AN INTRODUCTION TO ASTRONAUTICS

BY

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Although it is only a little over eight years since Sputnik I *was launched, the subsequent rate of launching man-made earth satellites and space probes has been so great that nowadays only the most spectacular shots receive much publicity. In the last two years over 120 successful launches have been recorded, and artificial satellites have become commonplace before many of us have had time to consider the principles which make them feasible.*

This article, written by a member of the Advanced Projects Group of the British Aircraft Corporation's Guided Weapons Division, discusses a few fundamentals and features of this fast-moving technology.

A Brief History of Rockets and Space Travel

The foundations of astronomy as a science as distinct from an occult art were probably laid by the ancient Egyptians and Greeks, and no sooner had they guessed at the probable nature of the sun and moon, the stars and planets, than the dreamers found the way open for imaginary journeys of celestial exploration. Two early pieces of science fiction describing journeys to the moon were written in the second century B.C. and are ascribed to a Greek satirist, Lucian of Samos. In the Dark Ages the theme of space travel in literature is lost; however, in about 1250 A.D. the invention of an explosive-propelled rocket by the Chinese provided the first practical step towards travel beyond the earth's atmosphere, and the discoveries by Copernicus, Galileo, Kepler and Sir Isaac Newton of some basic facts concerning planetary motion and gravitational attraction helped to put the space business on a rational foundation.

Rockets have been used for the discomfiture of devils and more tangible enemies ever since the Chinese discovery. The Englishman Congreve's solid-fuel war-rocket (c. 1800) was a notable technical advance, and was employed in military actions ranging from Malaya to North America in the early 19th century. In September, 1807, the British Fleet set fire to Copenhagen by bombarding the city with 25,000 incendiary rockets. Towards the end of the last century a Russian mathematician Ziolkowski (1857–1934) and a German lawyer Ganswindt (1856–1934) independently studied the possible use of rocket motors for propulsion outside the earth's atmosphere, and correctly concluded that such an activity would be feasible.

In the present century some early landmarks in astronautics were the publication of Dr. Robert Goddard's papers 'A Means of Reaching Very High Altitudes' and 'Liquid-Propellant Rocket Development' (U.S.A. 1919/20), Hermann Oberth's 'Rocket into Planetary Space' (Germany, 1923) and Goddard's practical achievement in launching the world's first liquid-fuel rocket (U.S.A., March 1926). Probably the first manned rocket flight occurred in 1928 when a glider fitted with two 44-lb thrust rockets flew a distance of 1,400 yards in the hands of a German pilot named Stamer.

A considerable step forward in rocket technology was taken with the construction during the Second World War of the V-2 missile by Werner von Braun and his team at Peenemunde. This 47-foot rocket had a range of about

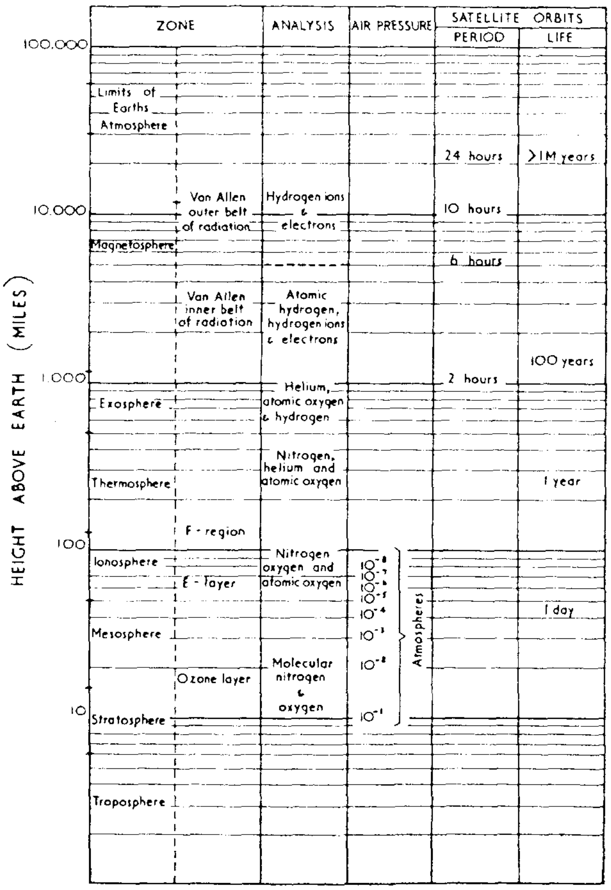


FIG. 1—THE EARTH'S ATMOSPHERE

200 miles and weighed 28,000 lb at launch. It carried a payload of 2,200 lb at a maximum speed of about 3,000 m.p.h. and after the war numbers of these rockets were used in the U.S.A. to begin the sequence of development which has led up to the present highly advanced state of the art in America. The post-war development of inter-continental ballistic missiles on both sides of the Iron Curtain has provided the rocket thrust and endurance necessary for a vehicle to achieve sufficient speed (17,000-25,000 m.p.h.) to proceed in orbit around the earth. Higher speeds still enable rockets (or their payloads) to escape from earth's gravity and to probe deeply into space without ever returning to earth or its vicinity.

Rocket Propulsion

The two major obstacles to orbital and space flight are the earth's atmosphere and its gravitational attraction. Considering first the atmosphere, the gradual attenuation of the gaseous envelope sets limits on the altitude attainable by aerodynamic vehicles with air-breathing motors. Both lift and thrust cease to be effective long before reaching the outer edge of the atmosphere (see FIG. 1). It follows that different principles of lift and propulsion are necessary for a space vehicle; fortunately the application of Newton's Third Law provides the answer; the equal and opposite reaction engendered by any action is in no way dependent upon the presence either of earth's atmosphere or its gravity, so that a rocket can provide lift and thrust very efficiently in outer space as well as in the earth's vicinity.

Atmospheric resistance to the passage of an object increases as the square of its velocity, so that too high a speed in the densest air will create excessive drag and kinetic heating. Fortunately an earth-launched rocket is travelling at its lowest speed while still close to the surface and if launched vertically will accelerate through air of decreasing density. Nevertheless it is necessary to design the rocket to have a minimum resistance to supersonic flight and to absorb the effects of skin heating so that vehicle and payload are undamaged. Obviously the propulsive thrust must be augmented to overcome this drag as well as the pull of gravity.

Considering now the effect of earth's gravity on a rocket-launched space vehicle, the inverse-square law established by Newton is of great importance, for it means that an object at a distance of twice the earth's radius will be subject to a pull of only one-quarter of that which it would experience at ground level. At sixty radii away (the moon's distance) the value of 'g' has fallen to one three thousand six hundredth of its familiar 32 feet per second, per second. Thus the two greatest obstacles to space flight, gravity and air

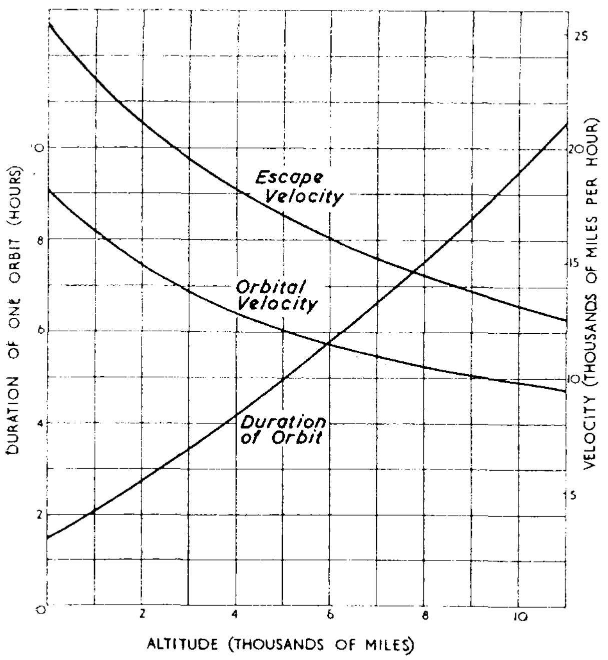


FIG. 2—ORBITAL AND ESCAPE VELOCITIES

density, are most severe close to the earth's surface. The systems 'Rockair' and 'Rockoon' overcome these impediments by lifting research rockets to high altitudes (by aircraft and balloon respectively) before firing the rocket motors, enabling a greater payload to be lifted by a smaller rocket than would otherwise be possible. Clearly there are limits of size and weight which no practical aircraft or balloon could handle, but the principle points the way to the possibility of establishing orbiting space stations from which deeper penetrations into space may be launched with comparative ease.

Orbital Flight

This is best understood by imagining a very powerful gun, of variable muzzle velocity, mounted to fire horizontally from a very high mountain. A series of shots fired at increasing muzzle velocities will follow parabolic trajectories and strike the ground at increasing distances. At some very high velocity the shot will fall under gravity a distance equal to the earth's curvature, and so will not strike the earth but will continue to 'fall' around its periphery. The shot is constrained from moving away on a straight line into space by the earth's gravity, but the resultant motion on a curved path generates centrifugal force. At various combinations of height and speed these forces are equal and opposite, so that (for the moment ignoring the air friction present at lower altitudes) the shot will orbit the earth in the same manner as does the moon.

The smallest orbit which can be achieved without the shot (which we will now call the vehicle) spiralling back to earth is obviously a circle, and the so-called 'circular velocity' needed to achieve this state of orbital flight depends upon the height at which the vehicle is injected into orbit (see FIG. 2).

The circular velocity of a body orbiting close to earth is about five miles per second; at the moon's distance it is only 0·6 miles per second. A particularly interesting circular velocity is that for a radius of 22,300 miles; at 6,872 miles per hour (a little under two miles per second) this combination of height and speed gives a 24-hour period of revolution, and the vehicle appears to hang motionless in space. Such a satellite is known as 'synchronous' and may usefully act as a relay station for fixed point-to-point radio communications.

There is no reason, of course, to limit the launch velocity to the minimum speed required for a circular orbit at a given height. By increasing the speed the circle may be stretched out into an elliptical orbit in which the earth's centre remains at one of the foci. This trajectory is suitable for space probes in which it is required to retrieve the vehicle back to earth. In the case of an elliptical orbit the vehicle velocity is not constant, but in accordance with the second of Kepler's Laws the line joining the satellite to earth sweeps out equal areas in equal periods of time (see Fig. 3). From this it will be seen that the greatest velocity occurs close to the earth (at perigee) and the least at apogee, the greatest distance.

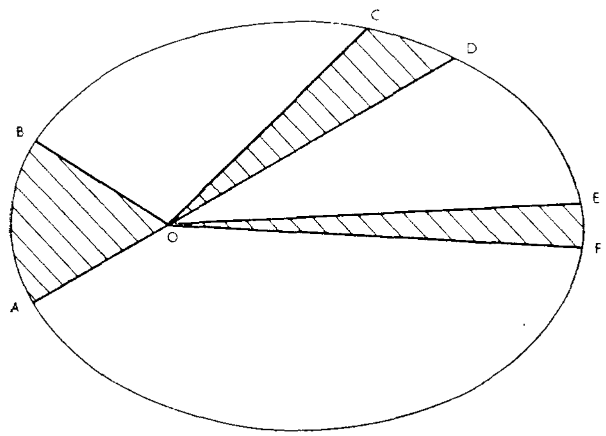


Fig. 3—Illustrating Kepler's Second Law

Escape Velocity

If the launch speed is increased up to about seven miles per second, the elliptical trajectory stretches until it 'comes apart' at the far end. The flight then becomes a parabola continuing into space. A vehicle following this escape path would not, however, be manœuvrable with respect to other planets, since the parabola is a critical path between ellipse and hyperbola and a slight reduction of speed or error in course would change the path back into an ellipse. A further increase of launch speed, however, results in a hyperbolic trajectory and this is the basis for all schemes for inter-planetary flight and deep space probes. The application of rocket thrust at a suitable time to a vehicle in hyperbolic flight may be needed to manœuvre it into the gravitational field of another planet; failing this the hyperbola will blend into an elliptical orbit around the sun.

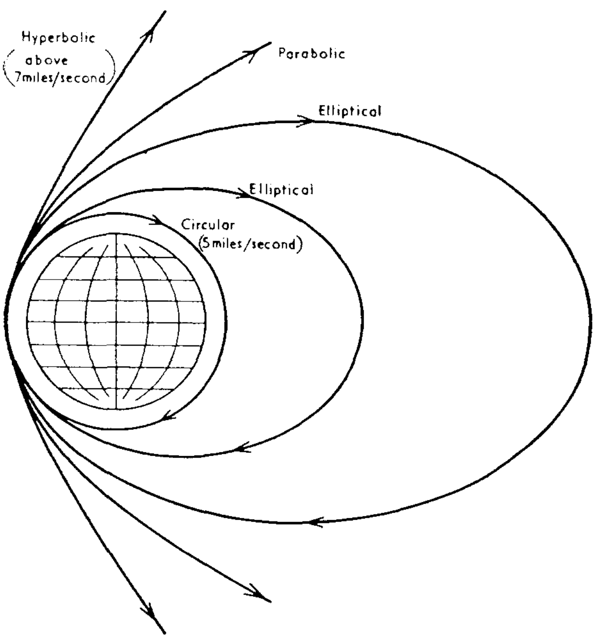


Fig. 4—Typical orbits and trajectories

It can be seen from Fig. 4 that only elliptical and hyperbolic trajectories are of practical use in true 'space' flight. Circular orbits are nevertheless useful for certain specialized 'terrestrial' applications, as will be seen later.

Obtaining the Speeds

Previous paragraphs have spoken lightly about speeds of five miles and more per second, but the problem of accelerating a substantial mass of ironmongery to such velocities is naturally very real. A slow acceleration for a long time would achieve these speeds, but is prohibited by the enormous amount of fuel needed to give the necessary endurance. Equally, a very rapid ascent requires much greater thrust, causing an increased thirst for fuel; it also causes greater frictional heating and excessive drag while passing through the denser levels of the atmosphere. These effects demand greater structural strength of the launching system, and hence more weight and more fuel still.

The optimum relationship between weight and velocity may be obtained from the expression

$$V = c \log_e \frac{M_0}{M_1}$$

where V = rocket velocity at motor burn-out in free space,

c = exhaust gas velocity,

M_0 = initial mass of rocket and fuel,

M_1 = final mass, all fuel spent.

The ratio $\frac{M_0}{M_1}$ is known as the 'mass ratio', and to obtain the highest possible value is most important since it determines the maximum rocket speed obtainable from a given exhaust gas velocity. This gas velocity depends on the fuel and oxidant chosen; as a typical case the combustion of alcohol and liquid oxygen gives a sea level gas velocity of about 1·4 miles per second. Higher speeds are obtainable from other combustible combinations, but some are highly dangerous or expenive or both and may be offset by a higher specific gravity.

Substituting the typical gas velocity and a circular orbital vehicle speed of five miles per second in the above equation, we get a mass ratio of 55. If escape velocity (7 m.p.s.) is required the mass ratio becomes 400. Clearly it is not at present easy to construct a rocket whose initial weight when fully fueled is 400 or even 55 times the weight of the empty structure, but we have noted earlier that the greatest difficulties occur in the earliest stages of flight, and a solution to the mass ratio problem lies in a multi-stage system which jettisons surplus weight when it has fulfilled its function. The first stage accelerates the total load against the greatest gravitational pull and densest atmosphere and, having spent its fuel, is detached. The second stage motor is ignited at this point and the much lighter remainder of the system continues the ascent in less severe conditions. This second stage is in turn discarded when it has reached its maximum velocity and by the time the propulsion of the third stage is spent the real payload has been carried to the outer atmosphere or beyond and has achieved a velocity equal to the sum of the speeds of the three individual stages.

Having accelerated the last thrust-producing stage to orbital or escape velocity, it is usually necessary to separate it from the payload before the latter can perform its task. A small amount of specially-generated separation thrust achieves this and the two components continue independently but in similar orbits. Consequently the ever-growing total of man-made hardware in space includes many final stages of the launching systems as well as their satellite payloads.

Practical Satellite Orbits

The foregoing discussion has in the interest of simplicity ignored the effect of air resistance on orbit shape. Nor has any mention been made of the perturbing effects of the earth's oblateness. Even the pressure of solar radiation can, in some circumstances, modify the shape of a satellite's orbit.

Considering air friction first, a satellite whose orbit lies wholly or partly within the atmosphere (however rarified) will be impeded by collision with air particles and will lose velocity. This will cause a reduction of centrifugal force and the satellite will turn downwards under gravity. But this 'fall' towards earth will accelerate the orbital velocity and restore the centrifugal force so that the satellite moves outward again. However, the higher velocity now creates increased drag which once again slows down the satellite, and this cycle of oscillation continues, with the orbital height slowly decreasing, until the air is dense enough to cause more drag than can be compensated for by the acceleration due to gravity. At this point orbitting ceases and the satellite dives towards earth, its substance vaporizing and dispersing (unless a re-entry shield is provided to prevent this) on account of the intense frictional heat generated in the denser levels of the atmosphere.

Even if the launch into orbit is carried out with a high degree of precision in speed and direction, the actual orbit achieved is subject to some modification from the ideal because of atmospheric density variations. This density is only roughly constant at a given altitude; it changes with daylight and darkness, with latitude and sunspot cycles, and the life of a satellite which spends an appreciable amount of time within the earth's outer atmosphere is limited and (like its period of rotation) somewhat unpredictable. Atmospheric drag is not, however, wholly a disadvantage; it may be harnessed to slow down a satellite prior to re-entry and recovery. By manœuvring the satellite into an elliptical orbit whose perigee is within the earth's atmosphere, a progressive retardation is imposed which reduces the apogee at each consecutive orbit until, with a near-circular orbit, the drag is sufficient to end the flight. This series of 'braking ellipses' would be used by a space vehicle returning to earth from an expedition to the moon.

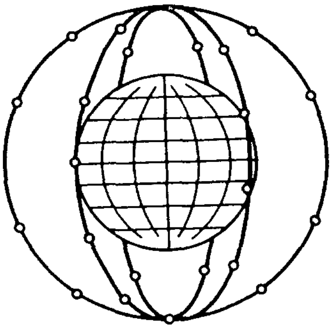
Perturbations due to Gravity

It has long been known that the earth is flattened at the poles. More recently it has been discovered that the flattening is not equal at each pole and that sections of the earth cut along the equator or parallels of latitude are not true circles either. In consequence, the exact value of the acceleration due to gravity varies slightly at different points on the earth's surface. At the equator the average value of 'g' is 978 cm./sec.^{2}, at the poles 983. This variance has two effects on the orbit of an artificial satellite; a slow rotation of the plane of the orbit, and a rotation of the line of apsides (joining the points of apogee and perigee). Without indulging in a rigorous mathematical treatment of these motions it may be said that the former causes a regression of the nodes (the points where the orbit cuts the equator); this takes place in a direction opposite to the motion of the satellite. The amount of regression depends on the inclination of the orbit to the equator; a 90-degree polar orbit has zero regression but an orbit constrained to lower latitudes will regress several degrees every day and make a complete rotation of 360 degrees within a few months.

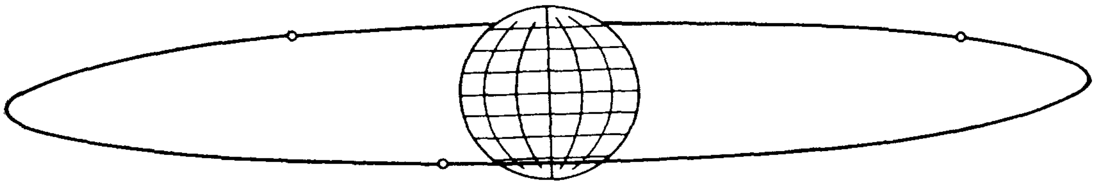
The rotation of the line of apsides causes the positions of apogee and perigee of an elliptical orbit to change with respect to the earth. The rate of rotation of the line depends on the inclination of the orbit to the equator; an equatorial orbit (zero inclination) causes maximum rotation in the direction of the satellite's motion and a polar orbit (90 degrees inclination) gives a maximum in the opposite direction. At about 63 degrees inclination the rotation of the line of apsides is zero. The practical effects of this form of perturbation are to cause variation of satellite altitude at different passes over the same point on the earth's surface and to add yet another variable to the causes of change in air density experienced by a satellite at perigee.

Solar Pressure and Gravity

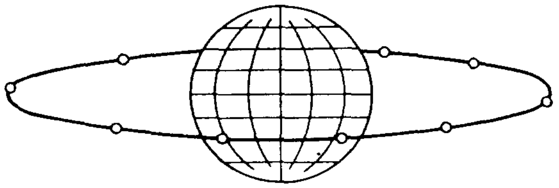
Mention was made earlier of the effect of radiation pressure from the sun. This can be appreciable when considering the orbit of a large satellite of low density (*e.g.* the 100-foot balloons *Echo* 1 and 2) but is usually ignored in other cases. The gravitational pull of the sun (and also of the moon) is sufficiently small to be disregarded when predicting satellite orbits close to the earth, but in a more precise assessment of large orbits or deep space probes these forces must be taken into account.



Random Orbits



Synchronous Orbits



Medium Altitude Orbits

FIG 5—ALTERNATIVE ORBITS FOR COMMUNICATION SATELLITES

Some Practical Space Craft

In the period between *Sputnik I* in 1957 and the end of 1964, well over 300 launches of space craft were made in the U.S.A. and in the U.S.S.R. Almost all of these may be classified under two broad headings: research into the earth's environment ('scientific satellites') and practical facilities for improving world-wide communications, weather forecasting, navigation and the like ('technological satellites'). A third category of space craft includes space probes and sounding rockets; these also may be subdivided into research projects and data-collectors for immediate practical use (e.g. the *Skylark* weather rocket).

We can consider in the space available in this article only a small proportion of the total number of active and proposed projects. An article on the *Ariel*-I (UK-1) satellite appeared in the *Naval Electrical Review* dated April, 1963; since this satellite was typical of the scientific experimental variety we need not consider the type further at present but may devote our attention to 'technological' satellites. Before doing so, however, it may be of interest to record that *Ariel*-2 (UK-2) was successfully launched on 27th March, 1964. It orbits the earth every 100 minutes in an elliptical orbit whose apogee is at 840 miles and perigee at 180 miles at an inclination to the equator of about 52 degrees. This is very similar to the orbit of *Ariel*-I (100 mins/750 miles/240 miles/53·8 degrees). Because of its lower perigee its life will be less than the 20 years predicted for *Ariel*-I, but nevertheless it should be ample to provide a wealth of data on galactic noise, ozone and micro-meteoroids encountered in its orbit. *Ariel*-3 (UK-3), the first satellite built entirely by British industry, is due to be launched towards the end of 1966. It will carry a number of experiments for British Universities and for the Meteorological Office.

Communications Satellites

The first-proposed and perhaps most obvious practical use for artificial satellites is the relaying of radio signals around the earth's curvature. The *Echo* series of vehicles achieves this by merely reflecting a signal beamed at it by the ground transmitter, the reflection being picked up at the receiving station in the same manner as from the ionized layers of the atmosphere. These passive-reflector satellites are little but inflated metal-foil balloons 100 feet or so in diameter, but a small VHF beacon transmitter is provided to make tracking by ground stations easier. While *Echo* has the great advantage that it contains very little technical equipment to fail, its orbit is somewhat erratic due to solar radiation pressure and micrometeorite bombardment, and the reflected radio signal is weak since it receives no amplification within the satellite. It is also very prone to damage during the actual launch, as in the case of *Echo* 2, since the metal foil which forms the skin of the vehicle is only a thousandth of an inch thick.

The active-repeater type of satellite is typified by the *Couriers*, *Relays* and the well-known *Telstars*; these contain receivers, amplifiers, transmitters, aerials and the necessary power supply arrangements. This equipment, sometimes on VHF and sometimes on microwave frequencies, is normally quiescent until commanded to operate by a ground station, thus conserving power and preventing unnecessary clutter in the traffic channels. The useful life of these satellites is often determined by their electronics rather than by the orbits; *Telstar* I launched in July, 1962 is no longer transmitting (having died of an overdose of radiation) though its orbital life is estimated at 10,000 years. Its successor, *Telstar* II, is still transmitting after two years of life, but it is doubtful whether this condition will persist for the 600,000 years the vehicle may be in orbit.

The amount of radio energy received back on earth from a space vehicle is so small that it is difficult to imagine in terms of normal power engineering. As a rough approximation, the signals received from a moon-shot just before impact are about the same level as would be received from a 2-kW heater located on the moon and beamed towards earth.

Orbits for Communications Satellites

It is evident that no single satellite can maintain uninterrupted contact between two fixed ground stations during the whole of its orbit, and much thought has been given to methods of eliminating or minimizing gaps in coverage. Broadly, there could be three multiple-satellite systems which would provide reasonably constant communication on a worldwide basis: the random low-altitude vehicle, the high-altitude synchronous system and the medium-altitude system. Each has its merits and disadvantages.

The so-called random system uses a relatively large number of simple and easily-launched vehicles in a series of circular polar orbits at 4,000-5,000 miles radius. The launches are not truly random, but aim to establish a pattern of satellites such that any two points on the earth's surface between which communication is desired can both 'see' a particular satellite until another has moved into a position for taking over the relay service. Contact between points at opposite sides of the world requires signals to be relayed through several satellites and ground stations, and there is a risk of gaps in the coverage unless the number of vehicles is very large indeed. The simplicity of each satellite is offset economically by the number required and by the complexity of the tracking stations needed to follow fast angular orbital rates. In favour of the random system it must be said that the failure of one of its elements causes a smaller loss of coverage than would occur with a synchronous or medium-altitude pattern.

The synchronous system briefly mentioned earlier would consist of only three repeater satellites equally spaced around an equatorial orbit 22,300 miles in radius. At this height their orbital speed is such that they require 24 hours for a complete rotation around the earth and so, when viewed from the revolving world, each appears stationary in space over a particular point on the equator. From these vantage points the whole earth is covered except for the vicinity of the poles, and radio point-to-point communication may be established with fixed ground-station aerials. The main difficulty with this apparently ideal system lies in launching and manœuvring each vehicle into exactly the right orbital conditions; the slightest error in speed or direction at the point of injection into orbit will cause the satellite to precess in one direction or another until it will no longer be in a useful position. A further difficulty with synchronous satellites arises from the great height at which they operate. The resulting radio path length is sufficient to cause a time delay of 0·3 second or more. While this is of little significance in unidirectional communication (e.g. television), it may be an embarrassment when two-way telephony is undertaken.

Syncom 3 was placed in synchronous orbit on 19th August, 1964 and is now successfully operating over the Pacific Ocean in longitude 180 degrees W and, of course, over the equator, the only possible plane for this type or orbit. Its predecessors *Syncom* 1 and 2 were launched at an angle to the equator; they appeared to describe a figure-of-eight manœuvre and were thus not synchronous in orbit. A fourth *Syncom* was launched this year to a station over the Atlantic; it is available for commercial traffic and will test public reaction to the inherent time delay.

The medium-altitude system would be a very practical pattern, forming a reasonable compromise between the random and synchronous systems. Twelve satellites in circular equatorial orbits at 8,000-9,000 miles radius would be equally spaced and ground stations would need tracking facilities since the vehicles will not be stationary. The coverage for such a pattern would extend from the equator to about 60 degrees north and south latitudes; most of the world's population lives within this zone and the loss of coverage would be of little commercial importance. The speech transmission delay problem present in *Syncom* systems would be reduced since the length of the radio propagation paths would be halved.

By the end of 1965 it should be possible to determine from practical experience which of the alternative types of system is best suited for commercial exploitation in the coming years.

Weather Satellites

Nine *Tiros* meteorological satellites have been launched since early 1960. Their function is to photograph the cloud cover of the entire sunlit surface of the world once or more every 24 hours and to transmit the pictures thus obtained to ground stations in the U.S.A. when suitably positioned in orbit. In five years nearly half a million pictures have been produced and these have contributed notably to the confidence placed in long-range weather forecasts.

The *Tiros* vehicles are in 400-mile high near-circular orbits, the first four at inclinations to the equator of 48 degrees and the remainder at 58 degrees, thus providing two rates of precession and of scanning the earth. Future *Tiros* spacecraft will establish the first operational chain, to be called *Tos* (*Tiros* Operational Satellite), but these will differ from earlier launches in that a number of new orbits will include several elliptical paths. In some vehicles TV cameras with 800-line resolution supplement the optical cameras and in others infrared sensors measure heat radiation from clouds over the dark side of the earth.

The second generation of weather satellites began in August, 1964, with the launch of *Nimbus* I. Although this particular vehicle was short-lived (its power-supply solar paddles jammed) it was the first of a series which will carry infra-red sensors and an advanced TV system as well as photographic cameras. In a near-polar orbit, *Nimbus* will see the whole of the earth's surface twice daily. It will be controlled in attitude by horizon-sensors and gas-jets, so that the camera, I-R and TV lenses always face the earth. A proposed system of synchronous weather satellites known as *Aeros* will (if adopted) provide continuous cloud data uninterrupted by orbital precession; it will, however, lack the ability to report on polar regions and, of course, its pictures will be on a smaller scale than those from closer orbits.

Navigation Satellites

Lack of space permits only a brief mention of the *Transit* system of navigation satellites. The aim of this system is to determine the positions of ships with respect to a satellite whose location at any time is accurately known. In this sense it resembles astronomical navigation, but here the similarity ends.

The celestial position of the satellite relative to the ship is found not by angular measurements by sextant, but by the Doppler effect on a satellite-borne radio transmitter as it approaches and recedes from the ship. Not only is the sextant dispensed with, but the chronometer also, since the transmission (based on a high-stability oscillator) provides an encoded time-reference. The astronomical tables moreover may be thrown overboard; the ephemeris relevant to the satellite's orbit is stored magnetically within the vehicle, and only those lines of the tables appropriate to its vicinity are broadcast during each transmission, which occurs at two-minute intervals. Within the ship, a dual-frequency receiver feeds the satellite signal through a data processer into a computer, from which may be read directly the ship's position co-ordinates in latitude and longitude, together with the time to which the fix refers.

The accuracy obtainable by the *Transit* system varies from a mean error of about one mile, using comparatively simple terminal equipment, to maybe one tenth of a mile with the most comprehensive installation; this accuracy also depends on the precision with which the satellites have been tracked from the ground, since any orbital deviations due to the perturbing effect of the earth's eccentricity must be allowed for in computing ship's position.

Conclusion

No reference has been made to the dramatic exploits of human astronauts, because these are the most publicized of all activities, in space, and in any event are more 'scientific' than 'technological', at present. The author has knowingly given less than fair treatment of many aspects of his subject, and is conscious that by the time his words appear in print they may have been overtaken by events. He is consoled by the thought that any furiously critical letters to the Editor will themselves be subject to the same attrition.