PROJECT RAND

(AAF PROJECT MX-791)

REFERENCE PAPERS RELATING TO A SATELLITE STUDY

J. E. LIPP

RA-15032

February 1, 1947

DOUGLAS AIRCRAFT COMPANY, INC.

PROJECT RAND

(AAF PROJECT MX-791)

REFERENCE PAPERS RELATING TO A SATELLITE STUDY

J. E. LIPP

RA-15032

February 1, 1947

DOUGLAS AIRCRAFT COMPANY, INC.

TABLE OF CONTENTS

---

*This initial external distribution list includes the distribution of all related technical reports on the satellite vehicle.

NOTE

Pages 2, 16, 24, and 38 are blank, unnumbered pages in the original and are not reproduced in this PDF copy.

SUMMARY

This report contains a selection of memoranda which discuss various aspects of the satellite, both as to its technical development and as to its value. Several of the papers have been included as a matter of general interest rather than for their direct application to the satellite study. Since the subjects covered are somewhat scattered, no particular organization of the report has been possible, and no overall conclusions are drawn.

Additional discussions of a similar character are to be found as appendixes in the two following references:

1. Status of Satellite Study, RA-15006, (Reprinted from the Second Quarterly Report, RA-15004) Project RAND, Douglas Aircraft Company, Inc., September 1, 1946.
   See Appendix II - Approximate Formula for Use in Trajectory Calculations.

2. Third Quarterly Report, RA-15013, Project RAND, Douglas Aircraft Company, Inc., December 1, 1946.
   See Appendix I - Problems Relating to Long-Range Radar Tracking.

PERTURBATIONS OF A SATELLITE ORBIT

Lyman Spitzer, Jr.

YALE UNIVERSITY
CONSULTANT TO RAND

SUMMARY

The motion of a small body, revolving in a nearly circular orbit around the earth about 800 km above the earth's surface, is considered. Perturbations by the sun and moon are negligible, causing the orbit to depart from a circle by less than one meter. Perturbations caused by the oblateness of the earth are much larger. An orbit nearly in the plane of the equator will not be distorted appreciably, but will precess in space; the pole of the orbit will move in a circle about the celestial pole, taking 55 days for a complete revolution. An orbit passing over the poles will deviate from a circle by 1.5 km, which is less than the deviations of the earth's surface from a sphere; the body will be 18 km higher above the earth's surface at the poles than at the equator.

The orbit of a small satellite vehicle revolving about the earth, in a gaseous medium so rare that its resistance may be neglected, is to a first approximation an ellipse, with the center of the earth at one focus. In this approximation the earth is assumed to be spherical and the gravitational attractions of other bodies on the satellite are neglected.

Higher approximations may be found by the standard methods of celestial mechanics. In the present analysis these methods are applied to compute the orbit in a second approximation. Specifically, the magnitude of the perturbations produced by the moon and sun (Sec. I), and by the oblateness of the earth (Sec. II) are computed to a first approximation, on the assumption that the satellite is in a nearly circular orbit. Numerical values are found for a satellite 800 km above the earth's surface. Since the perturbations produced by the sun and moon are shown to be very small, it is obvious that those produced by the other planets are wholly negligible.

The only perturbations discussed here are the short-term deformation of the orbit and the steady motion of the orbit in space. Other perturbations are of higher order and may certainly be neglected during a time interval of only a few hundred years. A more elaborate investigation would be required to prove the stability of the orbit over very long time intervals. For example, the stability of the solar system during a billion years has not been proved, since the series used for analyzing the situation diverge after so long a time. While this question of long-term stability is of considerable theoretical interest, it has little practical importance and will not be considered here.

Symbols used a number of times in the following analysis are as follows:

n	Mean angular motion of the satellite relative to the earth, taken as as 1.0×10^{-3} radians/sec
M	Mass of the earth
M_M, M_S	Mass of the moon and sun, respectively
R	Mean distance of the satellite from the center of the earth, taken as 7,200 km
R_M, R_S	Mean distance of the earth from moon and sun, respectively
A	Moment of inertia of the earth about an equatorial radius
C	Moment of inertia of the earth about the polar radius
G	Gravitational constant
r	Distance of satellite from center of earth
ρ	r - R, the deviation from circularity
ω	Angular rate of regression of the nodes (the points at which the orbit crosses the ecliptic or equator)

I. PERTURBATIONS BY MOON AND SUN

A distant body will exert an attraction on both the earth and a neighboring satellite. Thus both earth and satellite will accelerate toward the distant body. The difference between the acceleration of the earth and the acceleration of the satellite is the "disturbing acceleration" which perturbs the satellite orbit relative to the earth. The magnitude of this acceleration may be computed very simply when the satellite is on the line joining the earth and the sun, at a distance R from the earth. If the x axis is taken along the line joining earth, satellite, and sun, then the acceleration of a satellite relative to the earth is given by

$$\frac{d^2x}{dt^2} = \frac{GM}{R^2} - \frac{GM_S}{(R_S-R)^2} + \frac{GM_S}{R_S^2} \tag{1}$$

The sum of the second and third terms is the disturbing acceleration. Let ψ be the ratio of this acceleration to the earthward acceleration represented by the first term in eq. (1). On expanding $(R_S-R)^{-2}$ and retaining only the first two terms, we have

$$\psi = 2\,\frac{M_S}{M}\left(\frac{R}{R_S}\right)^3 . \tag{2}$$

For a satellite at a height of 800 km, eq. (2) gives 0.73×10^{-7} for ψ. For perturbations of the satellite by the moon the corresponding value of ψ is 1.6×10^{-7}. The value of ψ is approximately the ratio of the tidal force at the surface of the earth to the gravitational force towards the earth, and it is well known that the solar tides are about half the lunar ones, in agreement with the above result. By comparison, for the perturbations of the sun's attraction on the moon's orbit, ψ is 1.1×10^{-2}. While for a value of ψ as great as 10^{-2} the perturbations can become relatively large and complicated, for values as small as 10^{-7} one may expect these perturbations to be negligible.

First the approximate deviation of the orbit from a circle will be computed. The shape of a satellite orbit perturbed by the sun has been computed by G. W. Hill[1]. For the deviations of an orbit from circularity we have his result, expressed in the present notation,

$$\rho = Rm^2 \cos 2(n-n')t \quad , \tag{3}$$

where n and n' are the mean motions of satellite and sun respectively, relative to the earth, and

$$m = \frac{n'}{n} \quad . \tag{4}$$

In these equations, the many terms found by Hill in m^3 or higher have been neglected. The mean motion n of the satellite is given to a first approximation by

$$n^2 = \frac{GM}{R^3} \quad , \tag{5}$$

which gives a value of 1.0×10^{-3} for n when R is 7200 km, corresponding to a height of about 800 km above the surface. Since also

$$n'^2 = \frac{GM_S}{R^3_S} \quad , \tag{6}$$

we have for ρ_{max}, the greatest value of ρ,

$$\rho_{max} = \frac{1}{2} R \psi \quad . \tag{7}$$

Substituting the numerical values used above into eq. (7), we have

$$\rho_{max} = 26 \text{ cm} \quad . \tag{8}$$

Hill's theory cannot be directly applied to perturbations of a satellite by the moon, since the Coriolis force and the disturbing force are no longer related in the same simple way as in the perturbations of a satellite by the sun. However, examination of the basic equations in this situation show that eq. (7) is still valid,

---

For references see page 10.

provided that the value of ψ for lunar perturbations is used. Thus the perturbations by the moon give a value of 57 cm for ρ_{max}. When the sun and moon are in conjunction or opposition, these values of ρ_{max} are directly additive, and we have

$$\rho_{max} = 83 \text{ cm} \quad . \tag{9}$$

This resultant value is probably much too small to be measurable.

Next we must compute the rate at which the orbit plane precesses about the pole of the ecliptic. In this motion, the inclination of the orbit plane to the ecliptic remains constant. The pole of the orbit (the intersection with the celestial sphere of a line perpendicular to the orbit plane) moves in a small circle about the pole of the ecliptic, the direction of this motion being opposite to the direction in which the satellite revolves. Thus the nodes, or intersections of the orbit with the ecliptic, as plotted on a celestial sphere, (i.e., as viewed from the center of the earth) move slowly backwards.

For perturbations of the satellite by the sun, the results summarized by E. W. Brown[2] may be used. The angular velocity ω of this regression of the nodes is

$$\omega = \frac{3}{4}\,\frac{n'^2}{n} \tag{10}$$

or, using the relationships (5), (6) and (2) as before, we find

$$\omega = \frac{3}{8}\,\psi\, n \quad . \tag{11}$$

If we substitute numerical values, we find

$$\omega = 2.7 \times 10^{-11} \text{ radians/sec} \quad . \tag{12}$$

This corresponds to a period $2\pi/\omega$ of 7,400 years.

For perturbations of the satellite orbit by the moon, the conventional results are no longer applicable. It may be readily shown, however, that eq. (11) is valid in this case also, provided that the appropriate value of ψ for perturbations by the moon is taken. For example, eq. (11) may be derived by a computation of the average torque L on the satellite, relative to the earth's center, and use of the formula for precession of a gyroscope, which in this case becomes

$$\omega = \frac{L}{nmR^2} \quad , \tag{13}$$

where m is the mass of the satellite. Since the values of ω found for perturbations by the sun and by the moon are additive, we have, finally for the total luni-solar perturbations

$$\omega = 8.7 \times 10^{-11} \text{ radians/sec} \quad , \tag{14}$$

yielding a period of 2,300 years. It will be shown in the next section that this motion is overshadowed by a much more rapid motion resulting from the earth's oblateness.

II. PERTURBATIONS BY OBLATENESS OF EARTH

The motion of a particle of negligible mass in the neighborhood of an oblate spheroid has recently been considered by Brouwer[3]. The gravitational potential U in such motion may be written approximately in the form

$$U = \frac{GM}{r} \left\{ 1 + k \left(\frac{1}{r^2} - \frac{3z^2}{r^4} \right) \right\} , \tag{15}$$

where z is the coordinate of the particle along an axis parallel to the poles. The quantity k is defined as

$$k = \frac{C-A}{2M} , \tag{16}$$

where C and A are the moments of inertia of the earth about the polar and equatorial radii, respectively.

The term in parentheses in eq. (15) gives rise to a "disturbing acceleration" which again perturbs the orbit. Let χ be the ratio of this disturbing acceleration to the average acceleration, given by the first term, for a particle over the equator. If we differentiate eq. (15) when z is set equal to zero, divide the second term by the first, and substitute for k from eq. (16), we have, when r equals R,

$$\chi = \frac{3(C-A)}{2MR^2} . \tag{17}$$

The value of C-A has been determined from gravity measurements in widely separated regions. Jeffreys[4] gives the result

$$\frac{3}{2} \frac{C-A}{Ma^2} = 1.64 \times 10^{-3} , \tag{18}$$

where a is the radius of the earth. From this result it follows that

$$\chi = 1.3 \times 10^{-3} . \tag{19}$$

This ratio χ is about 10,000 times as great as the corresponding ratio ψ, and hence we may expect the perturbations produced by the oblateness of the earth to be enormously greater than those resulting from the sun and moon.

First we consider an orbit whose inclination to the earth's equator is small. In such an orbit the disturbing acceleration will be nearly constant in magnitude and the orbit will be very closely circular. The mean motion n will be slightly greater than that given in eq. (5), since the disturbing acceleration increases the inward force somewhat.

If such an orbit has a slight inclination to the equator, the pole of the orbit will move in a circle about the celestial pole. Thus the nodes, defined here as the intersections, on the celestial sphere, of the orbit with the equator will regress in a direction opposite to the satellite's revolution. The magnitude of this effect has been analyzed by Brouwer in ref. 3. In the present notation, we have, from his equation (35.2)

$$\omega = \chi n \quad . \tag{20}$$

The higher order terms given by Brouwer are not considered here. If we substitute numerical values, eq. (20) becomes

$$\omega = 1.3 \times 10^{-6} \text{ radians/sec} \quad , \tag{21}$$

yielding a period of 55 days, or about 770 revolutions of the satellite about the earth. This effect could be readily observed.

Eq. (20) was derived for small inclinations. When the inclination is large, the value of ω will be less than the value found above. By use of eq. (13) the rate of regression of the nodes may be computed directly for arbitrary inclination. Such an analysis leads again to eq. (20), but with the right hand side multiplied by cos i. Thus the period for the regression of the nodes will be proportional to the secant of the inclination, amounting to 78 days for an inclination of 45°.

As the inclination increases towards 90°, ω diminishes, and vanishes for an orbit passing over the poles. For such an orbit, however, the variation in the disturbing force will produce a deviation of the orbit from circularity. Since a situation of this type is unknown in the solar system, or elsewhere, orbits of this type have apparently not been analyzed.

The perturbations may be computed to the first order by a relatively simple analysis in the case of a nearly circular orbit which passes over the poles. We shall let θ represent the angle which the line from the earth's center to the satellite makes with the equator; then z equals $r \sin \theta$. The usual equations of motion in polar coordinates become, on differentiation of eq. (15),

$$\frac{d^2 r}{dt^2} - r\left(\frac{d\theta}{dt}\right)^2 = \frac{\partial U}{\partial r} = -\frac{GM}{r^2} - \frac{3kGM}{r^4}\,(1 - 3\sin^2\theta) \quad , \tag{22}$$

$$2 \frac{dr}{dt} \frac{d\theta}{dt} + r \frac{d^2\theta}{dt^2} = \frac{\partial U}{r\partial\theta} = - \frac{6kGM}{r^4} \sin\theta \cos\theta \quad . \tag{23}$$

If eq. (23) is multiplied by r, this equation may be written in the form

$$\frac{d}{dt} \left(r^2 \frac{d\theta}{dt} \right) = - \frac{3kGM}{r^3} \sin 2\theta \quad . \tag{24}$$

As a first approximation we may replace r on the right hand side of eq. (24) by its mean value R, and let θ equal nt. Thus when t is zero the satellite is above the equator. Then by a simple integration we have

$$\frac{d\theta}{dt} = \frac{R^2}{r^2} n + \frac{3kGM}{2nR^5} \cos 2nt \quad . \tag{25}$$

The constant of integration in eq. (25) is determined by the condition that on the average $d\theta/dt$ is, by assumption, equal to n. Throughout the following analysis, r will be replaced by R in all terms which are of the first order in k. In terms of zero order in k, r is replaced by $R + \rho$ and terms in the first order of ρ/R are retained, since ρ/R and k are of the same order.

If eq. (25) is substituted into eq. (22), and r^{-2} and r^{-3} are expanded in terms of ρ/R, then to terms of the first order we have

$$\frac{d^2\rho}{dt^2} - n^2 R + \left(3n^2 - \frac{2GM}{R^3} \right) \rho = - \frac{GM}{R^2} + \frac{3kGM}{2R^4} (1 - \cos 2nt) \cdot \tag{26}$$

The mean distance R of the satellite is related to the mean angular motion n by the equation

$$n^2 = \frac{GM}{R^3} - \frac{3kGM}{2R^5} \quad ; \tag{27}$$

thus for a fixed distance R the mean angular motion for a satellite passing over the poles of an oblate spheroid is less than for a body revolving about a sphere of the same mass M. From eqs. (26) and (27) we find for ρ the following equation, including only terms of the first order,

$$\frac{d^2\rho}{dt^2} + n^2\rho = - \frac{3kGM}{2R^4} \cos 2nt \quad . \tag{28}$$

The following solution for ρ is readily obtained

$$\rho = A \cos nt + B \sin nt + \frac{k}{2R} \cos 2nt \quad . \tag{29}$$

In the derivation of eq. (29), higher order terms in the coefficient of cos $2nt$

have been neglected. The terms in cos nt and sin nt represent deviations from circularity, corresponding to an eccentric orbit of the usual type; these terms bear no relation to the perturbation by the earth's oblateness and will not be considered here. If eqs. (16) and (17) are used to eliminate k, then we have, finally,

$$\rho = \frac{1}{6} \chi R \cos 2nt \quad . \tag{30}$$

It will be noted that ρ is positive when t is zero and the satellite is over the equator. Thus the satellite is nearest to the center of the earth when it is over the poles. If we insert numerical values, we have for ρ_{max},

$$\rho_{max} = 1.5 \text{ km} \quad . \tag{31}$$

This result may be compared with a difference of 21.4 km between the equatorial and polar radii of the earth. Since the satellite is 3.0 km nearer the center of the earth when over the poles than when over the equator, the perturbations of the orbit partly counterbalance the varying altitude of the satellite above the earth's elliptical surface. It is evident that the satellite will be 18 km nearer to the surface of the earth at the equator than at the poles.

References

[1] Collected Works, Memoir No. 32; also American Journal of Mathematics, vol. I, pp. 5, 129, 245: 1878

[2] "An Introductory Treatise on the Lunar Theory", (Cambridge Univ. Press, 1896). See especially p. 130.

[3] Astronomical Journal, vol. 51, p. 223, 1946

[4] "The Earth, Its Origin, History and Physical Constitution", (Cambridge Univ. Press, 1929), see. p. 210.

CONTROL AND NAVIGATIONAL METHODS FOR SATELLITES

Luis W. Alvarez
UNIVERSITY OF CALIFORNIA
CONSULTANT TO RAND

The problem of control, and of navigational methods for satellites can be divided into two phases, which have quite different requirements. In the first, we are concerned with the navigation of a test satellite, under peacetime conditions, where it is possible to have a large number of observational and control stations spaced at intervals under the orbit. In the second phase, we must operate under combat conditions, where for the most important part of the trajectory, we shall be unable to employ the simple and accurate observational methods available in the first phase.

A test satellite should be observable on many successive trips around the earth, and this places some restrictions on the orbit, if we are to do our observing from fixed stations. The period of a satellite is given by $T = 2\pi\sqrt{\frac{r}{g}}$, where r is the radius in feet, g is 32 ft /sec^2, and T is in seconds. For a 4000 mile radius orbit, T = 1 hour and 25 minutes (1.41 hrs). A satellite which is fired in a plane through the center of the earth, which makes an angle θ with respect to the equatorial plane, will pass over certain points on its first circumnavigation. On its second trip, it will in general pass over different points, and the maximum distance between the two tracks will occur at the equator, and will have a value equal to 1470 miles x sin θ. (1470 is equal to the velocity of a point on the equator times the period of the satellite.)

For orbits with θ near 90°, the satellite passes close to the poles, and the displacement per revolution is very near the maximum value of 1470 miles which is too great for successive observations from a fixed point. For orbits with θ small, the situation is somewhat different. For example, for θ = 5.7°, a sin θ = .1, the maximum displacement per revolution is 147 miles, which if it stayed constant at a particular point would amount to 17 × 147 = 2500 miles per day. But the track can obviously never be farther from the equator than 5.7°, or 400 miles, so for these orbits, we can merely take the latitude of the launching point as the maximum displacement from a series of observation stations on the equator. The orbit should therefore not be inclined to the equator by much more than 6 or 7 degrees if the satellite is to be visible at all times from stations on the equator. Unless adequate azimuthal control is available, this condition limits the launching site to within a band of ± 6 or 7 degrees of latitude.

Before discussing the problem of control, it is necessary to investigate the measurements which can be made on the satellite. When the projectile is in a stable orbit, the problem is exceedingly easy, since we can use our knowledge of celestial mechanics, which tells us that the orbit is in a plane, and that angular momentum is conserved. In other words, if at any time we have measured the radius of the orbit and the component of velocity normal to the radius vector, we can determine either of these two quantities by a measure of the other alone. If we have a continuous measure of the height of the satellite above the earth, as from a radar altimeter in the body itself, and at any time a simultaneous measurement of its range and range rate, from a ground radar station, all further information can be derived from the altitude measurements alone. This is of course an over-simplified case, as it assumes that the projectile has been put in a stable orbit before the measurements have been started.

What we are really interested in is the set of measurements which is made during the critical stages while the projectile is being maneuvered into a stable orbit, by control schemes to be discussed later. The Navy proposal assumes that the projectile will be made to circle the globe below the *F* layer, so that two-way, world-wide communications can be established between it and a control station. This appears to be an unwise restriction for two reasons. In the first place, the initial control will have to be more accurate the lower the maximum height allowed, and in the second, world-wide communication is not necessary to control a projectile which must be observed at many stations spaced around the track. Both of these reasons will disappear as the art advances, but in the early stages of development, it would seem reasonable to shoot the missile into the highest attainable orbit, and to use microwave communication and microwave observational equipment over a line of sight path.

Probably the most critical information to be obtained by observation is the altitude of the satellite, and through a continuous knowledge of altitude, its rate of change with time. The altitude rate determines the goodness of the orbit more sensitively than any other parameter which is susceptible to measurement. For example, it is approximately true that if the projectile is traveling with a speed appropriate to a closed orbit 100 miles high, and is 100 miles above the surface of the earth, but with a rate of change of altitude equal to 650 feet per second, it will intercept the surface of the earth in 20 minutes. If we compare 650 ft/sec with the satellite velocity of 26,000 ft/sec, we see that this corresponds to an error in the direction of the missile of about 1.5°.

We must therefore be able to measure altitude rates of this order of magnitude, and the problem is then presented of how to accomplish this. If we consider the problem from the point of view of a radar operator on the ground, observing at an altitude of 45°, with the missile at 100 miles above sea level, we see that 650 feet change in altitude corresponds to an angular change of 1/30 of a degree. This is just at the limit of accuracy of the most advanced radar sets now known, and if we couple to this the requirement that some of the observation stations on an equatorial track would have to be on ships for lack of islands, the precision of vertical stable elements would not allow this accuracy in any case.

We are led therefore to the relatively simple expedient of putting the altitude determining device in the satellite itself, and of transmitting this information to control stations on the track. A rate of change of altitude of 650 feet per second corresponds to a change in the arrival time of the radar altimeter pulse by 1.3 microsecond every second. This is obviously very easy to measure with simple airborne radar equipment, so the observational problem may be dismissed as solved at the moment.

The continuous altitude information can be relayed to observation and control stations under the track by well known methods of the type used in AEW, for example. These stations should be equipped with radar sets of the 584 type, which have been modified for long range operation. This modification would entail the reduction of the recurrence rate and the introduction of range circuits operating for distances up to 1000 miles. It would also be necessary to install a microwave radar beacon on the projectile, to allow it to be seen at such great distances. These beacons are available at the present time, having been built for ASPEN and similar applications.

This equipment will locate the satellite well enough at any time to allow corrections to be made to the radio altimeter. These corrections will be necessary in view of the non-spherical shape of the earth as a reference surface, and also because of the presence of mountains under part of the track. If uncorrected altitude data were used in solving the control problem, the satellite would experience many violent and unnecessary changes in direction when passing over the coastline of mountainous regions.

We will assume that each control and observational station will have associated with its radar set, a three dimensional cam, or its equivalent, which will automatically correct the telemetered altitude data from the satellite. This will work directly from the range and angular data of the radar set in such a way as to feed out continuously the distance from the satellite to the center of the earth, and dr/dt. The radar set will also feed out continuously the latitude and longitude of the satellite, which incidentally is used to position the cam. It is interesting to note that the radar set can perform this function particularly well by itself, at all times, out to the horizon, whereas it can determine the altitude and altitude rate accurately only when the satellite is at a considerable angular distance above the horizon, or in other words, close to the radar set.

There is now available at the closest ground station, all the independent pieces of information which can describe the motion of a satellite. From here on, the problem consists of several independent steps. The first involves the integration of the equation of motion of the satellite, with the initial conditions as measured. This will be a regenerative calculation in which the path is calculated from one set of initial conditions, and continuously improved to match later observational data. The constantly improved observed orbit will be at all times compared with a closed orbit through the present position of the satellite, and corrections will be computed on the basis of this comparison.

The decision as to where the computors are to be located is not of great importance at the moment, but there does seem to be a good reason for having a central computing station. A central computor could have a complete record of the orbit details from the firing, and extending over all the trips around the earth. There is no way to estimate the complexity of the computor needed to handle this job, but it is certain that experienced mathematicians and astronomers would be invaluable in assessing the data and passing judgment on the correctness of the control information. It would seem wise that the best brains available in this field should work with the finest equipment under the most favorable circumstances, when the cost of the experiment will be so high. If we were to allow the senior man at any of the observation stations around the equator to introduce corrections to the motion of the projectile, without the correlation of a central authority, we would allow greater possibility for errors of judgment, and run the risk that severe hunting could be introduced by men trying to correct the motion in the short time they were in control.

The situation as it is envisioned now, then, is that into a central computing station will come continuous and accurate data on the position and rates of the satellite in spherical coordinates. These will be used to construct future positions and rates through the use of integrating machines. Corrections will be estimated, or perhaps calculated, from this information, and the effects of the corrections quickly analyzed by computing orbits with these changed conditions.

In this connection it is worth noting that modern calculating machines can now work out the trajectory of 16″ shell faster than the shell can complete it. The calculations take into account the continuously varying parameters such as atmospheric pressure, gyroscopic effects, normal gravitational effects, wind resistance, etc., which used to require the services of batteries of human computors for long periods of time.

A control officer will then O.K. the corrections to be relayed to the closest observational and control station, where they will be transmitted by microwaves to the satellite. When the missile is in free space, the response to the control signal will probably be the firing of definite rocket charges either normal or parallel to the direction of motion depending on whether dr/dt or $d\theta/dt$ is to be changed. While it is in the atmosphere, the signals can actuate control surfaces. The complete decision as to the nature of the control signals will be the responsibility of the control officer at the central station, and the equatorial posts will merely relay the information without changes.

The interesting possibility presents itself that many of the early servo problems connected with the control of guided missiles could be eliminated in this remote control system employing high speed analyzers. It could be that the movements of the control surfaces in the early stages of the motion through the atmosphere could be computed to damp the normal hunting, if the aerodynamics of the controls were sufficiently well understood, and a high speed computor were available to control the signals from the ground. With good performance data on the controls, plus telemetered gyro information from the missile, the problem might be soluble. This is of course pure speculation.

Almost everything which has been said so far is concerned with the situation where the missile has been introduced into a reasonable facsimile of a satellite orbit, and the controlling problems have to do with trimming this up to the point where it will need no further attention. The more difficult phase in many ways is the early stage where the missile is traveling through the atmosphere. We are fortunate here to have available the experience of the Germans, whose V-2 rocket was controlled with a high degree of accuracy in the atmosphere, entirely through airborne measurements and computors. If we apply the ground based observational techniques, which are much more accurate in many respects, together with telemetered gyro and accelerometer data, we have on the ground a great store of precision measurements concerning the state of motion of the missile. If we couple to this the modern tools of rapid analysis, and microwave communication, we can transmit to the satellite-to-be enough intelligence so that it can place itself in an appropriate orbit. All this of course is predicted on the assumption that enough controls are available in the missile so that it can react properly to the signals it receives.

The control and navigation of satellites under wartime conditions, in such a manner as to hit a given target in distant enemy territory with a probable error of atomic bomb destruction radius, presents interesting problems at this time. But one should not expect to be able to sit down and outline a method for solving it now, any more than one could have expected the Wright Brothers in 1906 to have set down the performance characteristics of a 3 cm blind bombing radar. A great deal of information will come out of the trials of satellites under peacetime conditions, and the military performance will have to be based on these findings. For example, at this time it is impossible to forecast which of two distinctly different methods of use will be most practical. In the first case, one could introduce the missile into an orbit which intersects the earth at two points, the firing site and the target. This would require very accurate control in the initial stages, and would allow a minimum of time for observing the correctness of the orbit. If the orbit were to make the satellite pass many hundreds of miles into space, navigational methods based on terrestrial effects would be exceedingly difficult. However, such a trajectory has the greatest chance of hitting a given point on the surface of the earth, since a more glancing trajectory could miss the aiming point even if the angular errors were small. Methods of navigating intercontinental missiles were discussed in a report by the writer, but most of these break down when the speed of the missile is increased into the satellite range.

The second possibility of navigating a satellite is to put it into a stable orbit by techniques outlined earlier, with improvements worked out during actual tests. When such a stable orbit has been achieved, it is a simple matter to predict with astronomical accuracy the exact time it will be over any part of its track. If under previous conditions, we have learned how to take the missile out of its orbit and return it to the surface of the earth, and have done this with reproducibility, we can then set a time clock going by a radio signal over friendly territory, which will bring the missile down on the aiming point in enemy territory.

In the present state of ignorance regarding the performance of satellites it is perhaps not worth speculating more on this possibility.

USE OF NUCLEAR ENERGY IN THE SATELLITE

Luis W. Alvarez
UNIVERSITY OF CALIFORNIA
CONSULTANT TO RAND

I. POLONIUM CATHODES

In the estimates of electrical power requirements for the satellite vehicle it appears that one-half of capacity is required for heating filaments of radio tubes while the other half is available for plate circuits and auxiliary controls. It would appear possible to increase the efficiency of a polonium power plant by using polonium to heat the cathodes directly instead of going around a circle involving the conversion of heat to mechanical energy, then to electrical energy and back again to cathode heat. This would involve the use of polonium directly in the cathode structure of the radio tubes. One curie of polonium gives about 1/30th of a watt, so it is easy to see that the cathode heating requirements of all tubes, even including power tubes such as the 6L6, could be taken care of with reasonable amounts of polonium. These amounts are reasonable at the present moment because of the large quantities of polonium available from existing piles. But, of course, these amounts are fantastic by pre-war standards.

There are no facilities available in the country at the moment for handling amounts of polonium giving 200 watts. This would require, of course, 6000 curies, but it is fair to say that by a reasonable expansion of present facilities these very large amounts could be handled. The important thing here is that trained personnel are available and the "know how" for handling very large quantities of polonium has been gained during the war. It was a much more difficult thing to go from the millicurie stage to that which now has been required, than it would be to extrapolate to the 6000 curies level.

II. STRONTIUM AS A FUEL

Dr. E. M. McMillan has collected the following information about radio-active Sr 89. Sr 89 has a half-life of 55 days and emits Beta rays with an upper limit of 1.48 mev. It is believed that an adequate amount already exists in the stored waste products at Hanford. It would be very difficult to separate Sr from the radio-active barium which emits strong Gamma rays with a half-life of 12.5 days. But if we allow the fission products to cool for 100 days or so, the shorter-lived barium will decay greatly with respect to the Sr, so that the separation can be much more easily effected. It is not possible from the data given by Dr. McMillan to tell what would be the optimum time after radiation to perform the chemical separation. If most of the Gamma rays after 50 days come from the barium as is quite possible, then the chemical separation would, of course, become easier the longer we waited. On the other hand, if the Gamma rays come from a longer-lived activity, then waiting would merely increase the shielding problems in the chemical separation. There is a strong gamma ray emitter of 60-day half-life so it is impossible to gain anything in the ratio of beta to gamma activity after the barium has died away. One hundred days would probably be a good time to wait. The complete data on the relative amounts of Beta and Gamma rays as a function of the cooling time, are available and can be reported later. Since there is so much activity available at any one time in the cooling tanks, it is not necessary to hurry the separation to make sure of getting the Sr out before it has decayed. This is a very favorable situation and there is a good chance that the chemical problems may turn out to be quite easy.

Another possibility which might offer some promise of making the separation easier is that, at present, all the fission products are dumped down the drain together. But they are separated out in several groups during the chemical purification of plutonium so it might be possible to divert a fraction of the fission products containing barium, Sr, and a few other substances to a particular storage tank which did not contain other products, which would later cause trouble in the purification of Sr. This is very difficult with the present chemical treatment at Hanford but the designer of the new equipment to be installed there soon assures me that this would be easy when that change has been made. He thinks the 55-day strontium could be very useful as a compact source of nuclear energy.

Sr is to be preferred to polonium for at least two reasons. In the first place, it is made free of charge, whereas polonium requires special loading of the pile with bismuth slugs. Secondly, polonium is a particularly toxic substance which requires extraordinary precautions from the health standpoint.

ESTABLISHING A MISSILE TRAJECTORY

Leonard I. Schiff
UNIVERSITY OF PENNSYLVANIA
CONSULTANT TO RAND

This memorandum is intended to be an introductory discussion of the problem of establishing a missile as a satellite of the earth. Several formulas that are likely to be useful are given, but few explicit numerical results are given, mainly because of lack of time to obtain them.

Orbits

Certain well-known results are collected here for convenience in reference. M is the mass, E the total energy, V the initial speed (on termination of motor thrust), and r, ϕ the polar coordinates of the missile; R is the radius of the earth, g the gravitational acceleration at the surface of the earth. Air drag is neglected throughout. Put $u = 1/r$, $U = 1/R$, $U - \delta = 1/(R+h)$, where h is the greatest height of the missile and occurs at $\phi = 0$; $\phi = \phi_0$ is the polar angle at which the missile leaves or strikes the earth, as shown in Fig. 1. V_h is the speed at the greatest height, and θ the angle with the surface of the earth when the missile leaves or strikes the earth.

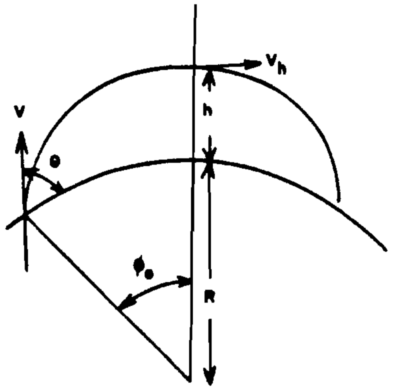


FIG. 1

The equations of motion are

$$\frac{\frac{1}{2}M(\dot{r}^2 + r^2\dot{\phi}^2) - MgR^2}{r = E - MgR}, \tag{1}$$

$$r^2\dot{\phi} = \alpha \tag{2}$$

where dots denote time derivatives, and a is the angular momentum per unit mass of the missile. Substituting for u and eliminating the time

$$\frac{d^2u}{d\phi^2} + u = \frac{g}{a^2U^2} , \tag{3}$$

which has the solution

$$u = \frac{ag}{(a^2U^2)(1 - e\cos\phi)} . \tag{4}$$

e and a are determined by putting $u = U$ when $\phi = \phi_0$, and $u = U - \delta$ when $\phi = 0$

$$e = \frac{\delta}{[U-(U-\delta)\cos\phi_0]}$$

$$a^2 = \frac{g(1 - \cos\phi_0)}{U^2[U - (U-\delta)\cos\phi_0]} . \tag{5}$$

Then the initial speed is

$$V^2 = \frac{2E}{M} = \frac{g}{U^2} \cdot \frac{2\delta + [(U - \delta)^2(1 - \cos\phi_0)]}{[U - (U - \delta)\cos\phi_0]} . \tag{6}$$

This speed is a minimum (minimum energy orbit) when

$$\delta = \frac{U\sin\phi_0(1 - \sin\phi_0)}{\cos\phi_0(1 + \cos\phi_0)} , \tag{7}$$

or when

$$h = \frac{R\sin\phi_0(1 - \sin\phi_0)}{1 + \cos\phi_0 - \sin\phi_0} . \tag{8}$$

In this case

$$V^2 = 2gR\sin\phi_0\sec^2\phi_0(1 - \sin\phi_0). \tag{9}$$

Eqs. (7), (8), and (9) are valid only for $0 \leq \phi_0 \leq \pi/2$; for larger ϕ_0, the minimum energy orbit is still the one that just grazes the surface of the earth at every point (same as for $\phi_0 = \pi/2$). Again, for this minimum energy orbit

$$\theta = \frac{\pi}{4} - \frac{\phi_0}{2} \quad . \tag{10}$$

Establishment of Satellite Orbit

To place the missile in a circular satellite orbit, it seems simplest to fire it in an elliptical orbit and then give it an additional momentum parallel to the surface of the earth when it attains its greatest height. Put

$$\lambda = \frac{\delta}{U} = \frac{h}{R + h} \quad . \tag{11}$$

For given h (and hence λ), we wish to find ϕ_0 and V^2 as functions of θ. The desired relations are

$$\frac{\tan \phi_0}{2} = \lambda \cot \theta , \tag{12}$$

$$V^2 = gR \frac{2\lambda + (1 - \lambda)^2 (1 - \cos \phi_0)}{1 - (1-\lambda) \cos \phi_0} \quad . \tag{13}$$

The speed at maximum height is

$$V_h{}^2 = V^2 - 2\lambda g R . \tag{14}$$

The quantity of greatest interest is the total speed that must be imparted to the missile. This is

$$V_t = V + V_s - V_h \quad , \tag{15}$$

where the speed V_s for the circular satellite orbit is

$$V_s = \left(\frac{gR^2}{R + h} \right)^{1/2} \quad . \tag{16}$$

Expressed in terms of θ

$$V_t = V_s \quad 1 + \left(\frac{2h}{R}\right)^{1/2} \frac{(\tan^2\theta + 2\lambda - \lambda^2)^{1/2}}{1 - \lambda + \sec\theta} \quad . \tag{17}$$

This quantity increases monotonically from a smallest value when $\theta = 0$ and $\phi_0 = \pi$ (so that the missile is shot out horizontally and attains its maximum height when it is on the opposite side of the earth), to a largest value when $\theta = \pi/2$ and $\phi_0 = 0$ (so that the missile is shot straight up). For $R = 6370$ km, $g = 9.81$ m/sec², $h = 500$ km, we get V_s=7.61 km/sec; in this case, V_t=1.077 V_s for θ=0, V_t=1.315 V_s for θ=45°, and V_t=1.396 V_s for θ = 90° .

Placement Errors

Since θ and V are the variables controlled at the outset, we are interested in finding first what the effect of errors in these two quantities will be on h, ϕ_0, and V_h. Assuming infinitesimal errors, we obtain:

$$d_h = \frac{(R+h)^2}{R}\, d\lambda \ .$$

$$d\lambda = V \sin^2\theta \, \frac{[1 + (2\lambda-\lambda^2)\cot^2 \theta]^2}{gR(1+\lambda^2\cot^2\theta)} \, dV + \frac{2\lambda(1-\lambda)^2\cot\theta}{1+\lambda^2\cot^2\theta}\, d\theta \ , \tag{18}$$

$$d\phi_0 = 2V \sin\theta\cos\theta \, \frac{[1 + (2\lambda-\lambda^2)\cot^2\theta]^2}{gR(1 + \lambda^2\cot^2\theta)} \, dV + 2\lambda \csc^2\theta \, \frac{[2(1-\lambda)^2\cos^2\theta - (1+\lambda^2\cot^2\theta)]}{(1+\lambda^2\cot^2 \theta)^2} \, d\theta \ , \tag{19}$$

$$dV_h = \frac{V}{V_h}\, dV - \frac{gR}{V_h}\, d\lambda \ . \tag{20}$$

For θ = 0, Eqs. (18), (19), and (20) become

$$d\lambda = \frac{(2-\lambda)^2 V}{gR}\, dV, \quad d\phi_0 = -\frac{2}{\lambda}\, d\theta \ , \qquad dV_h = -\frac{V(3-\lambda)\ (2\lambda-\lambda^2)^{1/2}}{(2\lambda gR)^{1/2}}\, dV \ . \tag{21}$$

For θ = $\pi/2$, these equations become

$$d\lambda = \frac{V}{gR}\, dV \ , \qquad d\phi_0 = -2\lambda d\theta \ , \qquad dV_h = -(1-\lambda)(2\lambda gR)^{1/2}\ d\theta \ . \tag{22}$$

Conclusions

It is apparent that with neglect of atmospheric drag, less total thrust is required to place a missile in a satellite orbit if it is shot out nearly parallel to the surface of the earth. On the other hand, the errors in placement are more pronounced in this case. A more obvious disadvantage to this procedure is the large distance of travel through the atmosphere, which increases both the thrust required and the errors.

Other Comments

Some data or theory of drag forces at various heights in the atmosphere should be obtained, since this will be an important feature of any practical device.

It might be desirable to make numerical computations of some of the formulas presented above, in order to obtain a clearer picture of the important variables. In this connection, one could go further with the section on errors, and find the resultant eccentricity, etc., of the orbit.

Use of the Doppler effect with CW radar could be used to establish the speed of the missile when it acquires its additional thrust at maximum height. This could be done preferably if the vertical launching were used, and at the same time another missile containing the radar were launched vertically nearby.

February 1, 1947

TEST DETERMINATION OF SATELLITE ORIENTATION IN SPACE

Leonard I. Schiff

UNIVERSITY OF PENNSYLVANIA
CONSULTANT TO RAND

It is suggested that a true vertical with respect to the earth can be established in a satellite moving around the earth in a circular orbit in the following way. A projectile is ejected from the satellite in a direction which it is desired to compare with the vertical (line through the satellite and the center of the earth). The speed of this projectile relative to the satellite is then measured as a function of time. The speed V of the satellite in its orbit of radius R, the speed v of the projectile relative to the satellite (initial value v_0), the time t, and the angle θ between the direction of ejection and the vertical, are connected by the following expression:

$$v = v_0 \left\{ 1 + \left(\frac{Vt}{R} \right)^2 \cdot \frac{1}{2} (3 \cos^2 \theta - 1) \right\} .$$

This is accurate only to lowest order in $(Vt/R)^2$, but except for that is exact with respect to dependence on angle θ and on the ratio v_0/V. Thus v is greatest at a given time if the projectile is shot straight up or down (no distinction is possible between these directions in this order), and is least if the projectile is ejected in a horizontal plane.

The accurate measurement of v/v_0 as a function of time should be possible with help of a CW radar transmitter contained in the projectile. The Doppler effect should enable one to obtain great accuracy since only "line of sight" speed is desired. If there is concern about the frequency stability of the projectile transmitter, the satellite could measure the frequency of echoes from the projectile. This has the disadvantage that it is more difficult to get great range with echoes than with direct reception. On the other hand, v/v_0 is independent of v_0, and so a relatively low ejection speed can be used, so that the range does not get large rapidly.

Introducing typical values, for a satellite at a height of 150 km $V = 7.82$ km/sec. Assuming that v/v_0 can be measured to one part in 10^6, we get for the uncertainty in direction near the vertical ($\theta=0$): $\Delta\theta=(2/3)^{½}(6520 \times 10^{-3}/7.82t)=$ $0.68/t$ radians (t in seconds); for one minute, this is 0.65°. For a direction some distance from the vertical the accuracy is much better. For an angle θ substantially greater than zero: $\Delta\theta=(2/3)(6520 \times 10^{-3}/7.82t)^2 \cdot csc\ 2\theta=0.46/t^2$ for $\theta=45°$; for one minute, this is 0.0073°. There is nothing to prevent several projectiles from being ejected at once in several directions, so that the one minute assumed above is of the order of the time required for the whole determination. In one minute, the satellite travels 4.1° around the earth.

Two more miscellaneous comments. (1) It would appear at first that this system couldn't work because the relative speed of satellite and projectile should be constant. However, the curvature of the lines of force of the earth's field cause the two to be acted on differently, and this shows up as soon as (Vt/R) becomes appreciable. (2) The formula above was obtained by an exceedingly arduous calculation which was carefully checked. The final answer is so simple in comparison with the intermediate steps that there is likely to be a simple way of getting it. This has not been looked into yet. If this method is considered worthy of further investigation, the next higher term in (Vt/R) should probably be calculated, preferably by a simpler method than that which was used.

COSMIC RAY RESEARCH
IN A
SATELLITE VEHICLE

Bruno Rossi
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CONSULTANT TO RAND

Cosmic ray research is of fundamental importance both in the field of Physics and in the field of Cosmology.

The importance of cosmic rays in the field of Physics has been underlined most strikingly by the discovery of *positive electrons* and by the discovery of *mesons*. Positive electrons were first detected in cloud chamber pictures of cosmic ray showers; it was later shown that they can also be produced by high energy γ-rays from terrestrial sources. Mesons form the so-called "hard component" of cosmic rays. The cosmic radiation has been, so far, the only source of mesons; however, it is possible that the development of accelerators in the hundreds of millions of electron volts range (betatron, synchrotron, f-m cyclotron, etc.) may provide a laboratory source of mesons. The reason for the great significance of cosmic ray research in physics lies in the very large energy of individual cosmic ray particles and quanta. Because of their large energies, cosmic rays are capable of producing the most unusual effects, and they provide the most powerful tool at our disposal for the investigation of the fundamental properties of atomic nuclei.

So far, the physical interest of cosmic rays has overshadowed their cosmological interest. It is very likely, however, that when the nature and the properties of cosmic rays are clearly understood, scientists will be able to use them as a tool for cosmological studies in the same way as they use them today as a tool for physical studies.

For the moment, even though we have learned a great deal about many of the phenomena produced by cosmic rays, the problem of the nature of the primary cosmic rays has not been solved. The peculiar difficulty of this problem lies in the fact that the cosmic radiation, as it enters the atmosphere, rapidly changes its character through the production of secondary rays. Therefore the radiation which reaches our detecting equipment is completely different in its nature and properties from the primary cosmic radiation.

It is clear that an observatory located *outside* of the terrestrial atmosphere would provide a new and much more direct method of attack on the cosmic ray problem. Such an observatory would make it possible to experiment on the primary radiation itself, whereas until now we have only been able to experiment on the primary radiation as modified by the passage through at least part of the atmosphere. In order to appreciate the results that one may expect from cosmic ray studies in an extra-terrestrial observatory, it is perhaps appropriate to review briefly our present knowledge about cosmic rays.

I. PRESENT STATE OF THE COSMIC RAY PROBLEM

A. Extra-terrestrial Origin of Cosmic Rays

The hypothesis of a radiation of extra-terrestrial origin was first advanced on the ground of observations showing that the ionization of air in a closed vessel increases with increasing height (Hess). The experimental evidence in favor of this hypothesis is today overwhelming. Perhaps the most convincing single argument is the influence of the earth's magnetic field upon cosmic rays, as shown, for instance, by the correlation between geomagnetic latitude and cosmic ray intensity. The magnetic field of the earth, because of its small intensity, could not deflect the trajectories of cosmic ray particles appreciably if these did not come from a distance at least comparable with the earth's radius.

B. The Known Components of the Observed (Local) Cosmic Radiation

The study of cosmic ray phenomena has revealed the existence of various kinds of rays, namely:

1. High energy electrons, both positive and negative
2. High energy photons
3. Positive and negative mesons
4. Protons
5. Neutrons.

Cosmic ray electrons and photons, because of their high energy, behave very differently from electrons and photons of radioactive origin. However, their properties seem to be accounted for very satisfactorily by existing theories.

About the mesons, we know that their mass is approximately equal to 200 times the electron mass. We also know that they are unstable and disintegrate with a lifetime of about 2 microseconds. The products of the disintegration are an electron and probably a neutrino. The properties of mesons have not yet been brought into a satisfactory theoretical scheme.

Most of the cosmic ray protons and neutrons *which have been directly observed so far* do not have energies much in excess of the protons and neutrons observed in ordinary nuclear reactions, although the existence of protons and neutrons of very high energy is strongly suspected.

C. Secondary Effects of Cosmic Rays and Correlations Between the Various Cosmic Ray Components

1. High energy electrons are known to produce high energy photons by "bremsstrahlung". High energy photons are known to produce electron pairs (a positive and negative electron) by a materialization process. Thus the electron and photon components of cosmic rays are intimately correlated to one another, in the sense that where electrons are present, photons must be present too and *vice versa*. When a high energy electron or photon impinges

upon matter, soon its energy subdivides itself into a large number of secondary photons and electrons through repeated processes of radiation and pair production. This phenomenon is known as a *cascade shower*. It reveals itself through the simultaneous appearance of large numbers of electron tracks in cloud chambers. It may be detected also by ionization pulses in ion chambers or by time-coincident discharges of Geiger-Mueller tubes properly arranged.

2. Mesons, by their disintegration, produce electrons. Moreover, they transfer part of their energy to atomic electrons by direct collision. In addition, they give rise to high energy photons by "bremsstrahlung", though in much smaller number than electrons. (The difference in the radiation probability of electrons and mesons is accounted for by their differences in mass). Thus part, at least, of the electron-photon component of the local cosmic radiation is produced by mesons.

3. The mesons themselves cannot be part of the primary cosmic radiation because of their very short lifetime. Hence they must be produced in the atmosphere by other rays (not necessarily all of the same kind), which, for the moment, we will denote as *meson producing rays*. Very little is known experimentally and very little can be predicted theoretically about the process of meson production. Both cloud chamber and counter experiments indicate that mesons are mainly produced in groups of several particles at a time. These production processes are very rare at sea level and increase rapidly with height.

4. The protons and neutrons of comparatively low energy associated with cosmic rays are also, for the most part at least, produced in the atmosphere. They seem to arise from nuclear disintegrations in which several protons and presumably several neutrons appear simultaneously; a phenomenon known as a *cosmic ray star*. The nature of the star producing radiation is unknown.

D. What is Known About the Primary Radiation

The study of geomagnetic effects provides some direct information on the *primary* cosmic radiation because the magnetic field of the earth extends to a distance much greater than the thickness of the atmosphere and therefore acts upon cosmic rays before they undergo any transformation by interacting with matter.

The observed geomagnetic effects are:

1. A gradual decrease of the total cosmic ray intensity with decreasing geomagnetic latitude (latitude effect).

2. A dependence of the *meson* intensity on the azimuthal angle. More specifically, for a given zenith angle, one observes a larger number of mesons coming from the west than from the east (east-west effect). The azimuthal dependence of *electrons and photons* has not yet been investigated satisfactorily.

The very existence of geomagnetic effects shows that *part at least of the primary cosmic radiation is electrically charged*. The sign of the east-west effect indicates that a *majority of the mesons observed are produced by primary rays carrying a positive charge*. The quantitative study of geomagnetic effects provides also some information on the energy distribution of the primary cosmic rays particles. It seems that very few, if any, charged particles of energy below 3 or 4 Bev exist in the primary radiation. This cut-off in the energy spectrum of cosmic rays has been tentatively attributed to a blocking effect of the magnetic field of the sun. From 3 or 4 Bev the spectrum falls off with increasing energy. For the differential spectrum, a power law with an exponent around -2.5 seems to fit the experimental results reasonably well. It must be pointed out, however, that all of these conclusions are very tentative because so far it has not been possible to measure the geomagnetic effects on the primary radiation directly.

E. General Picture of Cosmic Ray Phenomena

From the existing experimental information we can piece together the following still incomplete picture of cosmic ray phenomena.

First of all, we know that the primary cosmic radiation contains positive particles of very high energy. The hypothesis has been made that these particles are protons. Even though such an hypothesis appears reasonable, it still lacks direct experimental support.

These primary positive particles, in traversing the atmosphere, produce mesons either directly or indirectly. The cross-section for meson production is quite large, so that the primary meson producing rays are rapidly absorbed. Their "mean free path" in air seems to be of the order of 100 g/cm^2 (1/10 of the atmosphere).

Mesons, mainly by disintegration, but also by collision and radiation processes, produce electrons and photons, which then multiply into showers. It is likely that in the processes of meson production neutrons and protons of energy smaller than that of the hypothetical primary protons are also generated. The more energetic of these particles may be able to produce more mesons, while the less energetic may produce the nuclear disintegrations, observed as *stars*. Also, nuclear disintegrations may be produced by high energy photons.

Thus the origin of a large portion of the observed cosmic ray phenomena can be traced back to a primary radiation consisting presumably of protons, through the intermediary of secondary processes, some of which are well-known (disintegration of mesons, radiation and collision processes of electrons and mesons, materialization of photons), while others represent reasonable hypotheses (multiple production of mesons by protons, nuclear disintegrations by neutrons, protons, and photons).

The next question is whether or not all cosmic ray phenomena come within this picture. The answer to this question seems to be negative. The main reason is that the picture outlined above, as a quantitative analysis shows, does not account for the large increase in the number of electrons and photons with altitude, which is actually observed. The discrepancy is particularly evident if one considers electrons and photons of high energy, say above 10^9 ev.

The existence of a large number of electrons and photons in the high atmosphere could be easily explained if one assumes that the primary radiation contains high energy electrons and photons, in addition to protons. It is also possible that the primary radiation contains only protons, but that there exists some hitherto unknown process whereby these particles may generate a large number of high energy electrons or photons in the high atmosphere. It has been suggested, for instance, that protons, in addition to normal mesons, may produce mesons with a much shorter lifetime which immediately disintegrate and give rise to high energy electrons or photons. The further investigation of these various possibilities is one of the most pressing tasks of cosmic ray research.

II. ADVANTAGES OF A SATELLITE VEHICLE FOR COSMIC RAY RESEARCH

A. General Considerations

It appears from the brief outline presented above that the information which exists at present on the nature of the primary cosmic radiation is still very uncertain.

Efforts have been made to experiment on the primary radiation directly, by means of instruments carried by balloons and, quite recently, by rockets.

Rockets may reach altitudes at which the residual pressure is extremely small and where, therefore, the primary cosmic radiation exists in the pure state. However, they stay at such great altitudes for a very short time, of the order of minutes. This represents a very serious limitation, because, even at the top of the atmosphere, the intensity of the cosmic radiation is very small; probably of the order of ten or twenty particles per cm^2 per minute.

The experimentation with balloons suffers, to a lesser extent, of the same drawback. Moreover, balloons do not reach as high an elevation as would be desirable for the study of the primary cosmic radiation. The residual atmospheric depth at the maximum altitude which can be reached with balloons is of the order of 10 g/cm^2. This depth is smaller than the mean free path for secondary processes of all known high energy rays. For instance, the meson producing rays seem to have a mean free path of the order of 100 g/cm^2. High energy photons have in air a mean free path of 60 g/cm^2 for pair production. The average loss of high energy electrons in 10 g/cm^2 of air amounts to 25 per cent. Thus, if the primary radiation does not contain any new type of rays, a large fraction of it will penetrate to the depth of 10 g/cm^2 without considerable modification. However, the radiation observed at this depth certainly contains a large proportion of secondary rays, which might be difficult to separate from the primary radiation. If, for instance, there are high energy electrons among the primary cosmic rays, one will find at a depth of 10 g/cm^2, many secondary photons produced by radiative collisions of the electrons with the atoms of the atmosphere. Under these circumstances, it may be difficult to decide whether or not photons exist in the primary cosmic radiation.

Moreover, the primary.radiation may contain an hitherto unknown, very absorbable component. Indeed, one of the most attractive aspects of cosmic ray research at high altitude lies in the possibility of finding new types of high energy rays with such unusual properties as a very large absorption cross-section, even though there may not be any valid reason, at the present state of our knowledge, for suspecting the existence of such rays.

One thus comes to the conclusion that it would be very desirable for the study of the primary cosmic radiation to reach an altitude far in excess of the balloon ceiling; an altitude, say, corresponding to a residual depth of less than 1 g/cm^2. The satellite vehicle is the only device suggested so far which offers the possibility of experimenting at such an elevation, and for a sufficient length of time.

The question can be raised whether or not it is worth while experimenting at an atmospheric depth of less than 1 g/cm^2 when the walls of the detectors, to say nothing of the shell of the vehicle, will probably have a thickness larger than this amount. The answer is that, for most experiments at least, a small thickness of matter immediately above the detecting equipment will not represent as serious a limitation as an atmospheric layer of the same number of g/cm^2. The main reason for avoiding matter along the path of the primary cosmic rays is to rule out the possibility of production of secondary rays, which might be mistaken for primaries. Now secondary rays produced in the walls of the rocket or of the detector will be usually recognized as such because they will appear accompanied by the primary rays. This is not so if they are produced in the air, because in this case the point of production will be, for most of them so far away that practically all secondary rays will arrive upon the detector unaccompanied by the parent primary particle. As a concrete example, to which the above remarks apply, we may think of the problem of detecting photons in a primary radiation which contains high energy electrons.

Of course, at least in the exploratory work, it will be desirable to reduce the wall thickness to a minimum. There might be cases in which the secondary character of a radiation produced in the walls is not obvious. It has been suggested, for instance, that the primary cosmic rays may contain *negative protons* which undergo annihilation by colliding with ordinary protons, the total energy of the two particles being changed into photons. Photons thus produced in the walls of the rocket or of the detector could not be easily distinguished from primary photons (except that, in this case, the study of the geomagnetic effects would offer a clue).

B. Suggestions for a Program of Cosmic Ray Research in a Satellite Vehicle

The following suggestions are offered as concrete examples of experiments which, at the present time, appear likely to yield results of fundamental importance for the understanding of cosmic ray phenomena. It is, of course, obvious that any program of cosmic ray research in a satellite vehicle, formulated years in advance of its actual realization, will have to be revised continuously and kept abreast of the advances both in the knowledge of cosmic ray phenomena and in the experimental techniques.

1. *Geomagnetic Effects*

We have mentioned above that a considerable portion, if not all, of the primary cosmic radiation is formed by charged particles, the intensity distribution of which is affected by the magnetic field of the earth. The theory of the influence of the earth's magnetic field upon cosmic ray particles has been developed under the assumption that, at a large distance from the earth, cosmic rays are distributed uniformly and isotropically in space. If we confine our attention to a given geomagnetic latitude, λ, and to primary cosmic ray particles of a given sign, say positive, and a given energy $E^{(1)}$, we can subdivide the hemisphere of the sky into three regions. The region furthest to

---

For footnote$^{(1)}$, see page 33.

the *east* is in *complete shadow*; i.e., no positive cosmic ray particles of energy E arrive from directions corresponding to this region of the sky. The region furthest to the west is in *full light*; i.e., the number of positive cosmic ray particles of energy E coming from directions pointing to this region is the same as if the magnetic field of the earth did not exist. The region in between is filled with narrow bands, alternately of light and shadow. This region is called the *penumbral region*. If we consider negative instead of positive incoming particles, the whole pattern of light and shadow is changed into its specular image with respect to the meridian plane; i.e., the description sketched above is still valid if one only exchanges the word *east* with the word *west*, and *vice versa*.

If, without changing the latitude λ, we vary the energy E of the particles under consideration, we find that for a sufficiently small energy the whole sky is in shadow. As the energy is gradually increased, first a region of penumbra appears, then a region of full light. The latter extends more and more with increasing energy, until eventually it occupies the whole sky. On the other hand, if we keep the energy E constant and vary the geomagnetic latitude λ, we find that the nearer we approach the equator the wider becomes the region of shadow and the narrower becomes the region of light.

Without going into any finer details of the theory, one will readily recognize that an exact experimental knowledge of the intensity distribution of the primary cosmic radiation, both in latitude and in direction, will make it possible to determine the sign and the energy distribution of the incoming cosmic ray particles. The range of the "spectrometer" represented by the magnetic field of the earth is very wide. At the magnetic equator, no positive particle of energy less than about 60 Bev can arrive from an horizontal direction pointing to the east, and no negative particle of energy less than 60 Bev can arrive from an horizontal direction pointing to the west. At the magnetic poles, on the other hand, particles of both signs and of all energies can reach the earth, unimpeded by the magnetic field. Thus the range of energies which can be analyzed by means of the earth's magnetic field extends from zero to 60 Bev. It is estimated that all but a few per cent of the primary cosmic ray particles fall within this range of energies.

For the study of the directional intensity of the primary cosmic ray particles one can use instruments of the type of the well known "cosmic ray telescope". This consists of a number of Geiger-Mueller tubes arranged in a straight line. When a cosmic ray particle traverses all the tubes, each tube gives out a pulse and the practically simultaneous pulses of the various tubes are selected by a "coincidence circuit". There is nothing very critical either in the operation of Geiger-Mueller tubes or in the operation of the recording circuit so that one may reasonably expect that the instrument will run for a long time without any adjustment. No special difficulty should be encountered in the transmission of the information to a ground station since

---

(1) Strictly speaking, the quantity which determines the behavior of a charged particle in a magnetic field is the *momentum* rather than the *energy*. The relation between energy and momentum depends on the mass of the particle. For energies large compared with the rest energy, however, the energy becomes practically identical to the product of the momentum and the velocity of light.

the only requirement is counting the number of output pulses of the coincidence circuit. Several counter telescopes could be used in order to measure the cosmic ray intensity in various directions simultaneously. For this experiment, it would be desirable to have the trajectory of the satellite lie as closely as possible in a meridian plane so as to explore a wide range of latitudes.

The information on the energy spectrum of primary cosmic rays which could be obtained by the experiment outlined above would be incomparably more complete and more accurate than the information we may hope to obtain by means of balloon experiments. First, the maximum altitude that one can reach with balloons, while it may be sufficient for measuring with fair accuracy the number of primary particles coming in the vertical direction, is not sufficient for observations at a large zenith angle. Therefore, the range of energies which can be explored with balloons is considerably smaller than the one which could be explored with a satellite vehicle. Second, it would be very difficult with measurements carried out in separate balloon flights at different latitudes, to match the accuracy of measurements carried out by means of a cosmic ray recorder moving periodically, at a constant altitude, between the equatorial and polar regions.

The importance of an exact knowledge of the sign and energy distribution of primary cosmic rays can hardly be overestimated. Such a knowledge would provide a sound basis for the speculations concerning the origin of cosmic rays. Also it would help very greatly the understanding of the cosmic ray phenomena in the atmosphere. Among other things, it would make it possible to determine accurately the amount of energy per cm^2 and per second which falls upon the earth's atmosphere in the form of cosmic rays at the various latitudes. This determination is of great interest. For instance, it would enable one to calculate the amount of energy which goes into neutrinos and becomes thereby invisible. (Neutrinos are supposed to be produced by the disintegration of mesons; they could also arise in other processes). In fact, the total energy of the neutrinos produced in the atmosphere could be obtained from the following equation, which expresses the principle of conservation of energy;

(energy flux of cosmic rays at the top of the atmosphere per cm^2 per second)
= (energy flux of cosmic rays at sea level per cm^2 per second)
+ (energy per second dissipated in the ionization of an air column of 1 cm^2 cross section between sea level and the top of the atmosphere)
+ (energy per second going into the production of neutrinos in the same column of air).

2. *Absorption Measurements*

Valuable information on the nature and properties of the radiation observed in the satellite vehicle could be obtained by means of absorption measurements. Absorption measurements on cosmic ray particles are usually carried out by placing absorbers between the Geiger-Mueller tubes which form a cosmic ray telescope. With an absorber between the tubes, coincidences can only be produced by ionizing particles capable of traversing the absorber or by ionizing particles which produce within the absorber secondary ionizing rays capable of traversing the portion of the absorber below their place of production.

One of the first purposes of such absorption measurements would be to investigate whether or not all of the charged particles observed have actually as high an energy as primary cosmic ray particles must possess in order to penetrate the earth's magnetic field. Such a check is by no means superfluous. Even though there is practically no matter above the level at which the satellite vehicle is planned to travel, the possibility cannot be ruled out that secondary rays might be produced by the interaction of the primary radiation with the magnetic field of the earth. It has been pointed out, for instance, that electrons of very high energy must produce a considerable number of photons in traversing this field, on account of the acceleration which they experience. Also, it is possible that secondary particles produced in the atmosphere underneath may travel upward and be detected by cosmic ray meters located in a satellite vehicle.

Another even more important purpose of the absorption measurements would be to provide information on the nature of the primary cosmic ray particles. High energy particles of different nature have very different penetrating power. For instance, a 20 cm thick lead absorber stops practically all electrons of energy less than 100 Bev as well as all the secondary rays produced by these electrons. Thus, a cosmic ray telescope in which the tubes are separated by 20 cm of lead is practically insensitive to any electron component which might be present in the cosmic radiation. On the other hand, the same telescope would probably detect approximately as many primary cosmic ray *protons* as if there were no absorber between the counters. In fact, even though many of these protons might be absorbed in 20 cm of lead by meson production, the produced mesons can penetrate the absorber and discharge the counters underneath. It may be pointed out that it is possible to take advantage of the magnetic field of the earth in order to obtain information on the dependence of the penetration of primary cosmic ray particles on their energy and on their sign. For this purpose, one will have to carry out absorption measurements at different latitudes and with the telescope pointing in different directions.

3. *Measurements with an Integrating Ionization Chamber*

An integrating ionization chamber is an instrument which measures the total number of ion pairs produced within a certain volume of gas by all cosmic ray particles which traverse this volume per unit time. The output signal of an ionization chamber is an electric current (the ionization current) the magnitude of which can be transmitted by standard telemetering devices.

An integrating ionization chamber cannot be used for measuring the *directional* intensity of the primary radiation, but only its *total* intensity, integrated over all directions. Nevertheless, the information obtained from such an ionization chamber on the latitude dependence of cosmic ray intensity would represent a useful check of the more detailed data provided by cosmic ray telescopes.

Perhaps the most interesting experiment which could be made with an integrating ionization chamber is a measurement of the change in ionization current caused by absorbers of various materials and various thicknesses placed around the chamber. The importance of such measurement lies in the fact that it provides information on the secondary processes of high energy rays in matter. Consider, for instance, *electrons* of several billion electron volts incident upon an ionization chamber, and suppose that measurements are taken with lead shells of various thicknesses around the chamber. Because of the production of showers in lead, the ionization will first increase with increasing lead thickness, reach a maximum at about 1 inch and then decrease again. At the maximum, the ionization will be of the order of *100 times* the ionization recorded with the bare chamber. Consider next the case of *protons* in the same energy range. Each proton is supposed to produce several mesons by collisions with atomic nuclei. Therefore one should again expect an *increase* of the ionization by surrounding the chamber with lead. However, the increase will be much smaller than in the case of electrons (presumably a factor 4 or 5 as against a factor 100), and the maximum will occur for larger thicknesses.

One sees, therefore, that observations with integrating ionization chambers would provide an easy means of distinguishing between electrons and protons in the primary cosmic radiation and would in general yield useful, even though not very detailed, information on the secondary processes of the primary cosmic rays in matter.

4. *Measurements with Proportional Detectors*

These detectors include ionization chambers (usually operated at high pressure) and proportional counters. Like Geiger-Mueller tubes, they give out an electric pulse whenever ionization is produced within their sensitive volume. They differ, however, from Geiger-Mueller tubes because the output pulses, instead of being of constant magnitude are *proportional* to the ionization. These pulses, moreover, are much smaller than the pulses of the Geiger-Mueller tubes, which fact makes their detection a more delicate electronic problem.

Proportional detectors could be used in a satellite vehicle for the study of secondary processes of primary cosmic rays. The advantage of proportional detectors as compared with integrating ionization chambers consists in the possibility they offer to study individual rays. Proportional detectors can be used profitably in conjunction with Geiger-Mueller tubes. One can, for instance, select rays coming from a given direction by means of a Geiger-Mueller tube telescope, place an absorber below the telescope and investigate the groups of secondary rays emerging from the absorber by means of a proportional detector. The simultaneity between the pulse of the proportional detector and the pulses of the Geiger-Mueller tubes is used as a criterion to establish the correlation between the primary ray which discharges the Geiger-Mueller tubes and the group of secondary rays which activate the proportional detector. An experiment like the one sketched above would make it possible not only to detect, by their shower production, whatever electrons may be present in the primary radiation, but also to determine their angular distribution and to obtain some information on their energy spectrum. It would also provide very valuable and direct information on the properties of the hypothetical primary proton component.

5. *Cloud Chamber Experiments*

A cloud chamber, as is well known, reveals the paths of ionizing particles by causing individual ions to become centers of condensation in an atmosphere containing a supersaturated vapor. There is no doubt that if a cloud chamber could be operated successfully in a satellite vehicle, it would provide a much more complete and illuminating picture of the properties of the primary radiation than any other instrument. By placing plates of various substances inside the chamber it would be possible to study in detail the secondary processes of the incoming rays. If a strong magnetic field could be provided, one could deflect at least the less energetic cosmic ray particles and determine their sign and their energy distribution. This information could then be compared with the information obtained from the effects of the earth's magnetic field.

Such a program however, would require very substantial new developments in the cloud chamber technique. Up to this date, the cloud chamber is a very delicate instrument, which requires frequent, if not continuous supervision and adjustment. Moreover, the information is obtained in the form of photographs and the problem arises as to how to recover the records or how to transmit them to a ground station.

The unquestionably superior value of the cloud chamber method presents strong incentive toward a development program directed at making the operation of a cloud chamber in an unmanned satellite vehicle a practical possibility. The difficulties, even though considerable, do not appear insurmountable. Just to mention one of the problems, it is possible that, instead of recording the cloud chamber pictures by direct photography, one may succeed in transmitting them to a ground station by television techniques.

Conclusions

It has been shown that a satellite vehicle offers great advantages over any other device used or suggested so far for the study of primary cosmic rays.

Experiments, which appear both valuable at the present state of our knowledge of cosmic ray phenomena and feasible in the light of the available technical means, include a study of the directional intensity of primary cosmic ray particles at various latitudes by means of cosmic ray telescopes,. combined with absorption measurements of the rays coming from the various directions; and a study of the production of secondary rays in various thicknesses of different absorbers by means of integrating ionization chambers and of proportional detectors.

A more detailed and complete investigation of the nature and properties of primary cosmic rays would call for the use of a cloud chamber. Considerable technical developments will be necessary before a cloud chamber can be successfully operated in an unmanned satellite vehicle.

TACTICAL CONSIDERATIONS RELEVANT TO A TERRESTRIAL SATELLITE

Lyman Spitzer, Jr.
YALE UNIVERSITY
CONSULTANT TO RAND

The possibility of launching a small satellite which would revolve about the earth in a fixed orbit many hundreds of miles up has excited considerable interest. Such a development would open completely new pathways for scientific research. In addition, it could have important military uses, both strategic and tactical. The present brief discussion points out certain tactical uses of a satellite in naval warfare, and also various problems involved in attacking or defending a satellite.

An important property of a satellite is that it provides a platform from which a very wide expanse of the earth can be viewed. While small objects, especially on land, could probably not be distinguished from a point many hundred of miles away, a ship at sea could, in principle, be detected. A ship 25 feet wide would subtend an angle of 2 seconds of arc at a point 500 miles away. Thus a telescope of 4 inches aperture, with a resolving power of one second of arc, should be able to detect such a ship, provided the weather were clear. Since the sea should have a relatively uniform appearance from such a great height, any large floating object, such as a ship, should be readily distinguishable, and might even be detected by an automatic device. A satellite travelling over the poles, with a period of about one and a half hours, would scan all the oceans at least once every day. While the problems involved in scanning automatically the view beneath the satellite and sending the optical image back to a ground station would be very great, they might not be insuperable. Use of a suicide observer might be adopted by an enemy to solve this problem; however, food, oxygen and water supply for such an observer over a period of several years, as well as heat control, etc., might constitute a difficult problem. Possibly radar techniques could be used for detecting shipping from a satellite, although sending out radio waves near enemy territory or over enemy shipping would have the undesirable effect of betraying the satellite's position, and making easier the problem of its destruction by the enemy. Besides, distinguishing a ship from the sea return at such great distances might provide a very serious technical problem.

The tactical advantages of such a device would be considerable. While ships in harbors might be difficult to distinguish from piers, any ship at sea could be detected in clear weather. Thus any ship at sea could be spotted at daily intervals, and for the slower ships, at least, courses could be plotted. Such complete reconnaissance would be a great asset in naval warfare, even though during some of the time, clouds would interfere with the visibility. Use of radar would permit detection of each ship twice a day, independently of the weather, but would have the disadvantage already noted.

Information of this type would be of particular value to an inferior sea power, engaged in a submarine offensive. The submarine types developed by the Germans at the end of World War II have such high underwater speeds and operate submerged for such long intervals that they are very difficult to detect or to attack. Their chief weakness is that they can not detect enemy shipping at ranges beyond a few miles. If reconnaissance information from a satellite could be transmitted to submarines, the effectiveness of the submarine campaign could be enormously increased. Thus if anti-submarine warfare continues to be of interest, the location and destruction of an enemy satellite may be a prime military objective.

Another potential advantage which a satellite might provide is that of a relay station for communications with naval vessels when radio silence was imperative. With a directional high-frequency transmitter, pointed upward, a message could be sent to such a satellite with negligible risk of reception by the enemy. Such a message could then be retransmitted to the home station when the satellite was overhead not more than 12 hours later. Use of the satellite for transmitting information back to the ships would be open to the objection that it might betray the position of the satellite. Again, this advantage would be of greatest use to submarines, whose chief defense lies in their concealment.

It is evident that some interest attaches to the problem of destroying an enemy satellite or of protecting a friendly one. Periodic changes in a satellite orbit would probably exhaust fuel rather rapidly, and thus a satellite orbit must probably be assumed fixed, except for calculable perturbations. Hence any satellite which has been detected could readily be attacked with considerable accuracy from another satellite sent up especially for the purpose. Such an attack satellite might be a relatively small and inexpensive weapon.

While the odds of such a battle in space are not readily forecast, it is evident that concealment would be a primary defense of a satellite. Since the echo from a sphere 1 meter in diameter 500 miles away is much weaker than the echo obtained from the moon by a radar set on earth, it is obvious that radar detection of such a body would not be easy. Visual detection methods are somewhat more promising. A sphere 500 miles away, 1 meter in diameter, reflecting one percent of the sunlight striking it, would have a stellar magnitude of about 13 when viewed from a direction at right angles to the direction of the sun (corresponding to the position of the moon relative to the earth and sun at halfmoon). This is the faintest magnitude that can just be seen with a 6-inch telescope. About an hour after sunset, or an hour before sunrise, when the satellite would be illuminated but the sky would be dark, such a satellite could therefore be detected if an observer happened to be looking in the right direction at the right time. An elaborate program would probably be required to ensure that any such satellite would be detected. It is not impossible that with suitable design the amount of light reflected by the satellite could be reduced even below the low value assumed, thus making almost impossible the optical detection of a satellite by observers on the earth's surface. Optical detection of a satellite from another satellite designed especially for the purpose might still be feasible, however.

THE TIME FACTOR IN THE SATELLITE PROGRAM

J. E. Lipp

Serious engineering studies are now under way to evaluate the entire job of placing a satellite on a stable orbit around the earth. Each step of investigation strengthens the conviction that the project is feasible at the present stage of technological development: a satellite of modest payload can be placed in operation without requiring further fundamental research or discoveries.

Having entered the realm of engineering possibility, the spaceship must be examined for its usefulness in order to justify the large effort involved in its design, development, construction and operation. Stated differently, do the overall values point toward an immediate start or would it be well to wait a few years in order to make the task easier?

Before long someone will start on the construction of a satellite vehicle, whether in the United States or elsewhere. History shows that the human race does not allow physical development to lag very far behind the mental realization that a step can be taken. This is particularly true of progress which has a direct bearing on man's conquest of his environment. The Palomar telescope, a 6 million dollar job, is an example of such effort, as were the dirigible and the helicopter.

Since the United States is far ahead of any other country in both airplanes and sea power, and since others are abreast of the United States in rocket applications, we can expect strong competition in the latter field as being the quickest shortcut for challenging this country's position. No promising avenues of progress in rockets can be neglected by the United States without great danger of falling behind in the world race for armaments. The possibility of constructing a satellite has been well publicized both here and in Germany and the data of the Germans are available to various possible enemies of the United States. Thus, from a competitive point of view, the decision to carry through a satellite development is a matter of timing, depending upon whether this country can afford to wait an appreciable length of time before launching definite activity.

It is desirable, but not necessary, to have better fuels, materials and techniques than are now at hand. Future progress in such directions will lead to improved performance in terms of gross weight, and hence cost, required to do a given job, but the capability already exists of doing more than a minimum job with a vehicle of reasonable size.

Preliminary estimates of the cost of establishing the first satellite in its orbit have fallen in the neighborhood of 75 million dollars. This figure will depend somewhat on design features, but should be adequate to fix a scale for the present appraisal. If normal development in related fields, such as fuels, can reduce the expense by half in ten years, then a saving of roughly four million dollars per year can be realized by simply waiting for a limited number of years.

If prosecuted energetically, a satellite probably could be developed and built in about five years from the start of work. This report sets forth reasons to support the conclusion that any unnecessary delay in developing a satellite would be poor economy.

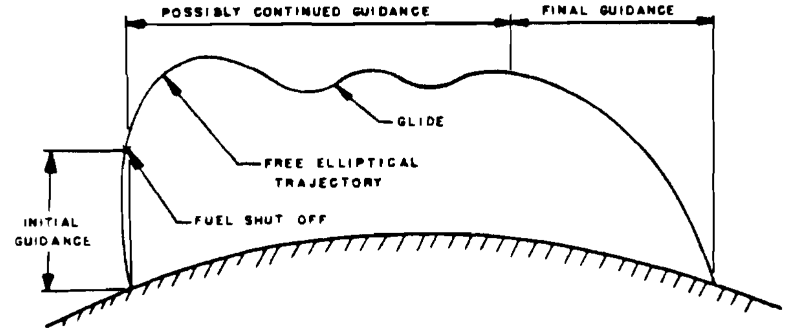
In the following pages, benefits to be derived from a satellite will be discussed under four headings.

I. Development of Long-Range Rockets
II. Direct Military Value
III. Scientific Research
IV. Psychological and Political Factors

These subjects are known to overlap each other considerably, although the discussion will treat them as independently as possible. Throughout the report, the assumption is made that the first experimental satellite will have a payload of the order of 500 pounds. Later versions are visualized as carrying larger loads according to their requirements.

I. DEVELOPMENT OF LONG-RANGE ROCKETS

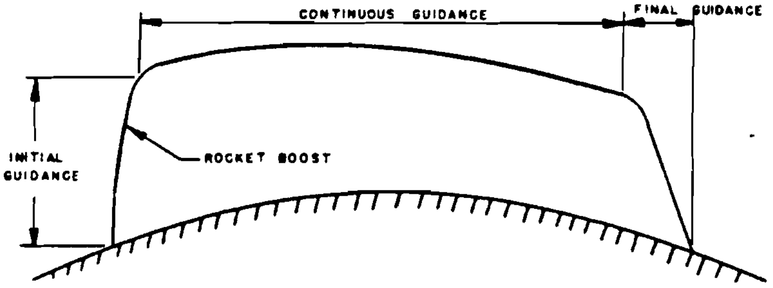
An analysis of the part that can be played by a satellite in developing long range rocket missiles must consider the points of similarity between the two types of vehicle. For this discussion long range rockets shall be considered as having a range adequate for intercontinental distances, i.e., from 2000 to 12,000 miles. Such missiles may be propelled by liquid rocket motors or by ramjets. The trajectories to be followed by these respective types are illustrated below in Figs. 1 and 2, taken from ref. 1, p. 10.



PROBABLE FLIGHT PATH OF LONG-RANGE ROCKET AIRCRAFT

FIG I

For references see page 49.



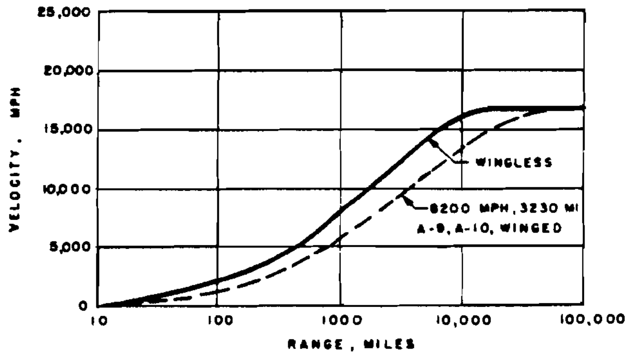
PROBABLE FLIGHT PATH OF LONG-RANGE RAMJET AIRCRAFT

FIG. 2

No analysis is yet available to display the relative merits of the two types of missiles. However, it seems quite likely that extreme ranges in the neighborhood of 5,000 to 12,000 miles will require the liquid rocket type, because the ramjet arrangement must remain within the atmosphere and overcome aerodynamic drag throughout its flight path.

It can be seen that the satellite duplicates features of the initial guidance and free elliptical portions of the rocket missile trajectory. Both are launched vertically, tilted during burning and allowed to coast outside the atmosphere after burning stops.

As has been stated in ref. 2, p. 17, a simple rocket missile without wings must achieve velocities very close to that of the satellite, thus leading to a strong similarity of power plant requirements. Even when wings are added it is expected that the rocket missile speeds must be greater than half of the satellite speed. For example, the German A-9, A-10 staged missile was designed to follow a trajectory similar to Fig. 1 and had a predicted maximum velocity of 8200 mph for a range of 3230 miles. Fig. 3 shows a rough prediction of velocities required for winged missiles (based upon the A-9, A-10 vehicle) superimposed upon a curve taken from ref. 2, p. 17 for wingless missiles. The "winged" curve is about 25% below the "wingless" curve until the ranges approach 12,000 miles at which point the velocity difference is only about 10%. Both curves have an upper limit equal to the satellite speed.



EFFECT OF VELOCITY ON RANGE

FIG 3

Another example of the correspondence in requirements between winged and wingless missiles is given in ref. 3, in which it is shown that for project MX-773 (payload = 5000 pounds, range = 1500 miles), three stages will be necessary for either type of vehicle, using a fuel whose specific impulse is 225, if the gross weight is to be kept within reasonable limits.

In regard to bringing a missile down to earth without allowing it to burn like a meteor, three basic methods are available and all three involve serious technical difficulties. First, the use of additional rocket fuel to apply negative thrust is wasteful and causes the gross weight of the staged vehicle to grow to astronomical size; therefore this method must be eliminated for the present. Second, the use of heavy plates for the outer skin and special materials to resist the aerodynamic heating will bring up problems as to overheating of guidance and homing equipment and also will add greatly to the gross weight required for a given job. Third, the use of wings or airfoils for a controlled velocity glide, is both heavy and difficult, although it may be possible. Either of the latter two methods will require a greater knowledge of the outer atmosphere than exists at present.

The problem of designing wings for final descent of a satellite is identical in many respects to putting wings on long-range rocket missiles. In both cases an enormous amount of kinetic energy must be converted into a long-range glide which will avoid overheating of the structure from air friction. Some difficult problems in kinetics of rarefied gases must be solved. In fact, such considerations may very well limit the maximum operating altitude of long-range missiles, since low ratios of lift to drag are expected in the outer atmosphere. The contribution of a properly instrumented satellite, whether winged or not, to knowledge in this field may prove to be of decisive importance to progress. It is by no means certain that any attempt will be made to bring down the first experimental satellite safely because of the unknowns that now exist in the problem. Succeeding satellites or missiles, however, may be provided with means for returning to earth on the basis of data obtained with the first unit.

The final portion of the glide to earth is simpler from a guidance standpoint for a satellite than for an operational long-range missile. This is because the landing point of the satellite can be chosen anywhere around the earth with ground beacon equipment set up for the purpose. Furthermore, pinpoint accuracy will not be needed. Within certain range limits, such a plan could be used in the early stages of missile development.

Summed up it can be said with confidence that the satellite will embody many of the problems of control, power plant, staging and construction that will be found in long-range rocket missiles. For investigating these features a satellite would be superior to a missile because its repeated passage over the launching point will permit an accurate determination of the results of control and guidance efforts and because the satellite can furnish continuous data on the upper atmosphere that would be difficult or impossible to obtain with a "conventional" missile. If started promptly, the satellite can be of tremendous value in accelerating the long-range missile program, in addition to its own inherent value as described in the sections that follow.

II. DIRECT MILITARY VALUE

Strategic or tactical uses now accessible to a satellite must exclude the conveyance of an explosive warhead. No chemical explosive has enough power to repay the expense of a satellite in terms of damage to the enemy, unless extreme accuracy can be achieved. An atomic warhead seems too heavy to handle at present, although future improvements in both the bomb and the satellite power plant may make this use practical later on. Such difficulties may not apply so strongly to long-range winged missiles, yet their design will surely be governed more by economics and strategic worth than by tactical value.

Aside from explosive action there are several ways in which one or more satellites can be of major value to military planning and operations.

Techniques now exist for transmitting data by television from a moving vehicle to a ground station, such apparatus having appeared in glide bomb projects toward the end of the war. The resolving power was poor, but can be improved without great difficulty. By installing television equipment combined with one or more Schmidt type telescopes in a satellite an observation and reconnaissance tool without parallel could be established. As mentioned previously in various reports on the subject, a spaceship can be placed upon an oblique or north-south orbit so as to cover the entire surface of the earth at frequent intervals as the earth rotates beneath the orbit.

An objection could be raised on the grounds of communication difficulties. A satellite in the ionosphere would require microwave communication, which is effective only for line of sight distances and cannot be received halfway around the world. This trouble can be overcome by using a relay system involving both satellite and ground stations. A satellite placed on a north-south orbit would pass over each pole once each revolution regardless of the daily rotation of the earth on its axis. A vehicle at 300 miles altitude could "see" a ground station at the northern tip of Alaska while in the north polar region. If the satellite could accumulate information on film or wire and televise the record rapidly when interrogated by the ground station, a workable system would result. The period of revolution of the satellite is about 1½ hours, so that its successive tracks over the earth would be about 1500 miles apart at the equator. If it is assumed that scanning to a distance of 100 miles on each side of the track is feasible, then a complete coverage of the earth would require about a week, depending upon a proper choice of altitude to give the right orbital period. For more rapid coverage, two or more vehicles could be placed in a "rat race" equally spaced around the same orbit. Obviously, scanning and recording would only be done over areas of interest in order to conserve power and space in the vehicle.

It goes without saying that a permanent system as described above involves problems of duration of electrical power supply that have not been solved. Rough estimates indicate that a closed steam plant, operated by a nuclear energy pile, can extend the useful life very greatly.

The advantages of widespread observation over foreign territory hardly need explanation to military men. However, there are two items to be observed that may overshadow all others. These are (a) isotope separation plants (while under construction and difficult to camouflage) and (b) weather conditions. Both types of information are vital to the United States during peacetime as well as wartime and both can repay the cost of a satellite many times over for each year that they are in hand. Any delay in obtaining such essential information can scarcely be measured in terms less than billions of dollars and hundred thousands of lives.

A satellite can be used also as a reference point and relay station for guiding long-range missiles. Suppose a spaceship is established on an orbit which is roughly parallel to the intended missile path. Over a period of time the orbit can be determined and predicted with high accuracy. If then the missile is launched so as to fly near the satellite during a portion of its trip, the latter can be used for making corrections to the missile trajectory. Or, to go a step further, the satellite can furnish a means of triggering the final dive of a missile onto the target.

In order to make such guiding operations worth while, a satellite would have to be used repeatedly for correcting single missiles or groups of missiles. It seems reasonable that accuracy could be maintained for several hundred miles on each side of the satellite track, so that one vehicle on an oblique orbit could serve attacks over a variety of major industrial areas. The chief restriction would be in scheduling an attack to agree with the satellite location.

Finally, a number of satellites at great altitude (thousands of miles) could act simply as communications relay stations. By using microwave frequencies the present difficulties with unreliable long-range communication would be avoided. It has been stated by eyewitnesses that such difficulties constituted a major handicap to operations in the Pacific theater during World War II. If a satellite could be placed high enough (about 25,000 miles) to have a 24-hour period of revolution it could be associated with a fixed ground station at the equator. Three such stations could broadcast to most of the globe. This idea is not as wild as it sounds. The initial gross weight, with several additional stages, would be about four times the weight of a 300-mile altitude vehicle of equal payload.

Judging by the tremendous investment and operating cost involved in present unsatisfactory communications, a radio relay network would be of major benefit. The enormous bandwidths attainable at microwave frequencies enable a very large number of independent channels to be handled with simple equipment.

One fact is clearly implied in all of the above suggested military uses for satellites. Each military purpose leads to the specialized use of additional vehicles so that several designs and sizes must be created. Before such special purpose rockets can be designed and built, one or more purely experimental satellites, probably traveling around the equator, must be constructed and tested. The time to be consumed in this development seems reason enough for making an early start.

III. SCIENTIFIC RESEARCH

There are so many ways in which physical science, both pure and applied, would advance by the use of satellites that no attempt at a complete discussion can be made. For the first few decades the chief problem will be to decide which of the sciences should have priority on the waiting list. It would be difficult to name a major branch of science that will not be profoundly affected by measurements in outer space. With this in view, the following paragraphs are meant to illustrate rather than to catalogue the scope of scientific uses for satellites.

First on the agenda would probably be cosmic rays because of their relation to nuclear energy and possible improvements in our present awesome weapons. When it is realized that even an A-bomb uses but a small fraction of the energy content of the material involved and that many first rate scientists believe the efficiency can be increased, the cosmic ray research takes on a new urgency in our struggle to maintain a lead in such devices. On the day of reckoning at Hiroshima, the United States was committed to a policy of maintaining dominance in this field because on that day this country discarded its basis for outlawing the A-bomb. Compared to this life and death pressure, the peaceful benefits of an increased standard of living that may accrue from nuclear research assume the role of by-products.

A seemingly remote but really closely related field is that of biology. At present seeds are being sent aloft in V-2's to determine chances of survival of life. This can later be extended to higher altitudes, longer durations, and higher forms of life such as bacteria, by the use of satellites. The relation to warfare of biological studies in missiles is greater today than ever before. For this we can again look to the A-bomb as a precedent, since it killed more people by radiation "disease" than by explosive action, clearly a form of biological warfare. The chief reason for avoiding biological warfare in the past has been fear of reprisal or spread of disease from the enemy into the user's army. Such fears may yet be set aside in view of the terror already created by the A-bomb and the probable minimizing of direct contact between armies in the next war. Although the United States would most certainly refuse to start the deliberate use of poisons and diseases in a war, the problems of prevention of their use by other countries against us and countermeasures or reprisals for such use are always present.

An acceleration free laboratory would be valuable for many scientific measurements, such as electrical or chemical constants, that require instruments of great precision and delicacy. This is possible because for the first time in history a satellite would provide an acceleration free laboratory where the ever present force of the earth's gravitational field would be cancelled by the centrifugal force of the rotating satellite. Such instruments could be supported to avoid damage during ascent, then "floated" after the vehicle is on its orbit.

The advantages of having an astronomical observatory outside of the earth's atmosphere would be tremendous. In the absence of atmospheric disturbance, the resolving power of a telescope can approach its theoretical limit, so that a small, wide field telescope in space could do the work of a number of larger telescopes on the ground. Spectrographic data of all stars would be vastly improved because no ultra-violet absorption by the atmosphere would occur. The relation of such apparently academic work to national defense may not be obvious, yet astronomy has made major discoveries in chemistry and nuclear physics and has served as a tool for verifying the theory of relativity as regards high speeds and strong gravity fields. As an example of practical astronomy, the effects of sunspots on communications and weather could best be solved by means of observation from a satellite above the atmosphere.

Scanning of the earth itself from an external vantage point will aid science in many ways. Not the least of these will be the ability to map uncharted regions of the earth, an activity closely related to the reconnaissance function already described in Sec. II, "Direct Military Value". For example, seasonal variations in both Arctic and Antarctic polar ice caps could be studied to good advantage. Geology and meteorology should both be advanced by data obtained in this way.

As a final illustration, distribution of the earth's magnetic field could be surveyed completely in a short time by a spaceship, free of the local surface disturbances which now affect surveys on the ground or by aircraft. Variations, whether daily or yearly, could be determined by repeating the survey. This research would serve to integrate magnetic data now obtained on the ground, detect major disturbing influences in the earth (for geological study), and could lead to advances in attempts to explain the origin of the earth's magnetism.

As far as long-range science is concerned, it is difficult to present a good case for high priority or urgency. If work along some lines does not proceed rapidly, we may never consciously realize a deficiency, simply because the effects are indirect or hidden. Yet in some ways, scientific advances that await the satellite must bear a relationship to the basic stamina and power of our country. The relationship is obvious in the field of cosmic rays and less obvious in the field of biology. Certainly it can be said that the needs of long-range science strengthen the reasons for starting a satellite program as soon as possible.

IV. PSYCHOLOGICAL AND POLITICAL FACTORS

Establishing a satellite on an orbit around the earth is the last intermediate step before actual space travel by man. Although trips around the moon and to neighboring planets may seem a long way off, the United States is probably in a better position at present to progress in this direction than any other nation. Since mastery of the elements is a reliable index of material progress, the nation which first makes significant achievements in space travel will be acknowledged as the world leader in both military and scientific techniques. To visualize the impact on the world one can imagine the consternation and admiration that would be felt here if the United States were to discover suddenly that some other nation had already put up a successful satellite!

The psychological effect of a satellite will in less drastic fashion supplement that of the atom bomb. It will make possible an unspoken threat to every other nation that we can send a guided missile to any spot on earth. Combined with our present monopoly of the atom bomb such a threat in being will give pause to any nation which contemplates aggressive war against the United States. It will be necessary to produce such deterrents from time to time because of the probability that other nations will eventually produce atom bombs of their own.

As an aid to maintaining the present prestige and diplomatic bargaining power of the United States, it would be well to give the world the impression of an ever-widening gap between our technology and any other possible rivals since other nations are obviously hoping to play for time in an effort to overcome the existing lead of this country. For this reason it may be advisable not only to start work on the satellite as soon as possible, but also to publicize the activity to a limited extent as soon as significant progress can be reported.

At present it appears convenient to launch the initial experimental satellite on an equatorial orbit in order to economize on ground observation stations. The foreign countries over whose territory or possessions such a unit will pass are: Belgium, Brazil, Columbia, England, Equador, France and Holland. At the present time and probably for a few years to come all of these countries are friendly to the United States, and it is probable that arrangements can be made to cover the territorial legal questions that will arise. Any oblique orbit will cover these countries plus all others within a zone on each side of the equator, depending on the amount of obliqueness of the orbit. With few or no exceptions all of the countries having territory within the tropic zones are now friendly to the United States. There is no way of telling how long this happy state of affairs will continue but it takes no great imagination to see that any unfriendly country could raise a tremendous hue and cry on the subject of violation of sovereignty by a satellite flying over its territory. Considerable diplomatic trouble might be avoided, therefore, if the satellite project were to be started and arrangement for its launching made in the immediate future while all of the governments involved are most likely to be sympathetic.

In conclusion it is hardly necessary to point out that most of the reasons for beginning a satellite development program cannot be assigned values in terms of dollars and cents lost in each year of delay. It is equally clear that some of the items discussed are of sufficient importance that the probable cost of the project becomes insignificant. It is therefore desirable that a satellite development program should be put in motion at the earliest possible time.

References:

1. North American Aviation, Report #NA46 - 417, Progress Report #1, Project MA-770, April, 1946.
2. First Quarterly Report, Appendix II, RA-15000, Project RAND, Douglas Aircraft Company, Inc., June, 1946.
3. Republic Aviation - Project MS-773, Progress Report No. 3 to August 10, 1946.

INITIAL EXTERNAL DISTRIBUTION LISTS

Initial distribution of all related technical reports on the satellite vehicle are given below. The code is explained on pages 51 through 60

Report No.	*Title*	*Distribution*
RA-15021	Flight Mechanics of a Satellite Rocket	A(1), C, D(1)
RA-15022	Aerodynamics, Gas Dynamics and Heat Transfer Problems of a Satellite Rocket	A(1), C, D(1)
RA-15023	Analysis of Temperature, Pressure and Density of the Atmosphere Extending to Extreme Altitudes	A(1), C, D(1)
RA-15024	Theoretical Characteristics of Several Liquid Propellant Systems	A(1), C, D(3)
RA-15025	Stability and Control of a Satellite Rocket	A(1), C, D(1), D(2)
RA-15026	Structural and Weight Studies of a Satellite Rocket	A(1), C, D(1)
RA-15027	Satellite Rocket Power Plant	A(1), C, D(3)
RA-15028	Communication and Observation Problems of a Satellite	A(1), C, D(2)
RA-15032	Reference Papers Relating to a Satellite Study	A(1), C, D(2)

Those agencies not on the initial distribution may obtain reports on a loan basis by writing to: Commanding General, Air Materiel Command, Attn: TSEON-2, Wright Field, Dayton, Ohio.

A (1). GOVERNMENT AGENCIES

Guided Missiles Committee
Joint Research & Development Board
New War Department Building
Washington, D.C.

Commanding General (4 Copies)
Army Air Forces
Washington 25, D.C.
Attention: AC/AS-4, DRE-3, Pentagon

Commanding General (25 Copies)
Air Materiel Command
Wright Field, Dayton, Ohio
Attention: TSEON-2

Commanding General
Air University
Maxwell Field, Alabama
Attention: Air University Library

Chief of the Bureau of Aeronautics (6 Copies)
Navy Department
Washington 25, D.C.
Attention: TD-4

Chief of the Bureau of Ordnance (4 Copies)
Navy Department
Washington 25, D.C.
Attention: Re-9

Chief of the Bureau of Ships (3 Copies)
Navy Department
Washington 25, D.C.
Attention: Code 633

Chief, Guided Missiles Branch
Technical Command
Edgewood Arsenal, Maryland

Commanding General
Proving Ground Command
Eglin Field, Florida
Attn: First Experimental Guided Missiles Group

Commanding Officer (2 Copies)
Office of Naval Research Branch Office
616 Mission St.
San Francisco, California

Commanding Officer
U.S. Naval Air Missile Test Center
Point Mugu, California

Commanding Officer
U.S. Naval Ordnance Test Station
Inyokern, California

Commanding Officer
Alamogordo Army Air Base
Alamogordo, New Mexico

Director, National Advisory Committee
for Aeronautics (4 Copies)
1500 New Hampshire Avenue, N.W.
Washington, D.C.
Attention: Mr. C.H. Helms

Director, Naval Research Laboratory (3 Copies)
Anacostia Station
Washington, D.C.

Library of Congress (2 Copies)
Technical Information Section
Washington 25, D.C.
Attention: Mr. J. Heald

Office of the Chief of Ordnance
Ordnance Research & Development Division
Rocket Branch
Pentagon
Washington 25, D.C.

Chief of Naval Operations
Navy Department
Washington 25, D.C.
Attention: Op-57

C. PRIME CONTRACTORS

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
Applied Physics Laboratory Johns Hopkins University Silver Spring, Maryland Attn: Dr. Dwight E. Gray (3 copies)	Development Contract Officer Applied Physics Laboratory Johns Hopkins University 8621 Georgia Avenue Silver Spring, Maryland	BUORD
Bell Aircraft Corporation Niagara Falls, New York Attn: Mr. R. H. Stanley Mr. B. Hamlin	Bureau of Aeronautics Rep. Cornell Aeronautical Lab. Box 56 Buffalo, New York	AAF BUAER & BUORD
Bell Telephone Laboratories Murray Hill, New Jersey Attn: Dr. W. A. MacNair		ORD DEPT
Bendix Aviation Corporation Special Products Development, East Teterboro, New Jersey Attn: Dr. Harner Selvidge		AAF & BUORD

C. PRIME CONTRACTORS (Cont'd)

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
Boeing Aircraft Company Seattle 14, Washington Attn: Mr. R. H. Nelson		AAF
Consolidated-Vultee Aircraft Corp. Lone Star Laboratory Daingerfield, Texas Attn: Mr. J. E. Arnold	Development Contract Officer Consolidated-Vultee Aircraft Corp. Daingerfield, Texas	BUORD
Consolidated-Vultee Aircraft Corp. Downey, California Attn: Mr. W. M. Robinson	Representative-in-Charge, BUAER Consolidated-Vultee Aircraft Corp. Vultee Field Downey, California	AAF BUAER & BUORD
Cornell Aeronautical Lab. Buffalo, New York Attn: Mr. W. M. Duke	Development Contract Officer Cornell Aeronautical Lab. Buffalo, New York	BUORD & BUAER
Curtiss-Wright Corp. Columbus, Ohio Attn: Mr. Bruce Eaton	Bureau of Aeronautics Rep. Curtiss-Wright Corporation Columbus 16, Ohio	BUAER & BUORD
Douglas Aircraft Co. El Segundo Branch El Segundo, California Attn: Mr. E. H. Heinemann	Bureau of Aeronautics Rep. Douglas Aircraft Co. El Segundo, California	BUAER
Douglas Aircraft Co. 3000 Ocean Park Boulevard Santa Monica, California Attn: Mr. A. E. Raymond (1) Mr. E. F. Burton (1)		AAF ORD DEPT
Eastman Kodak Co. Navy Ordnance Division Rochester, New York Attn: Dr. Herbert Trotter	Naval Inspector of Ordnance Navy Ordnance Division Eastman Kodak Co. 50 West Main Street Rochester 4, New York	BUORD
Fairchild Engine & Airplane Corp. NEPA Division P.O. Box 415 Oak Ridge, Tenn. Attn: Mr. A. Kalitinsky, Chief Engineer		AAF
Fairchild Engine & Airplane Corp. Pilotless Plane Division Farmingdale, Long Island, N.Y. Attn: Mr. J. A. Slonim	Representative-in-Charge. Fairchild Engine & Airplane Corp. Pilotless Plane Division Farmingdale, Long Island, N.Y.	BUAER
The Franklin Institute Laboratories for Research and Development Philadelphia, Pa. Attn: Mr. R. H. McClarren	Commanding Officer Naval Aircraft Modification Unit Johnsville, Pennsylvania	BUAER
General Electric Co. Project Hermes Schenectady, New York Attn: Mr. C. K. Bauer		ORD DEPT
General Electric Co. Federal & Marine Commercial Division Schenectady, New York Attn: Mr. A. L. Ruiz	Development Contract Officer General Electric Co. Schenectady, New York	BUORD
General Electric Co. Aviation Division Schenectady, New York Attn: Mr. S. A. Schuler, Jr. Mr. Phillip Class		AAF

C. PRIME CONTRACTORS (Cont'd)

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
Glenn L. Martin Co. Baltimore, Maryland Attn: Mr. N. M. Voorhies	Bureau of Aeronautics Rep. Glenn L. Martin Co. Baltimore, 3, Maryland	BUAER
Glenn L. Martin Company Baltimore 3, Maryland Attn: Mr. W. B. Bergen		AAF
Globe Corp. Aircraft Division Joliet, Illinois Attn: Mr. J. A. Waagle	Inspector of Naval Material 141 W. Jackson Blvd. Chicago 4, Illinois	BUAER
Goodyear Aircraft Corp. Akron, Ohio Attn: Dr. Carl Arnstein	Bureau of Aeronautics Rep. 1210 Massillon Road Akron 15, Ohio	BUAER
Goodyear Aircraft Plant "B" Akron 17, Ohio Attn: Mr. A. J. Peterson		AAF
Grumman Aircraft Engineering Corp. Bethpage, Long Island, N.Y. Attn: Mr. William T. Schwendler	Bureau of Aeronautics Rep. Grumman Aircraft Engr. Corp. Bethpage, L.I., N.Y.	BUAER
Hughes Aircraft Co. Culver City, California Attn: Mr. D. H. Evans		AAF
Jet Propulsion Laboratory California Institute of Technology (2 copies)	Officer-in-Charge Ordnance Research & Development Division Sub-office (Rocket) California Institute of Technology Pasadena 4, California	ORD DEPT
Kellex Corp. New York, New York	Inspector of Naval Material 90 Church Street New York 7, N.Y.	BUORD
M. W. Kellogg Co. Foot of Danforth Avenue Jersey City 3, N.J. Dr. G. H. Messerly		AAF BUORD
Chairman, MIT, GMC (2 copies) Project Meteor Office Massachusetts Institute of Technology Cambridge, Mass. Attn: Dr. H. G. Stever	Navy Ordnance Resident Technical Liaison Officer Massachusetts Institute of Technology Room 20-C-135 Cambridge 39, Mass.	BUORD & AAF
McDonnell Aircraft Corp. St. Louis, Missouri Attn: Mr. W. P. Montgomery	Bureau of Aeronautics Rep. McDonnell Aircraft Corp. P.O. Box 516 St. Louis 21, Missouri	AAF & BUAER
North American Aviation Inc. Los Angeles, California Attn: Dr. Wm. Bollay	Bureau of Aeronautics Resident Representative Municipal Airport Los Angeles 45, Calif.	AAF BUORD & BUAER
Northrop Aircraft Inc. Hawthorne, California		AAF
Princeton University Physics Department Princeton, New Jersey Attn: Dr. John A. Wheeler	Development Contract Officer Princeton University Princeton, New Jersey	BUC

C. PRIME CONTRACTORS (Cont'd)

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
Princeton University (3 copies) Princeton, New Jersey Attn: Project SQUID	Commanding Officer Branch Office Office of Naval Research 90 Church Street - Rm 1116 New York 7, New York	BUAER
Radio Corporation of America Victor Division Camden, New Jersey Attn: Mr. T. T. Eaton		AAF & BUORD
Radioplane Corporation Metropolitan Airport Van Nuys, California	Bureau of Aeronautics Rep. Lockheed Aircraft Corp. 2555 North Hollywood Way Burbank, California	BUAER
Raytheon Manufacturing Co. Waltham, Massachusetts Attn: Mrs. H. L. Thomas	Inspector of Naval Material Park Square Building Boston 16, Mass.	AAF & BUAER
Reeves Instrument Corp. 215 E. 91st Street New York 28, N.Y.	Inspector of Naval Material 90 Church St. New York 7, N.Y.	BUAER
Republic Aviation Corp. Military Contract Dept. Farmingdale, L.I., N.Y. Attn: Dr. William O'Donnell		AAF
Ryan Aeronautical Co. Lindberg Field San Diego 12, California Attn: Mr. B. T. Salmon		AAF
S. W. Marshall Co. Shoreham Building Washington, D. C.	Inspector of Naval Material 401 Water Street Baltimore 2, Maryland	BUAER
Sperry Gyroscope Co., Inc. Great Neck, L.I., N.Y.	Inspector of Naval Material 90 Church Street New York 7, N.Y.	BUAER ORD DEPT
United Aircraft Corp. Chance Vought Aircraft Div. Stratford, Conn. Attn: Mr. P. S. Baker	Bureau of Aeronautics Rep. United Aircraft Corp. Chance Vought Aircraft Div. Stratford 1, Conn.	BUAER
United Aircraft Corp. Research Department East Hartford, Conn. Attn: Mr. John G. Lee	Bureau of Aeronautics Rep. United Aircraft Corp. Pratt & Whitney Aircraft Div. East Hartford 8, Conn.	BUORD
University of Michigan Aeronautical Research Center Willow Run Airport Ypsilanti, Michigan Attn: Mr. R. F. May Dr. A. M. Kuethe		AAF
University of Southern California Naval Research Project, College of Engineering Los Angeles, California Attn: Dr. R. T. DeVault	Bureau of Aeronautics Rep. 15 South Raymond Street Pasadena, California	BUAER
University of Texas Defense Research Lab. Austin, Texas Attn: Dr. C. P. Boner	Development Contract Officer 500 East 24th Street Austin 12, Texas	BUORD
Willys-Overland Motors, Inc. Maywood, California Attn: Mr. Joe Talley	Representative-in-Charge, BUAER Consolidated-Vultee Aircraft Corp. Downey, California	BUAER

D. COMPONENT CONTRACTORS

(1) AERODYNAMICS & BALLISTICS

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
New Mexico School of Mines Research & Development Div. Albuquerque, New Mexico	Development Contract Officer New Mexico School of Mines Albuquerque, New Mexico	BUORD
New Mexico School of Agriculture & Mechanic Arts State College, New Mexico Attn: Dr. George Gardner	Development Contract Officer New Mexico School of Mines Albuquerque, New Mexico	BUORD
New York University Applied Mathematics Center New York, New York Attn: Mr. Richard Courant	Inspector of Navsl Material 90 Church Street New York 7, New York	BUAER
Office of the Chief of Ordnance Ordnance Research & Development Division Research & Materials Branch Ballistics Section Pentagon Washington 25, D.C.		ORD DEPT
Polytechnic Institute of Brooklyn Brooklyn, New York Attn: Mr. R.P. Harrington	Inspector of Naval Material 90 Church Street New York 7, New York	BUAER
University of Minnesota Minneapolis, Minnesota Attn: Dr. Akerman	Inspector of Naval Material Federal Bldg. Milwaukee 2, Wis.	BUORD
Aerojet Engineering Corp. Azusa, California Attn: K.F. Mundt	Bureau of Aeronautics Rep. 15 South Raymond Street Pasadena, California	BUAER
Marquardt Aircraft Co. Venice, California Attn: Dr. R. E. Marquardt	Bureau of Aeronautics Rep. 15 South Raymond Street Pasadena, California	BUAER

(2) GUIDANCE & CONTROL

Belmont Radio Corporation 5921 West Dickens Avenue Chicago 29, Illinois Attn: Mr. Harold C. Mattes		AAF
Bendix Aviation Corp. Eclipse-Pioneer Division Teterboro, New Jersey Attn: Mr. R. C. Sylvander	Bureau of Aeronautics Resident Representative Bendix Aviation Corp. Teterboro, New Jersey	BUAER
Bendix Aviation Corp. Pacific Division, SPD West North Hollywood, Calif.	Development Contract Officer Bendix Aviation Corp. 11600 Sherman Way North Hollywood, California	BUORD
Bendix Aviation Radio Division East Joppa Road Baltimore 4, Maryland Attn: Mr. J. W. Hammond		AAF
Buehler and Company 1607 Howard Street Chicago 26, Illinois Attn: Mr. Jack M. Roehn		AAF
Commanding General Army Air Forces Pentagon Washington 25, D.C. Attn: AC/AS-4, DRE-2F		AAF

D. COMPONENT CONTRACTORS (Cont'd)

(2) GUIDANCE & CONTROL

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
Consolidated-Vultee Aircraft Corporation San Diego, California Attn: Mr. C. J. Breitwieser	Bureau of Aeronautics Representative, Consolidated-Vultee Aircraft Corp. San Diego, California	BUAER
Cornell University Ithaca, New York Attn: Mr. William C. Ballard, Jr.		AAF
Director, U.S. Navy Electronics Laboratory, San Diego, California		NAVY
Electro-Mechanical Research Ridge Field, Connecticut Attn: Mr. Charles B. Aiken		AAF
Farnsworth Television and Radio Co. Fort Wayne, Indiana Attn: Mr. J. D. Schantz	DCO, Applied Physics Laboratory Johns Hopkins University 8621 Georgia Avenue, Silver Spring, Maryland	BUORD
Federal Telephone and Radio Corp. 200 Mt. Pleasant Avenue Newark 4, New Jersey Attn: Mr. E. N. Wendell		AAF
Galvin Manufacturing Corp. 4545 Augusta Blvd. Chicago 5, Illinois Attn: Mr. G. R. MacDonald		AAF
G. M. Giannini and Co., Inc. 285 West Colorado St. Pasadena, California	Bureau of Aeronautics Rep. 15 South Raymond St. Pasadena, California	BUAER
Gilfillan Corp. 1815-1849 Venice Blvd. Los Angeles 6, California Attn: Mr. G. H. Miles		AAF
Hillyer Engineering Co. New York, New York Attn: Mr. Curtiss Hillyer	Inspector of Naval Material 90 Church Street New York 7, New York	BUAER
Kearfott Engineering Co. New York, New York Attn: Mr. W. A. Reichel	Inspector of Naval Material 90 Church Street New York 7, New York	BUAER
Lear Incorporated 110 Iona Avenue, N.W. Grand Rapids 2, Michigan Attn: Mr. R.M. Mock		AAF
Manufacturers Machine & Tool Co. 220 Washington Street Mt. Vernon, N.Y. Attn: Mr. L. Kenneth Mayer, Comptroller		AAF
Minneapolis-Honeywwll Mfgr. Co. 2753 Fourth Avenue Minneapolis 8, Minnesota Attn: Mr. W. J. McGoldrick, Vice-President		AAF
Ohio State University Research Foundation Columbus, Ohio Attn: Mr. Thomas E. Davis, Staff Assistant		AAF

D. COMPONENT CONTRACTORS (Cont'd)

(2) GUIDANCE & CONTROL

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
Haller, Raymond & Brown P.O. Box 342 State College, Pennsylvania Attn: Dr. R. C. Raymond, Pres.		AAF
Office of Chief Signal Officer Engineering & Technical Services, Engineering Division Pentagon Washington 25, D.C.		ORD DEPT
Raytron, Inc. 209 E. Washington Avenue Jackson, Michigan Attn: Mr. John R. Gelzer, Vice-Pres.		AAF
L. N. Schwein Engineering Co. 5736 Washington Blvd. Los Angeles 16, California Attn: L.N. Schwein, General Partner		AAF
Senior Naval Liaison Officer U.S. Naval Electronic Liaison Office Signal Corps, Engineering Laboratory Fort Monmouth, New Jersey		NAVY
Servo Corporation of America Huntington, L.I., New York	Inspector of Naval Material 90 Church Street New York 7, New York	BUAER
Square D Co. Kollsman Instrument Division Elmhurst, New York Attn: Mr. V. E. Carbonara	Bureau of Aeronautics Rep. 90 Church Street New York 7, New York	BUAER
Stromberg-Carlson Company Rochester, New York Attn: Mr. L.L. Spencer, Vice-Pres.		AAF
Submarine Signal Company Boston, Massachusetts Attn: Mr. Edgar Horton	Development Contract Officer Massachusetts Institute of Technology Cambridge 39, Massachusetts	BUORD
Summers Gyroscope Co. 1100 Colorado Avenue Santa Monica, California Attn: Mr. Tom Summers, Jr.		AAF
Sylvania Electric Products Inc. Flushing, Long Island, N.Y. Attn: Dr. Robert Bowie	Inspector of Naval Material 90 Church Street New York 7, New York	BUORD
University of Illinois Urbana, Illinois Attn: Mr. H. E. Cunningham, Sec.		AAF
University of Pennsylvania Moore School of Electrical Engr. Philadelphia, Pa.	Commanding Officer Naval Aircraft Modification Unit Johnsville, Pa.	BUAER
University of Pittsburgh Pittsburgh, Pennsylvania Attn: Mr. E. A. Holbrook, Dean		AAF
University of Virginia Physics Department Charlottesville, Virginia Attn: Dr. J. W. Beams	Development Contract Officer University of Virginia Charlottesville, Virginia	BUORD

D. COMPONENT CONTRACTORS (Cont'd)

(2) GUIDANCE & CONTROL

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
Washington University Research Foundation 8135 Forsythe Blvd., Clayton 5, Missouri Attn: Dr. R. G. Spencer		AAF
Westinghouse Electric Corp. Springfield, Massachusetts Attn: J.K.B. Hare, Vice-Pres. (Dayton Office)		AAF
Director of Specialty Products Development Whippany Radio Laboratory Whippany, N.J. Attn: Mr. M.H. Cook		ORD DEPT
Zenith Radio Corporation Chicago, Illinois Attn: Hugh Robertson, Executive Vice-Pres.		AAF

---

(3) PROPULSION

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
Aerojet Engineering Corp. Azusa, California Attn: K.F. Mundt	Bureau of Aeronautics Rep. 15 South Raymond Street Pasadena, California	BUAER
Armour Research Foundation Technical Center, Chicago 16, Illinois Attn: Mr. W. A. Casler		ORD DEPT
Arthur D. Little, Inc. 30 Memorial Drive, Cambridge, Mass. Attn: Mr. Helge Holst		ORD DEPT
Battelle Memorial Institute 505 King Avenue Columbus 1, Ohio Attn: Dr. B. D. Thomas		AAF & BUAER
Bendix Aviation Corp. Pacific Division, SPD West N. Hollywood, Calif.	Development Contract Officer Bendix Aviation Corp. 11600 Sherman Way N. Hollywood, Calif.	BUORD
Bendix Products Division Bendix Aviation Corporation 401 Bendix Drive South Bend 20, Indiana Attn: Mr. Frank C. Mock		AAF BUORD
Commanding General Army Air Forces Pentagon Washington 25, D.C. Attn: AC/AS-4 DRE-3E		AAF
Commanding General Air Materiel Command Wright Field Dayton, Ohio Attn: TSEPP-4B(2) TSEPP-4A(1) TSEPP-5A(1) TSEPP-5C(1) TSORE-(1)		
Commanding Officer Picatinny Arsenal Dover, New Jersey Attn: Technical Division		ORD DEPT

D. COMPONENT CONTRACTORS (Cont'd)

(3) PROPULSION

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
Commanding Officer Watertown Arsenal Watertown 72, Massachusetts. Attn: Laboratory.		ORD DEPT
Continental Aviation and Engr. Corp. Detroit, Michigan	Bureau of Aeronautics Rep. 11111 French Road Detroit 5, Michigan	BUAER & AAF
Curtiss-Wright Corporation Propeller Division Caldwell, New Jersey Attn: Mr. C. W. Chillson		AAF
Experiment, Incorporated Richmond, Virginia Attn: Dr. J. W. Mullen, II	Development Contract Officer P.O. Box 1-T Richmond 2, Virginia	BUORD
Fairchild Airplane & Engine Co. Ranger Aircraft Engines Div. Farmingdale, L.I., New York	Bureau of Aeronautics Rep. Bethpage, L.I., N.Y.	BUAER
General Motors Corporation Allison Division Indianapolis, Indiana Attn: Mr. Ronald Hazen	Bureau of Aeronautics Rep. General Motors Corporation Allison Division Indianapolis, Indiana	BUAER
G. M. Giannini & Co., Inc. 285 W. Colorado St. Pasadena, California		AAF
Hercules Powder Co. Port Ewen, N.Y.	Inspector of Naval Material 90 Church Street New York 7, New York	BUORD
Marquardt Aircraft Company Venice, California Attn: Dr. R. E. Marquardt	Bureau of Aeronautics Rep. 15 South Raymond Street Pasadena, California	AAF BUAER
Menasco Manufacturing Co. 805 E. San Fernando Blvd. Burbank, California Attn: Robert R. Miller Exec. Vice-Pres.		AAF
New York University Applied Mathematics Center New York, New York Attn: Dr. Richard Courant	Inspector of Naval Material 90 Church Street New York 7, New York	BUAER
Office of Chief of Ordnance Ordnance Research & Development Div. Rocket Branch Pentagon, Washington 25, D.C.		ORD DEPT
Polytechnic Institute of Brooklyn Brooklyn, New York Attn: Mr. R.P. Harrington	Inspector of Naval Material 90 Church Street New York 7, New York	BUAER
Purdue University Lafayette, Indiana Attn: Mr. G. S. Meikel	Inspector of Naval Material 141 W. Jackson Blvd. Chicago 4, Illinois	
Reaction Motors, Inc. Lake Denmark Dover, New Jersey	Bureau of Aeronautics Resident Representative Reaction Motors, Inc. Naval Ammunition Depot Lake Denmark, Dover, N.J.	BUAER

D. COMPONENT CONTRACTORS (Cont'd)

(3) PROPULSION

CONTRACTOR	TRANSMITTED VIA	COGNIZANT AGENCY
Rensselaer Polytechnic Institute Troy, New York Attn: Instructor of Naval Science		BUORD
Solar Aircraft Company San Diego 12, California Attn: Dr. M.A. Williamson		ORD DEPT
Standard Oil Company Esso Laboratories Elizabeth, New Jersey	Development Contract Officer Standard Oil Company Esso Laboratories, Box 243 Elizabeth, New Jersey	BUORD
University of Virginia Physics Department Charlottesville, Virginia Attn: Dr. J. W. Beams	Development Contract Officer University of Virginia Charlottesville, Virginia	BUORD
University of Wisconsin Madison, Wisconsin Attn: Dr. J.O. Hirschfelder	Inspector of Naval Material, 141 W. Jackson Blvd. Chicago 4, Illinois	BUORD
Westinghouse Electric Co. Essington, Pennsylvania	Bureau of Aeronautics Resident Representative Westinghouse Electric Corp. Essington, Pennsylvania	BUAER
Wright Aeronautical Corp. Woodridge, New Jersey	Bureau of Aeronautics Rep. Wright Aeronautical Corp. Woodridge, New Jersey	BUAER
Bethlehem Steel Corp. Shipbuilding Division Quincy 69, Mass. Attn: Mr. B. Fox	Supervisor of Shipbuilding, USN Quincy, Mass.	BUAER