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LUNAR LANDMARK LOCATIONS - APOLLO 8, 10, 11, AND 12 MISSIONS

by Gary A. Ransford, Wilbur R. Wollenhaupt, and Robert M. Bizzell

Manned Spacecraft Center
Houston, Texas 77058

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16. ABSTRACT

Selenographic coordinates for craters that were tracked as landmarks on the Apollo lunar missions have been determined. All known sources of error, such as gimbal-angle drifts and clock drifts, are accounted for by addition of the proper biases. An estimate of the remaining errors is provided. Each crater is described with respect to the surrounding terrain, and photographs of these craters are included. The total photographic coverage of these craters from the Lunar Orbiter and the Apollo missions is listed.

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LUNAR LANDMARK LOCATIONS — APOLLO 8, 10, 11, AND 12 MISSIONS

By Gary A. Ransford, Wilbur R. Wollenhaupt, and Robert M. Bizzell
Manned Spacecraft Center

SUMMARY

The purpose of this document is to provide a consistent list of selenographic locations for all lunar landmarks that have been tracked on the Apollo 8, 10, 11, and 12 missions. Consistency is highly desired so that these landmark locations can be used as control points for extending selenodetic control to the lunar far side and for improving selenodetic control on the near side using the Apollo vertical stereostrip photography. Therefore, a single lunar gravitational potential model and a consistent technique were used for calculating the landmark positions from the landmark-tracking data. Error sources associated with the landmark tracking and data processing are identified, and the resulting uncertainties relative to the determined landmark positions are presented. A listing of the landmark photographic coverage is provided.

INTRODUCTION

During the Apollo 8, 10, 11, and 12 missions, 19 different lunar landmarks were tracked optically using either the sextant or the scanning telescope in the command module. Six landmarks are located on the lunar far side, and the remaining 13 are located on the near side (fig. 1). Some landmarks were tracked more than once per mission, and two landmarks — one near Apollo landing site 1 and one near Apollo landing site 2 — were tracked on two missions. The landmarks, relatively small craters ranging from 100 to 1500 meters in diameter, were located near the spacecraft lunar ground tracks.

Landmark-tracking data consist of (1) three gimbal angles that define the direction of the optical line of sight with respect to the inertial measurement unit (IMU), (2) a pair of shaft and trunnion angles that define the direction of the line of sight from the spacecraft to the landmark with respect to the optical line of sight, and (3) the time of the read-out of these five angles. In a typical tracking sequence, a set of five sightings (called marks) is taken as the spacecraft passes over the landmark. The first mark is taken when the approaching spacecraft is approximately 35° above the landmark local horizon; the third mark is taken when the landmark is at the spacecraft nadir; and the fifth mark is taken when the receding spacecraft is again at 35°. The second and fourth marks are spaced evenly between these three marks. The optimum time interval between marks is approximately 20 to 30 seconds for the nominal 60-nautical-mile-high circular orbit.

The selenographic locations of the landmarks are independently estimated from the sets of shaft and trunnion angles using least-squares techniques. This estimation is accomplished in a two-part procedure. The first part involves determining the spacecraft position at some specified time shortly before the scheduled landmark tracking (orbit determination), using Manned Space Flight Network (MSFN) Doppler tracking data. After the spacecraft orbit has been determined, the position of the spacecraft at each landmark-tracking time is obtained simply by integrating along the spacecraft trajectory from the initial orbit epoch to the time of interest. The second part of the procedure involves processing only the landmark angular measurements to solve for the selenographic parameters of the crater, while holding the spacecraft position and the inertial orientation of the IMU fixed. The IMU is realined during each revolution that includes landmark tracking. A factor compensating for platform drifts between alinement times (table I) is included in the landmark-position calculations. The effects of onboard-timing errors and instrument biases on the position solutions have been found to be negligible.

The accuracy limitations associated with the estimated selenographic positions are dominated by errors in the mathematical model used to describe the lunar gravitational effect. Primarily, these errors affect the MSFN orbit-determination process. The contribution of the MSFN state-vector errors to the total landmark-position uncertainty was almost a magnitude greater than any other source of error (e.g., libration, ephemerides, etc.), except for the Apollo 8 mission on which the landmark-position uncertainties were dominated by the relatively poor landmark-tracking geometry.

DESCRIPTION OF MSFN STATE-VECTOR-DETERMINATION PROCEDURE

The MSFN radar tracking stations obtain Doppler frequency-shift measurements by tracking the spacecraft whenever it is in earth view.[1] The location of the tracking stations and the earth-moon geometry are such that the spacecraft, when not occulted by the moon, is in simultaneous view of at least two stations. Two-way and three-way Doppler data were available for the orbit-determination computations. When the data were processed, the two Doppler types were given equal weight, and corrections were applied for three-way Doppler biases that exceeded 0.01 Hz.

The Doppler data are processed using a weighted least-squares technique to determine the selenocentric Cartesian components of the spacecraft orbit at a specified time, usually at the time of the first data point in the particular orbit solution. Basic earth-moon ephemerides information is obtained from Jet Propulsion Laboratory Development Ephemeris Number 19 (ref. 1). A single lunar gravitational potential

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[1] The MSFN angular-measurement data and some unified S-band pseudorandom-noise ranging data are also available. These data types are redundant with the Doppler data and therefore were not used to generate the orbits.

model (L1) was used for all MSFN orbit computations and trajectory integrations.[2] This model was selected because its use resulted in more consistent revolution-to-revolution landmark-position solutions. These position solutions agreed more closely than the solutions of other existing models with positions derived from available Lunar Orbiter photographic data. The L1 model does not fully account for the observed lunar gravitational effect; therefore, the data arc length used for obtaining the state-vector solution is of major importance. Postmission analyses of the MSFN Doppler data have shown that the best estimate of the spacecraft position while on the lunar near side is obtained by processing one full near-side pass of MSFN data.[3] Thus, for landmarks located on the lunar near side, one full pass of MSFN data that includes the landmark-tracking interval is used to determine the spacecraft position at the mark times. This procedure is not feasible for landmarks on the lunar far side because, in these cases, the question arises as to which of two errors is less significant — that of integrating outside the orbit-solution arc length with an inaccurate gravity model, or that of trying to fit the MSFN data over a longer arc length with an inaccurate gravity model. Either method will result in errors that are extremely difficult to evaluate. Constraining the orbit solution by fitting data on both sides of the landmark-tracking interval appears to be the more reasonable alternative. Therefore, for landmarks located on the lunar far side, two full passes of MSFN data that bracket the landmark-tracking data are used to determine the spacecraft position at the mark times. It is necessary to constrain the orbit plane in this type of solution, usually to the orbit plane from the latest pass of data.

The uncertainties in the MSFN state-vector solutions are primarily attributable to the inaccurate lunar-gravity model. Uncertainties resulting from MSFN station-location, station-timing, and station-frequency errors and from neglected three-way Doppler biases are at least an order of magnitude smaller than the gravity-model errors. Postflight analytical results of spacecraft-position uncertainties for the Apollo 8, 10, 11, and 12 missions are presented in table II in terms of the landmark-location parameters. From the table, it can be seen that MSFN spacecraft-position uncertainty in terms of landmark latitude is the largest of the three uncertainties, mainly because the MSFN Doppler data provide information only in the instantaneous plane of motion. Thus, for near-equatorial orbits, particularly on the Apollo 10 and 11 missions, the MSFN data provide very little latitude information. The MSFN spacecraft-position uncertainties in terms of landmark longitude and radius are approximately constant from mission to mission. Of the three parameters, radius is the least sensitive to gravity-field errors and, consequently, is the best determined parameter.

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[2]Coefficients of the L1 model are as follows.

$$J20 = 2.07108 \times 10^{-4}$$

$$J30 = -0.21 \times 10^{-4}$$

$$C22 = 0.20716 \times 10^{-4}$$

$$C31 = 0.34 \times 10^{-4}$$

$$C33 = 0.02583 \times 10^{-4}$$

[3]One full near-side pass of data is defined as all available MSFN data from acquisition of signal to loss of signal.

DESCRIPTION OF LANDMARK-POSITION SOLUTIONS

Two problems are associated with optically tracking a lunar landmark — acquiring and recognizing landmark tracking targets and performing the tracking sequence so that a good geometric spread with respect to the landmark nadir is obtained. Because the tracking of specific target craters is important only in the descent-landmark-tracking sequences, the problems of acquisition and recognition, in most cases, can be eliminated if the astronaut can positively identify the lunar feature that was actually tracked. (Of the 29 landmark-tracking sequences during the Apollo 8, 10, and 11 missions, two were on craters other than the premission-selected craters, and six were on different parts of the desired target crater.) For the second problem, experience has shown that the landmark-position determinations are significantly degraded if all marks are made on one side of the landmark nadir. However, if the noise on the landmark data is relatively low, the correct position for the landmark can be derived regardless of the geometric spread. Based on the landmark-geometry studies of the Apollo 8 and 10 missions, the following landmark-data-editing criteria have been established.

1. Marks taken when the command and service module (CSM) is below 35° elevation with respect to the landmark local horizon are disregarded in the landmark-position solution.

2. A mark spaced less than 20 seconds from the preceding mark is disregarded in the landmark-position solution. To process marks taken closer together than 20 seconds would require a complicated weighting structure capable of assigning separate weights to each mark. However, for marks that satisfy this criterion, equal weights can be assigned to all marks.

Application of these criteria was required to calculate position solutions from the Apollo 8 mission data. The tracking sequences on this mission, in most cases, had marks taken either at low elevations or spaced very closely together, with the result that many data had to be edited. However, the noise on the data was very low; consequently, good position solutions were obtained. On the Apollo 10, 11, and 12 missions, the geometric spread in the tracking sequences was much better because the marks were evenly spaced with time intervals greater than 20 seconds. Very little data from these three missions had to be disregarded in calculating the final landmark-position solutions.

The estimated uncertainties associated with each landmark solution were obtained by taking the root-sum-square of the MSFN spacecraft-position uncertainties (in terms of position-location parameters) and the least-squares filter uncertainties resulting from processing the landmark data. The latter uncertainties, which are called data noise, reflect to a large extent the uncertainties in IMU gimbal angles, shaft and trunnion angles, onboard timing, astronaut sighting errors, et cetera. Because very few passes were made over any one landmark, deriving a 1σ on the average position was not attempted.

INDIVIDUAL LANDMARK DESCRIPTIONS

The landmarks are discussed in this section, in which each landmark, the landmark location, and the mission situation relative to the landmark tracking are described.

The photographic coverage of the landmark from the Lunar Orbiter and Apollo missions is summarized in table III.

The nomenclature system used to identify landmarks consists of two parts, separated by a virgule. The first part is the name (e.g., CP-1) given the crater for flight-operations use; the second part is the number of the first Apollo mission on which the landmark was tracked. These identifications are not to be confused with any official International Astronomical Union (IAU) designations.

Landmark CP-1/8

Landmark CP-1/8 (fig. 2) is a smooth, circular crater on the far side of the moon west southwest of the 180° meridian and north northwest of IAU crater 313. The crater lies within a highland mare region currently designated by the IAU as Feature XV. Approximately 1 kilometer in diameter, the crater is at the top of a keyhole-shaped crater pattern (fig. 3). Feature XV is a large flattened area, possibly a butte- or mesa-type formation. The terrain inside Feature XV is rough and numerous craters scar the surface.

Astronaut James Lovell tracked landmark CP-1/8 on revolutions 5, 6, and 7 of the Apollo 8 mission. Because all marks were taken well before the spacecraft reached the landmark nadir, editing of the data was required before the position could be calculated. On revolution 5, the first two marks were taken while the spacecraft was below 35° elevation above the local landmark horizon. The last three marks were taken too closely together, but the spread between the third and fifth marks was adequate. The calculated position is listed in table IV. During revolution 6, only one mark was taken while the CSM was above 35° elevation. The radius for this mark was constrained to be the average of the fifth- and seventh-revolution determinations of the landmark radius, and a latitude and longitude solution was computed. This solution agreed with the solutions of revolutions 5 and 7. All five marks on revolution 7 were taken above 35° elevation, but the marks were too closely spaced. However, disregarding the second and fourth marks resulted in an optimum spread for the sequence. The calculated position is listed in table IV; the average position for landmark CP-1/8, computed from revolutions 5 and 7 data, is listed in table V. (Revolution 6 data were not used because no unconstrained solution could be generated.)

Landmark CP-2/8

Landmark CP-2/8 (fig. 4) is a smooth, conical, 400-meter-diameter crater located inside IAU feature 302. Feature 302, a large, shallow crater with central peaks comparable to those of Langrenus, is located in the far-side highland area east southeast of the 180° meridian. Landmark CP-2/8 (fig. 5) lies within the large indentation in the northern wall of the large crater in the eastern portion of feature 302.

Astronaut James Lovell tracked landmark CP-2/8 on revolutions 5, 6, and 7 of the Apollo 8 mission. Again, all marks were taken before the CSM crossed the landmark nadir. On the revolution 5 sequence, all marks were taken above 35° elevation but very closely together. However, by disregarding the second and fourth marks, ideal spacing was obtained. The calculated position is listed in table IV. During the revolution 6 sequence, the marks were taken above 35° elevation, but again too closely together. The spacing between the second and fifth marks was acceptable. The calculated position is listed in table IV. The tracking sequences of revolutions 6 and 7 were similar, with the last four marks taken above 35° elevation. The second and fifth marks represented nearly ideal spacing, although the fifth mark was taken at a very low elevation angle (approximately 43°). The calculated position is listed in table IV; the average position for CP-2/8 (derived from revolution 5, 6, and 7 data) is listed in table V.

Landmark CP-3/8

Landmark CP-3/8 (fig. 6) is a small, bright-rayed crater about 250 meters in diameter on the lunar far side just beyond the eastern limb. The landmark is just outside the rim of a highland crater southeast of IAU crater 266 on the southeast edge of Mare Smythii. The terrain around landmark CP-3/8 is rough, highland area with numerous bright crater formations.

Astronaut James Lovell tracked landmark CP-3/8 on revolution 7 of the Apollo 8 mission. Only one mark was taken after the landmark nadir. Because the marks were taken within less than 20 seconds of each other, the second and fourth marks had to be disregarded to achieve adequate spacing. The calculated position is listed in table IV and, as the only available data, also in table V. On revolution 6, Astronaut Lovell attempted to track this landmark, or one near it, and succeeded in getting five marks. The marks were all taken while the CSM was at a very low elevation with the result that the intersection of the lines of sight was poorly defined.

LANDMARK B-1/8

Landmark B-1/8 (figs. 7 and 8) is a smooth, circular crater on the lunar near side in southeastern Mare Tranquillitatis near Apollo landing site 1. Mare Tranquillitatis is one of the most scarred of the near-side maria, being nearly evenly divided by mountains. Landmark B-1/8, a shallow crater approximately 500 meters in diameter, is in the smooth, sparsely cratered area just east of these mountains.

Astronaut James Lovell tracked landmark B-1/8 on revolutions 5, 6, and 7 of the Apollo 8 mission. On revolutions 5 and 6, the marks were taken while the CSM was at a low elevation above the local horizon. The revolution 5 marks were quite noisy, and no data editing was possible. On revolution 6, only one mark was taken above 35° elevation. However, on revolution 7, no data editing was required because the tracking geometry and mark spacing were good. The calculated position is listed in table IV.

Astronaut John Young tracked landmark B-1/8 on revolution 30 of the Apollo 10 mission. The tracking geometry for this sequence was good, although the landmark was approximately 60 kilometers off the spacecraft ground track. The calculated position is listed in table IV, and the average of the Apollo 8 and 10 solutions is listed in table V.

Landmark B-1'/10

Astronaut Young was also scheduled to track landmark B-1/8 on revolution 4 of the Apollo 10 mission. However, he marked on a feature, later designated B-1'/10 (figs. 7 and 8), very close to landmark B-1/8. The tracking geometry for the landmark was good, although the first two marks were taken below 35° elevation. Consequently, only the last three marks were used in the solution. The calculated position is listed in table IV and, as the only available data, also in table V.

Landmark CP-1/10

Landmark CP-1/10 (fig. 9) is a small, circular crater, approximately 100 meters in diameter, situated atop a knoll on the lunar far side. The crater is west of the central meridian and close to IAU crater 225. The terrain in this area is rough highlands, scarred by numerous craters and mountains.

Astronaut John Young tracked landmark CP-1/10 on revolutions 25, 26, and 27 of the Apollo 10 mission. The tracking geometry on all revolutions was good and no data editing was necessary. The calculated positions for landmark CP-1/10 are listed in table IV; the average position from the three individual revolution solutions is listed in table V.

Landmark CP-2/10

Landmark CP-2/10 (fig. 10) is a dimple crater on the lunar far side approximately 1° northeast of IAU crater 282. Crater 282 is situated on the lunar equator in the mountainous region between IAU Feature IX and Mare Smythii. Landmark CP-2/10 is located on a ridge containing numerous crater holes (fig. 11).

Astronaut John Young tracked landmark CP-2/10 on revolutions 24, 25, 26, and 27 of the Apollo 10 mission. On revolution 24, only two marks were taken. Sufficient information was not contained in these marks to generate a reasonable solution. On revolutions 25, 26, and 27, the marking spread was good, and good solutions were obtained. The calculated positions are listed in table IV; the average of these three positions is listed in table V.

Landmark F-1/10

Landmark F-1/10 (fig. 12) is a medium-sized, conical crater in the northern part of Mare Smythii. The crater is on the lunar near side, very near the eastern limb. Landmark F-1/10, which is approximately 1.5 kilometers in diameter, is located on very flat, featureless terrain marked only by a ridge east of the landmark.

Astronaut John Young used landmark F-1/10 for practice tracking on revolution 4 of the Apollo 10 mission, and then tracked it on revolutions 24 to 27. The tracking geometry on all revolutions except 24 was good. On revolution 24, all marks were taken after the spacecraft passed the landmark nadir. Consequently, the fifth mark was taken while the spacecraft was below 35° elevation, and the solution had to be computed using only the first four marks. The calculated positions are listed in table IV; the average of the five single-revolution solutions is listed in table V.

Landmark 130'/10

Landmark 130'/10 (fig. 13) is a rock slide in the northeastern quadrant of a smooth-rimmed circular crater called Apollo landmark 130 (fig. 14). Landmark 130 is on the lunar near side in the southwestern quadrant of Mare Tranquillitatis, just north of Apollo landing site 2. This area is very flat with almost no sizable craters or rilles. Landmark 130'/10 is in the western half of Mare Tranquillitatis.

Astronaut John Young tracked landmark 130'/10 on revolutions 24 to 27 of the Apollo 10 mission. Because the tracking geometry for all four sequences was good, no data were edited from these solutions. The positions that were derived from these tracking sequences are listed in table IV; the average solution is listed in table V.

Landmark 130''/11

Landmark 130''/11 (fig. 13) is a small crater inside the northern rim of Apollo landmark 130 (fig. 14). On the Apollo 11 mission, Astronaut Michael Collins chose to track this small crater in lieu of landmark 130'/10. Landmark 130''/11 was tracked on revolutions 12 and 24. Because the tracking geometry for both revolutions was good, no data were edited for the solutions. The calculated positions for each revolution are listed in table IV; the average solution is listed in table V.

Landmark 150'/10

Landmark 150'/10 (fig. 15) is a relatively shallow, rough-edged crater in Sinus Medii on the lunar near side. The crater, near Apollo landing site 3, is almost due west of the intersection of the central meridian and the equator. Numerous craters of approximately the same size (500 meters in diameter) are located in this area, with the result that the recognition pattern that includes landmark 150'/10 is repeated several times.

Astronaut John Young tracked landmark 150'/10 on revolution 30 of the Apollo 10 mission. The target for this tracking was landmark 150, the prime landmark for Apollo landing site 3. As the sequence started, landmark 150 was being sighted. One mark was taken, but the very low sun elevation caused the numerous recognition patterns identical to that of landmark 150 to be seen. This repetition confused the astronaut, who switched to landmark 150'/10 for the last four marks of the sequence. The tracking geometry for the sequence was good, despite the change of targets, and the position of landmark 150'/10 was computable. This calculated position is listed in table IV and, as the only available data, also in table V.

Landmark A-1/11

Landmark A-1/11 (fig. 16) is a small, bright-rayed crater located in the northern area of Mare Spumans, which is one of the smallest of the near-side maria. Landmark A-1/11 is part of a four-crater pattern that stands alone on this mare area, which contains very few sizable craters. The diameter of landmark A-1/11 is estimated to be 100 meters.

Astronaut Michael Collins tracked landmark A-1/11 on revolution 4 of the Apollo 11. The tracking was done in practice for the descent landmark-tracking sequence. Because the tracking geometry for the sequence was good, no data had to be edited for the solution. The calculated position is listed in table IV and, as the only available data, also in table V.

Landmark LS2-1/11

Landmark LS2-1/11 (fig. 17) is a small crater in the landing ellipse for Apollo landing site 2. The crater is on a flat plain just southwest of the predominant feature in landing site 2. The exact crater could not be identified because tracking was performed with the sextant, which has only a 1.8° field of view. The postmission attempt to identify the landmark resulted only in an areal identification. This identified area is quite small and can be used as the approximate center of the landmark.

Landmark LS2-1/11 was tracked on revolution 15 of the Apollo 11 mission. Astronaut Michael Collins visually searched for the lunar module (LM) during this pass over the landing site; when he could not find the LM, he tracked landmark LS2-1/11. The tracking geometry over the landmark was good, although the first mark was not taken until the spacecraft was almost 76° above the local horizon at the landmark. Only the first four marks were usable for deriving a solution. The calculated position is listed in table IV and, as the only available data, also in table V.

Landmark H-1/12

Landmark H-1/12 (fig. 18) is a circular crater approximately 750 meters in diameter inside a rille in the mare area east of the Fra Mauro highlands. The crater is approximately 1° west of Turner F and due south of Gambart. Several other rilles are located in the area, but the terrain is mainly flat all the way up to the Fra Mauro highlands.

Astronaut Richard Gordon tracked landmark H-1/12 on revolution 4 of the Apollo 12 mission. The crater was the practice landmark for the descent targeting exercise that was scheduled later in the mission. Because the tracking geometry for this landmark was good, no data editing was necessary. The calculated solution is listed in table IV and, as the only data available, also in table V.

Landmark 193/12

Landmark 193/12 (fig. 19) is the landmark for Apollo landing site 7, which was the Apollo 12 landing area. The landmark, which is approximately 6 miles south and 3 miles east of the Apollo 12 landing site in Mare Cognitum, is a small elliptical crater with a major axis of approximately 300 meters. Mare Cognitum is a portion of Oceanus Procellarum, from which it is separated by Montes Riphaeus. This area has been the target for the Ranger 7, Surveyor III. and Apollo 12 missions.

Landmark 193/12 was tracked on revolution 12, which began the landing sequence on the Apollo 12 mission. The tracking geometry on this pass was excellent and the data noise was low, so no data editing was necessary. The landmark was tracked again by Astronaut Gordon on revolution 15 in the sequence used to locate the LM. The marking geometry on this revolution was good; however, the sequence was started late, and the last two marks were below 35° elevation. Consequently, only the first three marks were used to calculate the solution. The calculated positions are listed in table IV; the average of the two solutions is listed in table V.

Landmark CP-1/12

Landmark CP-1/12 (fig. 20) is the northern crater of a doublet twin on the rim of a large far-side crater near IAU crater 273. The crater is about 550 meters in diameter. Crater 273 is in the highland area approximately 15° east of Mare Smythii. Approximately 40 kilometers in diameter, crater 273 is situated among numerous, large, relatively shallow craters.

Astronaut Richard Gordon tracked landmark CP-1/12 revolutions on 42 and 43 of the Apollo 12 mission. The tracking geometry on both revolutions was good, and no data had to be edited from either pass. The calculated positions are listed in table IV, and the average solution is listed in table V.

Landmark CP-2/12

Landmark CP-2/12 (fig. 21) is the southern crater of a twin pattern. Approximately 1.4 kilometers in diameter, the crater is near the eastern edge of Langrenus D, which is located on the eastern edge of Mare Fecunditatis. The area around the landmark is pocked with many craters and gulley-type formations.

Astronaut Richard Gordon tracked landmark CP-2/12 on revolutions 42 and 43 of the Apollo 12 mission. The tracking was not on the crater center on either revolution, as revealed by the sextant photography. The western edge of the crater was tracked on revolution 42 and the northern edge on revolution 43. Both passes had good tracking geometry, but two marks on revolution 43 were taken too soon after preceding marks. These two marks were disregarded in deriving the calculated positions listed in table IV. To obtain a best solution, the latitude from revolution 42 and the longitude and radius from revolution 43 were used. This calculated position is listed in table V.

Landmark DE-1/12

Landmark DE-1/12 (fig. 22) is a bright, circular crater in the central highlands on the lunar near side. The landmark is due north of Dollond E, southwest of Dollond B, and west of Zölner D. The landmark, approximately 400 meters in diameter, is the westerly crater in a doublet pattern. The crater is the landing-site landmark for Descartes. The area around Descartes is very rough, with many rugged hills surrounding the proposed landing site. Because the albedo of this area is high the region is among the brightest areas on the lunar surface.

Astronaut Richard Gordon tracked landmark DE-1/12 on revolutions 42 and 44 of the Apollo 12 mission. The marking geometry for both passes was good; however, both passes included marks taken too soon after preceding marks. These premature marks were disregarded in deriving the calculated positions listed in table IV; the average calculated position is listed in table V.

Landmark FM-1/12

Landmark FM-1/12 (fig. 18) is a circular crater, approximately 1 kilometer in diameter, located in the central highland area north of Fra Mauro. The crater, which is the landing-site landmark for Fra Mauro, is on the rim of a large shallow crater. The hills above Fra Mauro are one of the prime Apollo landing sites, because the hills are thought to contain some of the oldest material on the lunar surface.

Astronaut Richard Gordon tracked landmark FM-1/12 on revolutions 42 and 44 of the Apollo 12 mission. The marking geometry for both passes was good; however, both passes included marks taken too soon after preceding marks. These premature marks were disregarded in deriving the calculated positions listed in table IV; the average position is listed in table V.

CONCLUDING REMARKS

The far-side landmarks, located during the Apollo 8, 10, 11, and 12 missions, provide good bases for extending selenodetic control to the lunar far side, because these landmarks represent the first direct measurements made on features in that region. The near-side landmarks can be used to improve selenodetic control on the visible surface, at least within the regions of the moon covered by these four missions. The landmarks are also valuable as ground-control points in analytical photogrammetric solutions. Many more landmarks will be required to extend or improve selenodetic control over larger regions of both the near and far sides of the lunar surface.

Several potential sources of error are present in the landmark-tracking technique for locating lunar craters. With the exception of the errors and uncertainties caused by the lunar-gravity model, these error sources can be eliminated, by compensating for biases, or reduced to an acceptable level (estimated to be 200 meters 3σ), by using correct operational procedures for landmark tracking. Another source of error, only briefly mentioned, is the lunar-libration model or the coefficients used to describe the physical libration. Hayn's coefficients were used for the selenographic computations reported in this document. On the basis of experience gained from processing the Apollo data and from a Lunar Orbiter selenographic transformation study using different libration-model coefficients, it appears that the uncertainty resulting from libration errors may be as large as 300 meters. The selenographic positions of the reported landmarks will be updated when improvements in the lunar-gravity or lunar-libration models warrant such updates.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, August 7, 1970
914-22-20-11-72

REFERENCE

1. Devine, Charles J.: JPL Development Ephemeris Number 19. Jet Propulsion Laboratory Tech. Rept. 32-1181, Nov. 15, 1967.

TABLE I. - INERTIAL MEASUREMENT UNIT ALINEMENTS AND

DRIFT RATES BETWEEN REALINEMENTS IN MERU[a]

Mission	Ground elapsed time, hr: min	Drift-rate coordinate until next alinement			Before revolution number -
		$\dot{X}$	$\dot{Y}$	$\dot{Z}$	
Apollo 8	76: 24	-1. 97	-0. 43	1. 31	5
Apollo 8	78: 28	-1. 73	. 07	-2. 36	6
Apollo 8	80: 28	-. 72	-. 13	1. 05	7
Apollo 10	81: 20	-1. 6	1. 2	-. 2	4
Apollo 10	121: 13	-1. 8	1. 6	-. 5	24
Apollo 10	122: 58	-. 9	1. 0	-. 3	25
Apollo 10	124: 50	-1. 5	. 9	-. 2	26
Apollo 10	126: 50	-1. 6	1. 1	-. 4	27
Apollo 10	132: 52	-1. 3	1. 3	-. 3	30
Apollo 11	81: 05	-. 7	-1. 5	-. 1	4
Apollo 11	96: 55	-1. 3	-1. 9	-. 2	12
Apollo 11	103: 00	-. 8	-2. 4	-. 3	15
Apollo 11	121: 15	-1. 2	-1. 9	. 4	24
Apollo 12	88: 55	-. 40	. 90	2. 13	4
Apollo 12	102: 50	-1. 51	. 68	. 0	12
Apollo 12	164: 06	-1. 50	1. 40	-. 05	42
Apollo 12	165: 52	-1. 70	1. 02	. 09	43
Apollo 12	167: 57	-1. 70	1. 02	. 09	44

[a]1 MERU ≅ 0. 015 deg/hr.

TABLE II. - MANNED SPACE FLIGHT NETWORK UNCERTAINTIES FOR VARIOUS TYPES OF STATE VECTORS USED TO DETERMINE LANDMARK POSITIONS

Mission	State vector	State-vector uncertainties, m		
		1σ latitude	1σ longitude	1σ radius
Apollo 8	1 revolution; unconstrained plane	670	430	300
Apollo 8	2 revolutions: plane constrained to be plane of second revolution	700	580	460
Apollo 10	1 revolution; unconstrained plane	610	300	300
Apollo 10	2 revolutions; plane constrained to be plane of second revolution	610	460	460
Apollo 11	1 revolution; unconstrained plane	610	300	300
Apollo 11	2 revolutions: plane constrained to be plane of second revolution	610	460	460
Apollo 12	1 revolution; unconstrained plane; revolutions 1 to 39	670	460	300
Apollo 12	2 revolutions; plane constrained to be plane of second revolution; revolutions 1 to 39	700	610	460
Apollo 12	1 revolution; unconstrained plane; revolutions 40 to 45	670	430	300
Apollo 12	2 revolutions: plane constrained to be plane of second revolution; revolutions 40 to 45	700	580	460

TABLE III. - INDEX OF LANDMARK PHOTOGRAPHIC COVERAGE

Landmark designation	Mission	Photographic frames
CP-1/8	Lunar Orbiter I	28M 30M 35M to 40M 38H2
	Lunar Orbiter V	30M
	Apollo 8	AS8-12-2052 to AS8-12-2054 AS8-17-2664 to AS8-17-2666
CP-2/8	Lunar Orbiter I	116M
	Lunar Orbiter II	33M and 34M 75M
	Apollo 8	AS8-14-2431 AS8-17-2703 to AS8-17-2705
	Apollo 10	AS10-32-4790 AS10-32-4823 and AS10-32-4824
	Apollo 11	AS11-38-5567 AS11-38-5570 AS11-38-5583 AS11-38-5585
CP-3/8	Lunar Orbiter II	196M
	Apollo 8	AS8-12-2161 to AS8-12-2163 AS8-12-2201 and AS8-12-2202 AS8-17-2771 to AS8-17-2778
	Apollo 10	AS10-27-3915 AS10-27-3918
	Apollo 12	AS12-51-7526 to AS12-51-7528 AS12-54-7973 and AS12-54-7974 AS12-55-8143
B-1/8, B-1'/10	Lunar Orbiter I	49M
	Lunar Orbiter II	42M
	Lunar Orbiter III	9M 11M 13M 15M 12H2
	Lunar Orbiter IV	73H

TABLE III. - INDEX OF LANDMARK PHOTOGRAPHIC COVERAGE - Continued

Landmark designation	Mission	Photographic frames
	Lunar Orbiter V	42M 52M 55M to 62M 60H
	Apollo 8	AS8-13-2343 AS8-17-2818 to AS8-17-2821
	Apollo 10	AS10-30-4440 AS10-31-4526 and AS10-31-4527 AS10-31-4583 to AS10-31-4585 AS10-32-4700 to AS10-32-4707 AS10-33-4922 to AS10-33-4930 AS10-34-5080 AS10-34-5146 and AS10-34-5147
	Apollo 11	AS11-41-6073 to AS11-41-6083 AS11-42-6234
CP-1/10	Lunar Orbiter II	33M and 34M
	Apollo 10	AS10-28-4068 and AS10-28-4069
	Apollo 11	AS11-42-6252 AS11-43-6485 and AS11-43-6486
CP-2/10	Lunar Orbiter I	102M 117M 136M
	Apollo 10	AS10-28-4110 and AS10-28-4111 AS10-34-5107 to AS10-34-5111
	Apollo 11	AS11-41-5978 to AS11-41-5982 AS11-43-6517 to AS11-43-6523
F-1/10	Lunar Orbiter I	8M to 16M
	Lunar Orbiter II	196M
	Lunar Orbiter IV	20H2
	Apollo 8	AS8-12-2202 AS8-12-2207 and AS8-12-2208 AS8-18-2845 and AS8-18-2846 AS8-18-2870
	Apollo 10	AS10-27-3888 AS10-27-3915 AS10-27-3918 AS10-30-4475

TABLE III. - INDEX OF LANDMARK PHOTOGRAPHIC COVERAGE - Continued

Landmark designation	Mission	Photographic frames
	Apollo 11	AS11-38-5613 AS11-38-5615 and AS11-38-5616 AS11-38-5636 to AS11-38-5640 AS11-38-5646 to AS11-38-5653 AS11-41-6013 to AS11-41-6027 AS11-43-6471 AS11-44-6547 to AS11-44-6563 AS11-44-6601 to AS11-44-6605 AS11-44-6630 to AS11-44-6650 AS11-44-6653
130'/10, 130''/11, and LS2-1/11	Lunar Orbiter II	76M to 79M
	Lunar Orbiter IV	85H
	Lunar Orbiter V	64M 71M to 78M 74H1 78H1 and 78H2
	Apollo 10	AS10-28-4052 to AS10-28-4054 AS10-30-4443 to AS10-30-4448 AS10-31-4537 to AS10-31-4539 AS10-32-4749 to AS10-32-4752 AS10-32-4848 AS10-33-4937 to AS10-33-4941 AS10-34-5100 AS10-34-5156 to AS10-34-5158
	Apollo 11	AS11-37-5437 AS11-37-5447 AS11-41-6089 to AS11-41-6092 AS11-41-6115 to AS11-41-6119
150'/10	Lunar Orbiter I	122M to 129M
	Lunar Orbiter II	93M 121M to 124M
	Lunar Orbiter III	84M
	Lunar Orbiter IV	101H and 102H 108H and 109H
	Lunar Orbiter V	108M to 115M 108H1 112H

TABLE III. - INDEX OF LANDMARK PHOTOGRAPHIC COVERAGE - Continued

Landmark designation	Mission	Photographic frames
	Apollo 10	AS10-27-3905 to AS10-27-3908 AS10-32-4818
A-1/11	Lunar Orbiter IV	184H1 185H1
	Apollo 10	AS10-30-4496 to AS10-30-4498
	Apollo 11	AS11-38-5596 to AS11-38-5598 AS11-41-6046 to AS11-41-6052 AS11-42-6205
H-1/12	Lunar Orbiter IV	114H 120H and 121H
	Apollo 12	AS12-50-7436 to AS12-50-7439
193/12	Lunar Orbiter I	157M to 161M
	Lunar Orbiter III	120M 136M to 150M 153M to 160M
	Lunar Orbiter IV	125H and 126H
	Apollo 12	AS12-54-8089 and AS12-54-8090
CP-1/12	Lunar Orbiter I	102M 102H
	Lunar Orbiter II	196M
	Apollo 8	AS8-12-2199 and AS8-12-2200 AS8-18-2854 AS8-18-2869 to AS8-18-2870
	Apollo 11	AS11-44-6657
	Apollo 12	AS12-54-7958 and AS12-54-7959 AS12-55-8127 and AS12-55-8128
CP-2/12	Lunar Orbiter IV	53M 53H
	Apollo 8	AS8-12-2203 AS8-13-2215 AS8-16-2616 AS8-18-2880 and AS8-18-2881
	Apollo 10	AS10-27-3921 AS10-27-3932 to AS10-27-3934
	Apollo 11	AS11-42-6217

TABLE III. - INDEX OF LANDMARK PHOTOGRAPHIC COVERAGE - Concluded

Landmark designation	Mission	Photographic frames
	Apollo 12	AS12-54-8012 to AS12-54-8014 AS12-55-8181 and AS12-55-8182
DE-1/12	Lunar Orbiter IV	89M 89H
	Apollo 12	AS12-50-7427 and AS12-50-7428 AS12-52-7631 to AS12-52-7648 AS12-53-7763 to AS12-53-7776 AS12-54-8051 to AS12-54-8053
FM-1/12	Lunar Orbiter III	133M 133H
	Lunar Orbiter IV	120H and 121H
	Apollo 12	AS12-52-7595 to AS12-52-7597 AS12-54-8084 and AS12-54-8085

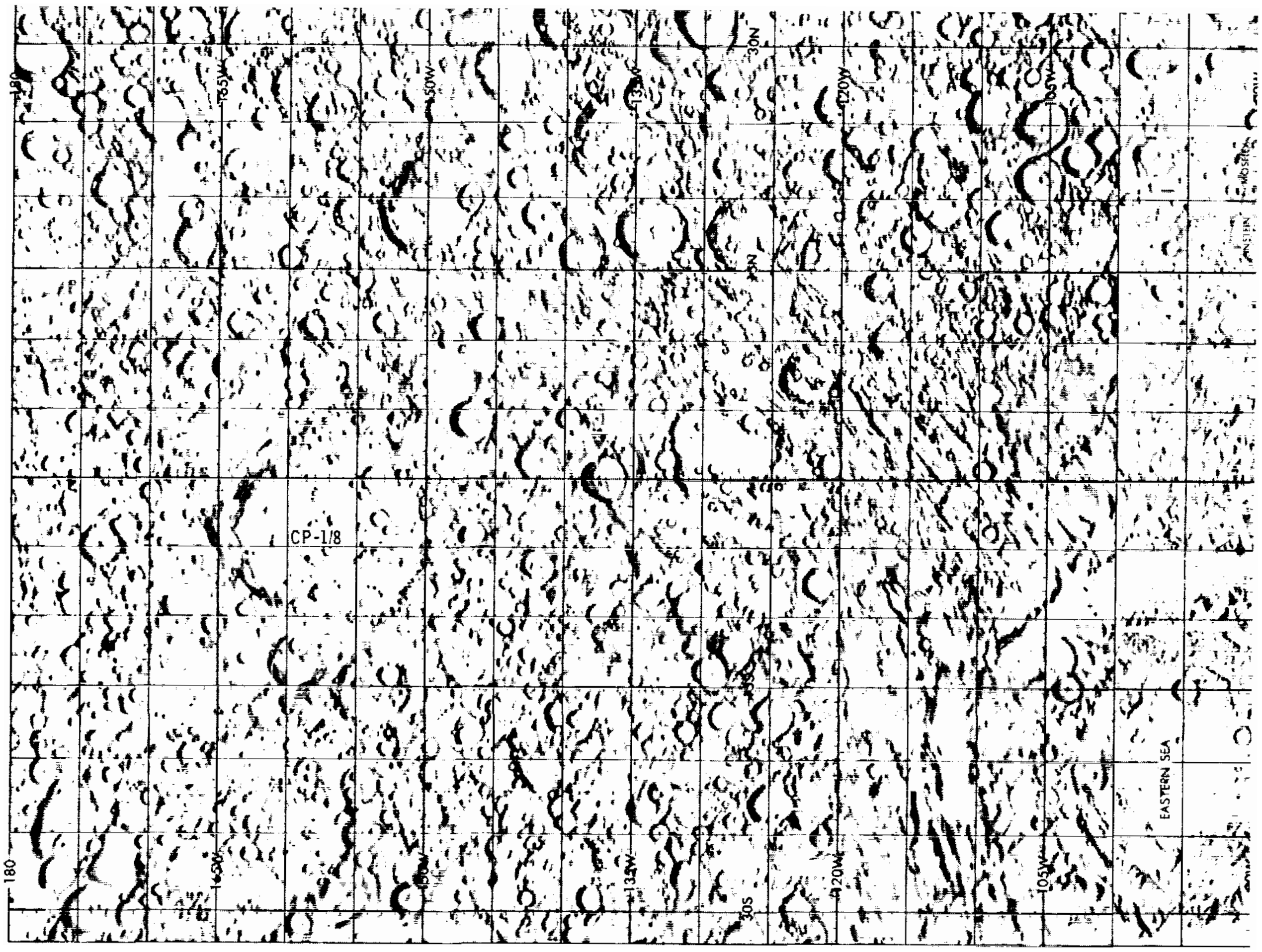
TABLE IV. - LANDMARK-POSITION SOLUTIONS FOR EACH TRACKING SEQUENCE

Landmark designation	Mission	Revolution number	Latitude ± 1σ, deg	Longitude ± 1σ, deg	Radius ± 1σ, km
CP-1/8	Apollo 8	5	-6.3136 ± 0.0228	-158.0509 ± 0.0549	1740.348 ± 1.540
	Apollo 8	7	-6.3021 ± .0234	-158.0414 ± .0214	1740.300 ± .657
CP-2/8	Apollo 8	5	-9.6948 ± .0226	163.2410 ± .0201	1737.548 ± .607
	Apollo 8	6	-9.7048 ± .0234	163.2508 ± .0350	1737.375 ± .893
	Apollo 8	7	-9.7111 ± .0244	163.2472 ± .0449	1736.951 ± 1.127
CP-3/8	Apollo 8	7	-8.8990 ± .0145	96.8915 ± .0226	1735.374 ± .430
B-1/8	Apollo 8	7	2.5766 ± .0218	35.0117 ± .0142	1736.591 ± .357
	Apollo 10	30	2.5629 ± .0206	35.0297 ± .0105	1736.608 ± .385
B-1'/10	Apollo 10	4	2.5101 ± .0205	35.2009 ± .0109	1736.419 ± .375
CP-1/10	Apollo 10	25	.8149 ± .0202	170.1190 ± .0151	1739.057 ± .486
	Apollo 10	26	.8582 ± .0201	170.1489 ± .0151	1739.069 ± .502
	Apollo 10	27	.8616 ± .0201	170.1482 ± .0152	1739.045 ± .500
CP-2/10	Apollo 10	25	.5809 ± .0200	127.9530 ± .0152	1742.211 ± .492
	Apollo 10	26	.5814 ± .0201	127.9574 ± .0154	1742.278 ± .496
	Apollo 10	27	.5833 ± .0201	127.9507 ± .0151	1742.473 ± .504
F-1/10	Apollo 10	4	1.8824 ± .0201	88.2476 ± .0104	1733.704 ± .355
	Apollo 10	24	1.8650 ± .0205	88.2744 ± .0108	1733.551 ± .409
	Apollo 10	25	1.8751 ± .0203	88.2438 ± .0104	1732.283 ± .387
	Apollo 10	26	1.8749 ± .0202	88.2505 ± .0104	1732.821 ± .361
	Apollo 10	27	1.8635 ± .0203	88.2496 ± .0104	1732.674 ± .376
130'/10	Apollo 10	24	1.2578 ± .0202	23.6862 ± .0103	1735.391 ± .366
	Apollo 10	25	1.2647 ± .0202	23.6845 ± .0105	1735.290 ± .379
	Apollo 10	26	1.2739 ± .0202	23.6863 ± .0103	1735.350 ± .359
	Apollo 10	27	1.2641 ± .0201	23.6877 ± .0104	1735.316 ± .365
150'/10	Apollo 10	30	-.0171 ± .0201	-1.5129 ± .0102	1736.499 ± .370
A-1/11	Apollo 11	4	1.7981 ± .0200	65.0741 ± .0103	1735.492 ± .339
LS2-1/11	Apollo 11	15	.6424 ± .0201	23.1589 ± .0102	1735.556 ± .381
130''/11	Apollo 11	12	1.2235 ± .0202	23.6724 ± .0101	1735.411 ± .359
130''/11	Apollo 11	24	1.2680 ± .0202	23.6692 ± .0102	1735.434 ± .363
H-1/12	Apollo 12	4	-1.5080 ± .0220	-15.2390 ± .0149	1736.087 ± .354
193/12	Apollo 12	12	-3.4927 ± .0220	-23.2368 ± .0150	1735.748 ± .362
193/12	Apollo 12	15	-3.5045 ± .0221	-23.2263 ± .0151	1735.908 ± .409
CP-1/12	Apollo 12	42	-5.7311 ± .0227	112.3108 ± .0189	1738.952 ± .504
CP-1/12	Apollo 12	43	-5.7407 ± .0227	112.3064 ± .0189	1738.939 ± .495
CP-2/12	Apollo 12	42	-10.5392 ± .0217	56.1176 ± .0141	1736.168 ± .363
CP-2/12	Apollo 12	43	-10.5261 ± .0218	56.1181 ± .0142	1736.386 ± .406
DE-1/12	Apollo 12	42	-8.9454 ± .0219	15.5087 ± .0151	1737.999 ± .384
DE-1/12	Apollo 12	44	-8.9379 ± .0220	15.5132 ± .0151	1737.799 ± .409
FM-1/12	Apollo 12	42	-3.2511 ± .0218	-17.3182 ± .0142	1737.083 ± .385
FM-1/12	Apollo 12	44	-3.2404 ± .0218	-17.3147 ± .0141	1737.014 ± .390

TABLE V. - BEST LANDMARK-POSITION SOLUTIONS FOR

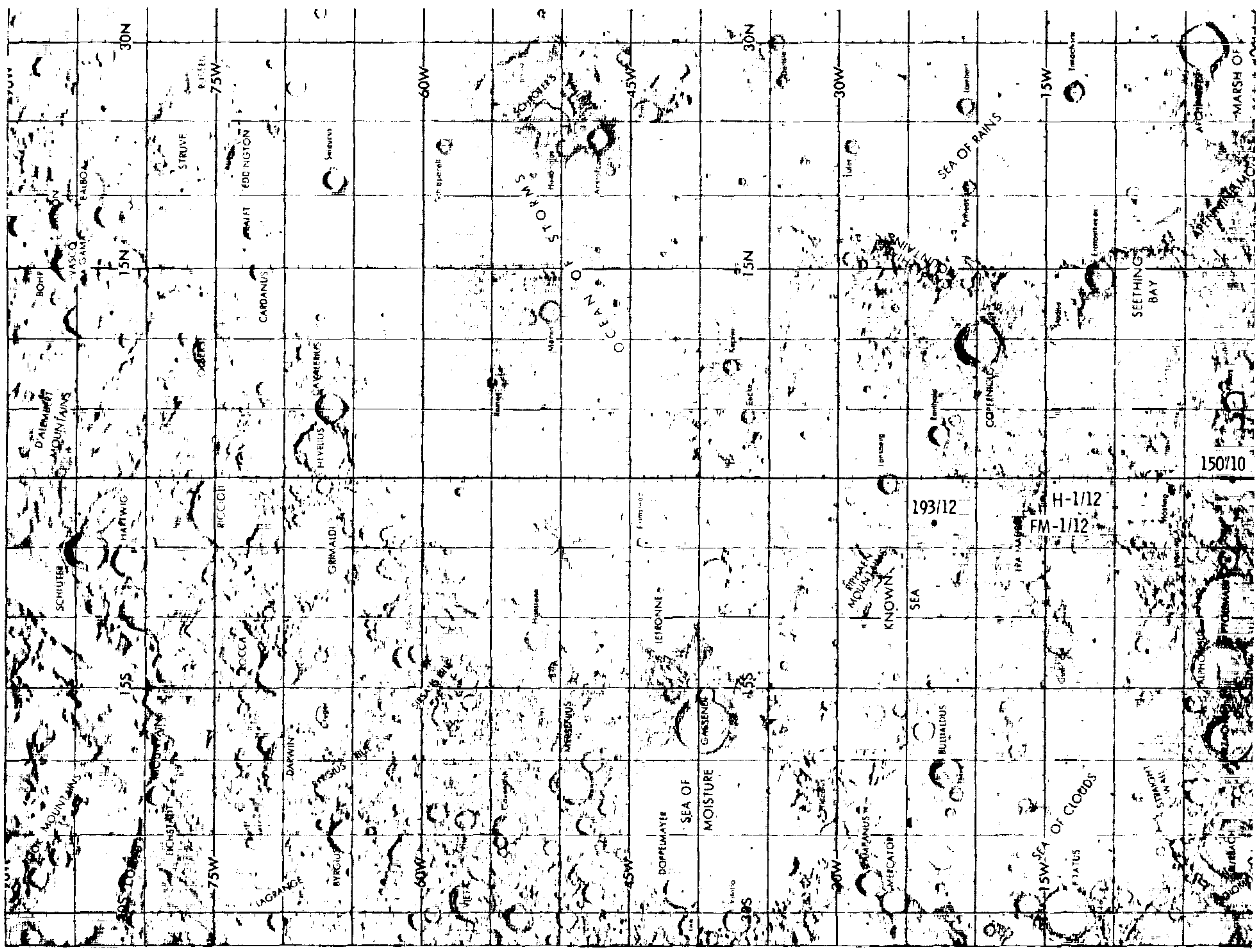
APOLLO LUNAR LANDMARKS

Landmark designation	Latitude, deg	Longitude, deg	Radius, km
CP-1/8	-6.3079	-158.0462	1740.324
CP-2/8	-9.7036	163.2463	1737.291
CP-3/8	-8.8990	96.8915	1735.374
B-1/8	2.5698	35.0207	1736.600
130'/10	1.2651	23.6862	1735.337
F-1/10	1.8722	88.2532	1733.007
CP-1/10	.8449	170.1387	1739.057
CP-2/10	.5819	127.9537	1742.321
150'/10	-.0171	-1.5129	1736.499
B-1'/10	2.5101	35.2009	1736.419
A-1/11	1.7981	65.0741	1735.492
130''/11	1.2458	23.6708	1735.423
LS2-1/11	.6424	23.1589	1735.556
H-1/12	-1.5080	-15.2390	1736.087
193/12	-3.4986	-23.2316	1735.828
CP-1/12	-5.7359	112.3086	1738.946
CP-2/12	-10.5392	56.1181	1736.386
DE-1/12	-8.9417	15.5110	1737.899
FM-1/12	-3.2457	-17.3165	1737.049



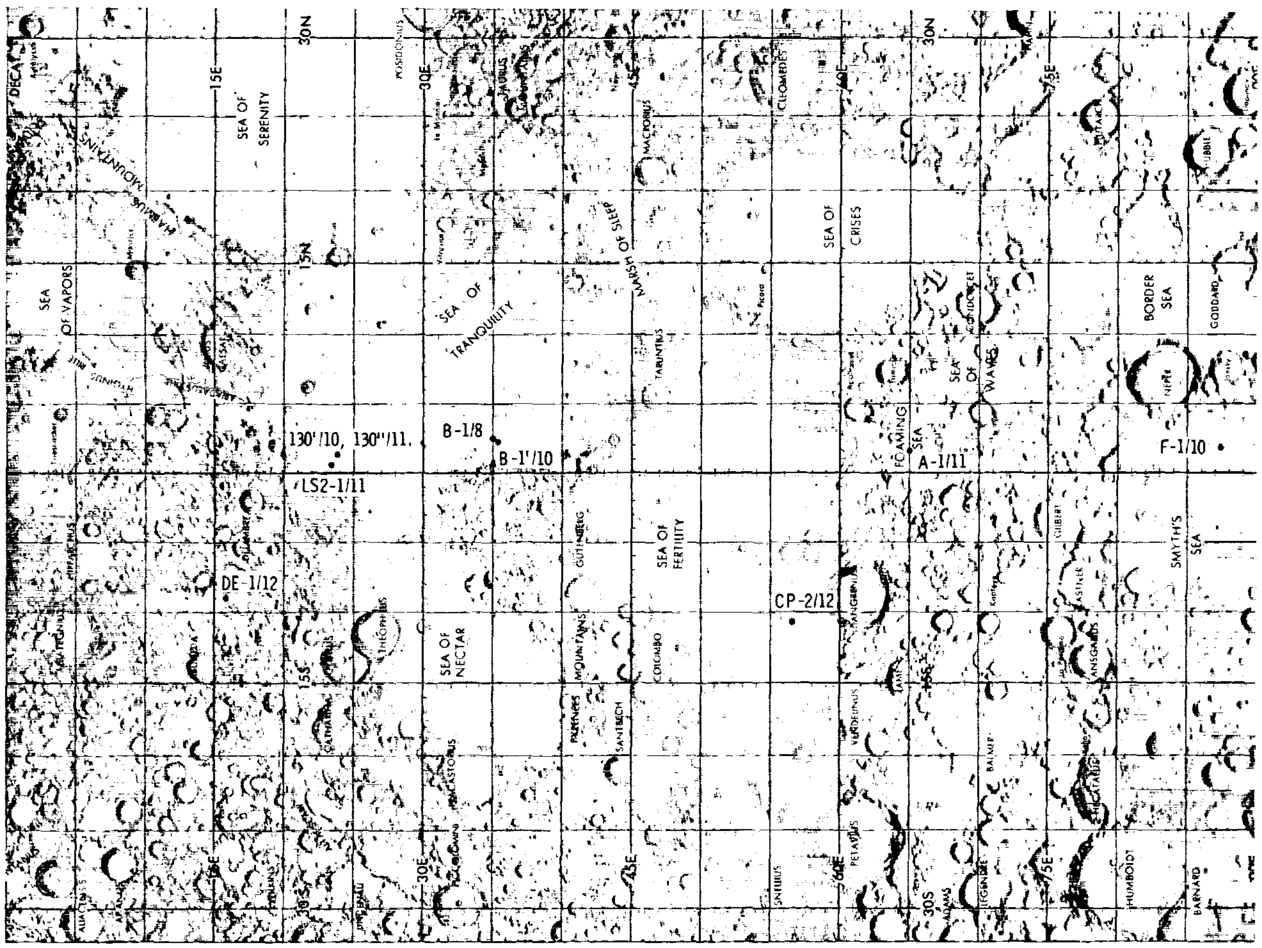
(a) 180° to 90° W.

Figure 1.- Lunar landmarks tracked on the Apollo 8, 10, 11, and 12 missions.



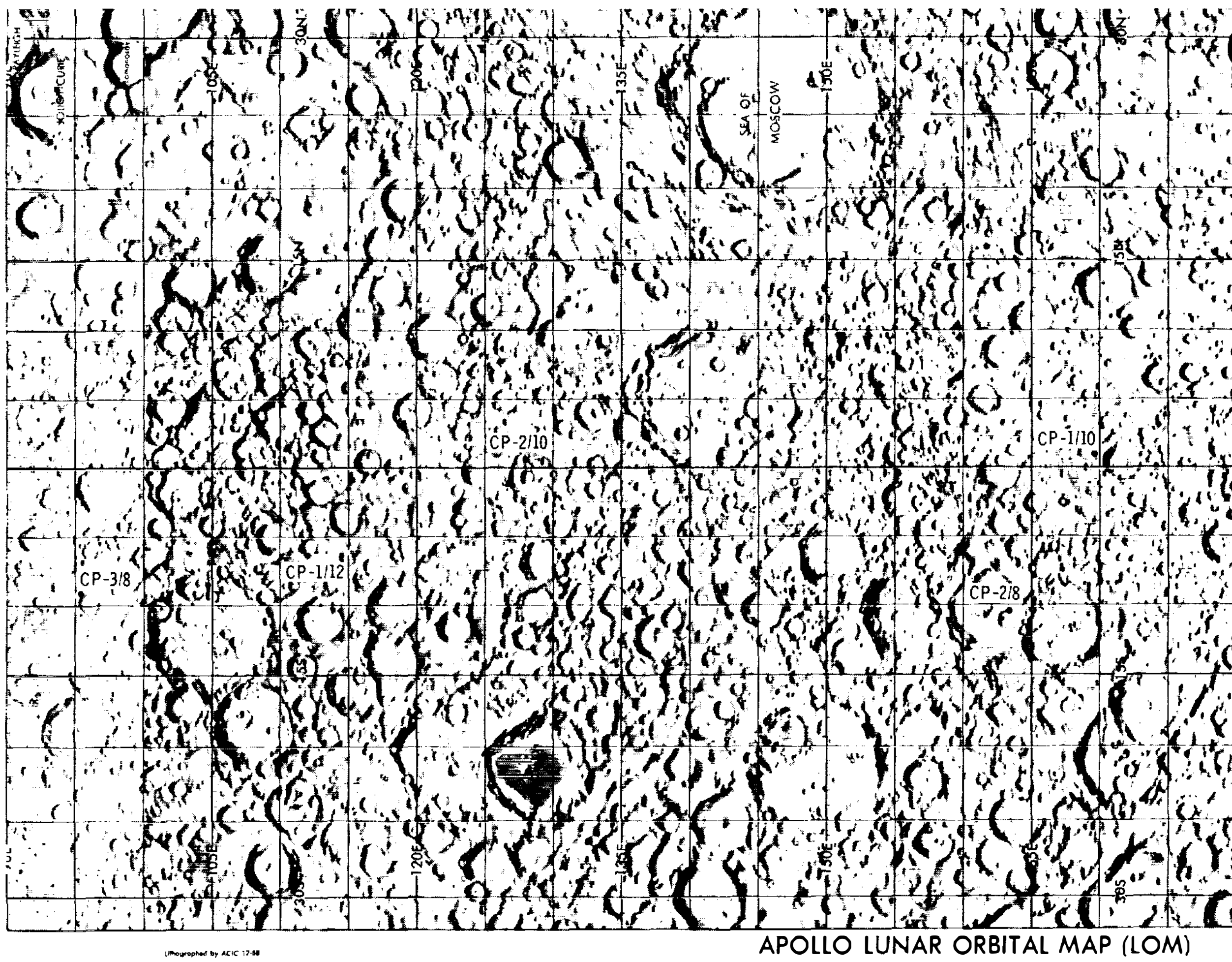
(b) 90° to 0° W.

Figure 1. - Continued.



(c) 0° to 90° E.

Figure 1. - Continued.



(d) 90° to 180° E.

Figure 1. - Concluded.

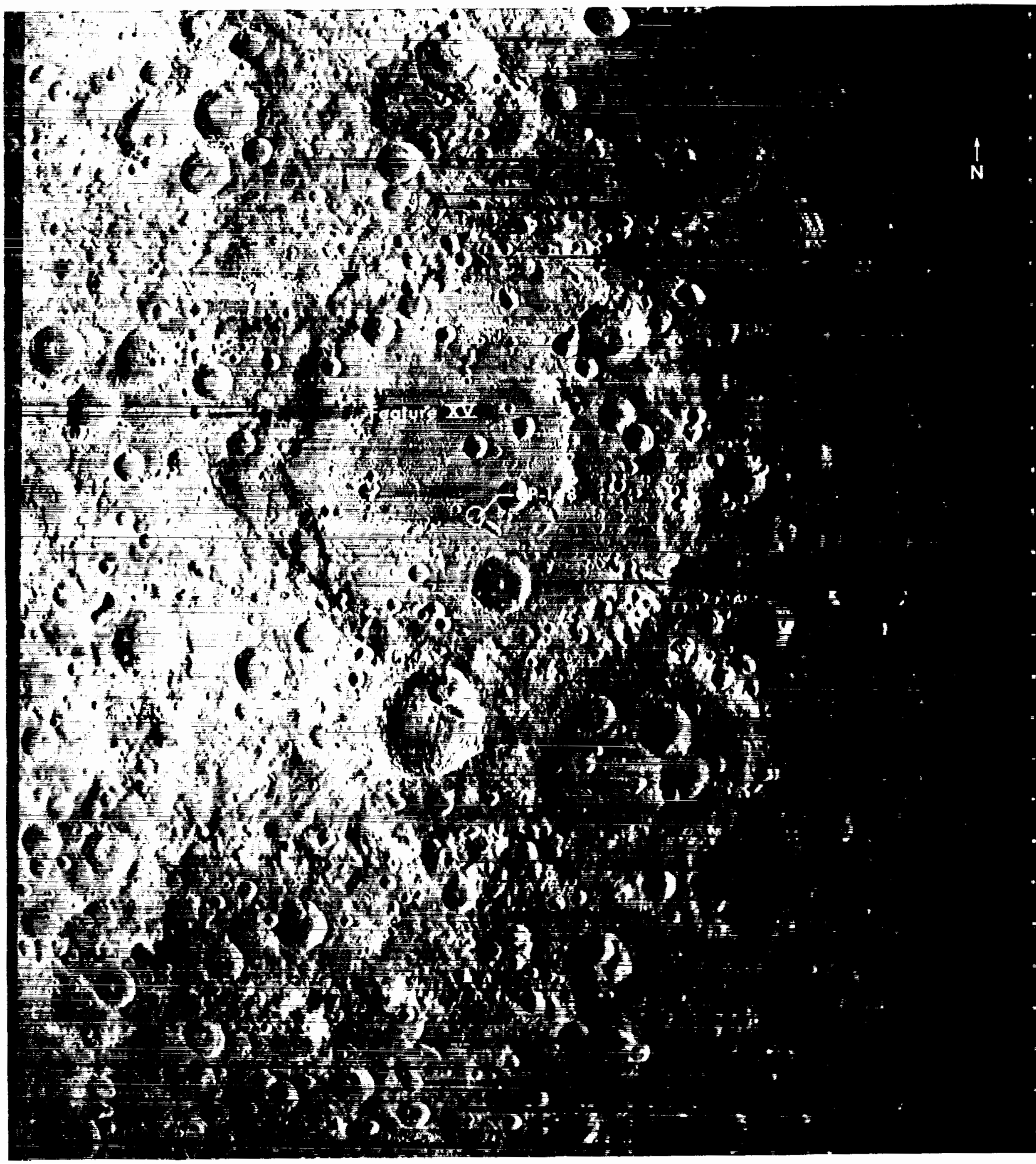


Figure 2. - Distant view of landmark CP-1/8 and IAU Feature XV.

Figure 3. - Closeup view of landmark CP-1/8.

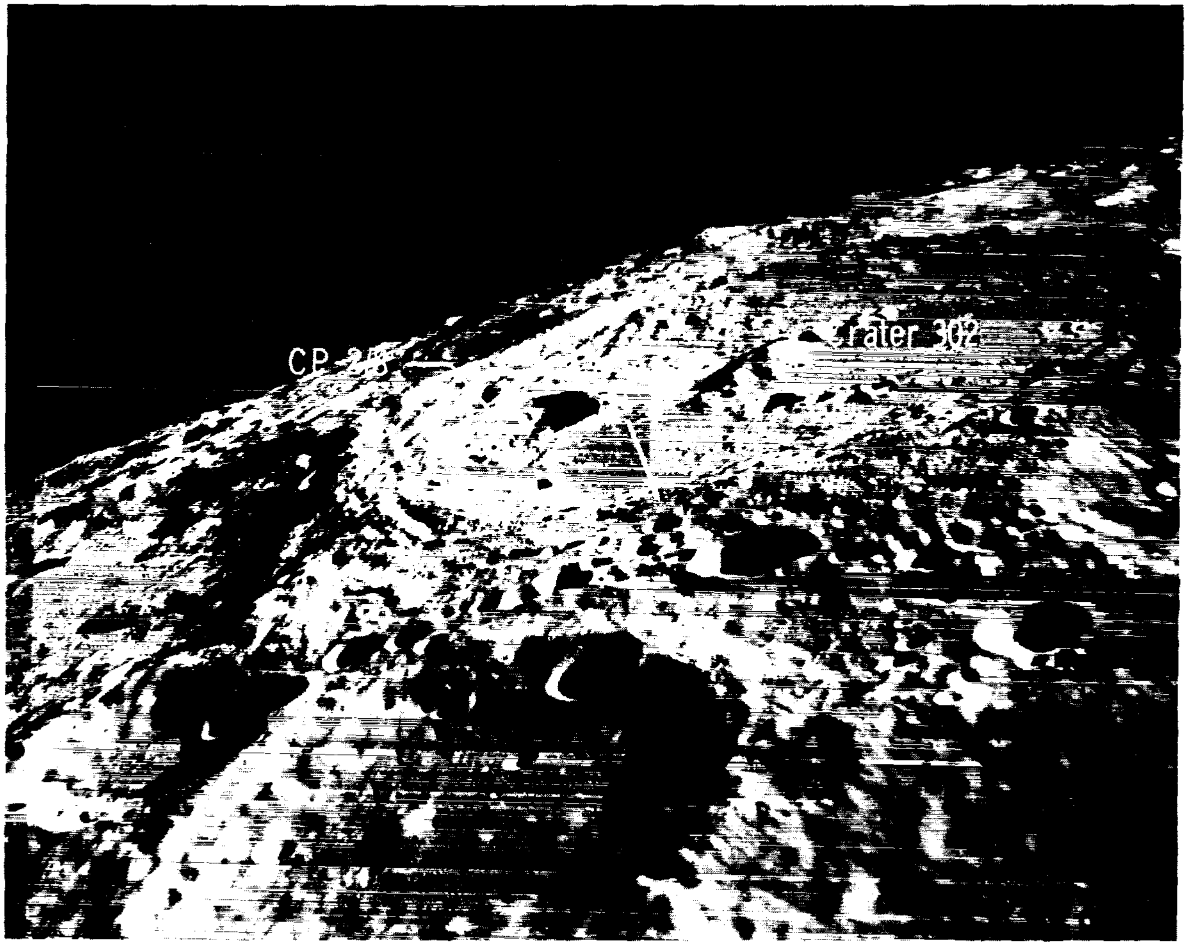


Figure 4. - Distant view of landmark CP-2/8 and IAU crater 302.

Figure 5. - Closeup view of landmark CP-2/8.

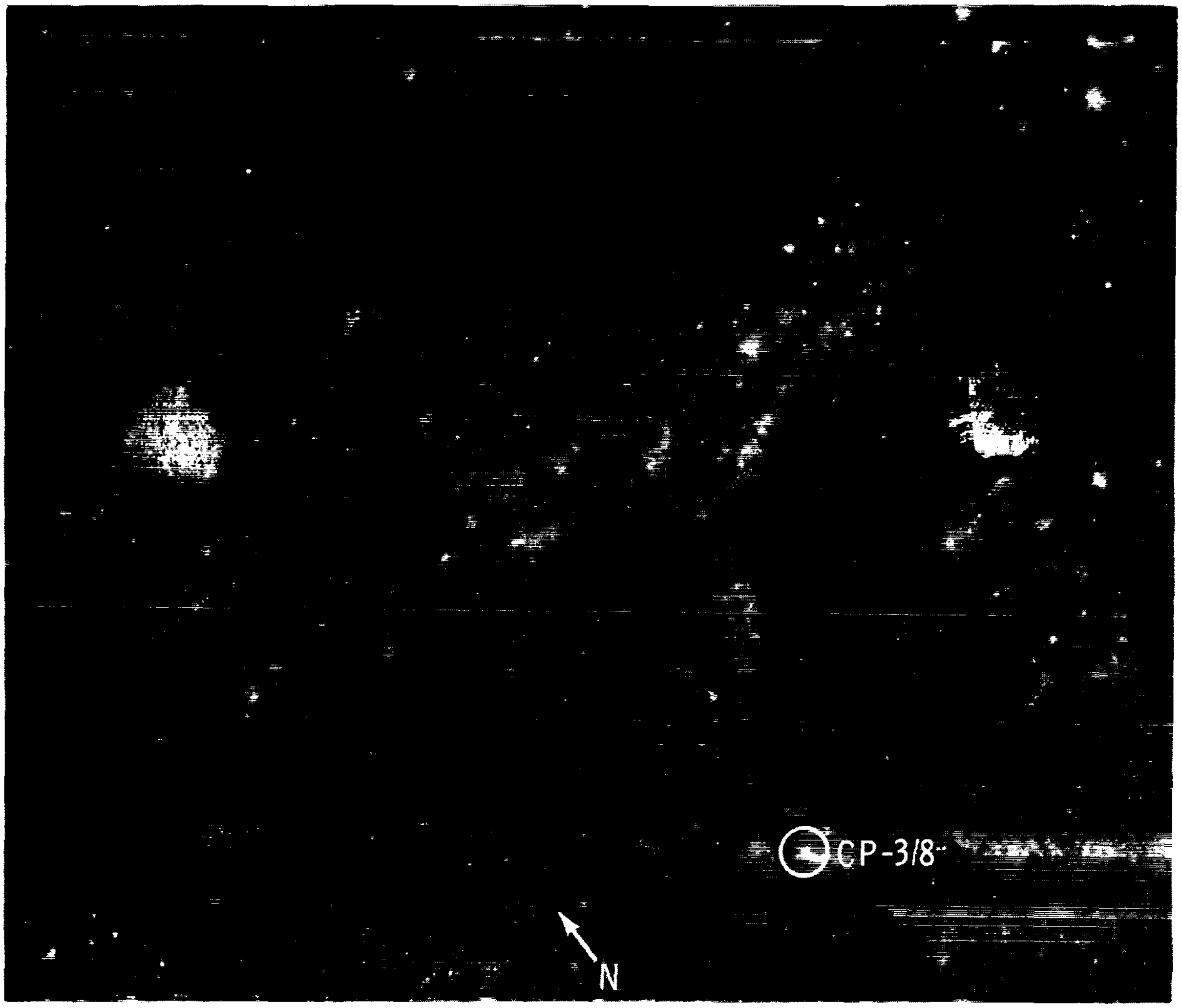


Figure 6. - Distant view of landmark CP-3/8.

Figure 7. - Distant view of landmarks B-1/8 and B-1'/10.

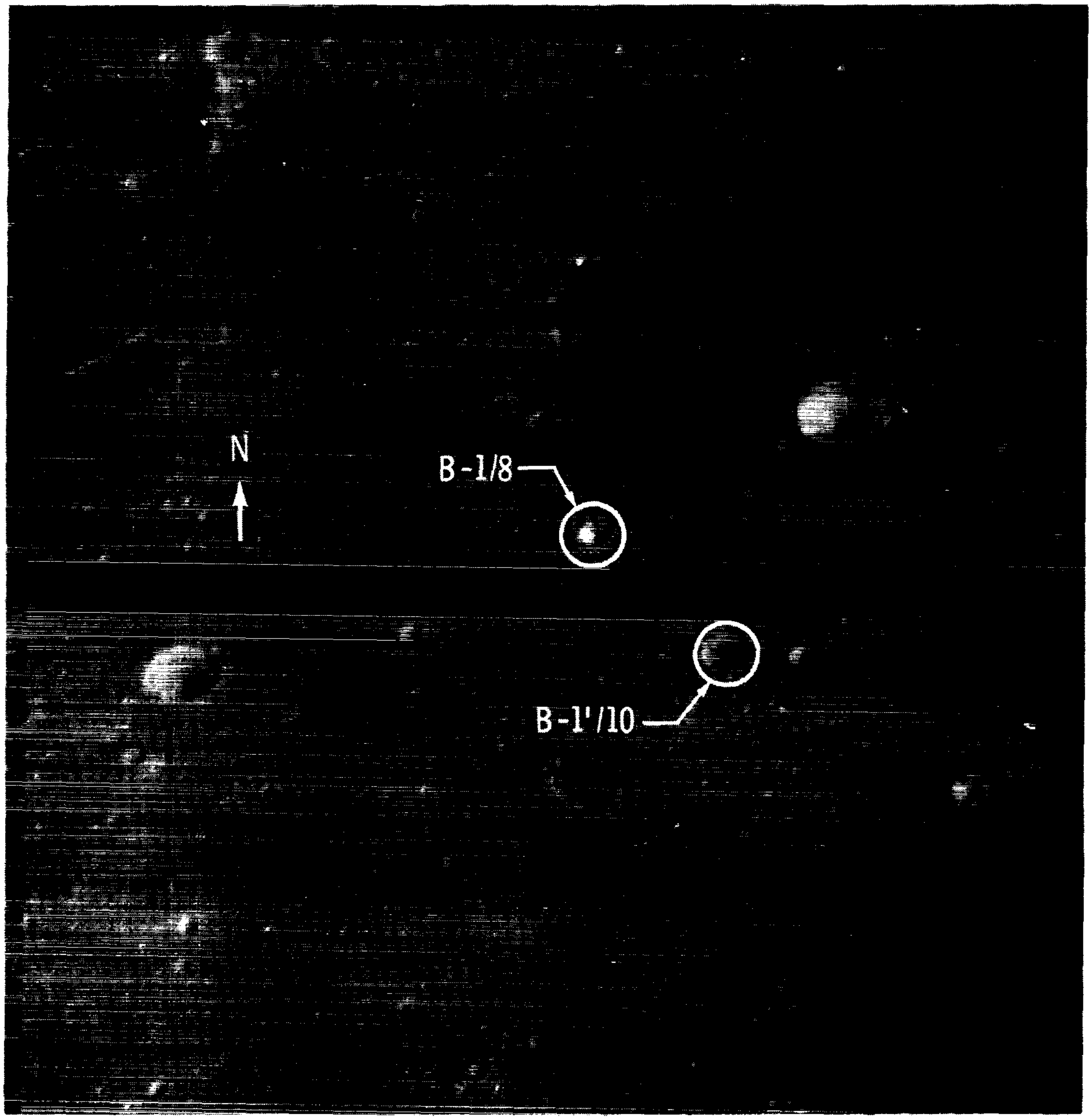


Figure 8. - Closeup view of landmarks B-1/8 and B-1'/10.

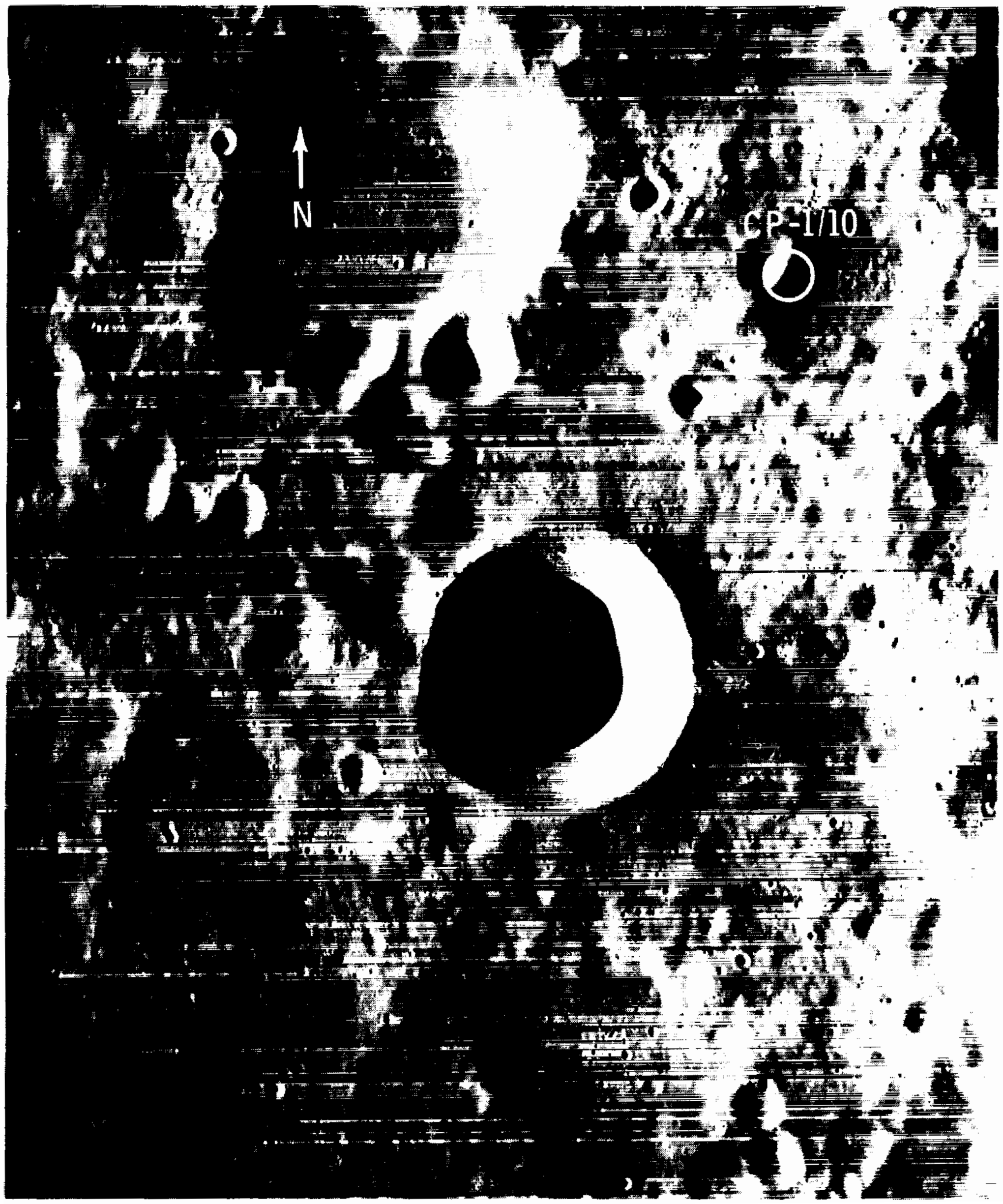


Figure 9. - Closeup view of landmark CP-1/10.

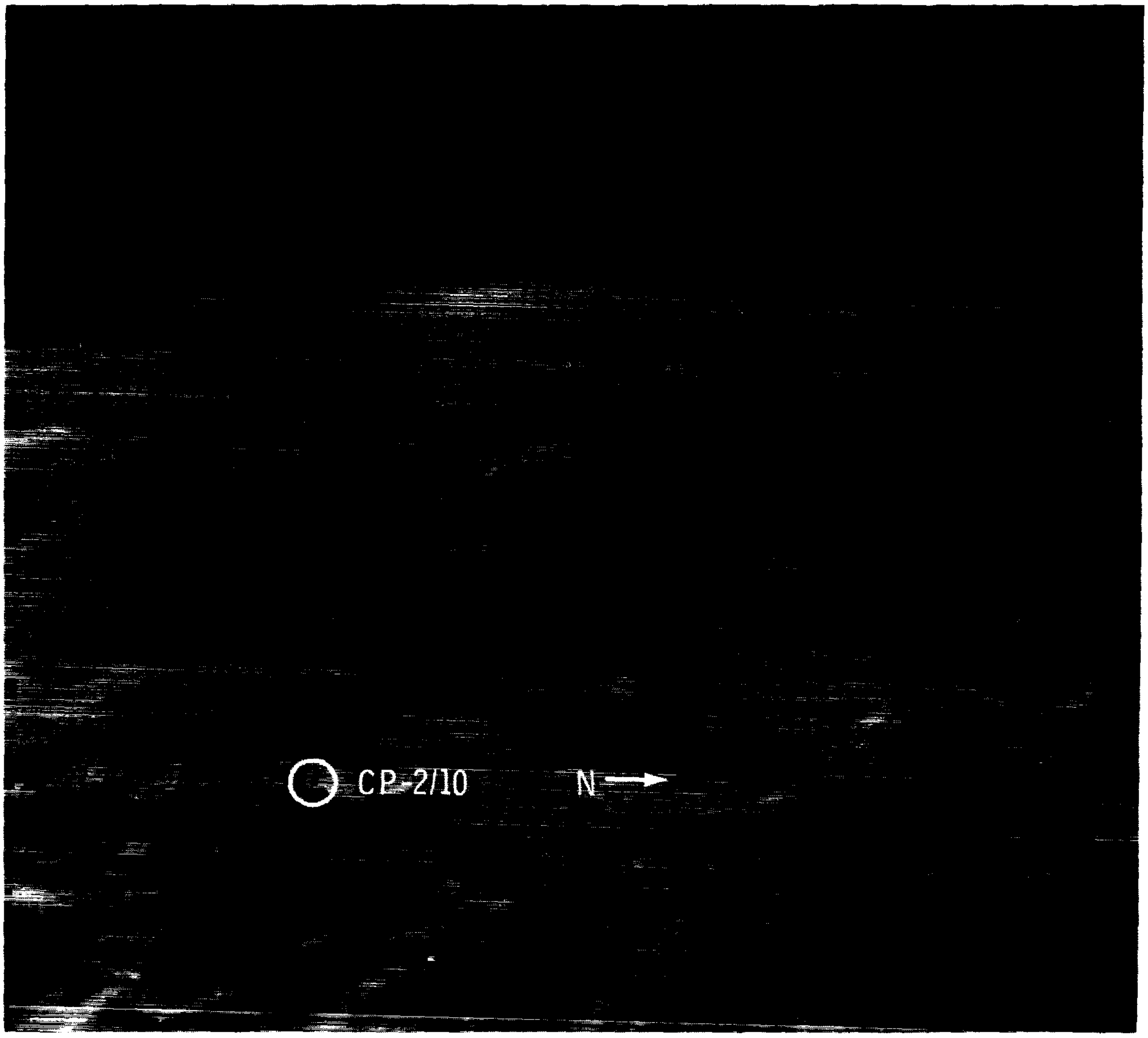


Figure 10. - Distant view of landmark CP-2/10.

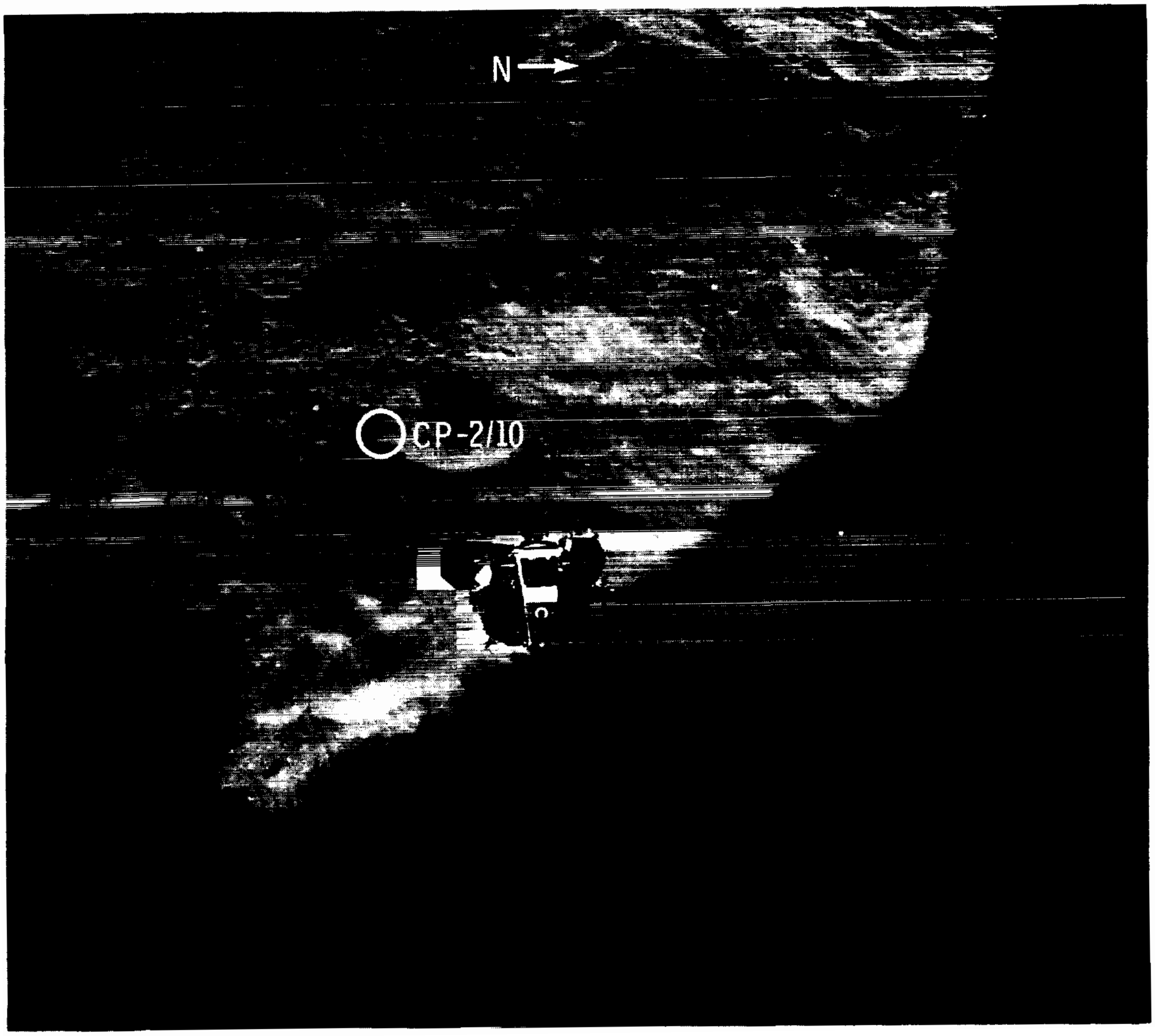


Figure 11. - Closeup view of landmark CP-2/10.

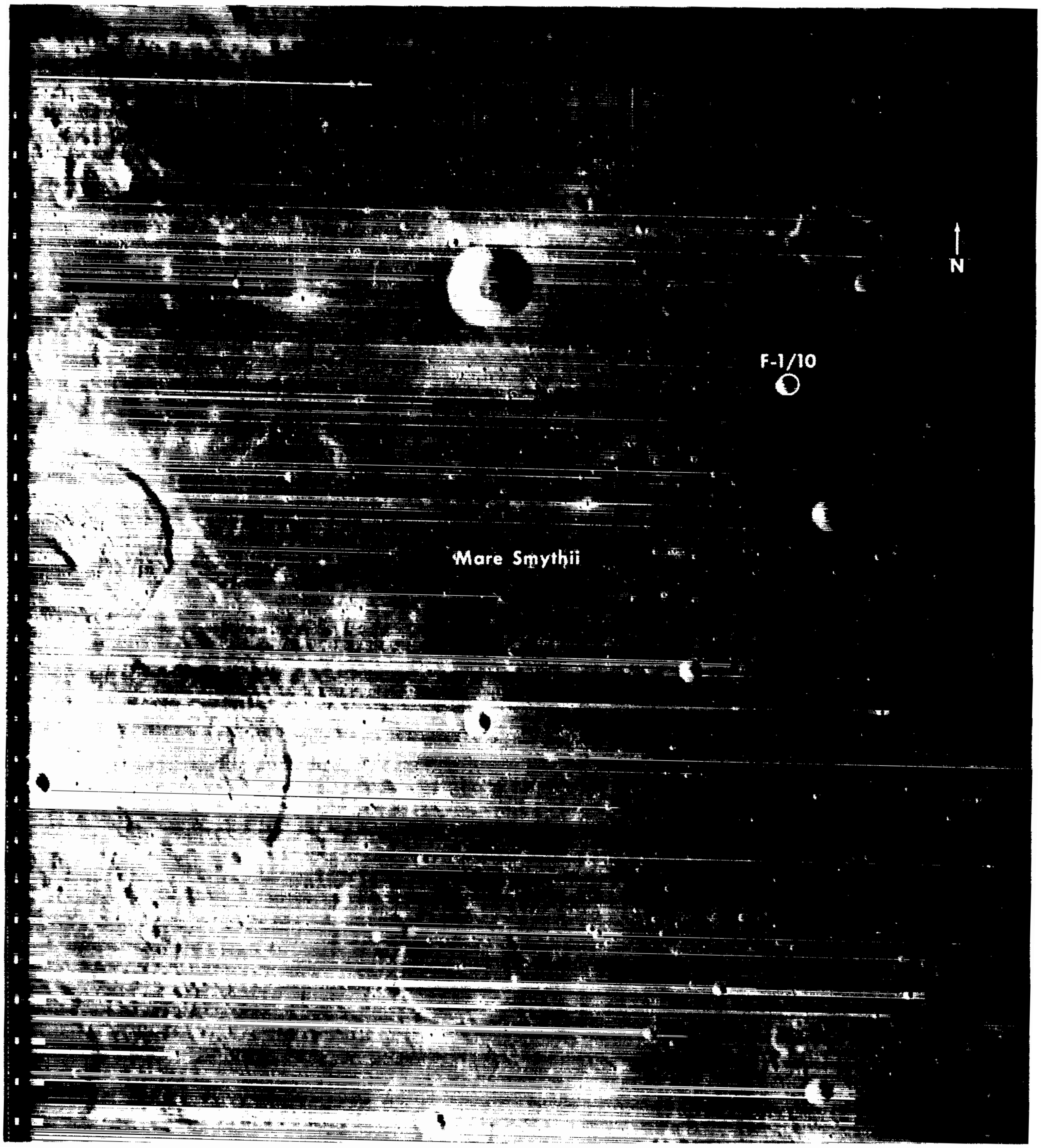


Figure 12. - Distant view of landmark F-1/10.

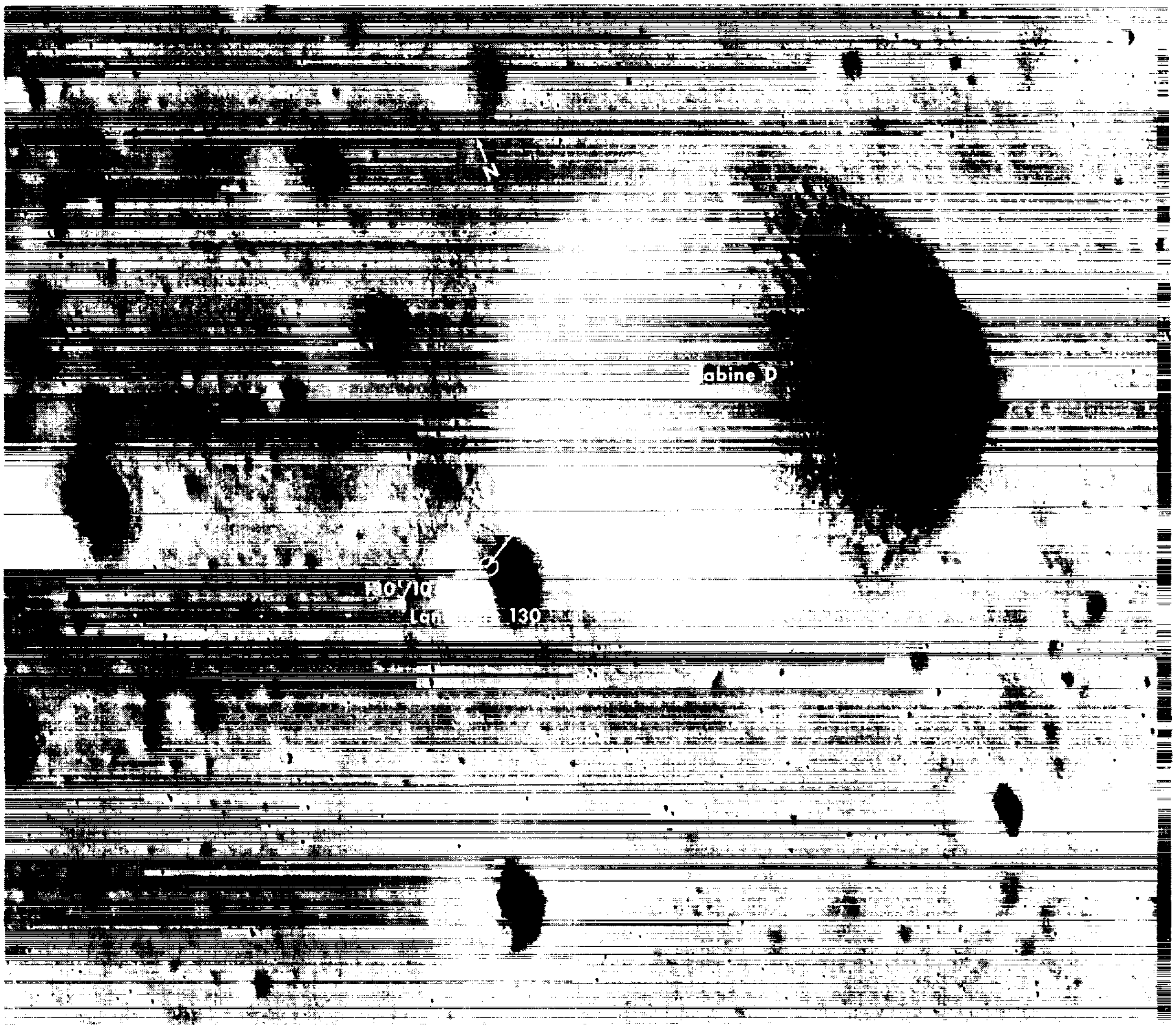


Figure 13. - Closeup view of landmarks 130'/10 and 130"/11 and Apollo landmark 130.

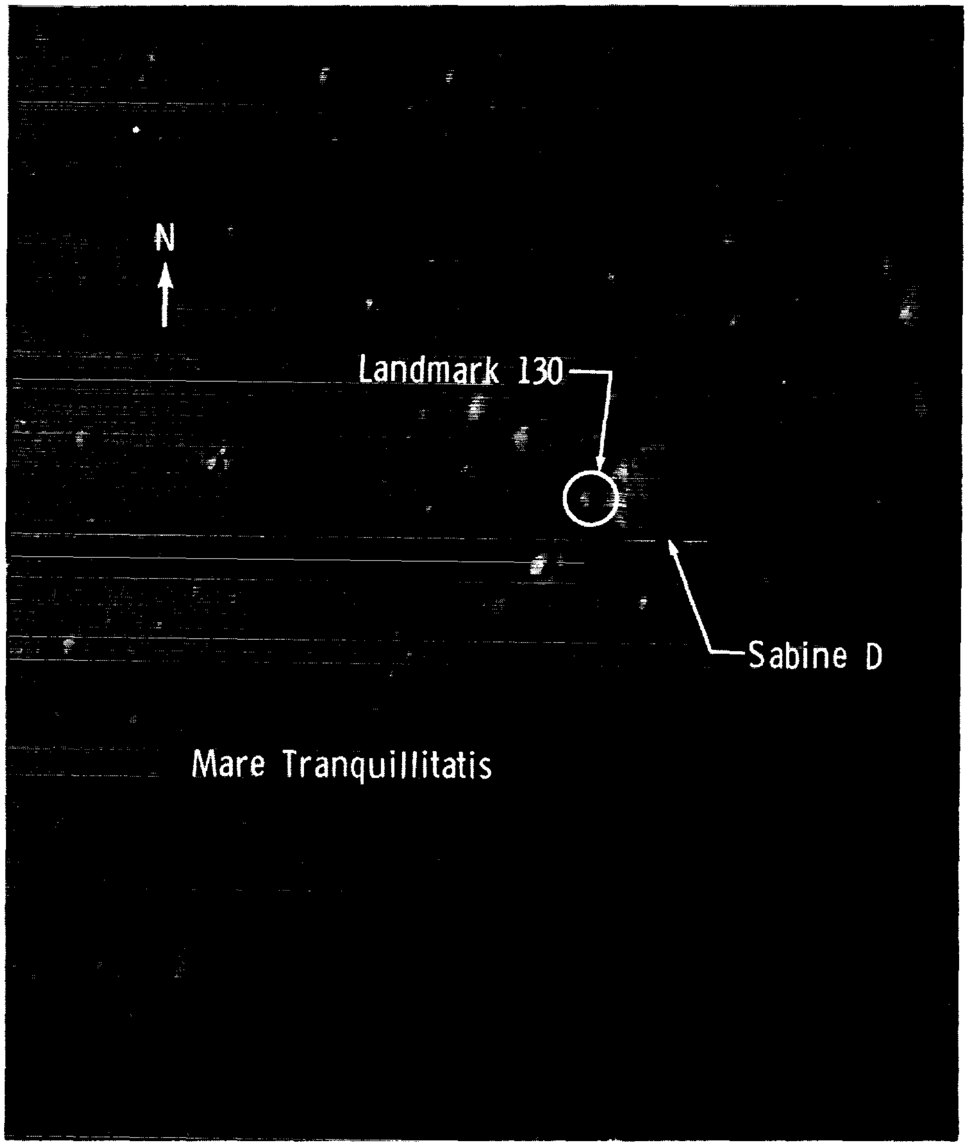


Figure 14. - Distant view of Apollo landmark 130.

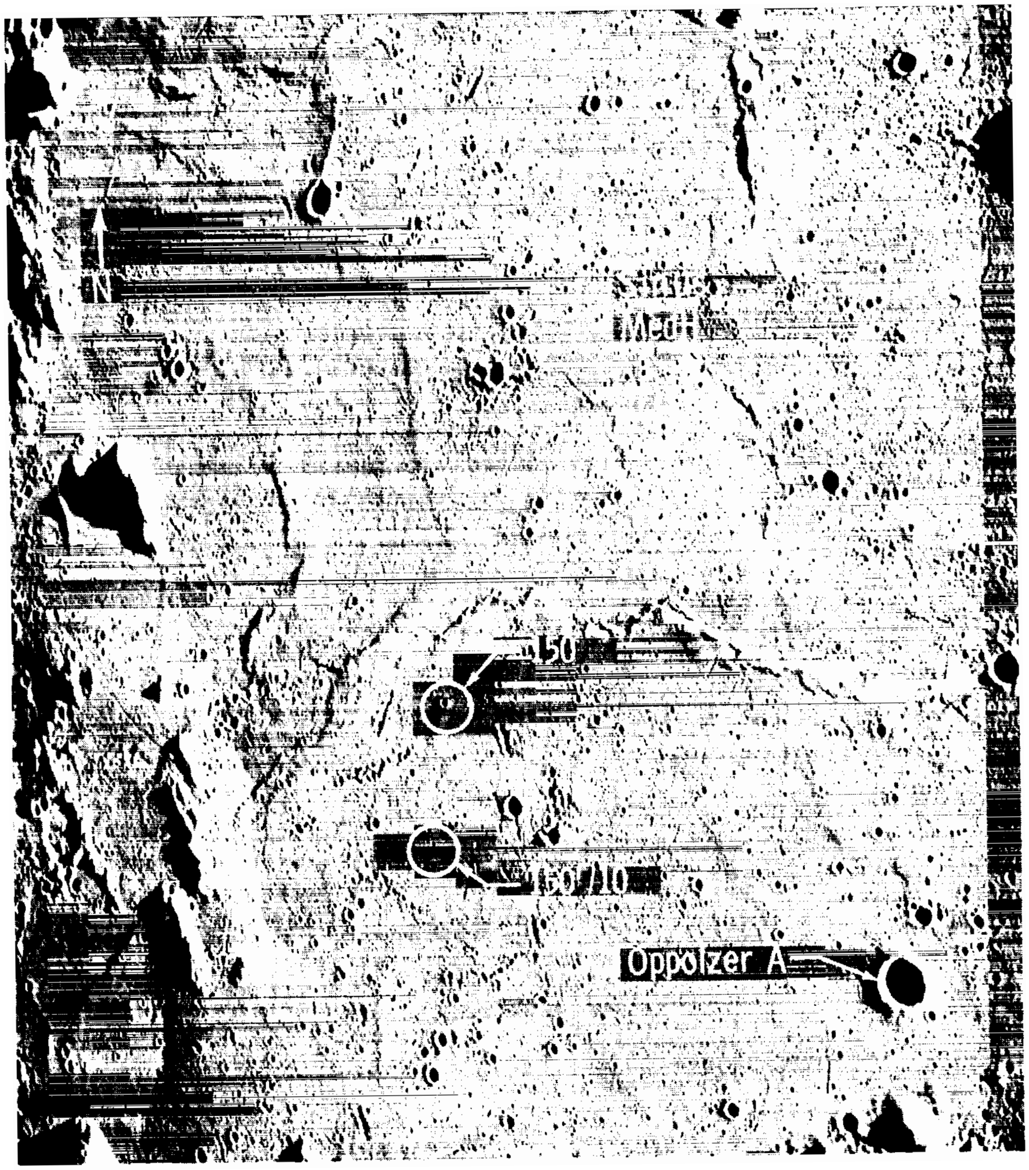


Figure 15. - Distant view of landmark 150'/10 and Apollo landmark 150.

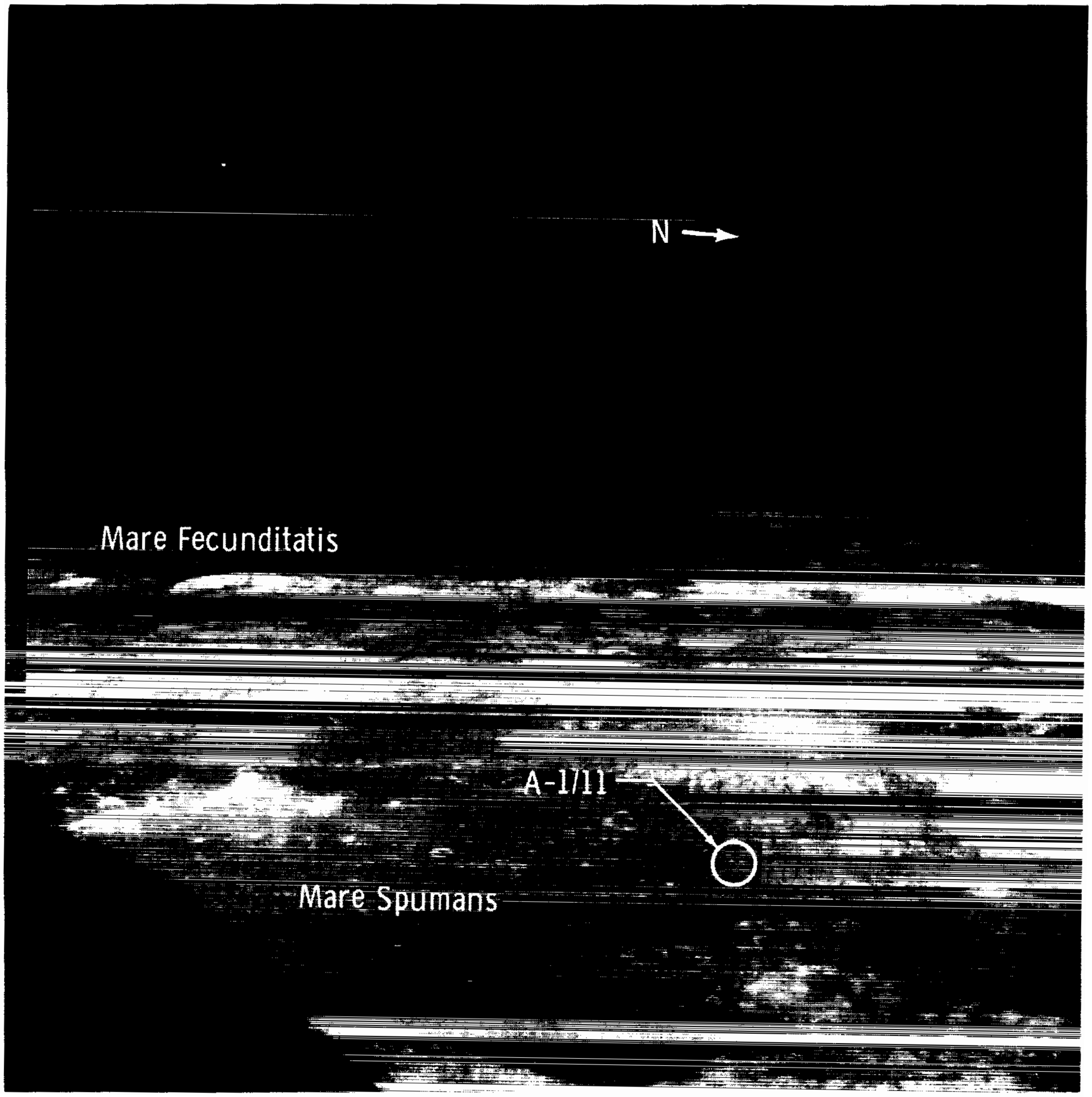


Figure 16. - Distant view of landmark A-1/11.

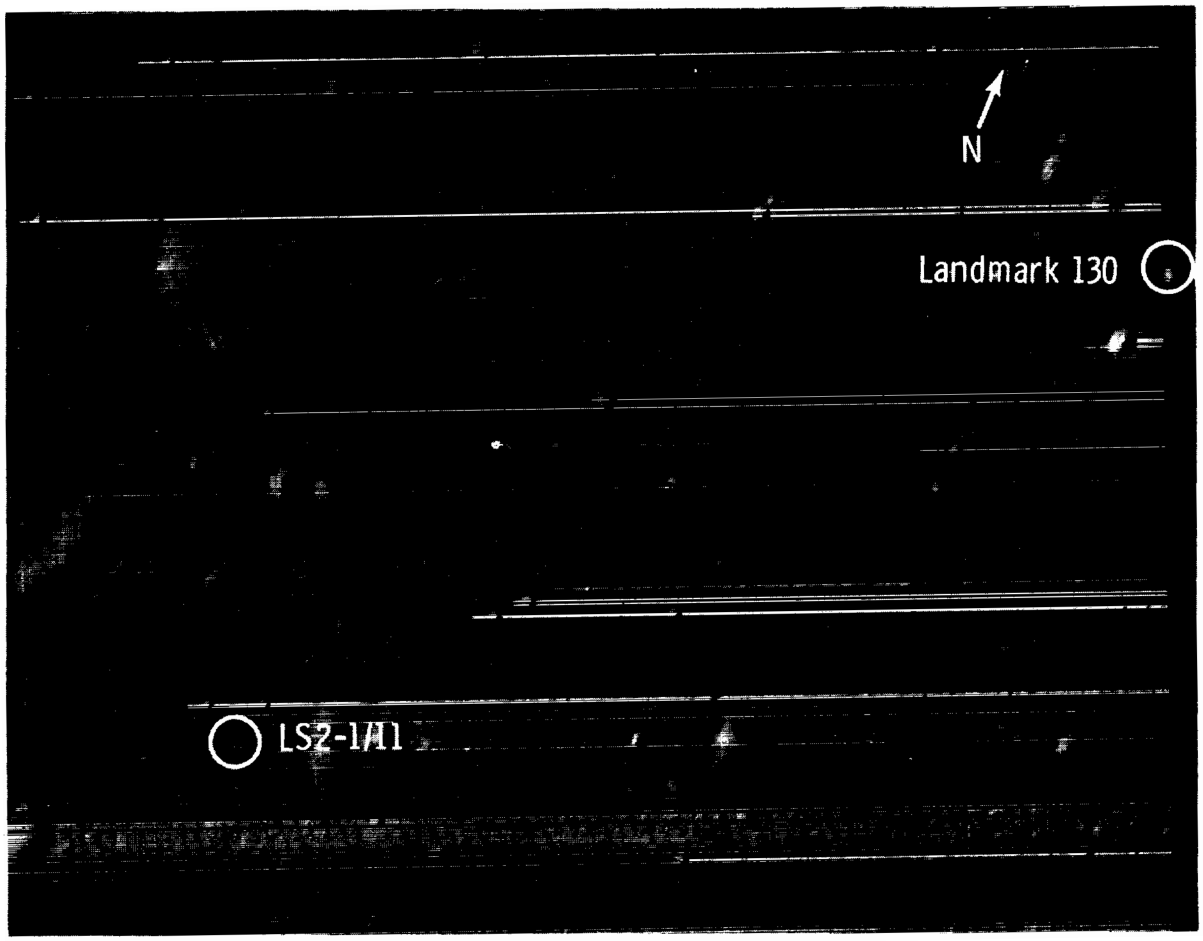


Figure 17. - Closeup view of western Mare Tranquillitatis, showing relative positions of landmarks 130 and LS2-1/11.

Figure 18. - Distant view of landmarks H-1/12 and FM-1/12.

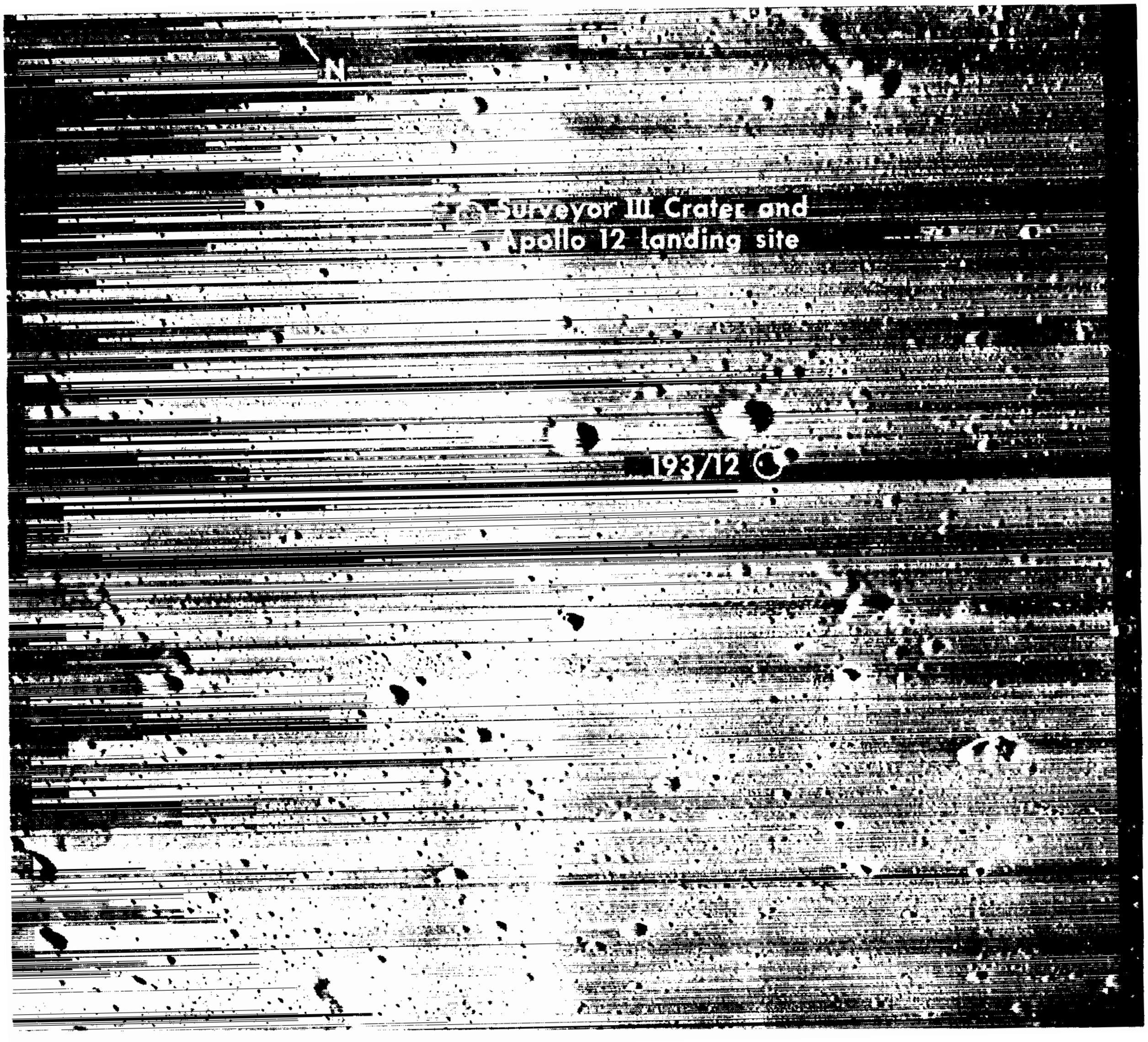


Figure 19. - Distant view of landmark 193/12 and the Surveyor III/Apollo 12 landing site.

Figure 20. - Closeup view of landmark CP-1/12.

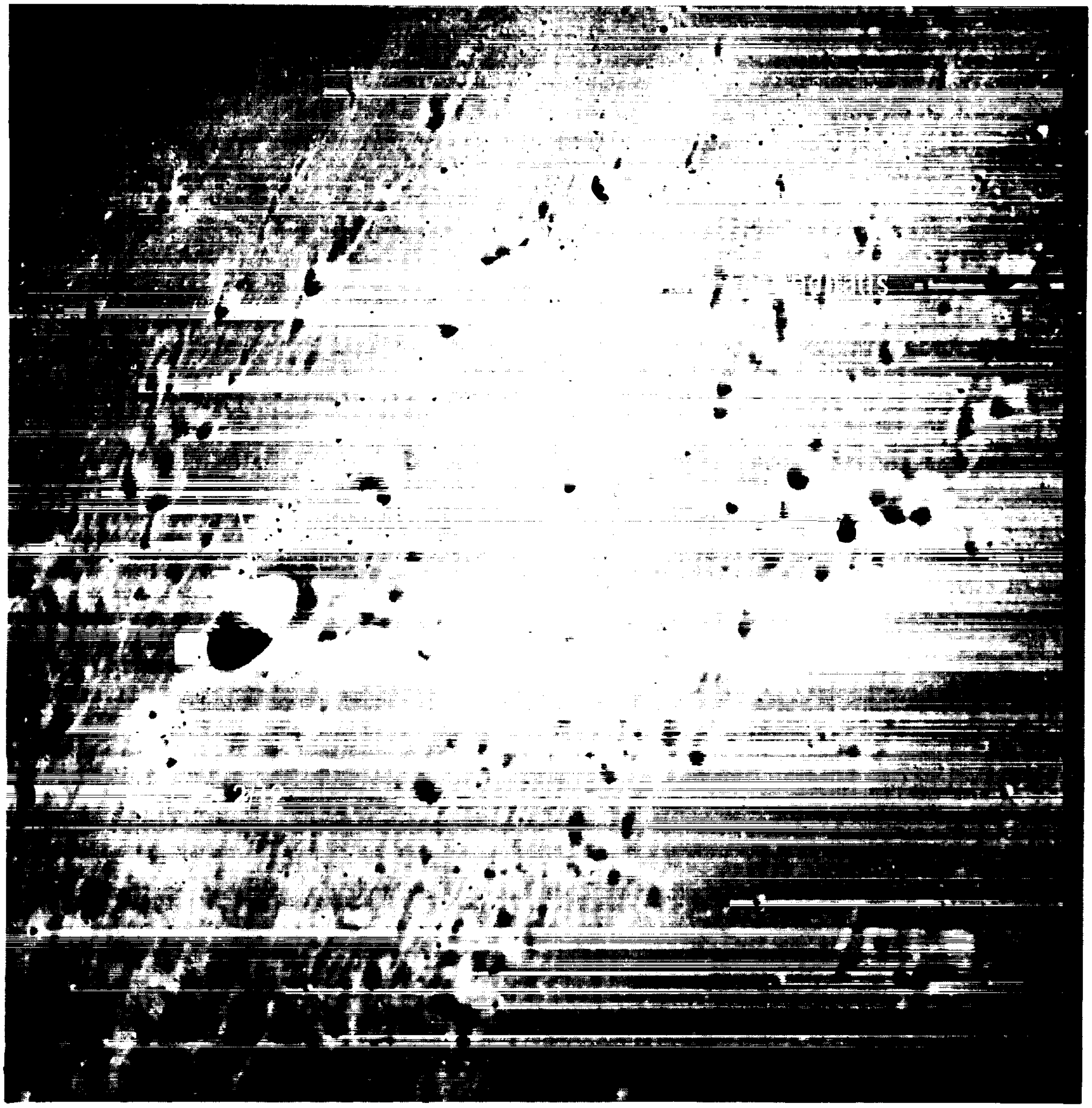


Figure 21. - Distant view of landmark CP-2/12.

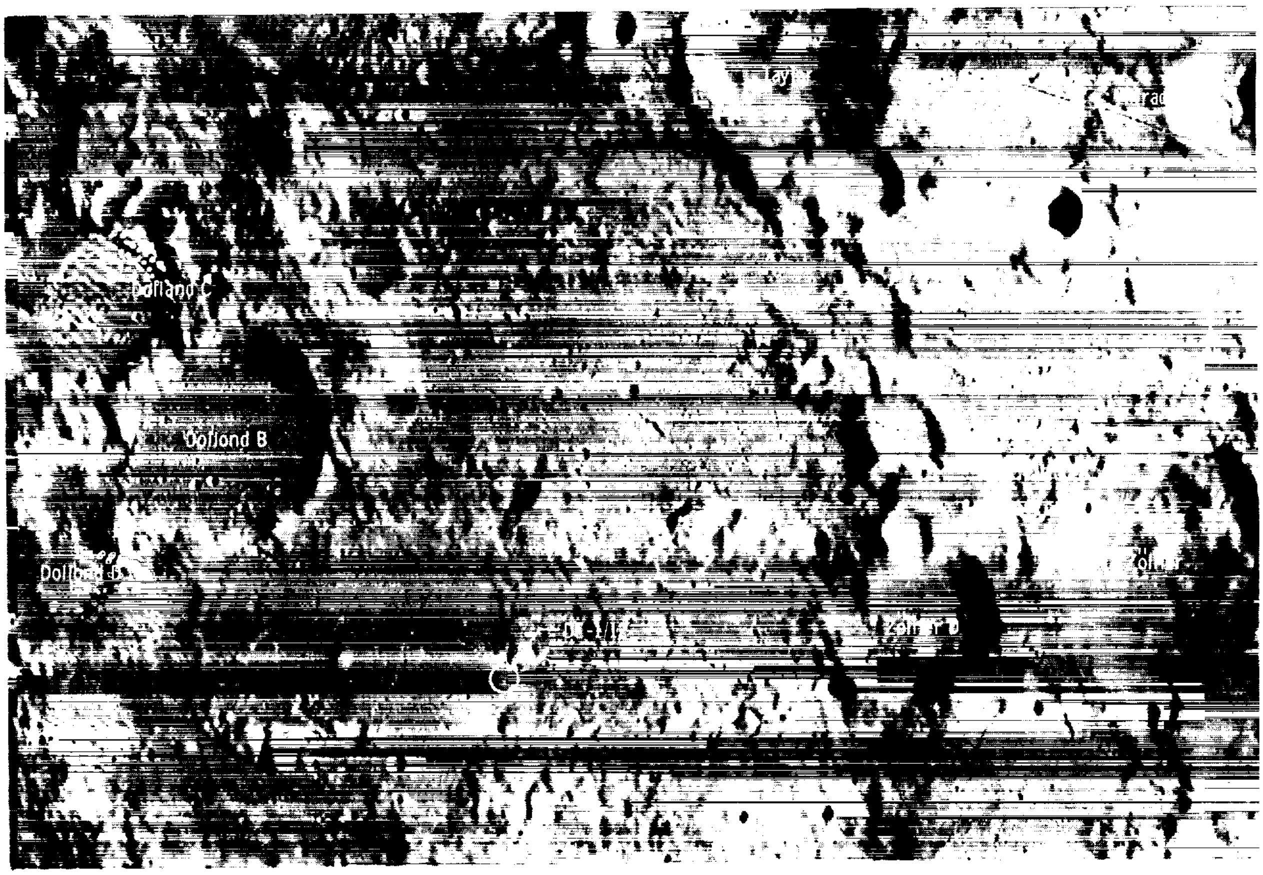


Figure 22. - Distant view of landmark DE-1/12.

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