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(54) **SYSTEMES DE RADIODIFFUSION PAR SATELLITE MOBILES ET EFFICACES DE ZONES DE SERVICE SITUEES DANS LES LATITUDES SEPTENTRIONALES**

(54) **EFFICIENT HIGH LATITUDE SERVICE AREA SATELLITE MOBILE BROADCASTING SYSTEMS**

(57) Satellite audio broadcasting systems include orbital constellations for providing high elevation angle coverage of audio broadcast signals from the constellation's satellites to fixed and mobile receivers within service areas located at geographical latitudes well removed from the equator.

D9347

ABSTRACT

Satellite audio broadcasting systems include orbital constellations for providing high elevation angle coverage of audio broadcast signals from the constellation's satellites to fixed and mobile receivers within service areas located at geographical latitudes well removed from the equator.

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EFFICIENT HIGH LATITUDE SERVICE AREA SATELLITE MOBILE BROADCASTING SYSTEMS

BACKGROUND OF THE INVENTION

Satellite broadcasting systems to mobile receivers have been proposed for radio ("Satellite DAB," International Journal of Communications; Robert D. Briskman; Vol. 13, February 1995, pp. 259-266) and other broadcast services, such as television or data from satellites at 35,786 km altitude located at or near the equatorial plane. These satellites well serve geographical regions at low and mid-latitudes but, as the latitude becomes higher, the elevation angles to the satellites decrease as shown in Figure 1. High elevation angles are most desirable in satellite broadcast systems using mobile receivers to reduce service outages from physical blockage, multipath fading and foliage attenuation. Recognition of this has led to satellite systems using 12-hour inclined elliptical orbits such as the Molniya communications satellites and the proposed Archimedes radio broadcast system. These systems are not efficient since many satellites are required for continuous coverage of practical service areas and the satellites' electronics and solar power subsystems are degraded by the four times daily passage through the Van Allen radiation belts surrounding the earth. The systems and methods of this invention surmount these problems.

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SUMMARY OF THE INVENTION

The systems and methods of this invention use satellites in 24 sidereal hour orbits (geosynchronous) with inclinations, orbital planes, right ascensions and eccentricities chosen to optimize coverage of a particular service area, region or country located at high latitudes. In contrast to the elevation angles of Figure 1, a satellite constellation of two, three or more satellites can provide during all or most of every day 50° – 60° elevation angles throughout a large service area located at high latitudes. The satellites' orbits can also be configured to avoid most of the radiation from the Van Allen belts.

Satellite systems of this invention, in preferred embodiments, serve geographical latitude service areas located at greater than approximately 30° N or 30° S by providing high elevation angles to mobile receivers in such areas for reception of broadcasting transmissions over all or most of the day. The preferred systems use geosynchronous satellites (i.e., having a 24 sidereal hour orbital period ___ 86, 164 seconds) in a constellation. The design of the constellation is configured to optimize the elevation angle coverage of a particular geographical high latitude service area for achieving minimum physical blockage, low tree foliage attenuation and small probabilities of multipath fading. For instance, 13 shows an improvement in foliage attenuation at a 1.5 GHz transmission frequency of many decibels for high service reliabilities when the reception elevation angel is doubled. Such dramatic improvement also occur for other Similar improvements occur for other microwave frequencies and for other service reliabilities.

The configuration design optimization is achieved by selection of the orbital parameters of the constellation's satellites and the number of satellites in the constellation. Satellite audio broadcasting systems to mobile receivers generally provide multichannel radio service and the satellite transmissions are nominally between 1 - 4 GHz.

Inclination. The inclination of the satellites is generally chosen between about 40° and about 80° so they cover the desired high latitude service areas during their transit overhead.

Eccentricity. The eccentricity is chosen to have a high apogee over the service area so the satellites spend the maximum amount of time overhead. Practically, the eccentricity is limited by the increased distance that the higher is from the service area since this extra distance must be overcome either by higher satellite transmission power, a more directive satellite antenna during this portion of the orbit or combinations thereof. The eccentricity range in preferred embodiments is from about 0.15 to about 0.30. Eccentricities between about 0.15 and about 0.28 are highly preferred since they avoid most of the Van Allen belts.

Planes/Number of Satellites. The number of orbital planes equals the number of satellites, and their spacing at the equator is equal to 360° divided by the number of satellites. Preferred embodiments have satellite constellations between 2 and 4 satellites. To illustrate, for a 3-satellite constellation, the satellites would be in orbital planes separated by approximately 120°.

Argument of Perigee. For service to latitude areas above 30° N, the argument of perigee is in the vicinity of 270° so that the apogee is in the northern hemisphere and the perigee is in the southern hemisphere. For service to latitude areas below 30° S, the argument of perigee is in the vicinity of 90° so that the apogee is in the southern hemisphere and the perigee is in the northern hemisphere.

Longitude of the Ascending Node. The orbit planes are chosen with a longitude of the ascending node such that the satellites have a good view (i.e., are at high elevation angles as viewed by mobile receivers) of the complete service area. Generally, this is accomplished by choosing the right ascension of the ascending node and the mean anomaly such that the center of the ground trace bisects the service area.

Ground Trace. In the preferred embodiment, the satellites follow the same ground trace and pass over a given point on the earth at approximately equal time intervals. The orbit of each satellite occupies its own orbital plane. For satellites in neighboring planes in a constellation of n satellites, the difference in right ascensions of the ascending nodes is $360°/n$, the difference in mean anomalies is $360°/n$ and the average time phasing between the satellites on the trace is 24 sidereal hours/n.

Orbit Control. Satellite constellations of this invention experience change in the aforementioned orbital parameters over time due to the earth's oblateness, gravity forces of the sun, moon and solar radiation pressure. These can be compensated by the satellites' on-board propulsion system. The amount of such propulsion can be minimized by analyzing the perturbations of each individual orbit parameter over the lifetimes of the satellites caused by the previously mentioned effects and choosing the initial conditions of the orbits so the minimum on-orbit changes are required. This choice is generally assisted by the fact that some perturbation sources partially cancel out others.

Satellite Spatial and Time Diversity. Figure 3 shows the elevation angle coverage from Seattle, WA to a three-satellite constellation optimized by the methods described herein for broadcast service to the United States of America. Two satellites are visible at all times. The techniques for satellite spatial and time diversity described in U.S. Patents #5319672 dated 6/7/94; #5278863 dated 1/11/94 and #5592471 dated 1/7/97 are fully applicable.

The satellite transmission power margin saved by using the invention for mitigation of multipath fading and for reduction of tree and foliage attenuation can be used to advantage. One use is by employing a smaller, less costly satellite. A second use is by transmitting more program channels.

BRIEF DESCRIPTION OF THE DRAWINGS

The systems and methods of this invention can better be understood by reference to the drawings, in which:

Figure 1 shows the elevation angles at mobile receivers in the 48 contiguous United States for the optimum location of a geostationary satellite (which is appropriately 101° W. Longitude on the equator). Most of the northern United States has elevation angles in the 30° – 35° range which could be lower in practice due to mobile platform tilt. Canada, Japan and most of Europe are at lower elevation angles from optimally located geostationary satellites due to their higher latitudes.

Figure 2 shows the elevation angles for a constellation of three satellites with orbits optimized for the 48 contiguous United States using the methods and techniques of the invention for Bangor, Maine; Figure 3 for Seattle, Washington; Figure 4 for San Diego, California; Figure 5 for Orlando, Florida; and Figure 6 for Kansas City, Missouri. The constellation provides one satellite at all times above 60° elevation angle throughout the northern United States and a second one at most times above 30° elevation angle.

Figure 7 depicts the ground trace of the satellites. With single satellite which provides no mitigation of multipath fading, a constellation of two satellites is feasible as shown in Figure 8 for New York City. Conversely, a four satellite constellation would provide multiple satellite coverage at higher elevation angles than Figure 2 – 6.

Figure 9 shows the ground trace for a three satellite constellation serving Europe with Figure 10 – 12 showing the high elevation angles achieved in various cities.

Figure 13 shows the fade margin required to overcome roadside shadowing from trees and leaves measured at L-band frequencies (1-2 GHz) in the 48 contiguous United States as a function of service unavailability and elevation angle. In cases where modest availability (e.g., 90% or 10% unavailability) is required any where moderate improvement in elevation angle coverage is implemented, the fade margin improvement will be several decibels. In cases where high availability (e.g., 99% or 1% unavailability) is required and where large improvement in elevation angle coverage is implemented, the fade margin improvement will be in the 12-14 dB range (i.e., 20 times). Reductions in required fade margins can be used by the satellite system designer to employ smaller, less expensive satellites or more audio program channels or combinations thereof.

Figure 14 is a simplified graph which shows the improvement the invention provides in reducing service outages from physical blockages (e.g., buildings, hills, etc.) of the satellite signal from the mobile receiver. The graph shows the worst case distance a car must be away from a building of a certain height to always avoid an outage from blockage as a function of elevation angle to a single satellite. The amount of blockage avoidance varies significantly for an assumed building height with satellite elevation angle improvement. Depending on the improvement in satellite elevation angle coverage, the distance of a mobile receiver from the building can typically be as close as several feet to as far as many yards away and not be affected by blockage.

Figure 15 shows what would happen to the orbit of one of the constellation's satellites, whose ground trace is shown in Figure 7, if the orbital parameters are not chosen to minimize the orbital perturbations and if no satellite propulsion is used over a fifteen year period to correct the remaining perturbations. The perturbations, caused by gravitational effects of the sun, moon and earth oblateness, and by solar radiation pressure, are a function of the orbits and their epochs (i.e., the actual time of orbit insertion).

DESCRIPTION OF PREFERRED EMBODIMENTS

The systems and methods of the invention are best described by enumerating the steps employed in the design of an audio satellite broadcast system to mobile receivers for providing service throughout a service area geographically well removed from the equator. The mobile receivers have antennas configured to view the sky where satellites would be visible. The invention is also applicable to fixed location receiver radio broadcast systems. In fact, when a mobile receiver stops, it is essentially a fixed receiver. The fixed location receiver case is less technically simpler, since there is little multipath fading and the blockage encountered is static with time.

The important analysis input parameters are the definition of the geographical service area and the quality of service to be provided. The quality of service is defined as the percent of time service will be unavailable due to outage from physical blockage, multipath and tree/foliage attenuation. The desired satellite elevation angles for minimizing outage from single path physical blockage can be derived from calculations similar to those graphically shown in Figure 14. Similarly, the desired satellite elevation angles for minimizing outage from tree/foliage attenuation can be derived from transmission measurements in the projected service area at the system's operating radio frequency, such as shown in Figure 13 for the United States at L-band frequencies, and knowledge of the satellites' transmission signal margin at the mobile receiver. Multipath and total blockage (i.e., all path blockage such as occurs when a mobile receiver passes under a large underpass) are dealt with by use of satellite spatial and time diversity. Diversity is analyzed as a requirement of the number of satellites simultaneously viewable by the mobile receivers and of the satellites' elevation angles.

The results of the aforementioned analyses are then used in the design of the satellite constellation which is a function of the orbital parameters and number of satellites in the constellation. Using known computer analysis programs, an optimization is performed of the elevation angles for the mobile receivers throughout the service area to the constellation's satellites throughout a day (i.e., since the satellites are geosynchronous, the elevation angles will repeat every day if perturbations are ignored). The optimization specifically varies inclination and eccentricity for given right ascensions to maximize the time the satellites remain over the service area (i.e., at high elevation angles). Also, the choice of the apogee and perigee of the orbit considers the avoidance of passage through the Van Allen belts so radiation damage to the satellites is minimized and avoids too high apogees so excess space loss or antenna beam forming is minimized as discussed subsequently.

Continuous coverage of a reasonably sized service area well removed from the equator cannot be achieved with a single satellite so analysis is generally performed on constellations with 2, 3 and 4 satellites. The analyses are performed using known computer programs. The amount of elevation angle coverage improvement diminishes for constellations with more than three satellites. Constellations with more than 4 satellites are technically feasible and only marginally improve both elevation angle coverage and redundancy. Figure 8 shows the elevation angle coverage of a two satellite constellation as seen from New York City. No appreciable satellite spatial diversity is possible making multipath mitigation from this technique unavailable. The selection of the number of satellites in the constellation from the analyses' data is based on the criteria adopted for the minimum required number of satellites visible to mobile receivers throughout the service area at the selected minimum elevation angles. The selection may also be influenced by system costs.

The next analyses take the selected satellite orbit constellation and further optimize it from the viewpoint of orbit perturbations. The purpose of this final optimization is to minimize the satellites' mass, particularly the amount of on-board propellant needed for correcting the orbits from long term perturbations. This is important since both the satellite and its launch vehicle will be less expensive.

The analyses are done by known computer programs. The programs calculate the perturbations of the satellites' orbits caused by the earth's oblateness, the gravity effects of the sun and moon and the solar radiation pressure. Although those effects are individually small on a short term basis, satellites of this type generally have a 15 year lifetime. The magnitude of some of the perturbations are a function of when the satellites are initially placed in orbit (i.e., epoch). The analyses consider which perturbations are additive and which are subtractive, and the minimization of the perturbations by small changes in the initial orbital parameters, particularly inclination and eccentricity, and their subsequent in-orbit correction strategy. The result of the optimization is the amount of satellite on-board fuel required and reflects the minimum satellite mass.

The last analyses involve the optimization of the satellite antenna which is directive towards the service area. The analyses result in the required pointing angle of the satellite antenna boresight with time (i.e., over one sidereal day) to keep it accurately pointed at the service area. Depending on the difference between apogee and perigee altitude, if the apogee is very high, the analyses provide the beamshaping of the satellite antenna with time required to offset the change in range (i.e., space propagation loss change) and also provide antenna pattern rotation requirements with time for antenna beamshapes which are not circular.

Two systems using this invention were designed for audio satellite broadcasting. One system was designed for service to the contiguous 48 United States. The input requirements were to have one satellite in the northern portion of the service area always in view with at least 60° elevation angle to mobile receivers in the area and a second satellite always visible with at least 25° elevation angle. The analyses were conducted with an orbital computation program called "Satellite Tool Kit" from Analytical Graphics, Inc. of Malvern, Pennsylvania. The results of the analyses resulted in a three satellite constellation. Figures 2 through 7 show specific final elevation angle coverage outputs of the program for the system.

A second system was designed for service to Europe using similar input requirements to the first system and the same computation program. Figures 9 through 12 reflect the final results regarding elevation angle coverage.

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WHAT IS CLAIMED IS:

Claim 1

A satellite audio broadcasting system for mobile and fixed receivers in a geographical service area at latitudes above about 30° N or below about 30° S comprising a satellite constellation of 2 or more satellites, each in its own geosynchronous orbit, with each orbit having orbital parameters that provide high elevation angles throughout said area.

Claim 2

The satellite audio broadcasting system of Claim 1 wherein audio broadcasts from said constellation to said mobile and fixed receivers are in the radio frequency range of about 1 to about 4 giga Hertz.

Claim 3

The satellite audio broadcasting system of Claim 1 having the satellites in said constellation located in orbital planes separated from one another by a number of degrees equal to 360° divided by the number of satellites in the constellation.

Claim 4

The satellite broadcasting system of claim 1 or claim 2 wherein said orbital parameters for each satellite in said constellation minimize passage of said satellites through the Van Allen radiation belts around the earth.

Claim 5

The satellite audio broadcasting system of claim 1 or claim 2 wherein said orbital parameters minimize onboard satellite propulsion required to maintain each satellite in said constellation in its desired orbit.

Claim 6

The satellite audio broadcasting system of claim 1 or claim 2 wherein said orbital parameters are selected from the group consisting of satellite antenna pointing angles, satellite pattern rotation angles and satellite antenna beam shapes.

Claim 7

The satellite audio broadcasting system of claim 1 or claim 2 wherein said orbital parameters are selected from the group consisting of the inclination of each satellite, the eccentricity of the orbit for each satellite, the argument of perigee for each satellite in said constellation, the longitude of the ascending node of each orbit for each satellite in said constellation, and the ground trance for each satellite in said constellation.

Claim 8

A method of providing audio satellite broadcast transmissions to fixed and mobile receivers in a target geographic area that is, at least in part, in a latitude above 30° N or a latitude below about 30° S comprising providing a constellation of satellites, with each satellite in its own orbital plane, each with a period of revolution around the earth substantially the same as the period of rotation of the earth on its axis, each with an inclination in the range of about 40° to about 80°, and each with an eccentricity of about 0.15 to about 0.30, and transmitting, from two or more of said satellites, audio broadcast signals that are substantially identical in content.

Claim 9

The method of claim 8 further comprising providing spacial diversity between said audio broadcast signals from two or more satellites in said constellation.

Claim 10

The method of claim 8 further comprising choosing orbital plane separations and relative satellite phasing among said satellites in said constellation to optimize transmissions of audio broadcast signals to said target geographic area.

Claim 10

The method of claim 8 further comprising receiving, at said fixed and mobile receivers, from at least one satellite in said constellation, audio broadcast signals for reproduction at said fixed and mobile receivers.

Claim 11

The method of claim 8 further comprising providing time diversity between substantially identical audio broadcast signals from two or more satellites in said constellation.

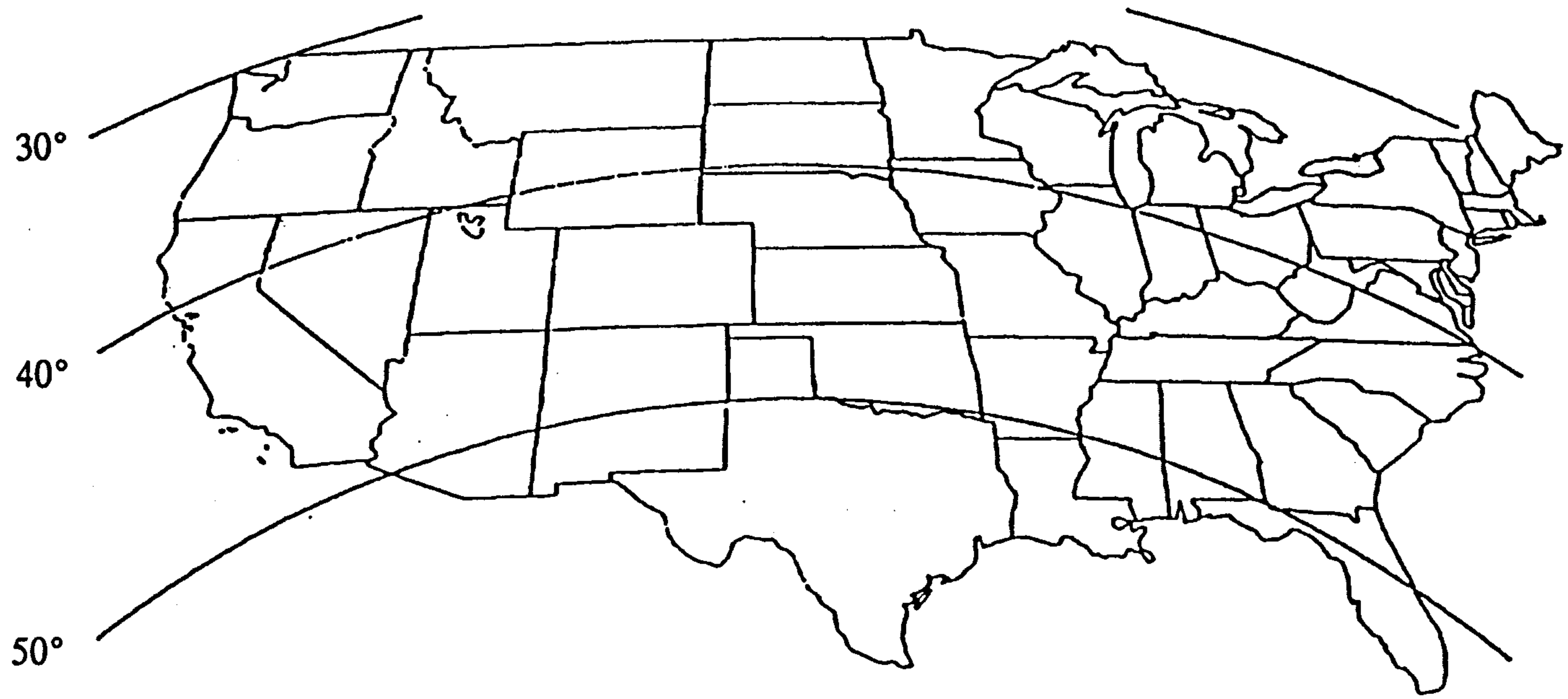


Figure 1

CONUS from 101° W Longitude

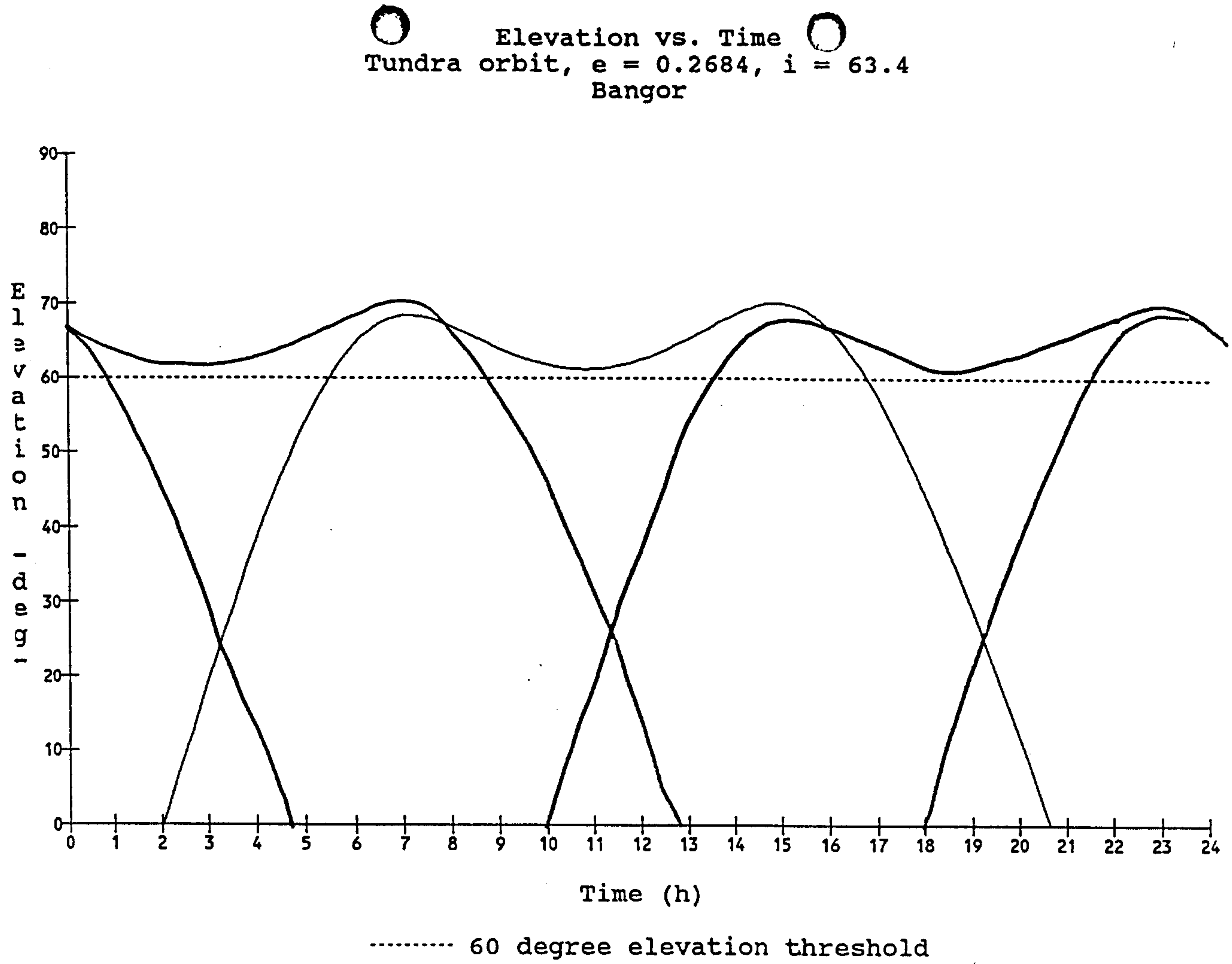


Figure 2

Scott & Aylen

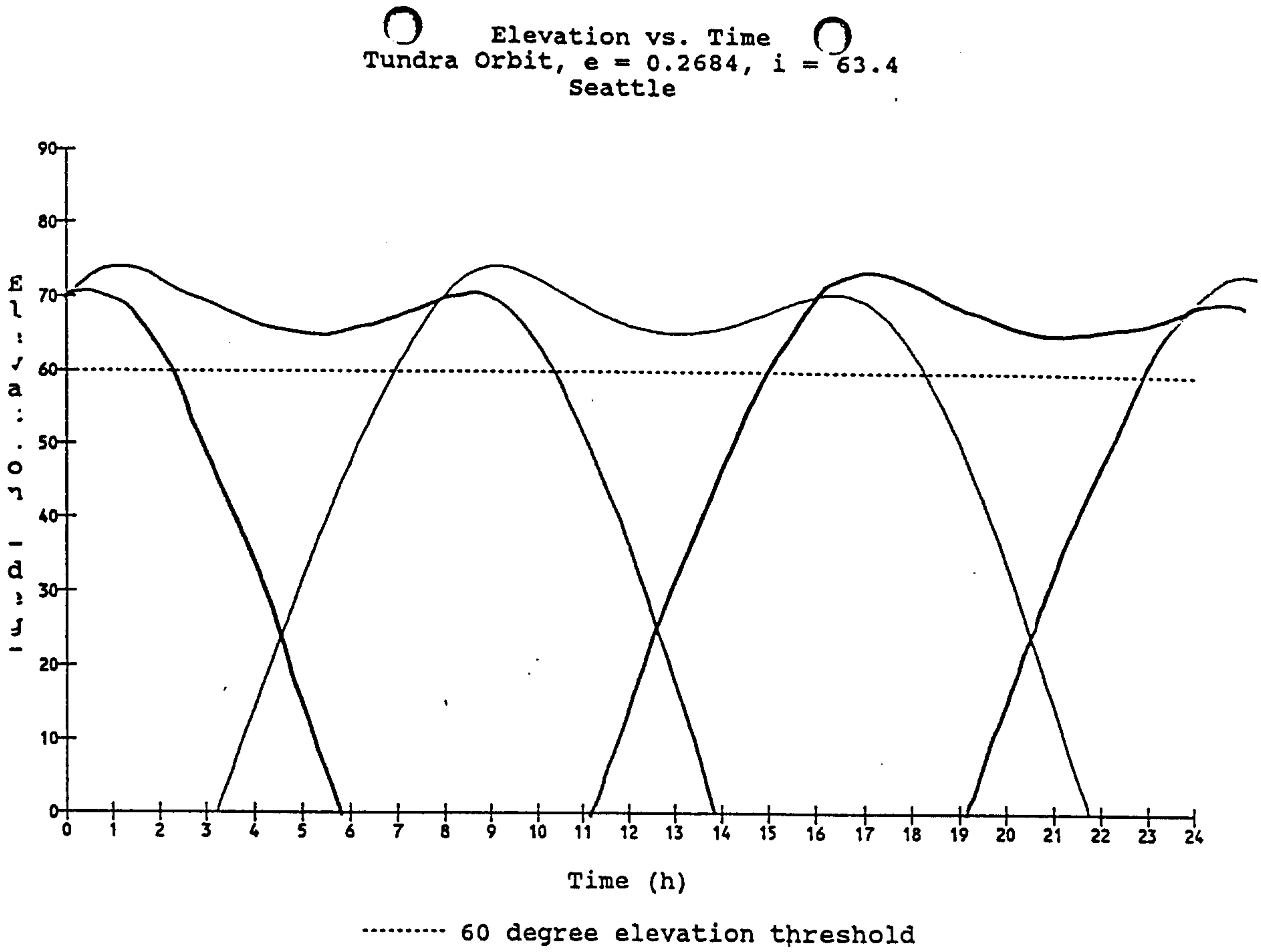

Elevation vs. Time
Tundra Orbit, e = 0.2684, i = 63.4
Seattle
Elevation (deg)
0
10
20
30
40
50
60
70
80
90
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (h)
60 degree elevation threshold

Figure 3

Elevation vs. Time
Tundra orbit, e = 0.2684, i = 63.4
San Diego

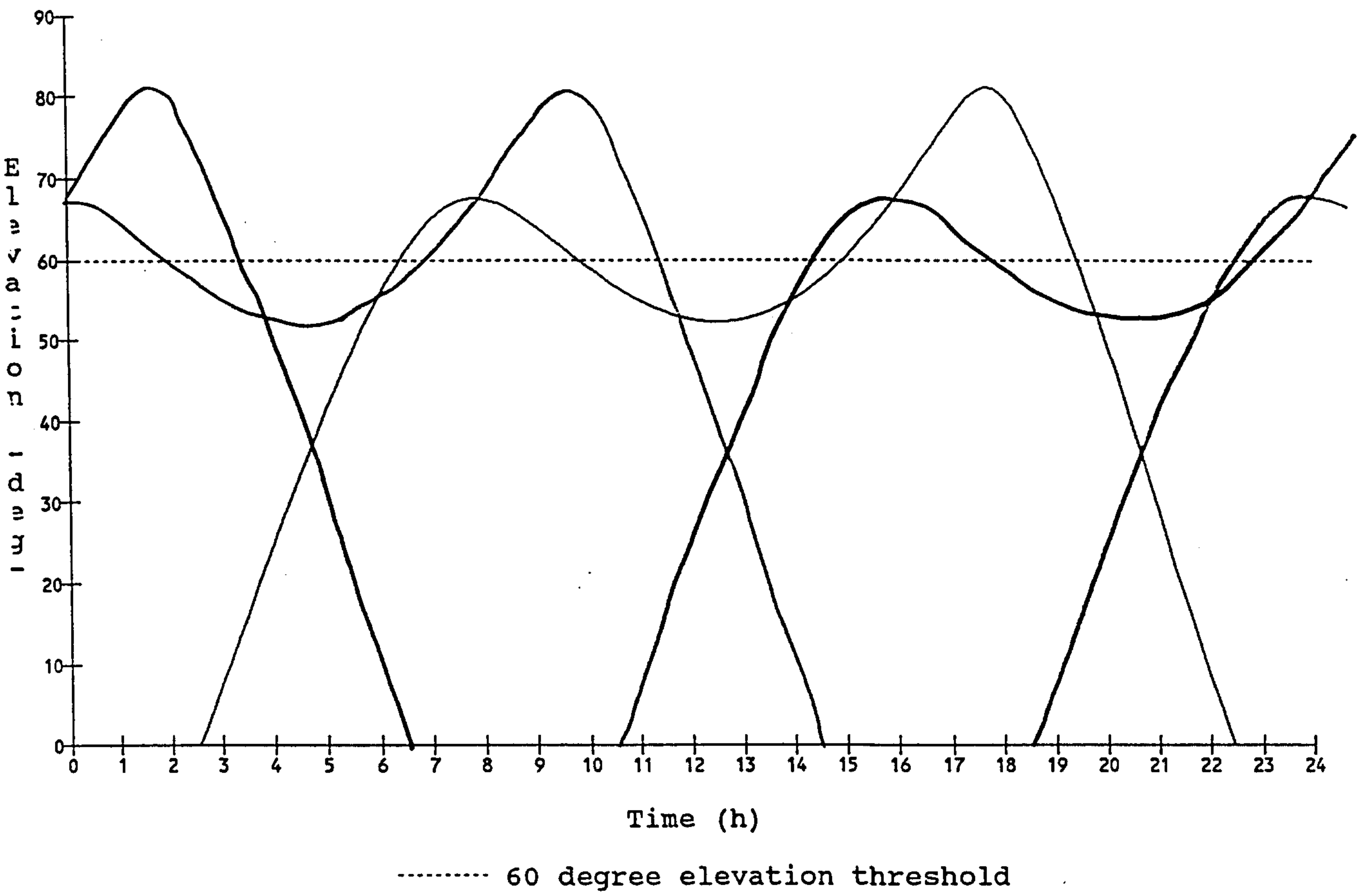


Figure 4

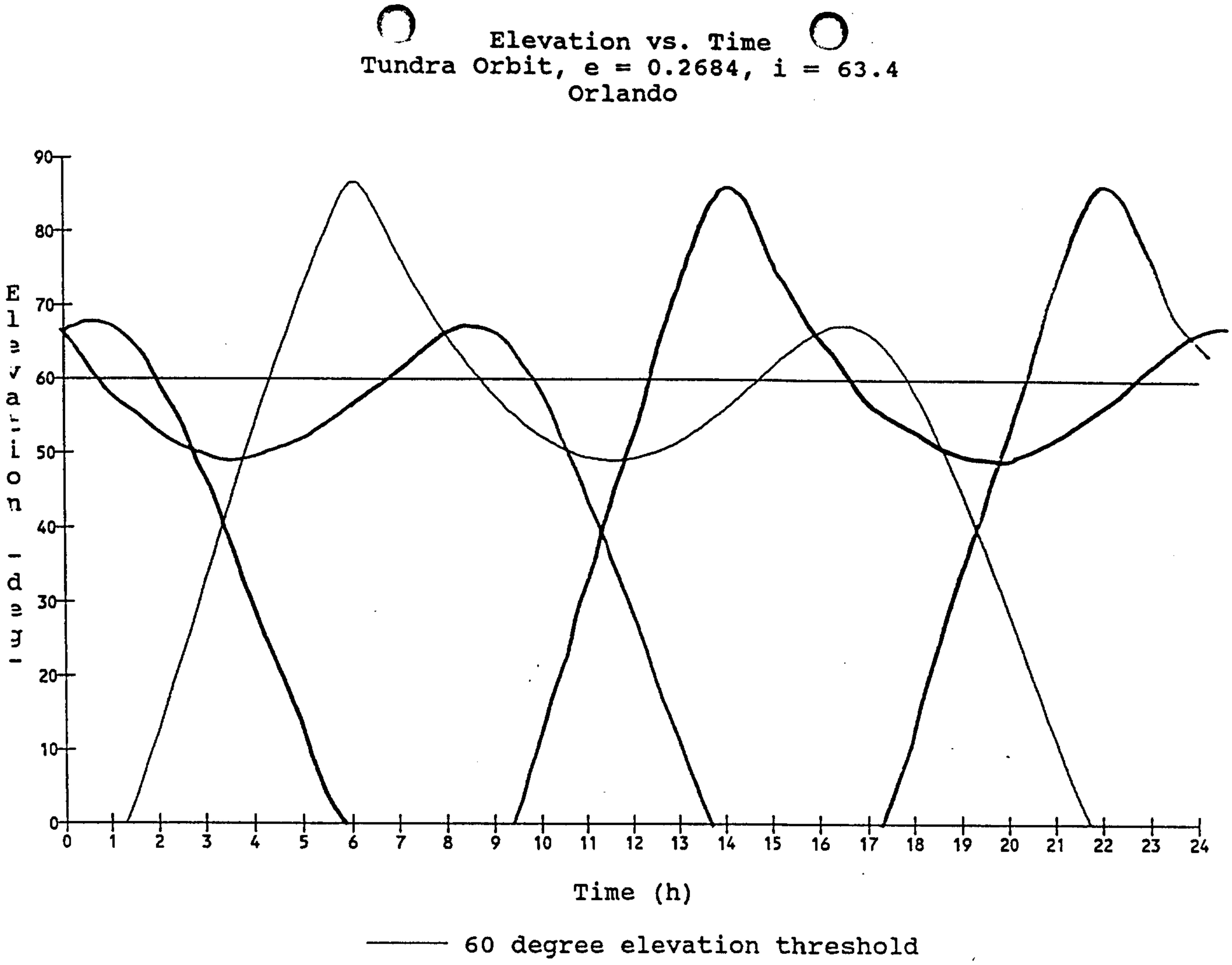

Elevation vs. Time
Tundra Orbit, e = 0.2684, i = 63.4
Orlando
Elevation (deg)
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (h)
60 degree elevation threshold

Figure 5

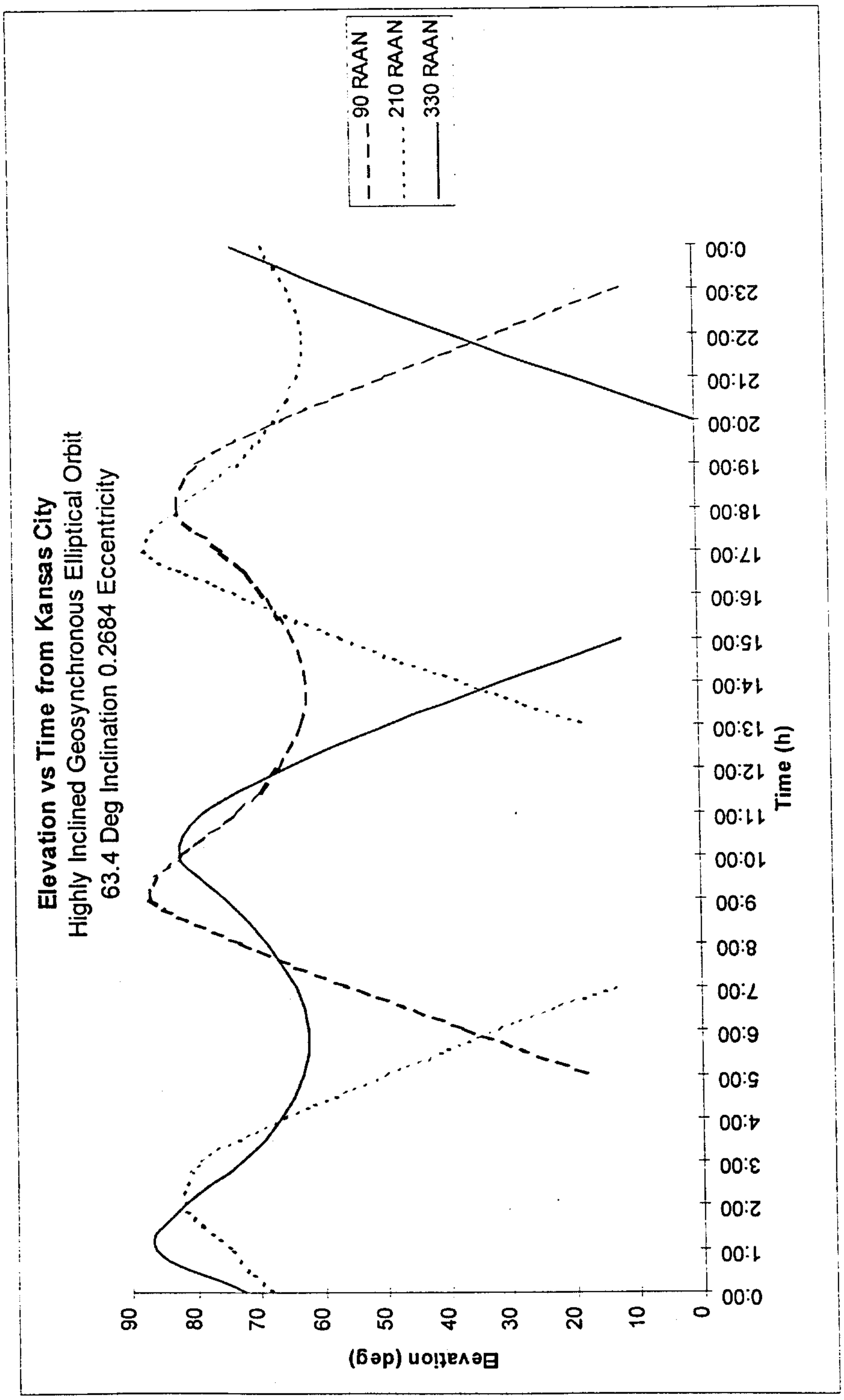

Elevation vs Time from Kansas City
Highly Inclined Geosynchronous Elliptical Orbit
63.4 Deg Inclination 0.2684 Eccentricity
90 RAAN
210 RAAN
330 RAAN
Elevation (deg)
Time (h)
0 10 20 30 40 50 60 70 80 90
0:00 1:00 2:00 3:00 4:00 5:00 6:00 7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 0:00

Figure 6

Ground Trace

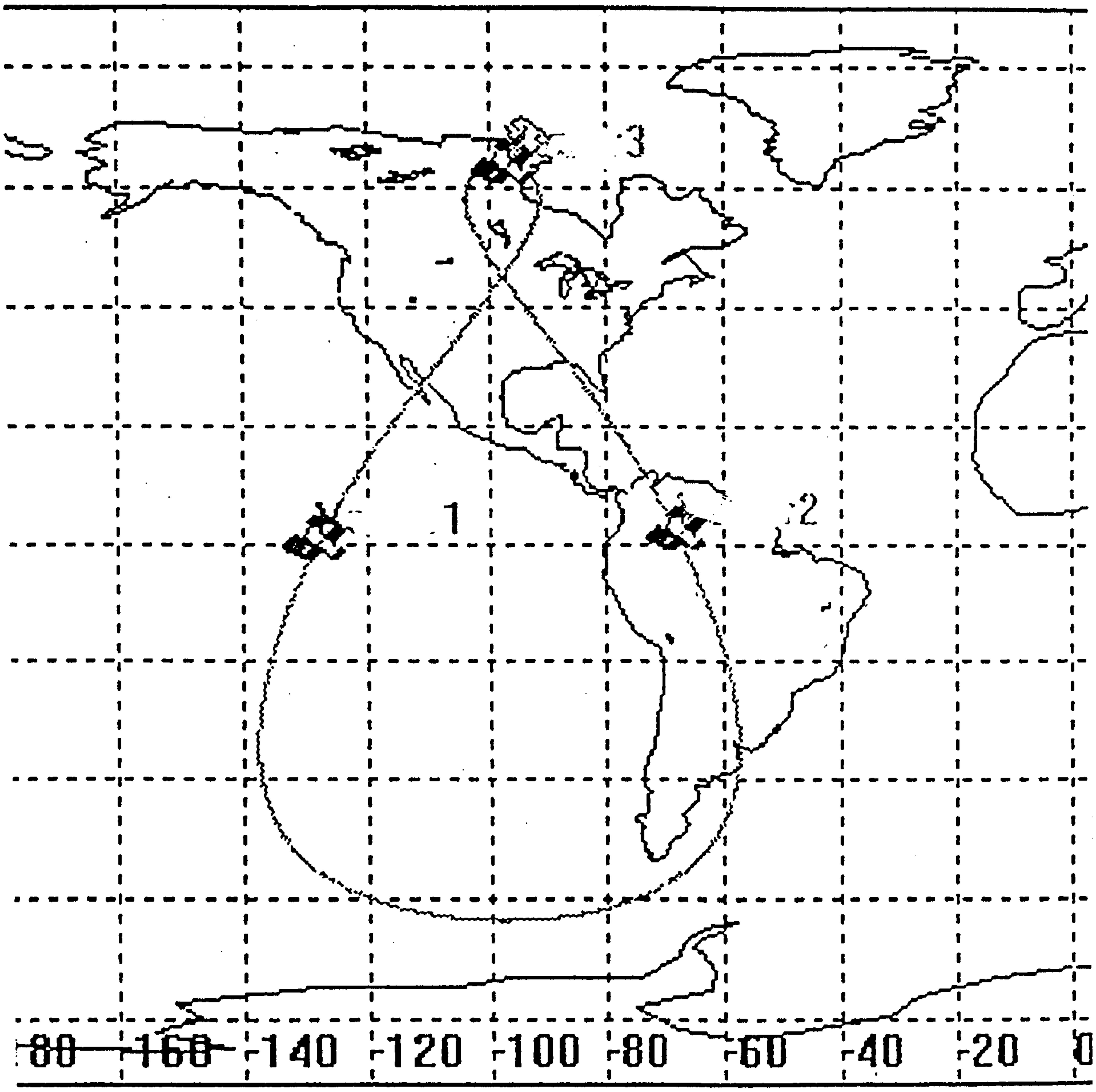
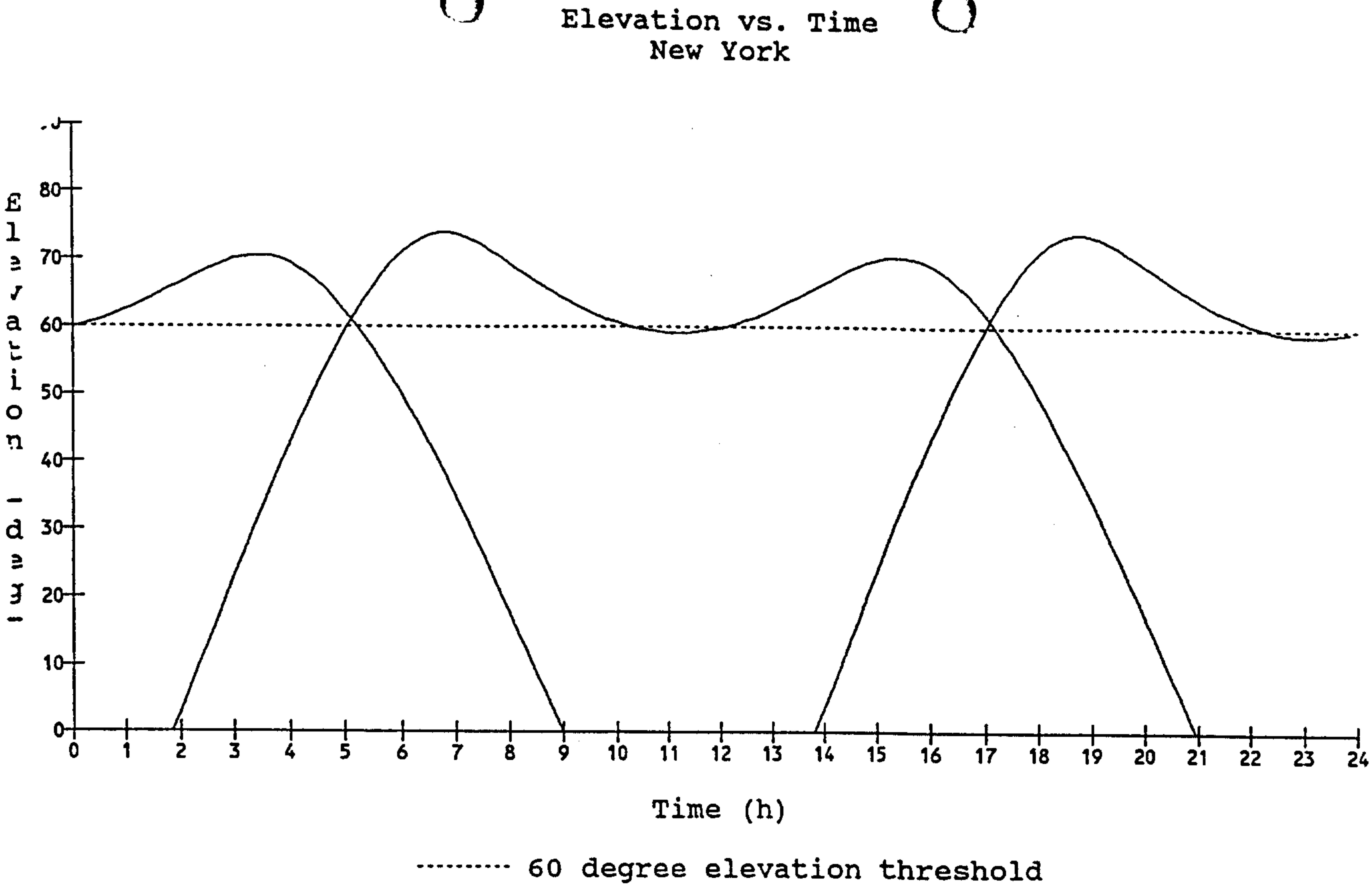


Figure 7



Elevation vs. Time
New York
Elevation (deg)
0
10
20
30
40
50
60
70
80
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (h)
60 degree elevation threshold

Figure 8

Vader Orbit Ground Trace
European Constellation

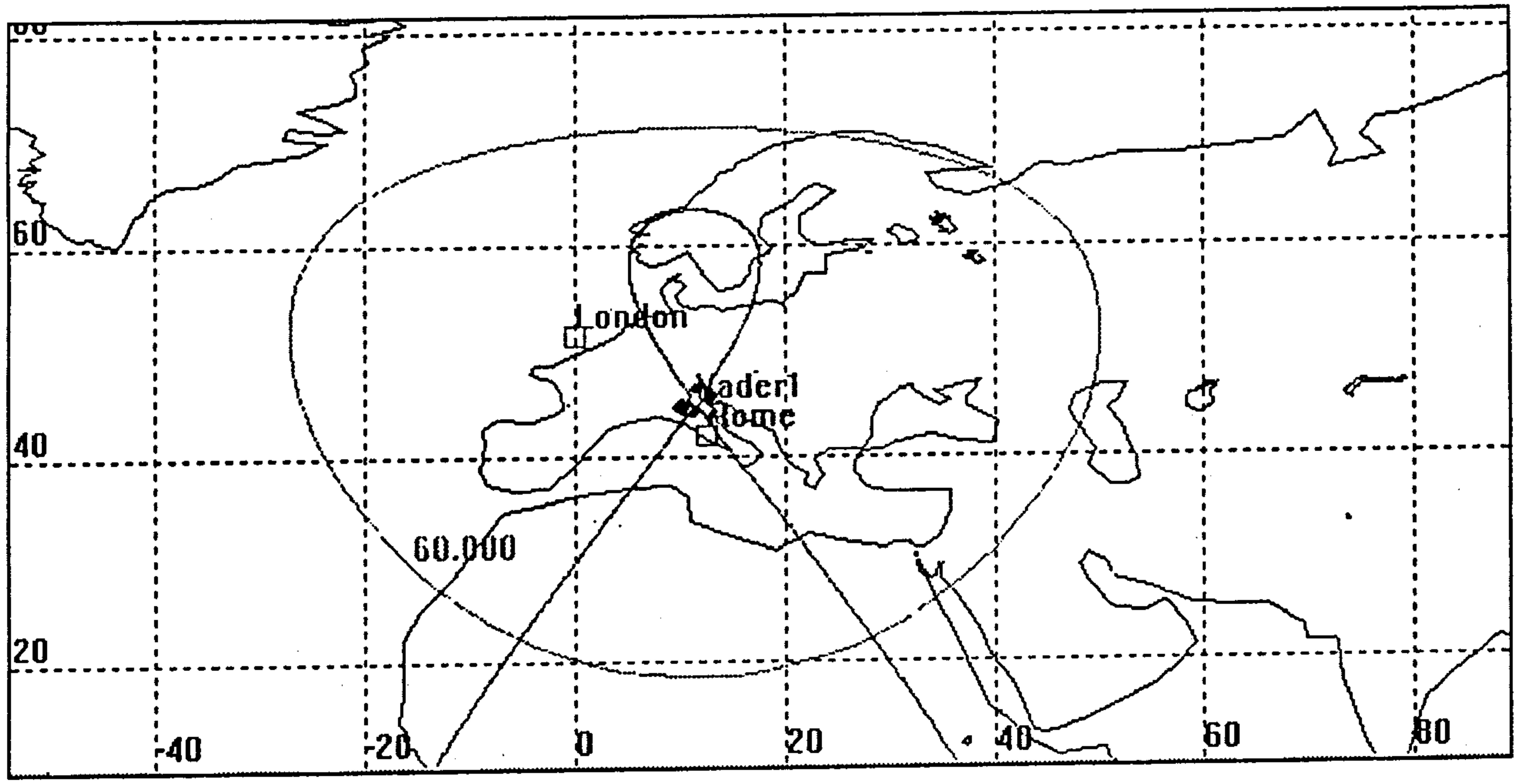
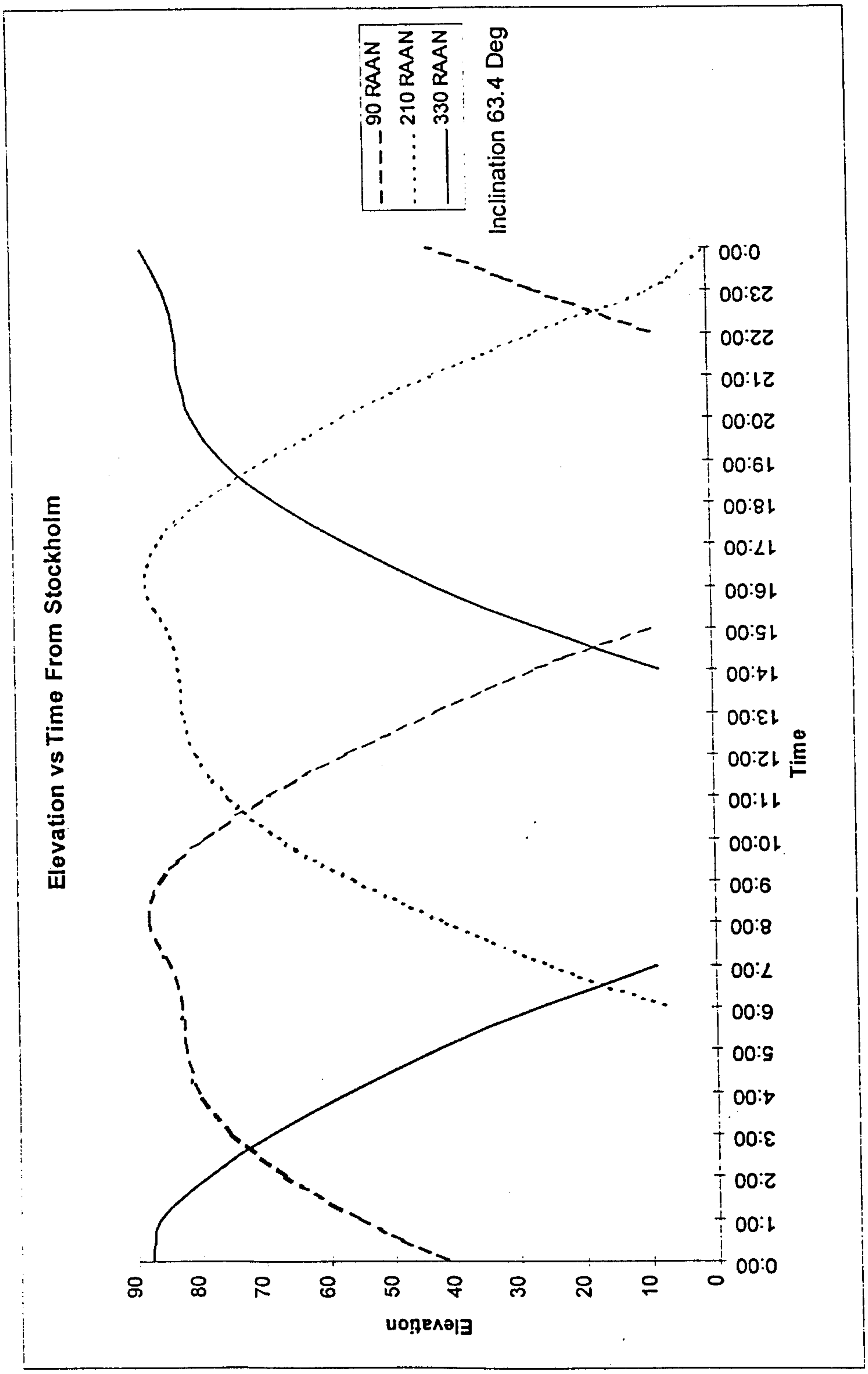


Figure 9


Elevation vs Time From Stockholm
90 RAAN
210 RAAN
330 RAAN
Inclination 63.4 Deg
Elevation
Time
0
10
20
30
40
50
60
70
80
90
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
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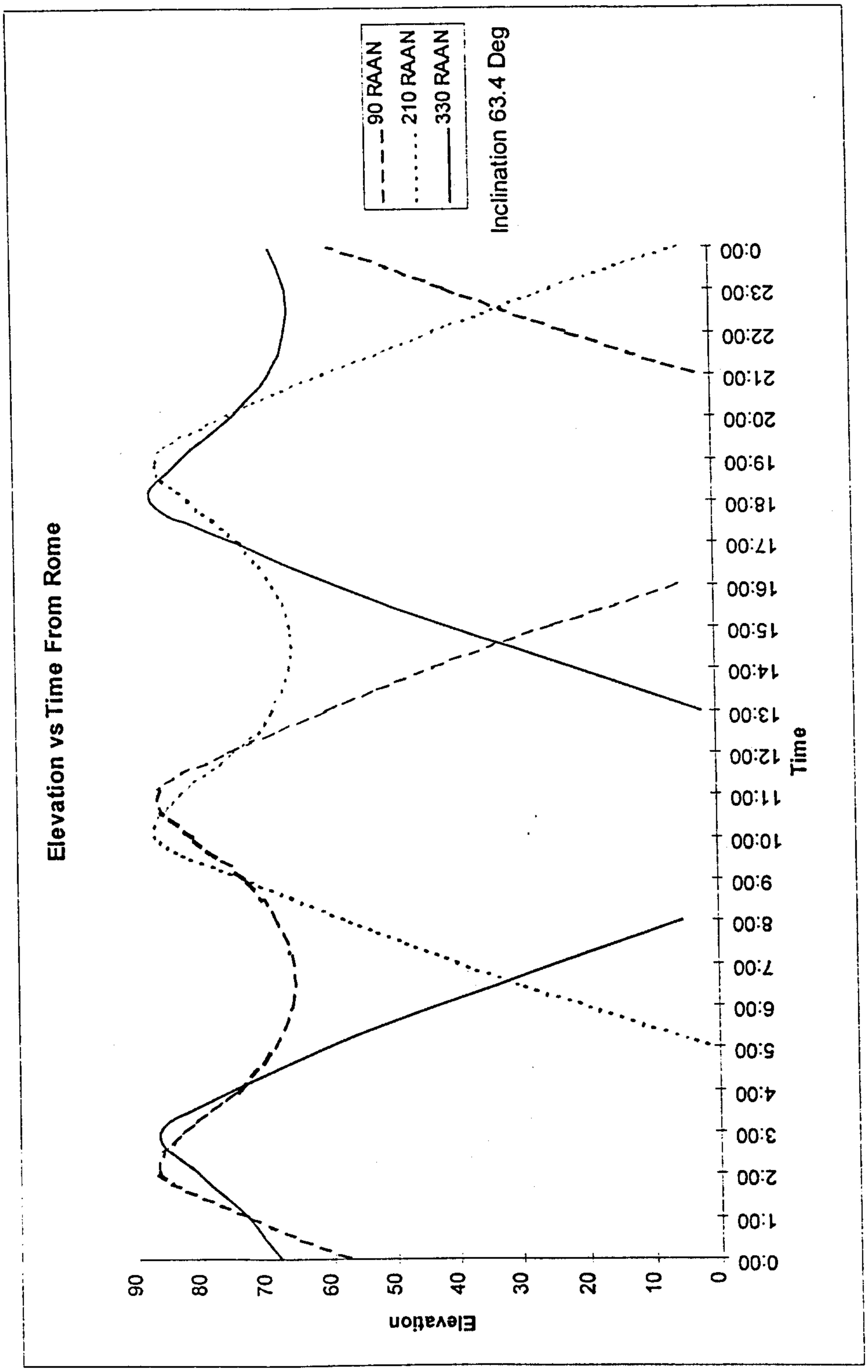
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
0:00

Figure 10


Elevation vs Time From Rome
90 RAAN
210 RAAN
330 RAAN
Inclination 63.4 Deg
Elevation
90
80
70
60
50
40
30
20
10
0
Time
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
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16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
0:00

Figure 11

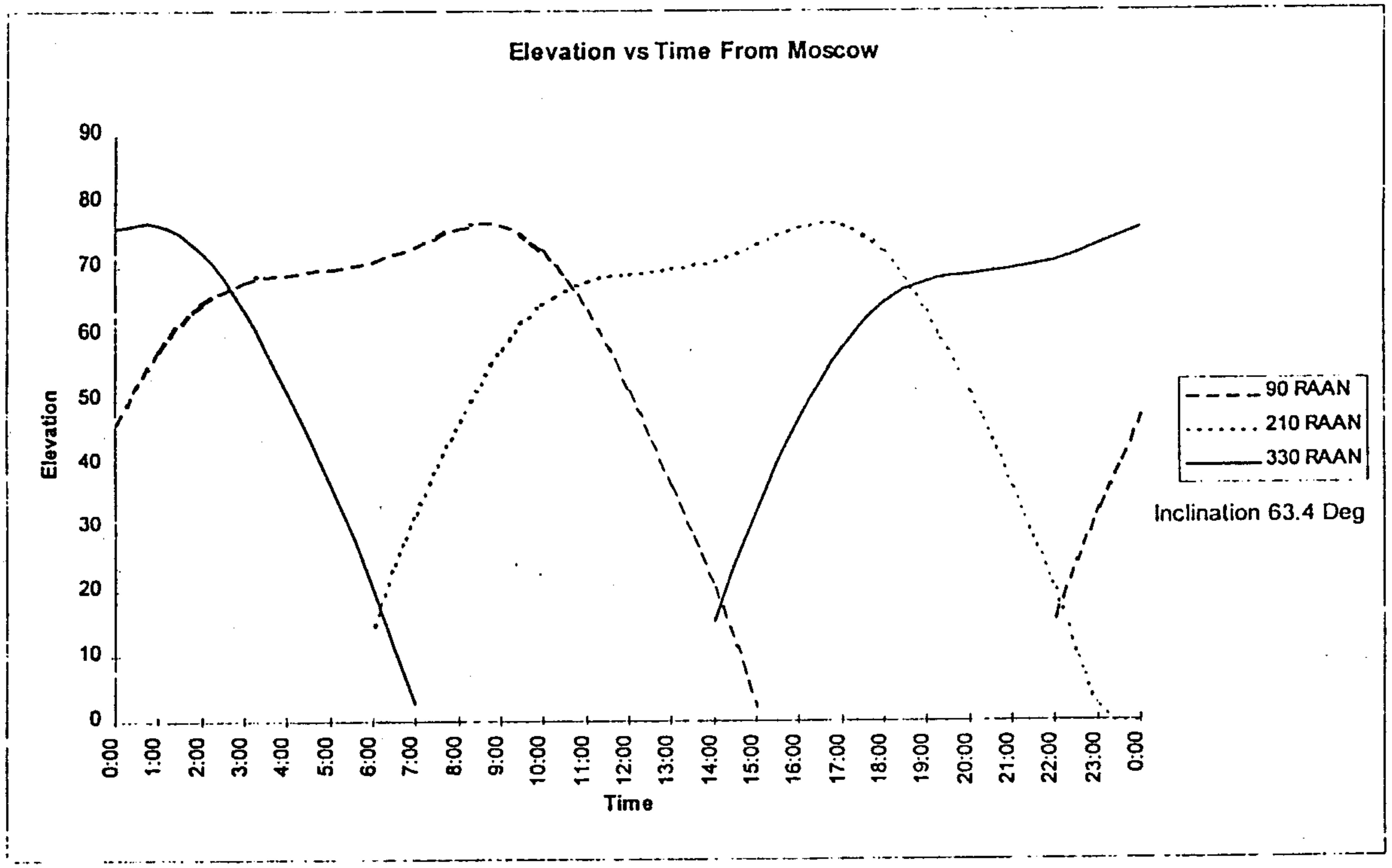

Elevation vs Time From Moscow
Elevation
90
80
70
60
50
40
30
20
10
0
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
0:00
Time
90 RAAN
210 RAAN
330 RAAN
Inclination 63.4 Deg

Figure 12

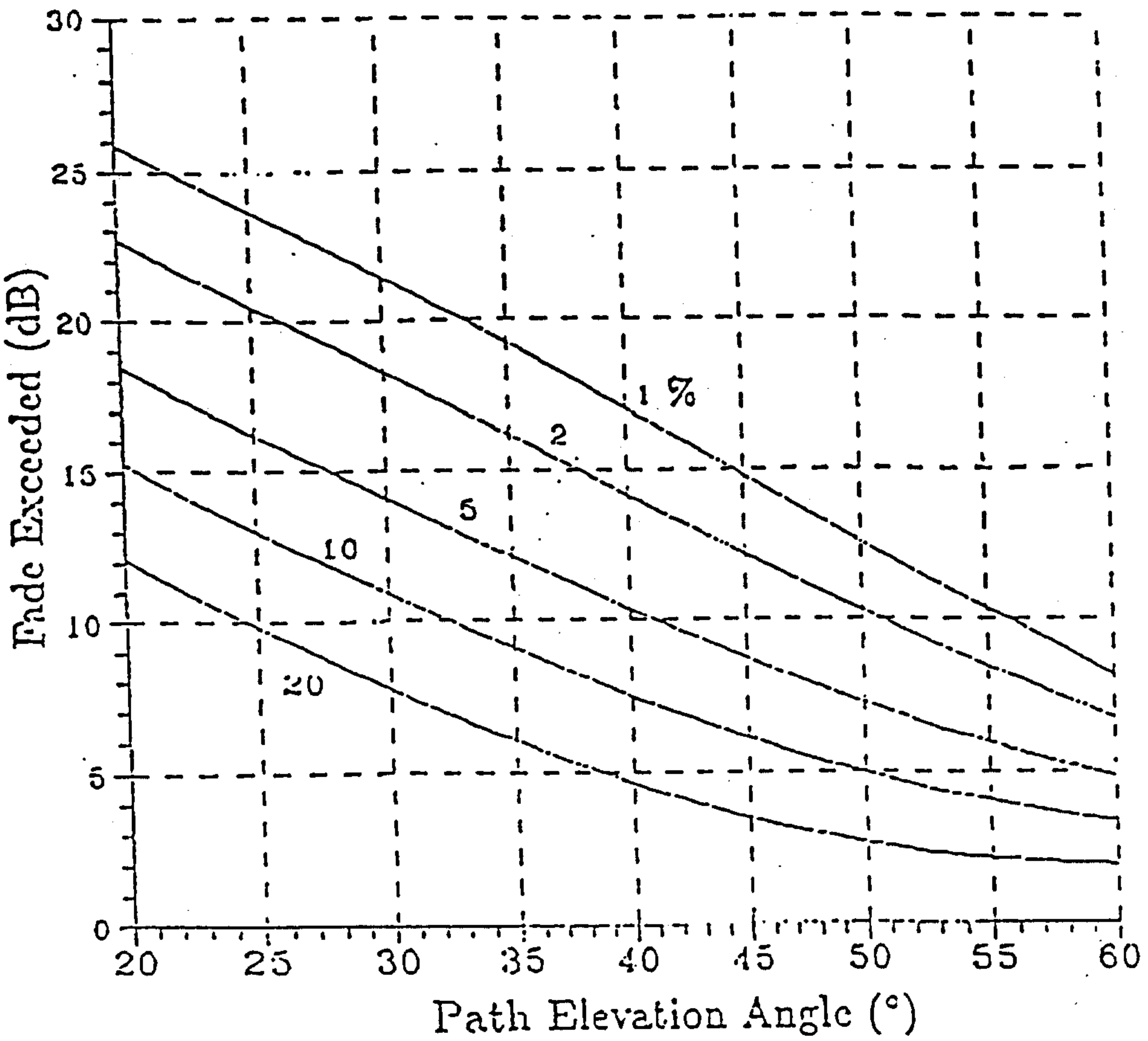

30
25
20
15
10
5
0
Fade Exceeded (dB)
1 %
2
5
10
20
20
25
30
35
40
45
50
55
60
Path Elevation Angle (°)

Figure 13

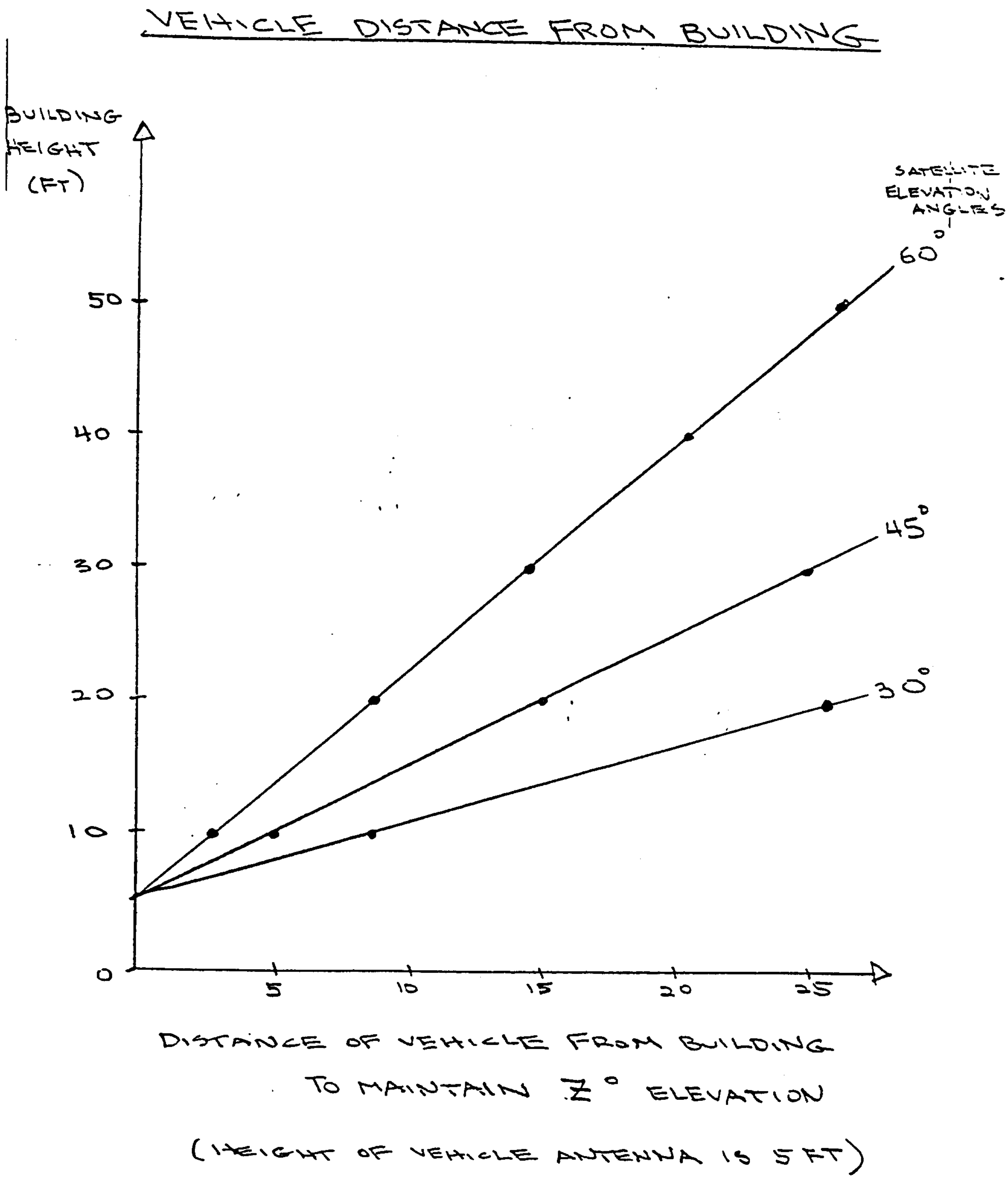
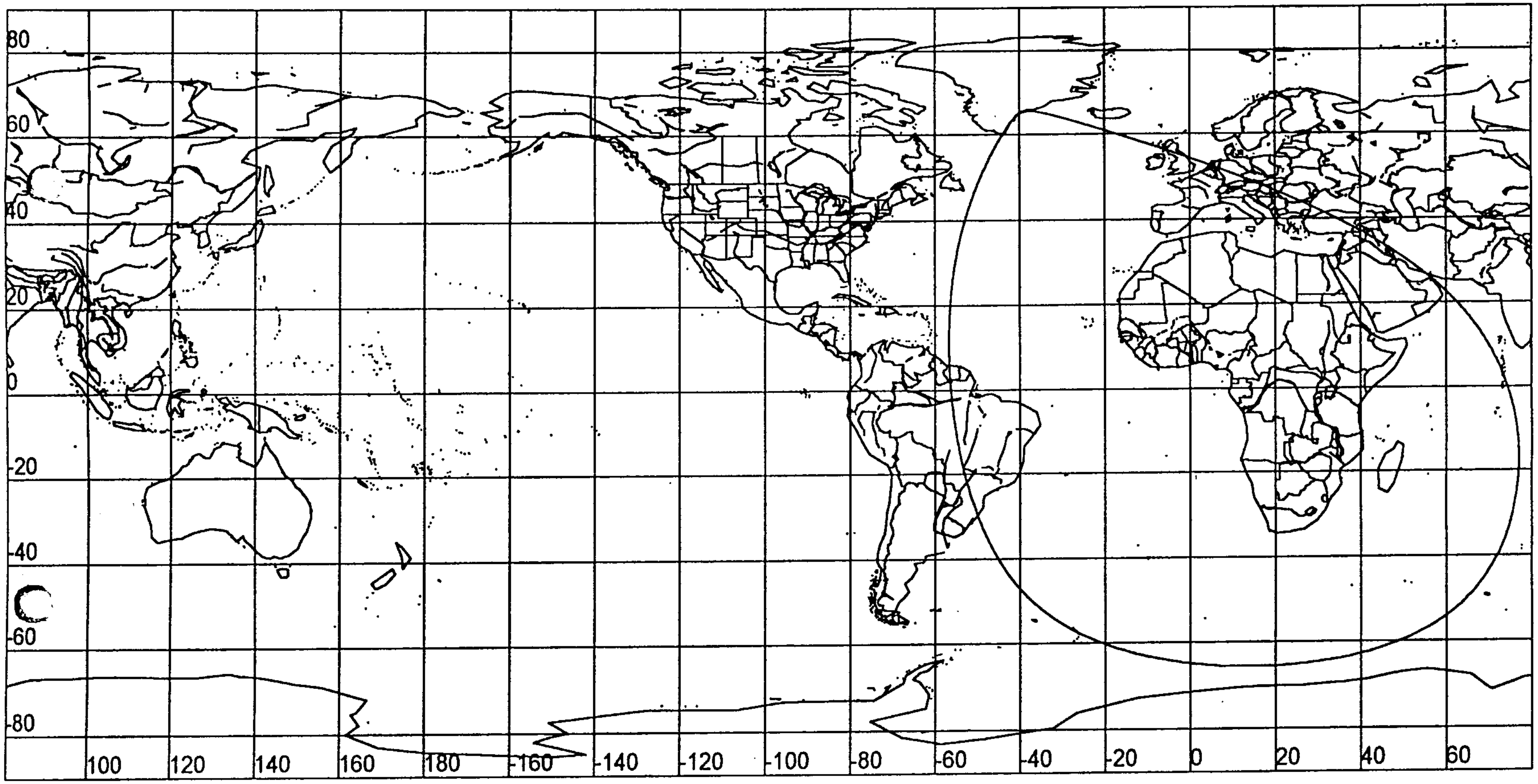


Figure 14

RDB 11/24/97



Ground trace at End of Life (15 years, no stationkeeping)
$i = 65.6°, e = 0.6264, \omega = 253°, \Omega = 8.0°$

Figure 15