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Chapter XIV - Radio Astronomy

Increase in the power and sensitivity of radar systems which were developed for military purposes during World War II has made it possible to detect the "echoes" of man-made transmissions after they have been reflected back from bodies outside the Earth. Study of celestial objects by radar techniques has come to be called radar astronomy and the first such object to be detected in this way was the Moon, in 1946. This year marks the beginning of a new chapter in planetary astronomy in which powerful radar installations, some of them developed primarily for tracking man-made satellites or providing surveillance against possible attack by intercontinental ballistic missiles, are being applied with conspicuous success to the refinement of our knowledge of the solar system. Perhaps the most significant contributions have been a much more accurate figure for the astronomical unit (i.e. the Earth's mean distance from the Sun) than can be obtained by optical means; and new and completely unexpected results on the rates of rotation of the planets Mercury and Venus. From the modification of the original transmissions introduced during the reflecting process it is possible to deduce information about the composition of the surface of the target and perhaps of its atmosphere, and even to map the surface topography. Data of this kind has been of considerable value to the planning of space missions and to the design of instrumentation for them. From the nature of the echoing process, however, an ability to experiment directly with celestial bodies in this way seems likely to be limited to the solar system.

The Echoing Process

In all previous chapters we have been concerned exclusively with the radio waves which arise spontaneously from natural and often powerful processes in celestial bodies: radar astronomy, however, is concerned with the detection and interpretation of specially-generated man-made signals after they have been reflected back to Earth from the celestial body which is being studied. The difficult problems involved become more evident if we consider the transmitter power and receiver sensitivity required to enable the returning echoes to be recognized.

Suppose we have a radar transmitter capable of producing a power output of P_T watts, and feed this to an aerial which has a gain G, that is, concentrates the signal in the desired direction by this factor. The gain of an aerial is a function of its effective area, i.e. $G = 4\pi A/\lambda^2$. Then the signal intensity at a target at a distance D will be $G\ P_T/4\pi D^2$.

Only a fraction of this will be intercepted by the target and reflected or scattered back to Earth, depending on the nature and shape of the scattering surface. If we call this fraction the echo cross-section of the target, σ, then the power per unit area due to the echo signal back at the Earth will be:-

$$\frac{G\ P_T}{4\pi D^2} \times \sigma/4\pi D^2 = \frac{P_T\ \sigma G}{(4\pi D^2)^2}$$

And if we use the same aerial of effective area A to receive the echo then the total power collected (P_R) will be :-

$$P_R = \frac{P_T\ \sigma G\ A}{(4\pi D^2)^2} = \frac{P_T\ \sigma\ A^2}{4\pi\lambda D^4} \qquad (\text{since } G = 4\pi A/\lambda^2)$$

Thus, for any particular radar system the echo strength

(i) increases with the transmitter power and/or the size of the aerial system.

(ii) increases with the echo-cross section of the target, i.e. with its size and reflecting properties.

(iii) decreases as the <u>fourth power of the distance</u>.

The echo cross section of bodies like the Moon and the planets is of the order 0.1 x their projected area, and their detectability relative to the Moon is as follows:-

Target	Minimum Distance (millions of miles)	Relative value of σ/D^4
Moon	0.25	1
Sun	93	$<1 \times 10^{-5}$
Venus	28	2×10^{-7}
Mars	46	1.3×10^{-8}
Mercury	56	1.7×10^{-9}
Jupiter	390	3.3×10^{-10}
Saturn	800	1.7×10^{-11}
Uranus	1700	1.7×10^{-13}
Neptune	2700	2.3×10^{-14}

Up to the end of 1969 the first five bodies on this list have been accessible to study by radar methods: detection of echoes from Jupiter has been claimed by several observers but on the other hand a careful search in 1964 with the 1000 ft system at Arecibo failed to detect any echoes. The possibility of substantially increasing the range of detection by using higher transmitter powers and/or larger aerial systems than are currently in use in the best installations is ruled out by considerations of cost and feasibility. The most promising avenue has been that of improving receiver sensitivity. The minimum echo signal that can be recognized in a receiver, as we saw in Chapter III, is determined by the level of the unwanted noise signals which originate in the components of the receiver itself. It is limited also, of course, by the level of any other signals entering the aerial system, such as those which may be generated naturally by the body whose echoes are being studied, or from the galactic background. In the case of the Sun, for example, the echo signals are superimposed on relatively intense radio waves from the corona. Radar astronomy receivers make use of the best low-noise techniques already in use in radio astronomy, and the substantial delay between outgoing and returning pulse allows the use of long pulses and consequent wide receiver bandwidths. The addition of integration and signal processing techniques enables the detection of echoes of accurately known recurrence frequency that are far below the already reduced background level.

The characteristics of some of the major radar astronomy installations currently in operation are given in Table 1.

Types of Measurements

The original objective of radar was to give warning of approaching enemy raiders and to provide information on their range and bearing for accurate control of gunfire, or their interception by aircraft. During the post war period these facilities have been extended to provide for the interception of intercontinental ballistic missiles and this has necessarily involved the development of larger, more powerful and more sophisticated systems. The application of these systems by scientists in the initial exploratory stages of the space age has led to still further advances, principally in the fields of spectral resolution and signal processing. The various kinds of information that can be derived from the application of radar systems are as follows:

Echo Delay

In the more conventional radar systems the outgoing transmissions are in the form of steep-sided pulses and the time interval between transmitted pulse and received echo can be measured with considerable accuracy. This is limited mainly by the fact that it is not possible to recognize individual pulse echoes from bodies as distant as the planets, and the signals must sometimes be integrated over periods of many hours, representing thousands of individual pulses. An alternative method of operation is by the transmission of continuous waves in which the phase of the wave is suddenly reversed in accordance with a pre-set code, thus simulating the transmission of a series of pulses. The use of the C.W. method with a coded set of phase reversals allows the time delay to the echo to be determined somewhat more precisely, and hence the distance to the echoing body, with a precision of about parts in 10^8. For most targets the performance of pulsed and C.W. systems having the same average power output is approximately equivalent, but the latter are more suitable for the measurement of Doppler shifts, and the associated mapping techniques, as we shall see below.

Because the target planet is roughly spherical in shape the measured time delay will be shortest for echoes reflected from the nearest or sub-Earth point, and will be spread in time corresponding to the increased distance to points on the curved surface (see Fig. 1). The echo returned from a short pulse will thus be greatly elongated, the signal received at any delay time representing echoes from a narrow circular strip of the planet's surface at the range corresponding to that time delay. Figure 2 shows the average shape of the echo from the Moon of a short pulse (30 μsec) at two different wavelengths. To obtain a recognizable echo from more distant bodies it is necessary to sum the signal power contained in hundreds or thousands of individual echoes, i.e. over a period of hours, in order to obtain a recognizable echo. During this time the distance between Earth and the target will have changed due to motions in their respective orbits and accuracies of a high order (several parts in 10^8) can only be achieved if these motions are known accurately enough to enable the changes in echo delay to be predicted so successive echoes can be accurately summed in synchronism.

The application of these techniques has led to a substantial increase in our knowledge of the distances involved within the solar system. The methods of optical astronomy provide a good indication of the scale of the planetary system in terms of the astronomical unit (the a.u.) the average distance of the Earth from the Sun but are not able to pinpoint the absolute value of a.u. to better than 1 part in 1000. Thanks to radar methods however this distance is now known to about 1 part in 10^6, the limit being set by the accuracy with which the velocity of light is known. The precision with which echo time delays can now be measured has, in fact, suggested a new test for the theory of general relativity, aimed at determining the change in the velocity of light when it traverses the gravitational field of the Sun. This involves measuring the difference between the round-trip time for signals to the planet Mercury and back at two different times, one of them being at superior conjunction when the path to the planet just grazes the Sun, and thus involves travel through the Sun's powerful gravitational field both going and returning.

Doppler Shifts

There will, in general, be some relative velocity between the Earth and the planet being studied due to motions in their respective orbits, so that the returning echoes will undergo a Doppler shift corresponding to this relative velocity. In addition, however, the target planet is rotating so that points in one hemisphere are approaching and in the other hemisphere receding at any one time. Doppler shifts are thus introduced from this cause. Echoes from points in the approaching hemisphere are received at a higher frequency than those at the sub-earth point, the amount of shift increasing with displacement from the axis of rotation, as indicated in Fig. 3. Each vertical strip in this diagram is associated with a particular Doppler shift, so that by tuning the receiver to an appropriate frequency echoes can be selected from any desired strip on the Moon. The echoes are also distributed in range because of curvature of the target planet, points at the same range and therefore returning echoes after the same time delay being situated in concentric rings as shown in Fig. 3. At any particular frequency and time delay the echoes recorded come only from the two small areas where the strip and annulus intersect. By varying the frequency and time delay echoes from each echoing region on the target can be studied in turn and thus a radar map of the planet obtained.

The use of Doppler shifts has provided a much more accurate data on planetary orbits and delay - Doppler mapping techniques have led to greatly reformed values of the radii of the planets and their rotational rates - in the cases of Mercury and Venus [illegible] a complete revision of earlier ideas.

Radar Studies of the Moon

Modern radar astronomy had its beginnings in 1946 when de Witt and de Stodola of the U.S. Army Signal Corps first obtained weak echoes from the Moon. They used modified military radar equipment. Bay in Hungary was also successful in detecting lunar echoes at about the same time. In the following year Kerr and Shain in Australia made use of the powerful short wave broadcasting station "Radio Australia" to transmit pulses as the Moon came into the beam normally used for transmissions to North America. They obtained echoes at the relatively low frequencies of 18 and 22 MHz and noted that the signals varied in strength. Relatively slow fading (minutes) they identified as due to variations in the Earth's ionosphere and a faster component (seconds) to the libration or apparent rocking of the Moon as seen from Earth.

The distance to the Moon varies by about ±8% because of the ellipticity of its orbit, but the mean distance is 384,400 Km (238,500 miles) and the mean echo delay 2.56 seconds. Improvements in equipment have made it possible to observe echoes continuously at all ranges out to the Moon's limb. Thus, application of delay-Doppler mapping techniques has made it possible to study the varying reflecting characteristics of the lunar surface, and by this means such features as the rayed craters can easily be identified. A resolution of about 10 Km is obtained by workers at Arecibo, Puerto Rico. The peak in the centre of the echo shown in Fig. 4 is due to enhancement by the large lunar crater Tycho, presumably because its surface is rougher and more dense than the bulk of the lunar surface.

The radar cross section of the Moon is broadly independent of wavelength, its mean value being about 7% of the projected area of the Moon. This implies an average dielectric constant for the material comprising the lunar surface of about 2.8; most of the nstituents of the surface layers are likely to have values roughly double this figure, suggesting that the layers in the immediate vicinity of the surface are porous or loosely packed - a prediction well verified during the subsequent landings on the Moon itself.

The Planets

The possibility and the technical difficulties involved in using radar as a tool for exploring the planets was first discussed by Kerr in 1952. It was not until 1958, however, that systems with sufficient sensitivity to bring the planets within reach began to become available. In that year weak echoes were obtained by the Lincoln Laboratory in the U.S.A. on two separate days: the Doppler shift was that appropriate for Venus and the echoes were probably genuine. By 1961-62 successful attempts to record echoes from Venus had been made in the U.S.A., England and the U.S.S.R.

The radar cross section for Venus lies between 10 and 20% of its projected area. This indicates a significantly higher reflectivity than for the Moon, and leads to a surface dielectric constant of between 4 and 5, consistent with a surface of dry rocks similar to many on the Earth's surface. There are, however, a number of localised regions which return much stronger echoes and hence are presumably much rougher than the rest of the planet. The nature of this roughness is not yet known.

The radar measurements have disclosed the presence of small but systematic errors in our assumed relative positions of the Earth, Venus and Mercury in their respective orbits. Their most surprising contribution, however, has been the revelation that Venus rotates in a retrograde direction, i.e. opposite to that of the other planets, the period as determined from data collected at Arecibo being 247 ± 5 days. There is no obvious explanation for the retrograde rotation: perhaps Venus was originally like the other planets but began to rotate "backwards" following collision with a rather large asteroid.

Mercury

Echoes from Mercury were first reported from the U.S.S.R. in 1962. The scattering cross section is about 6% of the geometric cross section, close to the value obtained for the Moon. The diameter of Mercury derived from radar measurements is 2400 ± 100 Km, in good agreement with the optically-determined value. The major contribution to our knowledge of Mercury which has come from the use of radar techniques is a revision of ideas as to its period of rotation. Previously this was thought to be 88 days, synchronous with the time taken for a complete revolution around the Sun, but delay-Doppler mapping indicates that revolution on its own axis takes 59 ± 5 days, i.e. approximately 2/3 of Mercury's orbital period. This is not inconsistent with Mercury being locked into synchronous rotation, however, because of the eccentricity of its orbit and this period implies that the same face is always presented to the Sun at one point in its path. Mercury is thus unique in having its spin and orbital periods locked in this way. The signal-to-noise ratio is not good enough to provide any details of the surface characteristics, although some areas of enhanced reflectivity are clearly present.

Mars

Mars was first detected in 1963 in both the U.S.A. and U.S.S.R. Its radar cross section varies over the range from 3 to 13 per cent, the average value of 3% implying (as for the Moon) that the surface is not solid rock. The strongest echoes come from a visually dark area known as the Trivium Charontis but there are a number of smooth areas of large extent and on the whole the Martian surface appears to be appreciably smoother than that of the Moon or of the other planets.

The rotational period of Mars is well determined from optical observations to be 24h 37m, and no refinement of this figure is provided from the radar measurements since the mapping techniques are not well suited to such a rapid rotational rate.

Jupiter

During the opposition of Jupiter in October-November 1963 two groups, one at the Jet Propulsion Laboratory in the U.S.A. and the other in the U.S.S.R., claimed to have detected echoes from Jupiter. The signals were extremely weak and evidence for an echo was only obtained after integration over extended periods (22 hours in the case of the U.S.S.R. observations). However, a careful series of observations with the 1000 ft Arecibo dish, using the equipment in its most sensitive mode, during 8 days in November 1964 when Jupiter was closest to the Earth, failed to detect any echoes at all from this planet. Jupiter has an atmosphere which is deep, dense and ionized and thus differs from the other planets from which echoes have already been detected. It seems likely, however, that echoing mechanisms could exist either in the ionosphere or in material suspended in its upper atmosphere.

Future of Radar Astronomy

The earliest use of echo-sounding techniques was for the investigation of the ionized regions of the Earth's upper atmosphere, and somewhat later for the study of meteors, which can be detected by the trail of ionization produced in their wake. Radar astronomy, however, is concerned with the exploration of celestial bodies and hence discussion of these matters has not been included in this review.

There has been a remarkable growth in the power and sensitivity of radar systems developed for research purposes since the end of World War II - an overall improvement, in fact, of more than 10 orders of magnitude. The active programme for lunar and planetary exploration by means of space vehicles by both the U.S.A. and U.S.S.R. has provided a further incentive for improved means of tracking space probes. However, it seems doubtful whether the almost exponential rate of increase in the overall capability of echo ranging techniques can be maintained at this rate, and thus there is no prospect for the forseeable future that planetary exploration by this means can be extended beyond the limits of the Solar System. Perhaps one of the most exciting prospects in view is the collection of enough data to check whether the velocity of light is indeed reduced in its passage through the Sun's gravitational field. Such an effect is predicted by the general theory of relativity, and accurate measurements of the echo time delay from a planet at superior conjunction, i.e. when so placed that the incident and reflected rays just graze the Sun, should provide another test for the validity of this theory.

SOME MAJOR RADAR ASTRONOMY INSTALLATIONS

Institute	Location	Approx. Frequency (MHz)	Antenna		Power (Kw)		Pulse Length	System Noise Temp. (°K)
			Diameter (ft.)	Aperture (m^2)	Mean	Peak		
California Institute of Technology (J.B.L.)	Goldstone Lake, California U.S.A.	2400	85	355	400	400	CW	30
Cornell University	Arecibo, Puerto Rico	430	1000	20000	150	2500	0.03 to 10.0 msec	400
Crimean Deep Tracking Station	Crimea, U.S.S.R.	700	8 of 50 ft.	700	(60)	(60)	CW	(100)
Institute for Telecommunication Science and Aeronomy	Lima, Peru	50	940 (square)	84000	250	6000	0.01 to 1000 msec	2000-3000
Manchester University	Jodrell Bank, England	408	250	2300	1.5 5	60 5	30 msec CW	1200 1100
Massachusetts Institute of Technology	Westford Mass. U.S.A. (Millstone)	1295	84	190	150	5000	0.04 to 4.0 msec	80
	Tyngsboro Mass. U.S.A. (Haystack)	8000	120	(525)	(100)	(100)	CW	(100)
Stanford University	Stanford, Cal. U.S.A.	24 50 420	1200 ft. array 150 150	6880 920 920	300 300 30	600 600 200	10 µsec to CW	Cosmic Noise Cosmic Noise 100
U.S. Naval Research Laboratory	Washington, D.C. U.S.A.	840	50	92	20	20	CW	145