA Mounting Plate		300	
9	High Gain Antenna assy		108	
	Column Total	**450**	**443**	**893**
		Added the Rows	**RSS'd the Rows**	**Sum of columns to left**

893 Error: Errors 1-3 and 6-9 are RSS'd together and then 4 and 5 are added to it.

Table 13-2. LRO High Gain Antenna Pointing Pre-Calibration Budget (TBD)

14.0 SOLAR ARRAY POINTING BUDGET

The solar array has a pointing accuracy requirement of 5.0 deg 3σ.

Table 14-1. LRO Solar Array Pointing Accuracy Budget Allocation

ACS/GN&C Knowledge/Command Errors	**Bias Errors (deg) (sum)**	**Random Errors (deg) (rss)**	
ACS/GN&C Knowledge/Command Errors	0.05	0.10	
Hardware Alignment	0.50		
Launch/Deployment/Gravity Release	3.00		
Dynamic Pointing Errors		0.10	
Thermal Distortion	0.10		
Total	**3.65**	**0.14**	**3.79 deg**
Requirement			**5.00 deg**
Unallocated margin			**1.21 deg**

Appendix A. Abbreviations and Acronyms

Abbreviation/ Acronym	DEFINITION
CG	Center of Gravity
CM	Configuration Management
CMO	Configuration Management Office
CRaTER	Cosmic Ray Telescope for the Effects of Radiation
DLRE	Diviner Lunar Radiometer Experiment
dB	decibel
FOV	Field of View
g	Acceleration due to Gravity at Earth's Surface (e.g. 9.81 m/s^2)
GCI	Geocentric Inertial
GN&C	Guidance Navigation and Control
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
HGA	High Gain Antenna
Hz	Hertz
km	kilometer
LEND	Lunar Exploration Neutron Detector
LOLA	Lunar Orbiter Laser Altimeter
LROC	Lunar Reconnaissance Orbiter Camera
LRO	Lunar Reconnaissance Orbiter
m	Meter
MCI	Moon Centered Inertial
Me V	Mega Electron Volt
Mini-RF	Mini-Radio Frequency
N/A	Not applicable
NAC	Narrow Angle Camera
NASA	National Aeronautics and Space Administration
PSD	Power Spectral Density
RLEP	Robotic Lunar Exploration Program
RMS	Root Mean Squared
WAC	Wide Angle Camera
RQMT	Requirement
SA	Solar Array
SC	Spacecraft