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Continuous Coverage of the North Polar Region with Only Two Communications Satellites

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ABSTRACT

The problem of providing continuous coverage of the north polar region with a small number of communications satellites is considered. The system described requires only two satellites to provide both this coverage and coverage of a considerable fraction of the northern hemisphere. Two orbit planes with 63.43° inclination, high eccentricity and ~24 hour periods are employed. The regions of the earth from which a satellite is continuously visible from terminals with various minimum elevation angles are shown. The regions in which mutual visibility of a satellite by two terminals is guaranteed are shown. A few comments concerning satellite design for this orbit are included.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

Continuous Coverage of the North Polar Region with Only Two Communications Satellites

I. Introduction

Continuous coverage of the north polar region is desirable, and in some cases mandatory, for many satellite communications systems. Synchronous, equatorial satellites provide coverage to only low and moderate latitudes. Satellites in inclined circular orbits can provide polar coverage but considerably more than two satellites are required.*

Consider the problem of providing continuous north polar coverage using a small number of satellites. It is clear that a single satellite in earth orbit cannot provide this coverage. To provide this coverage by keeping a single satellite hovering constantly over the northern hemisphere by firing jets on the satellite would be prohibitively expensive. In the next section we describe a system of only two satellites which provides this coverage and also provides continuous coverage down to moderate latitudes of a wide strip of the earth near an arbitrarily selected longitude. These two satellites can augment the coverage of synchronous equatorial satellites or can be used by terminals which operate in an area which includes both the north polar region and a strip of the earth near a particular longitude. An example of the latter case is military forces which are deployed in the polar region and must communicate with a base located in the continental United States (CONUS).

The system described has the further advantage that, whenever the earth casts its shadow on the solar array of a satellite, the terminals are using the other satellite. Thus the communications transmitter need not be used during solar eclipse so only a small storage battery need be included in each satellite.

II. Selection of the Satellite Orbits

In synthesizing a system to provide continuous north polar coverage with only two satellites, one must consider elliptical orbits since circular orbits cannot achieve this objective. A highly elliptical orbit with its apogee in the northern hemisphere is attractive since a satellite spends considerably more time near its apogee than its perigee.

*The advantage of these orbits would be that coverage of the south polar region would also be provided in those cases in which it is desired.

In general, such an orbit is unstable in the sense that the apogee will not remain over the northern hemisphere due to perturbations caused by the non-sphericity of the earth. The angular velocity with which the apogee rotates in the orbit plane is proportional to $5 \cos^2 i - 1$ where i is the orbit inclination, i.e., the angle between the equatorial and orbital planes (Ref. 1). When $i = 63.43^\circ$, apogee rotation is zero so this inclination has been chosen.†

If two satellites are placed in the same orbit plane phased such that when one is at apogee the other is at perigee, continuous north polar coverage can be provided if the apogee height is sufficiently large.

When continuous coverage of a wide strip of the earth down to moderate latitudes near an arbitrarily selected longitude is also required, two satellites in the same orbit plane no longer suffice. This coverage can be provided if each satellite reaches apogee only when it is over the selected longitude. Figure 1 shows the simplest way of achieving this. Both orbit planes intersect the equatorial plane in the same line, the line of nodes. Relative to the line of nodes the earth rotates with a period $T \approx 24$ hr. The orbital period of the satellites is also T and they are phased so that one reaches apogee every T/2 hr. The direction of rotation of the satellites are chosen so that they follow the rotation of the selected longitude when they are near apogee. If a particular set of terminals can point antennas toward one satellite in a particular direction at time t, they can point toward the other satellite in the same direction at time $t + T/2$. This symmetry is useful in the coverage analysis of the next section. It should be noted that T is slightly less than 24 hours so the satellites reach a particular point in orbit at slightly different times each day.

To insure negligible atmospheric drag the perigee altitude is approximately 700 km. The effects of drift of perigee altitude is discussed in Section VII. A semi-major axis of 6.60990995 earth radii and an eccentricity of 0.8321083 provide an orbital period of 23.93025 hours. This is the period of rotation of the earth relative to the line of nodes.* As shown in Fig. 1, the inclination of both orbital planes is 63.43°, the ascending nodes are separated by 180° and the argument of perigee is 270°.

†The Molniya satellites use this inclination for high latitude coverage.

*Relative to the vernal equinox the earth rotates at a rate of 360.99° per day. The line of nodes rotates at a rate of 0.06° per day because of perturbations of the orbit due to the earth's equatorial bulge. Thus, the earth rotates at 361.05° per day relative to the line of nodes, i.e., requires 23.93 hours to rotate 360°.

III. Region of Continuous Visibility

The earth's equatorial plane and the line of nodes determine an orthogonal coordinate system; the coordinates are the line of nodes, a line perpendicular to the equatorial plane and a line in the equatorial plane perpendicular to the other lines. Considering the effects of the second harmonic of the earth's gravitational field, both orbit planes are stationary in this coordinate system. Some higher order effects including perturbations due to the sun and moon must be canceled by adjusting the orbit with thrusters in the satellite. Fuel requirements for these adjustments are fairly small. We assume these adjustments are made.

Since the orbital periods and the periods of rotation of the earth in this coordinate system are equal, the coverage of the satellites during a single period is repeated exactly in all subsequent periods. Because of the symmetry described in the previous section, coverage provided by one satellite during one half-orbit is repeated exactly by the other satellite in the next half-orbit. Therefore, if a terminal with a particular location and minimum elevation angle can point its antenna toward one satellite for a half-orbit (~12 hours) it can always point toward one of the satellites, i.e., has continuous satellite visibility. Furthermore, if one satellite is simultaneously visible from two terminals for a half-orbit, one of the satellites is always visible from both terminals.

In Fig. 2, continuous visibility contours for terminals with minimum elevation angles of 0, 5, 10, 20 and 30 degrees are shown. A terminal with a particular minimum elevation angle located on the corresponding contour can point toward one satellite for ~12 hours and thus has continuous satellite visibility. A terminal located north of this contour also has continuous satellite visibility. The contours can be moved east or west on the map by changing the longitude of the ascending nodes of the orbits.

IV. Regions of Continuous Mutual Visibility

A terminal located on the contours of Figs. 3, 4, and 5 corresponding to its minimum elevation angle can point toward each satellite for 14, 17.5 and 21 hours per orbital period, respectively. These contours provide mutual visibility information in the following way. Consider the orbit plane of Fig. 6. The satellite is visible from terminals A and B for time intervals of length τ_A and τ_B. The satellite is visible from both terminals for time τ_{AB} and visible from neither for time $\overline{\tau_{AB}}$. From Fig. 6,

$$\tau_A + \tau_B - \tau_{AB} + \overline{\tau_{AB}} = T \approx 24 \text{ hr.} \quad ,$$

where T is the orbital period. For continuous mutual visibility we require $\tau_{AB} \geq 12$ hr. so we require

$$\tau_A + \tau_B - T + \overline{\tau_{AB}} \geq 12 \text{ hr.}$$

or

$$\tau_A + \tau_B \geq T + 12 - \overline{\tau_{AB}} \quad .$$

It can be shown for the northern hemisphere locations of interest, $\overline{\tau_{AB}} \geq 1$ hr. so if $\tau_A + \tau_B \geq 35$ hr., $\tau_{AB} \geq 12$ hr. and continuous mutual visibility is provided.

Consider two terminals with particular minimum elevation angles. If each is located on or north of the corresponding 17.5 hr. contour of Fig. 4, continuous mutual visibility is provided. If one is located north of the corresponding contour of Fig. 3 and the other north of the corresponding contour of Fig. 5, continuous mutual visibility is provided.

As with Fig. 2, the contours of Figs. 3, 4, and 5 can be moved east or west on the map. An existing computer program was employed to obtain the contours. Because of the form of the program, results were computed for particular terminal locations and were quantized to 1/3 hr. Contours were drawn between these particular terminal locations using straight lines. To the extent of the quantization and of the departure of the straight lines from smooth curves, the results are approximate.

V. Examples

In Fig. 7 we show coverage provided by two satellites to terminals with low (0 or 5^o) minimum elevation angles. A terminal located in the continental United States (CONUS) above the 21 hr. line has continuous mutual visibility with all terminals (e.g., aircraft) located above the 14 hr. line. Most of the northern hemisphere is above the 14 hr. line.

In Fig. 8 coverage is shown provided by three satellites, two in 63.43^o inclined orbits and one in synchronous equatorial orbit. Assume there are two 5^o elevation terminals located in CONUS as shown. The terminal in California has continuous mutual visibility with shipborne terminals located inside the curved contours in the Pacific and limited to elevation angles greater than 20 or 30^{o}. The terminal in Maine has continuous mutual visibility with shipborne terminals located in the Mediterranean Sea, and the North Atlantic, North Pacific and Arctic Oceans.

VI. Satellite Design Considerations

Relative to the earth's equatorial plane the orbit planes of both satellites are inclined by 63.4^{o}. Relative to the earth's orbit plane (ecliptic) the inclination varies from 40^{o} to 87^{o}. As seen from the satellite the sun can be located in any direction in the ecliptic plane and the earth can be located in any direction in the orbit plane. Thus if solar panels on the satellite are sun-oriented, an earth-oriented antenna must be able to point in almost all directions relative to the plane of the solar panel. This is not true of equatorial satellites because their orbit plane is inclined only 23^{o} relative to the ecliptic.

An attractive way to configure the satellite is shown in Fig. 9. A momentum wheel or control moment gyro is mounted on the solar panels. The wheel spins at a bias speed about an axis normal to the plane of the panels. The wheel axis always points toward the sun so the angular momentum vector must be rotated once per year by appyling external torque with thrusters. Once per orbit the spacecraft rotates about the wheel axis and the satellite body oscillates $\pm 180^{o}$ about the solar array shaft. A flexible cable transfers power and control signals from the solar panels to the body. Attitude control is accomplished by orienting the antennas toward the earth with earth sensors while using sun sensors to orient the solar array. With this configuration, antennas remain earth oriented but they rotate about an axis from the satellite to the center of the earth.

During the useful part of the satellite's orbit the angle subtended by the earth varies from $\sim 40^{o}$ to 9.5^{o} so use of variable beamwidth antennas would be desirable. At X-band (~8 GHz) a reasonable design is to include 4 or 5 antennas, with progressively narrower beams, and electronically switch between them as the satellite traverses its orbit. The antenna apertures would vary from 3 to 12 inches. If a lower frequency, e.g., UHF (300 MHz), transponder is included, providing a variable beamwidth antenna over the wide variation of satellite altitude is a more difficult problem due to the large aperture involved.

Thermal design of the satellite body is somewhat simpler than for a synchronous equatorial orbit satellite because the sun is always in the plane which is perpendicular to the solar array shaft.

Launch into the orbits from Cape Kennedy could be accomplished by initial launch into a 52^{o} inclined 180 km (100 nautical miles) parking orbit, non-coplanar transfer to 63.4^{o} inclination and 700 km (380 nm) orbit and finally coplanar transfer to the highly elliptical orbit. A launch vehicle would have slightly more payload capability for this orbit than for synchronous equatorial orbit.

VII. Stability of the Orbits

The inclination of the orbits relative to the ecliptic varies from 40 to 87^{o}. One of the effects of the second harmonics of the luni-solar disturbing functions (Ref. 2) is to cause the perigee height to vary in an irregular but predictable manner. This effect has been examined in Ref. 2 and the authors have developed computer programs to obtain quantitative results. When a satellite is launched into an orbit such that the perigee height initially decreases, the initial value must be large enough to insure that, before this height reaches a value so small that atmospheric drag is encountered, either it passes through its minimum and begins increasing or the satellite lifetime requirement is fulfilled. Thus, perigee height may be a few hundred kilometers higher than the 700 km assumed in the coverage analysis. Increasing the perigee height by as much as several thousand kilometers produces only a small change in the coverage if the orbital period is not changed. It may be desirable to increase perigee height to avoid exposure to radiation in the Van Allen belts.

For this orbit, doppler shift due to the velocity of a satellite relative to a terminal is quite high. Depending on the position of the satellite in orbit, doppler shift can vary from 0 to ±200 kHz when the satellite frequency is 8 GHz. Lincoln Experimental Terminal Number 1 demonstrated the feasibility of predicting, acquiring and tracking doppler shifts of this magnitude several years ago.

REFERENCES

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The valuable contribution of Ferenc Nagy, Jr. who made results from his computer programs available is greatly appreciated.

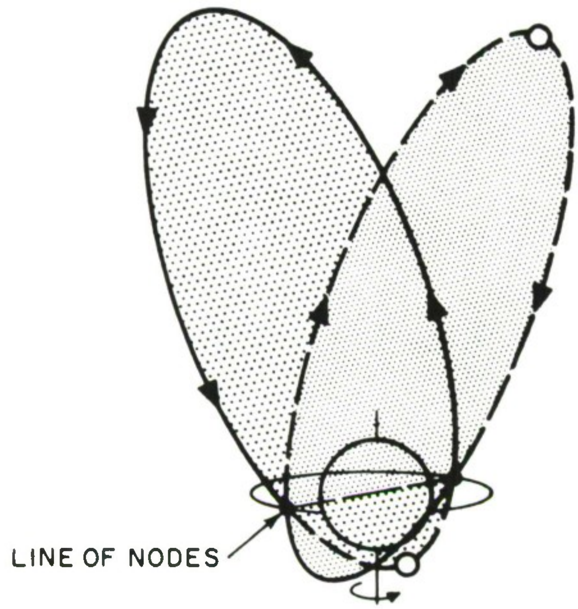

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Fig. 1. The earth, the satellites and their orbital planes.

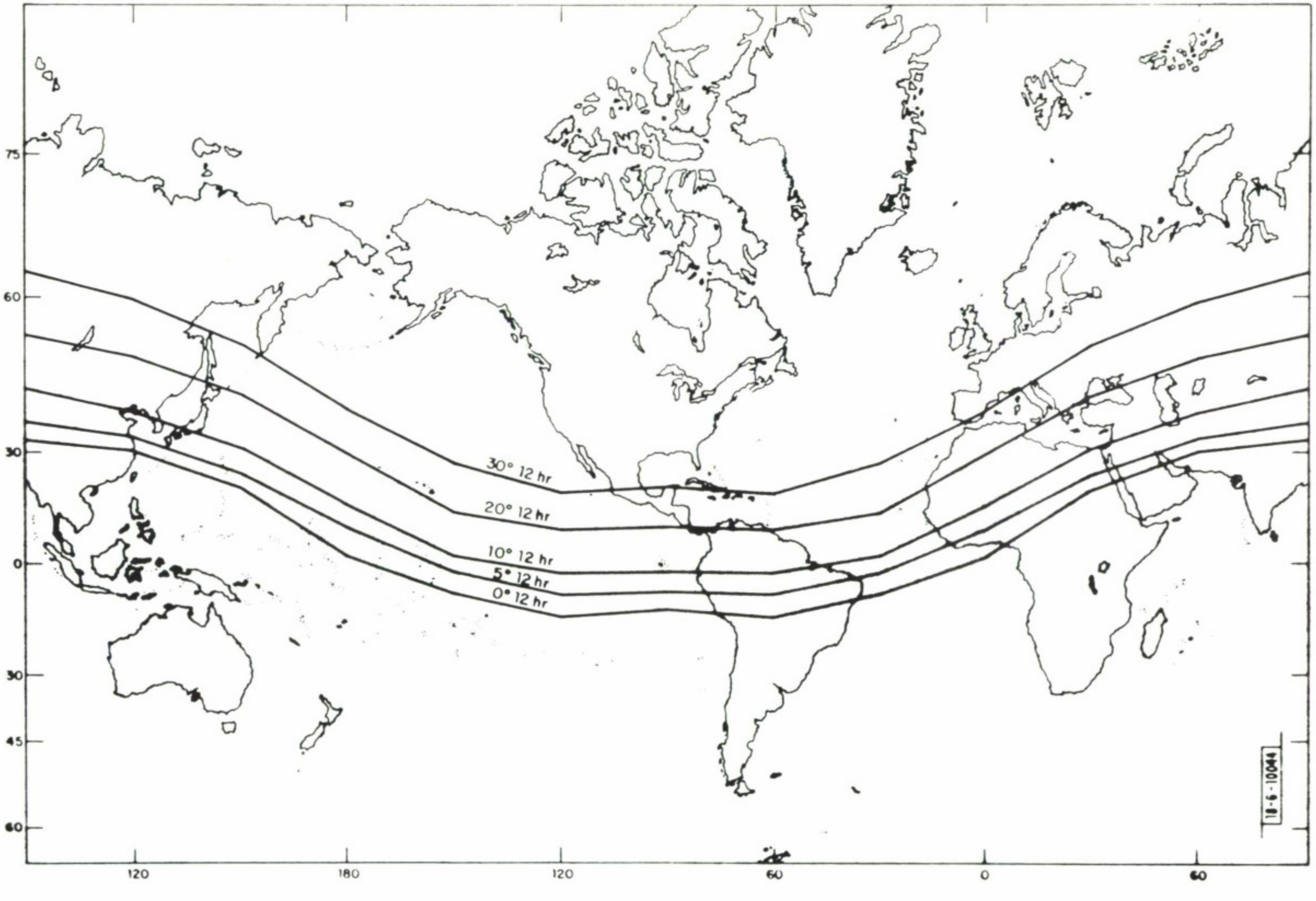

Fig. 2. Terminals located north of contours have continuous satellite visibility.

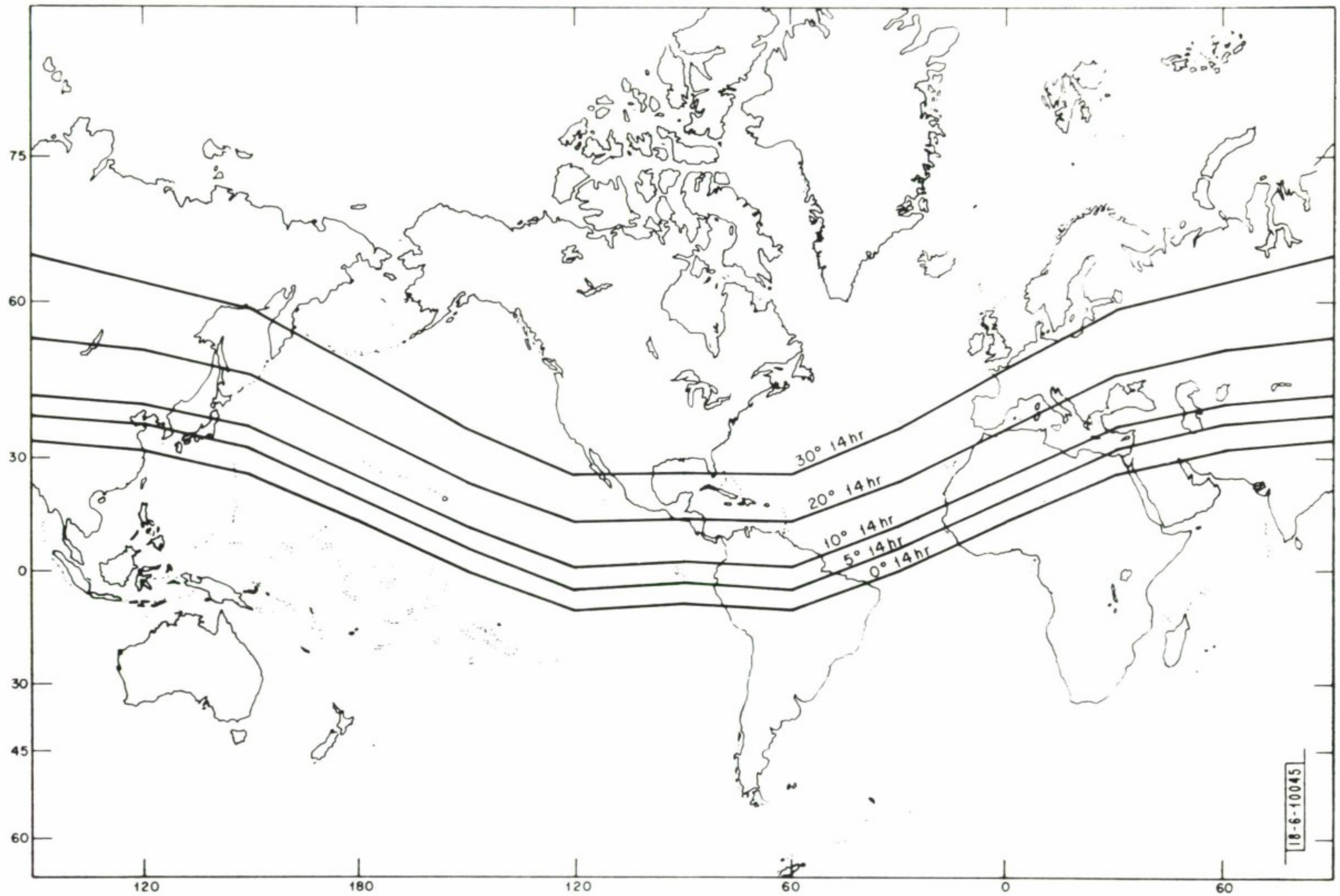

Fig. 3. Terminals located north of contours have continuous mutual visibility with terminals north of contours of Fig. 5.

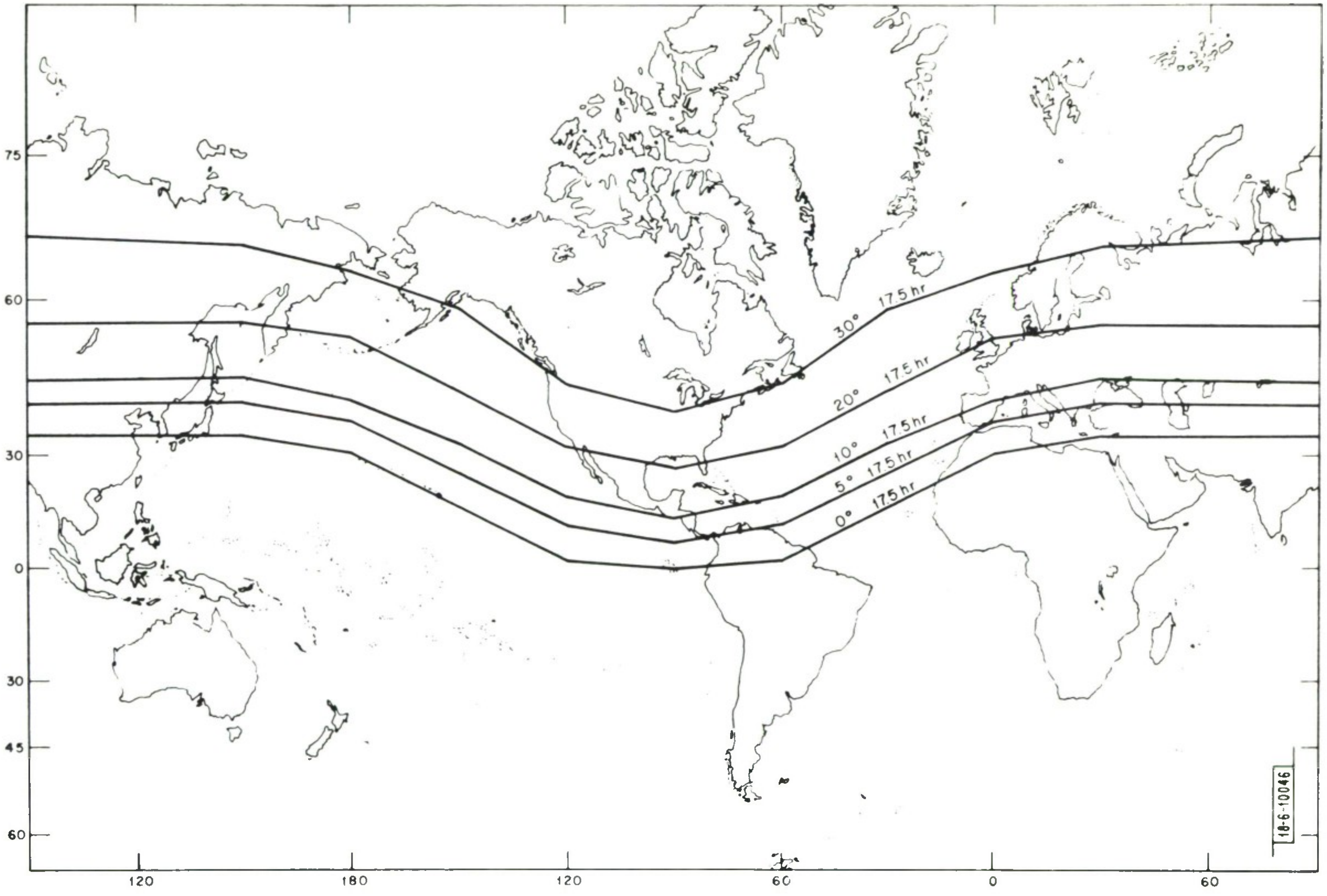

Fig. 4. Terminals located north of contours have continuous mutual visibility.

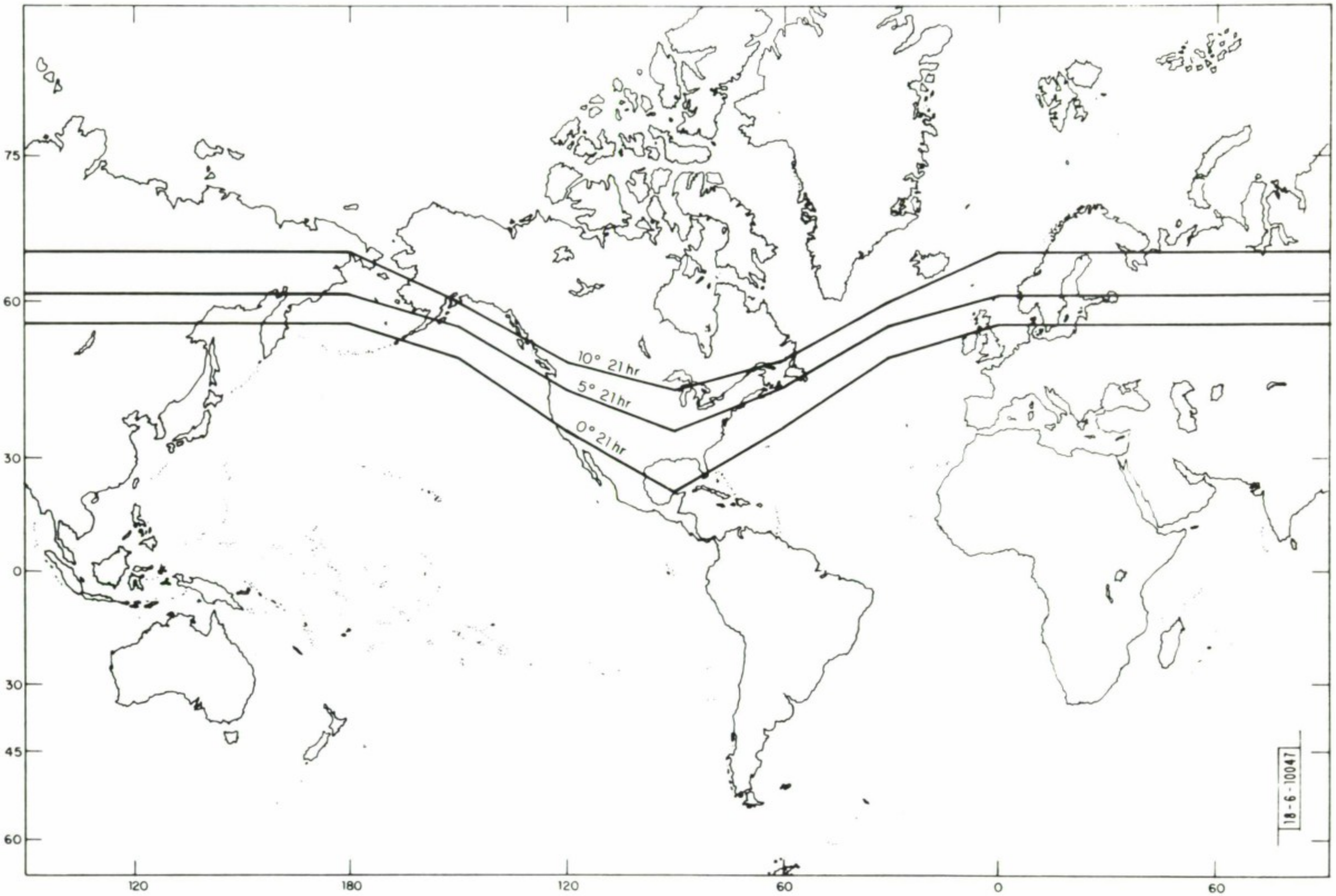

Fig. 5. Terminals located north of contours have continuous mutual visibility with terminals north of contours of Fig. 3.

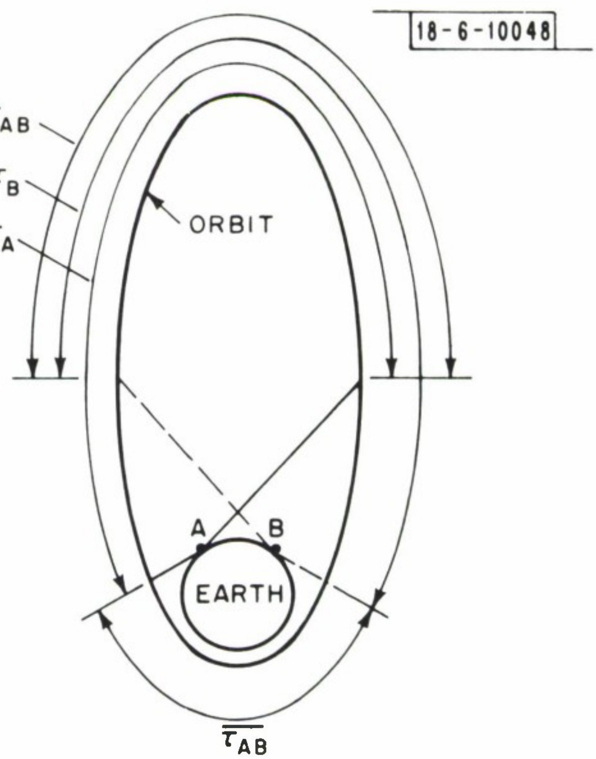

Fig. 6. Satellite orbit plane.

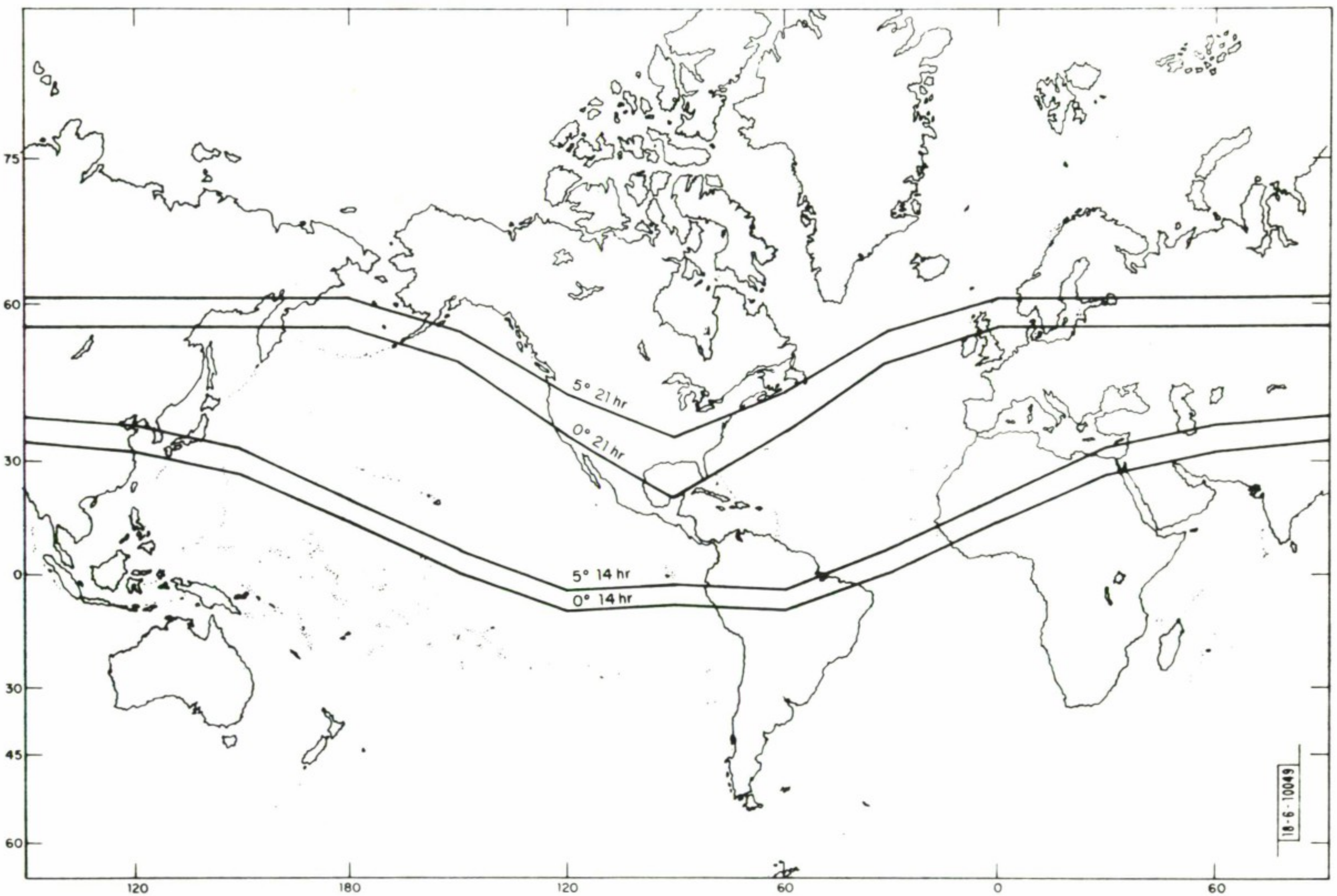

Fig. 7. Terminals north of 21-hour contours have continuous mutual visibility with terminals north of 14-hour contours.

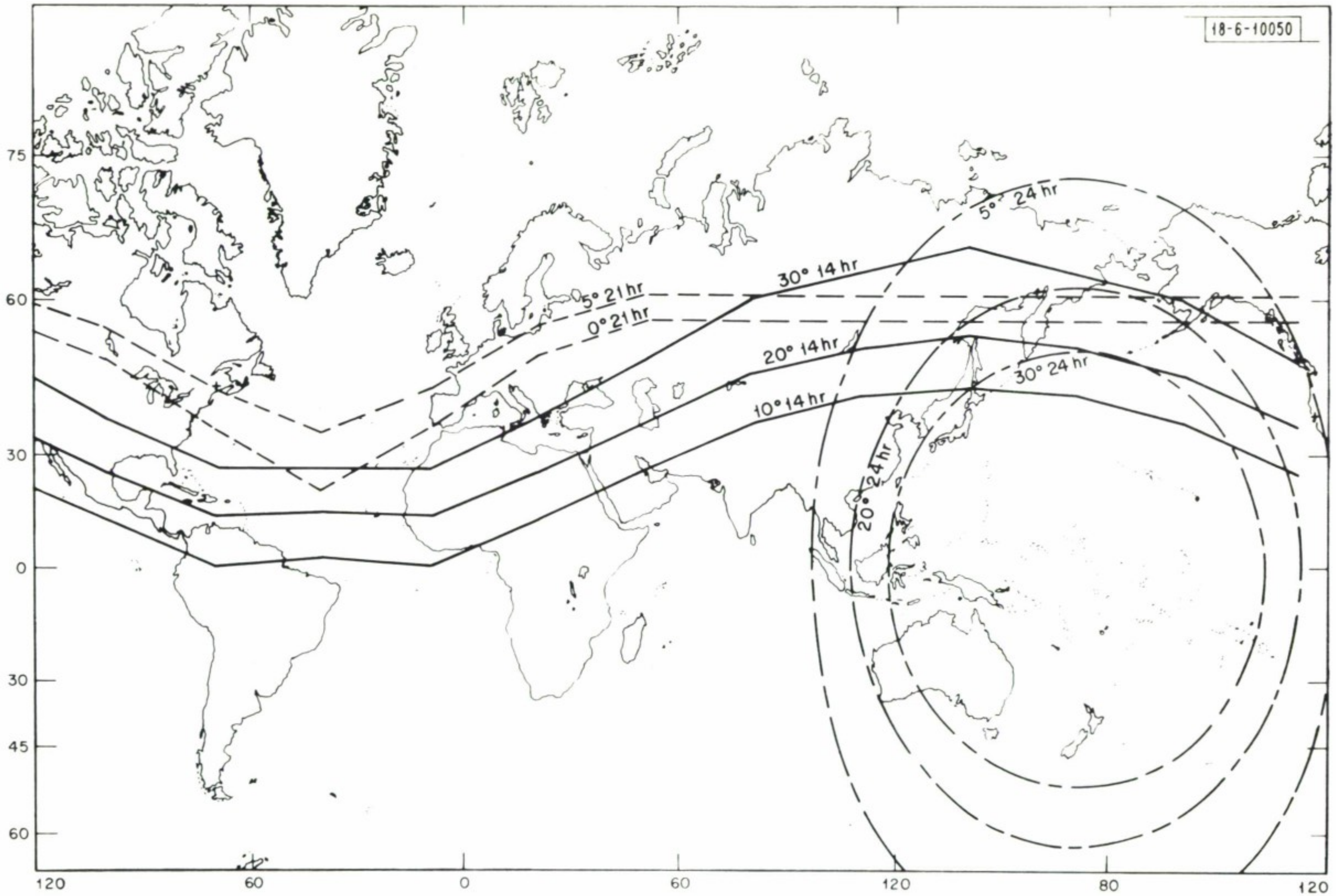

Fig. 8. Continuous mutual visibility with particular terminals; three satellites including one synchronous equatorial satellite.

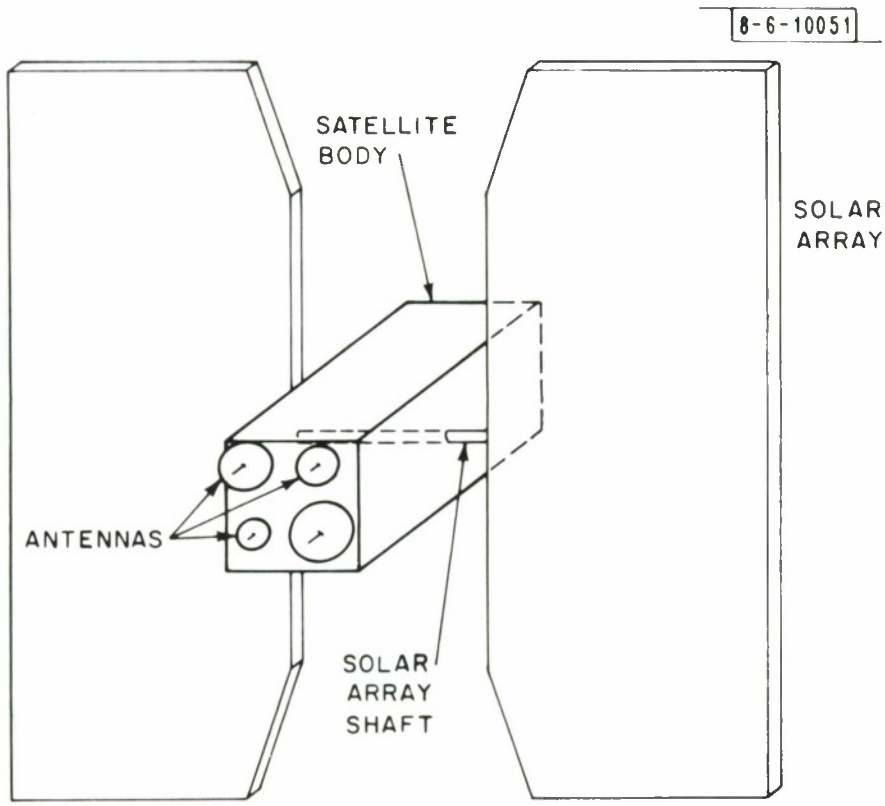

Fig. 9. Satellite configuration.

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13. ABSTRACT

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14. KEY WORDS

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communications satellites	satellite orbits