Bendix Aerospace Systems Division

Apollo 15 LRRR (300 Corner) Pointing Analysis	NO. ATM-933	REV. NO.
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	DATE 11 Jan 1971	

This report summarizes the results of the Apollo 15 LRRR (300 Corner) Pointing Analysis. This analysis provides the parameter values for the array tilt angle and shadow mark angle, each of which are necessary to properly align the experiment on the lunar surface. These parameters are used to set the suncompass plate angle, the leveling leg stop and leg length and the suncompass shadow mark settings. Three landing sites were analyzed: the primary site, Hadley Rille and two potential alternate sites, Marius Hills and Tycho.

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The pointing angle requirements for the LRRR reflector array and sun compass at the Hadley Rille, Marius Hills, and Tycho sites are presented in Section 1. The effect of launch date changes and pointing angle errors are considered in Section 2. The computational procedures employed in determining the pointing angles have been described in ATM-870.

1. Pointing Angle Requirements

The pointing angles required to aim the LRRR array to the mean position of the earth from the various sites are summarized in Table 1. The position of the shadow mark line on the sun compass is dependent on the time at which the experiment is emplaced on the lunar surface. The shadow mark locations have been evaluated for emplacement at sun angles of 15° and 25°, which correspond to emplacement of the LRRR experiment during the first and second EVA's respectively. Data are included for emplacement during each of the months of July through December, 1971. Emplacement would occur during the last week of each month (and for the July data it could actually occur on August 1). The sun compass gnomon is assumed to be vertical.

Definitions of the terms employed in specifying the pointing angles are as follows:

<u>Array Tilt Angle</u> - is the angle between the zenith vector and the normal to the reflecting surface of the array.

<u>Shadow Mark Angle</u> - is the angle from the tilt axis of the array to the shadow mark line. The angle is measured counterclockwise in the horizontal plane when viewed from above.

<u>Tilt Axis</u> - is the axis about which the reflector array is rotated to achieve the required tilt angle (from an initially horizontal position). The sense of the tilt axis is defined by the direction of advance of a right-handed screw turned through the tilt angle.

The angular relationships are illustrated in Figure 1.

2. Aiming Errors

The accuracy with which the LRRR array will be pointed to the mean position of the earth is considered below. The effect of launch date changes on aiming accuracy and/or sun compass specifications are discussed in Section 2.1. The effects of fabrication tolerances and astronaut emplacement accuracy are included in Section 2.2.

2.1 Launch Date Trade-Offs for Sun Compass

The shadow mark specifications given in Table 1 assume that the LRRR experiment will be emplaced at a sun angle of 15° or 25° during the corresponding months listed in the table. If emplacement should occur at a different sun angle or in a different month than specified, the array will be misaligned. The aiming errors (i.e., angular displacement between the aim point of the array and the mean position of the earth) that will result from such changes in sun angle or launch date are presented in Tables 2 (Hadley Rille Site), 3 (Marius Hills), and 4 (Tycho). Parts A and B of each table are based on shadow mark settings for emplacement at sun angles of 15° and 25°, respectively. Each column of data in these tables give the aiming error that would result if the shadow mark setting indicated at the top of the column were employed to emplace the experiment at the time indicated in the left most column of the table. The shadow mark settings for the column headings are taken directly from Table 1. For example, Table 2A indicates that with a shadow mark setting of 178.83° (the recommended setting for an August landing at 15° sun angle), the aiming error for emplacement at a 25° sun angle in September would be 2.26°. The algebraic sign affixed to the aiming error data indicates that the aimpoint lies either to the East or West of the Meridian on the celestial sphere which passes through the mean earth position.

Tables 2 through 4 give specific values for the aiming errors associated with the sun compass. Approximate values of the aiming error can be obtained with the error rate data presented in Table 5. The data show, for example, that at the Marius Hills site, an aiming error ~0.5° will be incurred if emplacement occurs one month before or after the design date employed in establishing the shadow mark position. Similarly, an error ~0.25° will be incurred for each degree difference between the sun angle at the time of emplacement and the assumed design value (15° or 25°).

2.2 Estimated Nominal and Worst Case Aiming Error

Three general categories of error which contribute to the misalignment of the array are: (1) trade-offs made in the design specifications for the sun compass, (2) fabrication tolerances anticipated during manufacture, and (3) misalignment errors incurred during emplacement on the lunar surface. Effects of sun compass trade-offs on aiming accuracy has been discussed above. Estimates of the probable errors that could result during fabrication and emplacement of the experiment package are presented in Part A of Table 6. Both nominal and worst case estimates of error are presented. These terms can be interpreted as one-sigma and three-sigma estimates of error, respectively.

The contributions to the net aiming error can be resolved into θ and ϕ components where θ represents an error in the polar orientation (e.g., tilt angle) of the array and ϕ represents an error in the azimuthal alignment (e.g., East-West alignment) of the base pallet. The net aiming error, α, is then given by

$$\alpha = (\theta^2 + \phi_w{}^2)^{1/2} \qquad 1)$$

where $\phi w = \phi \cdot \text{Sin} (T_A + \theta/2)$ is an appropriately weighted ϕ-component of error. The angle α is the angular displacement between the mean position of the earth and the aimpoint of the LRRR array and T_A is the tilt angle of the reflector array.

The contributions to the aiming error given in Part A of Table 6 have been combined using Equation 1 and the net aiming errors α are tabulated in Part B of the table. In calculating the net aiming error, the individual contributions to the θ and ϕ components of error were assumed to be additive.

TABLE I

POINTING ANGLE REQUIREMENTS AT HADLEY RILLE, MARIUS HILLS, AND TYCHO

	Hadley Rille	Marius Hills	Tycho
Coordinates:	2°27'E 24°57'N	56°33'W 14°46'N	11°12'W 40°54'S
Array Tilt Angle:	25.172°	58.010°	42.318°
Orientation of Tilt Axis:	84.21° East of South	170.44° East of South	16.83° North of West
Shadow Mark Angles:			
a) For Emplacement at 15° Sun Angle			
July	179.57	95.76	26.94
August	178.83	94.99	26.34
September	178.24	94.39	25.86
October	177.95	94.15	25.63
November	178.06	94.35	25.73
December	178.55	94.95	26.15
b) For Emplacement at 25° Sun Angle			
July	174.88	92.87	33.95
August	174.12	92.06	33.35
September	173.51	91.43	32.87
October	173.22	91.20	32.65
November	173.35	91.42	32.76
December	173.87	92.07	33.19
Gnomon:	The sun compass gnomon is vertical in all cases.		

TABLE 2A

SUN COMPASS AIMING ERRORS - HADLEY RILLE SITE

Shadow marks set for emplacement at 15° Sun Angle.

Time of Actual Emplacement		Shadow Mark Setting					
Month	Sun Angle	179.57 (July)	178.83 (August)	178.24 (Sept.)	177.95 (Oct.)	178.06 (Nov.)	178.55 (Dec.)
July	5	-1.85	-2.16				
	15	.0	-0.31				
	25	2.00	1.68				
	35	4.26	3.95				
August	5	-1.54	-1.85	-2.11			
	15	0.31	.0	-0.25			
	25	2.32	2.00	1.75			
	35	4.61	4.29	4.04			
September	5		-1.61	-1.86	-1.98		
	15		0.25	.0	-0.12		
	25		2.26	2.01	1.89		
	35		4.56	4.31	4.19		
October	5			-1.73	-1.85	-1.81	
	15			0.12	.0	0.05	
	25			2.14	2.01	2.06	
	35			4.44	4.31	4.36	
November	5				-1.90	-1.85	-1.64
	15				-0.05	.0	0.21
	25				1.96	2.00	2.21
	35				4.25	4.29	4.50
December	5					-2.05	-1.84
	15					-0.21	.0
	25					1.78	1.99
	35					4.06	4.27

TABLE 2B

SUN COMPASS AIMING ERRORS - HADLEY RILLE SITE

Shadow marks set for emplacement at 25° Sun Angle.

Time of Actual Emplacement		Shadow Mark Setting					
Month	Sun Angle	174.88 (July)	174.12 (Aug)	173.51 (Sept.)	173.22 (Oct.)	173.35 (Nov.)	173.87 (Dec.)
July	5	-3.84	-4.16				
	15	-1.99	-2.32				
	25	.0	-0.32				
	35	2.27	1.95				
August	5	-3.54	-3.86	-4.12			
	15	-1.68	-2.00	-2.26			
	25	0.32	.0	-0.26			
	35	2.61	2.29	2.03			
September	5		-3.61	-3.87	-3.99		
	15		-1.75	-2.01	-2.14		
	25		0.26	.0	-0.12		
	35		2.56	2.30	2.17		
October	5			-3.74	-3.86	-3.81	
	15			-1.89	-2.01	-1.96	
	25			0.12	.0	0.06	
	35			2.42	2.30	2.36	
November	5				-3.91	-3.85	-3.63
	15				-2.06	-2.00	-1.78
	25				-0.05	.0	0.22
	35				2.24	2.29	2.51
December	5					-4.05	-3.83
	15					-2.21	-1.99
	25					-0.22	.0
	35					2.05	2.28

TABLE 3A

SUN COMPASS AIMING ERRORS - MARIUS HILLS SITE

Shadow marks set for emplacement at 15° Sun Angle.

Time of Actual Emplacement		Shadow Mark Setting					
Month	Sun Angle	95.76 (July)	94.99 (Aug.)	94.39 (Sept.)	94.15 (Oct.)	94.35 (Nov.)	94.95 (Dec.)
July	5	-2.25	-2.90				
	15	.0	-0.65				
	25	2.45	1.80				
	35	5.31	4.65				
August	5	-1.61	-2.26	-2.77			
	15	0.66	.0	-0.20			
	25	3.14	2.49	1.98			
	35	6.05	5.40	4.89			
September	5		-1.76	-2.27	-2.47		
	15		0.51	.0	-0.20		
	25		3.02	2.51	2.31		
	35		5.97	5.46	5.25		
October	5			-2.06	-2.26	-2.09	
	15			0.20	.0	0.17	
	25			2.71	2.51	2.67	
	35			5.66	5.45	5.62	
November	5				-2.42	-2.25	-1.74
	15				-0.17	.0	0.51
	25				2.31	2.48	2.99
	35				5.23	5.40	5.91
December	5						
	15						
	25						
	35						

TABLE 3B

SUN COMPASS AIMING ERRORS MARIUS HILLS SITE

Shadow Marks set for emplacement at 25° Sun Angle.

Time of Actual Emplacement		Shadow Mark Settings					
Month	Sun Angle	92.87 (July)	92.06 (Aug.)	91.43 (Sept.)	91.20 (Oct.)	91.42 (Nov.)	92.07 (Dec.)
July	5	-4.70	-5.39				
	15	-2.45	-3.14				
	25	.0	-0.69				
	35	2.85	2.17				
August	5	-4.06	-4.75	-5.28			
	15	-1.80	-2.48	-3.02			
	25	0.69	.0	-0.53			
	35	3.60	2.91	2.38			
September	5		-4.25	-4.78	-4.97		
	15		-1.97	-2.51	-2.70		
	25		0.53	.0	-0.20		
	35		3.48	2.95	2.75		
October	5			-4.57	-4.76	-4.58	
	15			-2.31	-2.50	-2.31	
	25			0.20	.0	0.19	
	35			3.15	2.95	3.14	
November	5				-4.92	-4.73	-4.18
	15				-2.67	-2.48	-1.93
	25				-0.19	.0	0.55
	35				2.73	2.92	3.47
December	5					-5.22	-4.67
	15					-3.00	-2.45
	25					-0.55	.0
	35					2.31	2.86

TABLE 4A

SUN COMPASS AIMING ERRORS - TYCHO SITE

Shadow marks set for emplacement at 15° Sun Angle.

Time of Actual Emplacement		Shadow Mark Setting					
Month	Sun Angle	26.94 (July)	26.34 (Aug.)	25.86 (Sept.)	25.63 (Oct.)	25.73 (Nov.)	26.15 (Dec.)
July	5	4.48	4.08				
	15	.0	-0.40				
	25	-4.72	-5.13				
	35	-9.86	-10.27				
August	5	4.89	4.48	4.16			
	15	0.40	.0	-0.32			
	25	-4.32	-4.72	-5.04			
	35	-9.46	-9.86	-10.18			
September	5		4.81	4.48	4.33		
	15		0.32	.0	-0.15		
	25		-4.40	-4.72	-4.87		
	35		-9.54	-9.86	-10.02		
October	5			4.64	4.49	4.56	
	15			0.16	.0	0.07	
	25			-4.57	-4.72	-4.66	
	35			-9.72	-9.87	-9.80	
November	5				4.42	4.49	4.77
	15				-0.07	.0	0.28
	25				-4.80	-4.74	-4.45
	35				-9.96	-9.89	-9.61
December	5					4.22	4.50
	15					-0.28	.0
	25					-5.03	-4.74
	35					-10.20	-9.92

TABLE 4B

SUN COMPASS AIMING ERRORS - TYCHO SITE

Shadow Marks set for emplacement of 25° Sun Angle.

Time of Actual Emplacement Month	Sun Angle	Shadow Mark Setting 33.95 (July)	33.35 (Aug.)	32.87 (Sept.)	32.65 (Oct.)	32.76 (Nov.)	33.19 (Dec.)
July	5	9.20	8.80				
	15	4.72	4.32				
	25	.0	-0.41				
	35	-5.14	-5.55				
August	5	9.61	9.20	8.88			
	15	5.12	4.72	4.40			
	25	0.40	.0	-0.32			
	35	-4.74	-5.14	-5.46			
September	5		9.53	9.20	9.05		
	15		5.04	4.72	4.57		
	25		0.32	.0	-0.15		
	35		-4.82	-5.14	-5.29		
October	5			9.36	9.22	9.29	
	15			4.88	4.73	4.80	
	25			0.15	.0	0.08	
	35			-5.00	-5.15	-5.07	
November	5				9.15	9.22	9.51
	15				4.66	4.73	5.02
	25				-0.08	.0	0.29
	35				-5.23	-5.16	-4.87
December	5					8.95	9.24
	15					4.45	4.74
	25					-0.29	.0
	35					-5.47	-5.18

TABLE 5

APPROXIMATE VALUES OF SUN COMPASS ERRORS

Landing Site	Source of Aiming Error	
	Launch Date	Sun Angle
Hadley Rille	~ 0.2°/month	~ 0.2°/degree
Marius Hills	~ 0.5°/month	~ 0.25°/degree
Tycho	~ 0.3°/month	~ 0.5°/degree

TABLE 6

ESTIMATES OF NOMINAL AND WORST CASE AIMING ERRORS

A) Contributions to Aiming Error

	Nominal	Worst
1) Fabrication Process:		
a) alignment of tilt angle relative to reference plane of bubble level	±0.18°	±1.5°
b) alignment of shadow mark relative to tilt axis	±0.12°	±1.0°
c) alignment of corner reflectors relative to array	±0.04°	±0.25
2) Emplacement on Lunar Surface:		
a) alignment of shadow on shadow mark	±1.5°	±5.0°
b) accuracy in leveling experiment package	±1.5°	±5.0°

B) Net Aiming Error

	Hadley Rille		Marius Hills		Tycho	
	Nom.	Worst	Nom.	Worst	Nom.	Worst
1) Design	See Table 2 or Table 5		See Table 3 or Table 5		See Table 4 or Table 5	
2) Fabrication Process:	0.23°	1.80°	0.24	1.95	0.23	1.88
3) Emplacement Process:	1.63	5.44	1.97	6.56	1.81	6.02
Both Fabrication and Emplacement	1.85	7.22	2.20	8.45	2.04	7.87

Figure 1 Illustration of Pointing Parameters