m sec^{-1} for the vertical velocity over the 20-minute period. This velocity is consistent with previous values from thunderstorm research (*5*) for an average cell. Range height indication radar indicated a top growth rate of approximately 1.6 km in 20 minutes.

Thus we can speculate on the vertical mass transport of water vapor over larger areas into the upper troposphere and stratosphere. Thunderstorms east of Colorado reach much higher altitudes than storms in the Western Plains such as the storm discussed in detail, pushing well into the lower stratosphere. In addition, the tropopause is lower to the East during the thunderstorm season than in the Western Plains, and, as a result, there is a much higher stratospheric penetration in the East. Recently Lee and McPherson (*6*) reported on an observational survey of the tops of Oklahoma thunderstorms, stating that the tops of 469 thunderstorms exceeded 12.2 km during April, May, and June, 1967 through 1969. Of that number 33 percent exceeded 15.2 km. They (*6*) found the average base of the stratosphere during this period to be 12.2 km. On the other hand, only 25 percent of all Colorado thunderstorms penetrate into the stratosphere during the May-September thunderstorm season.

The Oklahoma thunderstorm statistics are at least typical for the eastern continental United States. If each of these approximately eight cells per day averages 10 km^2 and has a stratospheric injection of water vapor per cell of 20×10^{-4} g cm^{-2}, twice that of the drier Colorado storms, thunderstorms can transport vertically 1.6×10^9 g of water vapor per day into the Oklahoma stratosphere. Since the annual variability in the number of thunderstorms ranges from ½ to 1½ times the average number, we should consider this information when speculating on the effects of man-made additions of water vapor to the stratosphere. What finally happens to this injected water vapor remains an object for further study, as it may be swept out during the storm's dissipating stage.

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7. Work supported by the National Aeronautics and Space Administration, the Department of Transportation, and the National Oceanic and Atmospheric Administration.

17 August 1971

Martian Craters and a Scarp as Seen by Radar

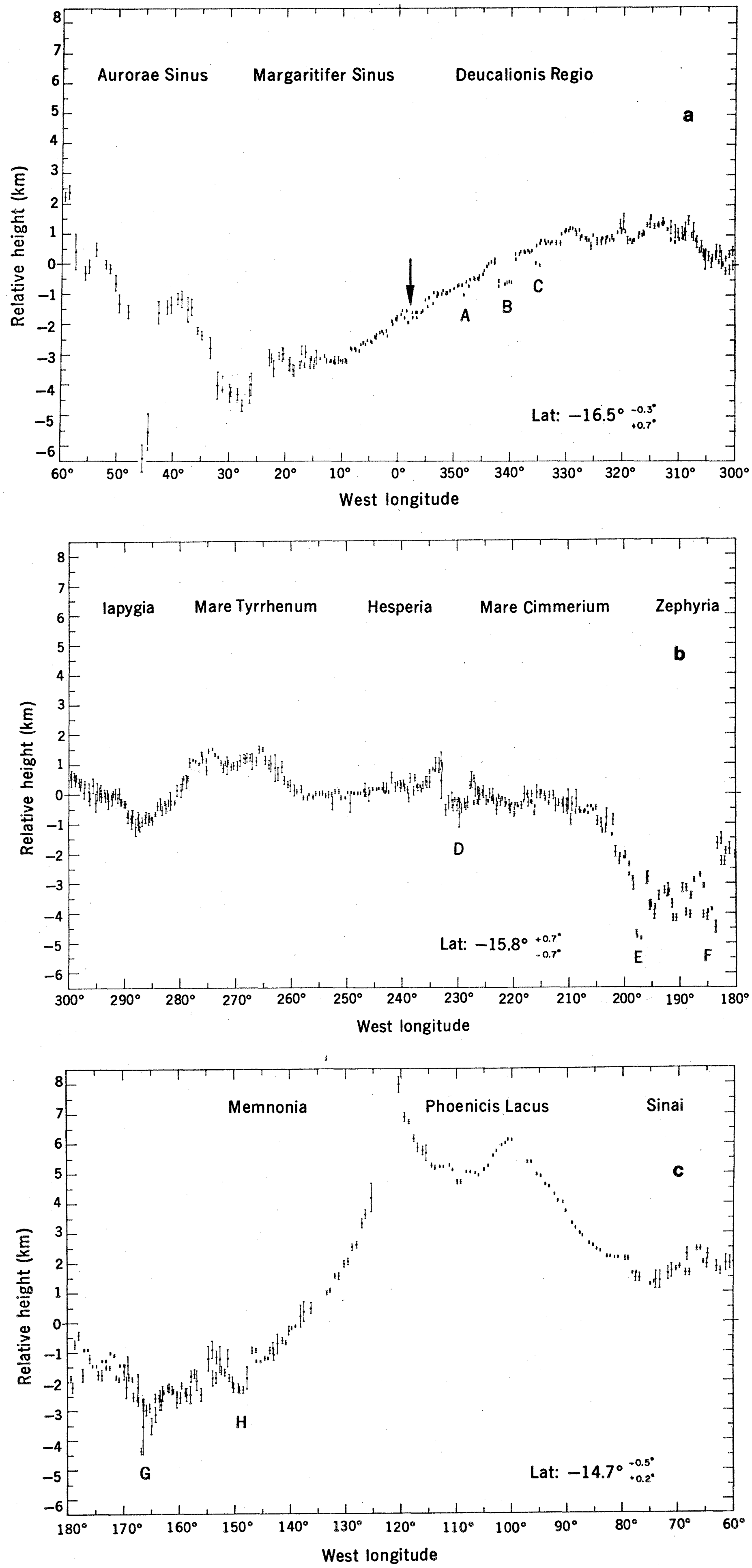
Abstract. *Radar observations of Mars with a surface resolution of 1.3° in latitude and 0.8° in longitude have been carried out during the opposition of 1971. With a precision in surface height measurement approaching 75 meters in regions of high reflectivity, it has been possible to measure the detailed characteristics of a number of craters. Many of these can be identified with craters shown in Mariner photographs of Mars. In addition, a scarp has been seen at 41° west, 14° south with an average slope of about 6° extending over about 40 kilometers.*

As previously reported, radar has been applied during the oppositions of 1967 (*1*) and 1969 (*2, 3*) to determine directly the surface topography of Mars along the subearth trace. Those measurements, entirely restricted to the northern Martian hemisphere, disclosed a topographic variation from peak to valley of some 12 km. At a lateral surface resolution of 1.5° to 6° of longitude and a vertical resolution of several kilometers, little detail at the limit of resolution was seen. With the increased signal strength associated with the extremely favorable opposition of 1971, as well as with recent advances in instrumentation, it has been possible at the Haystack Observatory to make radar observations of the surface altitude of Mars with a precision often approaching 75 m. These observations have disclosed a wealth of detail concerning relatively small-scale topographic features such as surface craters and scarps.

In mid-July 1971, a series of thrice-weekly radar observations was begun. A phase-coded continuous wave (CW) waveform with an effective resolution (baud length) of 6 μsec was used. After reception, the echo signals were coherently integrated for 6.12 msec in the decoding analysis, yielding an effective detection bandwidth of approximately 160 hz. At the operating frequency of 7840 Mhz (3.8-cm wavelength) this choice of parameters provides a basic lateral surface resolution, if a spherical surface is assumed, of 1.3° in latitude and 0.8° in longitude. (The extent in longitude is less than in latitude because of the narrow band of Doppler frequencies passed by the finite detection bandwidth.) In many cases the surface scattering law further limits the region under observation. In a single night the rotation of Mars permits observation of only slightly more than 100° of longitude at the latitude of Haystack, because of the high southerly declinations characterizing the 1971 opposition. With observations made at intervals over a number of weeks, however, it has been possible to connect the topographic variation entirely around the planet at latitudes varying between −14.5° and −16.8° (*4*). A preliminary reduction of data obtained between 15 July and 10 August 1971 yields the variation in surface height shown in Fig. 1, a through c.

These data have not yet been compared with the results of the observations of 1967 and 1969 in an orbital fitting program. Thus, the reference altitude shown represents the mean of these observations and cannot yet be assigned an absolute radius. The closure at a longitude of 60° (*4*) and the derived ephemeris corrections (which varied smoothly over an interval of only 16 μsec for this series of observations) are here based on a comparison of data that differ in latitude by about 2° and extend over only a small band of common longitudes. Thus, a small systematic error may exist in these preliminary reductions (*5*); however, there is no significant effect on the detailed shapes of the major features that form the basis for this report.

A general conclusion from these results is that the overall topographic variation of some 15 km is similar to the total variation from peak to valley reported in northern latitudes (*2, 3*). The elevated region at 110° longitude in the northern latitudes still persists



into southern latitudes, and is seen (Fig. 1c) to maintain the pair of separated, asymmetric highs also seen at latitude +6° (*2*). The other elevated region seen at low northern latitudes around longitude 300° has here blended in with the adjacent terrain to yield an area flat to within ± 1.5 km that extends from longitude 210° to 330°. The trough at longitude 30° is also seen in the earlier data. In general, the large-scale features correlate well with the earlier data at northern latitudes.

In more detail, and moving eastward at latitude −16.8° from the 60° longitude boundary in Fig. 1a, we note a 4.5-km-deep "hole" at a longitude of approximately 45°. This feature, in Pyrrhae Regio, stands out even more at slightly more northerly latitudes. Figure 2 shows data corresponding to Fig. 1a as well as data obtained during two subsequent passes over this region. Note particularly the profile obtained at −14.0°, where the drop of 4.5 km is observed to occur between 40° and 41°. This scarp, corresponding precisely with the white edge of a feature that appears in the Mariner near-encounter photographs (Fig. 3), apparently has a mean slope greater than 4.5° extending over about 60 km. Allowing for the scarp's azimuth of about N45°E as seen in Fig. 3, we may infer a true gradient averaging about 6° over a distance of 40 km. The depth reached here is the lowest recorded during the 1971 observations.

Moving eastward again, we find a sudden change in the surface scattering properties at a longitude of about 15°; this corresponds to the edge of the light channel (Fig. 3) running from Thymiamata through Deucalionis Regio. The entire channel region is characterized by an extremely high radar cross section, which makes it possible to measure altitudes with good precision. As the terrain rises slowly, a number of abrupt transitions may be seen (the most prominent of these are marked by letters A, B, and C); these corre-

Fig. 1. Martian topography as observed by radar at a wavelength of 3.8 cm. The error bars correspond to plus and minus 3 standard deviations. (a) Topography between longitudes 60° and 300°; (b) topography between 300° and 180°; (c) topography between 180° and 60°. The range of subearth latitudes encompassed by the data is shown at lower right in each part of the figure, with the more negative limit generally applying to the leftmost data.

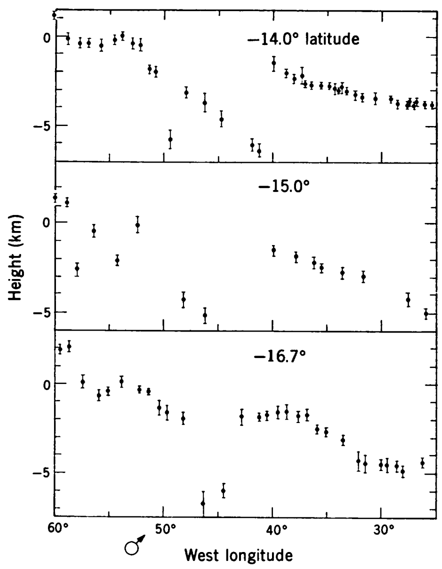


Fig. 2. Surface height profiles for a portion of Pyrrhae Regio at three values of subradar latitude. Slight adjustments in error bars and heights referred to the mean in these data, compared to the corresponding data of Fig. 1a, reflect a more accurate reduction.

spond to craters seen in Fig. 3 (*6*). The largest of these, at B, has a depth just under 1 km and can be seen plainly centered at 340.5° in Fig. 3. The data imply that the crater bottom has a slight slope corresponding closely to that of its surroundings. There is a suggestion of a lip, although the nearly specular scattering observed both inside and outside the crater argues against any significant amount of ejecta lying on the surface. The lateral resolution here is limited by the scattering law to about 0.1° in longitude, and the western crater edge is found to extend over less than this interval (*7*). These craters have most likely been heavily modified by some (presumably erosive) process. Note the two sets of data near 358°; the upper data were obtained a few days later and at a slightly more northerly latitude than the lower data, and apparently correspond to the northern edge of a small crater seen in Fig. 3.

As we pass from Deucalionis Regio into Iapygia, the terrain stops rising and the radar cross section decreases again at about 325°. The region of Iapygia, from about 275° to 310°, is apparently contained in a very large crater of the marial basin type centered at a longitude of 293° and a latitude of about −10°, as may be seen in Fig. 4, where data at three values of latitude are presented. This crater is more than 2 km deep and spans over 2000 km. Its shape is confused by a smaller internal crater seen clearly in a subsequent pass over this region at a latitude of −14°. The latter crater is centered at 296° and −12° (longitude, latitude) and has a southern wall falling near latitude −16°. The nearly concentric internal crater spans 500 km and has a depth of about 500 m. It is tempting to ask whether this crater can be identified with one shown in the Mariner far-encounter photographs as centered at 305° longitude and −14° latitude. The larger crater is clearly a major feature of the region extending well up into Syrtis Major.

A nearly level plain extends from 258° to 243° longitude (900 km) and rises only 150 m toward its eastern boundary, with evidence of a few small craters of several hundred meters depth. At 230° (feature D in Fig. 1b), there is a crater 1 km deep and 340 km across, with a well-developed lip. From other passes, the center of this feature can be placed at 231°, −15° to a precision of about a degree; it agrees reasonably well in position with a crater of similar size seen in the far-encounter Mariner photographs. Another major feature is the depression lying between 198° and 183° (E and F in Fig. 1b). The bottom of this depression in Zephyria is highly irregular (chaotic?) except for a moderately well-defined, 4-km-deep (possibly circular?) trough at its limits E and F.

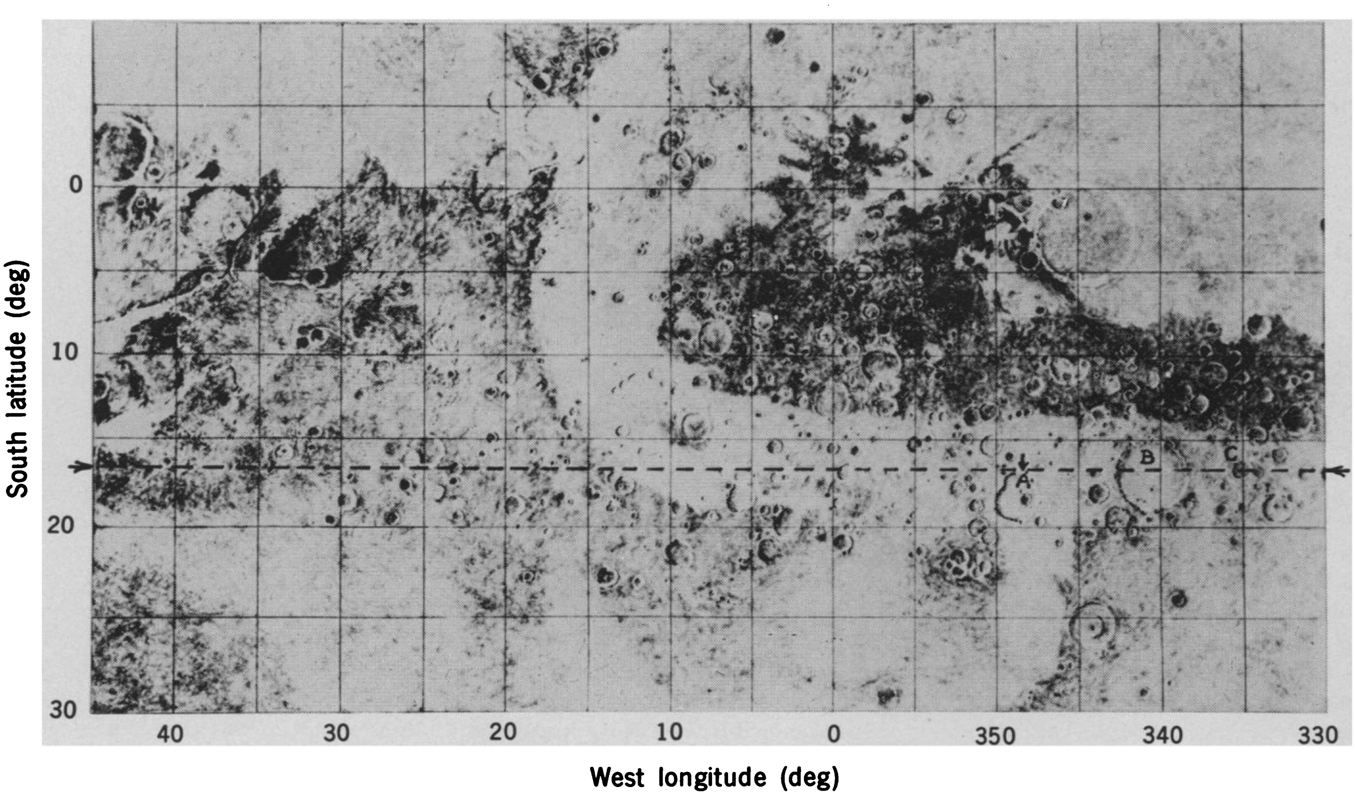


Fig. 3. Meridiani Sinus and environs. This region of Mars is near the equator and was photographed at high resolution during the close approaches of Mariners 6 and 7 to that planet in 1969 (*9*). The subradar track corresponding to Fig. 1a is shown as a dashed line; the letters indicate the craters labeled in Fig. 1a.

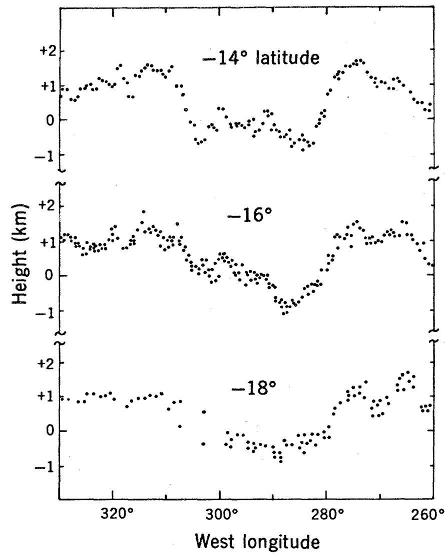


Fig. 4. Height variations in the region of Iapygia obtained from 3.8-cm radar observations in June (− 18° latitude), July (− 16°), and late August (− 14°) 1971. Error bars have been omitted for clarity but may be estimated from the internal consistency of the data. In June, 10-μsec baud lengths were used; from July on the data were obtained with 6-μsec bauds.

No other data for this region are yet available. A few craters, but no related feature, may be seen in the far-encounter Mariner photographs of this region.

Referring now to Fig. 1c, we see a small but nearly 2-km-deep feature (G) at 167° that correlates well with the northern limit of Titanum Sinus at the boundary between Mare Sirenum and Memnonia. At 149° (feature H) a crater can be seen that corresponds to a very weakly defined shading in the far-encounter photographs. The dominant features of Fig. 1c, however, are the twin "peaks" in Phoenicis Lacus at 122° and 100°. These features are unusually well defined, and the latter in particular offers a surface of extremely high radar reflectivity. The strongest echo strength obtained in the entire data span was observed at 108°. As mentioned earlier, these features appear to be a continuation into the southern hemisphere of the major topographic ridge seen at earlier oppositions in the northern hemisphere.

Repeated attempts to observe echoes in the longitude region 125° to 121° have been unsuccessful. The possibility that echoes from a region of this average slope (1°) might be displaced sufficiently in frequency as to lie outside the basic processing bandwidth has been ruled out by looking for echoes in frequency windows adjacent to the central one. Apparently the surface in this region is either exceedingly rough at the scale of the wavelength used or of extremely low intrinsic reflectivity (or it has a combination of these properties). The short gap evident at 98° was caused by a system failure and has been filled by (unremarkable) observations since the preparation of Fig. 1c. The downslope of the second peak extends from 95° to 80° longitude; it is strongly reflective and falls off smoothly. It is an area apparently free of even small craters. No optical features of prominence can be discerned over the longitude region from 140° to 80° at this latitude.

A surprising result of these observations is the failure to observe any correlation between regions of high radar reflectivity and optically dark areas. Such a correlation has been observed at northern latitudes (*1, 2, 8*), but it is expected that with the inclusion of these new data the composite correlation may disappear (an exact calculation has not yet been performed).

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4. Negative values of latitude correspond to south Martian latitude; all longitudes are given as increasing to the west. (These are the standard International Astronomical Union conventions.)
5. Observations made subsequently suggest that the topography at longitudes slightly west of (that is, greater than) 60° is shown as 0.3 km too low, whereas the topography at longitudes slightly east of (less than) 60° is shown as 0.3 km too high, as compared to the average. The intervening topography would be proportionately less affected.
6. The general behavior of the surface height variations in the region extending eastward from 40° to 350° longitude is consistent with earlier deductions made from the Mariner ultraviolet spectrometer measurements [C. A. Barth and C. W. Hord, *Science* **173**, 197 (1971)].
7. The altitude transition as this edge passes through the subearth point occurs in less than 20 seconds of time, which offers the attractive possibility of extremely accurate cartographic calibration.
8. R. B. Dyce, G. H. Pettengill, A. D. Sanchez, *Astron. J.* **72**, 771 (1967); R. M. Goldstein and W. F. Gillmore, *Science* **141**, 1171 (1963); see also C. Sagan, J. B. Pollack, R. M. Goldstein, *Astron. J.* **72**, 20 (1967).
9. Figure 3 is reproduced by permission of Mr. C. A. Cross of the Rand Corporation (Rand Publ. R-757-NASA).
10. We thank the staff of the Haystack Observatory for their valuable contribution to an often tedious observing program. Particular appreciation is owed to the observers H. H. Danforth, J. J. Kollasch, and B. G. Leslie, as well as to R. A. Brockelman for development of the computer program used in observation. The improved instrumentation that made possible a delay resolution of 6 μsec was developed by J. Levine and R. P. Ingalls. The Haystack Observatory is operated under agreement with the Massachusetts Institute of Technology by the Northeast Radio Observatory Corporation with support from NSF grant GP-25865 and NASA grant NGR-22-174-003.

21 September 1971; revised 4 November 1971

Mars Radar Observations, a Preliminary Report

Abstract. *Radar observations of a narrow belt of the surface of Mars, centered at 16° south latitude, show a very rugged terrain, with elevation differences greater than 13 kilometers from peak to valley. For nearby points, the relative altitude is measured to 40 meters at best; the precision is worse for points at different latitudes, or widely separated in longitude, because of orbital uncertainties. Some of the larger craters have been resolved, and their depth and, in some cases, the height of the raised rim have been measured. Where high resolution photographs are available, the correlation is excellent.*

Mars, during its opposition this summer, passed closer to the earth than it will again for 17 years. We have taken advantage of this favorable approach to conduct an extensive set of radar measurements at the Jet Propulsion Laboratory's Goldstone Tracking Station.

Mars has been studied by radar at each opposition since 1963 (*1, 2*). The current set of measurements, however, yields data of far greater precision. Part of the improvement is due to the much closer approach this time (radar obeys an inverse fourth power law), and part to improved radar capability. Measurements are still being made as of this writing. We publish these preliminary findings because of the current surge