SPUTNIKS over Britain

During the past months numerous newspaper and magazine articles have described the observational techniques used by US scientists associated with the "Moonwatch" and "Minitrack" programs designed for the systematic tracking of artificial earth satellites. The following account, written by an American science liaison officer with ONR's London branch, summarizes the tracking procedures employed by British observers of the first Russian Sputniks.

By ***George C. Sponsler***

SHORTLY after midnight on October 5 at precisely 0015 GMT, the British Broadcasting Corporation listening station at Tatsfield, just south of London, recorded the now famous "beep-beep" of Sputnik I on its very first transit. News of this detection and the official Russian announcement of the satellite launching were flashed almost simultaneously to a startled world. Thus began two months of feverish but magnificent improvisation and observation which saw the British in the forefront of the Western scientists engaged in tracking the Russian satellites.

Prof. H. S. W. Massey, FRS, who organized a meeting at the Royal Society in late November to review the British satellite observations, opened the discussions by recounting an anecdote somewhat at variance with a similar one related by Whipple and Hynek in their December *Scientific American* article. Massey, who was present at the IGY Cocktail Party at the Soviet Embassy in Washington the evening of October 4, told the story that Lloyd V. Berkner, President of Associated Universities, Inc., and also the man who first proposed that the IGY should be moved forward to its present date, was called out of the party by a newspaper reporter and questioned on the Moscow and BBC announcements. Berkner is then reported as returning to the assembled guests, calling for attention, and announcing the successful launching of Sputnik I. Whichever version of the tale is correct, it is an odd parody in which the Russian success is announced in the Russian Embassy by an American scientist. Massey went on to state that the British delegation at the party thereafter received particularly respectful attention by their Russian hosts because of the BBC vigilance at Tatsfield.

Radio Observations

WITHOUT doubt the British hero of the Sputnik affair was Martin Ryle, FRS, Director of the Mullard Radio Astronomy Laboratory of Cambridge University. Ryle, the nephew of the philosopher, Gilbert Ryle, is well known for his radio astronomy studies (cf. *Scientific American*, September 1956, p. 204). During the Second World War he was one of Churchill's so-called wizard warriors engaged in spoofing the German radar, i.e. as an adviser on electronic countermeasures. The Saturday morning after the Russian launching announcement of the previous night, Ryle and his colleagues attended a previously scheduled, regular staff meeting. Since no one in Britain was prepared or equipped to track Sputnik, it was decided at the meeting that they themselves should improvise an antenna and take the necessary measurements to determine the satellite orbit. This they proceeded to do, taking preliminary readings before midnight of the same day; by Sunday evening they were making accurate observations by two independent methods.

The first of these two methods was an application of a principle employed in various radio navigation systems. Ryle first erected a dipole antenna, accurately surveyed in an East-West direction with a four-wavelength separation at the 40 mc/s satellite frequency between the two arms of the aerial. (This latter choice was particularly fortuitous as the 20 mc/s signal quit after a few days' transmission.) Now the locus of points of equal phase difference between the two arms of such an antenna is known to be a hyperbola in two dimensions or a hyperboloid of revolution in three. The intersections of a family of such (two-sheet) hyperboloids with a surface parallel to the earth but elevated at some altitude above the earth's surface is a family of hyperbola-like curves. The curvature of the earth prevents these curves being true hyperbolae, as they would be if the intersecting surface were a flat plane. A typical family of such curves is shown in Figure 1. Assuming initially that the satellite remained in such a parallel surface above the earth, Ryle measured the time intervals between the nodal points or zeros of the received radio signal. These zero signal strength points were received when the satellite, following its orbit, intersected a particular member of

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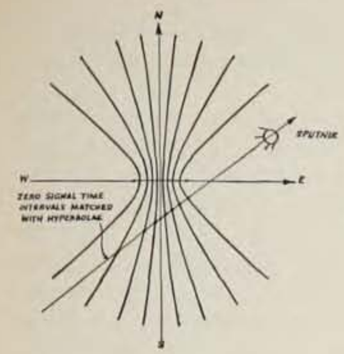

Fig. 1. Intersection of orbit with hyperbola-like curves.

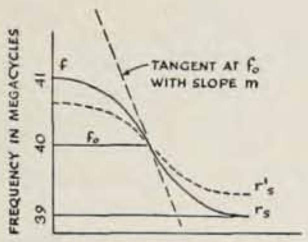

Fig. 2. Doppler shift method.

the family of hyperbolic curves at a particular altitude. By matching a ruler marked with these time intervals against the various sets of hyperbolae (as indicated in Figure 1), it was possible to determine a unique fit or match between the time interval points and a particular family of curves for a particular altitude. From related measurements it had first been determined at what inclination the orbit would cross the East-West axis of these curves near Cambridge and also the distance of closest approach, thereby simplifying the matching procedure. Employing successive approximations for the actual, elliptical orbit to improve the accuracy of the fit, it was thus possible for Ryle to determine the satellite orbit with high precision.

The second method employed depended upon accurate measurement of the Doppler shift of the received radio frequency as the satellite sped by at its high velocity of nearly 18 000 miles per hour. A plot of such a frequency shift would appear much as shown in Figure 2 in which two such curves are depicted, one for a near orbit, r_s, and one for a more distant orbit, r'_s. The slope, m, of this graph measured at the actual satellite transmitter frequency, f_0, when multiplied by an appropriate factor$\left(\dfrac{f_0 v^2}{c r_s} = m\right)$, gives a direct measurement of the slant range, r_s, from the center of the dipole antenna system to the point of closest approach of the satellite orbit. Now as time passes, the receiving station at Cambridge is carried beneath the essentially stationary satellite orbit by the earth's rotation. By measuring, say, three slant ranges upon three successive transits it is then possible to determine the point through which the orbit passes upon a plane perpendicular to the satellite orbit and upon which the

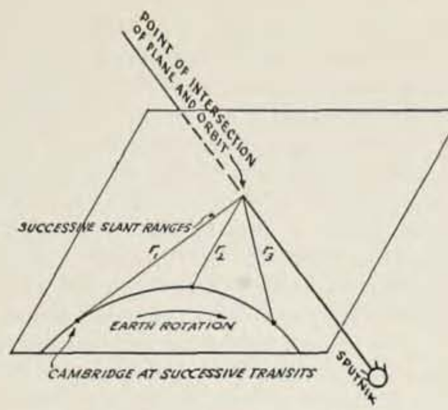

Fig. 3. Slant-range orbit determination.

three slant ranges are projected, as indicated in Figure 3. Such a construction with further refinements to improve the accuracy permits a unique determination of the actual satellite orbit, and provided the second, independent determination.

By means of these two methods Ryle found that the orbit of Sputnik I was an ellipse of eccentricity 0.059, the plane of which was inclined to the equator at an angle of approximately 65°. Perigee (the point of closest approach) was 170 kilometers, or 105 miles, above the earth's surface at 40° North latitude, and apogee was at 40° South latitude at an altitude of 990 kilometers, or approximately 615 miles. On October 10–11 the period for each orbit of Sputnik I was approximately 96 minutes 2 seconds and was decreasing at a rather constant rate of 1.85 seconds per day. Because of the earth's rotation each successive transit was 24° west of the preceding one. Due to the oblateness of the earth the orbit was also found to exhibit a net daily westward precession of 3° 50′ (this will be discussed in more detail further on). These various measurements were published in the *Manchester Guardian* on October 18 together with figures similar to those shown here as Figure 4.

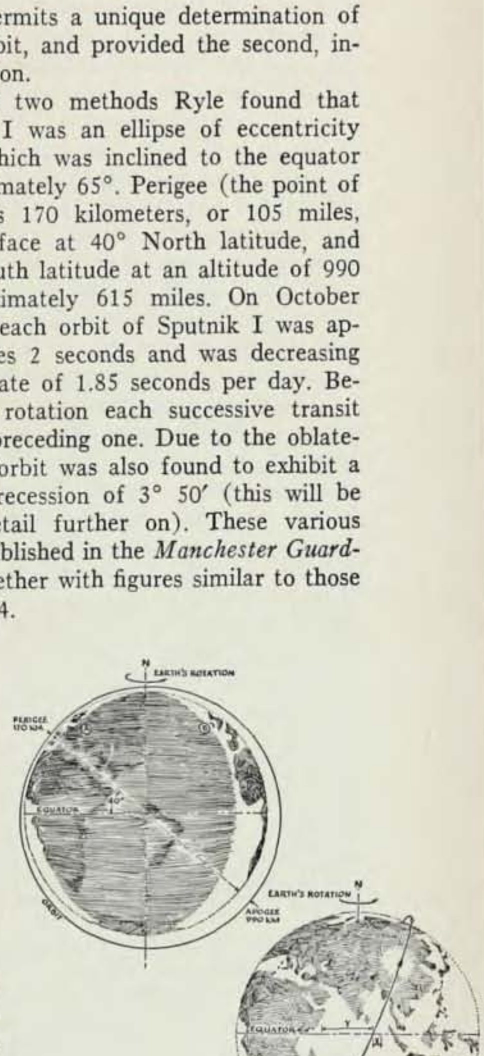

Fig. 4. Orbit of Sputnik I. In top diagram, position of observers in Britain on first evening transit was at *A*, and on the first morning transit was at *B*. In second diagram, *X* indicates orbit's daily westward precession of 3° 50′. Because of rotation of earth, each transit was 24° west of previous one (*Y*).

Superimposed on the received Sputnik I radio signal Ryle noticed a periodic amplitude modulation with a frequency of approximately 15 rpm at 40 mc/s. This perturbation could have been caused by rotation of the satellite, by rotation of the plane of polarization of the satellite radio waves caused by the Faraday effect experienced by the waves as they penetrated the ionosphere, or by a combination of both. The Faraday effect is a result of the interaction of the electrical ionization of the ionosphere with the earth's magnetic field and displays an inverse-square frequency dependence. Thus by measuring the apparent perturbation frequencies at Sputnik's two frequencies of 20 and 40 mc/s, a factor of four would exist between the two perturbation frequencies if the perturbation were caused by this effect. Ryle determined that such a factor was indeed present; he came to the conclusion that the major part of this perturbation was caused by Faraday rotation, with approximately 7 rpm left as the rotation of the satellite itself. To check this conclusion Ryle also measured the perturbation at the second harmonic of the 40 mc/s frequency (i.e., 80 mc/s) and thereby confirmed his conclusion.

The fact that the Russians chose to use 20 and 40 mc/s, two frequencies separated by a factor of exactly two, may be related to the ease with which one may determine the Faraday effect on the radio-signal propagation, as was done by Ryle. There has been some complaint in the West that the Russians did not employ the proposed American frequency of 108 mc/s for its own satellite transmitter. It should be noted in this regard that if one wishes to study the ionosphere itself it is much more preferable to employ the frequencies chosen by the Russians. The American choice was determined by the fact that the 108 mc/s frequency would propagate through the ionosphere almost unaffectedly and thus would be particularly useful in radio determination of the satellite orbit. Fine calculations of such an orbit, however, require optical measurements, as has been pointed out by E. H. Sadler of the British Nautical Almanac Office. At the Royal Society meeting previously referred to Sadler noted that one would require 0.01° and 0.01 second accuracy in such a satellite orbit determination if one wished to determine the earth's oblateness with good accuracy. If one wished to measure geodetic distances on the earth, one would require an additional factor of 10 in the accuracies of these measurements. Such accuracies require visual sightings, and thus the radio determinations would only be of value as a "training telescope", so to speak, to determine where the more accurate optical telescopes should be pointed to pick up the rapidly moving satellite on its orbit. Thus it might be better to select a frequency near 20 mc/s in order to study the effect of the ionosphere upon propagation phenomena. Ryle noted at an earlier meeting of the Royal Astronomical Society in London that the particular orbit chosen for Sputnik I was such that its radio transmitter was dipped in and out of the ionosphere, as perigee is below and apogee above the major portion of the ionosphere. Such an orbit would be ideal for permitting accurate calculations of propagation phenomena through the ionosphere itself.

Ryle has now returned to his original radio astronomy observations, leaving the radio sighting of future Sputniks to a group at the Royal Aircraft Establishment at Farnborough. A large radio interferometer designed by A. N. Beresford particularly for IGY satellite observations is now in operation near there. This instrument was planned for use at 108 mc/s and rapidly had to be altered to track the Russian Sputniks at their lower frequencies. The instrument was not completed at the time of the first launching and so its measurements were preceded by Ryle's. Farnborough has also employed the Doppler shift method for orbit determination and has a well-equipped computation service for this purpose under the direction of E.G.C. Burt. Other radio observations in Britain were also carried out at the Admiralty Signal and Radar Establishment, the Radio Research Station, and the General Post Office Engineering Department.

Radar Sightings

ON November 3, scarcely one month after the first launching, Sputnik II was put in its orbit. This satellite was even more startling than Sputnik I, which was startling enough with its reported weight of approximately 180 pounds and a cross section nearly two feet in diameter. Sputnik II was more nearly the size of Sputnik I's launching rocket which had been observed visually, first following then preceding Sputnik I at various observation points over the world. Physically, Sputnik II would seem to be the last stage of a multistage rocket; probably it is the same section as the Sputnik I rocket itself. The weight of Sputnik II was reported as being approximately one-half ton and its length something on the order of 20 to 30 feet. The most remarkable aspect of Sputnik II was the fact that the dog, Laika, was carried as passenger. Animal lovers in Britain were so incensed that a live dog had been enclosed in the satellite, even if for scientific purposes, that a delegation visited the Russian Embassy to present a formal protest to the First Secretary there. One member went so far as to suggest a one-minute silence be observed throughout Great Britain at 11 o'clock every day as long as the dog remained alive. It was, incidentally, later reported by the Russians that the dog had died of anoxia.

As was widely reported in the press, whereas the Sputnik I power-supply batteries lasted precisely the three weeks predicted by the Russians, the Sputnik II transmitters went dead about a week after the launching. Since the radio transmitters lasted such brief periods, most of the later sightings had to be done by radar and in this field the honors went to Prof. A. C. B. Lovell, FRS, and his associates at the radiotelescope installation just outside Manchester at Jodrell Bank. The huge 260-foot diameter paraboloid dish located there was originally designed only for reception of signals from radio stars; in order to track the Sputniks it was hurriedly connected to two old radar transmitters which were available at the laboratory. The equipment was first tested at a frequency of 120 mc/s on October 9 when reflections were obtained from the moon, but it was actually at the lower frequency of 36 mc/s on October 11 that the first radar observations on the satellites were made. The 120 mc/s equipment operated at a higher power than did the 36 (though only with 10 kilowatts), and theoretically could detect an echoing object the size of Sputnik II at a range of 2600 kilometers, whereas the 36 mc/s equipment would have a range of approximately only 700 kilometers on such an object. Subsequent measurements indicated that the Sputnik I rocket and Sputnik II itself had radar echoing areas on the order of 10 square meters, whereas the cross section, as it is called, of the satellite Sputnik I was only on the order of 0.4 square meter. These echoing areas would seem to substantiate the announced sizes of the two satellites.

After the satellite transmitters went dead, Lovell received a number of requests from Russia for radar sightings, which information was readily made available. Lovell's radar sightings were also the prime source of information in Britain from which the anticipated demise of the Sputnik I rocket was predicted. Figure 5 shows a plot of the period of the orbit of the Sputnik I rocket from October 10 to December 1, when it was presumably destroyed on its 879th transit. Lovell's radar observed what were presumably the last four transits of the Sputnik I rocket and it was he who announced to the world that the rocket had indeed disappeared early on the morning of December 1. The reason why Lovell could so predict the end of the rocket is apparent from Figure 5, which shows how rapidly the period of the rocket was decreasing as the days in late November passed. A satellite with an orbital period equal to 85 minutes would just graze the surface of a spherical earth without atmosphere and it is therefore unlikely that the rocket could have survived much beyond the first couple of days in December. Lovell was also instrumental in predicting the end of Sputnik II in mid-April, 1958. However, the radar sitings were not so essential then, as a fine view of the satellite was possible to the naked eye which permitted excellent optical sitings to be made in Britain on the last days of Sputnik II.

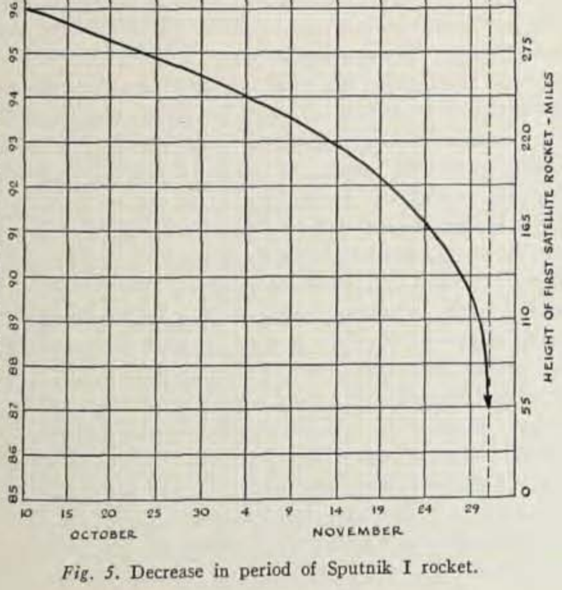

Fig. 5. Decrease in period of Sputnik I rocket.

J. S. Hey of the Ministry of Supply's Royal Radar Establishment at Great Malvern also obtained radar sightings on the Sputnik I rocket with his 45-foot diameter radio telescope. This equipment when altered to radar applications employed a 2-megawatt peak power transmitter at 10 centimeters wavelength and it was thought that a sphere of 30 centimeters radius could be detected at a range of 1000 kilometers. The beam, however, was so narrow that it is doubtful that Sputnik I itself was ever detected. Its rocket was first detected October 20 at 1400 kilometers range.

Although it was not observed in Britain, perhaps the longest radar sighting of Sputnik I was made by Prof. W. Dieminger of the Max-Planck-Institut for Physics of the Stratosphere and Ionosphere in Lindau, Germany. Using a rhombic antenna tuned to a frequency of 26 mc/s, Dieminger detected Sputnik I at a maximum range of 4500 kilometers. The probable reason for this success was that, as planned, the frequency of this radar was chosen to be roughly equal to the lower of the two Sputnik I transmitter frequencies. Such a frequency would resonate with the satellite antenna system and thereby increase the effective radar echoing area.

Analysis

THE work of D. H. Sadler of the Nautical Almanac Office has been alluded to previously. It was he who acted as a clearing center for all of the various satellite sightings reported throughout the British Isles and it was his office that published the British predictions of the various satellite orbits. To do this with Sputnik I, for example, he had eleven optical, 150 radio, and ten radar observations. Because of Britain's proverbially bad weather, very few visual observations or photographs of either the Sputnik I rocket or Sputnik II were made available to Sadler. He was, however, able to make good predictions of the satellite orbits with the comparatively scant amount of data available to him.

What was perhaps the high point of Massey's Royal Society meeting came with the presentation of a paper by D. G. King-Hele, also of the Royal Aircraft Establishment at Farnborough. King-Hele had computed the main effects of the earth's oblateness on a satellite near to the earth in an orbit of small eccentricity, that is of approximately 0.05 or less. He found first, as also described in Whipple's *Scientific American* article, that the orbital plane instead of remaining fixed rotates

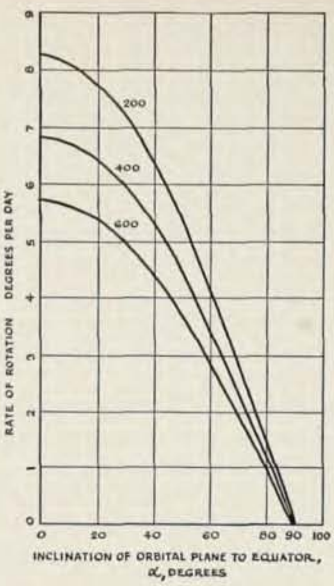

Fig. 6. Rate of rotation of the orbital plane about the earth's axis. (*Note:* Figs. 6, 7, and 8 are taken from figures appearing in D. G. King-Hele's RAE Tech. Note No. GW-475.)

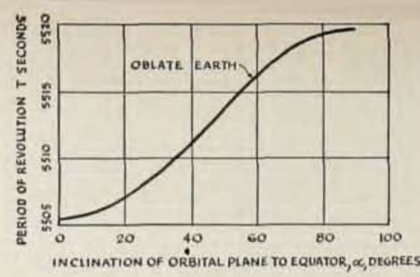

Fig. 7. Variation of Sputnik II period with angle of inclination.

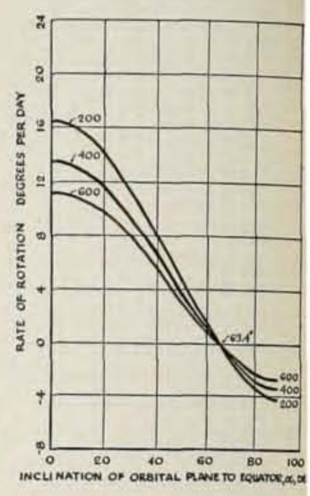

Fig. 8. Rate of rotation of major axis of orbit, measured in orbital plane.

about the earth's axis in the opposite direction to the satellite at a rate given by the equation

$$10.0\left(\frac{R}{\bar{r}}\right)^{3.5}\cos\alpha$$

in degrees per day, where α is the inclination of the orbital plane to the equator, R the earth's equatorial radius, and $\bar{r}$ the satellite's mean distance from the earth's center. This is the so-called retrograde or westerly motion of the orbit, which was found by Ryle to be slightly more than 3° per day in the case of Sputnik I. A graph showing the rate of rotation in degrees per day as a function of the angle of inclination of the orbit to the earth's equator is shown in Figure 6 for three different satellite mean-radii of 200, 400, and 600 nautical miles respectively.

Second, the period of revolution of a satellite from one ascending node, or northward crossing of the equator, to the next is $14.5\sqrt{R/F}\,\sin^2\alpha$ seconds greater for an inclined orbit than for an equatorial orbit if the mean distance from the earth's center is fixed. A graph showing this behavior for a Sputnik II type satellite is shown in Figure 7.

Third, during each revolution of the satellite the radius from the center of the earth to the satellite oscillates twice, the amplitude of the oscillation being given by $0.94\ (R/\bar{r})\ \sin^2\alpha$ for a given angular momentum.

Fourthly, and most important, King-Hele found that the major axis of the orbit rotates in the orbital plane at a rate of

$$5.0\left(\frac{R}{r}\right)^{3.5}(5\cos^2\alpha - 1)\text{ degrees per day.}$$

Thus for a 200 nautical-miles mean orbital radius it would rotate at about 16° per day in the same direction as the satellite for a near equatorial orbit, and at about 4° per day in the opposite direction for a polar orbit. There would be no rotation when $\alpha = 63.4°$. This is a particularly significant figure because it may explain why the Russian satellite orbits have been chosen to have inclinations of approximately 65°. The advantage to be gained by launching a satellite at an inclination of 63.4° to the Equator is that the point of closest approach or perigee will be kept within the latitude of the country launching the satellite, assuming the 63.4° latitude passes through that country, as it does in the Soviet Union. Such a consideration would be particularly valuable in tracking the satellite or making other measurements. King-Hele announced this preferred inclination at the June 1957 conference on satellites held at Cranfield at which there were a number of Russians present. The Russians themselves in papers on the determination of life-time studies of satellite secular orbits, which were presented both at the Barcelona and Washington satellite conferences in October 1957, announced that they planned to launch their satellite in this preferred orbit of approximately 65° inclination to the equator. Presumably, the actual launching was made at this inclination in the north-easterly direction as some additional force would thereby be gained from the earth's rotation. Also, if the launching site were in the Caspian Sea area as suggested by Whipple a north-easterly launching would keep the rocket over Russia for a longer period during the initial phases, when difficulties most likely arise in such firings, and thus would increase the probability of recovery of a misdirected rocket in Russian territory. Such a launching direction would also decrease the probability of detection by observers outside Russia in the case of failure.

King-Hele also investigated the effect of aerodynamic forces on satellites. For a perfect sphere there would be no lift force and therefore the entire aerodynamic force would be drag. For other shapes lift forces would be present but these would tend to cancel out for periodic orbits. The over-all effect of the atmospheric drag upon an elliptical orbit is to reduce the eccen-

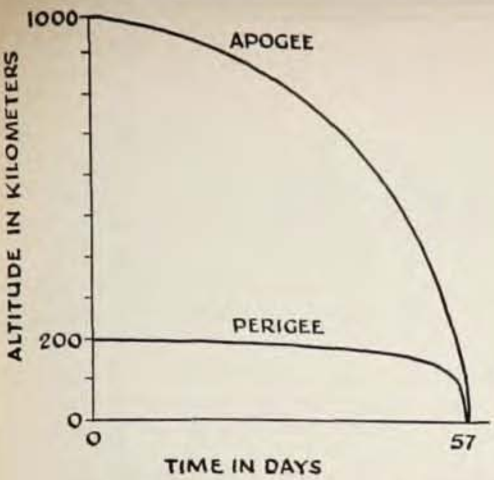

Fig. 9. Variation of apogee and perigee during descent of Sputnik I.

tricity, the orbital period, and the length of the major axis. The effect of the aerodynamic drag on a sphere executing a circular orbit would be to change the circle into a spiral. As the satellite spirals in toward the earth, half of its potential energy would be used up in overcoming drag while the other half would increase the speed of the satellite. The peak deceleration experienced by a satellite in entering the atmosphere would be on the order of ten times the acceleration of gravity, according to King-Hele. The altitude at which this peak deceleration would be encountered depends upon the drag to weight ratio of the satellite. For the Sputnik I rocket this altitude would be approximately 10 nautical miles whereas for Sputnik I itself it would be at some altitude between 7 to 14 nautical miles.

King-Hele was also concerned with the analytical side of the predictions of the end of the Sputnik rockets. As a satellite spirals in from an eliptical orbit the furthest distance from the earth, apogee, decreases very rapidly in comparison with the decrease of perigee, much in the fashion sketched in Figure 9. It was with such a figure and with knowledge as to the rocket period gained from Lovell's observations that King-Hele was able to predict the probable time of the end of the Sputnik I rocket within some 36 hours of the actual demise. He also correctly estimated over a month in advance the week in which Sputnik II came to its flaming end.

Explorer and Vanguard

A WORD should be added about the British observations on the American Explorer and Vanguard satellites. Unfortunately, from the European point of view, the American sputniks (if one may use that rather impolitic juxtaposition) are confined to a belt of latitudes between plus and minus 35°, and thus never came further north than the Straits of Gibraltar, for example. Although the 108 mc/s radio signals from the Explorer and Vanguard are picked up fairly regularly in Italy, only a few mostly unsatisfactory detections have been reported in Britain. The official IGY radio observation post operated by the Royal Aircraft Establishment at Lasham, referred to earlier, has received a number of contacts, but reports they have all been weak signals very near the background noise level. Incidentally, shortly before the advent of the American satellites, the Lasham station took over as the principal British observation post and has since become the clearing center for all British satellite reports.

Up to the time of the launching of Explorer III, no visual sighting of an American satellite was reported in Britain. This failure is explained both by the extreme distance of the closest approach of the US satellites and also by their comparatively small size resulting in much smaller optical scattering cross sections than was the case with the larger Russian Sputniks. Dr. Willmore at University College, London, has devised a special telescope equipped with a photocell with which he hopes to be able to see Explorer I when its apogee is at its northernmost extremity and aligned in the Greenwich meridional plane. Under such circumstances, Explorer I should be 40° above the London horizon. Given a clear sky at sunrise or sunset, an unlikely occurrence in misty England, Explorer I should be readily visible through Willmore's telescope which, he reports, can discern a tenth magnitude star.

Thus we see that the American 35° orbit inclination which makes observation so convenient in the States is a very poor choice as far as European and particularly British observations are concerned.

Conclusion

THE launching of the Russian satellites caused some consternation in the Western world and certainly found the Western scientists unprepared. However, observers both in England and America quickly improvised equipment and were soon following the satellites on their orbits. This article has told the story of the British effort. Of course, no one should have been surprised by the Russian launchings, for as early as June 1957 an article appeared in the Russian radio amateurs' journal, *Radio,* alerting their shortwave listeners to the impending launchings, anticipated then as some time in late September, stating the satellite transmitter frequencies, and giving other information as to the type of pulse-code modulation to be expected. This journal was available in the United States, and the particular article had been translated by the British Royal Society shortly after it was published. Just before the launching of Sputnik I, the Russians again announced their intention at the two international meetings in Barcelona and Washington. Regrettably at that time it would seem that no one on either side of the Atlantic took the Russian announcements too seriously. Be that as it may, when the Sputniks were launched the British responded with typical diligence, good humor, and fair play; the BBC tape recorded beeps; Ryle improvised his antenna and calculated the first orbits; Lovell tracked the satellites with his radiotelescope after the Sputnik transmitters had gone dead, and readily made his observations available to the Russians; Sadler computed the orbits at the Nautical Almanac Office; and King-Hele's analysis aided in predicting the orbits and the end of the Sputnik rockets. Altogether not a bad record for Britain.