Exploration of Venus by Radar

Precision range and velocity data can be obtained with a supersensitive radar receiving system.

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Abstract. A new tool is available to scientists for exploring the solar system, and modern-day explorers are discovering new worlds by radar. On 10 May 1961 a radar signal was beamed at the planet Venus, and for the first time in history the return echo was detected within a few minutes. A new value for the Astronomical Unit has been determined. The data indicate that Venus rotates slowly and that it is a better radio reflector than the moon.

Radar contact with the planet Venus was established almost daily from 10 March to 10 May 1961 at the Goldstone tracking and communications station of the Jet Propulsion Laboratory, California Institute of Technology (*1*). Hundreds of hours of recorded data about the planet were collected.

The principal result of the experiment was the determination of a new value for the Astronomical Unit. At present our best value is 149,599,000 kilometers, and we believe this number is good to 1 part in 10^5, or approximately 1500 kilometers. However, further data reduction and analysis will probably reduce the uncertainty in the value to ±150 kilometers by July or August.

In addition, spectral analyses of the reflected signal indicate that Venus rotates at an extremely slow rate, perhaps as slow as once every 225 days, which is the number of Earth days required for Venus to orbit the Sun.

Venus appears to be a much better radio reflector than the Moon. Relative to a polished conducting sphere of equal size, Venus appears to have a reflectivity of 10 to 15 percent at 2388 megacycles per second (Mcy/sec). Similar experiments on the Moon with our continuous-wave bistatic radar produce reflectivity numbers of 2 percent.

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Experimental Conditions

The polarization of the transmitted signal was normally right-hand circular, and the receiving antenna was designed to accept reflected signals that were left-hand circular. When the polarization of the transmitting antenna was reversed, the reflected signal was approximately 12 decibels (db) lower than the signal with normal polarization. Had Venus been a polished conducting sphere, the mismatched polarization would have produced a signal 20 db lower (due to the ellipticity of the transmitting and receiving feeds). Since similar experiments on the Moon produced a signal which was also 12 db lower for the mismatched polarization, this finding probably indicates that the surface roughness of Venus is quite comparable to that of the Moon when the roughness is commensurate with the wavelength of the radio-frequency signal.

For the experiment the Goldstone station was converted from its normal configuration to a high-capability planetary radar. The characteristics of the radar (see Table 1) were as follows: The transmitter had a continuous-wave output of about 13 kilowatts at a frequency of 2388 Mcy/sec. This radio-frequency power was fed to an antenna 85 feet in diameter which concentrated the signal into a conical searchlight beam about 0.35° wide in the direction of the planet. Venus was illuminated to the extent that about 10 watts were intercepted by its surface. Apparently about 9 of the 10 watts were absorbed, and the remaining 1 watt was scattered more or less uniformly in all directions. The 85-ft (diameter) receiving antenna, located about 7 miles from the transmitting antenna and shielded by natural terrain, intercepted the return signal and delivered to the receiver a typical input signal of about 10^{-20} watt, or −170 dbm. The capability of the receiver system in a typical configuration (see Fig. 1) was such that the 10^{-20}-watt signal was about 10 times stronger than the noise; or, in other words, with a typical threshold of −180 dbm the signal-to-noise ratio was 10 db. The total system temperature with the antenna aimed at Venus was typically 60°K, and the bandwidth of the receiver was about 1 cy/sec. The contribution to the system temperature, due to the presence of Venus in the antenna beam, was measured to be approximately 0.5°K.

Four different receiver configurations were utilized, and four different types of data were gathered: (i) received signal level, (ii) power spectrum of the reflected signal, (iii) Venus-Earth velocity, and (iv) Venus-Earth range. The signal level and power spectrum data were gathered with open-loop receiver configuration (see also Fig. 1). The velocity and range data were obtained with closed-loop automatic tracking receivers. The signal-level data were used to establish the radio reflectivity of Venus, the power spectrum to determine the rotation of Venus. The velocity of Venus with respect to Earth was measured by comparing the frequency of the Venus-reflected signal with the transmitted frequency. The accuracy of the velocity measurement is 1 part in 10^5 without further data

Table 1. Venus radar system parameters.

Parameter	Value
Unmodulated transmitter power (12.6 kw)	+ 71 dbm
Transmitter antenna gain	53.8 db
Transmitter line loss	0.3 db
$\sigma/4\pi R^2$ at 31 million miles	− 84 db
Power intercepted by Venus	+ 40.5 dbm
$(\lambda/4\pi R)^2$ at 31 million miles	−255 db
Receiving antenna gain	53.5 db
Maximum received signal level	−161 dbm
Apparent reflection and propagation loss	9 db
Typical received signal level	−170 dbm
Receiver threshold (T, 60°K; bandwidth, 1 cy/sec)	−181 dbm
Typical signal-to-noise ratio	11 db

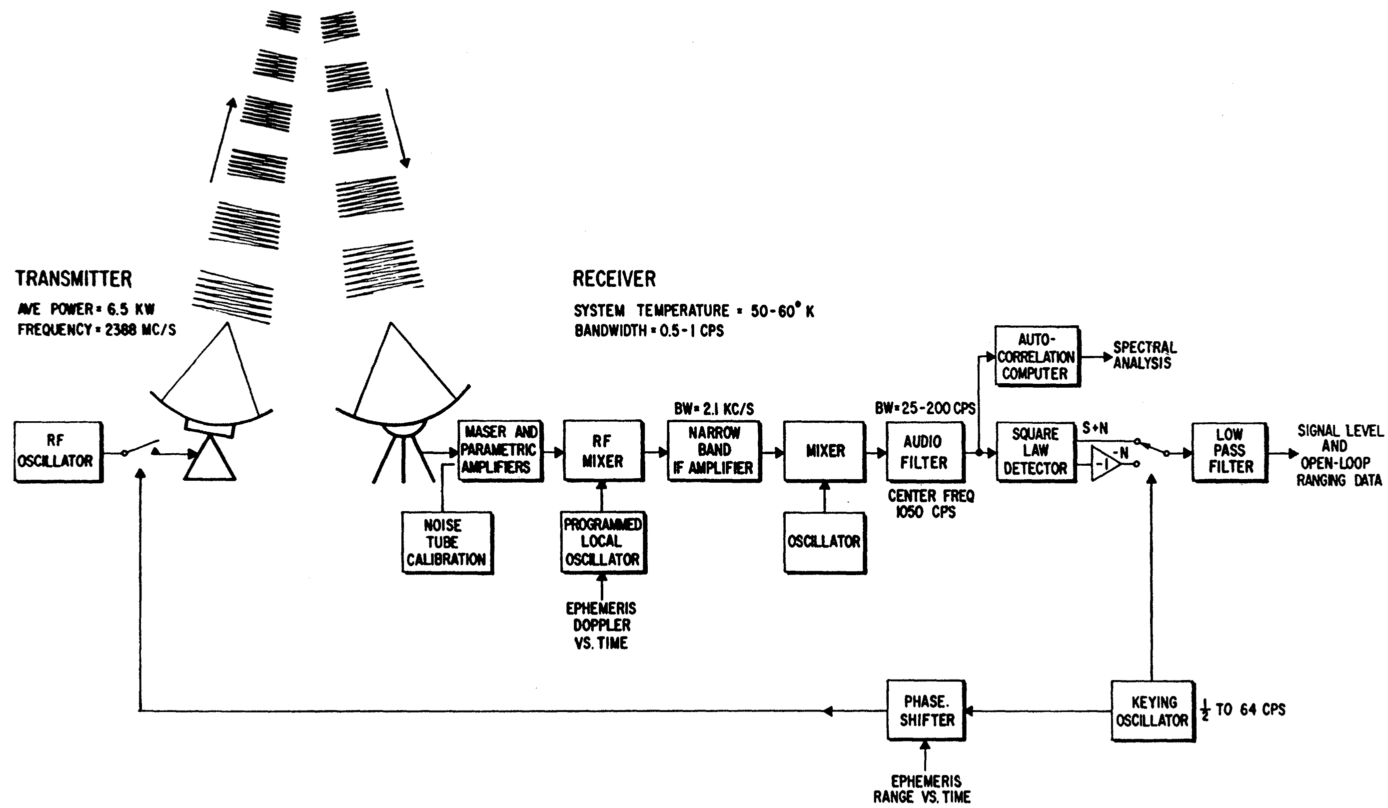

Fig. 1. Venus radar with nonsynchronous open-loop receiver.

smoothing. The width of the closed-loop range gate was 8.2 milliseconds; therefore, we believe that the accuracy of the time-of-flight measurement was about 1 millisecond in a typical round-trip flight time of 3×10^5 milliseconds. Our new value for the Astronomical Unit was determined from both velocity and range data. Both the radio-frequency signal used for velocity determination and the modulation frequency signal used for range determination were derived from an atomic frequency standard which is believed to be accurate to 1 part in 10^9 for the duration of the experiment and easily stable to 1 part in 10^{10} over the flight time of the signal from Earth to Venus and back.

The rotation rate of Venus may be determined from the Doppler spread (see Fig. 2) if the surface is rough enough to send returns from a considerable area on the surface and if the axis of rotation is known. Because the roughness of Venus with respect to our radio signal appears to be similar to that of the Moon, we assumed for the preliminary analysis that the same scattering law is applicable. The measured frequency spread of the Venus echo was about 5 to 10 cy/sec at the 3-db points and appeared to be quite stable over the 2 months' time for the experiment; therefore it was also assumed that the axis of rotation was not pointing directly at Earth. Based on these apparently reasonable assumptions, Venus appears to rotate very slowly, and this estimate of slow rotation rate is, of course, in agreement with other astronomical observations.

Effect on Radar Astronomy

The 1961 radar contact with Venus may be expected to have a significant effect on the nation's planetary program, on the new science of radar astronomy, and on observational planetary astronomy in general. For example, the Venus radar experiment will undoubtedly advance the gathering of significant data about Venus by at least 1½ years. This was accomplished by measuring the exact distance to Venus before the launching of the first Venus probe by the United States. Without this information the first spacecraft would have missed Venus by at least 20,000 miles, and another attempt could not have been made for 19 months. One of the objectives of the first Venus spacecraft, of course, was to establish the value of the Astronomical Unit. Fortunately, the Astronomical Unit has

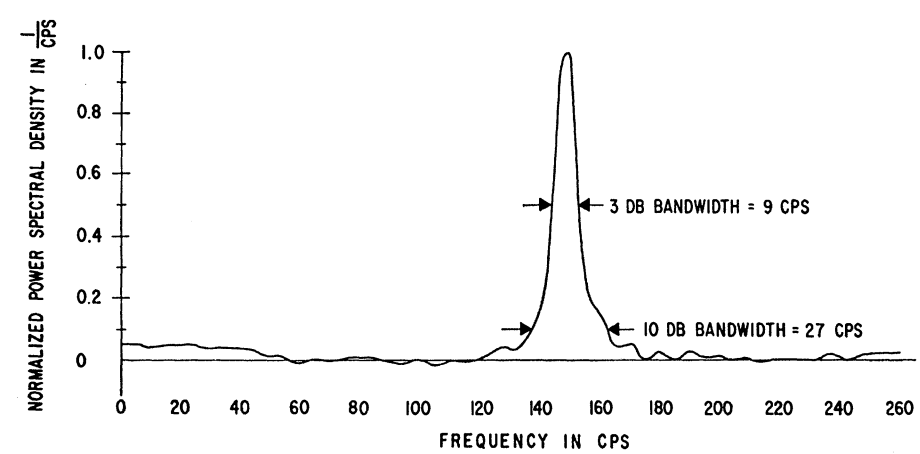

Fig. 2. Venus-reflected signal, 21 April 1961. Spectral analysis, using special autocorrelation computer with nonsynchronous receiver (integration time, 1 hr 23 min).

already been determined and to much higher accuracy than would be possible with a spacecraft, because the very precise angle observations of Venus over many decades can be utilized in the computation.

The Goldstone radar achieved its superior performance principally because it contained a supersensitive receiving system—as opposed to transmitting with extremely high power, for example. For this reason the receiving portion of the radar is presently capable of detecting a 50-milliwatt transmitter located on the surface of Venus at a distance of 30 million miles while radiating its power omnidirectionally. By comparison, the transmitters on the first Explorer satellite had outputs of 10 and 100 milliwatts, and the transmitter on the first lunar probe, Pioneer IV, had an output of 250 milliwatts. This capability will undoubtedly influence the choice of missions for future planetary spacecraft and may be expected to accelerate the landing of a capsule on the surface of Venus to measure temperature, pressure, wind velocity, and other scientific data in preparation for the first manned exploration to the planets.

Until this year the science of radar astronomy had been restricted to gathering and analyzing data principally about the Moon and the Sun. This science has now received new impetus with the gathering of hundreds of hours of data about Venus. The fact that Venus is now within radar range will encourage scientists to search for still more sophisticated techniques to map the surface features of Venus, to determine whether its surface is liquid or solid, and to discover the presence or verify the absence of an ionosphere, a magnetic field, or other phenomena of scientific interest on Venus.

But probably one of the most significant results of this experiment is that we now know how to specify and design a planetary radar observatory which is capable of almost continuous surveillance of our planetary neighbors, Venus, Mars, Mercury, and Jupiter. Prior to this year this information was not known with any degree of certainty. And because the precision range and velocity data of a radar complement the precise angle data obtained from optical devices, we believe that the combination of data obtained by radar and optics will permit the future computation of planetary ephemerides to much greater precision than heretofore believed possible. Such precision will undoubtedly reveal many minor perturbations in the orbits of the major planets, which could make it possible to discover new minor planets and natural satellites of our solar system.

Note

1. The Jet Propulsion Laboratory is operated by California Institute of Technology for the National Aeronautics and Space Administration. The Goldstone tracking and communications station is part of NASA's Deep Space Instrumentation Facility.

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Correlation between Mean Litter Size and Mean Life Span among 12 Inbred Strains of Mice

Abstract. In 12 inbred strains of mice there was no general correlation between litter size and parental life span within strains, although a significant between-strain correlation of +0.69 was found between mean life span of the dams and the mean size of their litters. When data for AKR/J mice, which characteristically die early from leukemia, were excluded, the correlation was increased to +0.90 for the remaining 11 strains. These findings indicate that the correlation is of genetic origin—that is, that genes affecting a dam's life span also affect the size of her litters.

Life span and litter size in mice are components of fitness, both affected by genetic constitution and environment. The present study was undertaken as part of a search for correlates of life span. It is an attempt to determine whether the environmental factors in this laboratory which influence litter size also influence parental life span and whether litter size and parental life span are genetically correlated.

Breeding records and life span data for 12 inbred strains of mice were made available to us through the kindness of Elizabeth S. Russell. These animals were bred and maintained in the pedigreed expansion stocks of the Jackson Memorial Laboratory. All strains had been inbred by brother-sister matings for many generations in this laboratory. Under the system used in the pedigreed expansion stocks, complete breeding records for each mating were maintained. When the breeders reached the age of 11 mo, they were retired and in many cases were set aside in groups of two to five to live out their lives. The pairs usually continued to be caged together until one of the pair died. If the survivor was the male, he was recaged with a surviving female from another pair. In some instances surviving females would be caged together, but in no instance were males caged together because of the fighting habits of males of many strains. The cages were checked once a week for dead animals, and the date of death was recorded. In some cases moribund animals were killed to obtain fresh histological material for determination of disease incidence by strain.

Breeding performance and life span data were tabulated for 1717 mated pairs of mice which had had at least five litters. It is known that litter size generally increases with parity, reaches a maximum, and then declines (*1*). If data from all mice had been included, the resulting mean would have been more heavily weighted by the smaller early litters, and mean litter size would have been partially a function of mean reproductive life. Therefore, only data from pairs having five or more litters were included, and the average litter size per dam was calculated from her first five litters. Life span data were computed for the breeding pairs whose litters were used to compute mean litter size. This procedure tended to result in stratification of the sample in favor of good breeders and longer lived animals, since any

Table 1. Within-strain correlations and strain parameters for the variables, litter size (x in mice), dam life span (y in days), and sire life span (z in days).

Strain	N	Within-strain correlations			Strain statistics (means ± standard error)		
		r_{xy}	r_{xz}	r_{yz}	$\bar{x}$	$\bar{y}$	$\bar{z}$
C57BR/cdJ	135	−0.15	−0.17*	+0.24†	6.34 ± 0.10	551.2 ± 10.6	483.3 ± 10.7
C57BL/6J	377	−0.02	−0.01	+0.14†	5.91 ± 0.06	600.4 ± 7.5	533.3 ± 0.8
129/J	51	+0.25	+0.24	+0.13	5.78 ± 0.15	543.6 ± 16.0	577.8 ± 17.1
RF/J	31	+0.27	−0.18	+0.34	5.48 ± 0.70	513.6 ± 62.8	578.2 ± 64.4
C57L/J	82	+0.06	−0.23*	+0.25*	5.39 ± 0.12	548.4 ± 13.0	538.0 ± 15.6
C3HeB/FeJ	143	−0.19*	+0.01	+0.16	5.37 ± 0.09	543.6 ± 10.8	549.5 ± 10.6
BALB/cJ	164	−0.05	−0.03	+0.25	5.20 ± 0.09	506.8 ± 8.8	494.4 ± 11.0
AKR/J	79	+0.07	+0.16	−0.05	5.20 ± 0.09	319.8 ± 8.6	291.1 ± 6.5
A/J	177	+0.04	+0.08	+0.26‡	4.97 ± 0.07	441.5 ± 7.5	488.0 ± 9.5
DBA/2J	82	+0.06	+0.01	+0.21	4.74 ± 0.10	458.6 ± 11.4	419.7 ± 11.8
DBA/1J	226	+0.02	+0.03	+0.11	4.42 ± 0.06	431.6 ± 5.6	453.1 ± 9.7
A/HeJ	170	+0.07	+0.05	+0.21†	3.91 ± 0.06	395.0 ± 6.5	461.2 ± 9.2
Total	1717	0.00	0.00	+0.18‡			

* $p < .05$ (all two-tail tests). † $p < .01$. ‡ $p < .001$.