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Data Collection by Robotic Precursors in Support of Project Apollo

Data Requirements, Program Review, and Evaluation of Results

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Exploration Programs Office
Johnson Space Center
Houston, Texas

National Aeronautics and
Space Administration

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Acronyms

CEP - Circular Error of Probability

JPL - Jet Propulsion Laboratory

OMSF - Office of Manned Spaceflight

OSS - Office of Space Science

OSSA - Office of Space Science and Applications

RFP - Request for Proposal

SEI - Space Exploration Initiative

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Abstract

Robotic missions that supported data requirements for Project Apollo had two distinct histories: earlier missions, such as Surveyor, were funded prior to the advent of the Apollo lunar landing goal and were adapted to support Apollo; later missions, such as Lunar Orbiter, were dedicated missions from the start and so were designed with the goal of supporting Apollo data requirements. The baseline documents controlling designs of robotic missions were data requirement documents issued by the Office of Manned Spaceflight to the Office of Space Sciences or to the Grumman Aircraft Engineering Company, delineating data requirements for either hardware or mission design. The experiments carried on Apollo precursors were adequate to provide the data requested. However, the disparity between the Apollo spacecraft design schedule and the time necessary to develop the robotic spacecraft resulted in this data being confirmatory, rather than supplying direct support to design efforts. On the basis of this work, it appears that SEI robotic precursor missions do not need to have a detection resolution greater than 1-2 meters in order to support SEI mission planning and design.

I. Introduction

This paper gives the results of investigations into the development and history of the lunar environment data requirements for the Apollo program, and how those requirements affected the Lunar Orbiter and Surveyor programs. This study was undertaken in an attempt to understand both the kind and the precision of lunar surface information from robotic precursor missions required by designers prior to design of Apollo hardware and how it was used. Four basic questions were addressed in the course of the study: 1) what kind of data about the lunar surface did the Apollo program require for spacecraft design, 2) to what precision was this data required, 3) what were the capabilities of the various robotic precursor spacecraft designed and flown to supply this data, and 4) what lunar surface model ultimately became the standard for the Apollo program? These same questions are faced by the Space Exploration Initiative (SEI), in defining studies of the potential robotic precursor missions for SEI. Of particular interest to SEI are the resolution capabilities for imaging systems on robotic precursor spacecraft, and the kind and precision of knowledge required of another planet's surface when designing manned and unmanned soft-landing spacecraft.

At the beginning of the Apollo program, NASA's Office of Space Science (OSS) had much the same charter as its descendant, the Office of Space Science and Applications (OSSA), does today, particularly in regards to planetary robotic science missions. A major goal of OSS was to assist the scientific community by advocating various robotic missions which would increase the general scientific knowledge about the space environment and planetary composition, evolution, and environment. In 1960, Ranger and Surveyor, two programs that were to have significant influence on the outcome of Apollo, were already on the books and well under way. When the Apollo program was approved, it had a pressing need for basic data on the Moon and for conducting the lunar and cislunar environment, for use in design of both the Apollo hardware and lunar landing missions. As a result, Ranger and Surveyor were significantly modified to support Apollo, even though such support was not part of the original mission design. This paper describes the types and precision of data the Apollo program needed, gives the history of several of the robotic programs that provided data to Apollo, and assesses the efficacy of the support these robotic missions supplied to the Apollo program.

II. Apollo Program Requirements for Lunar Environment Data

Table 1 lists the four baseline documents that apply to requirements for data from precursor robotic missions which were prepared and issued by the Office of Manned Spaceflight (OMSF) between 1962 and 1964 under the general title, "Requirements for Data in Support of Project Apollo." These documents were sent to OSS as levies against pre-existing OSS lunar robotics programs. The first issue of these documents is dated 15 June 1962. Two additional issues of this document were produced between 15 June 1962 and 25 February 1964.

All of these documents together lay out the requirements for support data to conduct a manned lunar landing. The 15 June 1962 issue divides the process into 3 phases: early Apollo support, 1962-1967; direct Apollo support, 1967-1969; and post Apollo operations, 1969 onward. Two broad groups of data are identified: technological data, used for hardware design, modification and for launch decisions, and operational support data, used for landing site identification, verification and for development of landing aids. It was expected that the technological data would be needed throughout the program, while the operational support data would be required in the 1967-1968 time frame.

Robotic missions that these documents identified in the early Apollo support phase were the Ranger and Surveyor programs; no mention is made of the Lunar Orbiter program. This may be because at this point in the OSS program, the Surveyor mission was planned as a dual orbiter-lander mission, similar to the mission profile executed for the Viking program a decade later (Nicks, 1962). However, delays in the Surveyor program and significant problems with mission success in the Ranger program, led to cancellation of the Jet Propulsion Laboratory's (JPL) work on a Surveyor orbiter.

A. Requirements for Data in Support of Project Apollo, Issue No. 1

The transmittal memorandum attached to issue no. 1 of "Requirements for Data in Support of Project Apollo" reported that design was proceeding, "relying on Earth-based and space probe observations" (NASA, 1962b). It was recognized, however, that, "Since Apollo spacecraft design must parallel and, in some cases, will precede data acquisition activity, the earliest determination of minimum gross data with follow-up refinement and enlargement is essential" (NASA, 1962b). Further, the definition of the early support phase included the charge, "Increasing scope or sophistication of techniques must not delay schedules. Earlier definition of minimum data [will be] considered superior to delay for efforts to increase the scope of data" (NASA, 1962b)."

Issue no. 1 established the following resolution requirements for photography in support of identification of landing sites:

- Photographs would cover a landing zone with a latitude spread of ±20°, with a ±5° zone of principal interest, and a longitude spread of 270° to 360° as a primary zone and a secondary zone of 0° to 90°; a landing zone was defined as a broad area of lunar surface within which Apollo landings were possible.

- Stereo TV was required as early as possible; non-stereo TV was also required if it could be obtained earlier than stereo TV.

Table 1. Apollo program requirements documents supporting robotic missions.

DOCUMENT	REVISION NUMBER	ISSUE DATE
Requirements for Data in Support of Project Apollo	1	15 June 1962
Requirements for Data in Support of Project Apollo	2	15 March 1963
Requirements for Data in Support of Project Apollo	3	25 February 1964
[Lunar Module] Landing Gear Design Criteria		11 December 1964

- Resolution within the landing zone had to be sufficient to allow interpretation of "50-foot[1] (15.3-m) size objects in areas of prime interest and 150-foot (46-m) size object capability over the entire zone. Areas of prime interest [were] to be selected on basis of current lunar knowledge with revisions reflecting acquired data and development of Apollo operational requirements" (NASA, 1962b).

- Further resolution requirements for each landing area were to allow, "identification of 4-foot (1.2-m) size objects -- cracks, protuberances, ridges, craters, etc. Optical resolution of 1-foot (31-cm) per line pair[2] is required to assure this photo interpretation capability" (NASA, 1962b). Landing areas were defined as a portion of a landing zone that was of specific interest as a location for Apollo landings.

- Area covered by this resolution was to be roughly circular, with a 30,000-foot (9.2-km) diameter.

- Photographs would be be indexed with existing lunar maps/photography.

- Data returns had to be of adequate resolution to determine surface roughness consisting of 1) discrete protuberances or objects (in 4-foot [1.2-m] size range) on a relatively smooth surface, 2) a pattern of small scale (10-foot [3.1-m] crest to crest) slopes or ridges, 3) cracks or depressions, and 4) a pattern of jagged protuberances. Further, the document called for a knowledge of the extent of roughness, particularly to answer the questions: 1) does rough terrain exist in a uniform distribution over large surface area, 2) are there patches of rough area in otherwise smooth areas and, 3) do patches of rough terrain constitute more than 50% of a large area?[3]

- Slope information needed was 1) the percentage of a landing area exceeding a slope of 20°, 2) whether the pattern of slopes within a landing area were parallel or random-crested, and 3) for areas with parallel crests, a measurement of the median crest-to-crest distance.

In addition to photographic resolution requirements, issue no. 1 delineated data requirements on the physical characteristics of the lunar surface for Apollo landing sites:

- Probable median depth and variations in the depth of any dust layer in the landing site area.

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[1]The history of the Apollo program crosses the period when NASA switched from the use of English units to the metric system; in the interests of historical accuracy, the original English units will be used in excerpts of various documents, with the metric units added parenthetically.

[2] Resolution of a certain number of feet per line pair refers to the minimum distance at which two adjacent parallel lines can be resolved as two separate lines. For the standard described in this requirement, the system would have to be able to resolve two dark lines that were 1-foot (0.3-m) apart against a lighter background.

[3] The specific meaning of "large area" at this point in the program was undefined, most likely because the size of the landing footprint of any proposed landing vehicle was similarly undefined. Based on the general discussion in memoranda at this time, the size of the area appears to be on the order of 1 to 10-km^2.

- Particle size, density, shape, chemical and mineralogical properties.

- Exhaust gas efflux trajectories

- Possible physical/chemical and physical/thermal interactions between exhaust gas and surface materials

- Early[4] requirements in probable Apollo landing areas were to determine if the static bearing strength of the soil was at least 5-psi with a typical sinkage ≤5-inches, or if static bearing strength excess of 12-psi with a sinkage <6-inches

- Final requirements in Apollo landing sites were bearing strength vs. sinkage data of 0 to 12-psi and/or 0 to 12-inch sinkage, variation in the bearing strength around the site area, and the existence of local soil bridging or soft filled depressions, etc.

Last, issue no. 1 defined the map products needed, and the standards these products would need to meet:

- Landing area maps would need to be at a scale of 1:250,000, with maximum contour intervals of 300-feet (92-m); 90% of the points depicted on the map were to be within 800 horizontal feet (244-m) of their actual location and within 150 vertical feet (46-m) of their actual location; no points were to be more than 2,000 horizontal feet (610-m) from their actual location.

- Landing site maps were to be at a scale of 1:25,000, with a maximum contour interval of 30-feet (9-m); 90% of all points were to be within 80 horizontal feet (24-m) of their true position, and within 15-feet (4.6-m) of true vertical position; no points were to be more than 200 horizontal feet (61-m) out of their true position.

The schedule requirements for acquisition of these data indicated target dates for low resolution landing zone photography by 1 January 1964, high resolution landing zone coverage by 1 January 1966, low resolution landing area coverage by mid-1963 and high resolution coverage by 1 January 1965. Data on surface roughness were to be in-hand by mid-1964.

B. Requirements for Data in Support of Project Apollo, Issue No. 2

Issue no. 2 of "Requirements for Data in Support of Project Apollo, dated 15 March 1963, went into further detail defining the geometry of shapes of particular interest, attempting to quantify the criteria that would be used to develop and evaluate imaging systems for the support phase. In particular, it stated, "The method used to determine the distribution of protuberances must permit a variety of shapes to be presented. No protuberances ... are more difficult to recognize and display than cones. Therefore, in order to assess the quality of the system used for this purpose, right circular cones will be used as reference shapes. Cones are assumed to be 'recognizable' if they protrude five times the

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4 The adjectives "early" and "late" refer to the fact that the scope of the requirements were expected to vary through time. An early requirement was to, "qualitative answers to general questions, to narrow the spectrum of conditions in proposed landing areas" (NASA, 1962b). A final requirement was for, "definitive quantitative data on actual conditions at the selected landing sites" (NASA, 1962b).

distance of their resolvable height above the average apparent near surface. They are assumed to be 'displayed' if signals relating to the slope of 40% of the conical surface differ from the signals from the average apparent near surface by three times the noise level of that area" (NASA, 1963b).

Further calls for data from issue no. 2 were as follows:

- In the pre-fall 1965 period[5], topographic data consisting of lunar surface contours which would permit a minimum of 3.5-m cones inclined 15° to be recognized and displayed over an area with a radius of 60-m; in the post-fall 1965 period, presentations of the lunar surface contours which would permit 8° cones with a 50-cm height to be recognized and displayed over an area with a radius of 1.6-km
- Information on areas 7-m in diameter with slopes >15°, areas >60-m in diameter with slopes >15°± 8°, all for the pre-fall 1965 period; in the post-fall 1965 period, slopes of >15°±4° over an area of 1.6-km in radius
- In the post-fall 1965 period, photography with a resolution of at least 25-m for the area within ±10° latitude of the equator and from 0° to 60° west of the zero selenodetic meridian
- In the pre-fall 1965 period, measurements of the weight needed to depress a sufficiently large area to a depth of 10-cm for soil bearing strengths of <8 x 10^5-dynes cm^{-2} (12-psi); measurements other than those determining static strength might also be required in the post-fall 1965 time period; these measurements were needed to determine if the lunar surface at the landing site had sufficient strength such that a static bearing pressure of 8 x 10^5-dynes cm^{-2} (12-psi) would depress the surface ≤50-cm.

Issue no. 2 also established possible two modes for a manned approach to the lunar surface, one in which lunar landing aids were to be provided for the crew prior to landing, and one in which no landing aids were available. At this point in the Apollo program, two scenarios were being used in conceptual designs for lunar module landing approach procedures. The first scenario proposed that astronauts would take over the landing approach and fly the lunar module manually to a safe touchdown on acceptable terrain. The second scenario required the lunar module to land automatically, using a landing beacon for terminal guidance with no input by the astronauts during landing. For this second scenario, it was necessary to be certain that all the terrain in the vicinity of the landing point would meet the lunar module design criteria.

For the scenario in which landing aids were not available, a satisfactory landing point would have to be visually selected within 300-m of all points within a 1.6-km radius of the normal aiming point. A satisfactory landing point would be one where terrain that met the design criteria would be available when the lunar module was within 1.6-km of the point to which the automatic guidance was taking it. For the scenario in which a landing aid was provided, it was assumed that the lunar module would track in on the landing beacon with a precision of ±30-m, and that within a 30-m radius of the beacon, 99% of all possible landing points would be satisfactory. In the event of a beacon failure, it was required that 95% of all points within 800-m of the beacon be satisfactory and that 80% of all points within 1.6-km

[5]Timing related to these calls for data were based on a schedule which froze the design process in the fall of 1965 (NASA, 1962b). Data available after fall of 1965 would be used for hardware modification, and for operational decisions.

would be satisfactory. For each landing scenario, a potential landing site would have to fit these criteria to be certified (Fig. 1).

C. Requirements for Data in Support of Project Apollo, Issue No. 3

Issue no. 3 of the document, dated 25 February 1964, specifically delineated the site selection and verification process. It stated, "The intent of the program policy is to locate sites on the Moon where a landing can be made with less than a one percent chance of catastrophe attributable to surface conditions" (NASA, 1964a). This issue somewhat widened the site selection area over that allowed by issue no. 2, to a latitude spread of ±10° and a longitude spread of ±60°, and required that a number of potentially verifiable sites be selected within this area. Verification would follow, the process insuring that, "... with reasonable confidence (90%) ... 95% of the site is good. It should also assure with high confidence (99%) that no more than 30% of the site is bad" (NASA, 1964a).

Issue no. 3 further stated that the size of an acceptable site would depend on the landing techniques employed. If a reliable beacon or marker was left on the lunar surface prior to arrival of a manned vehicle, "the site may be 0.3 square kilometers in area." If no beacon or marker was left, "the size of the area is roughly 10 square kilometers." A verified site would conform to the following lunar surface model:

- Effective protuberances would not exceed 50-cm; an effective protuberance is defined as a surface measured normal to the general surface slope within a horizontal distance of 10-m that might cause bottoming or tilting of the landing vehicle.

- The minimum surface bearing strength would be such that a static load of 1-psi would penetrate no more than 10-cm and/or a dynamic load of 12-psi (8×10^5-dynes cm^{-2}) would penetrate no more than 30-cm below the surface.

- Because of the possibility of surface sinkage, the effective protuberance, as contributed by both depressions and protuberances, could be from 20 to 50-cm.

- Provided that the first and third criteria were not violated, there were no limits on the density of protuberances.

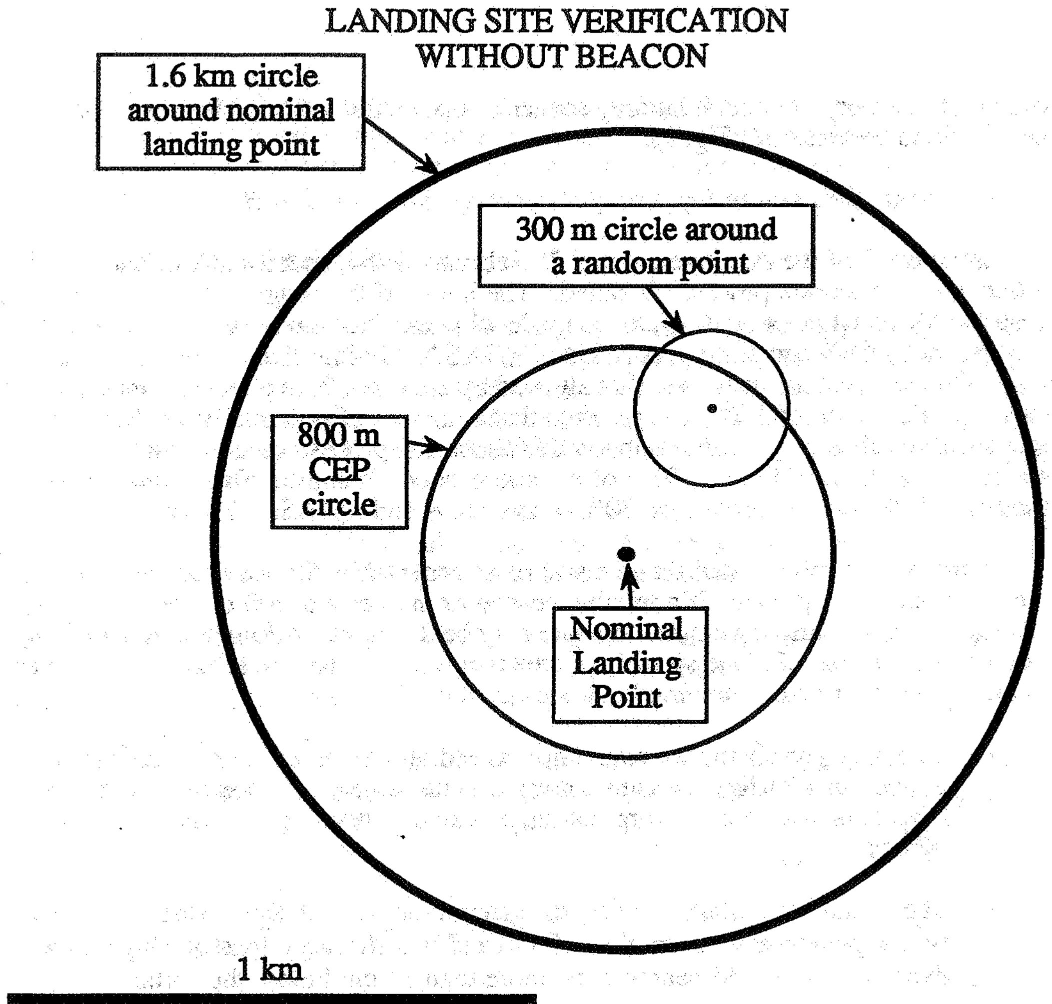
- The effective slope could not exceed 12°; effective slope was defined as the general slope of the touchdown area, plus or minus the combined effects of positive and negative landforms.

- Depending on the contribution to effective slopes by effective protuberances, the actual slope could range from 7° to 12° (NASA, 1964a).

D. Lunar Surface Model for Lunar Module Landing Gear Design

In a letter dated 11 December 1964 from the Lunar Module Project Officer to the Lunar Module Program Manager at Grumman Aircraft Engineering Corporation, NASA stated that the design criteria for the lunar module landing gear would be based on the following lunar surface model:

- The touchdown point at the landing site would be a circle 10-m in radius; the landing site would be an area $\approx$10-km^2.



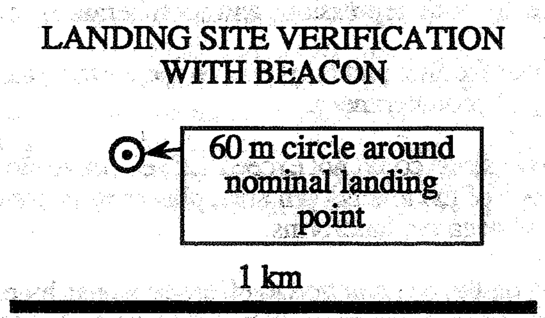


Figure 1. Landing site verification cases for proposed Apollo landing sites. This is a graphic depiction, to scale, of the two cases for landing site verification of Apollo landing sites. When no lunar based landing aids were supplied, and there was sufficient visibility and vehicle maneuverability to be able to select and land at an appropriate landing point, a landing site was considered verified only if within 1.6-km of the nominal aiming point there was a suitable landing point within 300 m of all points; when a lunar based landing beacon was available, and no selection of landing point was made on the basis of visual data, 99% of all points within 60 m of the landing beacon must have been verified as adequate landing points. CEP refers to the circular error of probability, essentially the error bars on the guidance system used in targeting the lunar module to the chosen landing point.

- For the purposes other than footpad design, the lunar surface was considered to have infinite strength and rigidity; footpad design would be based on a lunar surface bearing capacity of 12-psi (8×10^5-dynes cm^{-2}).

- The total effective slope at the landing site would not exceed 12°.

- Protuberance height above the base of the landing pads would be as great as 2-feet (61-cm) for determining the effects of potential interference between the protruberence and both the engine bell and engine exhaust (NASA, 1964b).

The touchdown conditions on the model lunar surface were originally assumed to be as follows:

- Vertical velocity: <10-ft sec^{-1} (<3.1-m sec^{-1})
- Horizontal velocity: ≤4-ft sec^{-1} (<1.2-m sec^{-1})
- Pitch attitude: ≤ 3°
- Roll attitude: ≤ 3°
- Yaw attitude: random
- Attitude rates: ≤ 3° sec^{-1}
- Engine thrust: off
- RCS thrust: off

The final specifications for touchdown velocities on the lunar surface were reduced, based on landing simulation data, to:

- Vertical velocity: 7-ft sec^{-1} (2.1-m sec^{-1})
- Horizontal velocity: 4-ft sec^{-1} (1.2-m sec^{-1}) (Rogers, 1972)

III. Apollo Robotic Programs

The Apollo program was supported by three primary robotic programs that provided data for use in design and operational planning: Ranger, Surveyor and Lunar Orbiter (see Table 2 and Fig. 2). The Ranger program, begun as a lunar hard-lander before the inception of the Apollo program, provided an initial source of qualitative data on the lunar surface. However, these data covered very small areas, and were superceded, both in areal extent covered, and in the type of information recoverd, by the Surveyor landers. Surveyor and Lunar Orbiter, in contrast to the Ranger data, gave Apollo program planners an areally wider data set to work with, and gave them the necessary confidence to design systems for lunar landing, to test designs already in place, or to develop operational planning for manned landings. For this reason, the discussion that follows will be limited to the Surveyor and Lunar Orbiter programs.

A. Surveyor Program

The Surveyor program was developed to send a fleet of soft-landing spacecraft to the Moon, there to undertake three major objectives: 1) develop and validate the technology for soft-landing on the Moon, and 2) add to scientific knowledge of the Moon (NASA, 1969). In addition, the program was tasked after its initial inception to provide data on the compatibility of the Apollo lunar module design with conditions to be encountered on the lunar surface. To that end, the Surveyor program can be seen as a complement to the Lunar Orbiter program in that each provided a different data set which would contribute to a

Table 2. Robotic missions in support of the Apollo project

MISSION	YEAR	PROGRAM OBJECTIVES AND RECORD
RANGER		
Ranger 1	1961	High earth orbit spacecraft test mission; spacecraft failed to leave initial parking orbit
Ranger 2	1961	High earth orbit spacecraft test mission; spacecraft failed to leave initial parking orbit
Ranger 3	1962	Hard lander; surface TV photography; spacecraft missed the moon
Ranger 4	1962	Hard lander; surface TV photography; spacecraft impacted the moon, but failed to return data
Ranger 5	1962	Hard lander; surface TV photography; spacecraft missed the moon
Ranger 6	1964	Hard lander; surface TV photography; cameras failed
Ranger 7	1964	Hard lander; surface TV photography; successful mission
Ranger 8	1965	Hard lander; surface TV photography; successful mission
Ranger 9	1965	Hard lander; surface TV photography; successful mission
SURVEYOR		
Surveyor 1	1966	Soft lander; surface TV photography, surface soil mechanics; successful mission
Surveyor 2	1966	Soft lander; surface TV photography, surface soil mechanics; spacecraft hard-landed
Surveyor 3	1967	Soft lander; surface TV photography, surface soil mechanics; successful mission
Surveyor 4	1967	Soft lander; surface TV photography, surface soil mechanics; telemetry lost prior to landing
Surveyor 5	1967	Soft lander; surface TV photography, surface soil mechanics, surface soil chemistry; successful mission
Surveyor 6	1967	Soft lander; surface TV photography, surface soil mechanics, surface soil chemistry, successful mission
Surveyor 7	1968	Soft lander; surface TV photography, surface soil mechanics, surface soil chemistry; successful mission
LUNAR ORBITER		
Lunar Orbiter 1	1966	Lunar orbital oblique and vertical photography; successful mission
Lunar Orbiter 2	1966	Lunar orbital oblique and vertical photography; successful mission
Lunar Orbiter 3	1967	Lunar orbital oblique and vertical photography; successful mission
Lunar Orbiter 4	1967	Lunar orbital oblique and vertical photography; successful mission
Lunar Orbiter 5	1967	Lunar orbital oblique and vertical photography; successful mission

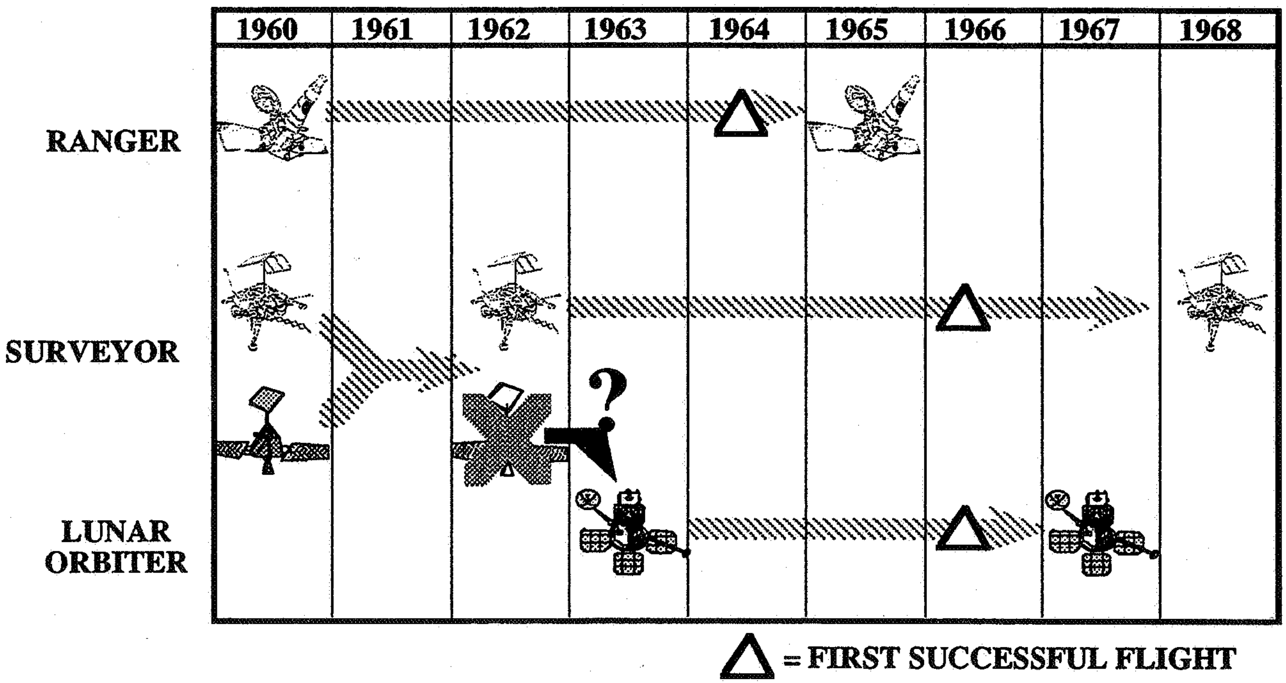


Figure 2. Schematic chart of the relationship between lunar robotics programs supporting the Apollo project. The first appearance of an icon denotes the year of contract award to the prime contractor for each spacecraft. The last appearance denotes the year of the last flight in the series. The question mark above the arrow linking the Surveyor orbiter and the Lunar Orbiter icons refers to the uncertainty concerning genealogical between these two programs. See Table 2 for specific flight dates and objectives.

complete lunar environment model to be used by Apollo spacecraft designers and mission planners. Surveyor spacecraft were designed to collect data specifically on soil cohesion, adhesion, permeability, compressibility, particle size distribution, surface bearing strength, elasticity, soil frictional properties and on surface light reflectance properties. These data were to be collected by interpretation of the television camera images that each spacecraft would return to Earth of footpad imprints, boulder tracks, and rock fragments lying on the surface in the vicinity of the spacecraft. In addition, several Surveyor spacecraft would be equipped with extendable sampling arms that could dig trenches, pick up surface samples, and potentially conduct breaking tests of lunar rocks. Further data on soil characteristics, particularly on the interaction of lunar soil with rocket engine exhaust, would be determined through firings of the spacecraft's vernier engines after touchdown at various power settings. Later spacecraft would be equipped with a capability to do rudimentary chemical analyses of lunar material, using an α-particle backscattering experiment.

Early in the planning for the Surveyor program, the landed spacecraft was to have a complementary orbiting spacecraft (Nicks, 1962), a conceptually similar program design to the Viking mission that flew to Mars over a decade later. However, after many developmental problems and cost overruns with the Surveyor lander, and after a string of failures with the Ranger spacecraft, OMSF indicated to OSS in October 1962 that program priorities were to be placed on successful completion of the Ranger program and on the earliest possible successful soft landing by the Surveyor lander (NASA, 1962c). In addition, OMSF stated, "The requirements for data which could be acquired by a lunar orbiter are applicable to Apollo mission planning rather than to [spacecraft] design and are therefore not required as soon as design data. Commitment to an orbiter during FY 63 should not be made if it would interfere with either the Ranger or Surveyor programs ... Such information will not be required before 1966" (NASA, 1962c). Further, in a meeting held in December 1962, JPL managers indicated that they would be unable to give adequate support to the Surveyor Orbiter program (NASA, 1963a).

The Surveyor spacecraft television camera system was originally to have included two cameras that had both wide and narrow angle capability and could provide stereoscopic capability with a resolution of 10' of arc. Stereoscopic coverage would be limited by the placement of the cameras in relation to other equipment on the spacecraft, and would increase with distance from the spacecraft. Ultimately, however, only a single camera was flown in each spacecraft. The camera system flown could be focused to a minimum distance of 1.2-m, which resulted in an object resolution at 2-m of 1.5-mm on the wide angle camera, and 0.4-mm on the narrow angle camera. Each camera was equipped with a color wheel and a polarizing filter, which allowed construction of color photographs of the lunar surface after Earth-based processing. The extendable sampler arm had a pantograph-type construction, and was capable of reaching between 58 and 163-cm from the spacecraft through an arc of 112° (Wilson, 1986). The arm was capable of being raised up to 102-cm above the plane defined by the spacecraft footpads, and could be depressed a nominal 46-cm below the same plane (Wilson, 1986). The scoop on the end of the sampler arm was 13-cm long and 5-cm wide (Wilson, 1986).

The original plans for the program called for Block I spacecraft to be flown on the first four missions. These were considered to be engineering test spacecraft, primarily flown to demonstrate, "successful soft-landing techniques" (JPL SPS 37-23, p. 13, quoted in Jackson, et al., 1964). These spacecraft were to be equipped with monoscopic television and a simplified touchdown dynamics experiment. Surveyors IV through VIII were to be Block II spacecraft, which would be flown with a stereo television system, a soil mechanics experiment, a touchdown dynamics experiment, and several other experiment packages designed to sample the micrometeorite environment and to begin basic geochemical and geophysical investigations of the Moon.

Experiments to be conducted by the spacecraft in support of Apollo design requirements were the soil mechanics experiment and the touchdown dynamics experiment, both of which were used to calibrate soil mechanics properties of the lunar surface. The objectives of the soil mechanics experiment, as laid out in JPL specification SAS-50150-FNC, dated 26 December 1963 (quoted in Jackson, et al., 1964) were "(1) to identify the lunar surface model in terms of material and configurations, (2) to determine the mechanical properties of the lunar surface material, and (3) to identify the mechanical properties of the each layer of surface material, if the model consists of more than one layer within the depth of investigation of the instrument." This experiment was designed to use the extendable surface arm as a probe of the physical characteristics of the lunar surface in conjunction with real time observations with the television camera system. The observations planned for the experiment were as follows:

- Observing the landing foot of the spacecraft with the television camera to obtain qualitative data on the behavior of the lunar surface on landing
- Obtaining data for a micro-topographic map of the lunar surface near the spacecraft by deploying the sampler arm throughout its reach
- Determining dynamic strength of the lunar surface by lifting and dropping the sampler arm at various areas within its reach; this experiment was later augmented by dropping rocks from various heights, and by using the sampler head to break rocks
- Making static measurements of surface strength by pulling the sampler head toward the spacecraft through the lunar soil

The touchdown dynamics experiment was designed to calibrate loads on the spacecraft at the moment of touchdown. The experiment consisted of strain gauges mounted on each of the landing pads, potentiometers mounted on the spacecraft frame, and blocks of crushable aluminum honeycomb on the landing pads and on areas of the base of the spacecraft bus which would come into contact with the lunar surface if the spacecraft legs were completely flexed. These aluminum blocks had a known crushing strength, and could be used, along with the other sensors, to calibrate loads on the spacecraft during landing. These data, integrated with data on the vertical and horizontal velocity of the spacecraft at touchdown, would allow calibration of the lunar surface bearing strength, shear strength, and coefficient of friction. In addition to these experiments, as confidence in the spacecraft systems grew later in the program, several experiments were conducted by turning on the spacecraft's vernier engines to evaluate the effect of exhaust gasses on the lunar soil, and to cause the spacecraft to hop across the lunar surface.

In addition to determining physical properties of the lunar surface, the Surveyors were considered at one time for use in deploying landing aids for an eventual manned lunar landing. In a memorandum concerning a joint Office of Manned Space Flight/Office of Space Science and Applications meeting dated 4 August 1965, the Office of Manned Space Flight was tasked with preparing a position paper on the requirements for deploying a visual marker at Apollo landing sites using Surveyor spacecraft. Ultimately, beacons and markers were dropped from the program because of the weight, volume, and electrical power restrictions on the basic Surveyor spacecraft design, and because the harshness of the lunar environment made it unlikely that an electronic beacon would survive the expected three years between a Surveyor landing and a the follow-on lunar module landing at the same site.

The Surveyor spacecraft were designed to execute a direct descent to the lunar surface, without any intermediate lunar orbit staging. Descent profile could be either vertical or inclined. Orbital dynamics considerations limited direct vertical descent to a few areas near the equator in the western hemisphere, while inclined trajectories opened up a wider area of possible landing sites. These potential landing sites included the western ≈60% of the equatorial belt that was considered most likely for an Apollo landing site (Jackson, et al., 1964). Regardless of the type of the trajectory favored, Jackson, et al. (1964) reported that the dispersion of the Surveyor landing point was much greater than the nominal landing dispersion of Apollo, and therefore could not be relied upon to give direct information about a small, preselected site. It was expected that the conclusions drawn about a particular landing site could be extrapolated to much of the lunar surface. However, Jackson, et al. (1964) felt that the landing dispersion was too large to allow targeting of the Surveyor spacecraft to locations of specific geologic interest.

Of the seven spacecraft launched by the Surveyor program, Surveyors II and IV were lost due to failures prior to landing on the lunar surface. Surveyor I was launched on 30 May 1966 and successfully soft-landed on the lunar surface on 2 June 1966. This was a block I spacecraft, and as such had no surface sampler arm. The spacecraft landed on a mare surface in Oceanus Procellarum at 2.44°S, 43.34°W, ≈14-km off its nominal targeting point. The spacecraft returned over 10,000 images during the first lunar day, and an additional 618 images after being reactivated during the second lunar day. The images return showed a surface that was composed of fine granular material, covered with meter-sized blocks.

Surveyor III was launched on 17 April 1967, and soft-landed in southeast Oceanus Procellarum on 20 April 1967 at 2.97°N, 23.34°W. Because of a radar-lock anomaly, the vernier engines continued firing after touchdown, initiating a series of 3 sideways hops before the spacecraft came to rest. An unexpected benefit of the landing anomaly for the soil mechanics experiment was visual analysis of the footprints left during the 3 hop bounce on landing. Although Surveyor III was originally planned as a Block I spacecraft, it was decided to add the surface sampler arm to the spacecraft. The surface sampler arm ultimately dug 4 trenches, conducted 7 bearing tests and 13 impact tests. In addition, the jaw at the end of the arm was able to pick up small samples and subject them to crushing pressure in an attempt to break them. The television camera system returned over 6,000 images during the one lunar day the spacecraft was operating. In addition to its service as a robotic spacecraft, the Surveyor III spacecraft ultimately provided information on long-term exposure to the lunar environment when its television camera and pieces of its sampling arm were returned to Earth by the Apollo 12 crew in 1969 after more than three years of exposure.

Surveyor V was launched on 8 September 1967 and successfully soft-landed on 11 September 1967 in Mare Tranquillitatis, at 1.5°N, 23.19°E. The spacecraft was a Block II spacecraft. In addition to the previous complement of experiments, the vernier engines were fired for 0.55-seconds to disturb the surface to investigate the interaction of rocket engines with the lunar surface. Surveyor VI was launched on 7 November 1967 and soft-landed in Sinus Medii at 0.53°N, 1.4°W on 10 November 1967. As part of the soil mechanics experiment, Surveyor VI became the first spacecraft to be launched off the surface of another planetary body during a 2.5-second burn of its vernier engines. The burn lifted the spacecraft 3-m in the air and translated it 2.5-m west, and gave the mission an opportunity to make additional observations on the effects of rocket engine exhaust on the lunar soil. Observation of the original footpad imprints was possible, and additional stereoscopic images were collected based on the variation in camera view caused by the short translation.

Prior to the launch of Surveyor VII, NASA program managers determined that the four previous successful Surveyors had gathered sufficient data to support Apollo program design. Accordingly, the last spacecraft was targeted to a location of purely scientific interest. Surveyor VII was launched 7 January 1968 and successfully soft-landed at 40.86°S, 11.47°W, on the ejecta blanket of Tycho, the youngest large impact crater on the lunar front side. In addition to the normal experiment protocol, the surface sampler arm was used to repair a recalcitrant deployment mechanism for the α-particle experiment, to fracture rocks and to determine the density of several samples. With the completion of Surveyor VII, the Surveyor program came to an end.

B. Lunar Orbiter Program

The Lunar Orbiter program was the most successful robotic mission that NASA flew in support of Apollo, flying five successful missions in five attempts. The photographs provided of the Moon have remained, to date, the best photographs of ≈80% of the lunar surface. The history of the program to place a photographic satellite around the Moon dates back to at least 1958, as suggested by a letter concerning, "Scientific Experiments for Surveyor Lunar Orbiter" dated January 12, 1962 from Mr. Newton Cunningham, Head of the Lunar Sciences Program in OSS to Dr. Charles P. Sonnett, Chief of Lunar and Planetary Sciences at the Manned Spacecraft Center (MSC). The following points on early program philosophy for a lunar orbiting spacecraft can be gleaned from this letter:

- Planning for a Lunar Orbiter-type mission goes back to 1958, when JPL conducted detailed study and design efforts for a possible lunar orbit mission to photograph of the lunar surface at close range as part of Pioneer IV. The proposed spacecraft was to be launched with a Jupiter-class booster.

- Initially, the photographic subsystem design was to use a 35-mm photographic film self-development process that sounds very similar to the Bimat process design that flew on Lunar Orbiters I through V. However, early results from the Explorer IV mission raised fears that the film used on such a process would be fogged during transit of the Van Allen radiation belts. Design efforts were then shifted to a vidicon TV system with a planned 200 line resolution capability. In December 1958, it was decided that Pioneer IV would carry radiation monitoring equipment rather than an imaging system, and development work was stopped, although a similar television camera was ultimately carried on the Tiros I spacecraft.

- In 1959, as part of the proposed Vega program, a detailed study was made of the possibility of a lunar orbital mission that would include photography among its objectives. The planned imaging system would be a vidicon TV system. Two spacecraft were planned, one "capable of obtaining low resolution photography in contiguous swaths and one capable of relatively high resolution of a smaller portion of the lunar surface." Other experiments were proposed for this spacecraft involving measurement of particles and fields data and micrometeorite data.

- Although no other mention of the Vega program is found in the correspondence, results of the pre-start program studies were applied in 1960 to plans for a similar spacecraft to be flown on an Atlas-Centaur booster in the 1963 time frame. At this time, there appears to be an attempt to decouple the photographic requirements from the other science experiments, apparently on the basis of performance requirements. This upgraded photographic mission was intended to provide "relatively low resolution photographs of the whole lunar surface for photogrammetric purposes and relatively high resolution photographs of selected areas of the lunar surface" (NASA, 1963b). The specific identification of these selected areas is not mentioned. It is tempting to surmise that these selected areas were potential landing sites. As the Space Task Group, out of which grew the Apollo program, was in existence by this time, and was beginning to plan for a program to land men on the Moon (Murray and Cox, 1989), it is possible that even at this early date, thought was being given to plans for landing that would translate into robotic missions. Regardless, the mission defined in this document has the broad outlines of the program which ultimately flew in the 1966-67 time frame as Lunar Orbiter.

- At the 23 March 1961 meeting of the Lunar Sciences Subcommittee, it was recommended that the lunar surface photography returned by the Centaur Program include, "high resolution photography (10-m or less) ... restricted to small areas such as a particular crater or a small portion of one of the maria; ... complete photo coverage of the limb area and backside of the Moon at one-kilometer; reconnaissance photography of the lunar surface at [a resolution of] 100-m; stereo pairs should be obtained of the high resolution areas if possible" (NASA, 1962a). Again, this was before the 25 May 1961 call by President Kennedy for a manned landing, but the broad outlines calling for high resolution photography of small areas of the lunar surface indicates that the agency was already planning robotic missions in support of a manned lunar landing.

The next pertinent document that applies to requirements for Lunar Orbiter was issue no. 1 of, "Requirements for Data in Support of Project Apollo," 15 June 1962. This document was discussed earlier in section II. A. In review, the resolution requirements for photography to support identification of landing sites was 1-foot (0.3-m) per line pair, presumed sufficient to identify objects on the order of 4-foot (1.2-m) in size that would be obstructive to landing. While this document was produced before the advent of Lunar Orbiter, it seems likely that these requirements were ultimately incorporated into the design basis for the Lunar Orbiter program. The only other program dedicated to lunar photography, the Ranger program, was implemented as a hard lander, and so was unable to provide these data to the level of precision required for the entire lunar surface.

As was discussed previously, early in the planning for the Surveyor program, the landed spacecraft was to have a complementary orbiting spacecraft (Nicks, 1962), a conceptually similar program design to the Viking mission that flew to Mars over a decade later. The Surveyor orbiter, as described by Nicks (1962), was to provide a stable orbiting platform to conduct the following activities:

- Broad area reconnaissance of the total visible and hidden faces of the Moon
- Preliminary selection of desirable landing sites for subsequent Surveyor and Apollo missions
- Monitoring of the radiation environment and other physical parameters in the immediate vicinity of the Moon
- Determining the properties and planet-wide variations of the moon's gravitational field
- Communications relay for possible manned landings on the lunar farside
- Use as a global positioning satellite for use in extensive exploration activities

After the deletion of the orbiter portion of the Surveyor spacecraft (described in section III. A. of this report), the general goals for reconnaissance and landing site photography were adapted for the Lunar Orbiter program.

The next document that applies to the history of Lunar Orbiter is enigmatic in that it bears only a date, with information on neither the addressee or author. The date on this document is 4 March 1963, and it is entitled, "Requirements for a Lunar Orbiter in the Lunar Science Program." A generic statement of the programmatic requirements that drove the need for some form of lunar orbiting photographic spacecraft. This document may have been a first draft defining requirements for the Lunar Orbiter Request for Proposals (RFP). The requirements delineated in this document were similar to those in the 15 June 1962 version of "Requirements for Data in Support of Project Apollo."

Further definition of the photographic requirements for the Lunar Orbiter program came in an April 1963 memorandum from the Office of Manned Spaceflight to the Office of Space Science, which was prepared to assist Langley Research Center in preparing the RFP for the Orbiter program. The requirements in this document are quoted in Destination Moon: The History of the Lunar Orbiter Program, NASA Technical Memorandum TM X-3487 by Bruce Byers, published in 1977. The requirements were 1) photographic data on lunar surface topography capable of showing cones 3.5-m high, 0.9-m wide and with slopes of 15° in an area of 60-m radius by the fall of 1965; 2) further refinement of this data showing cones of 50-cm in height and 8° slopes in an area of 1600-m radius; 3) measurement of slopes >15° in areas 7-m in diameter; and 4) photographs ≥25-m resolution over the largest possible area within ±10° latitude and 0° to 60° west longitude on the Moon.

Further guidance from NASA Headquarters suggested that Langley Research Center use the following guidelines for identifying slopes and cones on the lunar surface (quoted from Byers, 1977), "[Cones] could be considered as recognized if the standard deviation [1σ] of the cone's estimated height caused by system noise in the spacecraft was <1/5 of the cone's height. Slopes ... would be considered as recognized if the 1σ of estimated slope caused by system noise was <1/5 of the slope." The interpretation of this is that if the system noise caused less than a 20% error in measurement of the height of cones or the dip of slopes, one could be assured that the particular terrain feature was in fact there, and not an artifact of system noise. Further requirements on the spacecraft were to be able to determine the altitude of the spacecraft at the time of each photographic exposure, the orientation of the spacecraft with respect to lunar north, and the relative angle of the sun to the portion of the Moon's surface covered by any photograph.

The release by Langley Research Center of the RFP on 30 August 1963 marks the official start of the Lunar Orbiter program. The contract award to Boeing to build the Lunar Orbiter spacecraft was announced on 20 December 1963.

The final flight photographic system for Lunar Orbiter had the following demonstrated performance capability, quoted from, "Preliminary Terrain Evaluation and Apollo Landing Site Analysis Based on Lunar Orbiter I Photography," dated late 1966:

- Nominal 1-meter and 8-meter resolution from an altitude of 46-km
- High resolution lens: 610-mm focal length, ƒ5.6
- Medium resolution lens: 80-mm focal length, ƒ5.6
- Exposure time can be set at 1/25, 1/50 or 1/100 seconds
- Automatic sequences of 1, 4, 8 or 16 frames can be taken

This system used a Bimat development process, in which images were exposed on photographic film, which was then developed aboard the spacecraft by mating the exposed photographic film with a film that was coated with a developing emulsion, similar to the Polaroid system process that produces a black and white negative along with a positive print. The developed film was then scanned by a light source/vidicon tube combination to produce a variable signal, the strength of which was a function of emulsion density on the film. This signal was then transmitted back to Earth at appropriate intervals, and the photographs were built up a swatch at a time. The characteristic look of an orbiter photograph, which appears to be built up by pasting together numerous ≈0.5-cm photographs, is an artifact of the scanning process. A nominal total of 212 photographs could be taken on each mission, although occasional film reeling mechanisms caused several pictures to be lost in the course of a mission.

Lunar Orbiter I was launched on 10 August 1966, and after minor problems, entered lunar orbit on 14 August. The objectives of this first mission were to photograph the proposed landing areas in the Apollo Zone, mare areas ≈5° on either side of the lunar equator. Although there were some problems with the photographic system, the mission was able to photograph all nine potential Apollo landing sites. In addition, eleven pictures of the lunar farside and two Earth-Moon pictures were taken. Readout of all 205 exposed frames was completed by 16 September. In October, the spacecraft was deliberately crashed into the lunar farside to avoid a possible navigation hazard with Lunar Orbiter II.

The second mission was launched on 6 November 1966, and went into lunar orbit approximately 4 days later. The mission of Lunar Orbiter II was also to photograph potential Apollo landing sites. Photographs were taken almost continuously from 18 November until 26 November, and readout was completed 7 December. With the exception of one high resolution photograph of secondary landing site II S-1, all photographs were recovered intact.

Lunar Orbiter III was launched on 5 February 1967, and began taking photographs on 15 February. The primary objective was to continue photography of potential Apollo landing sites, but in this case, it concentrated on targets gleaned from detailed examination of photographs from Lunar Orbiters I and II. In addition, targets of scientific interest were to be taken as a secondary objective. Although the photographic portion of the mission went as planned, a failure in the film reeling system during the readback process resulted in loss of ≈75 photographs. In spite of this loss, determination was made that Lunar Orbiters I through III had satisfied the basic mission requirement, and that the remaining 2 spacecraft would be dedicated to photographing scientific targets of interest, and to increase the general state of knowledge of the cartography of the Moon.

Lunar Orbiter IV was dedicated to a broad, systematic survey of the Moon, with an eye toward identifying detailed targets that could be photographed by the remaining spacecraft. Lunar Orbiter IV was launched on 4 May 1967 and began photographing the lunar surface on 11 May. Photography continued until the final readout on 1 June 1967. The mission succeeded in photographing 99% of the lunar nearside at a resolution of better than 100-m, an order of magnitude better than the best Earth-based photography. In addition, coverage of the lunar farside resulted in an estimated 80% coverage at a resolution of better than 1-km during the first four missions.

Mission five of the Lunar Orbiter series was launched on 1 August 1967. The mission had the objectives of photographing additional Apollo landing sites for early engineering test missions and for later science-oriented missions, targeting sites of specific scientific interest, and completing cartographic coverage of the lunar farside. Photography was begun on 6 August 1967 and continued until 18 August 1967. Of the entire lunar surface, better than 95% was photographed by Lunar Orbiter. This data set still represents the most complete photographic coverage of the Moon, although it was later augmented by higher resolution metric and panoramic camera photographs during the latter part of the Apollo program.

IV. Discussion, Applications and Conclusions

A. Discussion

Any discussion of this topic has to evaluate four questions: 1) were the various subsystems flown on Surveyor and Lunar Orbiter adequate to provide the data required, 2) was the lunar surface data produced by Surveyor and Lunar Orbiter available in a timely fashion to support the design of critical Apollo systems, primarily the lunar module landing gear design, 3) if this data was not available for use in critical design, was it used in any way to support Apollo design, and 4) if the data derived did not match the data used in design of Apollo components, was the design sufficiently conservative to avoid last-minute redesign?

The various experiments flown on Surveyor appear to have been adequate to provide data on the nature of the lunar surface, particularly mechanical properties. The soil mechanics experiment was able to provide substantial visible evidence of a surface capable of supporting the weight of the lunar module. In addition, television surveys of the surrounding terrain gave significant visual data on the presence and physical characteristics of large surface blocks and craters, and complemented the data set developed by Lunar Orbiter on the nature of the meter-scale topography at the Apollo landing sites.

To a first order, the photographic system on Lunar Orbiter appears to have met the program design specifications. In the suite of photographs taken of each primary site in the Apollo landing zone, numerous images provided a design resolution at or better than 1-m for high resolution photographs, and at or better than 8-m for medium resolution photographs [see Appendix 1 for design resolution data on Lunar Orbiter photographs of all proposed Apollo landing sites]. What is not always clear is how the design resolution equates to actual, or detection, resolution. Several factors complicate this assessment. First, sun angle and shadow length play a significant part in the identification of specific features. In photographs with low sun angle (<45°), an object can often be located and recognized on the basis of its shadow, particularly when the shadow length is several times the size of the object. This assumes, however, that the shape of the shadow is known.

A memorandum dated 22 September 1967 from J.L. Dragg, an MSC Mapping Sciences Branch staff member, to the Assistant Chief of the Mapping Sciences Branch, discussed several of the factors involved in locating Surveyor spacecraft on Lunar Orbiter photographs. In particular, author Dragg reported on a comparison between a common area imaged by both Lunar Orbiter V at 2-m resolution and Lunar Orbiter II at 1-m resolution. The sole difference between these photographs was sun angle: in the LO V photograph, it was 18°, whereas in the LO II it was 28°. Dragg reported, "This tradeoff in resolution versus sun angle results in photography from both missions having the approximate same detection resolution. Using the prints, the resolution was at 4.5-m for both" (NASA, 1967a). Second, if one is looking for a specific target and the physiography of the area surrounding the target is known, then finding the proper terrain allows one to substantially narrow the area to be carefully screened. J.L. Dragg reported in the same memorandum that the location of Surveyor I on Orbiter III photography (frame LO III-194 H and LO III-183H) was determined visually rather than by using terrain, presumably on the basis of its shadow. In particular, Dragg reports, "Since the sizes of most of the craters visible in Surveyor I were badly estimated from Surveyor I photography alone, it is questionable if Surveyor I would have ever been located on the Orbiter III coverage if the spacecraft itself had not been visible" (NASA, 1967a). In contrast, locating Surveyor III on Lunar Orbiter III coverage was abetted by the fact that it landed inside a ≈200-meter diameter crater. The presence of both 4 to 25-m diameter craters and blocks up to several meters in size in recognizable juxtaposition in the vicinity of the lander made it possible to look for this pattern within the larger crater until the location of the spacecraft had been determined by a process of elimination.

The various conditions under which the photographs were taken, and for which they were ultimately used, suggest that detection resolution could be between four and five times worse than the design resolution. If this is the case, the best Lunar Orbiter resolution used on Apollo was 4 to 5-m for high resolution frames and 30 to 50-m for low resolution frames, although J.L. Dragg's memorandum strongly suggests that it is necessary to assess detection resolution on a frame-by-frame, case-by-case basis. It is not entirely clear that photographs better than several meters resolution are needed for landing safety and design requirements. Based on the available data, the Apollo 16 crew went to the Descartes site with no better than 20-m resolution photographs of the landing site, and had little trouble finding a safe place to land, although crew members felt that meter-scale resolution was needed for adequate mission planning (J. W. Young, personal communication, 1990). On that basis, it would seem that designing imaging systems for future robotic missions to a specification of 1 to 2-m detection resolution should be adequate to provide data for mission planning in terms of terrain analysis for mobility and safe landing operations. Further, it would appear, on the basis of Dragg's memorandum, that the best situation is a complementary set of ground- and orbital-based imaging systems, at least in terms of producing accurate topographic models of a landing site. This data set could be made more robust by mounting a camera on a roving platform, rather than a stationary one such as the Surveyor spaccraft. In any event, it seems clear that the combined use of Surveyor and Lunar Orbiter was not only adequate, but necessary to provide the Apollo program with the data required on landing site surface characteristics and topography.

Assessment of data availability as primary design information for Apollo is somewhat less clear. Documents on the history of design of critical subsystems for Apollo, particularly the design of the lunar module landing gear and landing radar, would suggest that this data were not available for primary designs. Table 1 in Rogers (1972) implies that the last major redesign of the lunar module landing gear took place in July of 1965. Further, development of all but one of the major components for the lunar module landing gear was complete by very early 1966, in advance of the May 1966 landing of Surveyor I and the August 1966 flight of Lunar Orbiter I (Rogers, 1972, Figure B-1). The exception is the aluminum honeycomb shock absorbant cartridges that were used as primary shock absorbers for the legs; development was complete on this component in early 1967. It is enticing to suggest that final development of the honeycomb shock absorbers was delayed pending acquisition of Surveyor data, but no specific references were found supporting this conjecture. The reference list for Appendix B, "Hardware Development and Certification Testing", in Rogers (1972) suggests that development and testing concerns were the primary reasons for the slower development of the honeycomb shock absorbers. Similar conclusions can be drawn on the use of Surveyor and Lunar Orbiter data for subsystem design of the lunar module landing radar (Rozas and Cunningham, 1972). Consequently, it would appear that data from Surveyor and Lunar Orbiter were not used in primary design of Apollo components.

It would appear, however, that Lunar Orbiter and Surveyor data did serve Apollo program in two extremely important ways. The first was as a confirmation of the basic lunar surface model used in design of Apollo hardware. In particular, Rogers (1972) states, "Data obtained from the NASA Surveyor and Lunar Orbiter programs ... verified the accuracy of the lunar-surface specifications." This conclusion can also be drawn in considering the data in the lunar surface model used for the Apollo 11 landing, when compared to the dearth of actual, in situ data needed in support of Apollo. Further, NASA (1969) states unequivocally, "Lunar Orbiter and Surveyor data have been reveiwed ... and found within the bounds of these models."

The second use of data was in preparing models of the topography of each potential landing site to be used for landing site evaluation and crew training and simulation. The available topographic data at the beginning of Apollo had a resolution of ≈1-km, compared with the meter-scale knowledge of the lunar surface around the Apollo landing sites developed from Lunar Orbiter. It seems clear that a program of manned lunar landings would not have proceeded without these data, and that in spite of its tardiness in support of Apollo design, Lunar Orbiter and Surveyor data did provide crucial support to successful Apollo landings.

In reference to the fourth question posed at the beginning of this section, the origin of the design specifications delineated in the 11 December 1964 memorandum from the Apollo Spacecraft Program Office to Grumman Aircraft is unknown. Presumably, they were derived from terrestrial experience, and Agency management probably felt that these specifications represented a conservative design, in case lunar data returned by Surveyor were significantly different from the model data on which the specifications were based. However, this memorandum also directed Grumman to, "perform analysis of parameter effects outside the ... envelopes given as requirements" (NASA, 1964b). Apollo program management was clearly attempting to produce as conservative a design as possible. Ultimately, the success of the six lunar landings during Apollo attests to the adequacy of the design of the lunar module.

B. Applications: Lunar Surface Model Used in Support of the Apollo Landings

The lunar surface model developed, in part, from Surveyor and Lunar Orbiter data for use in Apollo landings is summarized here, and detailed in a document entitled, "Natural Environment and Physical Standards for the Apollo Program and the Apollo Applications Program."[6] Although there were several versions of this report, the document used for this section was dated 10 July 1969, approximately 10 days before the first manned lunar landing. The candidate sites covered by this lunar model are the sites in the Apollo zone, located within 4° of the lunar equator. Identified by Lunar Orbiter target numbers, they are as follows:

I P-1, V V-8: in Mare Tranquillitatis at 1° S, 43° E
II P-2 (Apollo 11), V V-11: in Mare Tranquillitatis at 2° 30' N, 34° E
II P-6, V V-16: in Mare Tranquillitatis 1° N, 24° E
II P-8, III P-7 (Apollo 12), V V-27: in Sinus Medii at 0° 30' N, 1° W
II P-11, III P-8: in Oceanus Procellarum at 0° 30' S, 19° 30' W
II P-13, 3P-10: in Oceanus Procellarum at 1° 30' N, 41° 30' W
III P-9: in Oceanus Procellarum at 3° S, 23° W
III P-11, V V-42: in Oceanus Procellarum at 3° 30' S, 36° W
III P-12: in Oceanus Procellarum at 2° 30' S, 44° W

It is important to note that only two of these sites, II P-2 and II P-8, were ultimately targets for manned landings during the Apollo program.

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[6] In this context, the Apollo applications program refers to the "J" series missions flown by Apollos 15, 16 and 17, and not to the later Skylab program.

The touchdown point at each site was considered to be a circle with a radius of 10-m, and the landing site was considered to be an area of ≈10 square kilometers around the touchdown point. The surface was considered to be composed of both a highly porous (70 to 80 % within the upper few centimeters of the soil), cohesive or non cohesive aggregate of variable thickness, and a structurally competent material. The overall structure of the soil was felt to be granular, although individual clasts in the soil might be porous (NASA, 1967b). Particle size distribution ranged from 1-m to 1-mm clasts on the lunar surface, with the majority of the surface layer <0.5-mm, probably in the 0.005 to 0.1-mm size range (NASA, 1967b). The density of the soil was expected to be 0.6 to 0.7-g cm^{-3} at the surface, 1-g cm^{-3} at 10 to 20-cm and 2 to 3-g cm^{-3} at 1 to 10-m (NASA, 1967b). The minimum bearing strength of the high porosity material was expected to support a static load of 7 x 10^3-N m^{-2} (1-psi) with a penetration of no more than 10-cm below the surface, or a dynamic load of 8.3 x 10^4-N m^{-2} (12-psi) with a penetration of no more than 60-cm below the surface. The effective rigidity and strength of the structurally competent material was considered infinite. Results from the Apollo 11 landing indicate that the lower boundary of the bearing strength in the landing area was closer to 1.4 to 2.1 x 10^4-N m^{-2} (Rogers, 1972).

In terms of topography, it was considered that shallow depressions and low protuberances would be sufficiently numerous so that one or more of the landing pads would be horizontally constrained after moving along the surface a variable distance. The coefficient of friction of the surface to horizontal sliding would vary between 0.4 and 1.0. Apollo 11 experience indicated that 0.4 was a realistic value for coefficient of friction (Rogers, 1972). The effective protuberances at the touchdown point would be <60-cm. These protuberances would be made up of either single units, such as single blocks or craters, or they would be made up of combinations of positive and negative landforms within ≈10-m of the touchdown point. The effective slope of the touchdown point would not exceed 12°.

C. Conclusions

On the basis of this study, it is possible to reach the following conclusions about data derived for the Apollo program from robotic precursors:

- The experiments and photographic systems carried on Surveyor and Lunar Orbiter were more than adequate to supply the data about the lunar surface environment needed for Apollo designers and mission planners.

- Data were not available in time for initial vehicle design; however, the data was available for mission operations planning and for design confirmation.

- The best Lunar Orbiter resolution photographs had a detection resolution of approximately 4 to 5-m for high resolution frames and 30 to 50-meters for low resolution camera frame.

- It is not clear that resolution of better than 1-meter is necessary for lunar lander safety and design requirements. A successful landing was made at the Descartes site on Apollo 16 with no better than 20-m resolution, although the mission commander (Capt. John Young) has indicated that resolution on the order of 1-m would have been desirable (J. Young, personal communication, 1990).

- Designing the imaging system on SEI robotic precursors to a resolution of 1 to 2-m should be adequate for terrain analysis and SEI mission planning purposes.

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Appendix: Lunar Orbiter Photographic Data for Candidate Apollo Landing Sites

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-1	I-41M	44.09	256	83.5°
P-1	I-42M	46.07	265	86.5°
P-1	I-46M	14.72	86	82.0°
P-1	I-47M	14.52	85	81.6°
P-1	I-48M	12.02	72	76.1°
P-1	I-49M	11.78	70	75.4°
P-1	I-50M	10.22	60	64.6°
P-1	I-51M	10.22	60	64.2°
P-1	II-5H	1.13	52	74.4°
P-1	II-5M	8.65	52	74.4°
P-1	II-6H	1.13	52	74.3°
P-1	II-6M	8.63	52	74.3°
P-1	II-7H	1.13	52	74.2°
P-1	II-7M	8.61	52	74.2°
P-1	II-8H	1.13	52	74.1°
P-1	II-8M	8.60	52	74.1°
P-1	II-9H	1.13	52	73.9°
P-1	II-9M	8.58	52	73.9°
P-1	II-10H	1.12	52	73.8°
P-1	II-10M	8.57	52	73.8°
P-1	II-11H	1.12	52	73.7°
P-1	II-11M	8.55	52	73.7°
P-1	II-12H	1.12	52	73.5°
P-1	II-12M	8.54	52	73.5°
P-1	II-13H	1.12	52	73.4°
P-1	II-13M	8.52	52	73.4°
P-1	II-14H	1.12	51	73.3°
P-1	II-14M	8.51	51	73.3°
P-1	II-15H	1.12	51	73.2°
P-1	II-15M	8.50	51	73.2°
P-1	II-16H	1.11	51	71.4°
P-1	II-16M	8.49	51	71.4°
P-1	II-17H	1.11	51	72.9°
P-1	II-17M	8.47	51	72.9°
P-1	II-18H	1.11	51	72.8°
P-1	II-18M	8.46	51	72.8°
P-1	II-19H	1.11	51	72.7°
P-1	II-19M	8.45	51	72.7°
P-1	II-20H	1.11	51	72.5°
P-1	II-20M	8.44	51	72.5°
P-1	II-35H	1.05	49	68.0°
P-1	II-36H	1.05	49	67.9°
P-1	II-37H	1.06	49	67.8°
P-1	II-38H	1.06	49	67.6°
P-1	II-39H	1.06	49	67.6°
P-1	II-40H	1.06	49	67.4°
P-1	II-41H	1.06	49	67.3°
P-1	II-42H	1.06	49	67.2°
P-1	III-5H	1.30	60	76.7°
P-1	III-6H	1.30	60	76.5°
P-1	III-9H	1.29	59	76.1°
P-1	III-10H	1.28	59	76.0°
P-1	III-11H	1.28	59	75.8°
P-1	III-12H	1.28	59	75.7°
P-1	III-13H	1.27	59	75.5°
P-1	III-14H	1.27	59	75.4°
P-1	III-15H	1.27	58	75.2°
P-1	III-16H	1.26	58	75.1°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-1	III-17H	1.26	58	75.0°
P-1	III-18H	1.26	58	74.8°
P-1	III-19H	1.25	58	74.7°
P-1	III-20H	1.25	58	74.5°
P-1	IV-73H/3	59.19	2727	64.5°
P-1	V-6H	59.68	2648	97.7°
P-1	V-6M	455.02	2648	97.7°
P-1	V-8aM	455.54	2652	97.6°
P-1	V-8aH	59.75	2652	97.6°
P-1	V-8bM	455.54	2652	97.6°
P-1	V-8bH	59.75	2652	97.6°
P-1	V-66H	2.67	123	68.7°
P-1	V-66M	20.34	123	68.7°
P-1	V-38H	4.85	103	67.5°
P-1	V-38M	37.18	103	67.5°
P-1	V-41H	4.00	103	68.0°
P-1	V-41M	30.62	103	68.0°
P-1	V-42H	3.70	102	68.1°
P-1	V-42M	28.29	102	68.1°
P-1	V-55H	2.20	100	68.8°
P-1	V-56H	2.20	100	68.8°
P-1	V-57H	2.20	100	68.8°
P-1	V-58H	2.20	100	68.7°
P-1	V-59H	2.36	100	68.9°
P-1	V-60H	2.36	100	69.0°
P-1	V-61H	2.36	100	69.0°
P-1	V-62H	2.37	100	68.8°
P-2 (AS-11)	IS-7M	35.98	217	66.8°
P-2 (AS-11)	II-35H	1.05	49	68.0°
P-2 (AS-11)	II-35M	8.04	49	68.0°
P-2 (AS-11)	II-36H	1.06	49	68.0°
P-2 (AS-11)	II-36M	8.04	49	68.0°
P-2 (AS-11)	II-37H	1.06	49	67.8°
P-2 (AS-11)	II-37M	8.05	49	67.8°
P-2 (AS-11)	II-38H	1.06	49	67.6°
P-2 (AS-11)	II-38M	8.05	49	67.6°
P-2 (AS-11)	II-39H	1.06	49	67.5°
P-2 (AS-11)	II-39M	8.06	49	67.5°
P-2 (AS-11)	II-40H	1.06	49	67.4°
P-2 (AS-11)	II-40M	8.06	49	67.4°
P-2 (AS-11)	II-41H	1.06	49	67.3°
P-2 (AS-11)	II-41M	8.07	49	67.3°
P-2 (AS-11)	II-42H	1.06	49	67.2°
P-2 (AS-11)	II-42M	8.08	49	67.2°
P-2 (AS-11)	II-76H	1.07	49	62.0°
P-2 (AS-11)	II-77H	1.07	49	61.9°
P-2 (AS-11)	II-78H	1.07	50	61.7°
P-2 (AS-11)	II-79H	1.08	50	61.6°
P-2 (AS-11)	II-84H	1.11	51	60.3°
P-2 (AS-11)	II-85H	1.11	51	60.2°
P-2 (AS-11)	II-86H	1.12	52	60.1°
P-2 (AS-11)	II-87H	1.12	52	59.9°
P-2 (AS-11)	III-25H	1.22	56	67.1°
P-2 (AS-11)	III-25M	9.29	56	67.1°
P-2 (AS-11)	III-26H	1.22	56	66.9°
P-2 (AS-11)	III-26M	9.30	56	66.9°
P-2 (AS-11)	III-27H	1.22	56	66.7°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-2 (AS-11)	III-27M	9.31	56	66.7°
P-2 (AS-11)	III-28H	1.22	56	66.6°
P-2 (AS-11)	III-28M	9.32	56	66.6°
P-2 (AS-11)	III-29H	1.22	56	66.5°
P-2 (AS-11)	III-29M	9.23	56	66.5°
P-2 (AS-11)	III-30H	1.22	56	66.4°
P-2 (AS-11)	III-30M	9.33	56	66.4°
P-2 (AS-11)	III-31H	1.23	56	66.2°
P-2 (AS-11)	III-31M	9.34	56	66.2°
P-2 (AS-11)	III-32H	1.23	56	66.1°
P-2 (AS-11)	III-32M	9.35	56	66.1°
P-2 (AS-11)	III-33H	1.31	57	65.0°
P-2 (AS-11)	III-33M	9.99	57	65.0°
P-2 (AS-11)	III-58M	1.14	51	71.6°
P-2 (AS-11)	III-60H	1.11	50	70.9°
P-2 (AS-11)	III-63H	1.11	50	70.5°
P-2 (AS-11)	III-66H	1.11	50	70.1°
P-2 (AS-11)	III-68H	1.09	50	72.2°
P-2 (AS-11)	III-70H	1.08	49	71.1°
P-2 (AS-11)	IV-84H/1	59.19	2727	67.9°
P-2 (AS-11)	IV-85H/3	58.97	2717	65.5°
P-2 (AS-11)	V-11aH	59.85	2657	97.7°
P-2 (AS-11)	V-11aM	456.32	2657	97.7°
P-2 (AS-11)	V-11bH	59.85	2657	97.7°
P-2 (AS-11)	V-11bM	456.32	2657	97.7°
P-2 (AS-11)	V-52H	3.69	101	68.3°
P-2 (AS-11)	V-52M	28.27	101	68.3°
P-2 (AS-11)	V-9.1H	59.79	2654	97.8°
P-2 (AS-11)	V-9.1M	455.80	2654	97.8°
P-2 (AS-11)	V-64H	3.57	98	69.3°
P-2 (AS-11)	V-71H	2.14	98	69.8°
P-2 (AS-11)	V-72H	2.14	98	69.8°
P-2 (AS-11)	V-73H	2.14	98	69.7°
P-2 (AS-11)	V-74H	2.14	98	69.7°
P-2 (AS-11)	V-75H	2.39	98	69.9°
P-2 (AS-11)	V-76H/1	2.39	98	69.8°
P-2 (AS-11)	V-77H	2.39	98	69.8°
P-2 (AS-11)	V-78H	2.39	98	69.8°
P-3	I-118M	8.56	52	70.2°
P-3	I-119M	8.56	52	70.1°
P-3	I-120M	8.55	52	70.0°
P-3	I-121M	8.53	52	69.8°
P-3	I-122M	8.51	51	69.7°
P-3	I-123M	8.50	51	69.6°
P-3	I-124M	8.48	51	69.4°
P-3	I-125M	8.47	51	69.3°
P-3	I-126M	8.46	51	69.1°
P-3	I-127M	8.44	51	69.0°
P-3	I-128M	8.43	51	68.9°
P-3	I-129M	8.41	51	68.8°
P-3	I-130M	8.41	51	68.6°
P-3	I-131M	8.40	51	68.5°
P-3	I-132M	8.39	51	68.4°
P-3	I-133M	8.38	51	68.2°
P-3	II-43H	1.08	50	77.2°
P-3	II-43M	8.25	50	77.2°
P-3	II-44H	1.08	50	77.1°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-3	II-44M	8.23	50	77.1°
P-3	II-45H	1.08	50	76.9°
P-3	II-45M	8.21	50	76.9°
P-3	II-46H	1.07	49	76.8°
P-3	II-46M	8.19	49	76.8°
P-3	II-47H	1.07	49	76.7°
P-3	II-47M	8.16	49	76.7°
P-3	II-48H	1.07	49	76.5°
P-3	II-48M	8.14	49	76.5°
P-3	II-49H	1.07	49	76.4°
P-3	II-50H	1.06	49	76.2°
P-3	II-50M	8.10	49	76.2°
P-3	II-51H	1.04	48	75.6°
P-3	II-51M	7.94	48	75.6°
P-3	II-52H	1.04	48	75.5°
P-3	II-52M	7.92	48	75.5°
P-3	II-53H	1.04	48	75.4°
P-3	II-53M	7.90	48	75.4°
P-3	II-54H	1.03	48	75.2°
P-3	II-54M	7.86	48	75.2°
P-3	II-55H	1.03	48	75.1°
P-3	II-55M	7.87	48	75.1°
P-3	II-56H	1.03	47	75.0°
P-3	II-56M	7.85	47	75.0°
P-3	II-57H	1.03	47	74.9°
P-3	II-57M	7.84	47	74.9°
P-3	II-58H	1.03	47	74.7°
P-3	II-58M	7.82	47	74.7°
P-3	II-113H	1.01	47	62.3°
P-3	II-114H	1.02	47	62.2°
P-3	II-115H	1.02	47	62.1°
P-3	II-116H	1.02	47	61.9°
P-3	II-117H	1.03	47	61.8°
P-3	II-118H	1.03	48	61.7°
P-3	II-119H	1.04	48	61.6°
P-3	II-120H	1.04	48	61.4°
P-3	II-121H	1.07	49	60.7°
P-3	II-122H	1.07	49	60.6°
P-3	II-123H	1.08	50	60.4°
P-3	II-124H	1.08	50	60.3°
P-3	II-125H	1.09	50	60.2°
P-3	II-126H	1.09	50	60.0°
P-3	II-127H	1.10	50	59.9°
P-3	II-128H	1.10	51	59.8°
P-3	II-129H	1.13	52	59.2°
P-3	II-130H	1.13	52	59.0°
P-3	II-131H	1.14	52	58.9°
P-3	II-132H	1.14	53	58.8°
P-3	II-133H	1.15	53	58.6°
P-3	II-134H	1.15	53	58.5°
P-3	II-135H	1.16	53	58.3°
P-3	II-136H	1.17	54	58.2°
P-3	III-86H	1.11	47	77.0°
P-3	III-87H	1.11	47	76.8°
P-3	III-88H	1.11	47	76.7°
P-3	III-89H	1.11	47	76.6°
P-3	III-90H	1.10	47	76.4°
P-3	III-91H	1.10	46	76.3°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-3	III-92H	1.10	46	76.2°
P-3	III-93H	1.10	46	76.1°
P-3	III-94H	1.00	45	75.4°
P-3	III-95H	1.00	45	75.3°
P-3	III-96H	1.00	45	75.2°
P-3	III-97H	1.00	45	75.0°
P-3	III-98H	0.99	45	74.9°
P-3	III-99H	0.99	45	74.8°
P-3	III-100H	0.99	45	74.7°
P-3	III-101H	0.99	45	74.5°
P-3	IV-101H/1	59.04	2721	69.2°
P-3	IV-102H/3	58.60	2699	67.0°
P-3	IV-108H/1	59.01	2719	69.7°
P-3	IV-109H/3	58.48	2693	67.5°
P-3	V-108H	2.15	98	71.6°
P-3	V-109H	2.15	97	71.6°
P-3	V-110H	2.15	97	71.6°
P-3	V-111H	2.15	97	71.6°
P-3	V-112H	2.26	98	71.8°
P-3	V-113H	2.26	98	71.7°
P-3	V-114H	2.26	98	71.7°
P-3	V-115H	2.25	97	71.7°
P-4	I-59M	9.88	60	61.4°
P-4	I-176M	8.40	51	59.5°
P-4	I-177M	8.43	51	59.4°
P-4	I-178M	8.45	50	59.2°
P-4	I-179M	8.47	51	59.1°
P-4	I-180M	8.50	51	59.0°
P-4	I-181M	8.52	51	58.8°
P-4	I-182M	8.55	52	58.7°
P-4	I-183M	8.57	52	58.6°
P-4	II-60H	1.11	51	79.2°
P-4	II-60M	8.44	51	79.2°
P-4	II-61H	1.10	51	79.1°
P-4	II-61M	8.41	51	79.1°
P-4	II-62H	1.10	51	78.9°
P-4	II-62M	8.38	51	78.9°
P-4	II-63H	1.10	50	78.8°
P-4	II-63M	8.35	50	78.8°
P-4	II-64H	1.10	50	78.7°
P-4	II-64M	8.32	50	78.7°
P-4	II-65H	1.10	50	78.6°
P-4	II-65M	8.30	50	78.6°
P-4	II-66H	1.10	50	78.4°
P-4	II-66M	8.27	50	78.4°
P-4	IV-173H/1	59.12	2724	75.4°
P-4	IV-138H/3	57.99	2671	69.7°
P-4	V-169H	2.31	105	74.7°
P-4	V-170H	2.30	105	74.7°
P-4	V-171H	2.29	105	74.7°
P-4	V-172H	2.29	105	74.6°
P-4	V-173H	2.41	105	74.8°
P-4	V-174H	2.40	105	74.8°
P-4	V-175H	2.40	105	74.8°
P-4	V-176H	2.39	105	74.8°
P-5	II-67H	1.00	46	68.4°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-5	II-67M	7.55	46	68.4°
P-5	II-68H	0.99	46	68.3°
P-5	II-68M	7.55	46	68.3°
P-5	II-69H	0.99	46	68.2°
P-5	II-69M	7.56	46	68.2°
P-5	II-70H	0.99	46	68.1°
P-5	II-70M	7.56	46	68.1°
P-5	II-71H	0.99	46	67.0°
P-5	II-71M	7.57	46	67.0°
P-5	II-72H	0.99	46	67.8°
P-5	II-72M	7.57	46	67.8°
P-5	II-73H	0.99	46	67.7°
P-5	II-73M	7.58	46	67.7°
P-5	II-74H	1.00	46	67.6°
P-5	II-74M	7.59	46	67.6°
P-5	II-205H	1.06	49	69.8°
P-5	II-206H	1.06	49	69.7°
P-5	II-207H	1.06	49	69.5°
P-5	II-208H	1.06	49	69.4°
P-5	II-209H	1.07	49	69.3°
P-5	II-210H	1.07	49	69.1°
P-5	II-211H	1.07	49	69.0°
P-5	II-212H	1.07	49	68.9°
P-5	III-53H	1.14	51	72.2°
P-5	III-53M	8.71	51	72.2°
P-5	III-60H	1.11	50	70.9°
P-5	III-60M	8.48	50	70.9°
P-5	III-63H	1.11	50	70.5°
P-5	III-63M	8.47	50	70.5°
P-5	III-66H	1.11	50	70.1°
P-5	III-66M	8.47	50	70.1°
P-5	III-163H	1.25	55	79.5°
P-5	III-164H	1.25	55	79.3°
P-5	III-165H	1.24	55	79.2°
P-5	III-166H	1.24	54	79.1°
P-5	III-167H	1.24	54	78.9°
P-5	III-168H	1.23	54	78.8°
P-5	III-169H	1.23	54	78.6°
P-5	III-170H	1.23	54	78.5°
P-5	III-171H	2.61	52	68.5°
P-5	IV-143H/1	59.03	2719	72.7°
P-5	IV-144H/3	57.92	2669	70.2°
P-6	I-184M	8.07	49	65.0°
P-6	I-185M	8.07	49	65.9°
P-6	I-186M	8.08	49	64.8°
P-6	I-187M	8.08	49	64.6°
P-6	I-188M	8.09	49	64.5°
P-6	I-189M	8.09	49	64.4°
P-6	I-190M	8.10	49	64.3°
P-6	I-191M	8.11	49	64.1°
P-6	I-192M	8.11	49	64.0°
P-6	I-193M	8.12	49	63.9°
P-6	I-194M	8.13	49	63.8°
P-6	I-195M	8.14	49	63.6°
P-6	I-196M	8.15	49	63.5°
P-6	I-197M	8.16	49	63.4°
P-6	I-198M	8.17	49	63.3°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-6	I-199M	8.18	49	63.1°
P-6	I-200M	8.20	50	63.3°
P-6	I-201M	8.21	50	63.2°
P-6	I-202M	8.22	50	63.0°
P-6	I-203M	8.24	50	62.9°
P-6	I-204M	8.25	50	62.8°
P-6	I-205M	8.26	50	62.7°
P-6	I-206M	8.27	50	62.5°
P-6	I-207M	8.28	50	62.4°
P-6	I-208M	8.30	50	62.3°
P-6	I-209M	8.31	50	62.2°
P-6	I-210M	8.32	50	62.0°
P-6	I-211M	8.34	50	61.9°
P-6	I-212M	8.35	50	61.8°
P-6	I-213M	8.37	51	61.6°
P-6	I-214M	8.38	51	61.5°
P-6	I-215M	8.40	51	61.4°
P-6	II-76H	1.07	49	62.0°
P-6	II-76M	8.14	49	62.0°
P-6	II-77H	1.07	49	62.0°
P-6	II-77M	8.16	49	62.0°
P-6	II-78H	1.07	49	61.7°
P-6	II-78M	8.19	49	61.7°
P-6	II-79H	1.08	50	61.6°
P-6	II-79M	8.21	50	61.6°
P-6	II-80H	1.08	50	61.5°
P-6	II-80M	8.24	50	61.5°
P-6	II-81H	1.08	50	61.3°
P-6	II-81M	8.27	50	61.3°
P-6	II-82H	1.09	50	61.2°
P-6	II-82M	8.30	50	61.2°
P-6	II-83H	1.09	50	61.1°
P-6	II-83M	8.33	50	61.1°
P-6	II-84H	1.11	51	60.3°
P-6	II-84M	8.47	51	60.3°
P-6	II-85H	1.12	51	60.2°
P-6	II-85M	8.50	51	60.2°
P-6	II-86H	1.12	52	60.1°
P-6	II-86M	8.54	52	60.1°
P-6	II-87H	1.12	52	59.9°
P-6	II-87M	8.57	52	59.9°
P-6	II-88H	1.13	52	59.8°
P-6	II-88M	8.60	52	59.8°
P-6	II-89H	1.13	52	59.7°
P-6	II-89M	8.64	52	59.7°
P-6	II-90H	1.14	52	59.5°
P-6	II-90M	8.67	52	59.5°
P-6	II-91H	1.14	53	59.4°
P-6	II-91M	8.71	53	59.4°
P-6	III-68H	1.09	50	72.1°
P-6	III-68M	8.27	50	72.1°
P-6	III-70H	1.08	49	71.10
P-6	III-70M	8.23	49	71.10
P-6	III-181H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-182H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-183H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-184H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-185H	DATA NOT IMMEDIATELY AVAILABLE		

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-6	III-186H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-187H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-188H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-189H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-190H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-191H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-192H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-193H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-194H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-195H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-196H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-197H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-198H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-199H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-200H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-201H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-202H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-203H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-204H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-205H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-206H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-207H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-208H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-209H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-210H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-211H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-212H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-171H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-172H	DATA NOT IMMEDIATELY AVAILABLE		
P-6	III-171H	59.00	2717	65.5°
P-6	IV-85M	449.70	2717	65.5°
P-6	IV-143H/1	59.03	2719	72.7°
P-6	IV-144H/3	57.92	2669	70.2°
P-6	V-64H	3.57	98	69.3°
P-6	V-64M	27.28	98	69.3°
P-6	V-16aH	130.24	5757	114.5°
P-6	V-16aM	992.92	5757	114.5°
P-6	V-16bH	130.24	5757	114.5°
P-6	V-16bM	992.92	5757	114.5°
P-6	V-13H	130.23	5755	114.5°
P-6	V-13M	992.79	5755	114.5°
P-7 (AS-12)	I-157M	8.09	49	57.9°
P-7 (AS-12)	I-158M	8.11	49	57.8°
P-7 (AS-12)	I-159M	8.14	49	57.7°
P-7 (AS-12)	I-160M	8.17	49	57.5°
P-7 (AS-12)	I-161M	8.20	50	57.4°
P-7 (AS-12)	I-162M	8.22	50	57.3°
P-7 (AS-12)	I-163M	8.25	50	57.1°
P-7 (AS-12)	I-164M	8.28	50	57.0°
P-7 (AS-12)	I-165M	8.31	50	56.9°
P-7 (AS-12)	I-166M	8.33	50	56.7°
P-7 (AS-12)	I-167M	8.36	51	56.6°
P-7 (AS-12)	I-168M	8.39	51	56.5°
P-7 (AS-12)	I-169M	8.42	51	56.4°
P-7 (AS-12)	I-170M	8.45	51	56.2°
P-7 (AS-12)	I-171M	8.49	51	56.1°
P-7 (AS-12)	I-172M	8.52	51	55.9°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-7 (AS-12)	II-96H	0.86	41	70.2°
P-7 (AS-12)	II-96M	6.75	41	70.2°
P-7 (AS-12)	II-97H	0.89	41	70.1°
P-7 (AS-12)	II-97M	6.75	41	70.1°
P-7 (AS-12)	II-98H	0.89	41	70.0°
P-7 (AS-12)	II-98M	6.75	41	70.0°
P-7 (AS-12)	II-99H	0.89	41	69.9°
P-7 (AS-12)	II-99M	6.76	41	69.9°
P-7 (AS-12)	II-100H	0.89	41	69.8°
P-7 (AS-12)	II-100M	6.76	41	69.8°
P-7 (AS-12)	II-101H	0.89	41	69.7°
P-7 (AS-12)	II-101M	6.76	41	69.7°
P-7 (AS-12)	II-102H	0.89	41	69.5°
P-7 (AS-12)	II-102M	6.77	41	69.5°
P-7 (AS-12)	II-103H	0.89	41	69.4°
P-7 (AS-12)	II-103M	6.77	41	69.4°
P-7 (AS-12)	II-104H	0.89	41	68.6°
P-7 (AS-12)	II-104M	6.81	41	68.6°
P-7 (AS-12)	II-105H	0.89	41	68.5°
P-7 (AS-12)	II-105M	6.81	41	68.5°
P-7 (AS-12)	II-106H	0.90	41	68.4°
P-7 (AS-12)	II-106M	6.82	41	68.4°
P-7 (AS-12)	II-107H	0.90	41	68.3°
P-7 (AS-12)	II-107M	6.83	41	68.3°
P-7 (AS-12)	II-108H	0.90	41	68.2°
P-7 (AS-12)	II-108M	6.84	41	68.2°
P-7 (AS-12)	II-109H	0.90	41	68.1°
P-7 (AS-12)	II-109M	6.85	41	68.1°
P-7 (AS-12)	II-110H	0.90	41	68.0°
P-7 (AS-12)	II-110M	6.85	41	68.0°
P-7 (AS-12)	II-111H	0.90	42	67.9°
P-7 (AS-12)	II-111M	6.86	42	67.9°
P-7 (AS-12)	III-86H	1.11	47	77.0°
P-7 (AS-12)	III-86M	8.49	47	77.0°
P-7 (AS-12)	III-87H	1.11	47	76.8°
P-7 (AS-12)	III-87M	8.47	47	76.8°
P-7 (AS-12)	III-88H	1.11	47	76.7°
P-7 (AS-12)	III-88M	8.45	47	76.7°
P-7 (AS-12)	III-89H	1.11	47	76.6°
P-7 (AS-12)	III-89M	8.43	47	76.6°
P-7 (AS-12)	III-90H	1.10	46	76.4°
P-7 (AS-12)	III-90M	8.41	46	76.4°
P-7 (AS-12)	III-91H	1.10	46	76.3°
P-7 (AS-12)	III-91M	8.39	46	76.3°
P-7 (AS-12)	III-92H	1.10	46	76.2°
P-7 (AS-12)	III-92M	8.37	46	76.2°
P-7 (AS-12)	III-93H	1.10	46	76.1°
P-7 (AS-12)	III-93M	8.35	46	76.1°
P-7 (AS-12)	III-94H	1.00	45	75.4°
P-7 (AS-12)	III-94M	7.64	45	75.4°
P-7 (AS-12)	III-95H	1.00	45	75.3°
P-7 (AS-12)	III-95M	7.62	45	75.3°
P-7 (AS-12)	III-96H	1.00	45	75.1°
P-7 (AS-12)	III-96M	7.61	45	75.1°
P-7 (AS-12)	III-97H	1.00	45	75.0°
P-7 (AS-12)	III-97M	7.60	45	75.0°
P-7 (AS-12)	III-98H	0.99	45	74.9°
P-7 (AS-12)	III-98M	7.58	45	74.9°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-7 (AS-12)	III-99H	0.99	45	74.8°
P-7 (AS-12)	III-99M	7.57	45	74.8°
P-7 (AS-12)	III-100H	0.99	45	74.7°
P-7 (AS-12)	III-100M	7.56	45	74.7°
P-7 (AS-12)	III-101H	0.99	45	74.5°
P-7 (AS-12)	III-101M	7.55	45	74.5°
P-7 (AS-12)	III-137H	1.35	49	70.4°
P-7 (AS-12)	III-138H	1.35	49	70.2°
P-7 (AS-12)	III-139H	1.35	49	70.0°
P-7 (AS-12)	III-140H	1.36	49	69.9°
P-7 (AS-12)	III-141H	1.36	49	69.7°
P-7 (AS-12)	III-142H	1.36	49	69.6°
P-7 (AS-12)	III-143H	1.36	49	69.4°
P-7 (AS-12)	III-144H	1.36	49	69.3°
P-7 (AS-12)	III-145H	1.10	50	68.7°
P-7 (AS-12)	III-146H	1.10	50	68.5°
P-7 (AS-12)	III-147H	1.10	50	68.4°
P-7 (AS-12)	III-148H	1.10	50	68.3°
P-7 (AS-12)	III-149H	1.10	50	68.2°
P-7 (AS-12)	III-150H	1.10	50	68.0°
P-7 (AS-12)	III-151H	1.10	50	67.9°
P-7 (AS-12)	III-152H	1.11	50	67.8°
P-7 (AS-12)	III-153H	1.11	51	67.4°
P-7 (AS-12)	III-154H/2	1.11	51	67.3°
P-7 (AS-12)	III-155H	1.11	51	67.1°
P-7 (AS-12)	III-156H	1.12	51	67.0°
P-7 (AS-12)	III-157H	1.12	52	66.9°
P-7 (AS-12)	III-158H	1.12	52	66.8°
P-7 (AS-12)	III-159H	1.12	52	66.6°
P-7 (AS-12)	III-160H	1.13	52	61.7°
P-7 (AS-12)	III-136H	2.46	47	69.0°
P-7 (AS-12)	III-120H	2.63	45	73.9°
P-7 (AS-12)	IV-125H/1	58.96	2717	71.2°
P-7 (AS-12)	IV-126H/3	58.14	2677	68.8°
P-8	II-93H	2.84	44	77.3°
P-8	II-93M	21.50	44	77.3°
P-8	II-115H	1.02	47	62.1°
P-8	II-115M	7.79	47	62.1°
P-8	II-116H	1.02	47	61.9°
P-8	II-116M	7.81	47	61.9°
P-8	II-117H	1.03	47	61.8°
P-8	II-117M	7.84	47	61.8°
P-8	II-118H	1.03	48	61.7°
P-8	II-118M	7.87	48	61.7°
P-8	II-119H	1.04	48	61.6°
P-8	II-119M	7.90	48	61.6°
P-8	II-120H	1.04	48	61.4°
P-8	II-120M	7.93	48	61.4°
P-8	II-121H	1.07	49	60.7°
P-8	II-121M	8.14	49	60.7°
P-8	II-122H	1.07	49	60.6°
P-8	II-122M	8.17	49	60.6°
P-8	II-123H	1.08	50	60.4°
P-8	II-123M	8.21	50	60.4°
P-8	II-124H	1.08	50	60.3°
P-8	II-124M	8.24	50	60.3°
P-8	II-125H	1.09	50	60.2°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-8	II-125M	8.28	50	60.2°
P-8	II-126H	1.09	50	60.0°
P-8	II-126M	8.31	50	60.0°
P-8	II-127H	1.10	50	59.9°
P-8	II-127M	8.35	50	59.9°
P-8	II-128H	1.10	51	59.8°
P-8	II-128M	8.39	51	59.8°
P-8	II-129H	1.13	52	59.2°
P-8	II-129M	8.60	52	59.2°
P-8	II-130H	1.13	52	59.0°
P-8	II-130M	8.64	52	59.0°
P-8	II-131H	1.14	52	58.9°
P-8	II-131M	8.68	52	58.9°
P-8	II-132H	1.14	53	58.8°
P-8	II-132M	8.72	53	58.8°
P-8	II-133H	1.15	53	58.6°
P-8	II-133M	8.76	53	58.6°
P-8	II-134H	1.16	53	58.5°
P-8	II-134M	8.81	53	58.5°
P-8	II-135H	1.16	54	58.3°
P-8	II-135M	8.85	54	58.3°
P-8	II-136H	1.17	54	58.2°
P-8	II-136M	8.90	54	58.2°
P-8	III-84H	1.11	51	60.3°
P-8	III-84M	8.47	51	60.3°
P-8	III-124H	0.99	46	72.8°
P-8	III-124M	7.57	46	72.8°
P-8	III-125H	0.99	46	72.7°
P-8	III-125M	7.56	46	72.7°
P-8	III-126H	0.99	46	72.5°
P-8	III-126M	7.56	46	72.5°
P-8	III-127H	0.99	46	72.3°
P-8	III-127M	7.56	46	72.3°
P-8	III-128H	0.99	46	72.2°
P-8	III-128M	7.56	46	72.2°
P-8	III-129H	0.99	46	72.1°
P-8	III-129M	7.56	46	72.1°
P-8	III-130H	0.99	46	72.1°
P-8	III-130M	7.56	46	72.1°
P-8	III-131H	0.99	46	71.9°
P-8	III-131M	7.56	46	71.9°
P-8	IV-102H	58.60	2699	66.8°
P-8	IV-102M	446.82	2699	66.8°
P-9	II-138H	0.96	44	65.5°
P-9	II-138M	7.34	44	65.5°
P-9	II-139H	0.97	44	65.4°
P-9	II-139M	7.36	44	65.4°
P-9	II-140H	0.97	45	65.3°
P-9	II-140M	7.37	45	65.3°
P-9	II-141H	0.97	45	65.2°
P-9	II-141M	7.39	45	65.2°
P-9	II-142H	0.97	45	65.1°
P-9	II-142M	7.41	45	65.1°
P-9	II-143H	0.97	45	64.9°
P-9	II-143M	7.43	45	64.9°
P-9	II-144H	0.98	45	64.8°
P-9	II-144M	7.45	45	64.8°
P-9	III-137H	1.35	49	70.4°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-9	III-137M	10.30	49	70.4°
P-9	III-138H	1.35	49	70.2°
P-9	III-138M	10.31	49	70.2°
P-9	III-139H	1.35	49	70.0°
P-9	III-139M	10.32	49	70.0°
P-9	III-140H	1.36	49	69.9°
P-9	III-140M	10.33	49	69.9°
P-9	III-141H	1.36	49	69.7°
P-9	III-141M	10.34	49	69.7°
P-9	III-142H	1.36	49	69.6°
P-9	III-142M	10.35	49	69.6°
P-9	III-143H	1.36	49	69.4°
P-9	III-143M	10.36	49	69.4°
P-9	III-144H	1.36	49	69.3°
P-9	III-144M	10.38	49	69.3°
P-9	III-145H	1.09	50	68.7°
P-9	III-145M	8.34	50	68.7°
P-9	III-146H	1.10	50	68.5°
P-9	III-146M	8.35	50	68.5°
P-9	III-147H	1.10	50	68.4°
P-9	III-147M	8.37	50	68.4°
P-9	III-148H	1.10	50	68.3°
P-9	III-148M	8.38	50	68.3°
P-9	III-149H	1.10	50	68.2°
P-9	III-149M	8.39	50	68.2°
P-9	III-150H	1.10	50	68.0°
P-9	III-15OM	8.41	50	68.0°
P-9	III-151H	1.10	50	67.9°
P-9	III-151M	8.42	50	67.9°
P-9	III-152M	1.11	50	67.8°
P-9	III-152M	8.43	50	67.8°
P-9	III-153H	1.11	51	67.4°
P-9	III-153M	8.46	51	67.4°
P-9	III-154H	1.11	51	67.3°
P-9	III-154M	8.48	51	67.3°
P-9	III-155M	8.50	51	67.1°
P-9	III-156H	1.12	51	67.0°
P-9	III-156M	8.52	51	67.0°
P-9	III-157H	1.12	52	66.9°
P-9	III-157M	8.53	52	66.9°
P-9	III-158H	1.12	52	66.8°
P-9	III-158M	8.55	52	66.8°
P-9	III-159H	1.12	52	66.6°
P-9	III-159M	8.57	52	66.6°
P-9	III-160H	1.12	52	66.5°
P-9	III-160M	8.59	52	66.5°
P-10	II-146H	0.98	45	78.0°
P-10	II-146M	7.46	45	78.0°
P-10	II-147H	0.98	45	77.9°
P-10	II-147M	7.44	45	77.9°
P-10	II-148H	0.97	45	77.8°
P-10	II-148M	7.43	45	77.8°
P-10	II-149H	0.97	45	77.7°
P-10	II-149M	7.41	45	77.7°
P-10	II-150H	0.97	45	77.5°
P-10	II-150M	7.39	45	77.5°
P-10	II-151H	0.97	45	77.4°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-10	II-151M	7.38	45	77.4°
P-10	II-152H	0.97	45	77.3°
P-10	II-152M	7.37	45	77.3°
P-10	II-153H	0.96	44	77.2°
P-10	II-153M	7.35	44	77.2°
P-10	II-154H	0.95	44	76.2°
P-10	II-154M	7.27	44	76.2°
P-10	II-155H	0.95	44	76.1°
P-10	II-155M	7.26	44	76.1°
P-10	II-156H	0.95	44	76.0°
P-10	II-156M	7.24	44	76.0°
P-10	II-157H	0.95	44	76.0°
P-10	II-157M	7.23	44	76.0°
P-10	II-158H	0.95	44	75.8°
P-10	II-158M	7.22	44	75.8°
P-10	II-159H	0.95	44	75.6°
P-10	II-159M	7.21	44	75.6°
P-10	II-160H	0.94	44	75.5°
P-10	II-160M	7.20	44	75.5°
P-10	II-161H	0.94	43	75.4°
P-10	II-161M	7.19	43	75.4°
P-10	III-163H	1.25	55	79.5°
P-10	III-163M	9.52	55	79.5°
P-10	III-164H	1.25	55	79.3°
P-10	III-164M	9.50	55	79.3°
P-10	III-165H	1.24	55	79.2°
P-10	III-165M	9.47	55	79.2°
P-10	III-166H	1.24	54	79.1°
P-10	III-166M	9.45	54	79.1°
P-10	III-167H	1.24	54	78.9°
P-10	III-167M	9.42	54	78.9°
P-10	III-168H	1.23	54	78.8°
P-10	III-168M	9.40	54	78.8°
P-10	III-169H	1.23	54	78.5°
P-10	III-169M	9.38	54	78.5°
P-10	III-170H	1.23	54	78.5°
P-10	III-170M	9.36	54	78.5°
P-11	II-163H	1.11	51	61.8°
P-11	II-163M	8.42	51	61.8°
P-11	II-164H	1.11	51	61.7°
P-11	II-164M	8.46	51	61.7°
P-11	II-165H	1.11	51	61.5°
P-11	II-165M	8.50	51	61.5°
P-11	II-166H	1.12	52	61.4°
P-11	II-166M	8.53	52	61.4°
P-11	II-167H	1.12	52	61.2°
P-11	II-167M	8.57	52	61.2°
P-11	II-168H	1.13	52	61.1°
P-11	II-168M	8.61	52	61.1°
P-11	II-169H	1.13	52	61.0°
P-11	II-169M	8.64	52	61.0°
P-11	II-170H	1.14	52	60.8°
P-11	II-170M	8.68	52	60.8°
P-11	II-171H	1.18	54	60.1°
P-11	II-171M	8.97	54	60.1°
P-11	II-172H	1.18	55	59.9°
P-11	II-172M	9.02	55	59.9°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-11	II-173H	1.19	55	59.8°
P-11	II-173M	9.06	55	59.8°
P-11	II-174H	1.19	55	59.6°
P-11	II-174M	9.11	55	59.6°
P-11	II-175H	1.20	55	59.5°
P-11	II-175M	9.15	55	59.5°
P-11	II-176H	1.21	56	59.3°
P-11	II-176M	9.20	56	59.3°
P-11	II-177H	1.21	56	59.2°
P-11	II-177M	9.25	56	59.2°
P-11	II-178H	1.22	56	59.0°
P-11	II-178M	9.29	56	59.0°
P-11	III-171H	2.61	52	68.5°
P-11	III-171M	19.89	52	68.5°
P-11	III-173H	1.16	53	68.8°
P-11	III-173M	8.83	53	68.8°
P-11	III-174H	1.16	53	68.6°
P-11	III-174M	8.84	53	68.6°
P-11	III-175H	1.16	53	68.5°
P-11	III-175M	8.86	53	68.5°
P-11	III-176H	1.16	54	68.4°
P-11	III-176M	8.88	54	68.4°
P-11	III-177H	1.16	54	68.2°
P-11	III-177M	8.89	54	68.2°
P-11	III-178H	1.17	54	68.1°
P-11	III-178M	8.91	54	68.1°
P-11	III-179H	1.17	54	68.0°
P-11	III-179M	8.93	54	68.0°
P-11	III-180H	1.17	54	67.8°
P-11	III-180M	8.95	54	67.8°
P-11	IV-137H	59.00	2718	72.2°
P-11	IV-137M	449.82	2718	72.2°
P-11	V-42aH	3.70	102	68.1°
P-11	V-42aM	28.29	102	68.1°
P-11	V-42bH	3.70	102	68.1°
P-11	V-42bM	28.29	102	68.1°
P-12	II-179H	0.98	45	72.7°
P-12	II-179M	7.48	45	72.7°
P-12	II-180H	0.98	45	72.5°
P-12	II-180M	7.48	45	72.5°
P-12	II-181H	0.98	45	72.4°
P-12	II-181M	7.48	45	72.4°
P-12	II-182H	0.98	45	72.3°
P-12	II-182M	7.48	45	72.3°
P-12	II-183H	0.98	45	72.2°
P-12	II-183M	7.48	45	72.2°
P-12	II-184H	0.98	45	72.1°
P-12	II-184M	7.48	45	72.1°
P-12	II-185H	0.98	45	71.9°
P-12	II-185M	7.48	45	71.9°
P-12	II-186H	0.98	45	71.8°
P-12	II-186M	7.49	45	71.8°
P-12	II-187H	0.99	46	70.8°
P-12	II-187M	7.56	46	70.8°
P-12	II-188H	0.99	46	70.7°
P-12	II-188M	7.57	46	70.7°
P-12	II-189H	0.99	46	70.6°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-12	II-189M	7.57	46	70.6°
P-12	II-190H	0.99	46	70.5°
P-12	II-190M	7.58	46	70.5°
P-12	II-191H	1.00	46	70.3°
P-12	II-191M	7.59	46	70.3°
P-12	II-192M	1.00	46	70.2°
P-12	II-192M	7.60	46	70.2°
P-12	II-193H	1.00	46	70.1°
P-12	II-193M	7.60	46	70.1°
P-12	II-194H	1.00	46	70.0°
P-12	II-194M	7.61	46	70.0°
P-12	III-181H	1.23	53	73.1°
P-12	III-181M	9.35	53	73.1°
P-12	III-182H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-182M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-183H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-183M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-184H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-184M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-185H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-185M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-186H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-186M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-187H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-188M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-189H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-189M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-190H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-190M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-191H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-191M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-192H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-192M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-193H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-193M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-194H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-194M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-195H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-195M	DATA NOT IMMEDIATELY AVAILABLE		
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P-12	III-197H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-197M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-198H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-198M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-199H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-199M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-200H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-2OOM	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-201H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-201M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-202H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-202M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-203H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-203M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-204H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-204M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-205H	DATA NOT IMMEDIATELY AVAILABLE		

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
P-12	III-205M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-206H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-206M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-207H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-207M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-208H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-208M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-209H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-209M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-210H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-210M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-211H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-211M	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-212H	DATA NOT IMMEDIATELY AVAILABLE		
P-12	III-212M	DATA NOT IMMEDIATELY AVAILABLE		
P-13	II-197H	1.04	48	71.6°
P-13	II-197M	7.93	48	71.6°
P-13	II-198H	1.04	48	71.5°
P-13	II-198M	7.93	48	71.5°
P-13	II-199M	1.04	48	71.3°
P-13	II-199M	7.94	48	71.3°
P-13	II-200H	1.04	48	71.2°
P-13	II-200M	7.94	48	71.2°
P-13	II-201H	1.04	48	71.1°
P-13	II-201M	7.95	48	71.1°
P-13	II-202H	1.04	48	71.0°
P-13	II-202M	7.95	48	71.0°
P-13	II-203H	1.04	48	70.8°
P-13	II-203M	7.96	48	70.8°
P-13	II-204H	1.05	48	70.7°
P-13	II-204M	7.97	48	70.7°
P-13	II-205H	1.06	49	69.8°
P-13	II-205M	8.08	49	69.8°
P-13	II-206H	1.06	49	69.7°
P-13	II-206M	8.09	49	69.7°
P-13	II-207M	8.11	49	69.5°
P-13	II-208H	1.06	49	69.4°
P-13	II-208M	8.11	49	69.4°
P-13	II-209H	1.07	49	69.3°
P-13	II-209M	8.13	49	69.3°
P-13	II-210H	1.07	49	69.1°
P-13	II-210M	8.14	49	69.1°
P-13	II-211H	1.07	49	69.0°
P-13	II-211M	8.15	49	69.0°
P-13	II-212H	1.07	49	69.0°
P-13	II-212M	8.17	49	69.0°
Fra Mauro (AS-14)	III-132M	9.20	46	68.5°
(3°40'S, 17°29'W)	III-133H/2	1.22	47	67.9°
*may not cover	III-133M	9.27	47	67.9°
actual landing site	III-134H*	1.23	47	67.3°
	III-134M	9.35	47	67.3°
AS-12 photography	III-135H*	1.24	48	66.8°
also available; see	IV-120H/1*	58.98	2717	77.4°
Lunar Landing Site	IV-120M	449.59	2717	77.4°
Summary Book, LPI	V-138H			
Photo Library	V-139H	2.25	104	73.7°

Site Number	Photo Number	Design Resolution, m	Alt of Orb, km	Sun Angle
	V-140H	2.24	103	73.7°
	V-141H	2.24	103	73.6°
Hadley-Apennine (AS-15)	IV-102H/1	58.60	2699	67.0°
(24°57'N, 2°27'E)	IV-102M	446.82	2699	67.0°
*may not cover	IV-103H/3			
actual landing site	IV-109H/1	58.48	2693	67.5°
	IV-109M	445.90	2693	67.5°
	IV-110H/3			
	V-104H	2.77	127	70.7°
	V-104M	24.17	127	70.7°
	V-105H	2.86	131	70.7°
	V-105M	21.84	131	70.7°
	V-106H	2.95	135	70.8°
	V-106H	22.53	135	70.8°
	V-107H	3.05	140	70.9°
Hadley-Apennine	V-107M	23.29	140	70.9°
Descartes (AS-16)	IV-89H/1	59.12	2724	68.3°
(8°51'S, 15°34'E)	IV-89H/2	59.12	2724	68.3°
AS-10 &-12				
16mm photographs				
also available; see				
Lunar Landing Site				
Summary Book, LPI				
Photo Library				
The Apollo 17 site is not included as high resolution images were available from the AS-15				
panoramic and metric mapping camera film in time for detailed mission planning and simulation				

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13. ABSTRACT *(Maximum 200 words)*

Robotic missions that supported data requirements for Project Apollo had two distinct histories: earlier missions, such as Surveyor, were funded prior to the advent of the Apollo lunar landing goal and were adapted to support Apollo; later missions, such as Lunar Orbiter were dedicated missions from the start and so were designed with the goal of supporting Apollo data requirements. The baseline documents controlling designs of robotic missions were data requirement documents issued by the Office of Manned Spaceflight to the Office of Space Sciences or to the Grumman Aircraft Engineering Company, delineating data requirements for either hardware or mission design. The experiments carried on Apollo precursors were adequate to provide the data requested. However, the disparity between the Apollo spacecraft design schedule and the time necessary to develop the robotic spacecraft resulted in this data being confirmatory, rather than supplying direct support to design efforts. On the basis of this work, it appears that SEI robotic precursor missions do not need to have a detection resolution greater than 1-2 meters in order to support SEI mission planning and design.

14. SUBJECT TERMS
Robotic Precursor, Apollo Project, Surveyor Project, Ranger Project, Lunar Orbiter Project

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