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ENGINEERING PROBLEMS IN A LUNAR ENVIRONMENT

By

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ABSTRACT

The principal characteristics of the cislunar and lunar environments are identified, and the influences that such environmental parameters have upon engineering designs applicable to lunar operations are outlined. Basic astronomical data and some illustrations of typical lunar topography are also included.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

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1.0 INTRODUCTION

The moon is the earth's only natural satellite. Despite the fact that it has been observed for centuries, little fundamental information is available. This situation will persist until man or vehicle encounters the lunar surface and obtains firsthand information by experiment. However, it is possible, using the information presently available, and judiciously applying physical, chemical, and geophysical theory, to draw worthwhile conclusions regarding the relative importance and the general effects of the various features of the lunar environment.

Knowledge of the origin of the moon would answer many questions, in the fields of both geology and selenology. The actual origin of the moon is disputable, unfortunately, but there are three main hypotheses:

1. The earth and the moon were formed simultaneously from the same condensing cloud of cosmic gas;

2. The lunar material was spun off the elongated equatorial axis of a rapidly spinning earth at an early period in the coalescent stage of the earth's development.

3. The moon was "captured" by the earth on a close approach (Ref. 1).

The second hypothesis (Ref. 2) is quite attractive, as it offers a reasonable explanation for the close agreement between the specific gravity of the moon (3.34) and the specific gravity of the upper layer of the earth's mantle (3.32). Discovery of fundamental differences between the visible and non-visible surfaces of the moon (such as the size and density distribution of meteoritic craters or by finding a significant density variation between the two surfaces) would validate this hypothesis. The controversy may be resolved once a satellite is placed in a lunar orbit. For example, high-resolution film or television cameras could produce evidence of the size and density distribution of meteoric craters.

However, it is not the purpose of this report to establish the relative merits of the origin of the moon. The primary purpose of this report is to acquaint the engineer with some of the many problems involved in man's survival in the hostile environment involved on the lunar surface. It may prove of some value to briefly describe the physical

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characteristics and relationships of the moon and earth, the cislunar environments, and the lunar surface characteristics. This will be followed by a discussion of engineering and construction philosophies in a lunar environment.

2.0 ASTRONOMICAL DATA

For many centuries, astronomers have been observing the moon and gathering data about it. These data have been obtained through visual observations, photometric techniques, radio-telescopes, colorimetric analysis, etc. Much of the information accumulated by the astronomers prior to the "Sputnik" days was of pure academic interest. When the United States launched a program to land a manned vehicle on the lunar surface, it became apparent to the design engineer that detailed astronomical data must be made available. Consequently, extensive programs have been initiated during recent years to better define the astronomical parameters, planetary and interplanetary environments, and planet surface characteristics. Some of the physical properties of the moon-earth system are shown in Table 1.

Some of the more significant features presented in Table 1 reveal that the moon has a radius of about 1/4 that of the earth, a mass ratio of approximately 1/81 with respect to the earth and an average density of 3.34 grams cm^{-3}, which is quite similar to that of the earth's mantle. Perhaps the most important engineering feature is the low value of the lunar gravitational constant (5.15 ft sec^{-2}). In addition to the fact that objects on the moon's surface weigh only one sixth of their terrestrial weight, a major advantage is the increased payload capacity or, conversely, the decreased propulsive energy requirement of lunar-launched rockets. Another fact brought out in Table 1 is the relatively short spatial distance between the earth and the moon. Providing the hazardous environments can be resolved, sightseeing expeditions to the moon may some day become a reality.

For refresher purposes, Fig. 1 has been included. Figure 1 depicts the spatial relationships of the sun, the earth, and the moon.

The moon rotates about its axis with a period equal to the period of revolution about the earth - 27.32 earth days. However, the duration of a day/night cycle on the moon is slightly longer - 29.53 days, a fact apparent when Fig. 1 is studied carefully.

Its equator is inclined to the ecliptic 1-1/2 degrees in the direction opposite to the inclination of its orbit. Its rate of rotation is nearly constant in contrast to its rate of revolution, which varies according to Kepler's second law. As a consequence of these motions, we see the moon from a continuously varying angle, an effect called libration. Therefore, only about 59 percent of the moon's surface is visible over a one-year period (Ref. 7).

It becomes obvious why we must have orbiting lunar vehicles, such as the RANGER and ORBITER, to obtain data on the non-visible surface of the moon.

3.0 CISLUNAR ENVIRONMENTS

Cislunar environmental data, at best, are extremely limited and questionable. Numerous techniques such as utilizing orbiting satellites and space probes are presently gathering much needed environmental data to supplement the meager information available today.

The cislunar natural environments include such items as pressure and density, temperature, gas composition, electromagnetic radiations, particle radiations, meteoroids, and magnetic fields. Table 2 contains a summary of the cislunar environments.

Many significant events can result when encountering an environment as shown in Table 2. For example, in the pressure-density environment described, normal lubricants will vaporize, surface films will evaporate, metal-to-metal surfaces will "cold weld" together and atmospheric damping of vibrations will be non-existent. Consequently, for mechanisms to function properly, special precautionary measures must be designed into the equipments for lunar operation.

The lack of an atmosphere around the moon such as surrounds the earth has three additional major engineering effects:

a. The lunar surface is illuminated by the full intensity of the solar electromagnetic radiation. This intensity is 40 percent greater than that experienced at the surface of the earth. The ultraviolet segment of the spectrum is particularly important as this radiation will reach the lunar surface unattenuated, whereas on the earth the greater fraction is absorbed by the atmosphere. Ultraviolet radiation is especially harmful to organic compounds and special precautions are required to prevent retina burns in human eyes.

b. There is no shielding from the corpuscular solar plasma and solar flare high-energy radiation, nor from the extremely energetic primary cosmic ray particles. These particle radiations will have deleterious effects on living organisms, materials, and vehicle subsystems such as communications. Particle radiations may affect the properties of materials in many ways, such as chemical effects, phase transitions and the erosion of surfaces by sputtering.

c. The lunar surface is bombarded directly by meteoroids and cosmic dust particles of various sizes since the frictional forces needed to break and burn up even the smallest particles are non-existent.

Mention must also be made of the almost certain absence of a lunar magnetic field. The lack of a magnetic field permits the "solar wind" (the low-energy plasma stream from the sun) to come into direct contact with the lunar surface. In the case of the earth, the geomagnetic field acts to keep the solar wind a minimum distance of approximately four earth radii from the surface. Besides the very high surface radiation dosage this contact implies, the lunar surface, in the absence of ionizing photons, will acquire (Ref. 3) a negative charge. During daylight when the surface is exposed to the strongly photo-ionizing ultraviolet spectrum, the surface charge condition is more complex, since it may be positive, negative, or zero, depending upon the relative strengths of the plasma and the ultraviolet radiation.

4.0 LUNAR SURFACE CHARACTERISTICS

Information describing lunar surface characteristics varies from predictions of dust layers thick enough to envelop the lunar landing vehicle to dust or porous material of insignificant depth. An evaluation of the literature also brings forth the question: What is the origin and composition of the lunar surface material? Two theories have been produced: one implies that the lunar surface consists of slaglike matter created by the impact of meteoroids on the surface and the other theory supports volcanic eruptions as the source of matter which covers the lunar surface. It appears that each has merit and the lunar surface may be the result of both phenomena.

Astronomers have a good idea of the physical relief of the moon's visible face. Telescopic observations have revealed a multitude of cirques and craters, high plains called lunar seas or Maria, mountain ranges mostly on the edge of Maria extending many miles with altitudes exceeding 20,000 feet and separate highlands (Ref. 14). Figure 2 represents significant features which have been distinguished on the lunar surface.

Prominent features of lunar topography are shown in Figs. 2, 11, and 12; and more specific examples are as noted below (Ref. 15):

Craters - Copernicus and Kepler, Figs. 3 and 4

Lunar plains or circular Mare - Imbrium and Crisium, Figs. 5, 6, and 7

Mountains - Apennines and Alps, Figs. 8, 9, and 10

In general, the environmental conditions existing at the lunar surface are similar to those existing in cislunar space. Consequently, the environments included in Table 2 represent the hostile environments that must be overcome for man's survival on the lunar surface.

In concluding the discussion of the basic lunar environment, one factor that must be mentioned is surface temperature. The long day/night cycle of the moon (29.53 earth days) will affect the cycle of base activity and surface exploration. Surface temperatures will commence to rise rapidly at dawn in those areas exposed to direct sunlight, while shadowed areas will remain extremely cold. During the lunar day, the surface temperatures will depend upon the latitude and time. The daytime temperature rises steadily until local noon is reached. At the sub-solar point, the temperature reaches a maximum (Ref. 5) of approximately +130°C. As the terminator (day/night dividing line) is approached, the surface temperature falls steadily from the noon maximum to sub-zero values at the terminator. Shadowed areas, of course, will be much colder. Once the sun falls below the horizon, the temperature drops very rapidly to a value of approximately -150°C. A significant point of engineering interest is that the sub-surface equilibrium temperature at a depth of a few meters is about -23°C, and is independent of the lunar phase.

5.0 ENGINEERING AND CONSTRUCTION

In the evaluation of the available data pertaining to the cislunar environments and lunar surface characteristics, it soon becomes apparent that supplemental information is required. Fortunately, some of our nation's space programs, such as the RANGER and SURVEYOR, have been initiated to provide this additional scientific information.

One of our major efforts for the next few years will be the selection of the lunar landing site. Programs, such as mentioned above, are under way to resolve the lunar surface features. It is imperative that such things as surface bearing properties, surface roughness or protuberances, and dust conditions be well established prior to attempting a manned landing on the moon.

Upon arrival of the space vehicle carrying man and equipment to the lunar surface, the difficulties of sustaining life in the hostile environment becomes a reality. To discuss engineering and construction techniques with the meager data available to the engineer today would be somewhat facetious. However, to expound on a few philosophies might be of interest.

It can certainly be assumed that the initial manned flights to the moon will involve complete systems capable of survival independent of lunar resources. However, from the economy standpoint, it will be necessary in the future to plan lunar base operation. As J. W. Salisbury indicates (Ref. 16), lunar resources will play a primary role in establishing lunar bases by providing life support materials and vehicle fuels.

It has been conjectured that the moon consists of silicate material similar to the rocks constituting the outer part of the earth's mantle. Its most abundant elements are, according to Urey (Ref. 17), O, Si, Mg, and Fe; followed by S, Al, Ca, Na, Ni, and Cr in approximately that order. The primary lunar resource needed for survival and habitation of the moon is water. There are many who speculate that water in the solid state may be discovered in some of the permanently shaded areas in craters near the poles or beneath the lunar surface. If water can be obtained, it can be electrolyzed into hydrogen and oxygen. These in turn can be liquefied for use as rocket propellants or fuel cell loadings. Instead of attempting to hypothesize on the entire lunar base colonization, it might be more appropriate to restrict discussion in this report to several of the more important survival components:

Power

Life Support System

Protective Shelter

5.1 POWER

Without inexhaustible power available, colonization of the moon will be extremely difficult. Base power requirements lie in the range of 1-10 kw per man (Ref. 18) at a minimum. Of all possible sources only nuclear power units appear feasible. Solar cells, widely used on satellites and space vehicles today, and other solar-powered devices such as thermopiles and furnaces, have inherent limitations. They do not produce power during the long lunar night and even their power output during the lunar day is limited by the zenith angle effect, unless the complications of servo-driven sun-tracking arrays and collectors are introduced.

The nuclear plant must be transportable, capable of being "soft" landed on the moon, and be easily assembled with a minimum of special tools. Unprecedented reliability is essential.

5.2 LIFE SUPPORT SYSTEMS

The life support system is an integral part of every operation on the moon, be it exploring on the surface, unloading cargo rockets, or building the base itself. The life support system comprises many subsystems; the ecological subsystem retrieves the oxygen from the exhaled carbon dioxide; a monitoring subsystem samples the atmosphere to detect toxic or noxious gases; a pressure-regulating subsystem maintains cabin pressure at a preset value, and makes up air losses occurring through leakage and the use of the air locks; yet another subsystem processes or destroys body, kitchen, and laundry wastes.

The ecological subsystem is the heart of the life support system. Chemical regeneratives have weight and reliability advantages in systems designed for personal use or short duration, while larger systems could be supplied from the oxygen produced as the by-product of the hydrogen-oxygen fuel cell. In the case of very large bases, photosynthetic processes using algae or plants offer a more economical approach. In addition, as leakage from buildings and air locks is appreciable, the larger bases will require the means to process lunar minerals (Ref. 19) to obtain their water and oxygen content.

5.3 PROTECTIVE SHELTER

The engineer responsible for designing moon-base facilities must take into account the following restrictions:

a. A man's ability to move about and to use tools is severely limited if he is encased in a space suit.

b. Mechanical equipment can be used on the surface only if it has been specially designed to combat the vacuum, the penetrating radiation, and the temperature extremes.

c. Above-ground structures and equipment must be protected against meteoroid impact and the penetrating radiations.

d. All structures, above and below ground, must be as leaktight as possible.

Buildings at primitive, early bases probably will utilize modified, used vehicle shells covered with lunar rubble for protection against meteoroids and corpuscular radiation. Later, natural caves could be sealed and pressurized, thus solving the problems of drilling and mining rock under vacuum conditions. At larger bases, buildings would be constructed either in trenches, with the excavated soil being replaced over the pressure shells, or underground in cavities formed by explosives which fracture and pulverize the rock (Ref. 20).

Although no data are now available on the frequency and severity of moon quakes (which could be caused by subterranean shifting or the shock of meteoroid impact), the RANGER and SURVEYOR programs should obtain some of this information within the next few years.

6.0 CONCLUSIONS

This report has attempted to create an appreciation of the inter-disciplinary effort required to establish a viable moon base. Engineers should be aware that much technical information already available from research conducted to support satellite and space vehicle programs and ground-based space environmental facilities can be applied in the design of items intended for lunar use. For example, at Arnold Engineering Development Center, research has been carried out to develop special lubrication techniques for machinery that must be operated inside a space environmental chamber. Another contract assessed the various limitations of space suits and evaluated the functional capability of a man in a space suit and in a self-contained capsule. Similar programs are underway at other Centers. For example, radiation damage to humans and materials, caused by van Allen radiation, cosmic radiation, and solar storm protons, is being actively explored.

The first challenge facing the engineer responsible for designing items for a lunar colony is the need to adapt equipment and techniques to the hostile lunar environment. The second challenge is that, in addition, as every facet of twentieth century science and technology must be transplanted to the moon and as the colonists cannot be expected to know intimately the ramifications of every discipline, the engineer must incorporate the highest possible reliability and the necessary maintainability into every stage of the design and development of all equipments.

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TABLE 1

Summary of Astronomical Data

QUANTITY	MOON DATA Value	EARTH DATA Value	MOON/EARTH	REF.
Mass	8.1×10^{19} tons	658.6×10^{19} tons	0.0123	3
Volume	5.2×10^{9} mile^{3}	259.9×10^{9} mile^{3}	0.02	3
Specific Gravity	3.34	5.5 (Bulk Value) 3.32 (Mantle Value)	0.606 1.01	3,4 3,4
Equatorial Radius	1080 mile	3960 mile	0.27	3
Surface Gravitation Acceleration	5.15 ft sec^{-2}	32.17 ft sec^{-2}	0.16	3
Escape Velocity	1.5 mile sec^{-1}	6.86 mile sec^{-1}	0.22	3
Surface Orbital Velocity	5420 ft sec^{-1}	25,940 ft sec^{-1}	0.21	-
Mean Distance from Sun	93.0×10^{6} mile	93.0×10^{6} mile	1.0	3
Mean Distance from Earth	238,840 mile	-	-	-
Linear Orbital Velocity	0.64 mile sec^{-1}	18.52 mile sec^{-1}	0.03	5,6
Orbital Period	27.32 earth day (sidereal time) 29.53 earth day (synodic time)	365.27 day	-	3,6
Rotational Angular Velocity	2.66×10^{-6} radians sec^{-1}	7.32×10^{-5} radians sec^{-1}	0.036	-
Inclination of Body's Equator to Ecliptic Plane	1° 35'	23° 26'	-	3,6
Inclination of Orbital Plane to Earth's Equator	18° 19' to 28° 35'	23° 26'	-	5
Inclination of Orbital Plane to Ecliptic Plane	5° 9'	0°	-	5

TABLE 2

Summary of Cislunar Environments

QUANTITY	VALUE	QUALIFYING REMARKS	REF.
Surface Pressure	10^{-10} - 10^{-12} torr	Optical and radio astronomical observations	10
Surface Density	3×10^{4} - 3×10^{6} molecules cm^{-3}	-	-
Surface Temperature	+130°C -153°C	Maximum - sub-solar point Minimum - pre-dawn	10
Radiations			
Solar Radiation	1396 watt m^{-2}	Complete spectrum received	9
Solar Illumination	13,000 ft candles	40% greater than at earth's surface	9
Lunar Albedo	0.07	Average over disc.	8
Cosmic Ray Dosage	0.65 rem wk^{-1}	Dosage influenced by shielding thickness	-
Solar Plasma Cloud Dosage	10^{3} - 10^{6} rad hr^{-1}	Surface effects only	13
Solar Storm Dosage	100 rem $flare^{-1}$	Typical time-integrated dose	8
Solar "Wind" Flux	10^{8} - 10^{9} protons cm^{-2} sec^{-1}	Sputtering of 3 Å yr^{-1}	12
Lunar Crust Rad.	2.7m rem wk^{-1}	Induced and natural radioactivity	8
Meteoroids			
Flux	$>4 \times 10^{-4}$ m^{-2} sec^{-1} $<4 \times 10^{-5}$ m^{-2} sec^{-1}	Mass <0.001 gm Mass >0.25 gm	12
Density	0.05 gm cm^{-3} 3.0 to 3.5 gm cm^{-3} 7.0 to 8.0 gm cm^{-3}	Spongy type Spongy type Iron-Nickel type	12
Velocity	15 km sec^{-1} 28 km sec^{-1} 60 km sec^{-1}	Mass <0.001 gm Mass >0.25 gm For retrograde orbit	12
Magnetic Field	<100 gamma	Lunik III measurement	11

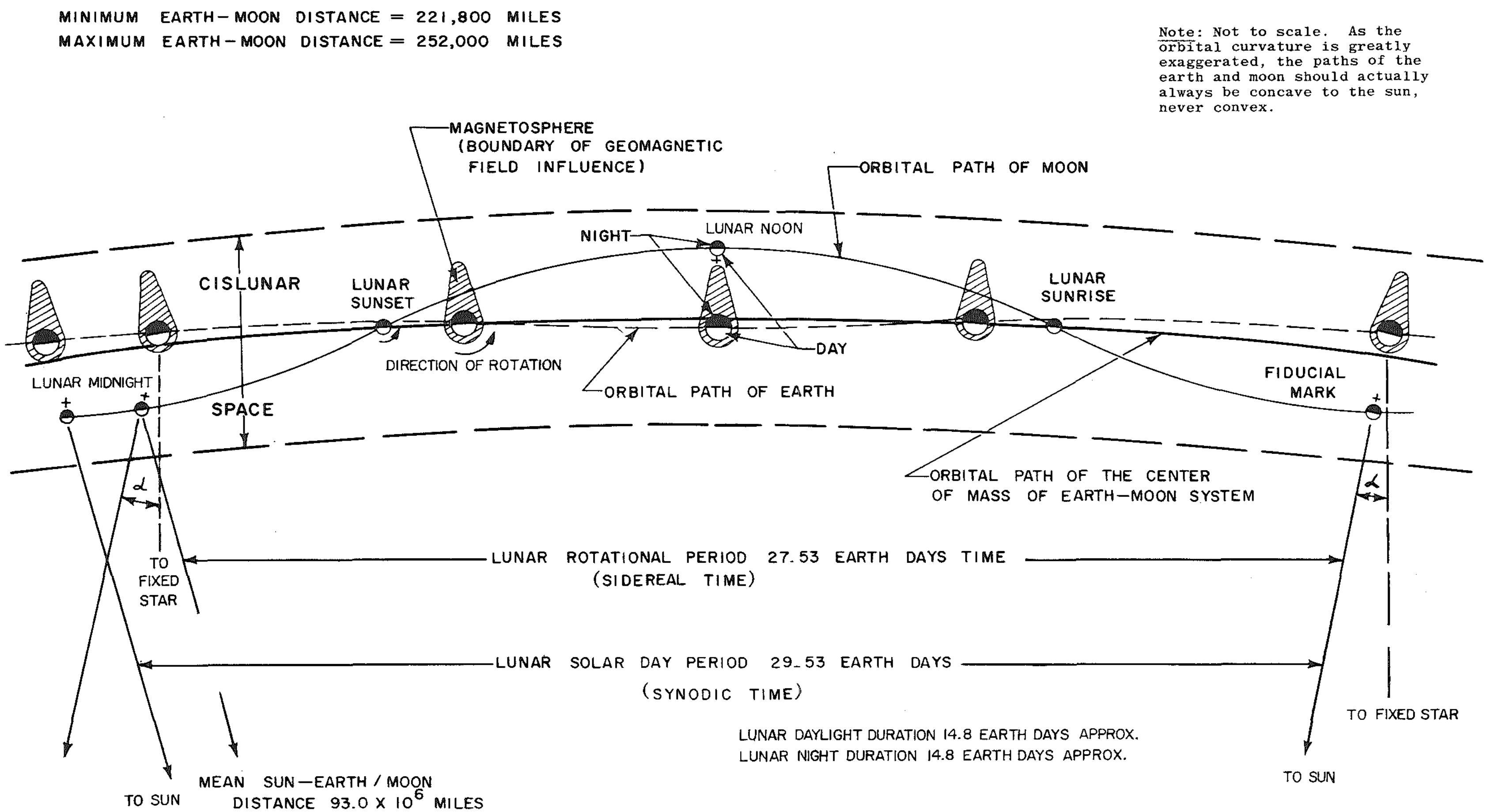


Fig. 1 Earth-Moon-Sun System

(North is down. Photograph from AF Lunar Atlas)

Fig. 2 Composite Photograph of Full Moon (Ref. 15)

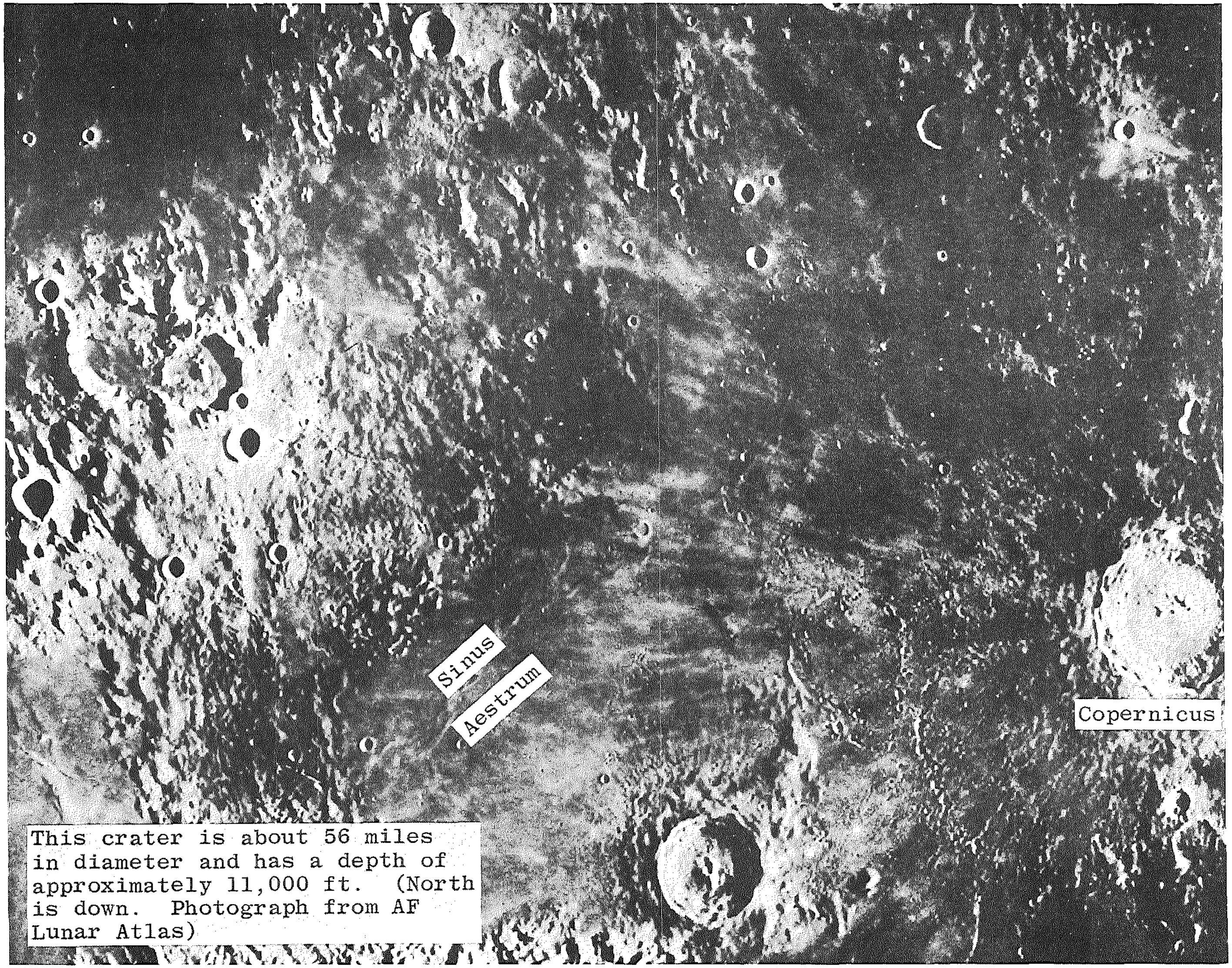


Fig. 3 Crater Copernicus (Ref. 15)

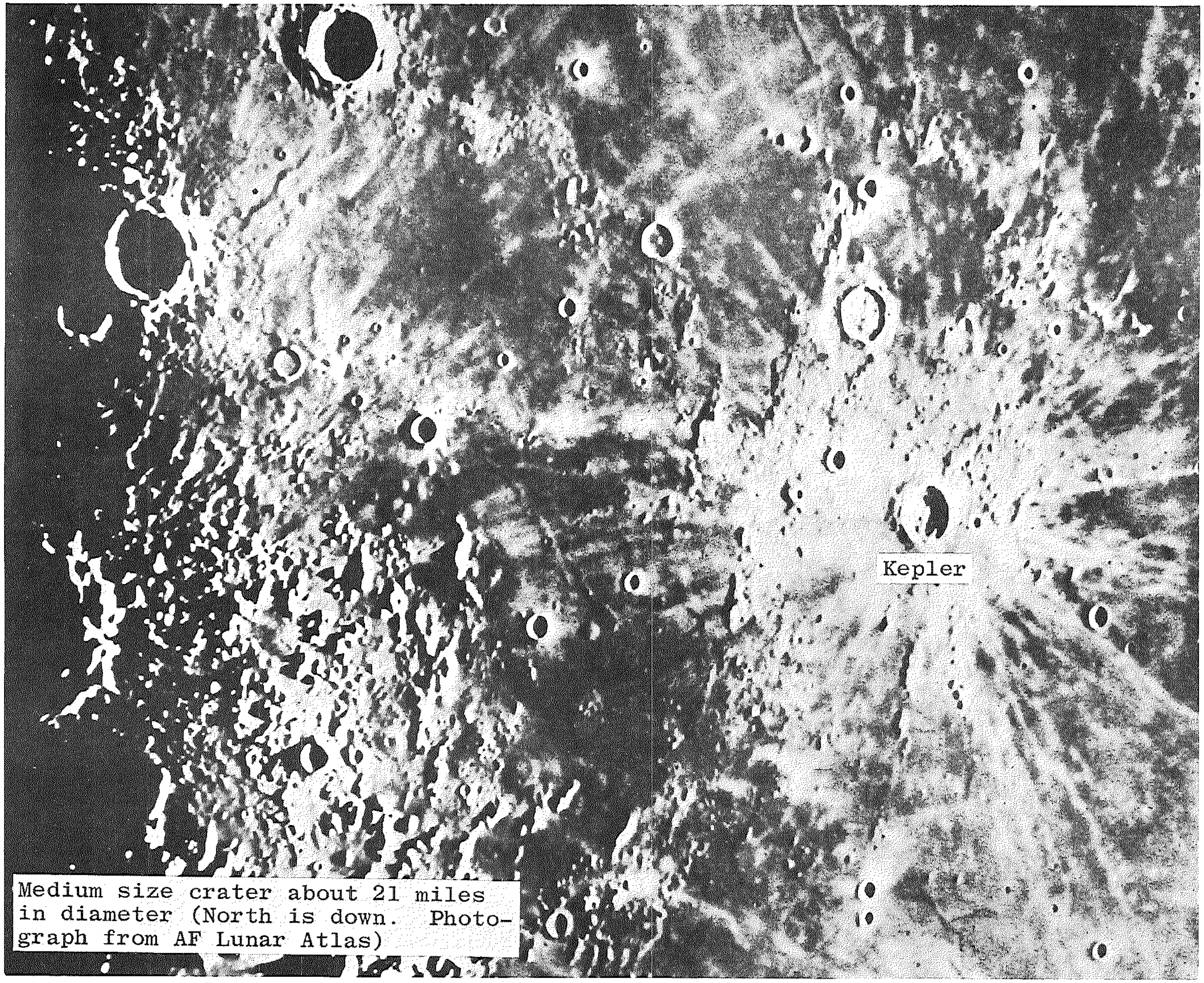


Fig. 4 Crater Kepler (Ref. 15)

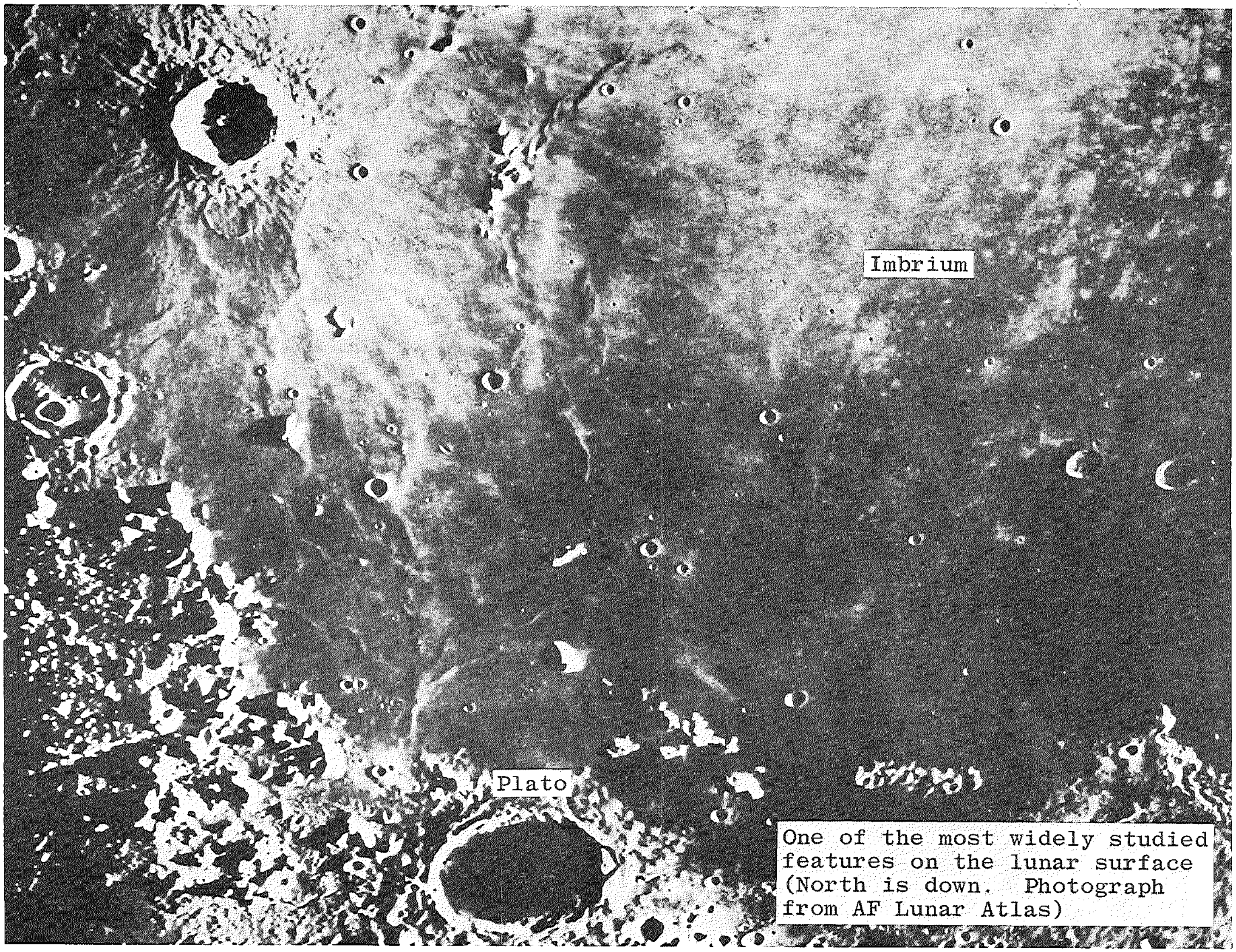


Fig. 5 Mare Imbrium (Ref. 15)

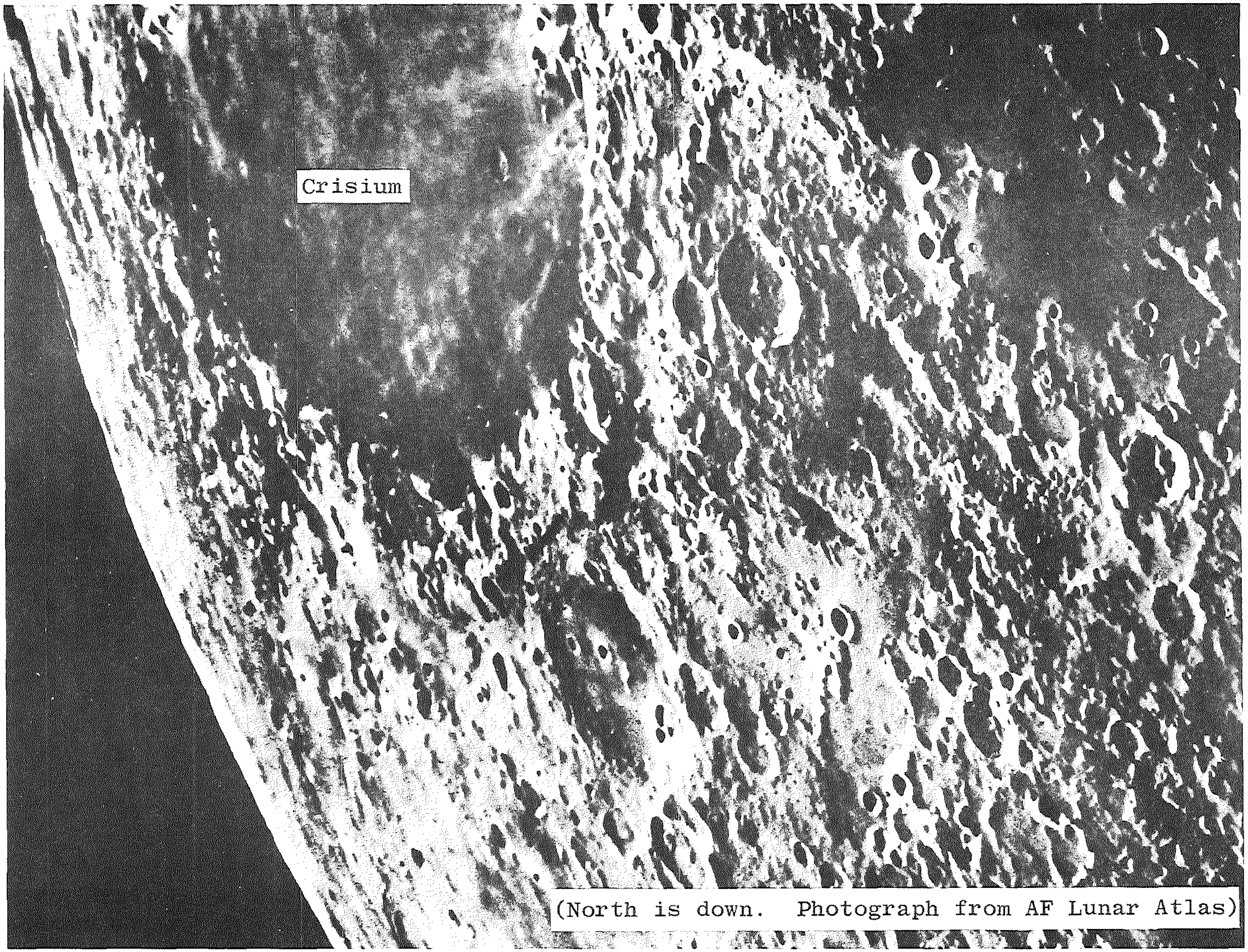
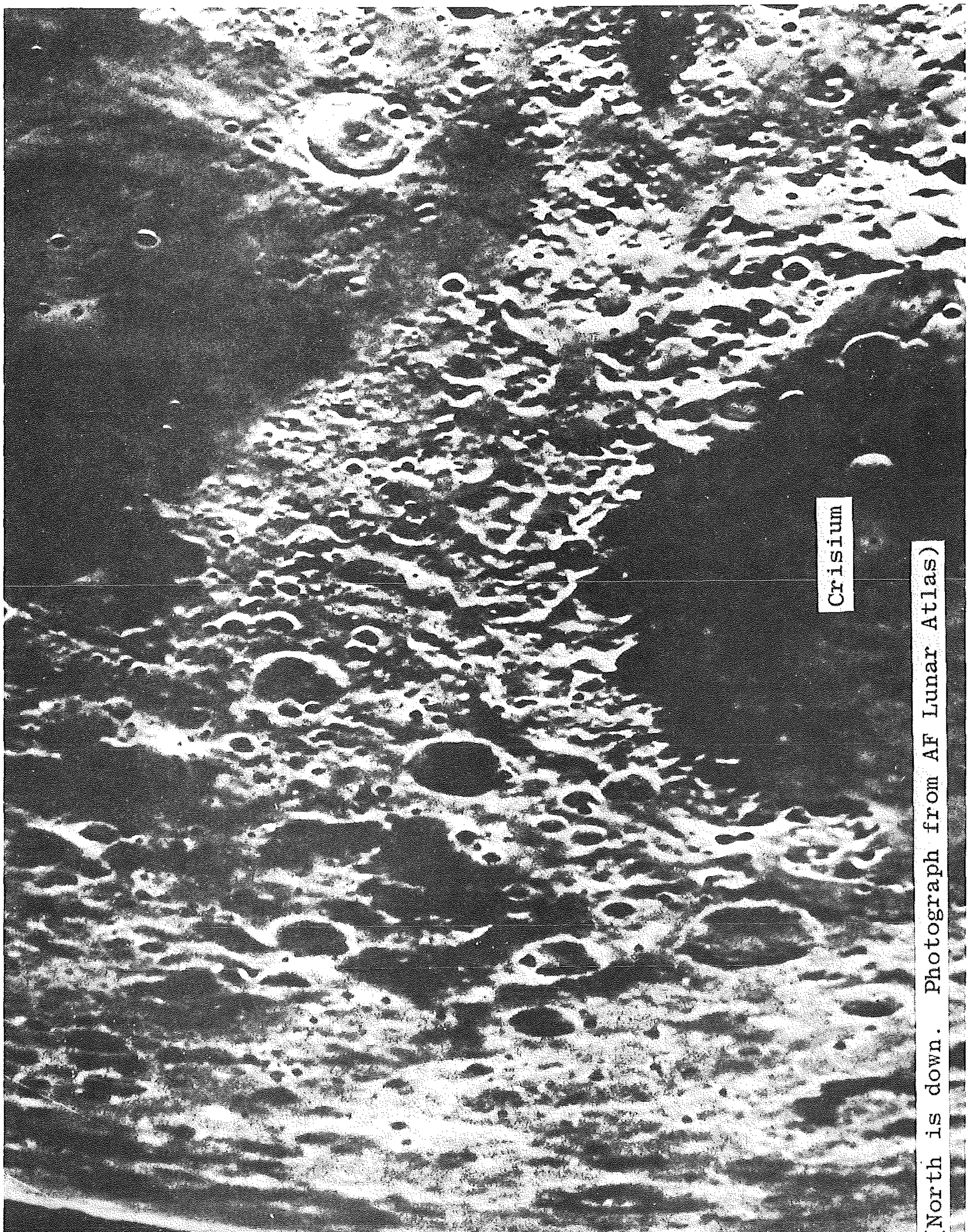


Fig. 6 Mare Crisium – Northern Portion (Ref. 15)



(North is down. Photograph from AF Lunar Atlas)

Fig. 7 Mare Crisium – Southern Portion (Ref. 15)

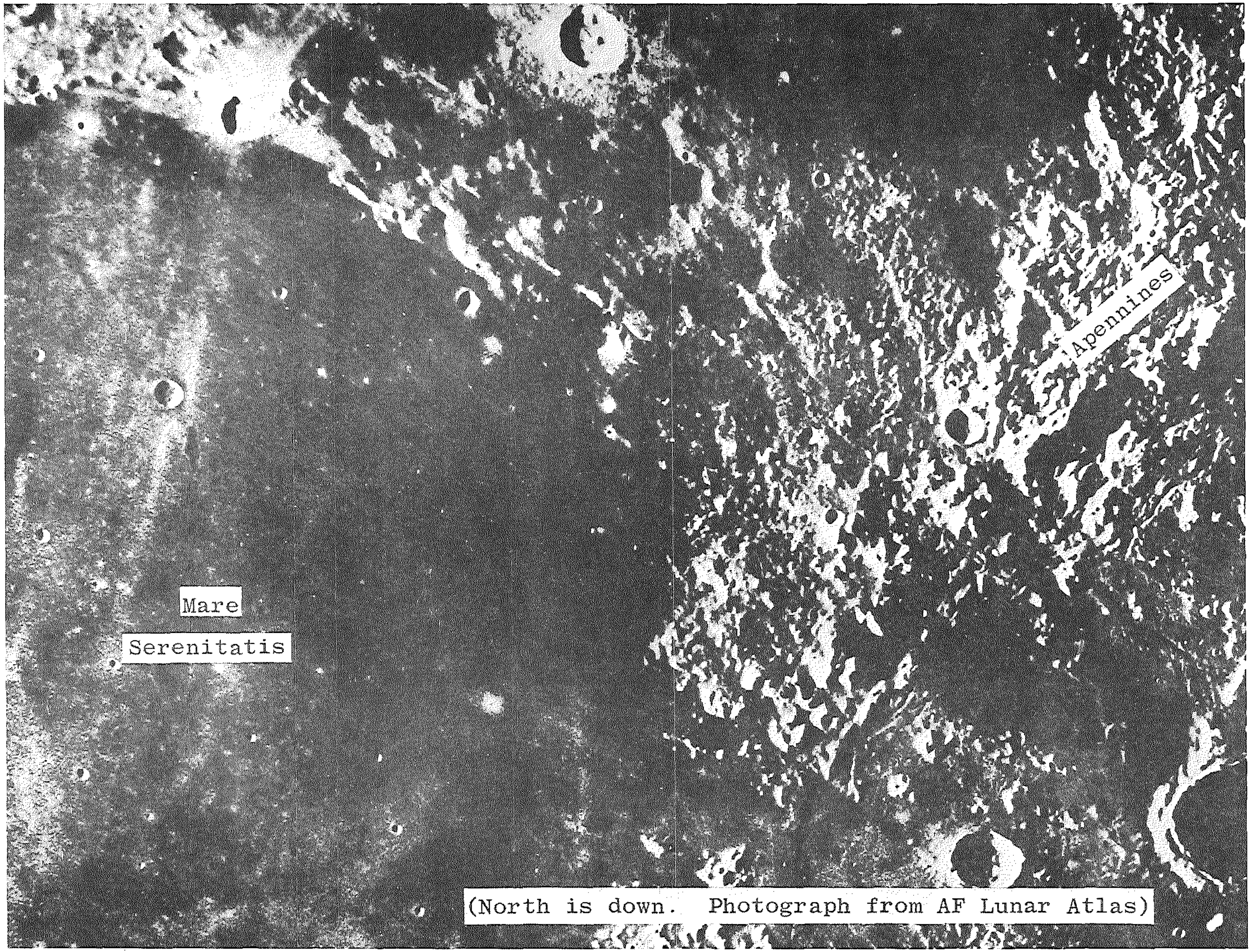
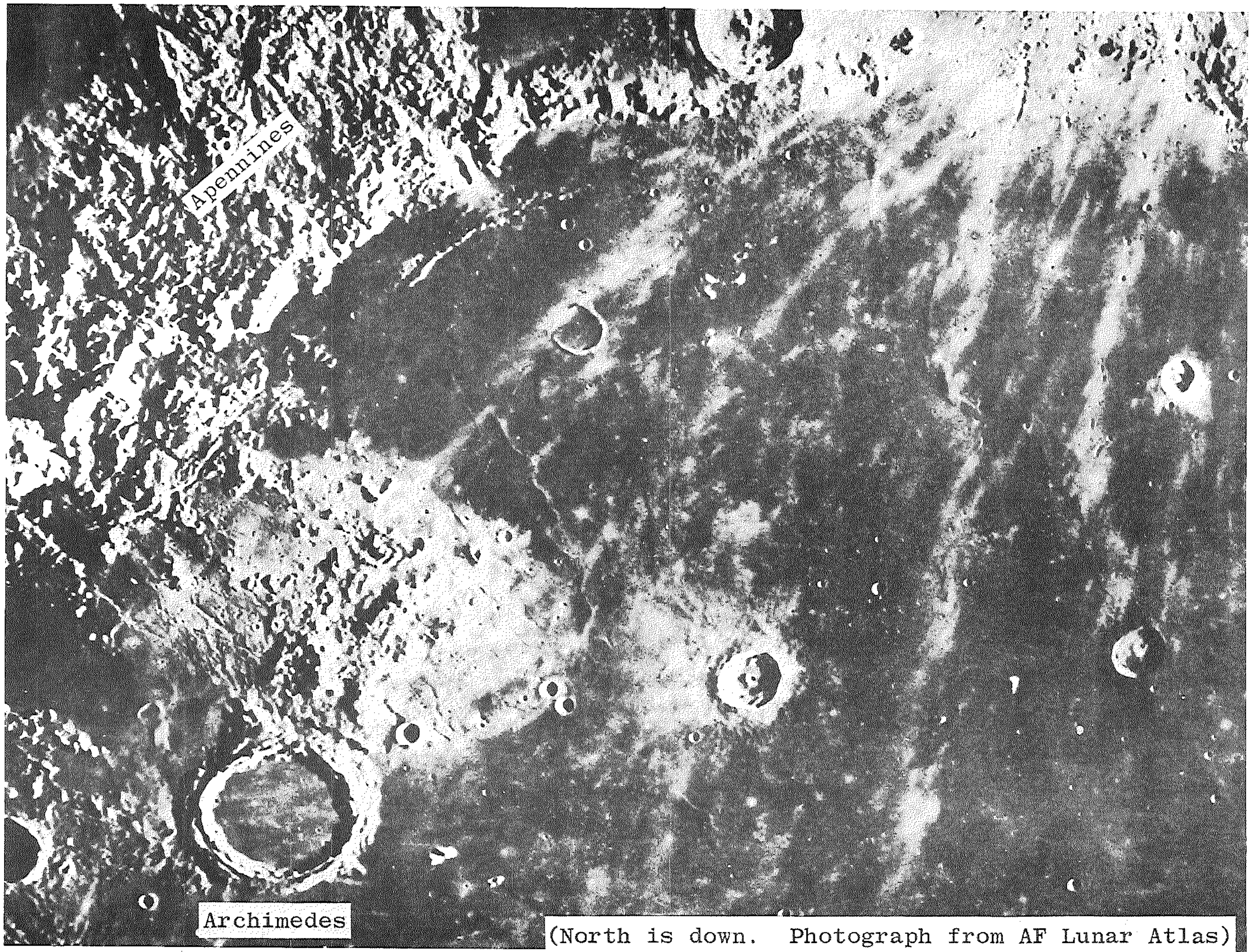


Fig. 8 Apennines (Mountain Range Bordering the Serenitatis and Imbrium Seas) (Ref. 15)



(North is down. Photograph from AF Lunar Atlas)

Fig. 9 Appennines (Mountain Range Bordering Mare Imbrium) (Ref. 15)

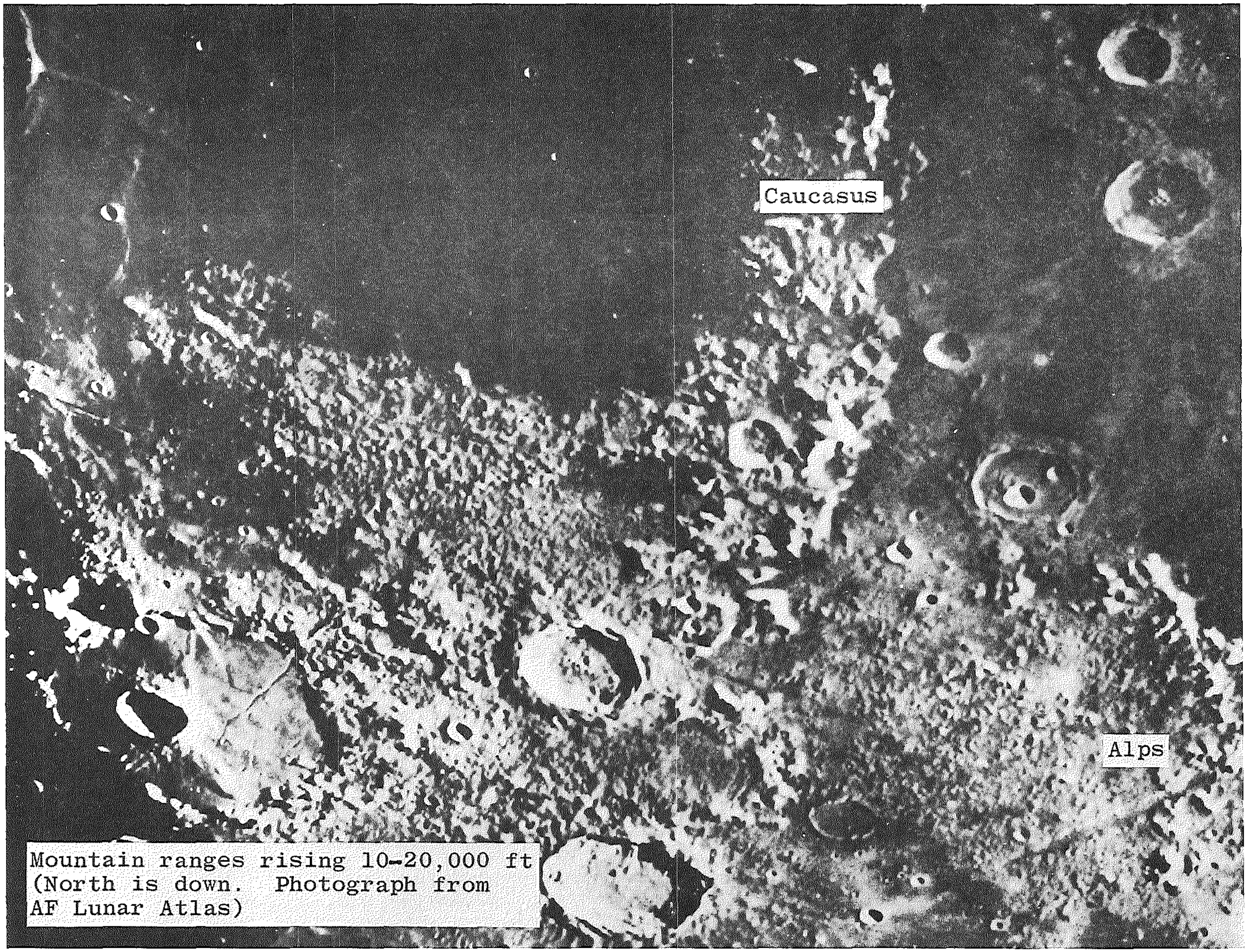
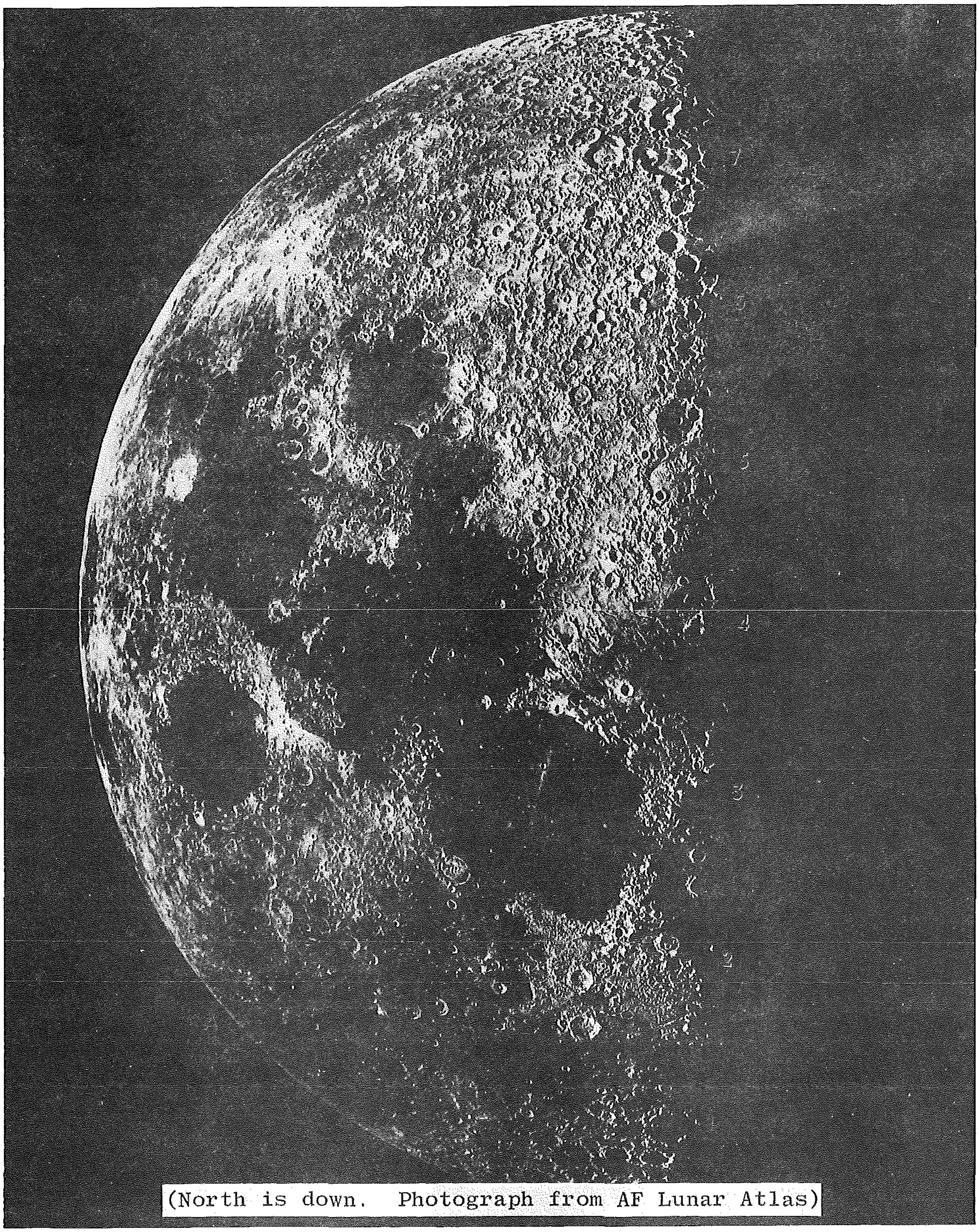
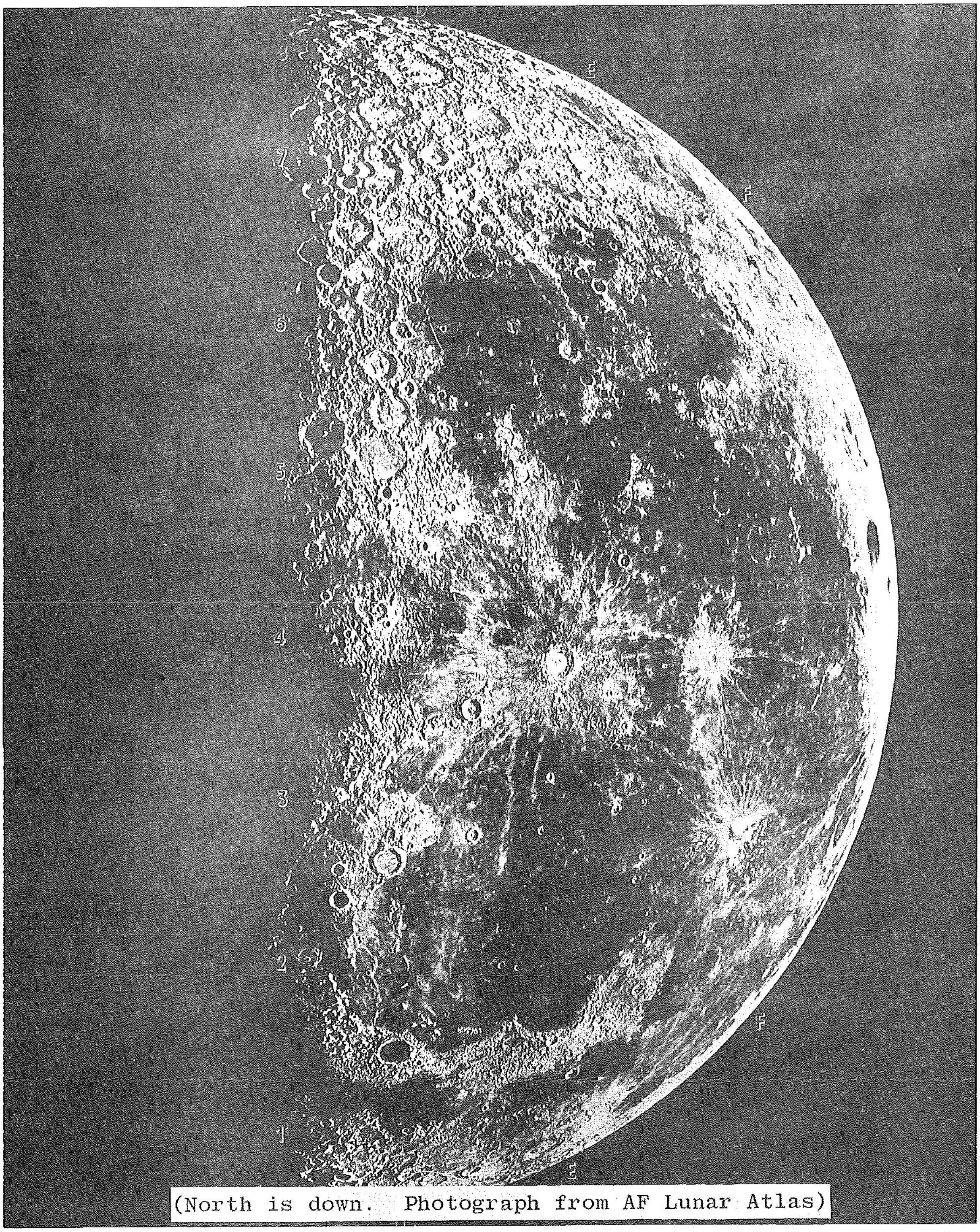


Fig. 10 Alps and Caucasus (Ref. 15)



(North is down. Photograph from AF Lunar Atlas)

Fig. 11 Half Moon – Eastern View (Ref. 15)



(North is down. Photograph from AF Lunar Atlas)

Fig. 12 Half Moon – Western View (Ref. 15)