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COORDINATE TRANSFORMATIONS FOR STUDIES OF INTERACTIONS BETWEEN INTERPLANETARY AND GEOMAGNETIC FIELDS

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ABSTRACT

A graphical procedure is provided for performing coordinate transformations between the geocentric-solar-equatorial, geocentric-solar-ecliptic and geocentric-solar-magnetospheric coordinate systems. This procedure should facilitate intercomparison of the many previously published studies of possible interactions between interplanetary and geomagnetic fields that have been carried out in various of these three coordinate systems. It will hopefully also make easier the performance of future studies of the interaction in the geocentric-solar-magnetospheric system, which of the three has been shown to give the most consistent results.

INTRODUCTION

The purpose of this report is to provide a convenient means of transforming satellite vector data from solar-equatorial (GSEQ) and solar-ecliptic (GSE) coordinates to solar-magnetospheric (GSM) coordinates, which have been shown to be the most appropriate of the three for use in studies of possible interactions between interplanetary and geomagnetic fields. The information presented herein can be used for two important purposes: first, to facilitate the performance of future studies of the interaction in a common coordinate system, and second, to make possible intercomparison of the many previously published studies that were, for reasons chiefly concerned with the expense involved in computer coordinate transformations, presented in various of these three different coordinate systems.

The solar-magnetospheric system was introduced by Ness (1965), who found that the position of the magnetotail neutral sheet showed a more systematic behavior in GSM coordinates than in GSE or geomagnetic coordinates. Subsequently Hirshberg and Colburn (1969), in examining the statistical relationship of geomagnetic activity to interplanetary magnetic field (IMF) parameters, found a better correlation when the IMF was expressed in GSM coordinates than when it was expressed in GSEQ coordinates. Similarly, Arnoldy (1971) examined the correlation between disturbances registered by the AE index and various IMF parameters for GSM and GSE coordinates, concluding that the relationship was more consistent for GSM coordinates. Arnoldy also showed that a nearly linear statistical relationship existed between the hourly average AE index and the previous hour's integrated GSM southward component of the IMF. Although this was a very significant statistical result, it did not imply that a southward IMF Z component was a necessary prerequisite for the occurrence of substorm activity in the auroral zone. In fact, examples of northward-IMF auroral-zone substorms have been pointed out by Burch (1972) and others. This does not mean, however, that the size or occurrence of substorms is not related to the IMF direction. Rather it simply implies that the relationship is more subtle than one that can be described by the mere "IMF southward" or "IMF northward" dichotomy that has been adopted or attacked by many investigators. The transfer of energy, if not mass and momentum, from the solar wind to the magnetosphere does seem to occur more efficiently when the IMF is directed more southward. The energy transfer does not, however, stop when the IMF Z component becomes northward in any particular coordinate system.

Plasma flow and magnetic-field observations in the tail (Hones et al., 1972, Nishida and Hones, 1974) are beginning to provide convincing evidence of the occurrence of magnetic merging across the neutral sheet. The situation there is much simpler than that at the interface between interplanetary and geomagnetic fields since the plasma densities and magnetic field strengths are equal and the fields are antiparallel on either side of the merging region. The more complicated situation existing at the magnetopause, coupled with the lack of coverage by spacecraft remaining in the magnetopause layer for extended periods of time, give us less hope of obtaining *in situ* evidence for merging between interplanetary and geomagnetic fields. Nevertheless, quantitative information on large-scale magnetospheric parameters, such as polar-cap electric fields (Mozer and Gonzalez, 1973) and the amount of magnetic flux transferred from the dayside to the nightside (Burch, 1973), as they respond to IMF variations have shown systematic behavior consistent with the results of recent geometrical merging models (Gonzalez, 1973; Sonnerup, 1974). Needless to say, it is crucial that such investigations be performed in an appropriate coordinate system, such as GSM, that takes into account the changing relative orientation of the magnetospheric field in the solar-wind flow.

The detailed relationship between IMF parameters and the occurrence of substorms is complicated further by the sparse network of ground-based observatories capable of detecting isolated substorms. It is rather firmly established that the IMF determines the size of the auroral oval (Akasofu et al., 1973; Kamide and Akasofu, 1974) and with it the size of and total energy involved in substorms. One should not conclude, however, from the observations of Akasofu et al., 1973), which indicated that contracted-oval substorms occur when the IMF Z component is GSEQ- or GSE- northward, that the occurrence of substorms is unrelated to the IMF direction. Burch (1974) has shown that re-examination of the contracted-oval substorms of the Akasofu et al. (1973) study with the IMF expressed in GSM coordinates results in a rather systematic behavior. That is, the IMF latitude was in the rather narrow range of about 10° to 30° northward for a half-hour or more before the onset of each substorm.

It is evident, therefore, that further progress in our understanding of the interplanetary-geomagnetic field interaction will be aided by the availability of IMF data in GSM coordinates. Unfortunately, almost all the data available in the National Space Science Data Center are in GSEQ or, to a lesser extent, GSE coordinates, and are in plotted form rather than in digital form, making transformation by computer both time-consuming and costly. Furthermore, there exist many published papers on the interaction in which GSEQ or GSE coordinates were used. As noted above, intercomparison of these would be aided by the existence of a quick visual means of coordinate transformation such as that described below.

DESCRIPTION OF COORDINATE TRANSFORMATION PLOTS

An example of the relative orientations of the GSM, GSE, and GSEQ systems on day 210 at 13 hrs. UT is shown in Figure 1. The relation between GSM coordinates and either of the other two is specified by the single parameter α. The value of α represents the rotation angle from the positive Z_{GSM} axis, about the X-axis, which in all three systems is directed from the earth toward the sun. Positive values of α correspond to cases in which the Z axis of the GSEQ or GSE system is tilted toward dusk, or toward the $+Y_{GSM}$ axis, as in Figure 1.

The matrix formulations of Russell (1971) were used in generating the plots in Figures 2 through 10. The paper by Russell (1971) also describes in detail the three coordinate systems discussed here as well as other systems of geophysical interest.

Figures 2 and 3 show contour plots of constant α as functions of UT and day of year for GSEQ and GSE coordinates respectively. The value of α derived from one of these plots is then used to choose one of the seven plots (one for each 5° increment in α) in Figures 4 through 10 which transform to the GSM system. The same plots are used for the GSEQ-GSM and the GSE-GSM transformation since the information in Figures 4-10 depends only on the value of α. In each of the plots in Figures 4-10, contours of constant GSM latitude (solid curves) and of constant GSM longitude (dashed curves) are plotted versus latitude and longitude in either GSEQ or GSE coordinates. Note in Figures 4 through 10 that the upper signs on the GSE/GSEQ latitude axis and on the GSM latitude contours are used for positive values of α while the lower signs are used for negative values of α.

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FIGURE CAPTIONS

Figure 1: Relative orientations of the GSM, GSE and GSEQ coordinate systems on day 210 at 13 hrs. UT. The positive direction for α as used in figures 2 and 3 is illustrated.

Figure 2: Contours of constant α, where α is the angle of rotation about the X axis from the GSM system to the GSE system. The plus signs mark the extreme values, $\alpha = \pm 35^{\circ}$.

Figure 3: Contours of constant α, where α is the angle of rotation about the X axis from the GSM system to the GSEQ system. The plus signs mark the extreme values, $\alpha = \pm 37.8^{\circ}$.

Figure 4: Contours of constant GSM latitude and longitude as functions of GSE or GSEQ latitude (λ) and longitude (ϕ) for the rotation angle $\alpha = \pm 5^{\circ}$. The upper signs on the GSE/GSEQ latitude axis and on the GSM latitude contours are used for positive values of α, while the lower signs are used for negative values of α.

Figure 5: Same as Figure 4 except for $\alpha = \pm 10^{\circ}$.

Figure 6: Same as Figure 4 except for $\alpha = \pm 15^{\circ}$.

Figure 7: Same as Figure 4 except for $\alpha = \pm 20^{\circ}$.

Figure 8: Same as Figure 4 except for $\alpha = \pm 25^{\circ}$.

Figure 9: Same as Figure 4 except for $\alpha = \pm 30^{\circ}$.

Figure 10: Same as Figure 4 except for $\alpha = \pm 35^{\circ}$.

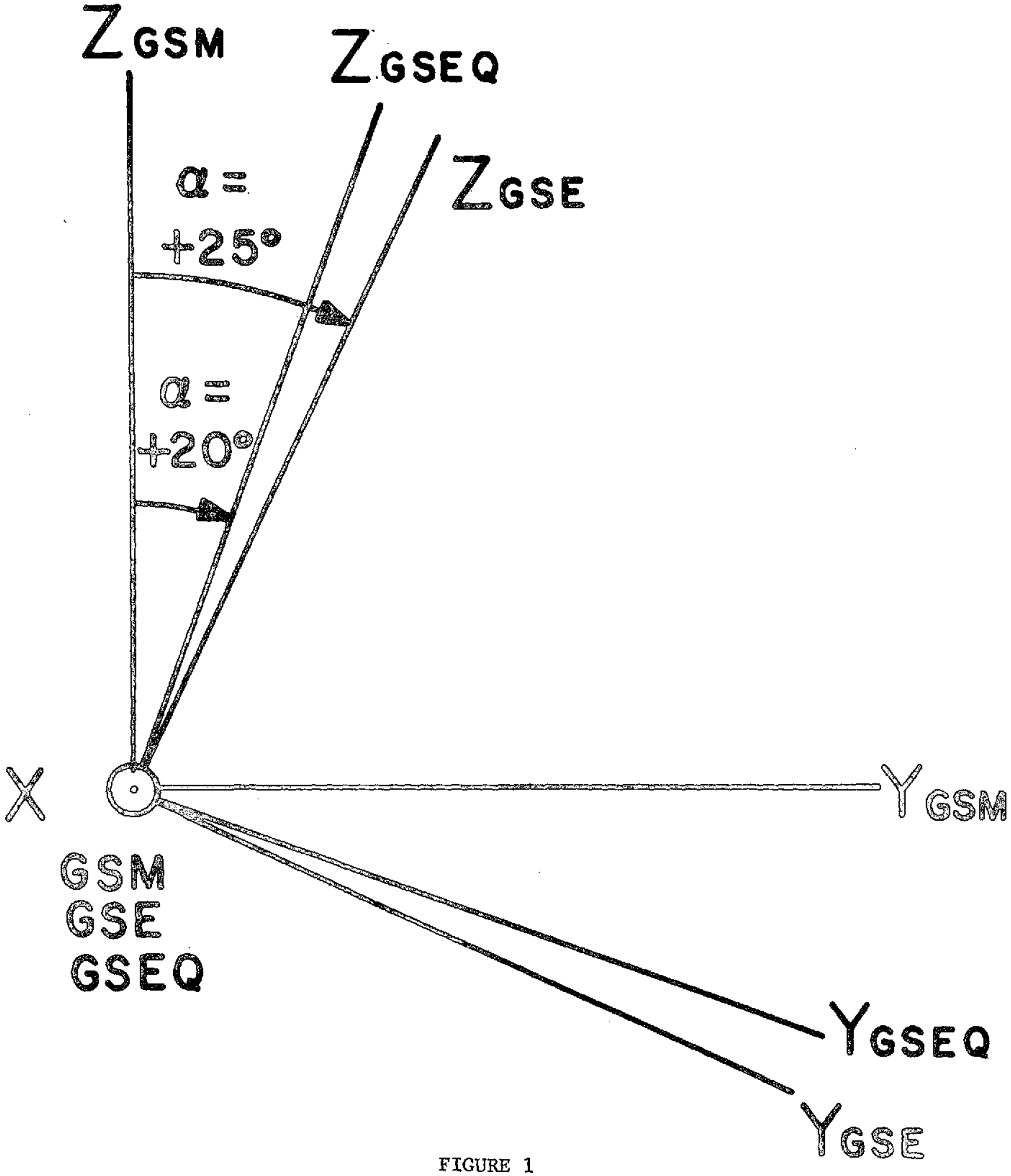
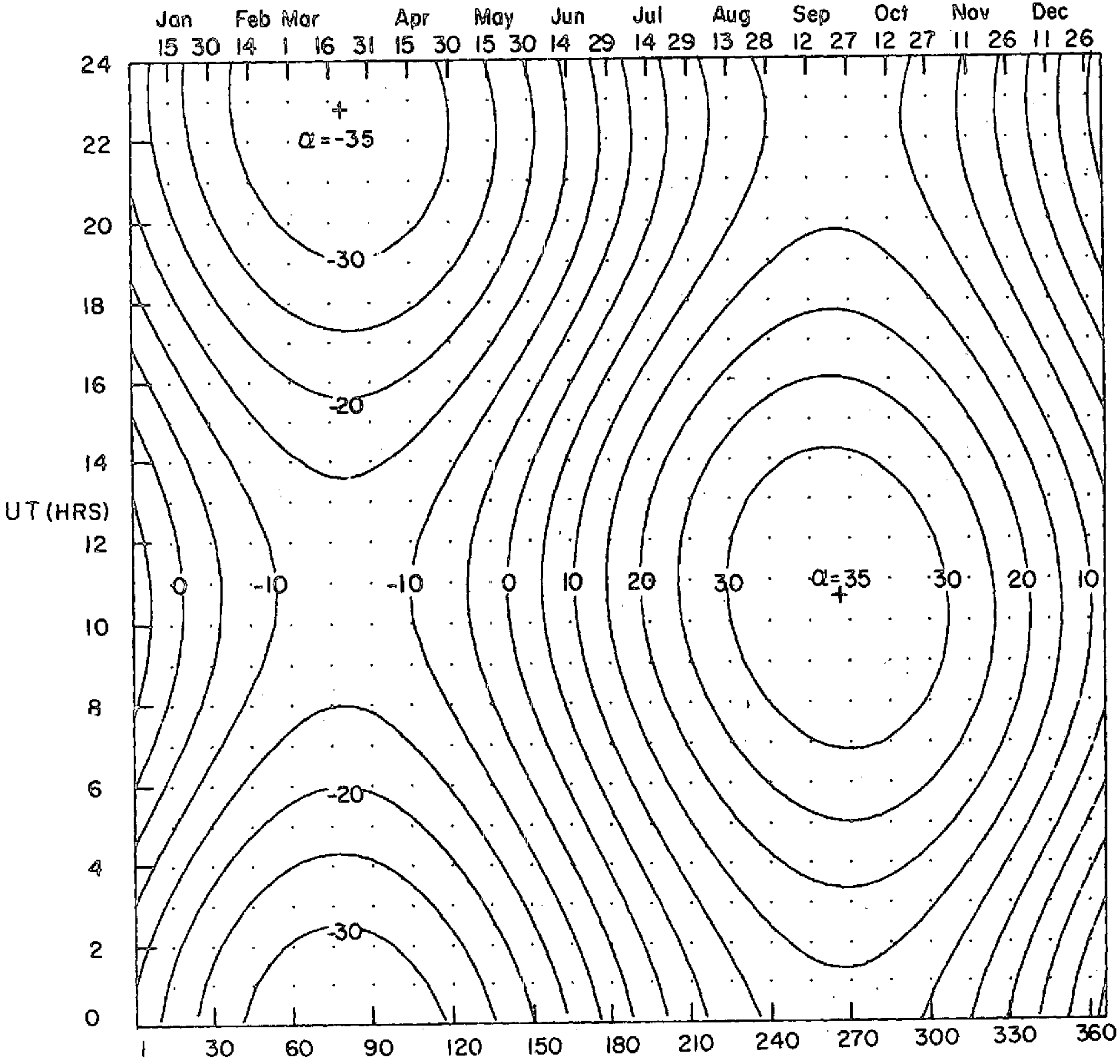


FIGURE 1



Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15 30 14 1 16 31 15 30 15 30 14 29 14 29 13 28 12 27 12 27 11 26 11 26
24
22
20
18
16
14
UT (HRS)
12
10
8
6
4
2
0
1
30
60
90
120
150
180
210
240
270
300
330
360
DAY OF YEAR
α=-35
-30
-20
0
-10
-10
0
10
20
30
α=35
30
20
10
-20
-30

FIGURE 2

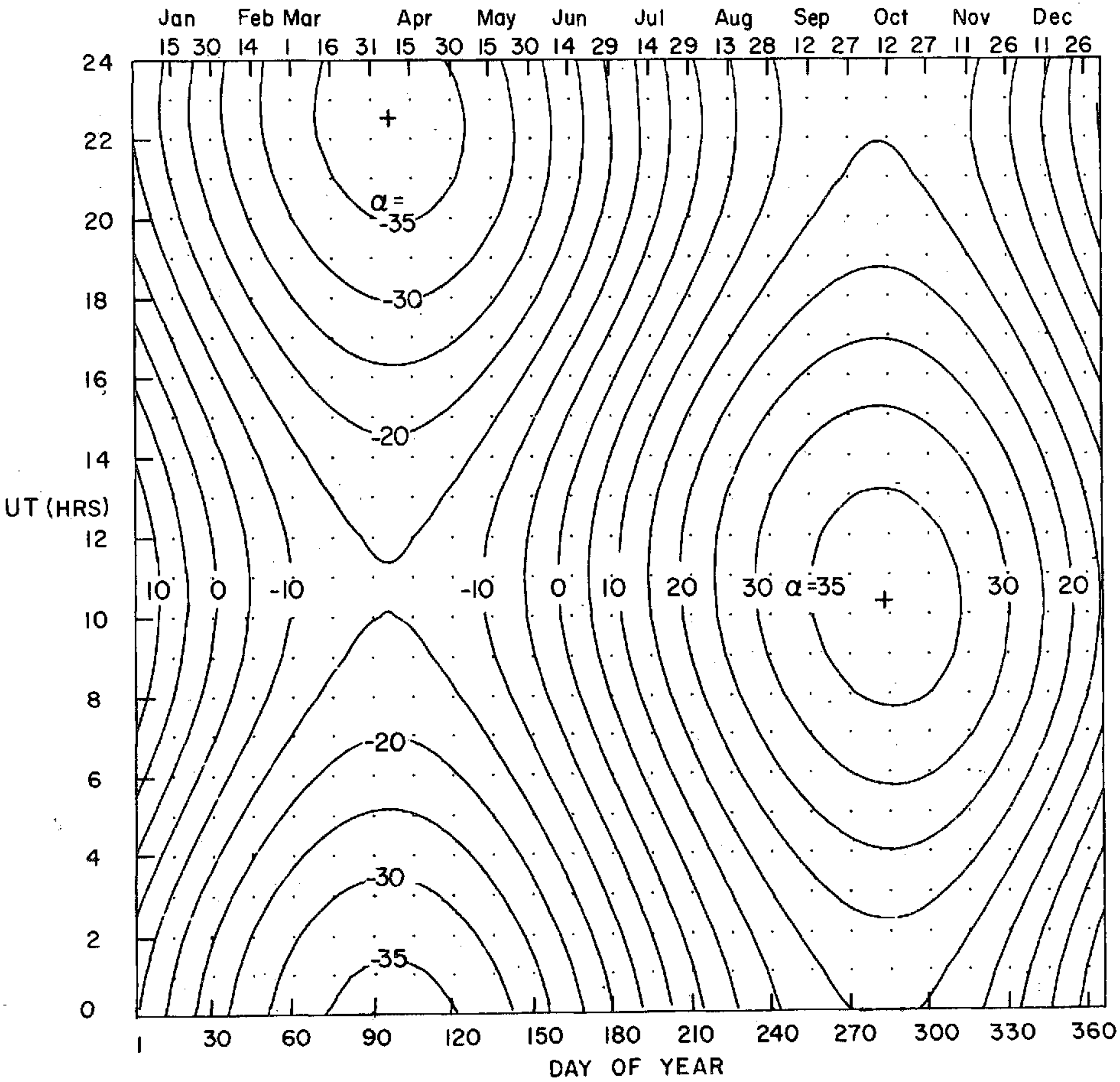

Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15 30 14 1 16 31 15 30 15 30 14 29 14 29 13 28 12 27 12 27 11 26 11 26
UT (HRS)
0
2
4
6
8
10
12
14
16
18
20
22
24
α = -35
-30
-20
-20
-30
-35
10
0
-10
-10
0
10
20
30
α =35
30
20
1
30
60
90
120
150
180
210
240
270
300
330
360
DAY OF YEAR

FIGURE 3

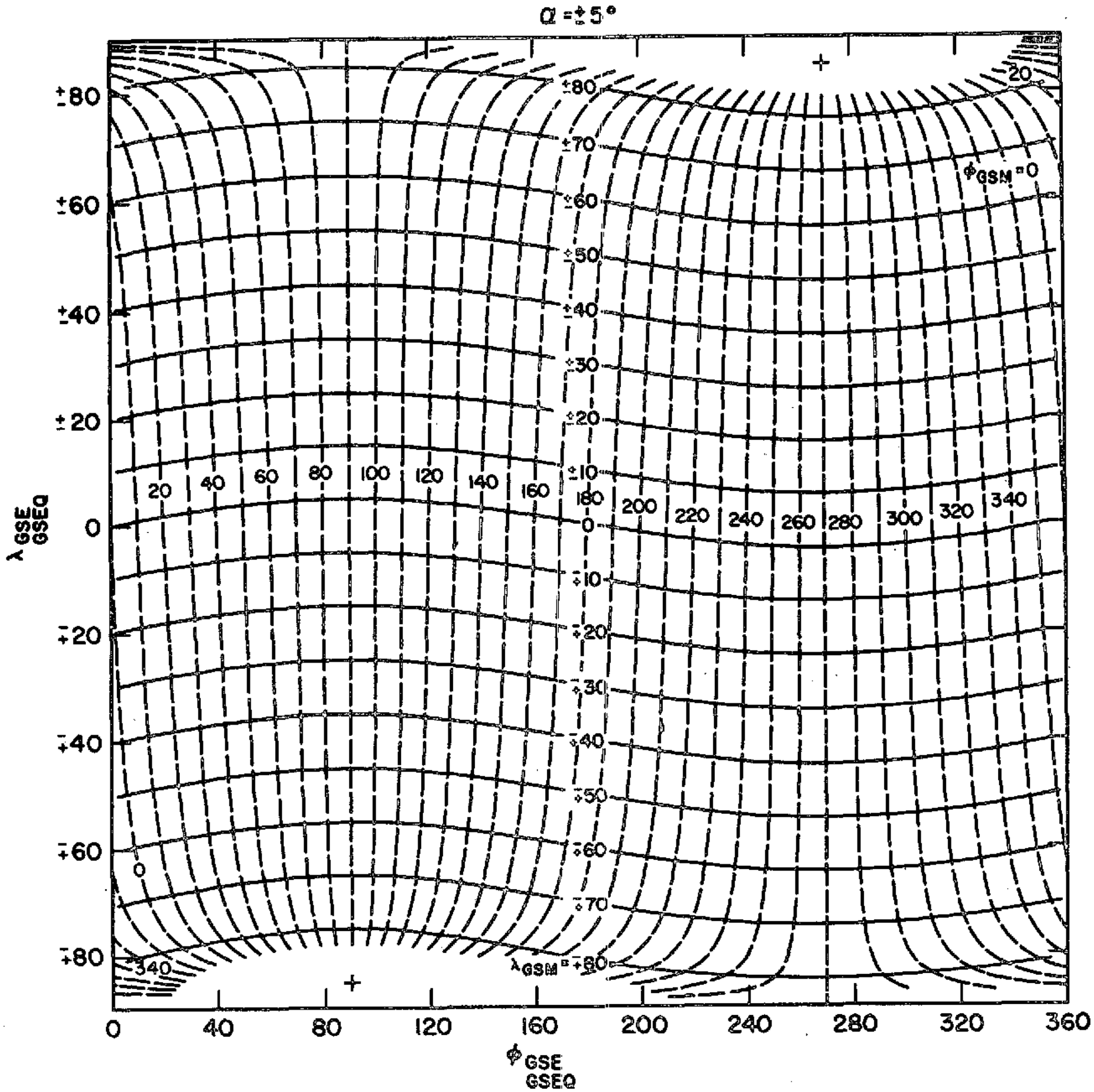

α = ±5°
±80
±60
±40
±20
0
∓20
∓40
∓60
∓80
λ GSE GSEQ
0
40
80
120
160
200
240
280
320
360
φ GSE GSEQ
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
±80
±70
±60
±50
±40
±30
±20
±10
0
∓10
∓20
∓30
∓40
∓50
∓60
∓70
λGSM = ∓80
φGSM = 0
20
0
340

FIGURE 4

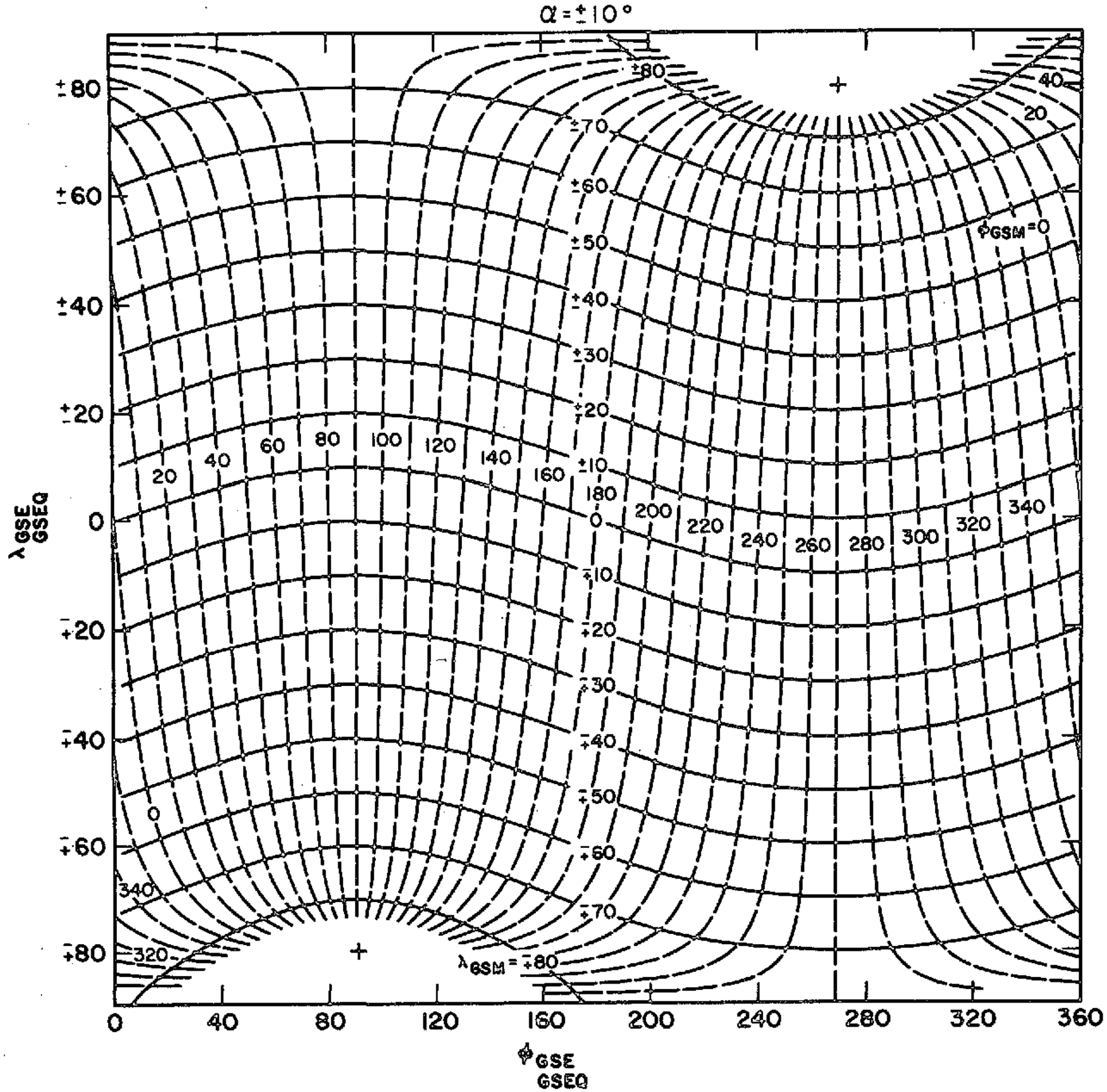

α = ±10°
$\lambda_{GSE, GSEQ}$
±80
±60
±40
±20
0
∓20
∓40
∓60
∓80
0
40
80
120
160
200
240
280
320
360
$\phi_{GSE, GSEQ}$
±80
±70
±60
±50
±40
±30
±20
±10
0
∓10
∓20
∓30
∓40
∓50
∓60
∓70
λ_{GSM} = ∓80
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
ϕ_{GSM} = 0
40
20
0
340
320

FIGURE 5

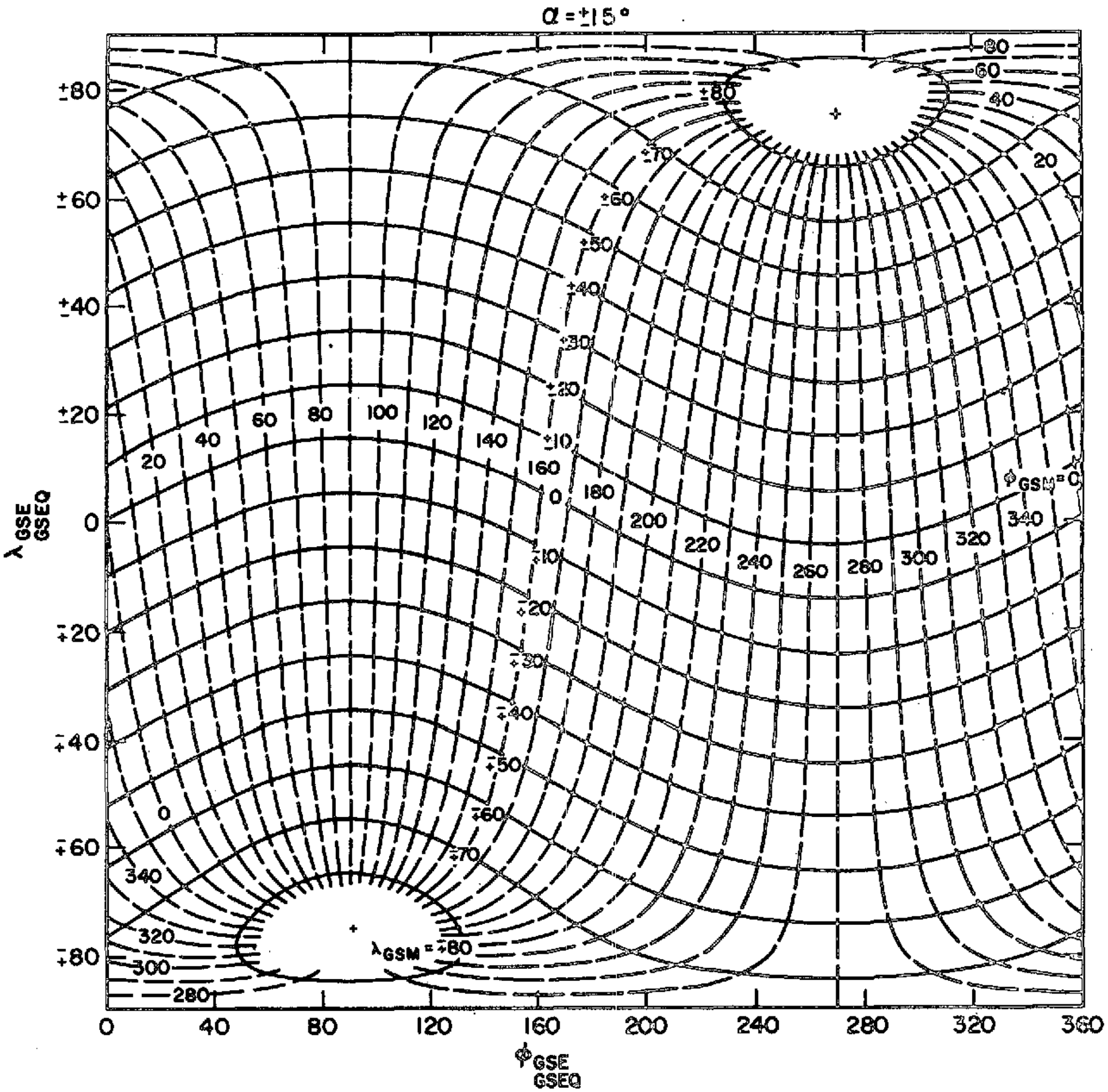

α = ±15°
λ GSE GSEQ
±80
±60
±40
±20
0
∓20
∓40
∓60
∓80
φ GSE GSEQ
0
40
80
120
160
200
240
280
320
360
λGSM = ∓80
±80
±70
±60
±50
±40
±30
±20
±10
0
∓10
∓20
∓30
∓40
∓50
∓60
∓70
φGSM = 0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
80
60
40
20
0
340
320
300
280

FIGURE 6

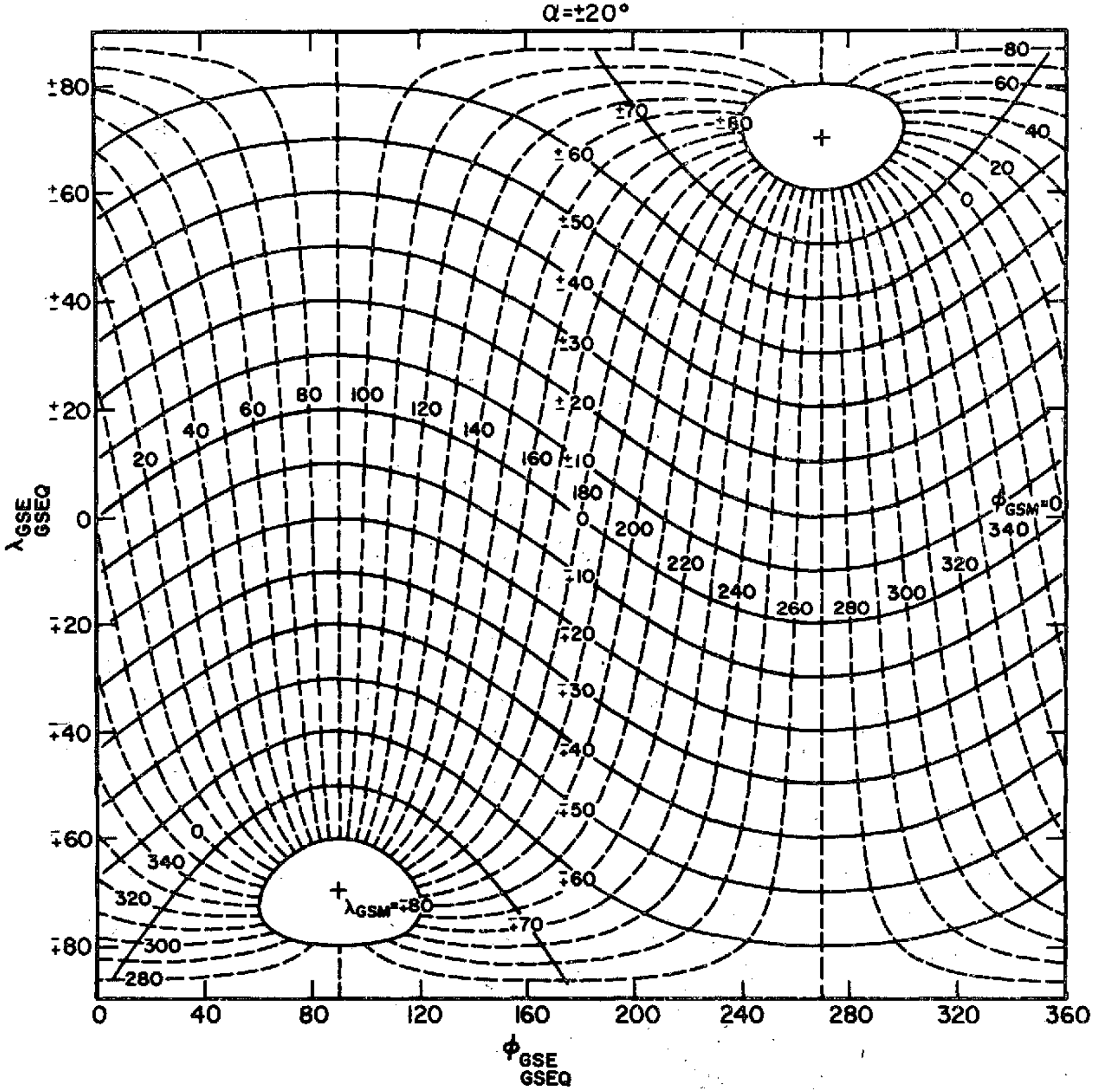

α=±20°
λ_{GSE} GSEQ
±80
±60
±40
±20
0
∓20
∓40
∓60
∓80
0
40
80
120
160
200
240
280
320
360
ϕ_{GSE} GSEQ
±70
±60
±50
±40
±30
±20
±10
0
∓10
∓20
∓30
∓40
∓50
∓60
∓70
λ_{GSM}=∓80
ϕ_{GSM}=0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340

FIGURE 7

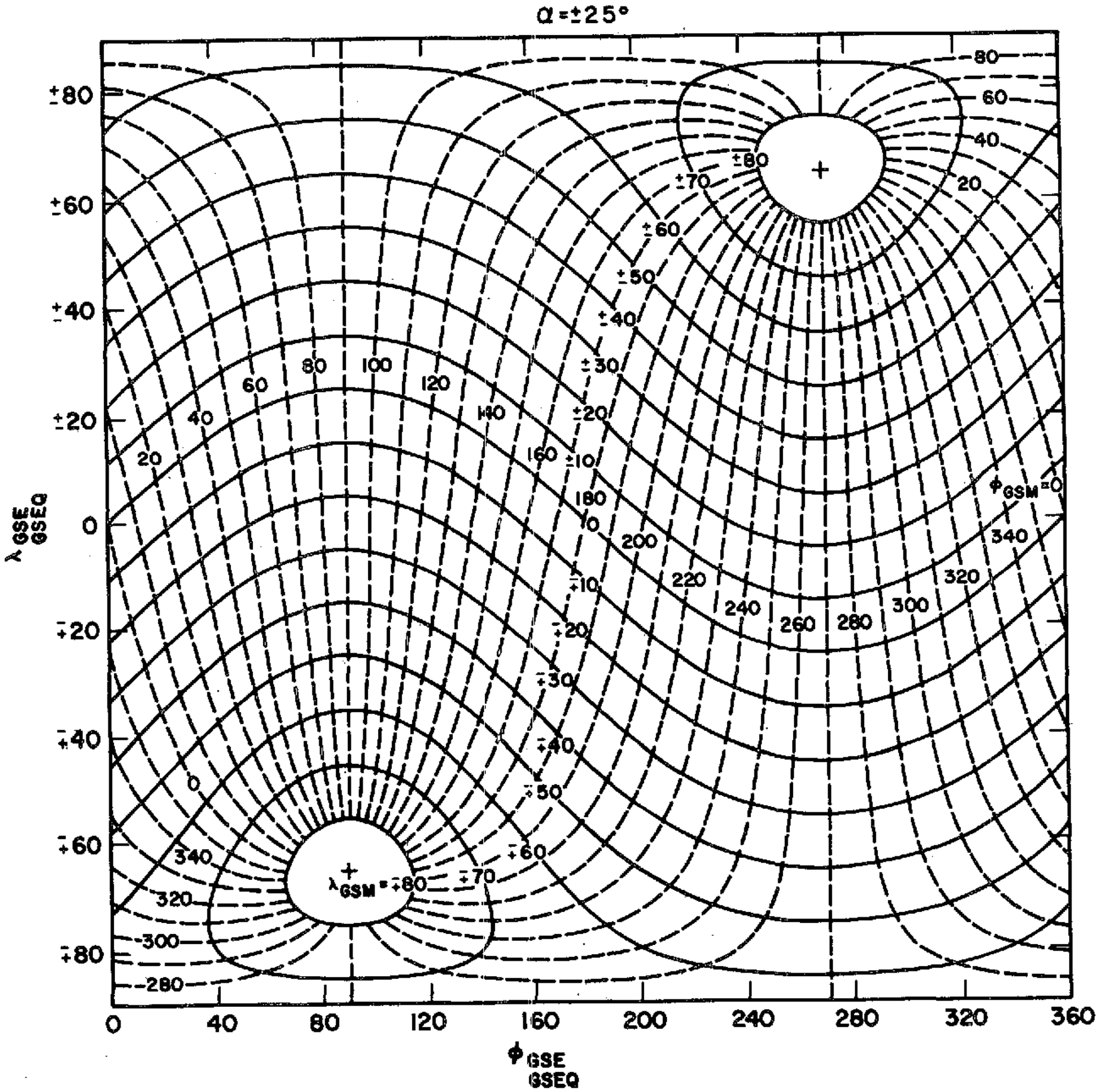
α=±25°
±80
±60
±40
±20
0
∓20
∓40
∓60
∓80
$\lambda_{\substack{GSE\\GSEQ}}$
0
40
80
120
160
200
240
280
320
360
$\phi_{\substack{GSE\\GSEQ}}$
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
$\phi_{GSM}=0$
80
60
40
20
±80
±70
±60
±50
±40
±30
±20
±10
0
∓10
∓20
∓30
∓40
∓50
∓60
∓70
$\lambda_{GSM}=\mp80$
0
340
320
300
280

FIGURE 8

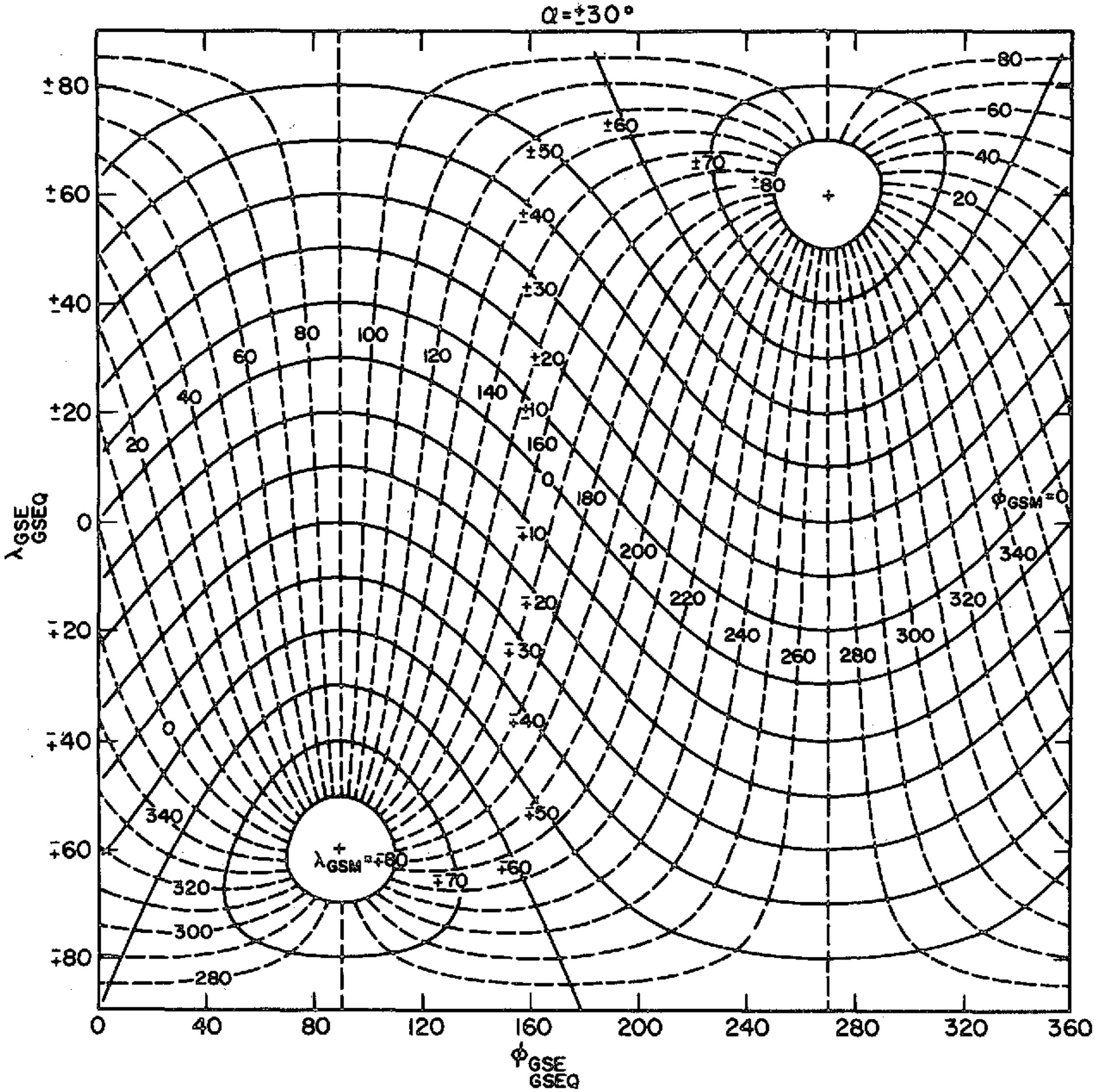

α=±30°
±80
±60
±40
±20
0
∓20
∓40
∓60
∓80
λ GSE GSEQ
0
40
80
120
160
200
240
280
320
360
φ GSE GSEQ
λ GSM = ∓80
∓70
∓60
∓50
∓40
∓30
∓20
∓10
0
±10
±20
±30
±40
±50
±60
±70
±80
φ GSM = 0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340

FIGURE 9

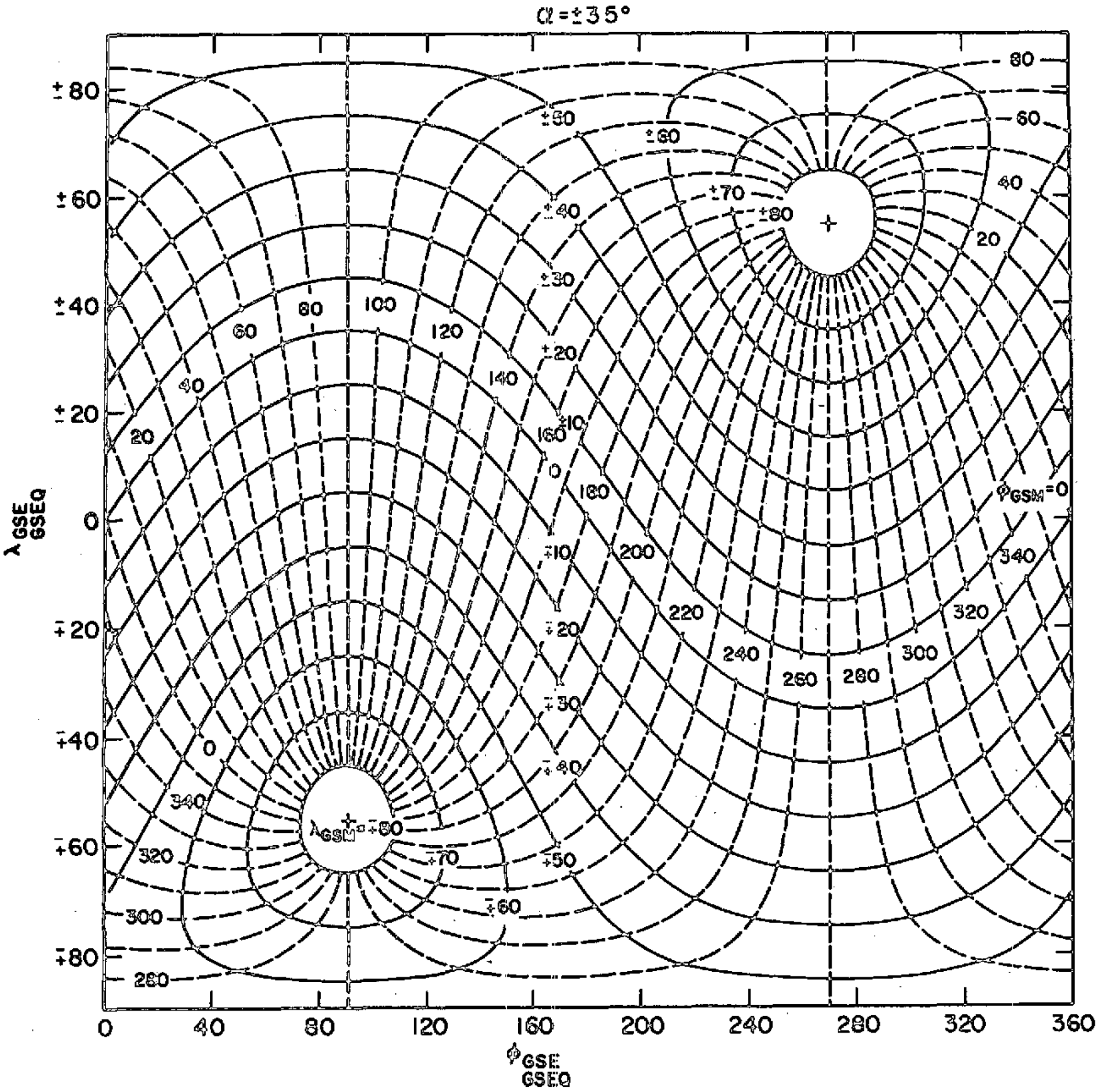

α=±35°
λ GSE GSEQ
±80
±60
±40
±20
0
∓20
∓40
∓60
∓80
φ GSE GSEQ
0
40
80
120
160
200
240
280
320
360
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
0
φ GSM=0
±10
±20
±30
±40
±50
±60
±70
±80
∓10
∓20
∓30
∓40
∓50
∓60
∓70
λ GSM=∓80

FIGURE 10