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Introduction

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In the past two decades the exploration of much of the Solar System has become a reality. More than one hundred missions have been flown to the Moon and planets by the United States and the Soviet Union. Many of these missions have carried imaging systems that, collectively, have returned an incredible wealth of information on the shape and surface characteristics of planetary objects.

Throughout history, maps and charts have played an integral role in the exploration of Earth. Their importance holds true for Solar System exploration as well. Maps of the planets are needed by planners of spaceflights to design missions, including the selection of safe and scientifically fruitful landing sites, and are the framework for recording measurements from a wide variety of spacecraft instruments. During the data analysis phase following the completion of mission operations, maps and charts provide the basis for understanding local, regional, and global characteristics of planets and satellites.

The making of planetary maps has required the development of new methods and techniques. Many of the basic principles derived from the mapping of Earth must be reconsidered in the mapping of other planets. For example, the traditional datum on Earth is sea level, but what does one select as the datum on planets without oceans? Most topographic data on Earth are derived photogrammetrically from conventional aerial photographs. How can these techniques be applied to a planet completely covered in perpetual clouds, such as Venus, where only radar images can be obtained? How can the geological evolution of a planet be determined when its surface has not been visited and when photographs are the primary data that are available? These problems have been addressed by planetary mapmakers since the early 1960s, and as is true for much of Solar System exploration, some of the answers have direct application to Earth.

As reviewed in Chapter 2, mapping our closest planetary neighbor, the Moon, began in the seventeenth century with Galileo. Rapid advances in the quality of telescopes led to the preparation of detailed maps of the Moon and the establishment of formal procedures for naming surface features (see Chapter 4). Simple maps were also produced for Mars and Mercury based on

telescopic observations. But by the early 1900s astronomers had determined the orbits, rotations, sizes, masses, and other whole-body properties for the planets and many satellites almost to their satisfaction and had turned their attention to stellar and galactic problems that they regarded as more significant. Consequently, the study of the Moon and planets was in a state of neglect when Sputnik 1 initiated the Space Age in October 1957.

During the period of neglect prior to the launch of Sputnik 1, a few pioneers, such as Ernst Opik, Ralph B. Baldwin, Harold C. Urey, Gerard P. Kuiper, and Eugene M. Shoemaker, were quietly paving the way for what would become an intensive and productive program of lunar and planetary investigations, including mapmaking. Official U.S. interest in the solid bodies of the Solar System increased when the National Aeronautics and Space Administration (NASA) was established in October 1958 in response to the success of the Sputniks. In 1959 the race for the Moon began in earnest when the first spacecraft, the Soviet Lunas 2 and 3, reached the Moon, and when the United States initiated Project Ranger.

With the formation of NASA, major cartographic and geologic mapping programs were also initiated. Working with Gerard Kuiper and Zdenek Kopal at the University of Manchester, the U.S. Air Force Aeronautical Chart and Information Center (ACIC) began its fundamental program of lunar cartography, which has been continued and extended to the planets and outer satellites by the U.S. Geological Survey. The U.S. Army Corps of Engineers commissioned a lunar study by the Military Branch of the U.S. Geological Survey that included the first modern geologic map of the lunar surface. Shoemaker began his highly productive studies of impact and volcanic craters, geologically mapped a key area of the Moon, and launched a major effort of lunar geologic mapping that has similar programs for each newly photographed planet and satellite (see Chapter 7).

1.1. PLANETARY VERSUS TERRESTRIAL MAPPING

Through the centuries, maps of Earth's surface have been produced primarily by piecing together large-scale sketches and diagrams. "Control" networks were derived through extensive and laborious ground surveying. By the late nineteenth century, regional maps were produced in this fashion that were relatively accurate. With twentieth-century technology came the ability to obtain the so-called synoptic view. Photographs taken first from aircraft and later from Earth-orbiting satellites enabled the rapid production of accurate maps. When combined with well-established control networks, these maps have enabled surface features on Earth to be located precisely.

Planetary explorers, on the other hand, have had the global perspective from the beginning, and they have progressed from global, through regional, to local vantages. Solar System exploration – and the production of planetary maps – typically involves data reduction from a sequence of progressively

more complex missions. The first stage in the exploration of a planet typically involves "flyby" reconnaissance missions, in which a spacecraft takes pictures and records other data as it passes a planet or planetary system. The Voyager mission through the outer Solar System is an example of a flyby mission in which careful planning allowed extensive data returned from both the major planets and from the moons that surround them (Figure 1.1). Rapidly rotating planets can be imaged completely as a spacecraft approaches and departs, but data resolution is extremely variable because different longitudes are viewed from different distances. The pictures of Rhea in Figure 1.2, for example, show typical ranges of image resolutions in flyby missions.

Later missions involve orbiting spacecraft, such as Mariner 9 and the Viking Orbiters to Mars. Orbiters enable systematic collection of data at a consistent range of resolutions. A planet rotating beneath the elliptical orbit of a spacecraft presents mission planners with a variety of data-gathering possibilities. For example, lighting geometry greatly influences the type of information returned by images. As shown in Figures 1.3 and 1.4, pictures taken when the Sun casts shadows reveal surface features such as small hills had fractures; in contrast, pictures taken when the Sun is high reveal the reflective properties of planetary surfaces.

Landings on planetary surfaces are made in the advanced stages of exploration. Although the primary objectives of such missions do not include mapping, very-large-scale maps are made to record data gathered around the landing sites and, if appropriate, to document sample collection sites. These missions also have important geodetic significance because the coordinates of the landing sites can be located precisely. Many techniques have been used for this purpose, including laser-ranging from observatories on Earth to corner reflectors left on the Moon by Apollo astronauts and analysis of radio-tracking data from the Viking Landers on Mars. When precise locations of landing sites can be positioned on mapping images, the measurements serve the very important function of tying a planetary control net to monumented bench marks on the ground (see Chapter 5).

The naming of features is as much a part of mapmaking as are the measuring and plotting of their locations. Without names, communication of ideas is impossible. The names applied by explorers on Earth often bear their provincial outlook. Ambiguities abound; settlers on different parts of the same river often know the river by different names. Invaders rename the territories of the invaded.

The tradition that the privilege of naming belongs to the discoverer resulted (on the Earth as on the planets) in hopeless ambiguities, redundancies, and inconsistencies. The International Astronomical Union (IAU) has therefore assumed control of the naming process. Its working groups are composed of planetary scientists from many nations, and although the process is often an emotional and politically contentious one, a system of nomenclature has emerged that is accepted by the international scientific community, as discussed in Chapter 4.

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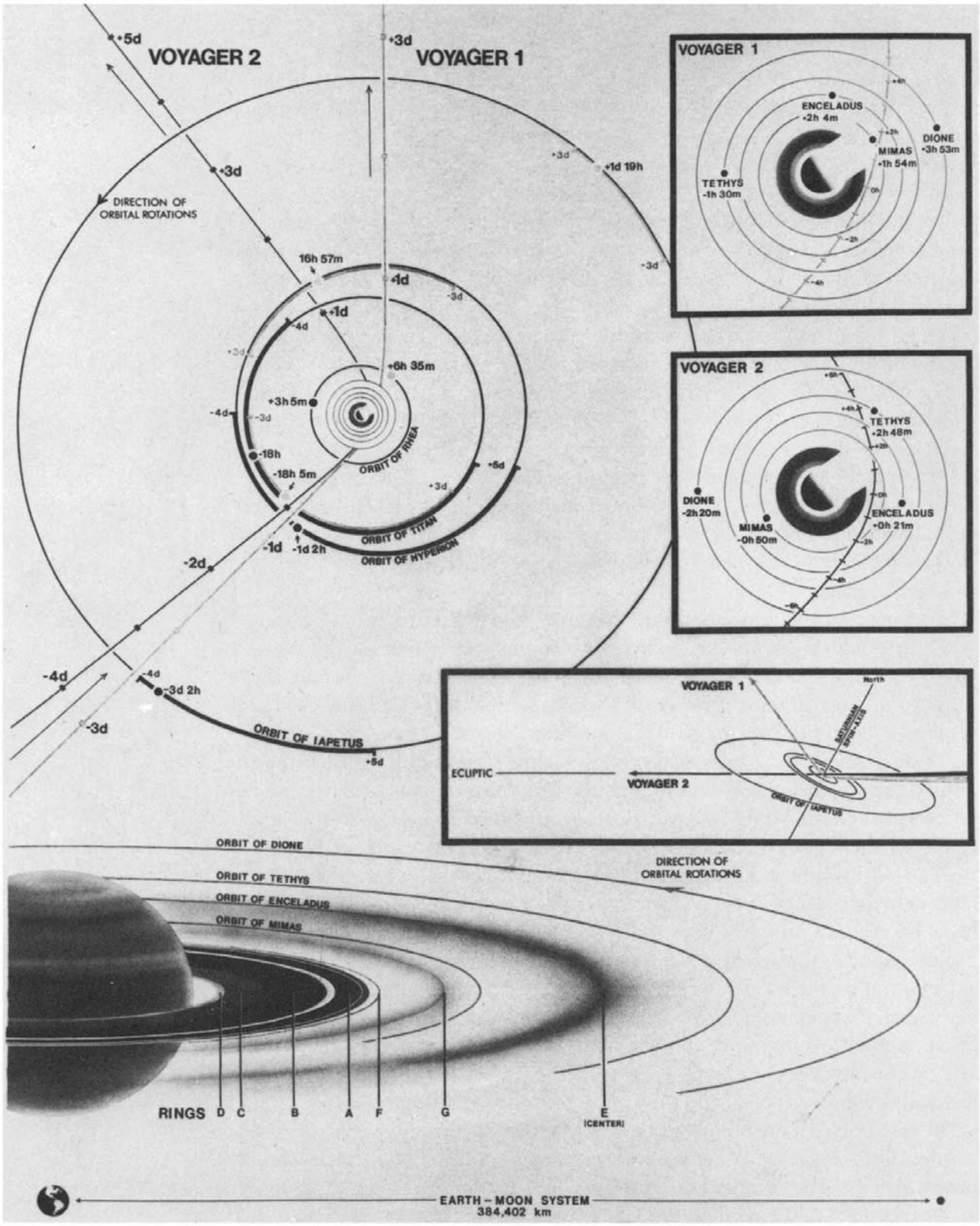


Figure 1.1
The flights of the Voyagers through the Saturnian system. Voyager 1 was deflected northward out of the ecliptic, whereas Voyager 2 was programmed to use the gravity of Saturn to propel it on to Uranus and eventually to Neptune. The Earth–Moon system is shown for scale.

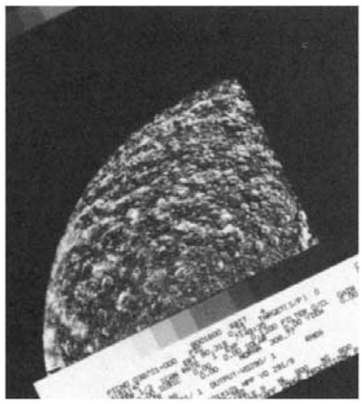
1.2. DATA FOR MAKING PLANETARY MAPS

Monoscopic television images are the primary resource for mapping the planets. Techniques for making maps from aerial photographs of the Earth were developed many years ago, and a stereoscopic approach to mapping was used almost from the beginning. Terrestrial methods have been refined and modified for specialized use on the planets, but there are several important differences between terrestrial aerial photographs and digital television images returned by spacecraft.

Most aerial cameras have fields of view of 90 degrees or more across a frame, whereas spacecraft television images commonly have fields of view of less than 2 degrees, and in some cases are as small as one-tenth of a degree. Aerial-mapping cameras have minimal, almost unmeasurable, geometric distortions; spacecraft television systems tend to produce images that are too distorted for cartographic use until they have been modified through complex computer processing. The spatial resolution of an aerial image is limited by the grain size of the film emulsion, whereas the resolution of a television image is limited by the size of a digital picture element, or "pixel." The area of the film plane of an aerial camera is more than 500 times larger than the image plane of a spacecraft television camera; if television vidicon tubes and film could be compared directly in terms of sensitivity and resolution, film images would contain five hundred times as much spatial information as television images.

Most importantly, for applications to Earth, aerial film cameras and photogrammetric mapping instruments were designed as components of precision mapping systems to utilize the stereoscopic effect available in overlapping images taken from different points of perspective. Such image pairs are rare in planetary exploration, and even when they are available, their geometry is incompatible with most stereoscopic mapping instruments. These and other factors make the aerial film camera a far more effective mapping tool than spacecraft television systems. Except for some Apollo and Soviet missions, however, it has not been practical to use film cameras to obtain data for making extraterrestrial maps.

There are, however, some advantages in the use of digital television cameras rather than film systems. The television camera can record a much wider range of brightness values than film, and it can record them more precisely. Consequently, more subtle color changes can be recorded electronically than on film. In addition, the total number of images recovered from a mission is limited only by the power available on the spacecraft. From a mission like Voyager, which has lasted for more than a decade, tens of thousands of pictures can be acquired. Television images are returned to Earth at the speed of light, rather than at the speed of a spacecraft. Thus, Voyager images of the Saturnian system were recovered only 1.5 hours after they were taken, whereas it would have taken 2 or more years to send them back to Earth by a returning spacecraft!



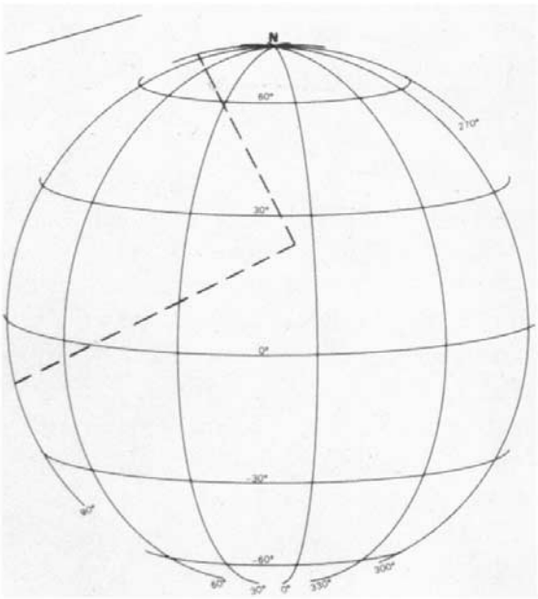
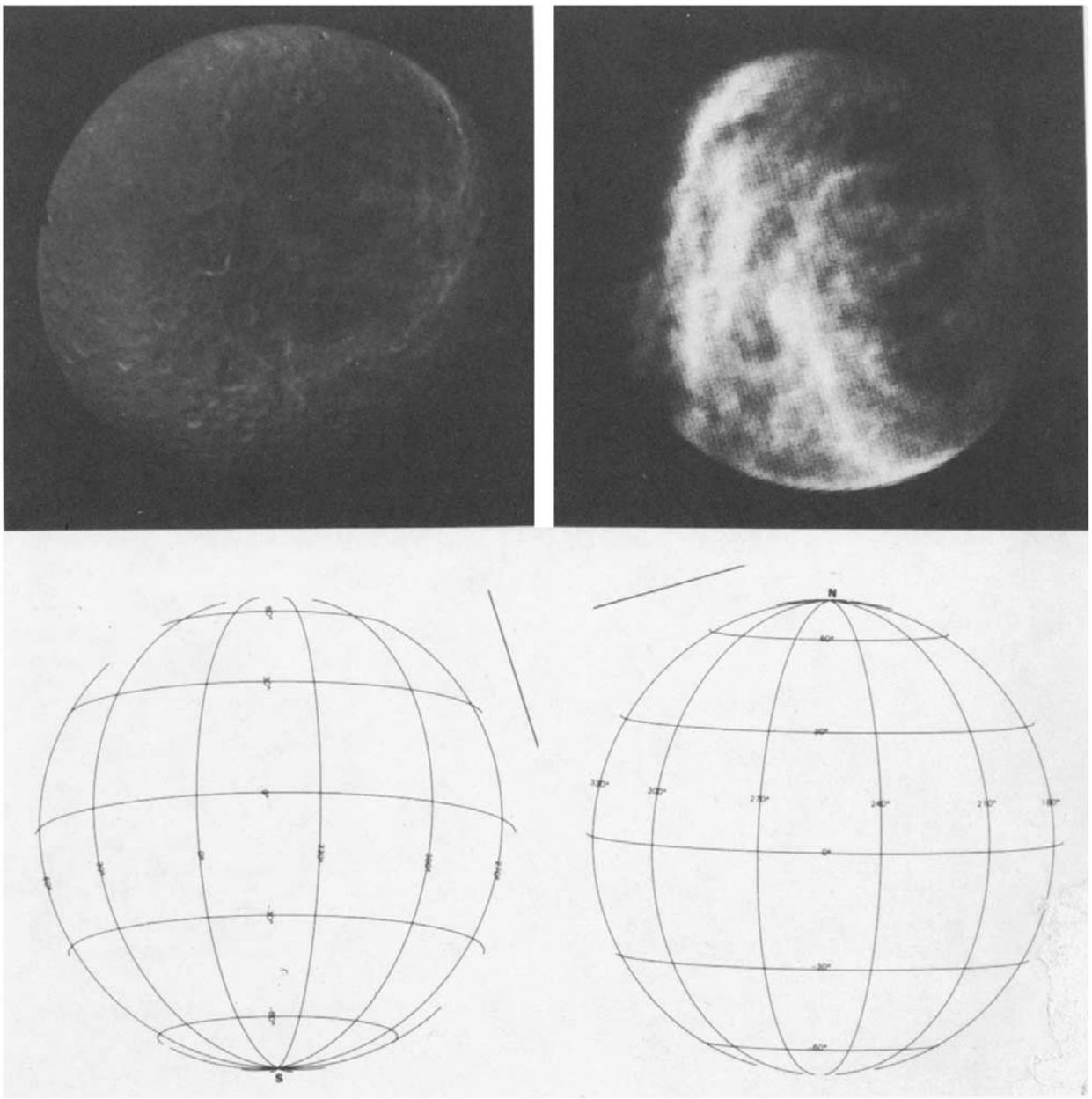


Figure 1.2
Voyager 1 pictures of Rhea, a satellite of Saturn. On the facing page, the image on the right (PICNO 115S1-002) was taken from a distance of 1,850,000 km; the one on the left (PICNO 1558S1-001), from 720,000 km. The facing image (PICNO 0338S1 + 000) was taken from a distance of 121,000 km. The perspective grids below each picture were derived from the radio-tracked positions of the spacecraft at the time each exposure was made. Note that only albedo patterns are apparent on pictures taken from great distances; image resolution must be better than 2 or 3 km per pixel to show landforms.

The image plane of most spacecraft cameras is the surface of a television vidicon tube. A pattern of reference marks called a reseau is inscribed in the phosphor of the tube (Figure 1.5). The coordinates of these marks are measured prior to spacecraft launch so that distortion can be measured and the correct geometry can be reconstructed when the images are received from a spacecraft. Vidicon systems have an undesirable characteristic: The electronic beam used to scan an image from the vidicon tube is deflected slightly when



it encounters bright areas, so image geometry can never be precisely reconstructed.

Imaging tubes vary in sensitivity over the image area. Some of this variation is inherent in the manufacture of the tube and can be calibrated prior to spacecraft launch, but some is caused by temperature changes, strong radiation, and magnetic fields, such as those that surround Jupiter and Saturn. These effects cannot be predicted prior to the mission and must be calibrated in flight by taking pictures of black sky and measuring deviation from black in

Figure 1.3
Mosaic of part of the Arabia Terra region of Mars, taken from low altitude under morning illumination.

the image. The deviation changes slowly, so calibrations of this "dark current" must be made several times during a mission.

The vidicon television tube has been replaced on planetary imaging systems of the 1990s with a "charge coupled device," or CCD. The CCD consists of an array of tiny solid-state sensors, the location of each of which is precisely known, covering an entire image plane. This system, planned for its first planetary use on the Galileo mission to Jupiter, will be a boon to cartographers and photogrammetrists because many of the difficulties with the vidicon system will be eliminated, such as the beam-bending and reseau-fitting problems.

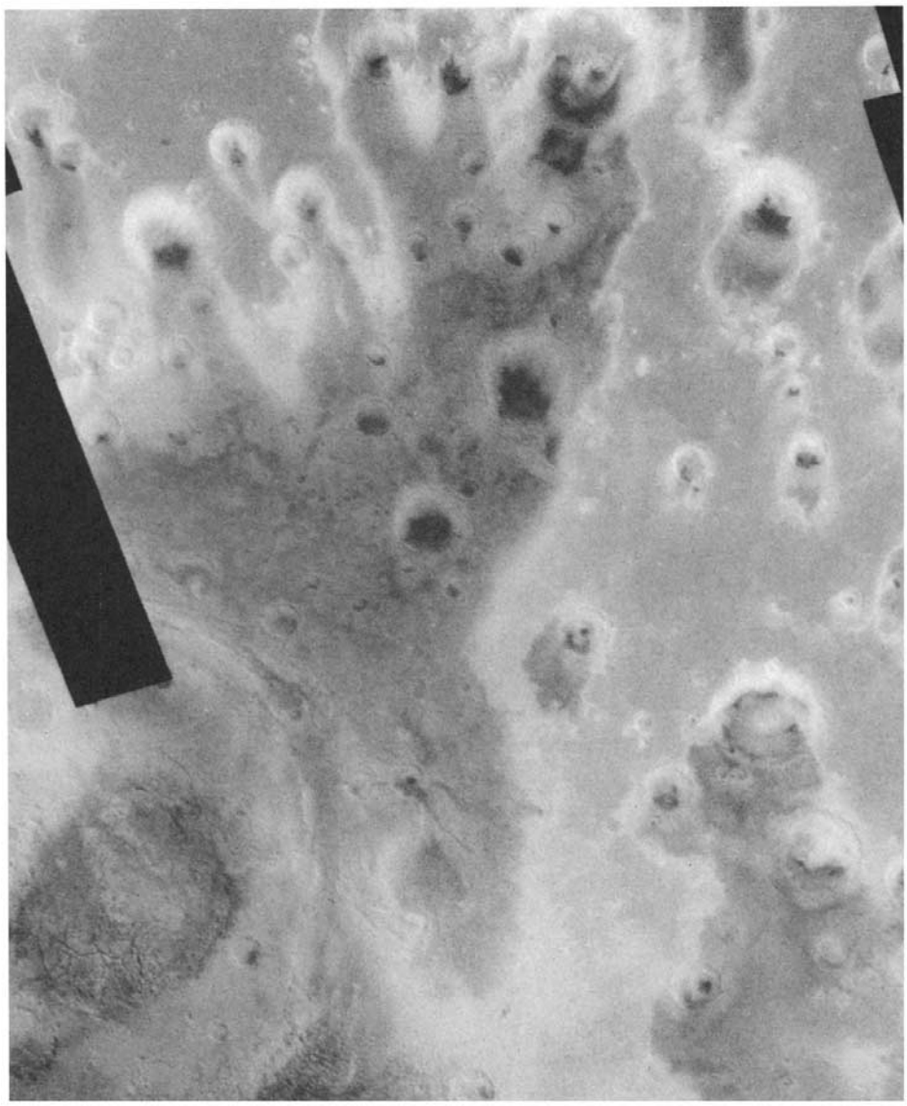


Figure 1.4
Mosaic of part of the Arabia Terra region taken from high altitude under noontime illumination.

1.3. TOPOGRAPHIC MAPS AND GEODETIC CONTROL OF PLANETARY SURFACES

Topographic measurements provide a third dimension to maps by showing the height of features above some reference elevation. This dimension enables more complete studies of surface morphology, structure, and local gravity. Without this additional dimension, many scientific questions are difficult or impossible to answer. For example, what is the volume of a river channel, and by implication, what is the volume of the material that was excavated to form the channel? How high are the mountains, and how deep are the basins

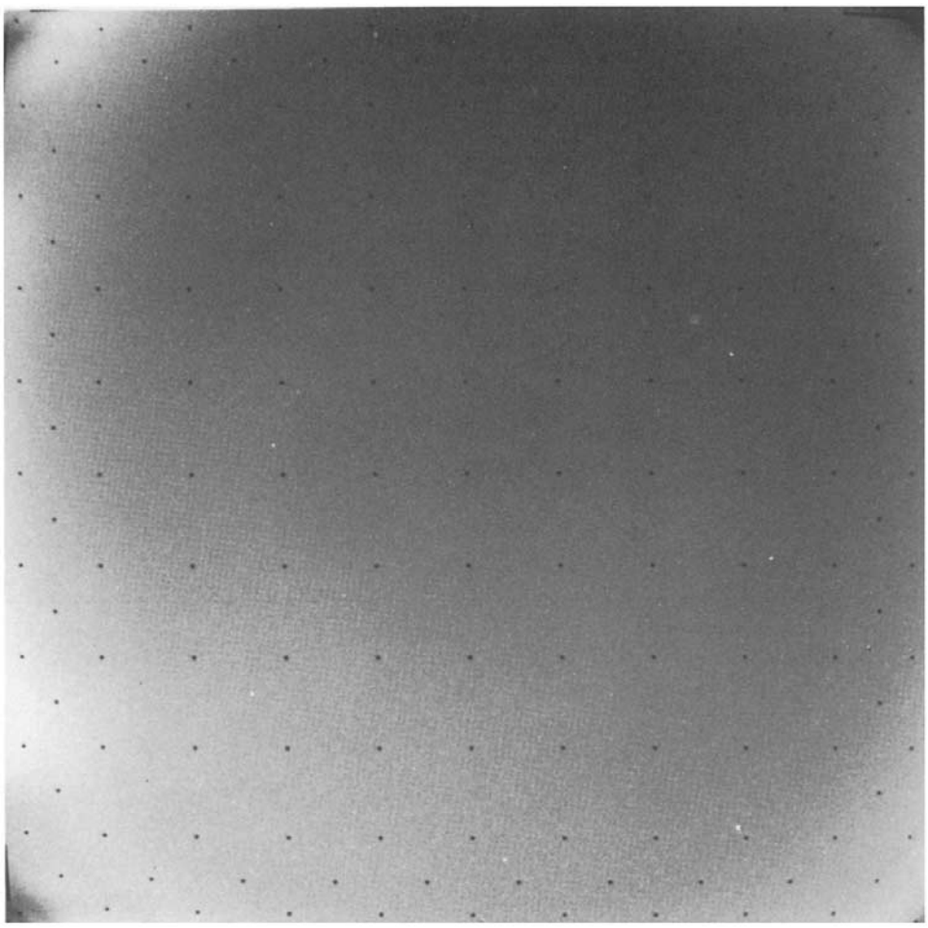


Figure 1.5
Image of black sky, taken by a Voyager camera for radiometric calibration. Note the pattern of reseau marks, used for geometric correction of the image.

with respect to local gravitational acceleration? Which way might liquids have flowed in the past? Has the surface been tilted so that they would flow in a different direction today?

The relevance of these questions extends beyond normal scientific inquiry; planners of future missions are vitally interested not only in the scientific questions, but in the operational ones as well. Can a remotely controlled vehicle climb a particular slope? Is a selected site sufficiently smooth for a spacecraft landing? Will the descent trajectory of the spacecraft intersect the surface at the desired landing site, or is there a mountain in the way?

Measuring topography on the planets is very different than it is on Earth. On Earth extensive oceans and shorelines, absent on planets explored to date, provide an obvious datum from which to measure elevations. Sea level is a surface that is linked to the shape of the Earth's gravitational field, incorporating a necessary geophysical element. Definition of a topographic datum on other planets is less direct. The gravity field of the Moon, for example, was defined by radio tracking of orbiting spacecraft, and a topographic datum based on this field was proposed. Similarly, the topographic datum on Mars