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ANALYSES OF SOLAR VIEWING TIME, BETA ANGLE, AND DOPPLER SHIFT FOR SOLAR OBSERVATIONS FROM THE SPACE SHUTTLE

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Program Development

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16. ABSTRACT

Studies of solar physics phenomena are aided by the ability to observe the Sun from Earth orbit without periodic occultation. This report presents charts for the selection of suitable orbits about the Earth at which a spacecraft is continuously illuminated through a period of a few days. Selection of the orbits considers the reduction of Doppler shift and wavefront attenuation due to relative orbital velocity and residual Earth atmosphere.

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ANALYSES OF SOLAR VIEWING TIME, BETA ANGLE, AND DOPPLER SHIFT FOR SOLAR OBSERVATIONS FROM THE SPACE SHUTTLE

1.0 INTRODUCTION

Man has been observing the Sun and its effects on Earth for centuries, and through improved instrumentation, he has gradually been able to overcome many of the drawbacks arising from observations through the Earth's atmosphere. However, his resolving power of the Sun and its details are still limited by cloud cover and heat waves. To eliminate these effects, Orbiting Solar Observatories (OSO) have been placed in Earth orbit for a better look at the Sun. These nearly circular orbits are 340 miles in altitude and have an inclination of 32.9°. At this altitude and inclination there is still the problem of occultation of the Sun as OSO orbits the Earth. The plan for the Space Shuttle Solar Astronomy Sortie Missions is to have a 7-to-14-day continuous solar viewing time with a telescope pointing accuracy of .01 arc-sec and a resolving power of .1 arc-sec. This increased accuracy requirement (OSO has a pointing accuracy of 1 arc-min) introduces a new problem; compensation for Doppler shift. With the lower resolving power of the OSO's, the problem of Doppler shift is much less significant. Earth-based solar observatories utilize Doppler shift compensators, but they only take into account one revolution of the Earth per day. The Shuttle Solar Observatory (SSO) will probably orbit the Earth about once every 90 minutes, sixteen times faster. State-of-the-art Doppler shift compensators cannot handle this problem rapidly enough to satisfy the pointing requirements. Because of this problem, a parametric study was performed to define the altitudes and inclinations for the Shuttle Solar Astronomy Sortie Missions for the available time periods of continuous solar viewing with sufficiently low Doppler shift levels as to not affect resolution in the desired range.

2.0 OBJECTIVE

The goal of this study was to define by the use of a set of graphs the time of the year for specific altitudes and inclinations when solar astronomy sortie missions on the Space Shuttle would be feasible. These missions must maintain a Doppler shift of .01 Å or less without the use of a Doppler shift compensator.

3.0 GUIDELINES AND ASSUMPTIONS

- The SSO should have continuous solar viewing times of 7-to-14-days per mission.
- The minimum altitude at which the Shuttle must fly to eliminate absorption of far UV wavelengths is 240 N. Mi.
- The range of Shuttle altitudes to be considered is 275 N. Mi. to 400 N. Mi.
- The inclinations selected will be the lowest possible to avoid using up payload by extra fuel reqired for large inclinations (over 75^{o}).
- The Doppler shift at any time during the 7-to-14-day mission will not exceed .01 Å.
- The Space Shuttle orbits are assumed to be circular.
- KSC is assumed to be the launch site; (if another launch site is selected Equation 7 must be modified accordingly to determine the time of launch).

4.0 TECHNICAL APPROACH

The first step in the problem was to find the times of the year for various altitudes and inclinations during which 7 to 14 days of continuous solar viewing would occur (see Figure 1). The minimum inclinations at which continuous solar viewing is possible for specific altitudes is shown in Figure 2. These times of solar viewing were then analyzed by studying the effects of change in beta angle on the Doppler shift (see Figure 3). The beta angle is the angle between the Earth-Sun line and the Shuttle orbit plane.

4.1 Calculation of Continuous Solar Viewing Times

For a circular orbit, the percentage of time of solar viewing t_s is given by

$$t_s = \frac{90 + \sin^{-1}\left[\dfrac{\sin\alpha}{\sin\eta}\right]}{180} \times 100\% \qquad (1)$$

where

$\alpha = \cos^{-1} (R/ (R + h))$

R = earth radius + atmosphere (see guidelines & assumptions)

h = R - Earth's radius

η = angle between the Earth-Sun line and the normal to the Shuttle orbit

Using an equatorial co-ordinate system, with the X-axis in the equatorial plane pointing to the vernal equinox, the direction cosines for the Earth-Sun line are

$$(\cos\theta , \cos\phi \sin\theta , \sin\phi \sin\theta) \qquad (2)$$

and the direction cosines for the normal to the orbit are

$$(\sin i \sin\psi, -\sin i \cos\psi , \cos i) \qquad (3)$$

where

i = inclination of the orbit to the equator

θ = angle between X-axis and Earth-Sun line

ψ = angle between X-axis and ascending node of the orbit

ϕ = angle between the ecliptic and the equator

Figure 5 shows the relationship between these angles.

The dot product of (2) and (3) gives

$$\cos\eta = \sin i \sin\psi \cos\theta - \sin i \cos\psi \cos\phi \sin\theta + \cos i \sin\phi \sin\theta \quad (4)$$

A contour map can then be made, plotting t_s as a function of ψ and θ (see Figures 4a - 4i). For this problem, only t_s equal to 100% is of interest and these are the only contours shown on the graphs (Figures 4a - 4i). On these graphs, a trace is plotted representing the change of θ and ψ with respect to time. The location of the sun is given by θ, and θ is essentially a linear measure of the date. This relationship is given by

$$\theta \times \frac{365.25}{360} = \text{days past March 21.} \quad (5)$$

The value of ψ, ψ_o which locates the initial orbital ascending node (see Figure 5) is set by selection of the launch instant on any given launch date.

$$\psi_o = \theta + \gamma + \alpha' \quad (6)$$

where

θ = launch day (Deg):. θ = days past 21st March x $\frac{360}{365.25}$

γ = time of day (Deg):. $\gamma = (T_L - 12) \times 15$ Deg/Hr

T_L = time of launch using a 0-24 hr clock

α' = longitude of ascending node with respect to longitude of launch site is given by $\alpha' = \sin^{-1} \frac{\tan 28.46}{\tan (inc)}$ (7)

inc = orbit inclination

(7)

Once the Space Shuttle is in orbit, ψ will change owing to orbital precession. A simplified expression for precession of a circular orbit is

$$\frac{d\psi}{dt} = -9.97 \left(\frac{R_e}{R_e + h} \right)^{3.5} \cos i \quad \frac{\text{deg}}{\text{day}} \tag{8}$$

where

R_e = Earth's radius

h = Shuttle altitude above the Earth's surface

i = orbit inclination

Since both θ and ψ change at a known constant rate, the trace showing time history of t_s will be a straight line of slope

$$\frac{d\psi}{d\theta} = \frac{d\psi / dt}{d\theta / dt} \tag{9}$$

With the slope printed on a transparent overlay, select a launch day, place the overlay on the contour map with the slope intersecting the contour at the highest point for that day* (see Figure 4f, point a). The horizontal distance between points a and b is the number of days of unobscured solar viewing for the particular value of ψ at a. Using equation 6, and solving for γ gives the time of day for launch to give this length of viewing time for a particular altitude and inclination. The same charts can be used for the months between September 21 and March 21 (i.e., March 21 on graph corresponds to September 21, April 21 corresponds to October 21, etc.).

* Note: The rectangles on the overlays are for alignment. The size of the rectangle is of no significance.

4.2 Effects of Change of Beta Angle on the Doppler Shift

Many types of ground-based solar observations are affected by Doppler shifts of solar spectrum lines caused by the radial component of relative motion between the observer and the point on the Sun being observed. Ground observers are concerned with Doppler shift due to solar rotation. Orbiting observations are concerned with doppler shift due to the approaching and receding of the orbiting observatory. The Doppler shift due to this has significantly more effect than due to solar rotation. If the orbit plane is perpendicular to the Earth-Sun line, the Doppler shift, due to the orbit, is zero.

The beta angle, which is the angle between the Earth-Sun line and the orbit plane (see Figure 3), changes from day to day due to rotation of the Earth around the Sun and orbital precession. Figure 6 shows the change in beta angle over a period of a year for various inclinations. Figure 7 shows the orbital inclination required for a certain beta angle at a specific time of the year.

The minimum allowable beta angle, which in turn determines the orbit inclination, is a function of wavelength to be observed (see Figure 8). If 3000 Å is the longest wavelength to be observed, an allowable Doppler shift of .01 Å would be maintained if the beta angle never drops below 83° during the mission for a Shuttle altitude of 300 N. Mi.

4.3 Example

If a seven-day mission with a maximum of 3000 Å to be observed,

1. When would a mission be possible during the year,
2. What is the lowest inclination allowable, and
3. What is the lowest altitude?

To maintain a Doppler shift of less than .01 Å for wavelengths up to 3000 Å, a beta angle of at least 83° must be maintained (see Figure 8). Figure 9 could also be used as it is a normalized graph of Figure 8 to be used for any wavelength. Using Figure 7, it can be seen that the allowable orbit inclination range is between 60° and 90°, depending on the time of the year. Using Figure 4d with its corresponding overlay, (disregarding beta angle requirements), it can be seen that possible seven-day missions occur from:

1.	May 9 - July 21 November 9 - January 21	for 275 N. Mi.
2.	April 30 - August 3 October 30 - February 3	for 300 N. Mi.
3.	April 27 - August 11 October 27 - February 11	for 350 N. Mi.
4.	April 11 - August 18 October 11 - February 18	for 400 N. Mi.

Using Figure 7, a beta angle of 83° for an inclination of 65° occurs from May 1 (and November 1) to August 11 (and February 11). This means that Shuttle missions can take place from:

1.	May 9 - July 21 November 9 - January 21	for 275 N. Mi.
2.	May 1 - August 3 November 1 - February 3	for 300 N. Mi.

3. May 1 - August 11
November 1 - February 11 for 350 N. Mi.

4. May 1 - August 11
November 1 - February 11 for 400 N. Mi.

Compare the above time ranges with the ones just preceding these.

5. CONCLUSION

The example shows that by using the working graphs in this document, a quick, fairly accurate approximation can be made to determine the feasibility of Shuttle Solar Astronomy Sortie Missions for any altitude, inclination, or time of the year.

ORBITING SOLAR OBSERVATORY VIEWING TIME

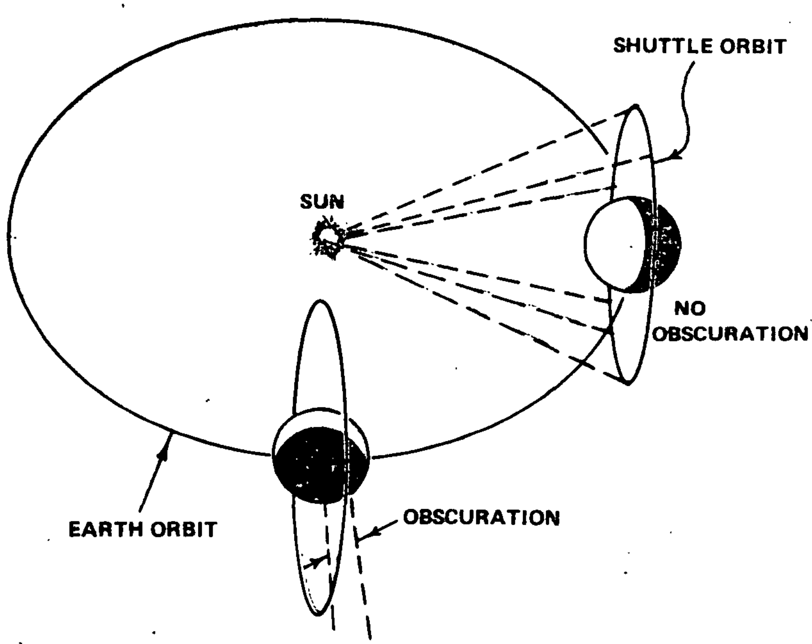


FIGURE 1. OBSCURATION OF THE SPACE SHUTTLE IN EARTH ORBIT

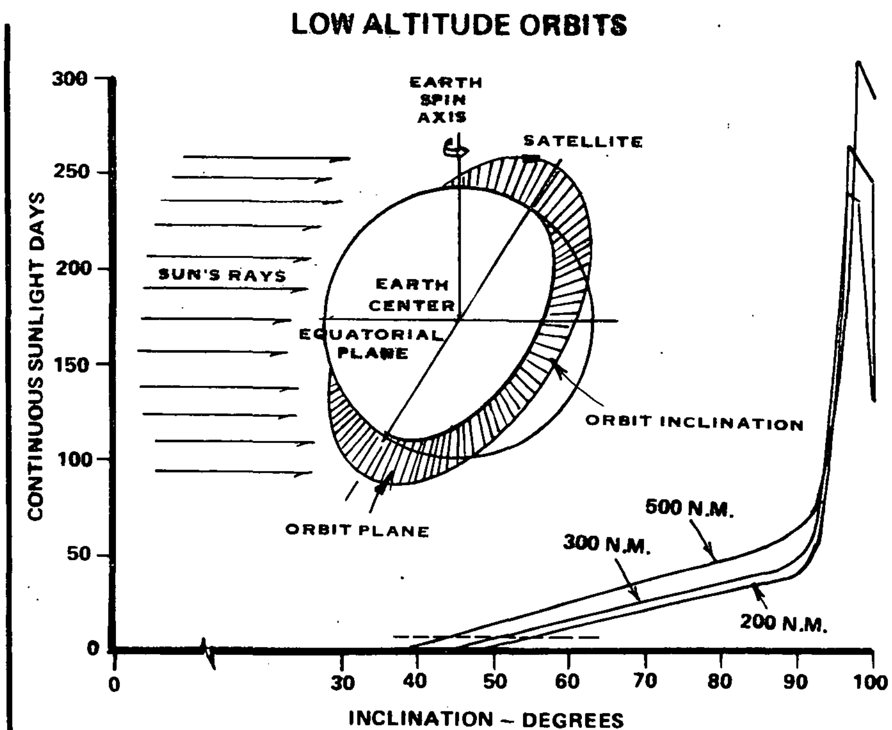


FIGURE 2. CONTINUOUS SUNLIGHT DAYS VS. ORBITAL INCLINATION FOR VARIOUS ALTITUDES

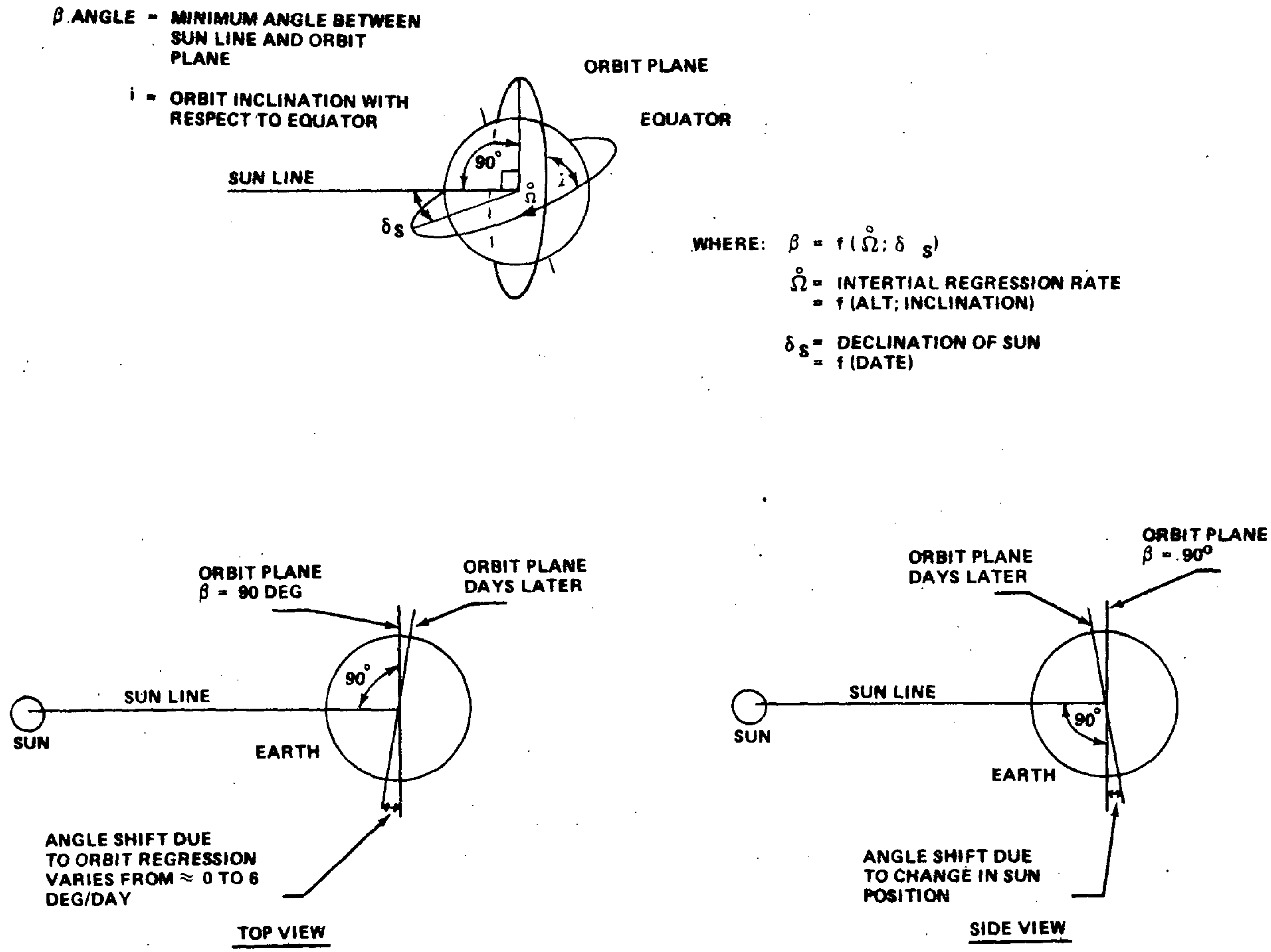


FIGURE 3 SUN LINE-ORBIT PLANE BETA ANGLE (β) RELATIONS

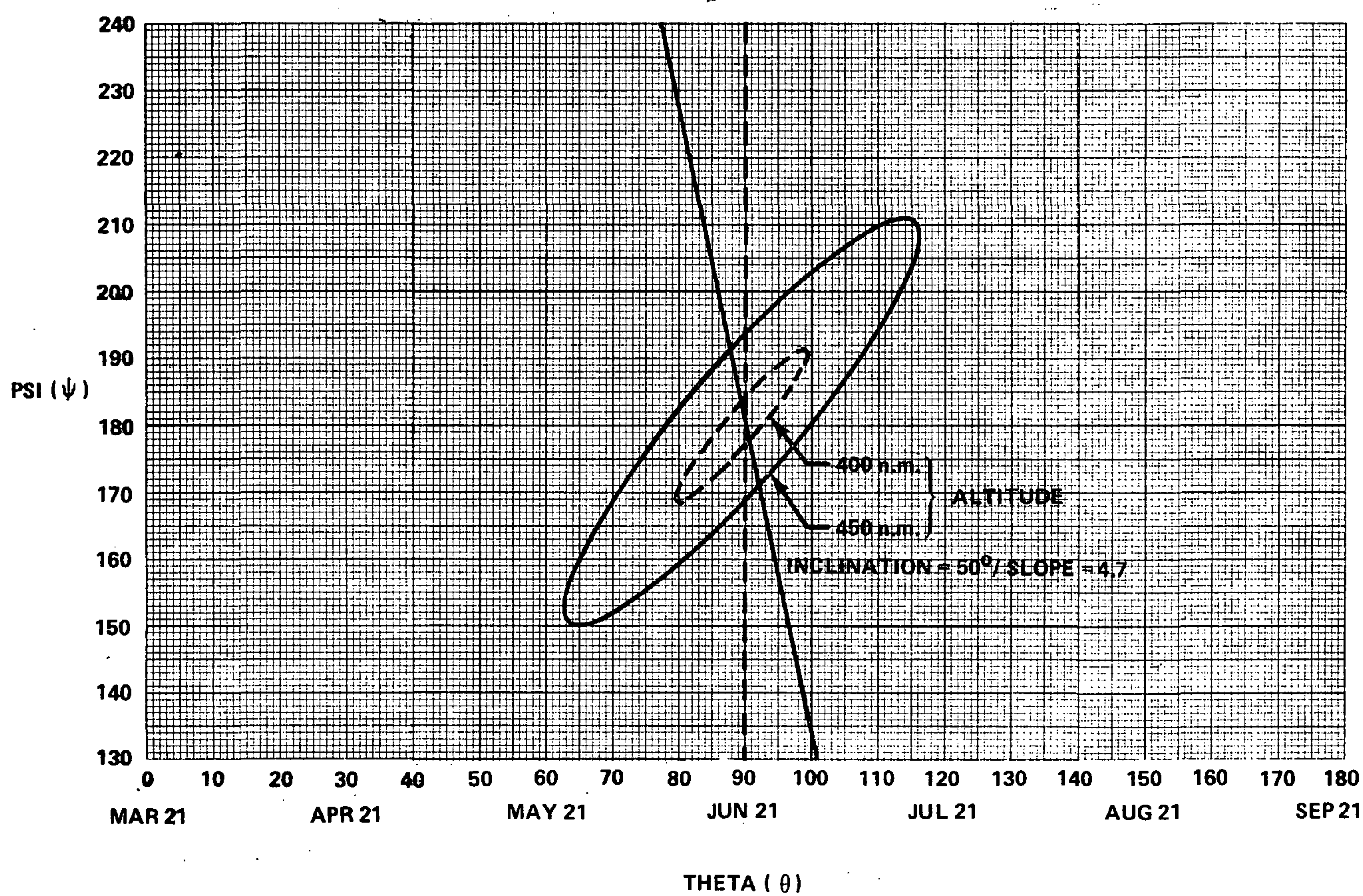


FIGURE 4a. CONTOUR MAP FOR VARIOUS ALTITUDES WITH AN INCLINATION OF 50°

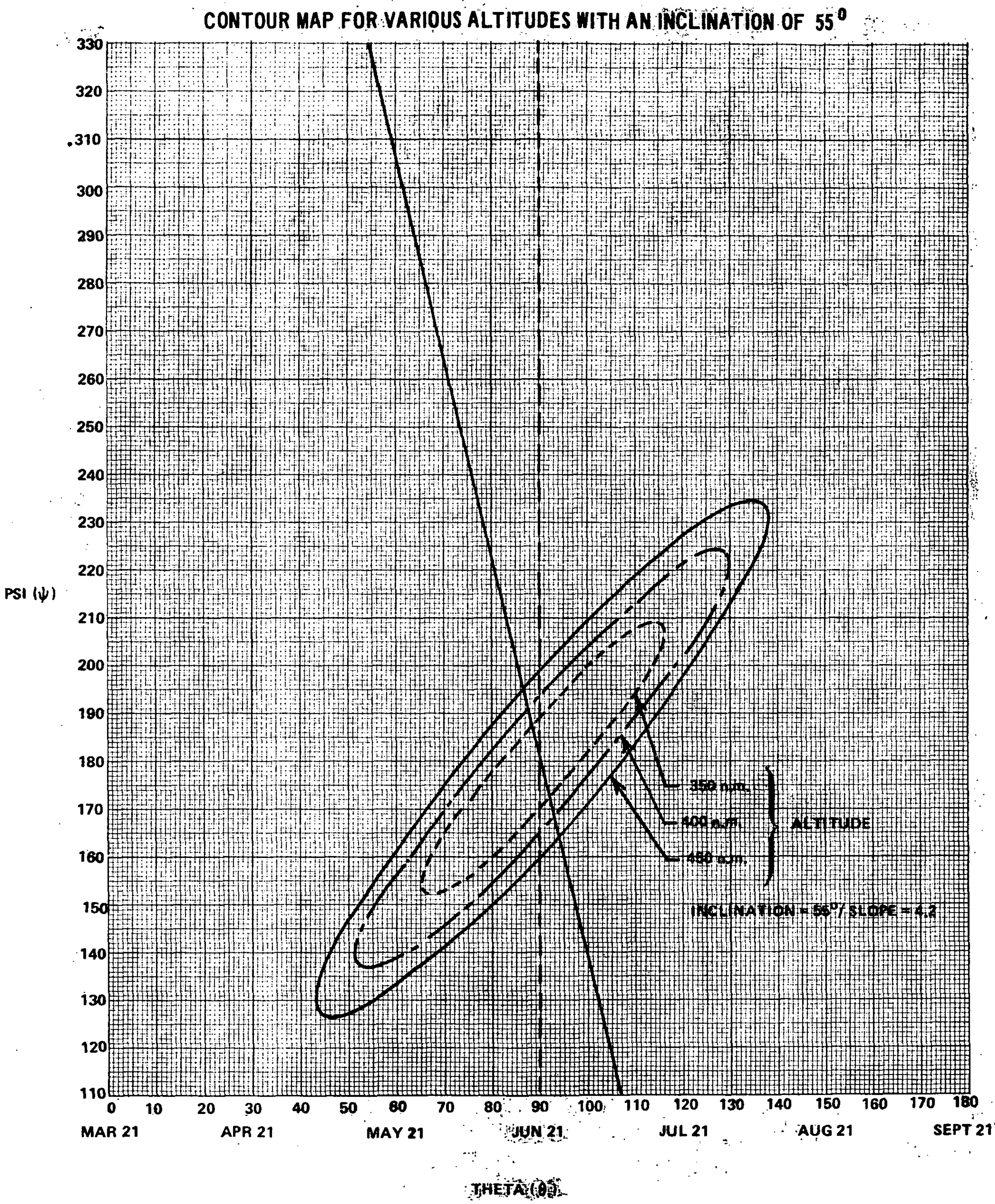


FIGURE 4b. CONTOUR MAP FOR VARIOUS ALTITUDES WITH AN INCLINATION OF 55°

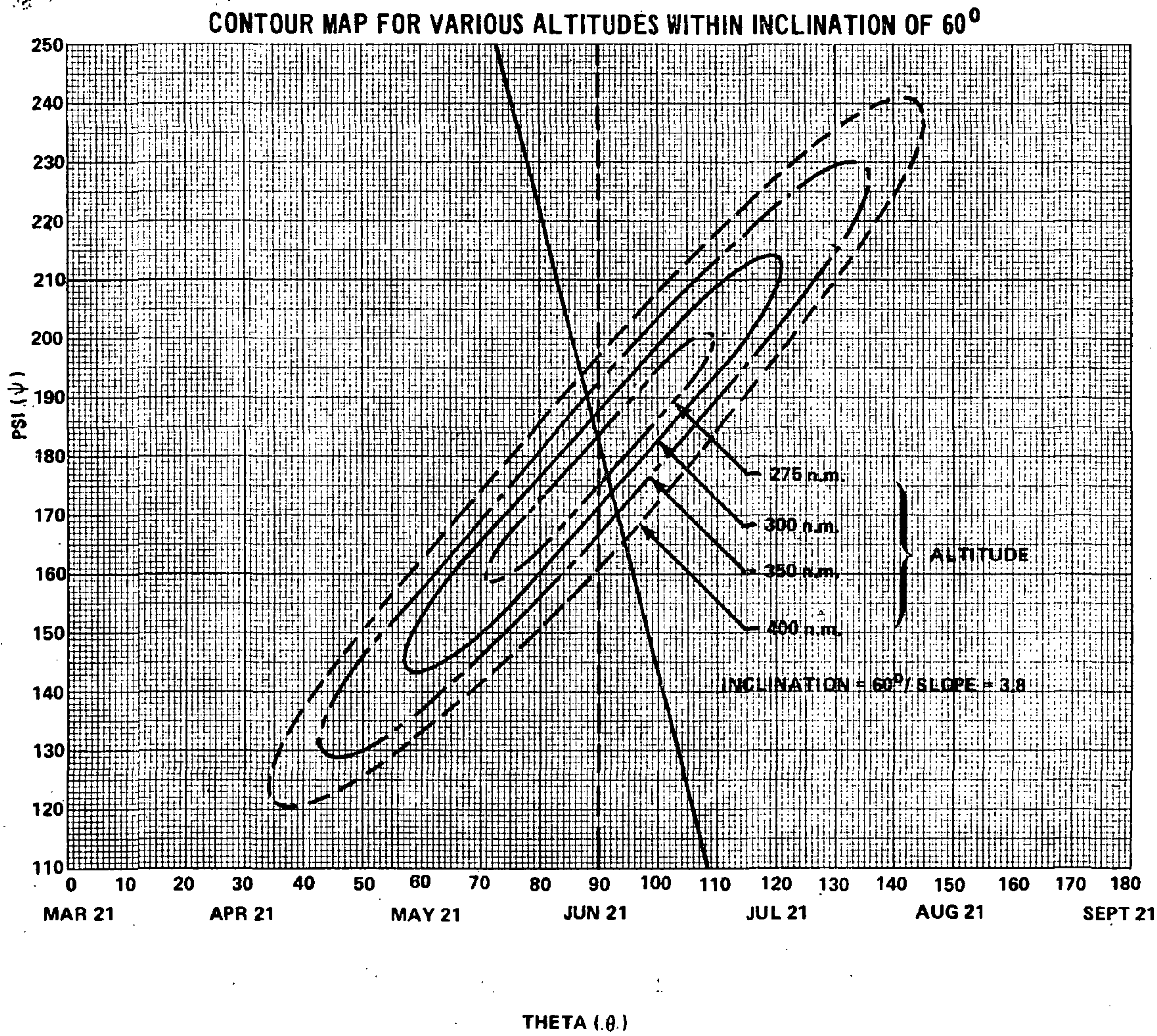


FIGURE 4c. CONTOUR MAP FOR VARIOUS ALTITUDES WITH AN INCLINATION OF 60°

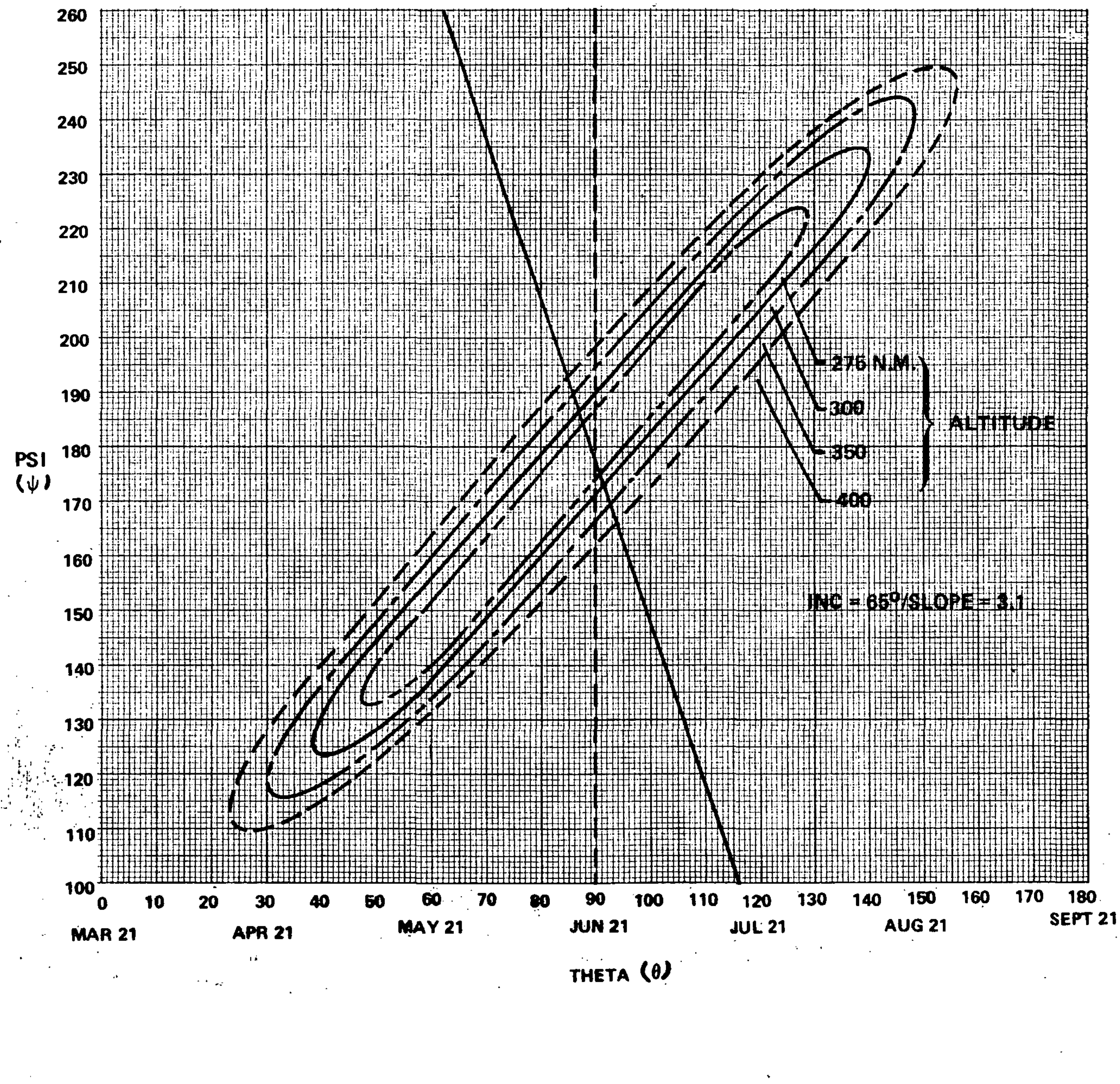


FIGURE 4d. CONTOUR MAP FOR VARIOUS ALTITUDES WITH AN INCLINATION OF 65°

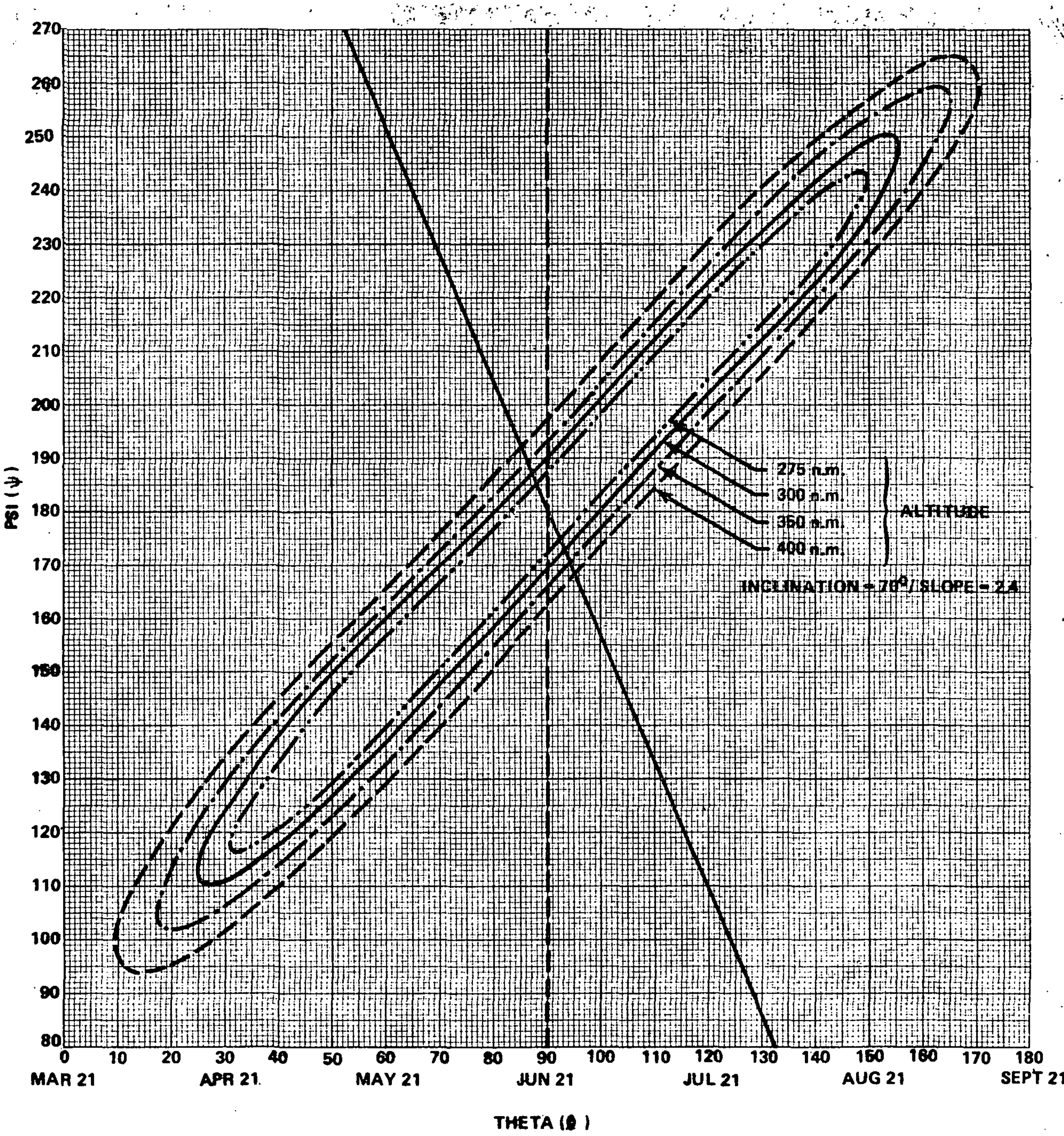


FIGURE 4e. CONTOUR MAP FOR VARIOUS ALTITUDES WITH AN INCLINATION OF 70°

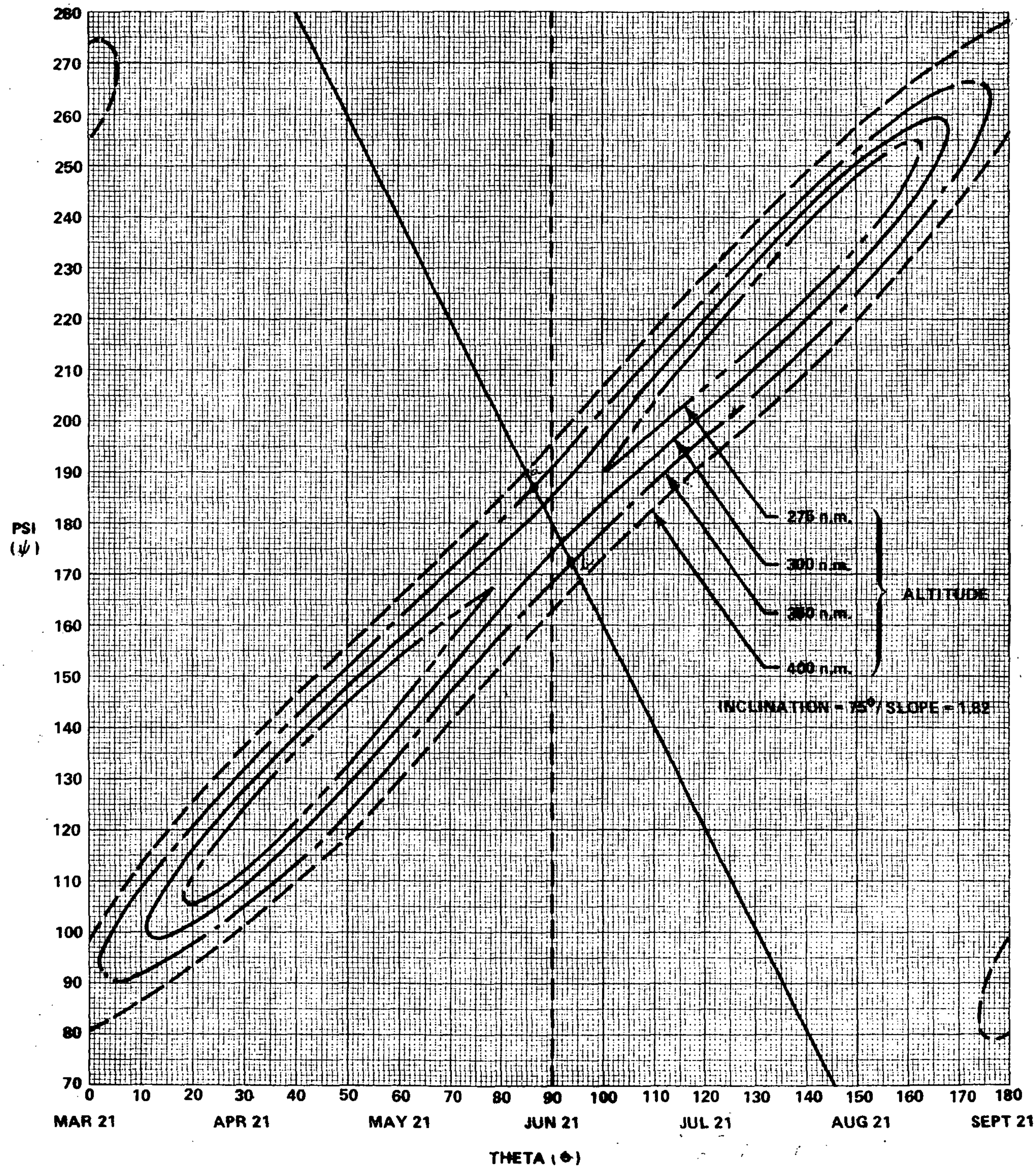


FIGURE 4f. CONTOUR MAP FOR VARIOUS ALTITUDES WITH AN INCLINATION OF 75°

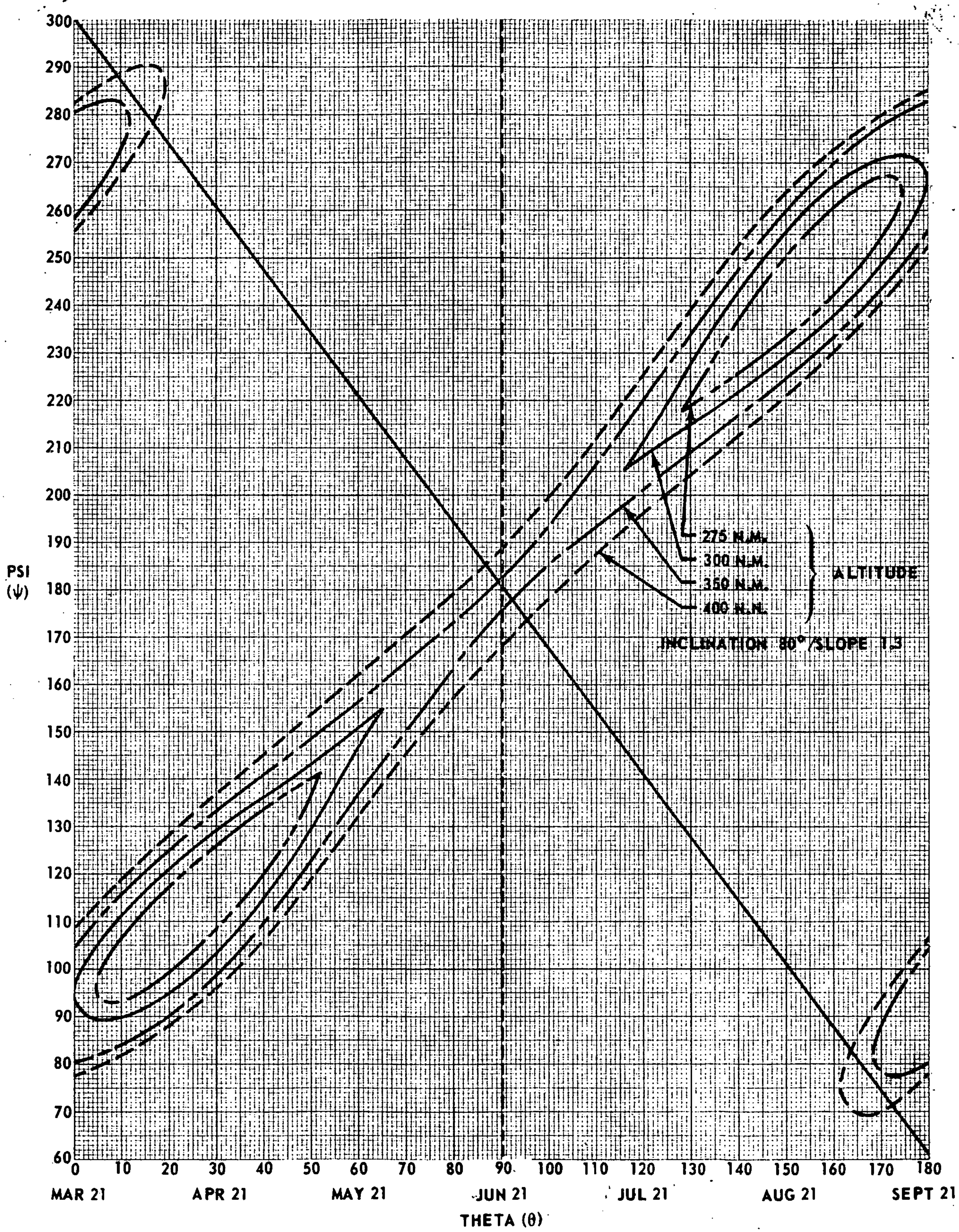


FIGURE 4g. CONTOUR MAP FOR VARIOUS ALTITUDES WITH AN INCLINATION OF 80°

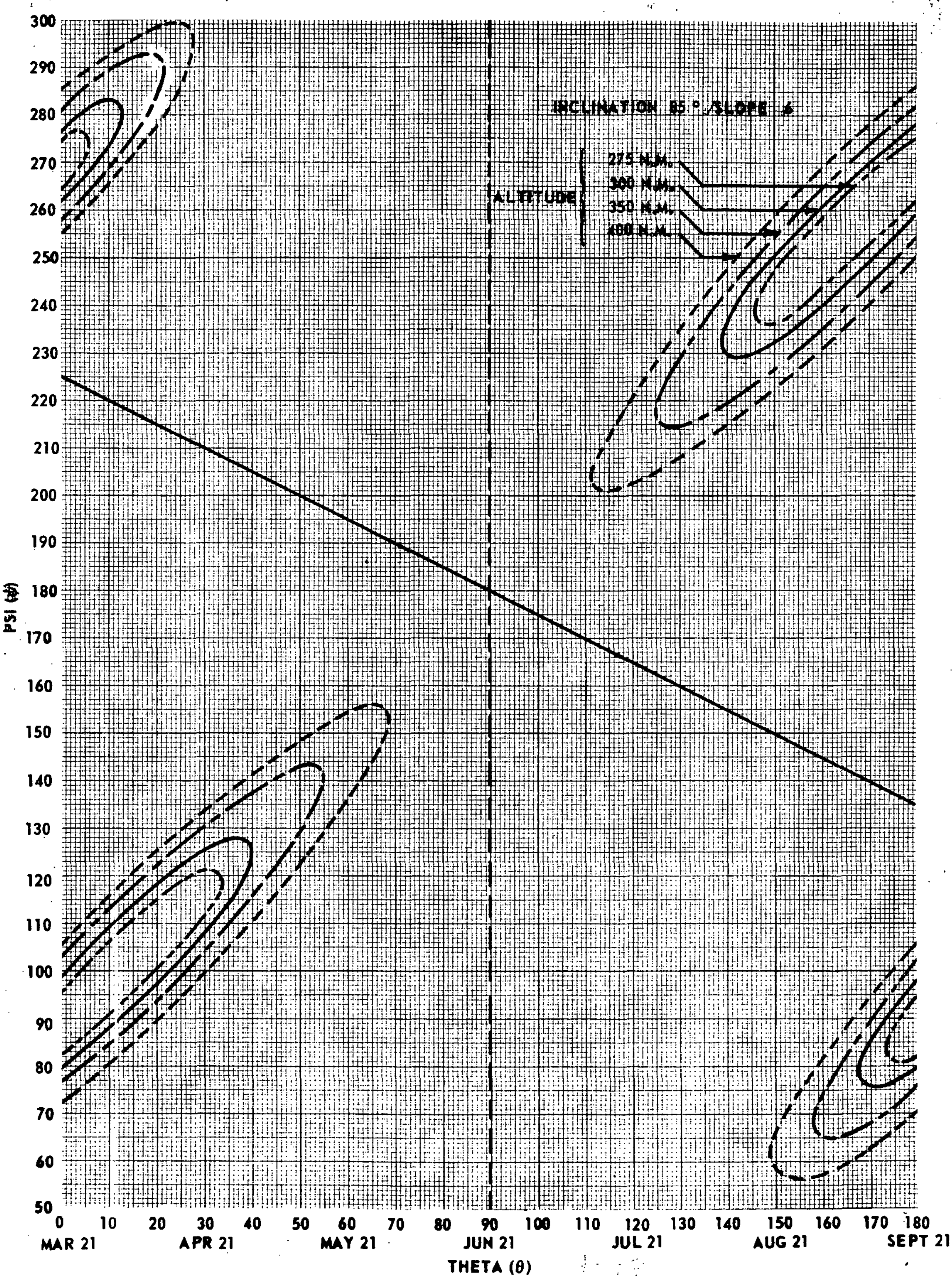


FIGURE 4h. CONTOUR MAP FOR VARIOUS ALTITUDES WITH AN INCLINATION OF 85°

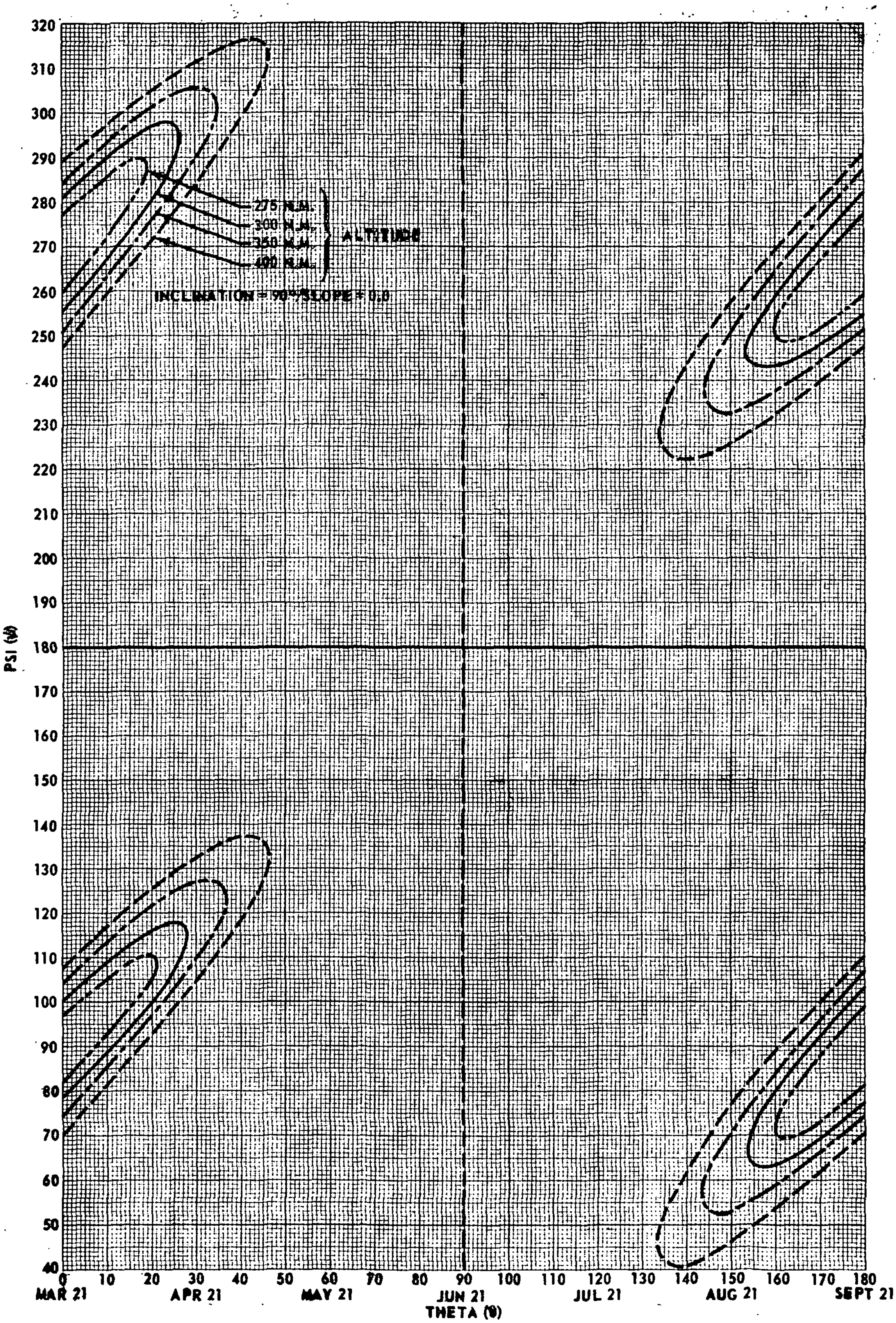


FIGURE 4i. CONTOUR MAP FOR VARIOUS ALTITUDES WITH AN INCLINATION OF 90°

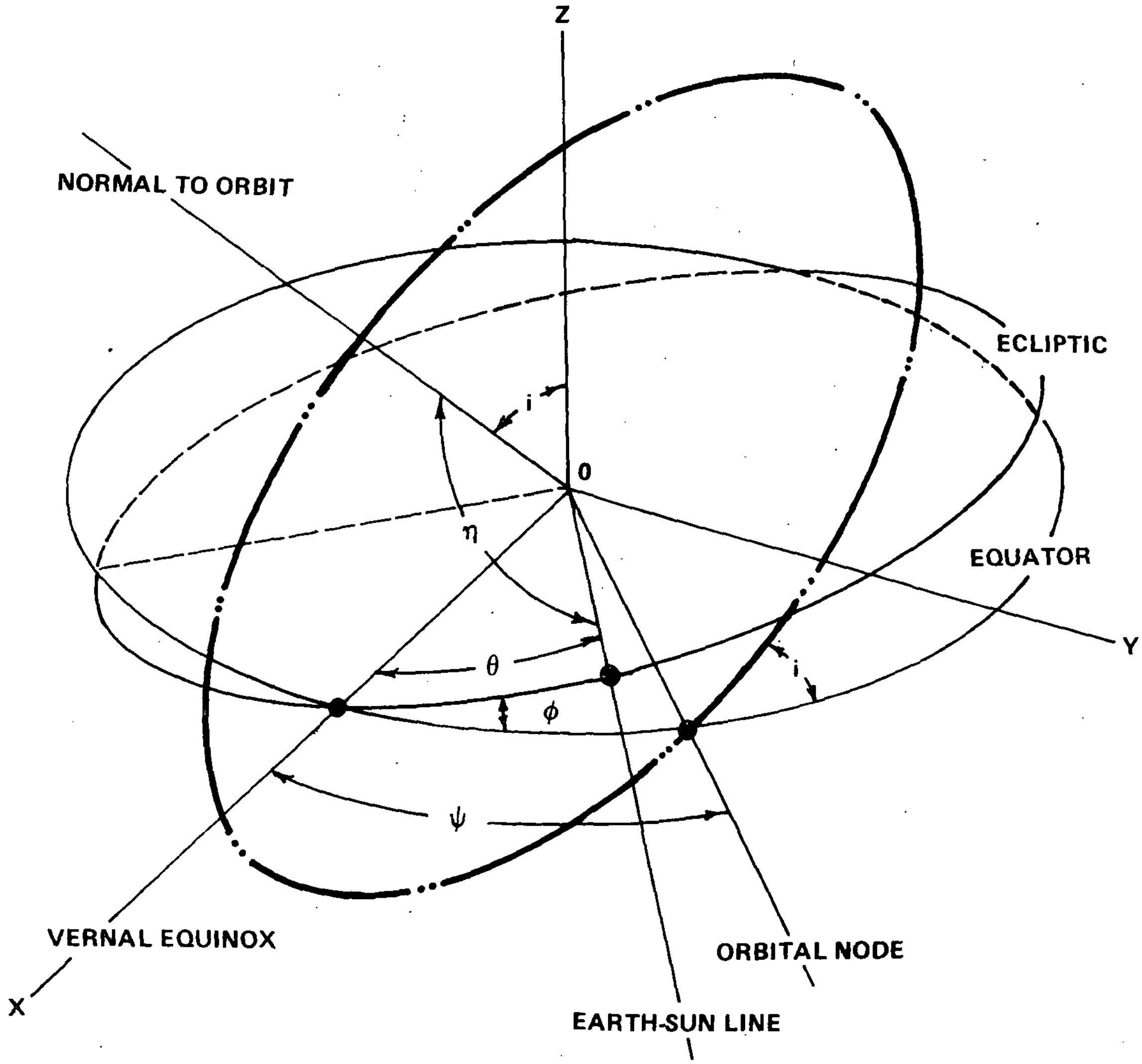


FIGURE 5. GEOMETERY OF THE EARTH ORBIT AND SATELLITE ORBIT ANGLES

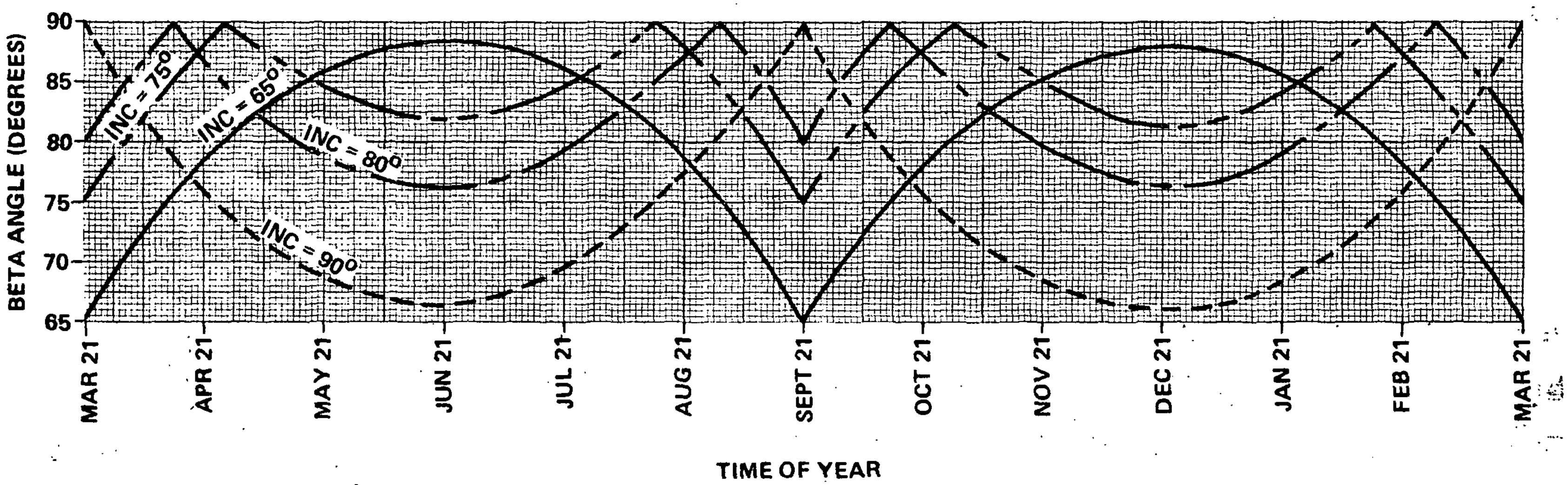
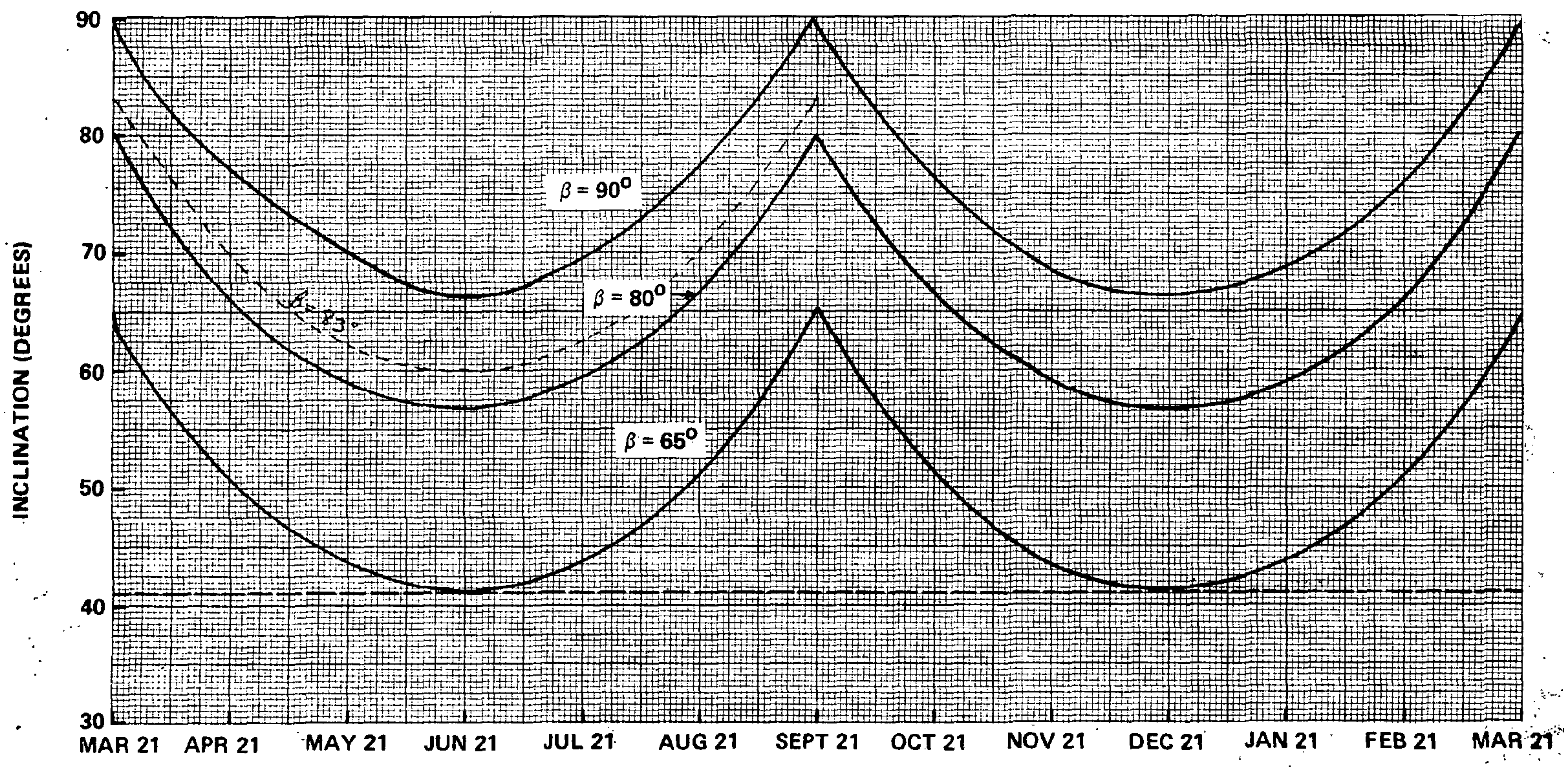


FIGURE 6. BETA ANGLE VS TIME OF YEAR FOR VARIOUS ORBIT INCLINATIONS



NOTE:
65° IS THE MINIMUM BETA ANGLE ALLOWABLE FOR $\lambda \geqslant 1000Å$
BETA IS LIMITED BY THE RESOLUTION OF .01Å FOR $\lambda = 1000Å$

FIGURE 7. INCLINATION VS TIME OF YEAR FOR VARIOUS BETA ANGLES

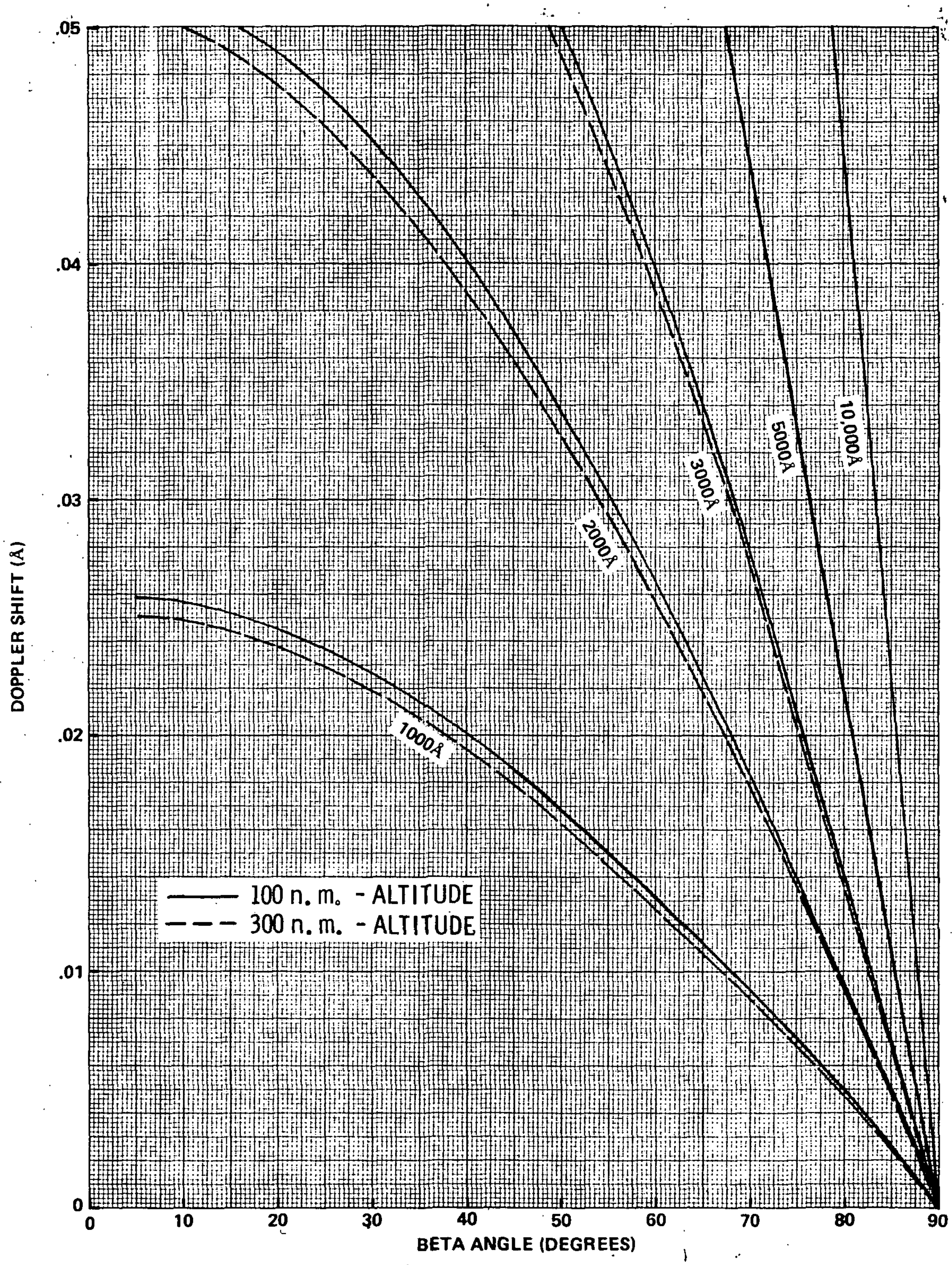


FIGURE 8. BETA ANGLE VS DOPPLER SHIFT

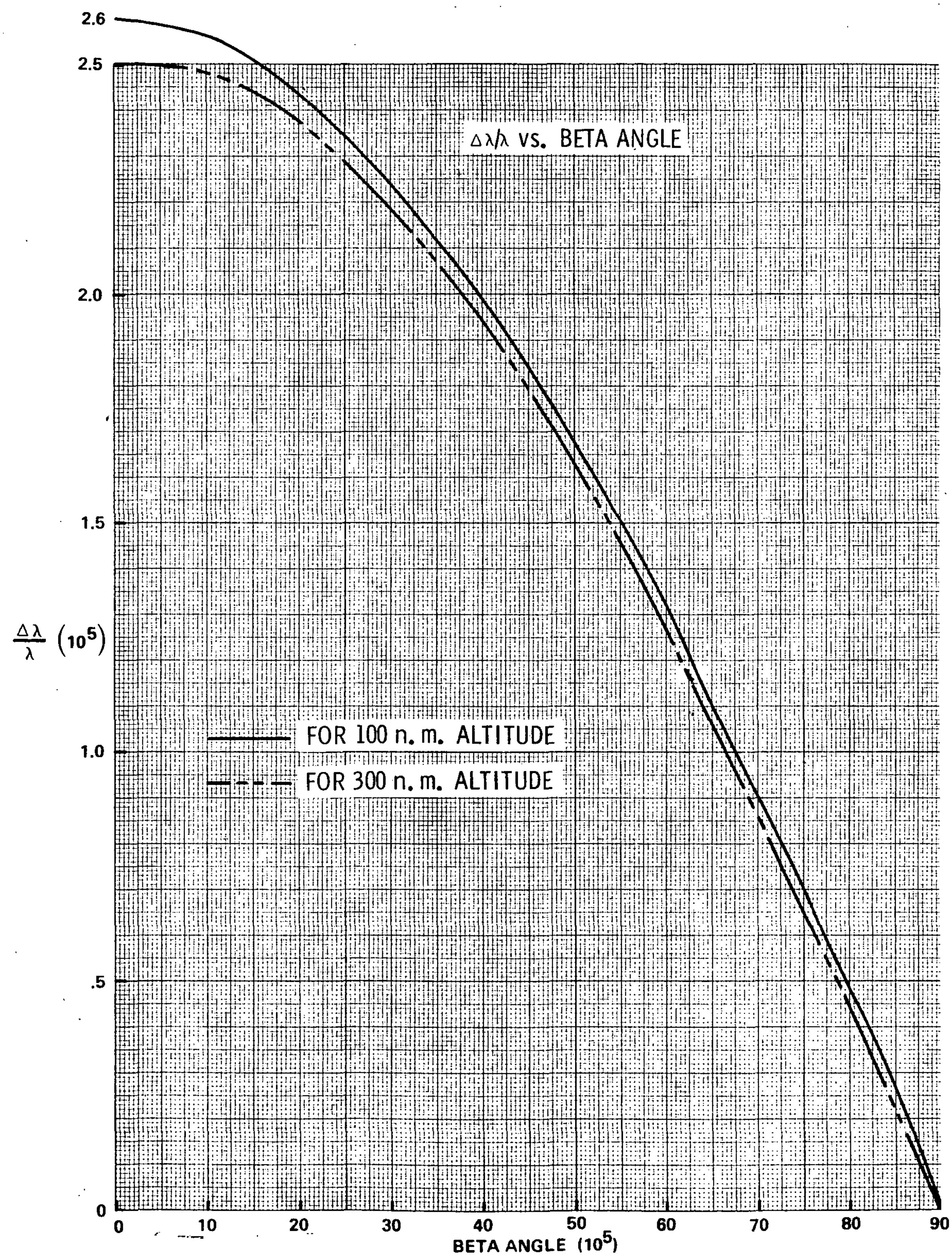


FIGURE 9. NORMALIZED DOPPLER SHIFT VS BETA ANGLE

APPROVAL

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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