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ORBIT SELECTION CONSIDERATIONS FOR EARTH RESOURCES OBSERVATIONS

by Byron L. Swenson

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SUMMARY

The application of Earth satellites to the examination of the static and dynamic nature of the Earth's surface involves a compromise between observational requirements of the user and the realities of orbital mechanics. This paper examines the orbital mechanics problem to determine, in general, if various observational requirements (solar elevation angle, sensor and resolution requirements, observational repetition frequency, and the seasonal time and location of the observation) can be satisfied and, in particular, whether a number of different types of observations can be made from a single satellite. Parametric material is presented for determining the extent to which the observational constraints must be relaxed either to perform a single observation or to make several observations compatible. In general, it was determined that high resolution coverage of broad surface areas (i.e., areas of the order of 2000 km and greater in width) was possible within reasonable solar angle constraints but that the rapid repetition of such observations (e.g., within less than a month) was not possible with a single satellite. If rapid repetition of observations is required, either low resolution observations must be made, or much smaller surface areas must be considered, or multiple satellites must be used.

INTRODUCTION

Earth satellites are receiving considerable attention as a viable means for examining the physical state of various areas of the Earth's surface. While observations of the Earth made in this manner are classified under the general heading of "Earth resources," some concern the dynamics of phenomena occurring on the Earth's surface and have little to do with physical resources. The applications of such observations are numerous and many have been cataloged and documented in reference 1.

A set of observational objectives, of course, results in a set of constraints outside of which the interpretation of the observations becomes relatively more difficult and the observations have significantly less value. The purpose of this paper is, thus, to examine the orbital mechanics problem to determine if the observational objectives of reference 1 can be satisfied in general and, in particular, whether a number of observations can be made from a single satellite. A further purpose is to provide parametric information for determining the extent to which the observational constraints must be relaxed either to satisfy a single observation or to make several observations compatible.

DISCUSSION

Observational Requirements

The constraints associated with the observational objectives in reference 1 are numerous and, of course, in most cases cannot be defined sharply. For example, a discrete solar elevation angle range may be specified for a given observation but this does not mean that the value of the observation is a step function at each of the limits. Rather, experience (or in some cases theory) has indicated that the interpretation of the observation will be enhanced if the solar lighting is approximately within this range. Therefore, to make the problem tractable, it appears reasonable not to treat each observation individually but rather to classify each of the pertinent observational constraints coarsely and to examine the possibility of achieving each constraint classification. In addition, inconsistencies between constraint classifications can be identified.

The Earth resources applications have been cataloged in reference 1 into six user categories: oceanography, agriculture/forestry, geography, geology, hydrology, and disaster assessment. The observational characteristics pertinent to the orbit selection in each category are the size and location of the area to be observed and the seasonal time of the observation, the solar elevation angle constraints, the swath width requirements (determined primarily from sensor limitations and resolution requirements), and finally the observational repetition frequency.

With regard to the first characteristic, the observations were primarily constrained to the continental United States, except in the oceanography category, and were thus constrained between about 30° and 50° north latitude; observations of Alaska were constrained between 60° and 70° north latitude. In most cases, the area to be observed exceeded a width of 2000 km. The desired time of given observations followed no particular pattern but varied throughout the year.

Solar elevation angle constraints were given for the various observations in terms of a minimum and a maximum elevation angle of the Sun relative to the horizon at the area to be observed. The majority of the observational requirements can be grouped into four solar elevation angle ranges: 20°-40°; 30°-60°; 30°-90°; and 60°-75°.

The swath width[1] requirements for the observations indicate that the majority of these requirements were in three classes; 50, 100, and 200 km. Most of the observations required a 20-percent side overlap.

Most of the observations required repeating after 1 day; 1 week; 1 month; 2 months; or 3 months.

Orbit Selection Considerations

The selection of the orbit for an Earth resources satellite is governed by the amount of coverage desired within the various constraints. For this analysis, only circular Earth orbits will be

[1] Swath width is defined as the width of the area within the sensor's field of view directly downward and measured perpendicular to the orbit trace.

considered. Coverage is assumed to be contiguous in space and time. Contiguous coverage is obtained by an apparent drift of the orbit traces from one day to the next providing the required overlap in the imaging swaths and "filling in" the spaces between adjacent orbit traces. This apparent daily drift is obtained by choosing an orbit period nearly synchronous with the Earth's rotation; thus, the orbit can be characterized by the nearly integer number of orbits occurring per day.[2] The analysis of so-called integer orbits is contained in the appendix of this report. The plane of integer orbits will, in general, drift relative to the Sun. This drift is the sum of two inertial motions, the motion or regression of the orbit plane due to the Earth's oblateness, and the motion of the Earth about the Sun. So-called Sun-synchronous orbits exist when these two motions exactly balance.

The altitudes of integer circular orbits are shown in figure 1 as a function of orbit inclination for several integer orbits per day. The range of inclinations shown is only for those orbits over all of the continental United States. The particular orbit-altitude/inclination combinations for Sun-synchronous orbits are shown by the dash-dot line. The apparent solar drift rates measured with the Sun at equinox (i.e., its declination is zero) and relative to the node of the orbit for integer orbits are shown in figure 2. Positive drift rates are defined as apparent counterclockwise motion of the Sun relative to the orbit plane as viewed from above the North Pole.

Since the area to be observed from these orbits is not at the node but is centered at approximately 40° north latitude, the apparent solar drift rate is also a function of the solar elevation angle. The seasonal motion of the subsolar point from south to north and back again introduces an additional effect shown in figure 3. The apparent solar drift rate is shown as a function of the solar elevation angle at a latitude of 40° north for 15 orbits per day and for various orbit inclinations. The dashed and solid lines indicate the slight differences due to orbit inclination between morning and afternoon lighting conditions. The effect of the seasonal position of the subsolar point is shown for an orbit inclination of 50°. The apparent drift rate of solar elevation angle at the location being observed from orbit is very important in determining the amount of time available for achieving the observation objectives within stated solar elevation angle constraints. For example, a 50° inclined orbit has an average apparent solar drift rate of approximately 4°/day for solar elevation angles between 20° and 40° and for the Sun at equinox. It will thus provide solar elevation angles in this range for approximately 5 days. Orbits that are more nearly polar provide lower drift rates and hence, longer available times within stated solar elevation constraints, but less flexibility for varying solar elevation angles. Thus, the choice of an appropriate orbit for an Earth resources satellite is a compromise based on the number of experiments with different observational constraints to be carried on a single satellite, the number of days available and the number of days required to accomplish a given observation, and the repetition frequency desired and available to repeat an observation.

While the number of days available within certain solar elevation angle constraints is determined by the solar drift rate, the number of days required to complete the coverage is determined by the daily orbital drift of the orbit traces over the Earth's surface. The desired orbital drift is, in turn, determined by the swath width and overlap requirements of the observation, the size and latitude of the area to be observed, and the inclination of the orbit plane. Since in most

[2]The use of the word "day" here is not quite accurate. It refers to the period of time required for an orbit trace to return to a given position on the surface of the Earth. The effects of oblateness on the orbital plane make this time period somewhat different from a sidereal day.

cases the area to be observed exceeded 2000 km in width and since the distance between two adjacent orbit traces is of the same order, it is apparent that complete coverage between adjacent orbit traces is required. This coverage is obtained by drifting the orbit trace on subsequent days to fill in the area between adjacent traces. For example, if orbit number 1 passes over the eastern edge of the area to be observed and orbit number 2 passes over the western edge and there are nearly 15 orbits per day, then the selection of the appropriate orbital period will cause orbit 16 to pass slightly to the west of orbit trace 1. On subsequent days, orbits 31, 46, 61, etc., pass farther and farther west until orbit trace number 2 is essentially repeated. The appropriate distance between orbit traces 1, 16, 31, 46, 61, etc., measured normal to the orbit trace at the latitude of the observation should be made equal to the swath width requirement of the observation less the amount of overlap required. It should be noted that if coverage is complete between adjacent orbit traces for a given latitude range, then it is also complete in that latitude range worldwide, and all the coverage is obtained at nearly the same solar elevation angle if the coverage is completed in a reasonably short period of time. That period of time is determined by the solar elevation angle range that is acceptable and by the solar drift rate of the orbit.

It is apparent that the amount of drift required to fill the area between two adjacent orbit traces depends strongly on the latitude of the area to be observed. Obviously, the distance between orbit traces, measured normal to the orbit trace at a given latitude, shrinks drastically as the latitude becomes equal to the inclination of the orbital plane. Thus, the number of days required to complete the coverage at a given latitude depends strongly on the swath width and overlap requirements and the inclination of the orbital plane. This dependency is illustrated in figures 4(a) to 4(d), where the number of days required to complete coverage at various latitudes across the United States is shown for integer orbits of 15 per day and with various orbit inclinations as a function of orbital drift per day relative to the Earth's surface. The orbital drift is measured normal to the orbital plane at the indicated latitude. The swath widths (with a 20-percent overlap) corresponding to various orbital drift rates are indicated by the auxiliary scale at the bottom of each figure.

It is, of course, apparent that if an observation is to be repeated, the period of the repetition cycle cannot be less than the period of time required to complete the coverage. Thus, for example, short repetition requirements as indicated by the dashed horizontal lines in figure 4(a) indicate by their intersections with the solid coverage time lines the minimum swath widths that will meet that repetition requirement. As can be seen from the figure for this particular example, weekly repetition requirements for areas of the order of 2000 km in width are compatible with swath widths greater than 200 to 400 km. Daily repetitions of areas of the order of 2000 km in width are achievable only with swath widths larger than 1000 km. Observational constraint incompatibility is indicated by the vertical dash-dot lines in the same figure which indicate the desired swath width or drift rate requirement classes. It is apparent that daily or even weekly repetitions of observations over large areas (like the midwestern states for crop inventories) with instrument/resolution factors that dictate 50 or 100 km swath widths are not possible for any of the latitudes considered. However, monthly repetition does seem possible with the same constraints.

Having determined the amount of time required to achieve a given observation within swath width and overlap requirements and the minimum repetition cycle for those same constraints, it is necessary to examine in detail the period of time available for observations within certain solar elevation angle constraints and the available repetition cycles of those solar elevation angle ranges. A typical solar elevation angle cycle for observations of the region near 40° north latitude is shown in figure 5. For this example, the orbit inclination is 50° and the results are for 15 orbits per day. For simplicity, the Sun is assumed at equinox (i.e., its declination is zero) and time is measured from the time of solar zenith at the ascending node. Curves are shown for both the south-to-north pass and the north-to-south pass over 40° north latitude.

As an example of the time available for coverage within certain solar elevation angle constraints, the shaded regions on each curve indicate the times when the solar elevation angle is between 20° and 40°. Four 5-day periods exist within the 2-month period before the cycle repeats. Repetitions of these periods occur at 2-week intervals during the 2-month cycle except for the third interval. It is interesting that for these solar constraints and for this orbit, it is possible to observe an area at 40° north latitude during the second repetition in the cycle under both morning lighting and afternoon lighting angles during the same day.

Seasonal effects on solar elevation angle cycle were neglected in figure 5 by assuming that the declination of the Sun during the two months shown on the figure remained at zero. A seasonal change in the declination of the subsolar point results effectively in an amplitude modulation on the cycle shown in figure 5. The peak amplitudes of the solar elevation angle cycle change from 26.5° during the winter solstice to 73.5° during the summer solstice. This modulation history is shown in figures 6(a)–6(f) where the solar elevation angle at 40° north latitude is shown as a function of time during the year for orbit inclinations from 50° to 130°. A starting condition was assumed for each of the figures by placing the orbit ascending node at the subsolar point at the spring equinox. The solar elevation "peaks" can be shifted in time by the appropriate positioning of the ascending node at the starting condition. Figures 6 contain all the information on the time available within stated solar elevation angle constraints and the repetition of those conditions later in time. These figures show the compromise that must be made between the time available within stated solar constraints and the repetition of those conditions. Orbits of moderate inclinations, both posigrade and retrograde, regress rapidly and, therefore, do not present desirable solar lighting conditions for very long periods of time. On the other hand, the repetition of those conditions is relatively frequent.

Particular attention should be called to the solar elevation angle histories for various Sun-synchronous orbits in figure 6(d). All the results are for 15 orbits per day and for three practical values of the right ascension of the ascending node of the orbit. This figure illustrates that a Sun-synchronous orbit does not present constant solar elevation angles the year around at a given latitude but exhibits rather substantial seasonal effects.

The effect of the latitude of the area to be observed on the solar elevation angle history is shown in figure 7 for Sun-synchronous orbits with 15 orbits per day and for three practical values of the right ascension of the ascending node of the orbit. Results are presented in figures 7(a) and 7(b) for observations of the southern United States and of Alaska, respectively. It is, of course, evident that observations at high solar elevation angles of areas like Alaska are not possible. For the solar elevation angle constraints considered here, it is apparent that only observations with lower solar elevation constraints of 20° or 30° can be achieved and then only in summer. It is apparent that observations at 60°–75° can only be made over the southern United States near the summer solstice. Furthermore, if observations in the solar elevation region of 20°–40° are desired from the same orbiter, they can only be made near the winter solstice. If the ascending node is chosen such that observations between 20° and 40° solar elevation angle are achievable during the summer (i.e., right ascension near 60°), then observations at higher solar elevation angles are not possible from this orbit.

The maximum time available for observation between various solar elevation angle constraints at various times of the year is illustrated in figures 8 for orbits that are not Sun synchronous. The curves indicate the maximum time available for observations of the central United States for various solar elevation angle constraints. This time period has been centered about a given time after the spring equinox, assuming that the ascending node of the orbit was appropriately positioned. A given orbit will not, of course, provide this amount of time continuously throughout the year but will provide periods of this length repetitiously. The period of repetition is shown in figures 6(a) through 6(f). The discontinuities apparent for the 20°–40° and the 30°–60° solar elevation angle constraints result when the maximum amplitude of the solar elevation angle becomes less than the upper constraint (see figs. 6). When this occurs, contiguous coverage is then possible for a period approximately twice as long. It is apparent that, as was noted before, coverage in the solar elevation angle range of 60°–75° (the small dashed line) is only possible during summer and coverage in the 30°–60° or 30°–90° range (the dashed line and the dash-dot line, respectively) is not possible for approximately one month either side of the winter solstice. Coverage in the 20°–40° solar elevation angle range is possible the year around and appears least constrained during the period near the winter soltice.

CONCLUSIONS

The following general conclusions are apparent from the parametric results presented in this report for low Earth orbits:

1. Daily repetitive and contiguous coverage of areas wider than 2000 km is not possible with swath widths less than about 1000 km.

2. To complete coverage of areas within the United States greater than 2000 km in width in less than 1 week with near polar orbits requires swath widths of at least 400 km.

3. The time required to cover areas indicated above with near polar orbits and a maximum swath width of 200 km (the maximum given by Stratton in AAS paper 69-587) is approximately 2 weeks. Higher resolution coverage in a contiguous manner will require as long as one month.

4. Moderate inclination orbits both posigrade and retrograde (inclinations just slightly higher than the latitude of the area to be observed) can be used to reduce the time to cover at a given swath width or reduce the swath width at a given time to cover by a factor of approximately 2.

5. Seasonal effects on the time available for coverage within stated solar angle constraints are profound for all orbit inclinations. High solar elevation angle observations are not feasible in the United States, including Alaska, during the winter solstice.

6. Moderate inclination orbits provide relatively short periods of time for coverage within stated solar angle constraints but such conditions occur repetitively within short periods of time. Near polar orbits provide long periods of time within stated solar angle constraints but the repetition of such observations is infrequent.

The major observational incompatibility noted from the orbital analysis is due primarily to a requirement for small swath widths (50 or 100 km) and large areas to be observed, resulting in long periods of time to complete coverage. A suitable compromise may be either to increase the swath width (i.e., primarily reducing resolution) or to sample the area rather than cover it.

National Aeronautics and Space Administration
Moffett Field, Calif., 94035, June 8, 1970

APPENDIX

ORBITAL CHARACTERISTIC OF INTEGER ORBITS

The class of orbits referred to in this report as "integer orbits" are circular Earth orbits that have a repeating ground trace each day. The term "day" refers to the period of time required for an orbit trace to return to a given position on the surface of the Earth. The effects of oblateness on the orbit plane make this time period somewhat different from a sidereal day. The altitude of such a circular orbit can be determined by equating the time for N (integer) revolutions of the orbiter in the orbital plane and the time for given point on the surface of the Earth to return to a position coplanar with the orbital plane. Figure 9 illustrates the inertial motion of an inclined orbital plane from the first orbit to the Nth orbit. Oblateness causes the orbit to regress each orbit by an amount $\Delta\Omega$ measured at the ascending node. This nodal regression is given (see ref. 2) by

$$\Delta\Omega = -3\pi J_2 \left(\frac{R}{a}\right)^2 \cos i \qquad (1)$$

where $J_2 = 0.001082$, and R is the radius of Earth. Here a is the radius of the orbit and is given by

$$a = R + h$$

where h is the altitude of the orbit. Equating the times of rotation as indicated before yields

$$N\tau = \frac{86164.1}{2\pi} (2\pi - N\Delta\Omega) \qquad (2)$$

where τ is the period of the orbit and is given by

$$\tau = \frac{\tau_O}{1 + (3/2)J_2(R/a)^2[1 - (3/2)\sin^2 i]} \qquad (3)$$

where

$$\tau_O = 2\pi \sqrt{a^3/\mu} \qquad (4)$$

and μ is the gravitational potential. Substituting equations (1), (3), and (4) into equation (2) and solving for the highest power term of the orbit radius yields

$$a^{7/2} = \frac{86164.1\sqrt{\mu}}{2\pi N} \left(a^2 - \frac{3}{2} J_2 R^2 \cos i\, N\right) + \frac{3}{2} J_2 R^2 \left(1 - \frac{3}{2} \sin^2 i\right) a^{3/2} \qquad (5)$$

Equation (5) can now be solved in an iterative fashion. Since oblateness effects are small, an excellent starting solution for a to be used in the right hand side of equation (5) in the first iteration is the zero oblateness solution, or from equation (5) with $J_2 = 0$,

$$a = \left(\frac{86164.1 \sqrt{\mu}}{2\pi N}\right)^{2/3}$$

It was found that accuracies in the orbital radius of 0.01 percent are obtained from the iterative procedure in less than 10 iterations.

REFERENCES

1. Stratton, Alan J.: Earth Resources Satellites: Capabilities Versus Requirements. Paper AAS 69-587, Oct. 1969.

2. Roy, Archie E.: The Foundations of Astrodynamics. The Macmillan Company, 1965, pp. 217-225.

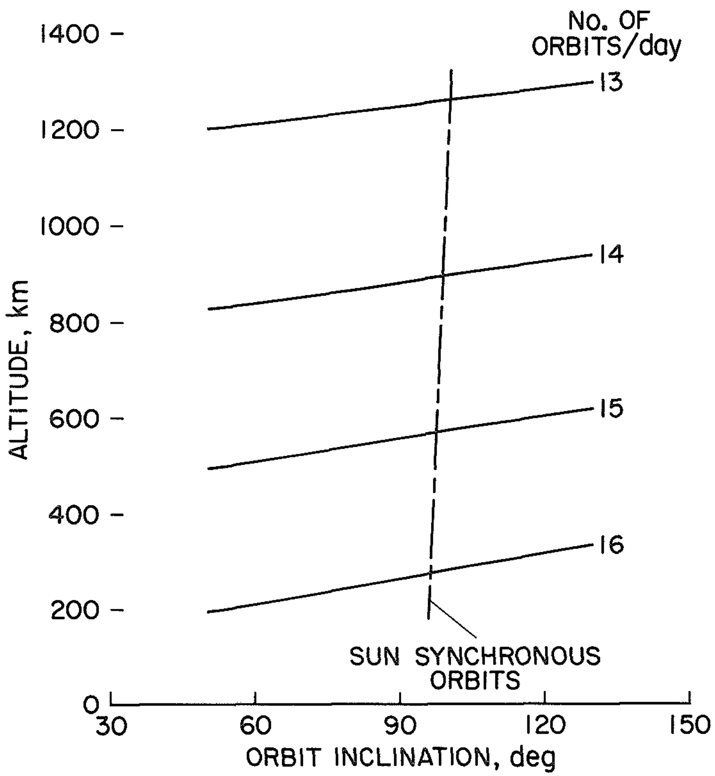


Figure 1.- Orbit altitudes for integer orbits.

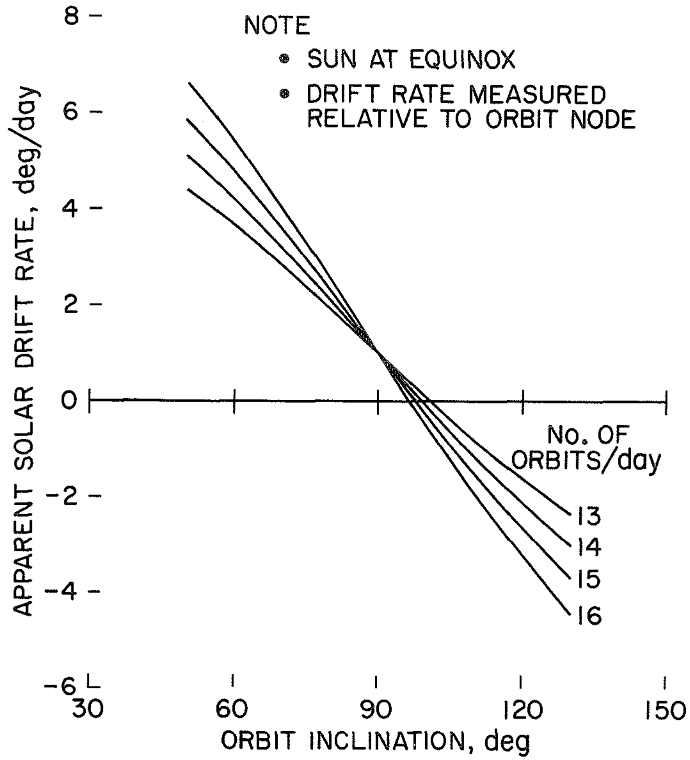


Figure 2.- Solar drift rates for integer orbits.

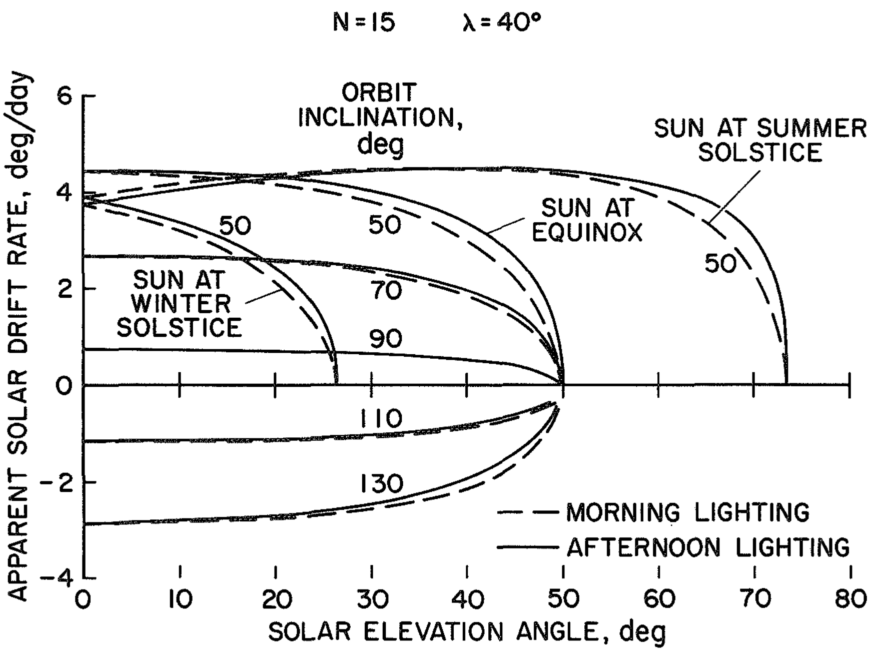
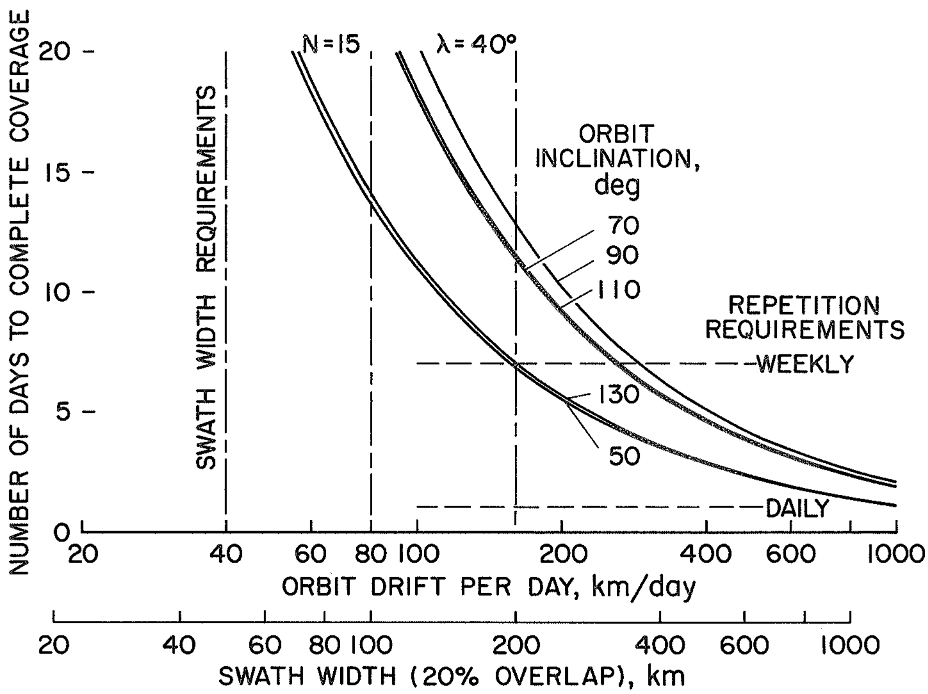
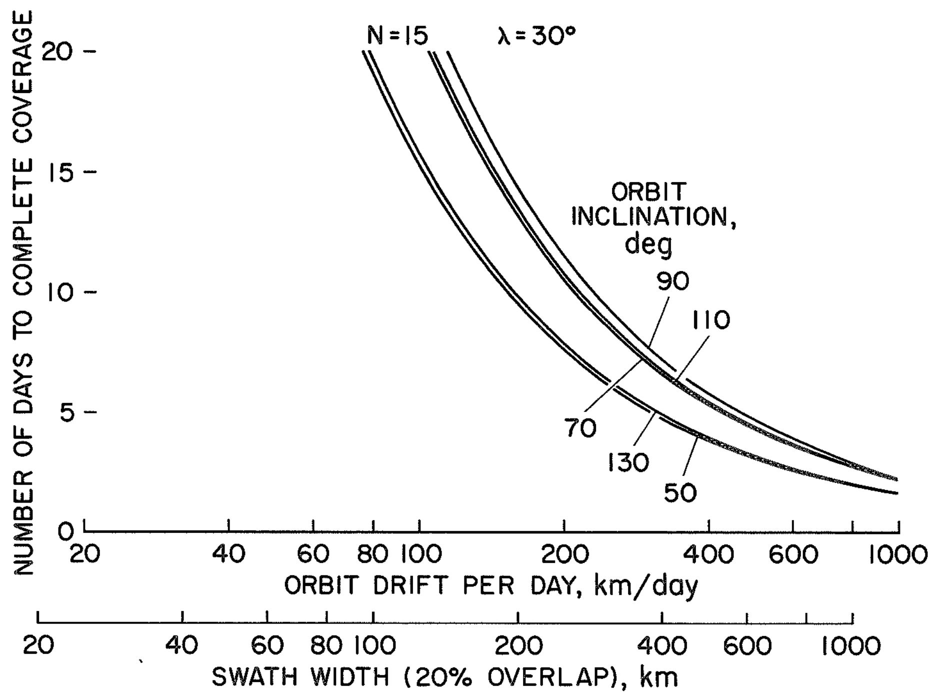


Figure 3.- Typical solar drift rates for U. S. centered observations.

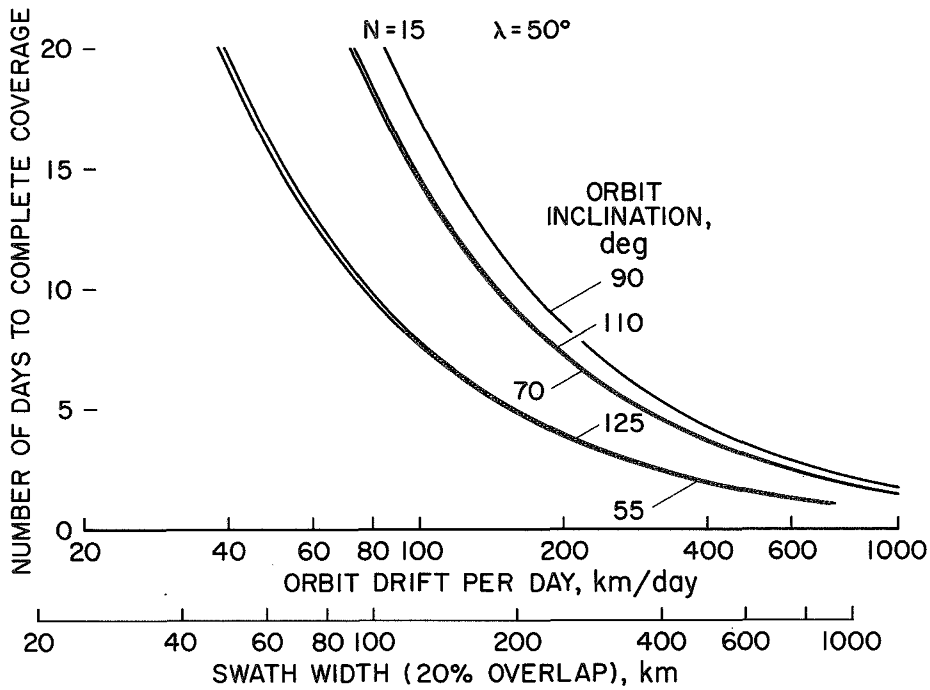


(a) Central United States.

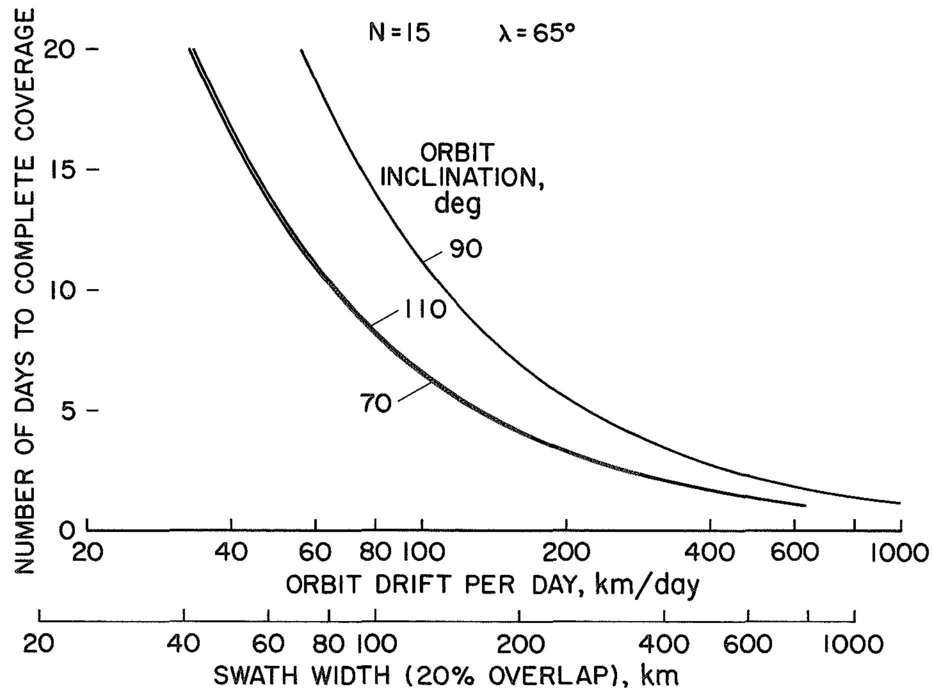


(b) Southern Unites States.

Figure 4.- Coverage time period requirements.



(c) Northern United States.



(d) Alaska.

Figure 4.- Concluded.

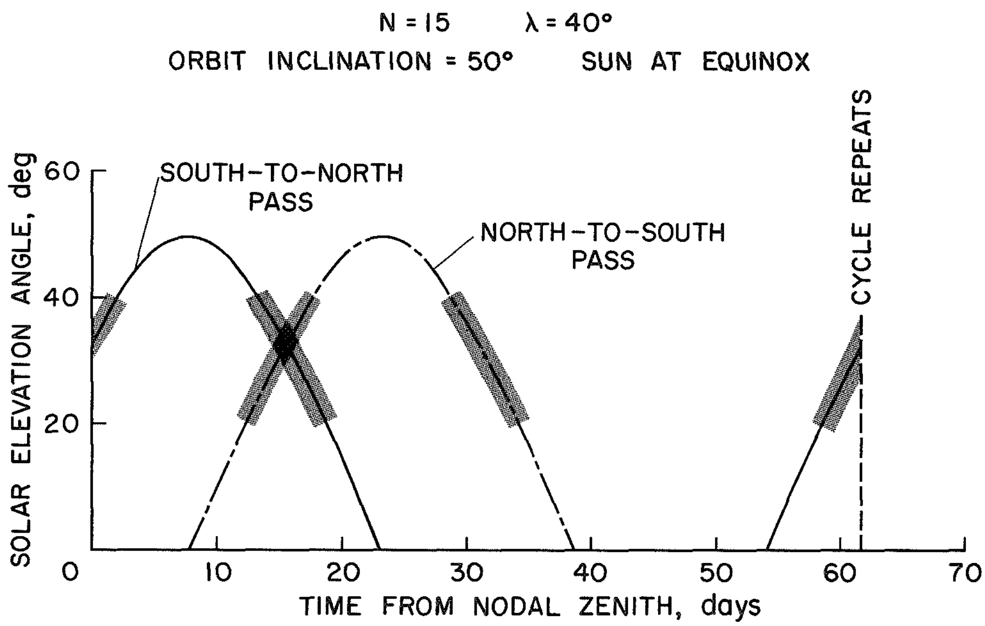
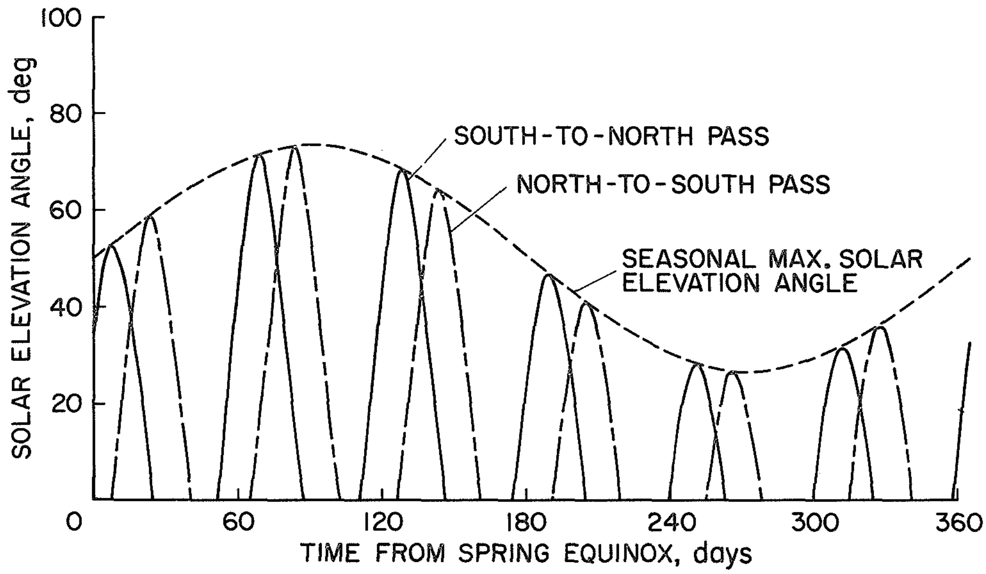
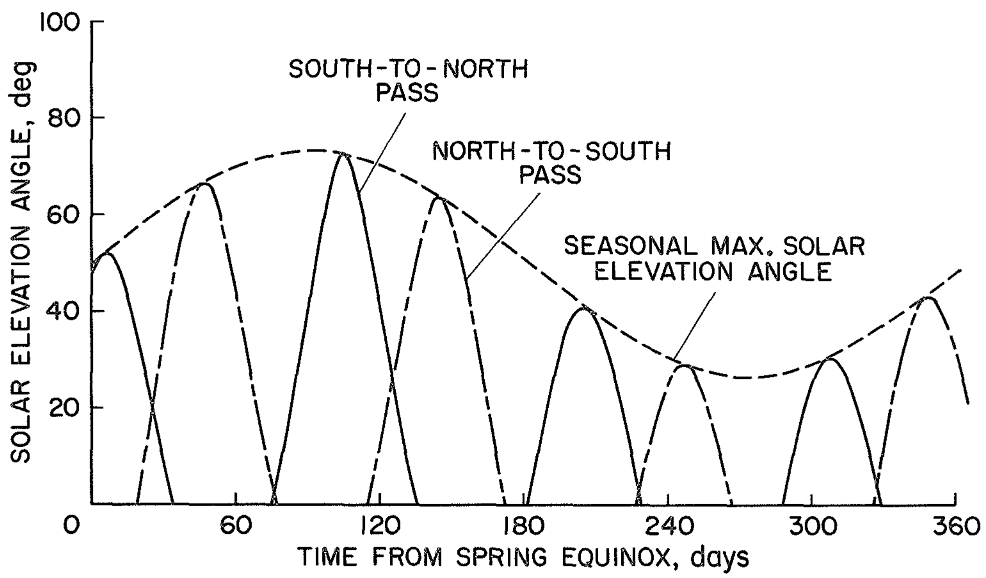


Figure 5.- Typical solar elevation angle cycle.

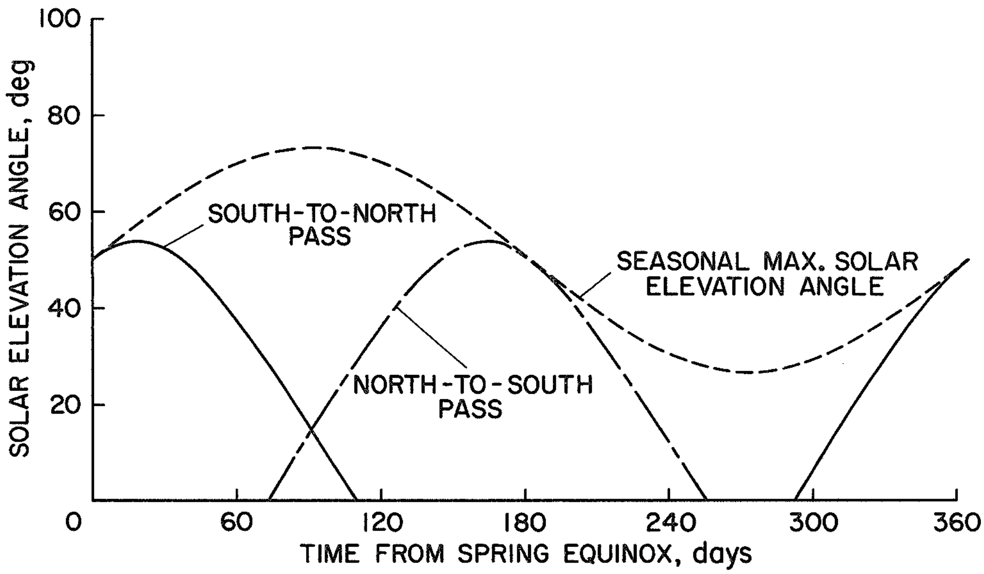


(a) N = 15; viewed latitude = 40°, orbit inclination = 50°.

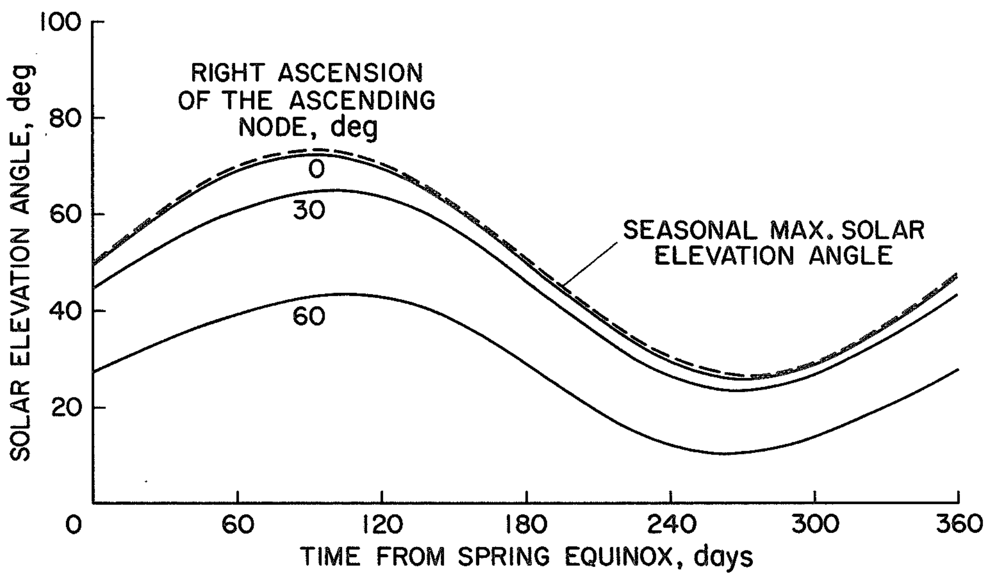


(b) N = 15; viewed latitude = 40°, orbit inclination = 70°.

Figure 6.- Solar elevation angle histories.

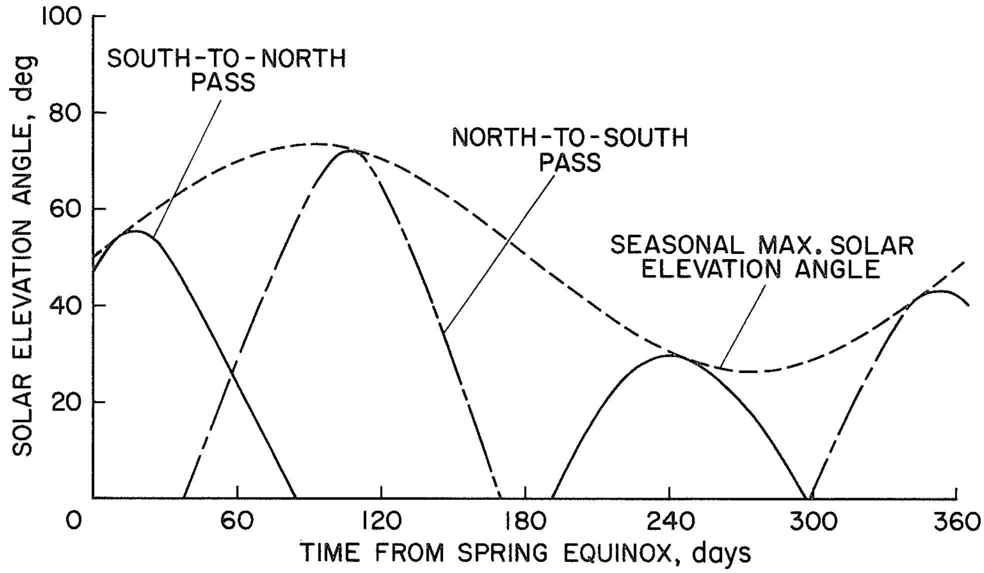


(c) N = 15; viewed latitude = 40°, orbit inclination = 90°.

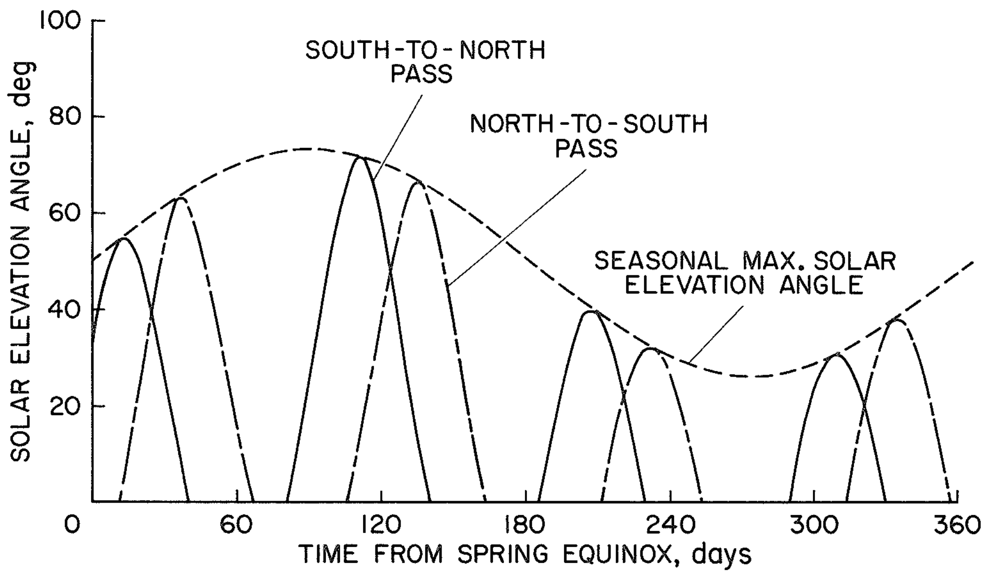


(d) N = 15; viewed latitude = 40°, orbit inclination = 97.6°, south-to-north pass.

Figure 6.- Continued.

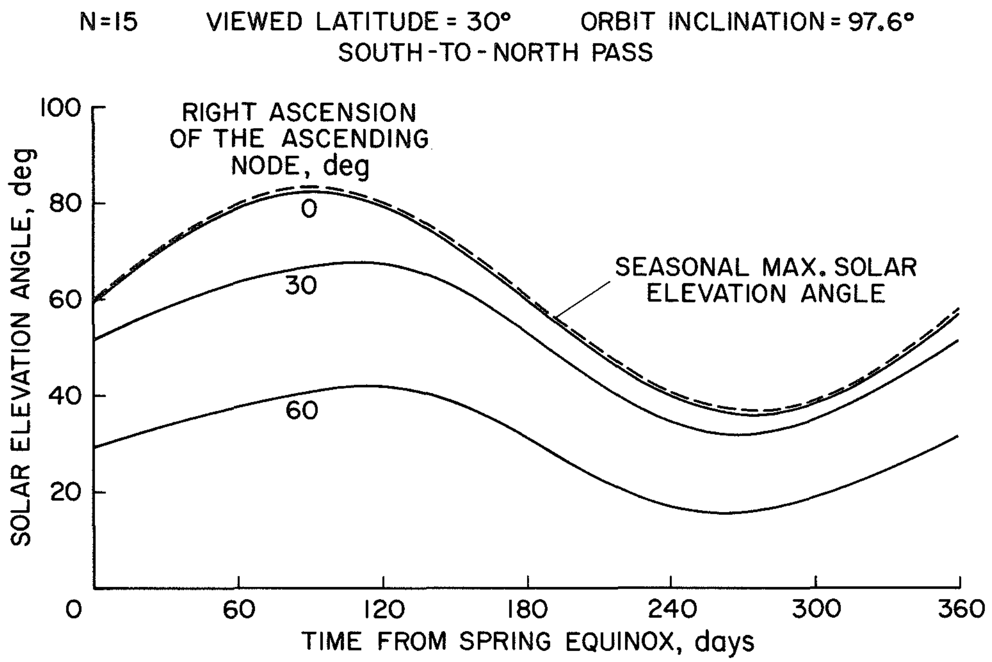


(e) N = 15; viewed latitude = 40°, orbit inclination = 110°.

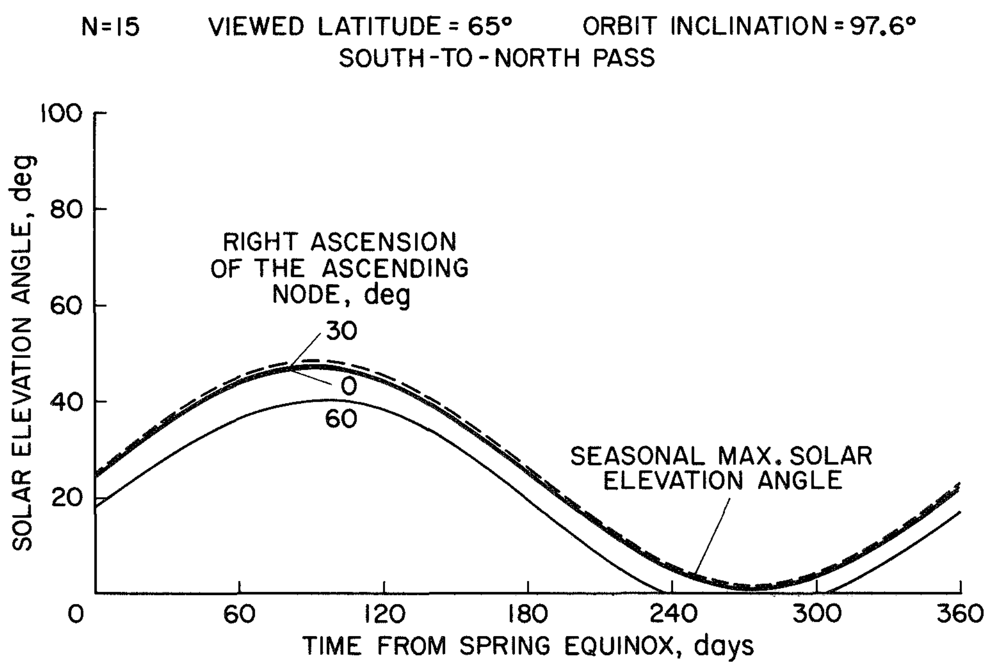


(f) N = 15; viewed latitude = 40°, orbit inclination = 130°.

Figure 6.- Concluded.

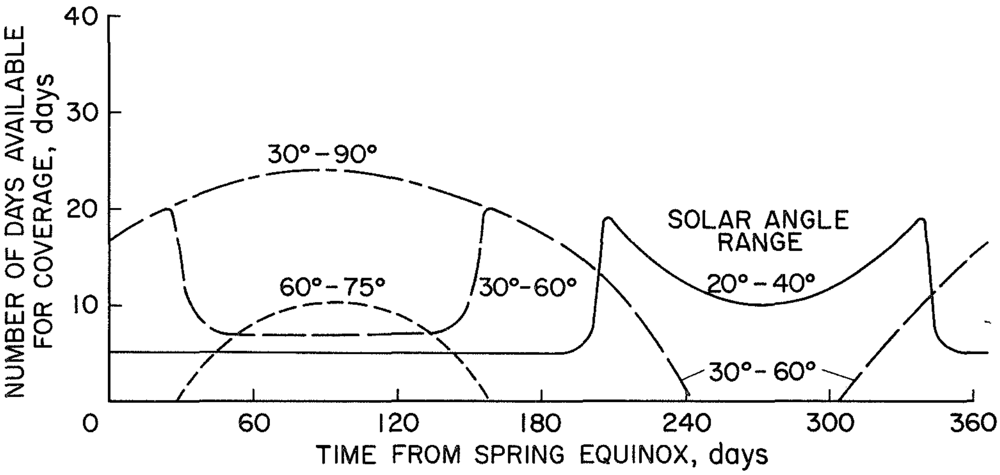


(a) Southern United States viewing.

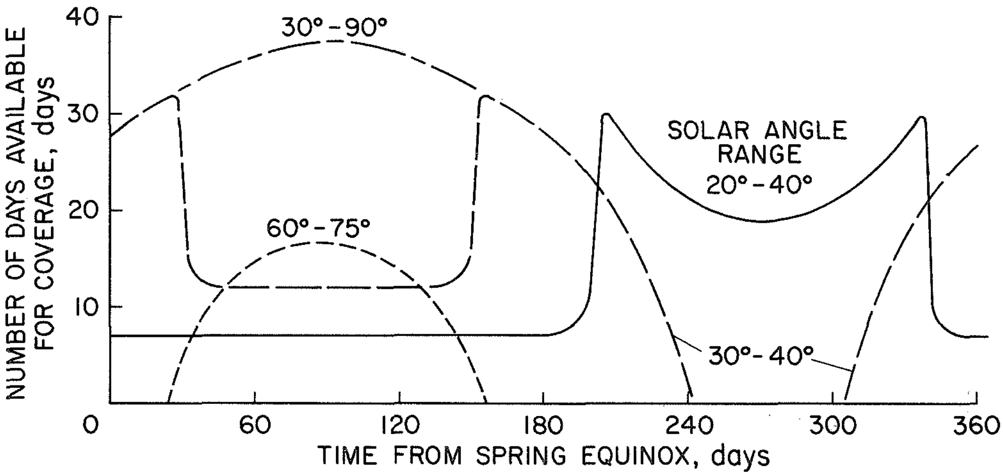


(b) Alaska viewing.

Figure 7.- Solar elevation angle history for Sun-synchronous orbits.

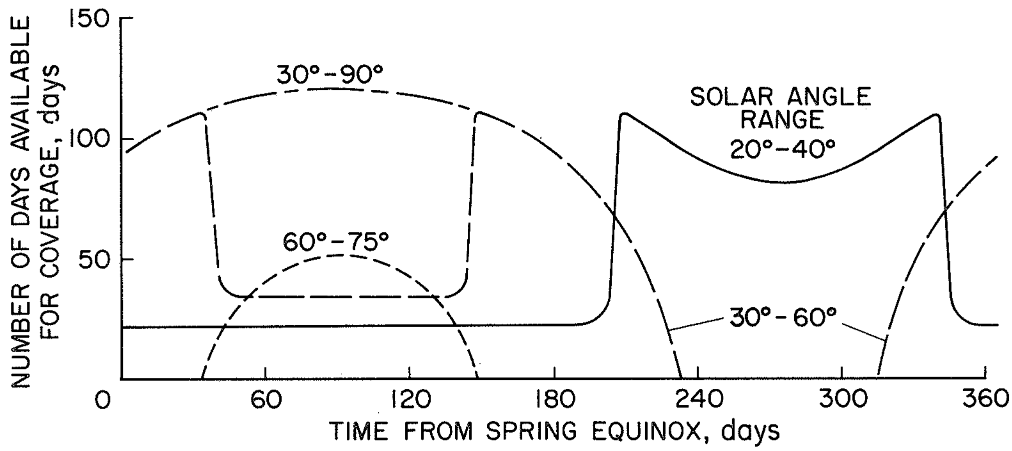


(a) N = 15; viewed latitude = 40°, orbit inclination = 50°.

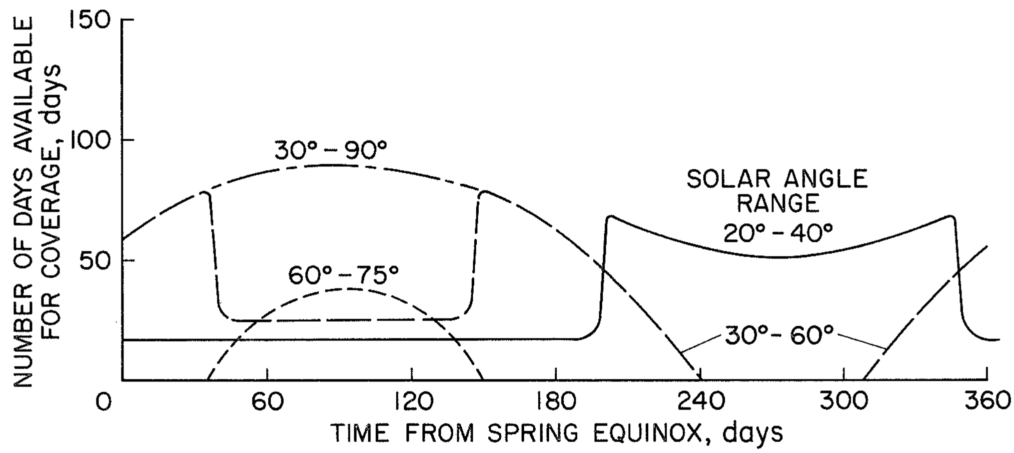


(b) N = 15; viewed latitude = 40°, orbit inclination = 70°.

Figure 8.- Seasonal effects on coverage availability.

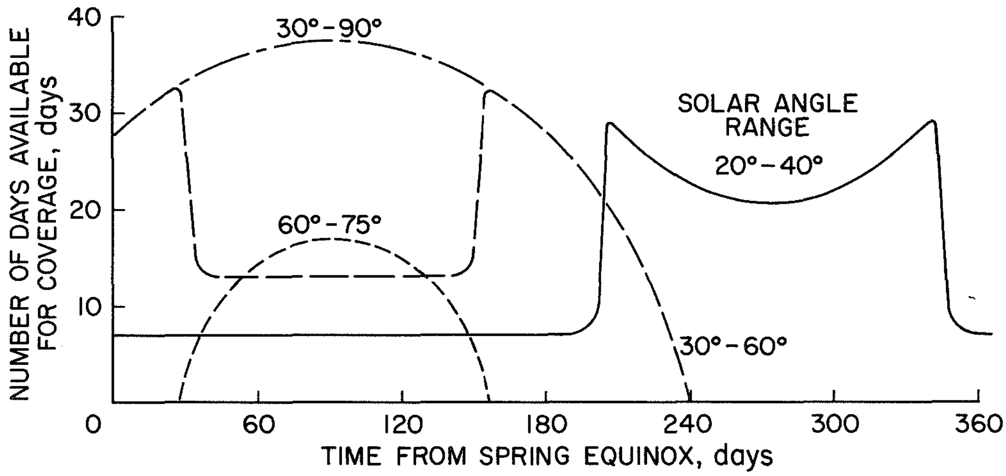


(c) N = 15; viewed latitude = 40°, orbit inclination = 90°.



(d) N = 15; viewed latitude = 40°, orbit inclination = 110°.

Figure 8.- Continued.



(e) N = 15; viewed latitude = 40°, orbit inclination = 130°.

Figure 8.- Concluded.

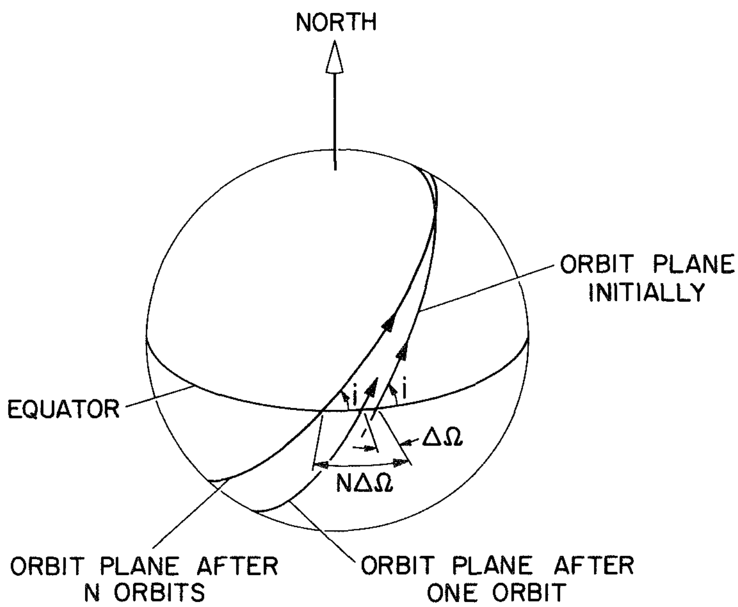


Figure 9.- Orbit plane geometry.

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15. Supplementary Notes

16. Abstract

The application of Earth satellites to the examination of the static and dynamic nature of the Earth's surface involves a compromise between observational requirements of the user and the realities of orbital mechanics. This paper examines the orbital mechanics problem to determine, in general, if various observational requirements (solar elevation angle, sensor and resolution requirements, observational repetition frequency, and the seasonal time and location of the observation) can be satisfied and, in particular, whether a number of different types of observations can be made from a single satellite. Parametric material is presented for determining the extent to which the observational constraints must be relaxed either to perform a single observation or to make several observations compatible. In general, it was determined that high resolution coverage of broad surface areas (i.e., areas of the order of 2000 km and greater in width) was possible within solar angle constraints but that the rapid repetition of such observations (e.g., within less than a month) was not possible with a single satellite. If rapid repetition of observations is required, either low resolution observations must be made, or much smaller surface areas must be considered, or multiple satellites must be used.

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