NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-825

The Effect of the Interplanetary Medium on S-Band Telecommunications

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The space within our solar system, which is normally thought of as being empty, we know, in reality, is not, although it is extremely tenuous. Consideration of the accumulated effects on microwave signals traveling through many millions of miles of space becomes important. Mechanisms have been theorized for the generation of multipath, rotation of polarization, deflection, attenuation, and other telecommunication problems in space. There is no a priori way of assessing the magnitude of the effects of the interplanetary medium on telecommunications. However, since the advent of radar astronomy, we have a method of measuring these influences under the actual conditions of interest. The medium has been tested by sending waves through it, then analyzing the echoes reflected from the planets. The techniques used and the results obtained at S-band over a considerable area of the plane of the ecliptic are described in this paper.

Author

I. INTRODUCTION

The telecommunication system used with a deep-space craft serves two major functions: One is the transmission of information to and from the spacecraft. The other is making measurements from which the position and velocity of the spacecraft can be determined, not only to provide location tags for the scientific data collected but, also, as a means for guiding the spacecraft to its desired destination.

The propagation properties of interplanetary space, which is not a void, have profound effects on both of these functions. Mechanisms have been theorized for the generation of multipath, change of sense of polarization, deflection, attenuation, and other telecommunications problems in space. There is no a priori way of assessing the magnitude of space medium effects, but it was obviously of first importance to determine such effects before launching spacecraft to the planets. Accordingly, a number of planetary radar experiments have been conducted at various times since 1961; one of the purposes was to determine the propagation properties of the interplanetary medium at S-band near the frequencies to be used for spacecraft telecommunications. This report describes the measurements made, the conclusions to be drawn from the data, and gives tracking data from the *Mariner II* and *Mariner IV* spacecraft that confirm some of the conclusions.

II. HISTORY OF RADAR EXPERIMENTS AND *MARINER* FLIGHTS

The first JPL planetary radar experiments were in 1961 with Venus as the target; they were conducted near the time of that planet's closest approach to Earth. Equipment used was the bistatic radar that had been used for *Project Echo*, two 85-ft antennas, a 10-kw transmitter, and a receiver with a maser amplifier. The frequency selected was 2388 Mc, which was near the operating frequency planned for future spacecraft. This experiment demonstrated the feasibility of using microwaves for interplanetary tracking and communications.

The first successful interplanetary spacecraft, which was launched August 27, 1962, flew past Venus on December 14 of that year. The frequencies used were 890 Mc on the up-link and 960 Mc on the down-link. Originally, these frequencies had been chosen for the *Ranger* spacecraft because the S-band components were not sufficiently developed. Even so, the *Mariner II* verified the results of the planetary radar experiment by maintaining communications with the Earth until the attitude stabilization system expended its gas, 20 days after Venus encounter.

During 1962, near the time of closest approach of the planet, a second Venus radar experiment was conducted; this one was during the *Mariner II* tracking. The radar was a monostatic version of the 1961 radar with some improvements, particularly in system temperature. The results confirmed the findings of the 1961 experiment.

Early in 1963 the first experiment was conducted with Mars as a target. This was made possible by the addition of a 100-kw transmitter to the radar used on Venus in 1962. In May of 1963 a second experiment was conducted with Mercury as a target.

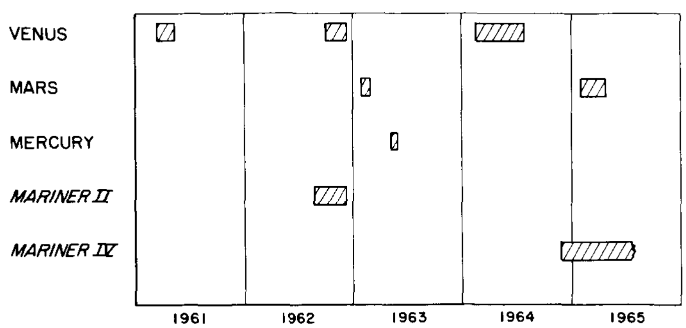

Fig. 1. JPL radar and tracking experience

During the latter part of 1963, extensive rebuilding of the radar resulted in a considerable improvement (a decrease from 65°K to 30°K) in system temperature and in advanced signal processing methods. The following experiment was a lengthy one, lasting over five months; the long duration was possible because of the greatly improved radar performance.

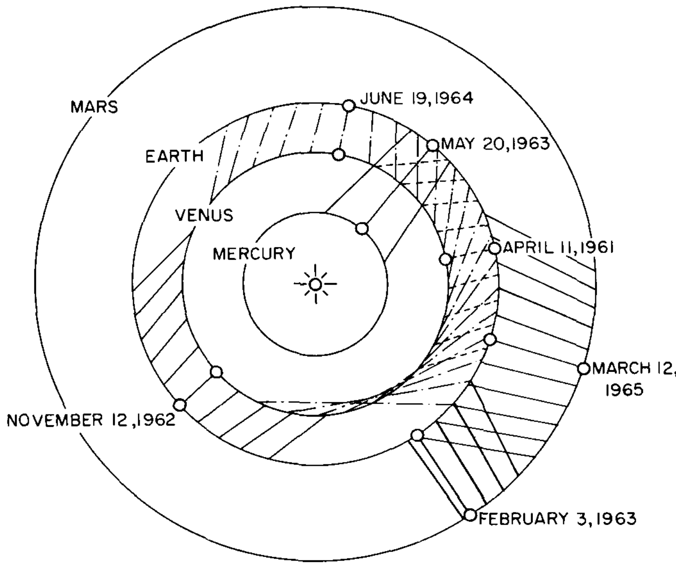

Fig. 2. Area of the ecliptic probed by radar

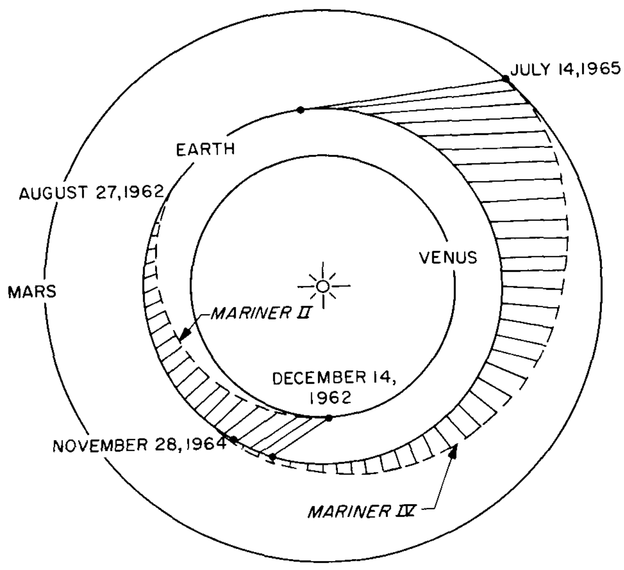

Fig. 3. Area of the ecliptic probed by tracking

The latest experiment was conducted during February, March, and April of 1965 with Mars as a target; this activity took place during the flight of *Mariner IV*, which was launched on November 28, 1964, and flew past Mars on July 14, 1965. Duration of the aforementioned experiments and of the *Mariner* tracking are shown in Fig. 1.

As a result of the combined radar experiments and *Mariner* tracking, a significant portion of the plane of the ecliptic has been probed. Figure 2 shows the region probed by the several radar experiments, all at 2388 Mc. Figure 3 shows the region probed by the *Mariner* tracking. The *Mariner II* tracking was done at L-band using 890 Mc on the up-link and 960 Mc on the down-link. The *Mariner IV* used S-band, 2115 Mc on the up-link and 2295 Mc on the down-link. Together, the radar and spacecraft tracking have covered the region between the orbits of Venus and Mars fairly well.

III. ATTENUATION

The inverse square law is usually assumed in the design of deep-space communications. But the question arises as to whether this law remains valid over distances of millions of kilometers. Perhaps there is an absorption effect that must be accounted for in such a design. Insofar as S-band is concerned, the planetary radar experiments have answered these questions for a considerable area of the ecliptic plane. For these experiments, the radar was configured as a radiometer and the total power of the echo was measured. Such measurements were made of Venus (over several conjunctions), Mercury, and Mars. The results are expressed in terms of the radar cross section of the target plane. Radar cross section is a function of the object and is, thus, independent of transmitter power, receiver sensitivity, and distance (the latter *only* if the inverse square law is valid). Figures 4, 5, and 6 are plots of the measured radar cross sections of Venus, Mercury, and Venus (1½ yr later).

If space had no attenuation effect, the radar cross sections would be constant. Of course, some fluctuations must be expected because of the extremely minute amount of power contained in a planetary echo, which is immersed in relatively strong random noise. Additional fluctuations are caused by rotation of the target planet, bringing into view surfaces of possibly different reflection characteristics. However, if an unexpected space loss

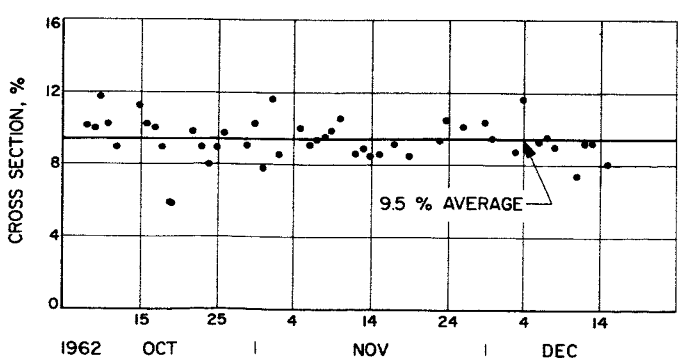

Fig. 4. Radar cross section of Venus, 1962

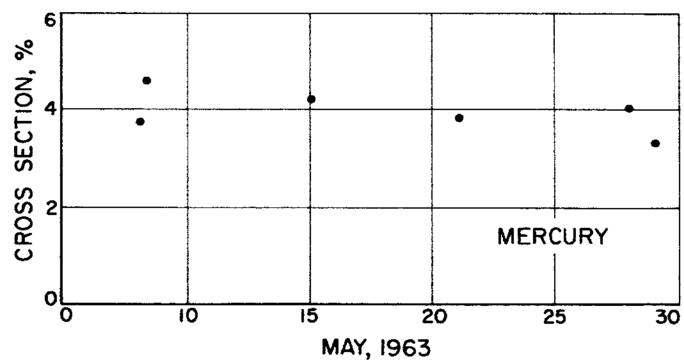

Fig. 5. Radar cross section of Mercury, 1963

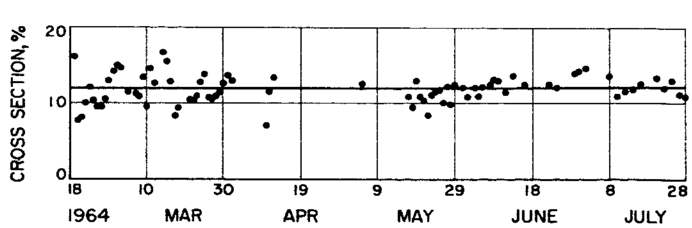

Fig. 6. Radar cross section of Venus, 1964

exists, the cross section would diminish with distance. The radar is a sensitive instrument for this measurement, as the wave must propagate through the medium twice. Figure 7 shows the radar cross section of Venus replotted, with distance as the abscissa.

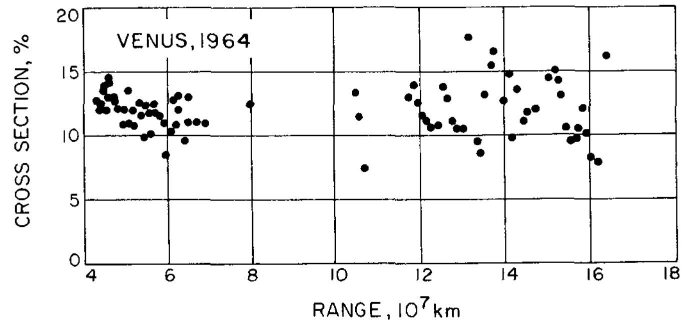

Fig. 7. Radar cross section as a function of range

In all of these figures, it can be seen that there was no measurable space loss—even to distances greater than 160×10^6 km.

The *Mariner* spacecraft tracking experiences confirm the results of the radar experiments concerning the attenuation of the interplanetary medium at microwave frequencies. The *Mariner II* spacecraft used L-band frequencies, but the results are consistent with the radar results. Figure 8 shows the down-link received signal strength for typical tracking intervals during the flight. The nominal signal levels were computed from measurements taken in the spacecraft before launch and based on the assumption that propagation was through free space. The discrepancy between the nominal and the measured signal level is due partly to changes in the spacecraft equipment caused by launch and exposure to the space environment and partly to drifts in the ground equipment and difficulties in calibration. Since experience with spacecraft equipment under test indicates that it is quite stable and the transmitted power is monitored and telemetered back to the Earth, most of the discrepancy must be attributed to the ground station and the great difficulty in making accurate calibrations at these signal levels. However, even though there is a discrepancy between the measured signal level and the expected signal level, there is no significant trend to the data which can be attributed to the presence of a lossy medium in interplanetary space.

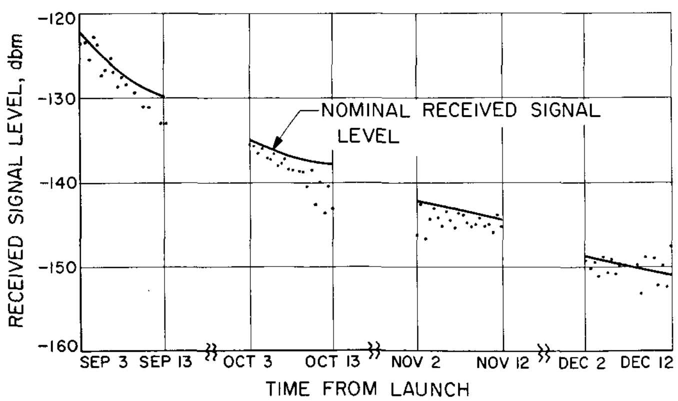

Fig. 8. *Mariner II* tracking data

Typical tracking data from the *Mariner IV* are shown in Fig. 9. The frequency range here, 2115 Mc on the up-link and 2295 Mc on the down-link, is much closer to the radar frequency (2388 Mc). The data for the first segment were taken when the spacecraft was transmitting on its low-gain antenna, so the signal level is lower than the others which were taken when the spacecraft was transmitting on its high-gain antenna. The irregularities in the nominal signal level are due to the antenna pattern.

In the cases of both spacecraft, the data are offset from the nominal data by several db, but a good fit could be obtained merely by displacing the nominal value. In the case of *Mariner IV* the skew of such a fit would certainly be less than 1 db. From these data it can be inferred that the loss due to the medium itself, as distinct from the loss due to the geometry, is less than 1 db over 200 million kilometers—truly a lossless medium!

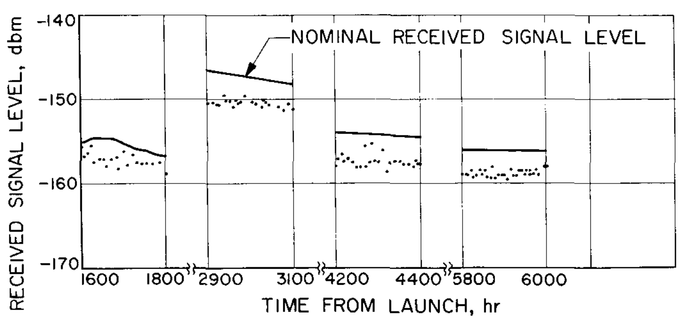

Fig. 9. *Mariner IV* tracking data

IV. POLARIZATION

A subtle, but potentially disastrous, type of interaction between radio waves and the interplanetary medium has been proposed by Lusignon (Ref. 1). According to this mechanism, protons driven from the Sun at relativistic speeds can change the sense of polarization of a radio wave from, say, right-hand circular polarization to left-hand. The implied hazard is serious. An antenna that is set to receive an expected type of polarization would not be able to receive a signal at all were the polarization to become reversed during transit across space.

A method of utilizing the planetary radar for determining the magnitude of this effect was devised, as follows. A spectrally pure, right-hand, circularly polarized wave was beamed at Venus. Echoes were observed in both right and left circular polarization, and spectrograms of these echoes were produced. Analysis was complicated by the fact that Venus, itself, as well as the space medium under investigation, causes changes in the polarization of the echo. Most of the signal will be left-hand circularly polarized (having been reflected only once), but some will be in the right-hand sense (double, or other even-order reflections).

However, it is possible to separate the Venus-induced depolarization from that induced by the medium, because the spectra of the two polarizations of a Venus echo have quite different shapes. Most of the single reflections occur near the sub-Earth point, where there is little doppler broadening of the spectrum. Consequently, this spectrum shows a tall central peak. On the other hand, double reflections occur more uniformly over the surface; the resultant spectrum is much wider, and the central peak is completely lacking.

Figure 10 is a pair of spectrograms (one normal polarization, one reversed) taken of Venus near the conjunction of 1964. The total echo power in the reversed case is less by a factor of 18, so that spectrum has been drawn to a magnified scale (times 30). The two peaks in that spectrogram are the result of topographic features on the planet Venus. They were seen to move slowly across the spectrograms, from the high frequency side to the low, carried by Venus' rotation. Notice that the central peak is completely missing in this mode. The error flag represents ± 3 times the standard deviation imputable to random fluctuations.

Any mechanism of the medium that changes the sense of polarization would cause some fraction of the spectrum with the high central peak to be superposed on the other spectrum. No such peak can be seen in the spectrum of Fig. 10, nor were there any observed in any of the measurements taken during the two months about the 1964 Venus conjunction.

We may, therefore, place a severe upper limit on the magnitude of any such depolarizing effect. Reasoning that if a peak of 3σ magnitude were present, it would be observed, we can establish the limit of the effect as $<1/1250$ parts. That is, the amount of power coupled from one mode of polarization to the other during the entire round trip flight to Venus and back was less than -31 db.

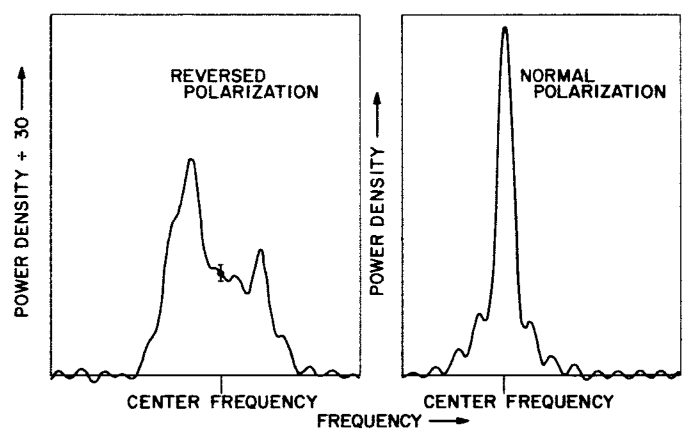

Fig. 10. Venus spectrograms, normal and reversed polarization

V. PATH LENGTH

One of the two major uses of a spacecraft telecommunications system is to gather data from which the trajectory of the spacecraft can be computed. The trajectory is used to provide location tags for the scientific data collected and, projected into the future, as a basis for guiding the spacecraft to its desired destination. This use of ground-based radio guidance rather than, for example, on-board navigational equipment, results in considerable simplification of the spacecraft. However, it would not be feasible were the tracking data from the telecommunications system inadequate. The data that can be obtained are of three kinds: angle, doppler, and range. Angle data are useful only during the very first part of a mission because of lack of resolution. The doppler data are very powerful and quite adequate in cases in which the model on which the celestial mechanics is based is well determined. In cases in which the model is not so well determined (for example, the lunar or planetary mass and motion accuracy required for precise orbiting), range measurements are also needed. It was determined that, if the propagation path of the microwaves were in fact along the geometrical path, it would be possible to measure the doppler and range with sufficient accuracy to guide a spacecraft. Therefore, one of the purposes of the planetary radar experiments has been to examine the path length of microwave signals in interplanetary space.

The technique that has been used to examine the path length is to assume that the microwaves follow a geometrical path as though they were traversing truly free space and to look for discrepancies in the measurements. Three kinds of variations in path length that might have been expected to occur are: a short-term variation in path length, a long-term variation in path length, and a systematic variation in path length with distance.

The power spectrum of the radar return from Venus provides direct evidence concerning both the short- and long-term variation of path length. In measuring the power spectrum the local oscillator is continuously tuned according to an ephemeris so that the signal presented to the spectrum analyzer is centered at some fixed frequency. The purpose of the ephemeris-controlled local oscillator is, of course, to remove the doppler shift due to the relative motions of the radar and the target planet. The important point is that the ephemeris is computed with the assumption that the microwaves are traveling in free space. Figure 11 shows a typical power spectrum taken of Venus over an observation time of 31 min. We

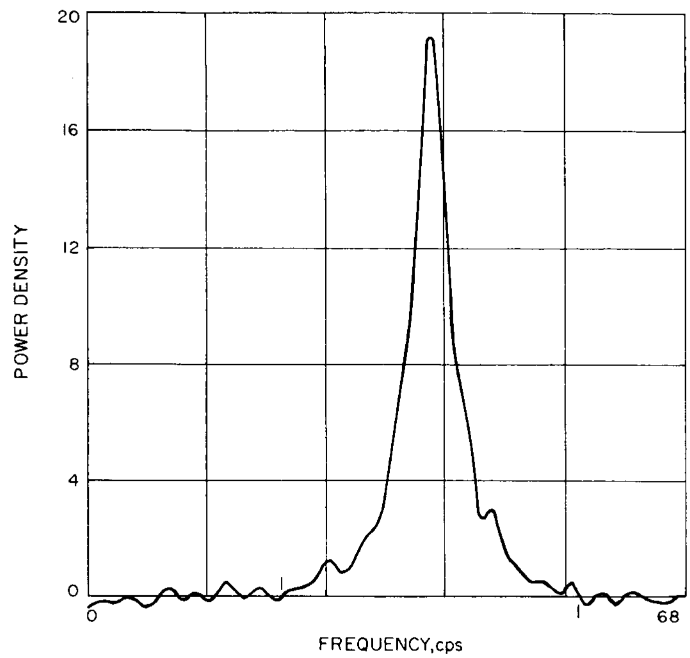

Fig. 11. Venus spectrogram averaged over 31 min, November 10, 1962

are fortunate in the shape of the Venus spectrum. The central peak is very sensitive to changes in the path length (or to imperfections in the measuring equipment or ephemeris, for that matter). The width of the peak is only about 5 cps. From this, we may infer that the change in path length relative to that predicted is less than 5 wavelengths/sec. Since a wavelength is 12.5 cm and the path length was twice the 42×10^6 km distance from Earth to Venus at that time, the variation in path length was less than 1.5 parts in 10^{12}/sec.

The spectrum of Venus shown in Fig. 12 is even more startling. It is a composite of 135 hr of observation over the period of February 19 through March 30, 1964. The many spectrograms averaged together were averaged by computer, with no corrections made to their center frequencies. The center peak is nearly 11 cps wide, but the effect is due mostly to the broadening of the entire spectrum. The width of the entire spectrum is determined by the rotation of Venus about its axis and the width varies with the aspect from which the planet is viewed. The total width of the second spectrum is approximately 100 cps, while the width of the first is only 35 cps. Thus, the width of the peak in the spectrum is relatively narrower than that in the first.

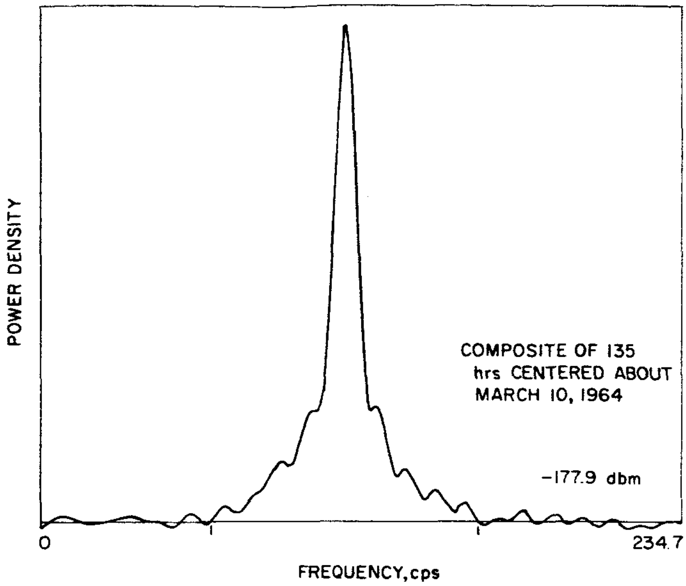

Fig. 12. Venus spectrogram averaged over 135 hr

Tracking data were used as the basis for guiding the spacecraft to their destinations in both the *Mariner II* flight to Venus in 1962 and the *Mariner IV* flight to Mars in 1965. Not only did the guidance perform satisfactorily, but the tracking data provided confirmation of the radar results. In particular, the doppler data from tracking the spacecraft provide an even more sensitive indicator of path-length change than does the radar power spectrum because, except for the doppler shift, the signal returned from the spacecraft is monochromatic and coherent, with the signal being transmitted from the ground. The measured doppler shift is then an accurate measure of the rate of change of path length, and the measured doppler may be compared precisely with that computed, using the assumption, among others, that the path is in free space. Many such comparisons were made. A typical figure for *Mariner II* is that the measured radial velocity agreed with the computed radial velocity within 3 cm/sec at a distance of 50×10^6 km over periods of a minute. This implies that the actual path length is changing relative to the geometrical path length by no more than 1.6 parts in 10^{13}/sec.

A typical set of doppler residuals from a *Mariner IV* tracking pass is shown in Fig. 13. Each day an orbit is fitted to the tracking data and the residuals plotted out, hour by hour, by the computer. The residuals show the variations of the doppler relative to that predicted by the orbit. The fitting process removes any average offset between the doppler shift predicted from geometrical considerations but does not remove the short-term variations. Because the doppler is counted for a minute, the resolution is to a fraction of a cycle. The largest variation is less than 0.030 cps or 0.36 cm/sec. This is somewhat less than 1 part in 10^{13}/sec.

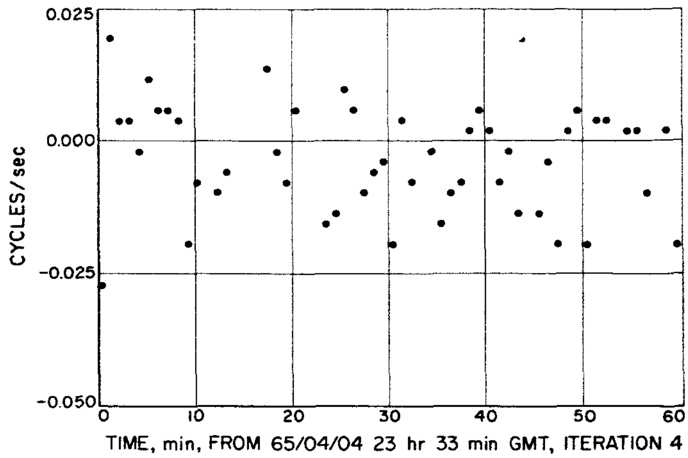

Fig. 13. Typical *Mariner IV* doppler residuals

The doppler measurements provide a means for determining the rate at which the actual path may vary relative to the geometrical path; range measurements provide a means for determining the amount. The several Venus radar experiments have all included ranging experiments. A complete discussion of the ranging technique would be out of place here. Suffice it to say that the transmitted signal is modulated by a binary pseudo-random waveform. By crosscorrelation, the phase of the returned modulation is determined relative to the transmitted modulation. Since a very accurate clock is used to time the transmitted modulation, the time displacement between the two is accurately determined and, therefore, the time of flight. With the assumption that the propagation velocity is constant, the actual path length can be compared with the geometrical path length.

The results of the 1961 Venus ranging experiments are shown in Figs. 14 and 15. The reference to open-loop ranging and closed-loop ranging pertains to two somewhat different techniques that were used for determining the time of flight, and the two ephemerides pertain to the Duncombe ephemeris and the Newcomb corrections to the Duncombe ephemeris (Refs. 2, 3). At the time of this experiment there was considerable uncertainty about the value of the Astronomical Unit (AU) and about the accuracy of the ephemerides of the Earth and Venus, which is why the data were reduced in this particular way. The important point to be noted here is that any trend in the data is quite small. There is an average offset of some

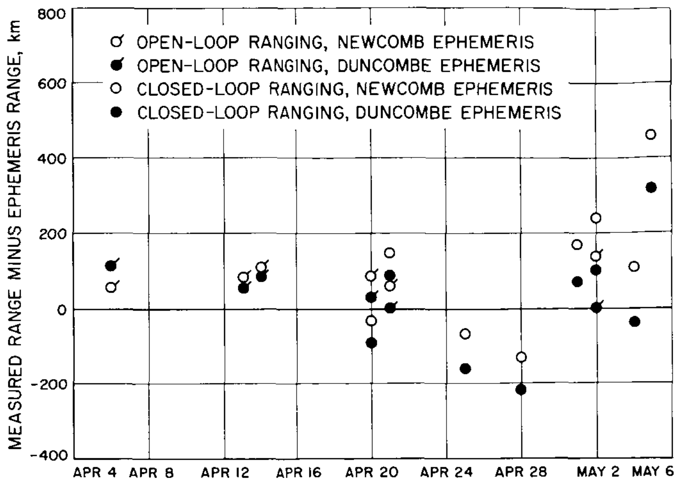

Fig. 14. 1961 Venus range measurements vs time

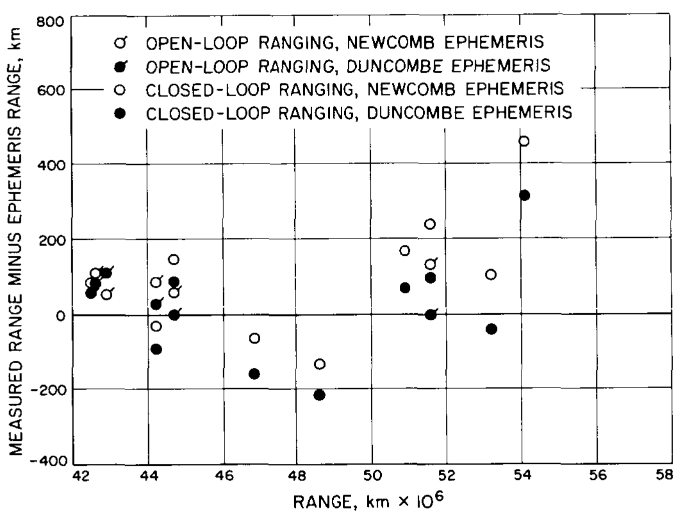

Fig. 15. 1961 Venus range measurements vs distance

100 km in the measured range relative to the geometrical range, but this is attributed to flaws in the ephemerides. The trend in these residuals would be something like 40 km over a time interval of 28 days or 12×10^6 km of range. A best fit line could be passed through the data in order to make a more precise statement, but two difficulties are encountered. The one is that the data at the longer distances are considerably more noisy than those at the shorter distances, and no adequate statistical model exists for weighting the data. The other is that the shape of the line to be fitted is not known, since it depends on the particular flaws which exist in the ephemerides. Even so, it is reasonable to say that the long-term drift in actual path length relative to geometrical path length is less than 3.5 parts in 10^{10}/sec or 1 part in 10^6/unit distance. Furthermore, the average discrepancy between the actual path length and geometrical path length is less than 2 parts in 10^6.

In one sense the ranging results from the 1962 Venus experiment (shown in Figs. 16 and 17) were disappointing because they showed a larger difference between measured distance and computed distance than did the 1961 experiment. This is not really a proper conclusion. Prior to the 1961 experiment, the accepted value of the

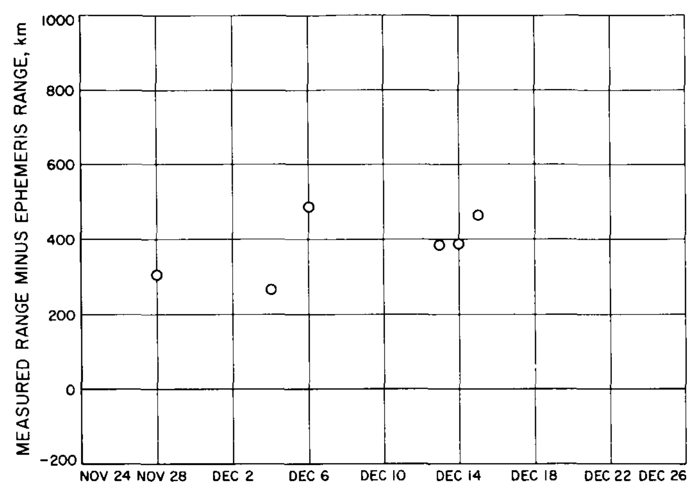

Fig. 16. 1962 Venus range measurements vs time

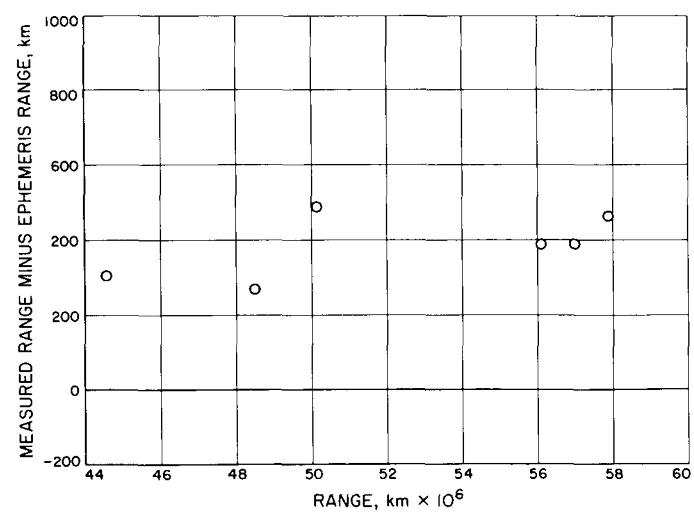

Fig. 17. 1962 Venus range measurements vs distance

AU was in error by several tens of thousands of kilometers. When the value was adjusted, as indicated by the radar results, the agreement shown in Figs. 14 and 15 was obtained. However, all of the error in the ephemerides was not in the value of the AU, and the other errors forced the 1962 results to be off. Here again, it is evident that there is no large-scale drift with time or with distance.

By the time of the 1964 Venus radar experiment, a new method of measuring range had been devised (Ref. 4) which was capable of making much better measurements. The results of the 1964 Venus ranging experiment are shown in Figs. 18 and 19. From these figures it is evident that there is a definite trend to the data. Analysis shows that this trend is the kind of trend that would exist if there were an error in the orientation of the orbital ellipse of Venus, and much work is being done to attempt to refine the values of the orbital elements. If this premise is accepted, then the data can be compared with a best fit line to determine the maximum rate at which the actual path varies relative to the geometrical path. The rms variation of the data from a straight line over the first portion of the experiment is approximately 6 km at an average distance of 50×10^6 km, and some of this variation may be due to surface relief on the planet. There is a strong temptation to continue on and draw conclusions about the actual variations in path length based on reasonable assumptions about the errors that must exist in the ephemerides. However, the only real conclusion is that the path length can be measured more accurately than it can be computed, possibly by as much as two orders of magnitude. From an engineering point of view this means that ground-based radio guidance of spacecraft is not limited at this time by any discrepancy which may exist between actual path length and geometrical path length.

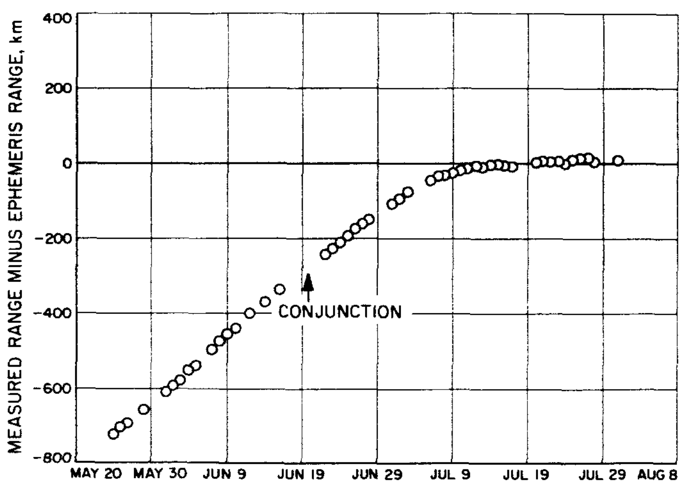

Fig. 18. 1964 Venus range measurements vs time

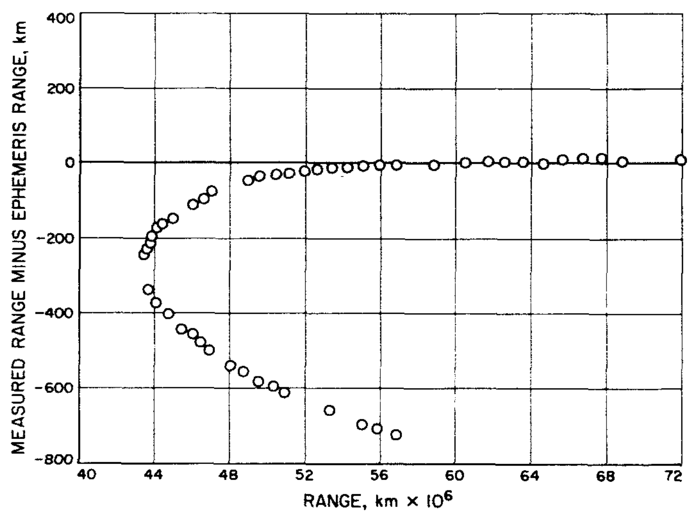

Fig. 19. 1964 Venus range measurements vs distance

VI. SUMMARY OF CONCLUSIONS

From the results of the several radar experiments, it may be inferred that the attenuation of the interplanetary medium to S-band between the orbits of the Earth and Venus is certainly less than 1 db at distances up to 170×10^6 km. The *Mariner II* gave similar results at L-band and the *Mariner IV* showed the attenuation of the interplanetary medium between the orbits of the Earth and Mars is less than 1 db at distances over 200×10^6 km.

In addition, radar experiments on Venus show that any mechanism which might reverse the sense of the polarization of circularly polarized signals at S-band is less than 0.1% effective. The tracking of the *Mariner* spacecraft does not yield direct information on this matter, but the tracking data are consistent with these conclusions.

The path length of S-band signals in the region between the orbits of Venus and Earth has been shown by the radar experiments to be essentially the same as the geometrical path length. Specifically, the radar shows the path length varies relative to the geometrical path length by no more than 1.5 parts in 10^{12}/sec. The *Mariner* tracking improves this figure to less than 1 part in 10^{13}/sec. Range measurements on Venus show that the difference between the electrical and geometrical path lengths is less than 2 parts in 10^6 and that much of this uncertainty is probably due to flaws in the mathematical model used to compute the geometrical path length.

The general conclusion is that the interplanetary medium in the region between the orbits of Venus and Mars has no deleterious effects on communications with or tracking of spacecraft using S-band signals.

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