Over-all heat-transfer tests on a tightly coiled, coaxial-tube boiler indicated approximately 20% greater heat-transfer coefficients, but with an increase in over-all pressure drop of 50%. Reynolds' analogy[4] indicates that the film coefficient should vary directly with pressure drop for equal mass velocities, and it may be assumed that the variance shown in the tests was caused by the reduction of flow area when the tubes were wound into the tight coil.

Conclusions

The experimental data obtained from the tests on the straight coaxial-tube boiler indicate that the conventional heat-transfer relationship for forced convection can be used for steam at temperatures up to 1600°F and 1500 psia and for propellant hot gas up to 2000°F at mass velocities as high as 1.5×10^6 lb/hr-ft^2 and temperature differences up to 800°F.

Stable conditions were obtained for forced convection boiling between mass velocities of 0.5 and 1.5×10^6 lb/hr-ft^2, and no instability was noted at any time in tests using hot gas from the solid propellant as the heat source.

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Dependence of Ground Station Acquisition Effectiveness on Geographic Location and Satellite Orbit

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The "effectiveness" of any geographical location as a ground site for satellite data acquisition depends significantly upon 1) length of time available for acquisition during each pass and 2) elevation angles to the satellite during acquisition. Together, these two criteria determine the percentages of passes from which data may be acquired. The geometric relationships are examined analytically to determine the dependence of station "effectiveness" on satellite altitude and orbital inclination. In general, both elevation angles and acquisition times are larger (and site effectiveness therefore greater) for polar orbits (inclination = 90°) than for sun-synchronous orbits (where the inclination departs from 90° with increasing altitude). For a sun-synchronous orbit, a single station at temperate or subpolar latitudes below 69° can never acquire data from every daily pass, regardless of satellite altitude. For any station, the percentage of passes acquirable from a sun-synchronous orbit is maximum when the satellite is near 1200-naut-mile alt. For a polar orbit, a station at 65° latitude (viz., Fairbanks, Alaska) can acquire data from every pass at all altitudes above 550 naut miles. For any station, the percentage acquisition, average elevation angle, and length of acquisition time increase with increasing altitude.

Effective Acquisition Range

A COMMAND and data acquisition (CDA) station can successfully interrogate a satellite only while the satellite is within radio range for a period of time long enough to acquire data. The satellite rises above the station's effective radio horizon during only a small portion of any one orbital pass, and in general there may be one or more passes each day on which the satellite fails to appear above the station's horizon at all. The effectiveness of any geographic location as a CDA station site depends in part on the percentage of each day's passes on which the satellite comes within acquisition range for an adequate length of time.

The effective acquisition range (EAR) is defined as the distance on the earth's surface from a CDA station within which the subsatellite track must pass if the satellite is to remain for a length of time t or longer above an elevation angle e from the station. The EAR is a function of the e, minimum elevation angle for data acquisition at the station; t, the time period that satellite must remain above e for adequate data acquisition; and h, the satellite's orbital altitude above the earth's surface. The EAR is geometrically independent of the station's geographic location, although local terrain features and radio transmission conditions may affect e. It is conveniently measured in degrees of geocentric arc. Figure 1 shows the EAR for two special cases of $t = 0$: $\mathrm{EAR}_{0,0}$ is the "grazing" EAR for $e = 0$, and $\mathrm{EAR}_{e,0}$ is the "grazing" EAR for elevation angle e. For a spherical earth of radius R, and a circular orbit,

$$\mathrm{EAR}_{0,0} = \cos^{-1}[R/(R+h)] \tag{1}$$

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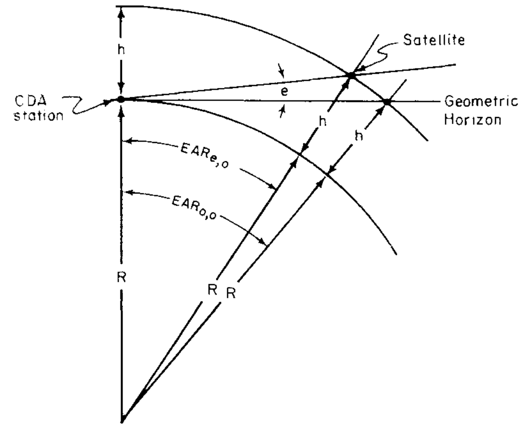


Fig. 1 Diagram of $EAR_{0,0}$ and $EAR_{e,0}$.

$$EAR_{e,0} = 90° - e - \sin^{-1}[R/(R+h)\cos e] \qquad (2)$$

Figure 2 shows how the EAR is reduced for nonzero values of t through the relation

$$EAR_{e,t} = \cos^{-1}[\cos EAR_{e,0}/\cos(D/2)] \qquad (3)$$

The distance D is the geocentric arc traveled by the satellite subpoint in time t and is defined by

$$D = 360t/T \qquad (4)$$

where T, the satellite's orbital period, is given by

$$T = 84.4[1 + (h/R)]^{3/2} \text{ min} \qquad (5)$$

Figure 3 shows plots of $EAR_{e,t}$ vs h for several values of e and t. h_{min} is the satellite altitude at which the distance traveled in time t equals twice the $EAR_{e,0}$. At this limiting satellite altitude, the station can acquire data for a time interval t only if the satellite passes through the zenith. At lower altitudes, the satellite's orbital velocity is too great for the station to maintain contact (above elevation angle e) for a time interval t.

Table 1 lists values of various parameters for selected satellite altitudes. Table 2 lists values of $EAR_{e,t}$ computed for selected values of e, t, and h.

Orbital Inclination and Sun Synchronism

It is frequently mentioned as desirable for meteorological purposes that satellite coverage be obtained at the same local time each day. To maintain this sun-synchronous operation from week to week, it is necessary that precession of the orbital plane $\dot{\Omega}$ be 360° in 365 days to compensate for the earth's seasonal travel around the sun. Precession is a function of satellite altitude and orbital inclination and is given by the expression

$$\dot{\Omega} = 10.0\, a^{-3.5} \cos i \qquad (6)$$

where i is the orbital inclination and $a = (1 + h/R)$ is the semimajor axis of the orbit expressed in earth radii (3440 naut miles). The desired precession is achieved when the sun-synchronous inclination i_{ss} is such that

$$\cos i_{ss} = 0.0986[1 + (h/R)]^{3.5} \qquad (7)$$

Note that if the standard sign convention is followed, sun-synchronous precession is achieved when $\dot{\Omega}$ has the negative value -0.986 and i_{ss} is greater than 90° (a retrograde orbit). For the purposes of this analysis, however, sun-synchronous $\dot{\Omega}$ is taken to be positive, and the symbols i and i_{ss} for inclination are here defined to be the small angle between the equatorial and orbital planes for a retrograde orbit.

The orbital inclination is also equal to and defines the maximum geocentric latitude (north and south) reached by the satellite subpoint on each orbital pass. The maximum poleward excursion for sun-synchronous inclination is plotted as a function of satellite altitude in the top portion of Fig. 4.

For any station in the northern hemisphere, the EAR added to the station's latitude measures the northernmost limit of the station acquisition range. The one satellite pass each day whose nearest point of approach falls farthest from the station is the one that reaches its maximum latitude directly across the north pole from the station, i.e., at or nearest to the meridian 180° from the station's meridian. This "worst" pass can be acquired only if the station's EAR extends across the pole and down the far side to the latitude equal to the satellite's orbital inclination. If the EAR does not extend this far, then on at least some days the station cannot acquire all passes.

The lower part of Fig. 4 shows a typical EAR curve taken from Fig. 3. This example is plotted for a station at latitude 65°N (Fairbanks, Alaska). The failure of this curve

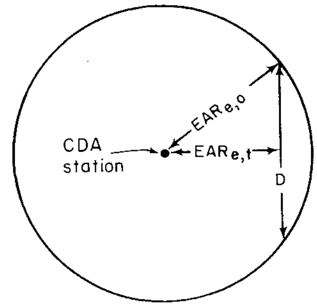


Fig. 2 Diagram of $EAR_{e,t}$. D is the distance traveled by subsatellite point in time t.

Table 1 Orbital parameters for selected satellite altitudes

h, naut miles	T, min	N[a]	D_5[b]	i_{ss}[c]
0	84.4	17.1	21.2	84.2
200	91.9	15.7	19.6	83.0
450	101.5	14.2	17.8	81.1
600	107.4	13.4	16.8	79.9
750	113.5	12.7	16.0	78.6
1000	123.8	11.7	14.6	75.9
1200	132.3	10.9	13.7	73.4
1500	145.3	9.9	12.3	69.3
2000	167.9	8.6	10.9	60.3
2500	191.5	7.5	9.4	48.3
3000	216.0	6.7	8.3	27.5

[a] Orbital frequency, passes per 24 hrs.
[b] Distance traveled in 5 min, degrees of geocentric arc.
[c] Orbital inclination required for precession of 360°/365 days.

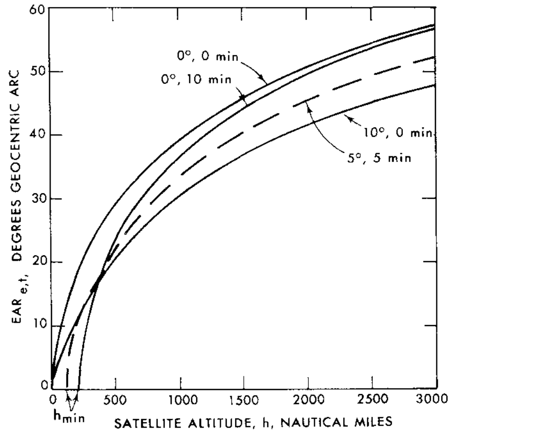


Fig. 3 Variation of $EAR_{e,t}$ with satellite altitude for selected values of e and t.

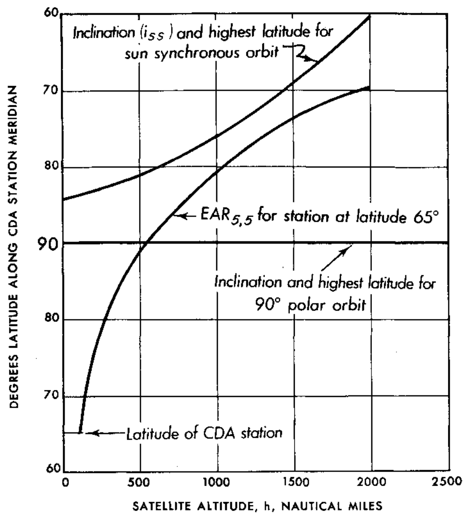


Fig. 4 Variation with altitude of $EAR_{5,5}$ and orbital inclination i_{SS}.

to intersect the i_{ss} curve shows that, under the constraint of a sun-synchronous orbit, there is no satellite altitude at which Fairbanks could acquire data from every pass every day. The spacing between the two curves of Fig. 4 is a qualitative measure of the passes missed, on the average, each day. The percentage of passes missed is least for satellites at altitudes near 1200 naut miles. For other CDA stations, the EAR curve may be displaced vertically, setting the lower left end at the station's latitude. Displacing the EAR curve northward about 5° (equivalent to moving the CDA station to 70°N) would permit acquisition of all passes, but only for orbital altitudes between 1000 and 1700 naut miles. Further northward displacement would permit acquisition of all passes over a wider range of altitudes.

If the constraint of sun-synchronism is removed, a true polar orbit of inclination 90° would be most favorable for permitting stations to acquire data from the greatest percentage of passes. In a polar orbit the satellite subpoint reaches 90° latitude on every pass regardless of the orbital altitude. Figure 4 shows that a CDA station at latitude 65°, under the criteria $e = 5°$, $t = 5$ min, could acquire data from every pass of a polar orbit if the satellite altitude is about 550 naut miles or greater.

Frequency Distribution of Elevation Angle During Data Acquisition

During data acquisition, it is desirable that the elevation angle to the satellite be large to shorten the path length through the ionosphere and through auroral disturbances

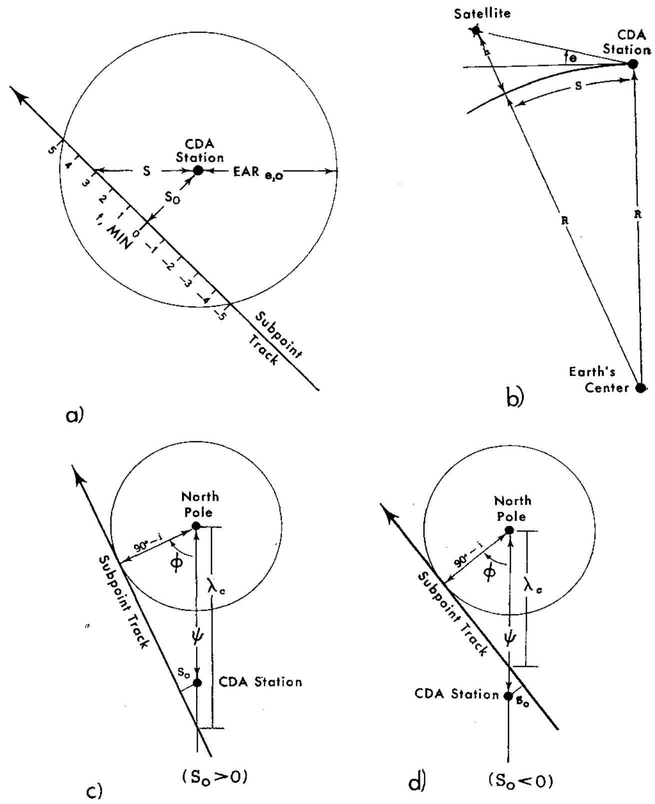


Fig. 5 Diagrams of angular quantities relating to CDA station and satellite subpoint track.

and thus minimize radio interference. The elevation angle changes continuously during satellite passage, and the distribution of angles experienced during one pass is a function of how close the satellite subpoint track approaches the ground station. Referring to Fig. 5a, let S_0, measured in degrees geocentric arc, be the distance of nearest approach of the satellite subpoint to the station during a particular pass, and let the time of nearest approach be designated as $t = 0$. Then, at any time t, the distance S in geocentric arc between the station and the subpoint is

$$\cos S = (\cos S_0) \cos(vt) \tag{8}$$

where v is the velocity of the satellite subpoint in degrees geocentric arc per minute. The small effect of the earth's rotation during the few minutes that the satellite is above the horizon is neglected. Referring to Fig. 5b, the elevation angle e is then given by

$$e = \tan^{-1}\{[h/(R + h)] \operatorname{ctn}[\tfrac{1}{2} \cos^{-1}(\cos S_0 \cos vt)]\} - \tfrac{1}{2} \cos^{-1}(\cos S_0 \cos vt) \tag{9}$$

Table 2 $EAR_{e,t}$ in degrees geocentric arc for selected values of e, t, and h

e:	0°			5°			10°		
t, min:	0	5	10	0	5	10	0	5	10
h, naut miles									
0	0.0	...	...	0.0	...	...	0.0	...	...
200	19.1	16.3	...	14.8	10.9	...	11.4	5.7	...
450	27.7	26.4	21.7	23.1	21.4	15.0	19.3	17.1	7.7
600	31.5	30.3	26.9	26.8	25.3	21.2	22.9	21.1	15.6
750	34.8	33.9	31.2	30.1	29.0	25.8	26.1	24.9	20.8
1000	39.2	38.6	36.8	34.5	33.9	31.7	30.2	29.4	26.7
1200	42.1	41.7	40.2	37.3	36.8	35.1	33.0	32.3	30.3
1500	45.8	45.4	44.4	41.0	40.5	39.5	36.7	36.1	34.8
2000	50.7	50.4	49.8	45.9	45.6	44.9	41.3	41.0	40.1
2500	54.6	54.5	54.1	49.8	49.7	49.2	45.2	44.9	44.4
3000	57.7	57.6	57.3	52.9	52.8	52.5	48.3	48.2	47.8

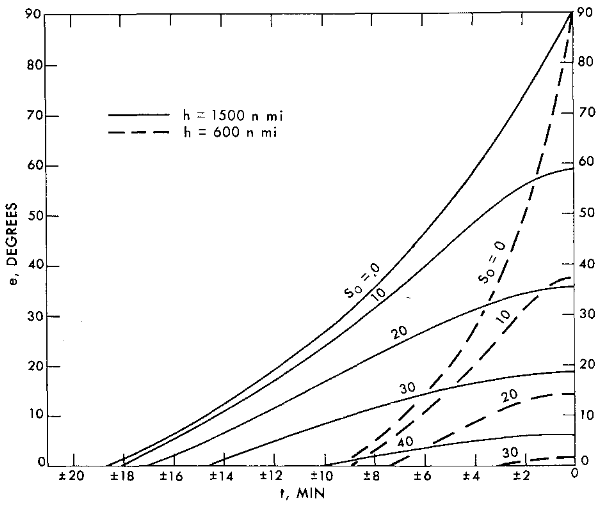


Fig. 6 Elevation angle e as a function of time for two satellite altitudes and for selected values of S_0.

where e and t now denote elevation angle and time as general variables rather than the specified minimum values previously defined. The variation of elevation angle with time during any one pass is graphed in Fig. 6 as a family of curves for various values of S_0. Separate families of curves are shown for satellite altitudes $h = 1500$ and 600 naut miles. At 1500 naut miles, not only are the elevation angles significantly larger than at 600 naut miles for a given S_0, but because of both higher altitude and slower velocity, the total time above the horizon is much longer, and the changes in e during the pass are less rapid.

The frequency distribution of elevation angles occurring during data acquisition at a station over a period of many passes depends on the frequency of occurrence of various values of S_0, and S_0 in turn is a function of station latitude and orbital inclination. Referring to Fig. 5c, let ϕ be the longitude difference between the CDA station meridian and the meridian of the northernmost point on the subpoint track. As mentioned previously, the latitude of this northernmost point equals the orbital inclination. The functional relation between S_0 and ϕ in terms of the station colatitude ψ and orbital inclination i, is

$$\text{for } i < 90^\circ \qquad \sin S_0 = \sin(90 - i)\,\frac{\sin(\lambda_c - \psi)}{\sin\lambda_c} \tag{10}$$

where ψ_c, the colatitude of the point where the subpoint track crosses the station meridian, is given by

$$\tan\psi_c = \tan(90 - i)/\cos\phi \tag{11}$$

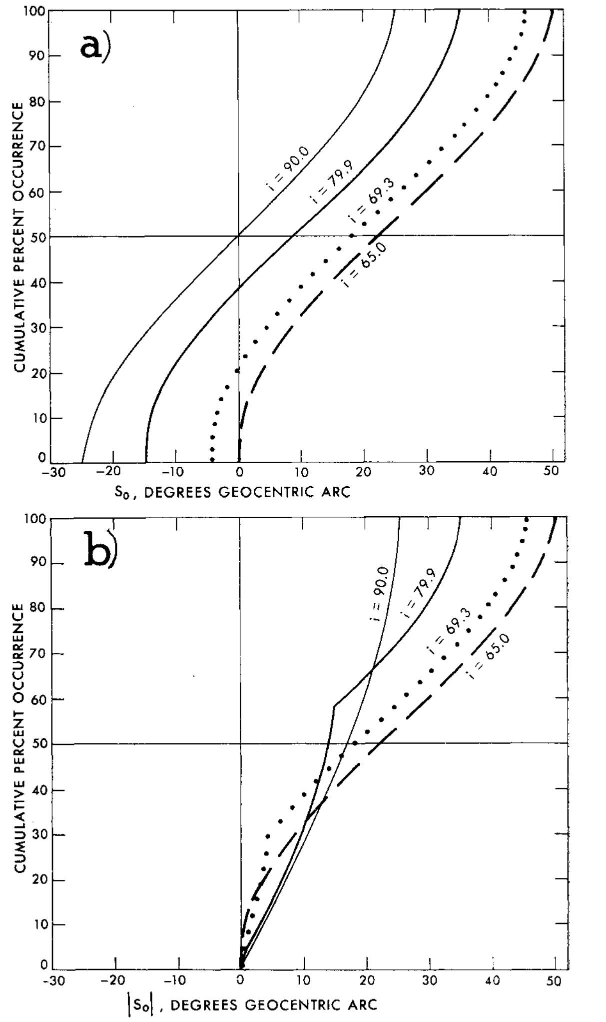


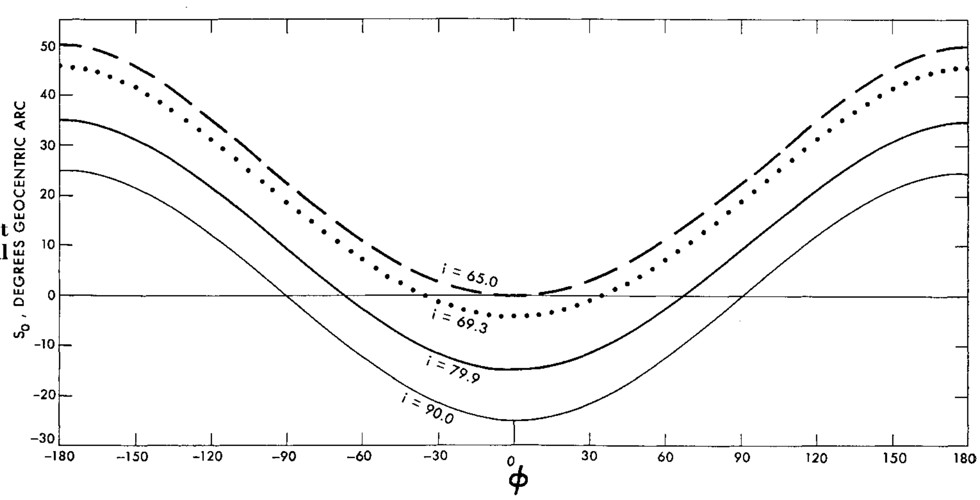
Fig. 8 CPO curves for S_0 and $|S_0|$ for a station at 65° latitude and for four orbital inclinations.

For a polar orbit, let ϕ be the angle at the pole between the station meridian and the perpendicular to the subpoint track. Then

$$\text{for } i = 90^\circ \qquad \sin S_0 = \cos\phi \sin\psi \tag{12}$$

The effect of the earth's rotation between time $t = 0$ and the time that the subpoint reaches latitude i is again neglected. For $i < 90°$, S_0 has positive values when the station and the north (or nearest) pole lie on the same side of the subpoint track (Fig. 5c), and has negative values when the track

Fig. 7 S_0 vs ϕ for a station at 65° latitude and for four orbital inclinations.



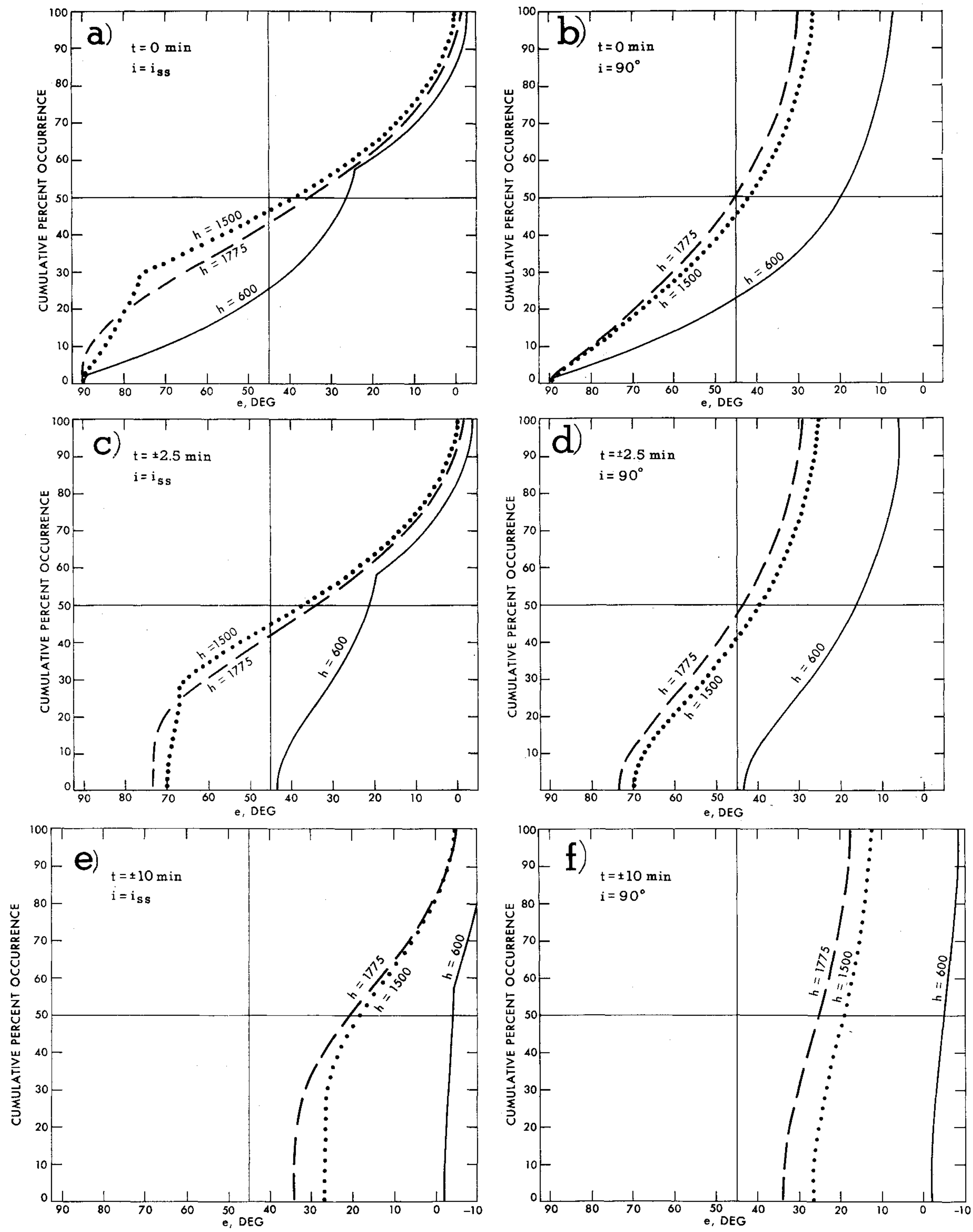


Fig. 9 CPO of elevation angle for a station at 65° latitude for three satellite altitudes. Graphs for sun-synchronous orbits at left (parts a, c, and e) and 90° polar orbits at right (parts b, d, and f) show CPO of elevation angle at three times during pass (pairs a-b, c-d, and e-f, respectively).

passes between the station and the nearest pole (Fig. 5d). When $i = 90°$, S_0 is considered positive when the satellite approaches the pole along meridians within 180° W of the station and is negative when approaching the pole along meridians up to 180° E of the station.

Figure 7 shows graphs of S_0 against ϕ for a CDA station at 65° latitude and for four different orbital inclinations. Three of these inclinations represent sun-synchronous orbits at altitudes of 600, 1500, and 1775 naut miles, but S_0 itself depends only upon inclination, not upon satellite altitude.

The frequency distribution of S_0 that is experienced at a station over a period of many passes is determined by the frequency of occurrence of various values of ϕ. It is assumed that over a reasonably long period of time the satellite subpoint tracks will be randomly distributed around the $i°$ latitude circle, so that the associated values of ϕ will also be randomly distributed. This assumption fails only if the orbital period (adjusted slightly for the precession $\dot{\Omega}$) is an exact submultiple of 24 or 48 or etc. hr, with the consequence that ϕ would be limited to a few values repeated once each period.

Even under this unlikely condition, the resulting set of ϕ's would be equally spaced and thus would constitute a representative sample of a random distribution.

The frequency distribution of S_0 is best expressed by the cumulative percent occurrence (CPO) of values of S_0, where the CPO goes from 0 to 100% as S_0 goes from its minimum to its maximum value. For any value of S_0, the CPO expresses the percentage of passes for which S_0 is less than or equal to that value. Figure 8a shows cumulative percentage occurrence curves of S_0 for a station at 65° latitude and for four orbital inclinations. The four curves are very similar, the major effect of varying inclination being to displace the curve along the S_0 axis.

Since, in general, only the magnitude of S_0, not its sign, is significant for data acquisition, the CPO of $|S_0|$ is shown in Fig. 8b. Figure 8 demonstrates that orbits with lower inclinations have a slightly greater percentage of subpoint tracks with $|S_0|$ less than 15°, but also have a significant percentage greater than 25°. For a polar orbit, however, all tracks come within 25° of the station. As inclination decreases from 90°, an increasing number of tracks pass at increasing distances from the station.

For a given satellite altitude h, the S_0 of a pass determines the elevation angle e occurring at any time t during the pass [see Fig. 6 and Eq. (9)]. Thus, the frequency distribution of $|S_0|$ for a sample of passes determines (for a given h) the frequency distribution of e occurring at any selected time t. The frequency distribution of e is best expressed by the CPO of all values greater than e as e decreases from 90°. Figure 9a shows the CPO of e at time $t = 0$ (the maximum e for a pass) for three satellite altitudes and their associated sun-synchronous inclinations.

Figure 9b shows the CPO of e at time $t = 0$ for $i = 90°$, the polar orbit, for three different orbital altitudes. Figures 9c and 9d show the occurrence of e at time $t = \pm 2.5$ min, representing the beginning and ending of a 5-min period of data acquisition centered at $t = 0$. In Figs. 9e and 9f are shown the curves for $t = \pm 10$ min.

The diagrams in Fig. 9 demonstrate that elevation angles during data acquisition are significantly better for 90° polar orbits than for sun-synchronous orbits at the same altitudes. During the 5 min centered at $t = 0$, elevation angles of sun-synchronous orbits are, in general, better at 1500-naut-miles alt than at either 1775 or 600 naut miles.

Figures 9e and 9f show that, at 1500- and 1775-naut-miles alt, 20 min of data acquisition time (above elevation angle 5°) are available on more than 70% of the passes in a sun-synchronous orbit and on all passes in a polar orbit. On the other hand, at 600 naut miles no pass ever remains above the horizon for 20 min, either in a sun-synchronous or a polar orbit. A related analysis from a different viewpoint is developed in Ref. 1.

Conclusions

The preceding analysis leads to the following conclusions:

1) A CDA station's effective acquisition range is more sensitive to the required minimum elevation angle than to the minimum time of acquisition.

2) Under the condition that acquisition requires a satellite to be above 5° elevation angle for 5 min, a single CDA station at temperate or subpolar latitudes below 69° can never acquire all daily passes of a sun-synchronous orbit, regardless of orbital altitude. The percentage of passes missed is least at altitudes near 1200 naut miles. Fairbanks, Alaska (latitude 65°), misses 18% of the passes at 1500-naut-miles alt and misses 32% of the passes at 600-naut-miles alt. A single station at latitude 70° could acquire all daily passes of a sun-synchronous orbit only at altitudes between about 1000 and 1700 naut miles. A single station at the equator could acquire all daily passes at altitudes above 2500 naut miles, where the sun-synchronous inclination falls to 48° or less.

3) A 90° orbit is the most favorable inclination, regardless of altitude, for permitting a single station to acquire the greatest percentage of passes. Fairbanks can acquire all daily passes of a 90° polar orbit at all altitudes above 550 naut miles.

4) The average elevation angles experienced during acquisition become higher (and therefore more favorable for good signal reception) with increasing satellite altitude. At a given altitude, elevation angles are significantly better for 90° polar orbits than for sun-synchronous inclinations. At Fairbanks, for a 1500-naut-mile alt and a 90° polar orbit, the worst daily pass remains between 25° and 27° elevation angle for the 5 min of closest approach, and the zenith pass remains above 60° for 5 min. At 600 naut miles, the worst acquirable pass remains between 5° and 7°, and the zenith pass drops to 35° at 2.5 min away from zenith.

5) At higher satellite altitudes, the total time available for acquisition is significantly greater, thereby permitting repeated readout to aid in overcoming signal interference. At Fairbanks, for a 1500-naut-mile 90° polar orbit, the satellite remains above 5° elevation angle for at least 28 min on all passes (33 min on a zenith pass). At 600 naut miles, the acquirable daily passes range from 5 to 15 min above 5° elevation angle.

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