

P	Location	Location of an Earth station, At latitude ϕ , which may be either a GEO or LEO Earth station or both
A	Ascending LEO	Location of the ascending LEO satellite
D	Descending LEO	Location of the descending LEO satellite
C	Center of Earth	Location of the center of the Earth for purposes of geometric calculation
T_p	Tangent at P	The tangent to the surface at location P
β	GEO Protection Angle	Angle either side of line from P to GEO, sweeping out a region inside of which LEO cannot communicate with P
α	Horizon Elevation Angle	Minimum angle between horizon and LEO at which LEO and P may communicate, as viewed from location P
γ	Angle to GEO	Acute angle between horizon and vector pointing to GEO at location P
λ	Angle of Trailing Beam	The angle of the trailing beam with respect to the LEO orbit radius, viewed from the LEO (in quadrant 1)
ψ	Angle of Leading Beam	The angle of the leading beam with respect to the LEO orbit radius, viewed from the LEO (in quadrant 1)
ϕ	Latitude of P	Latitude of a particular point P under consideration (equator at 0 degrees, quadrant 1)
σ	Latitude of LEO	Latitude of a particular LEO under consideration, in orbit (equator at 0 degrees, quadrant 1)
θ	LEO Spacing Angle	Angle between two LEO satellites in a single plane, where angle vertex is the Earth's center
a	Distance to LEO Ascend	Distance from point P to the Ascending LEO, labeled point A, when viewed from point P
d	Distance to LEO Descend	Distance from point P to the Descending LEO, labeled point D, when viewed from point P
g	Distance to GEO SAT	Distance from point P to a geostationary satellite at the same longitude as P, or otherwise projected into the plane of the LEO orbit
s	Distance Between LEOs	The line-of-sight distance between LEO satellites orbiting at height h spaced at angle θ
r_E	Radius of Earth	6371 km
h	Height of LEO Orbit	Orbit height above Earth of the LEO satellite constellation
r_L	Radius of LEO Orbit	Radius of LEO Orbit (referenced to center of Earth), Nominally (6371 + h) km
r_G	Radius of GEO Orbit	Radius of GEO Orbit (referenced to center of Earth), Nominally 42,157 km

FIG.1

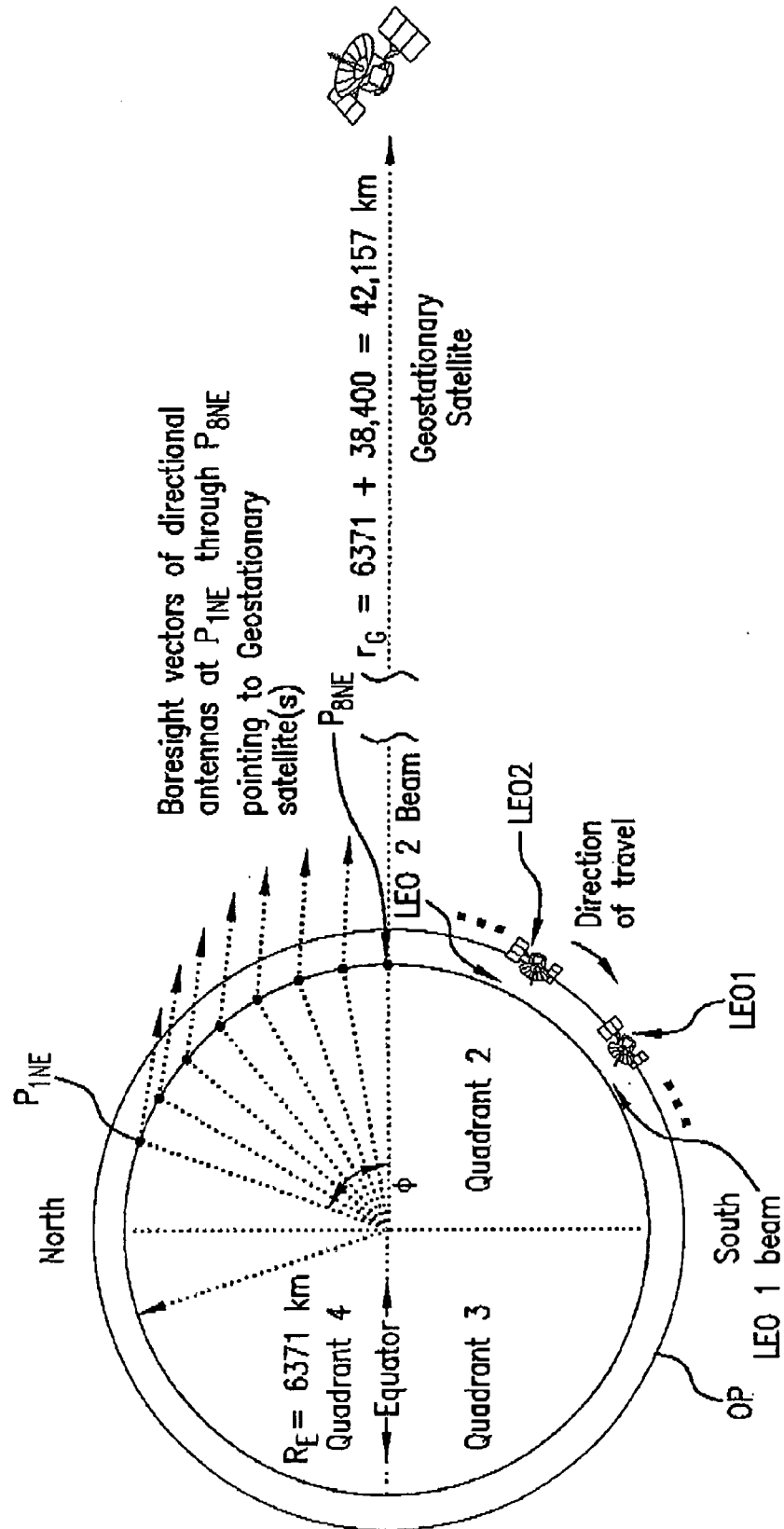


FIG.2

$$g = r_G \left[1 - \left(\frac{r_E}{r_G} \right)^2 - 2 \left(\frac{r_E}{r_G} \right) \cos(\phi) \right]^{1/2}$$

$$\gamma = \cos^{-1} \left[\frac{r_G}{g} \sin(\phi) \right]$$

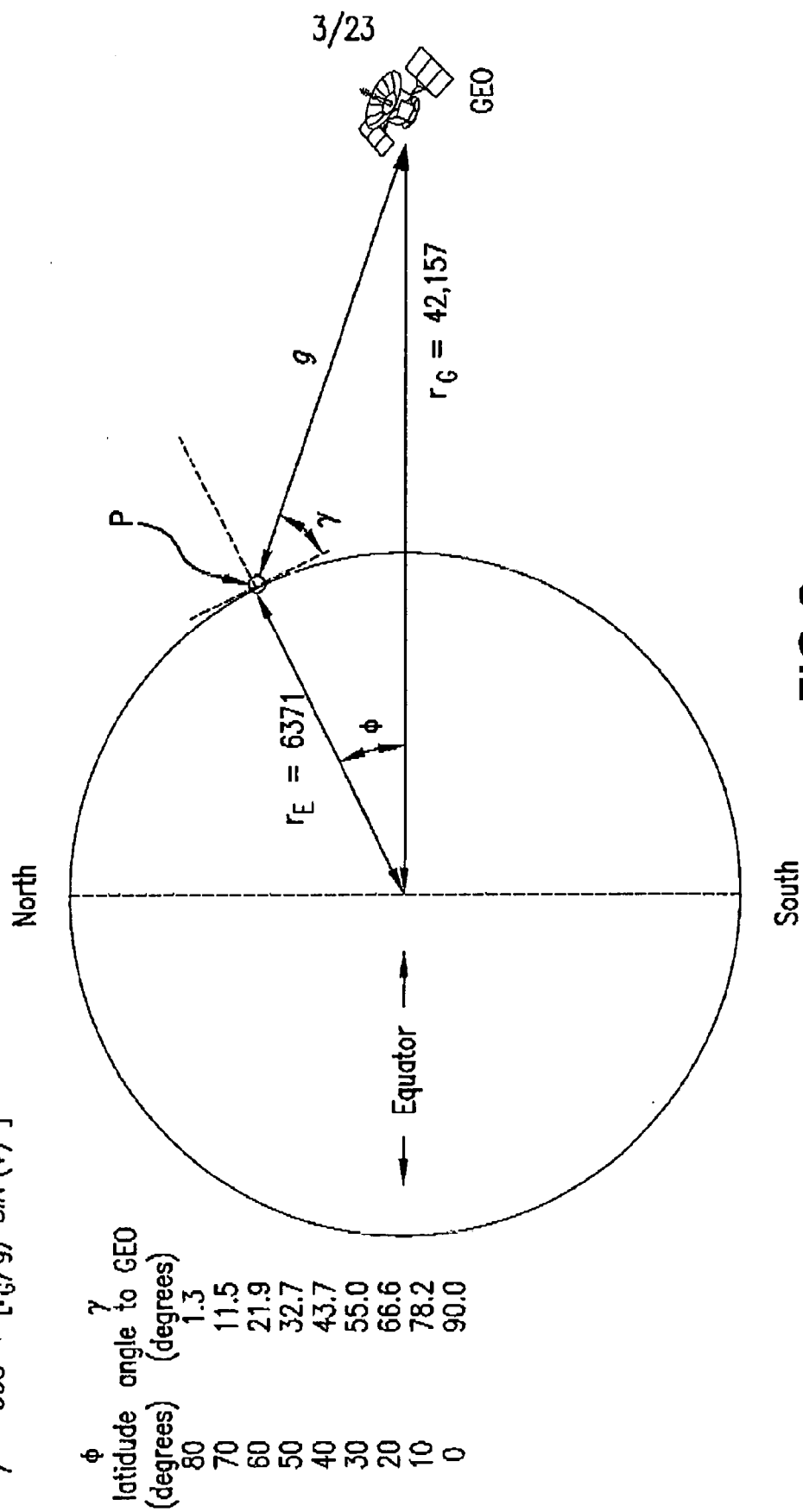


FIG.3

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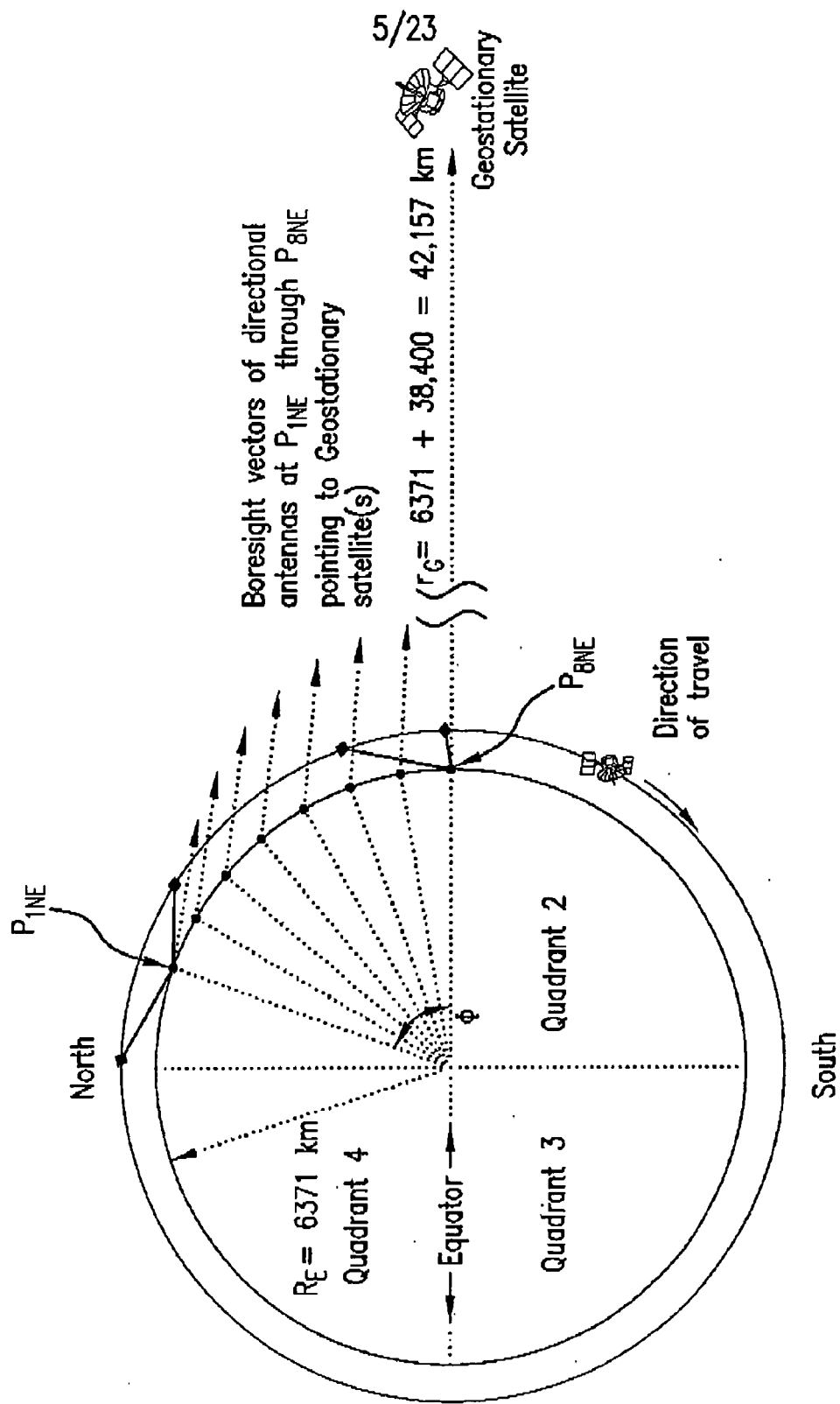


FIG.5

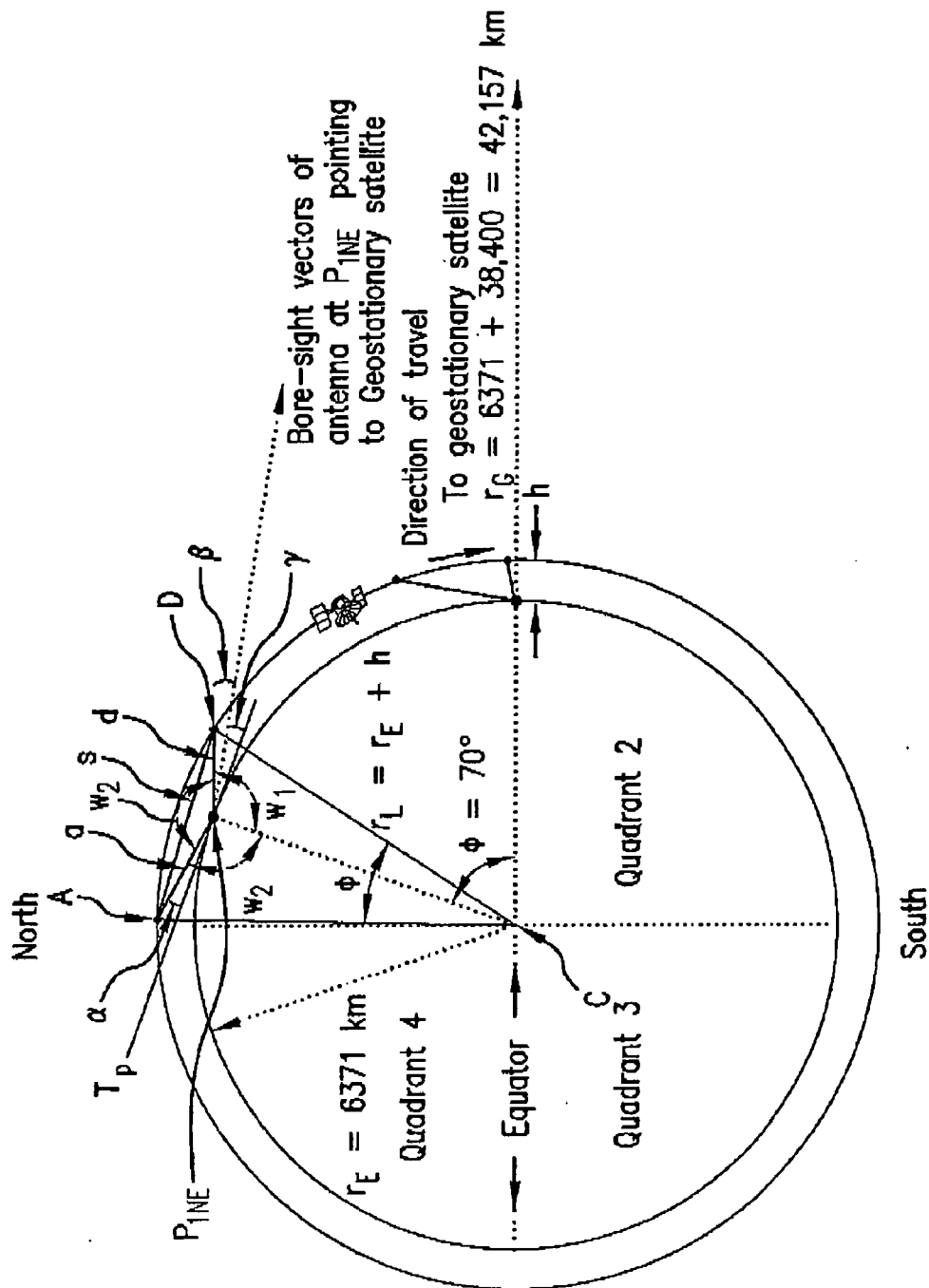


FIG.6A

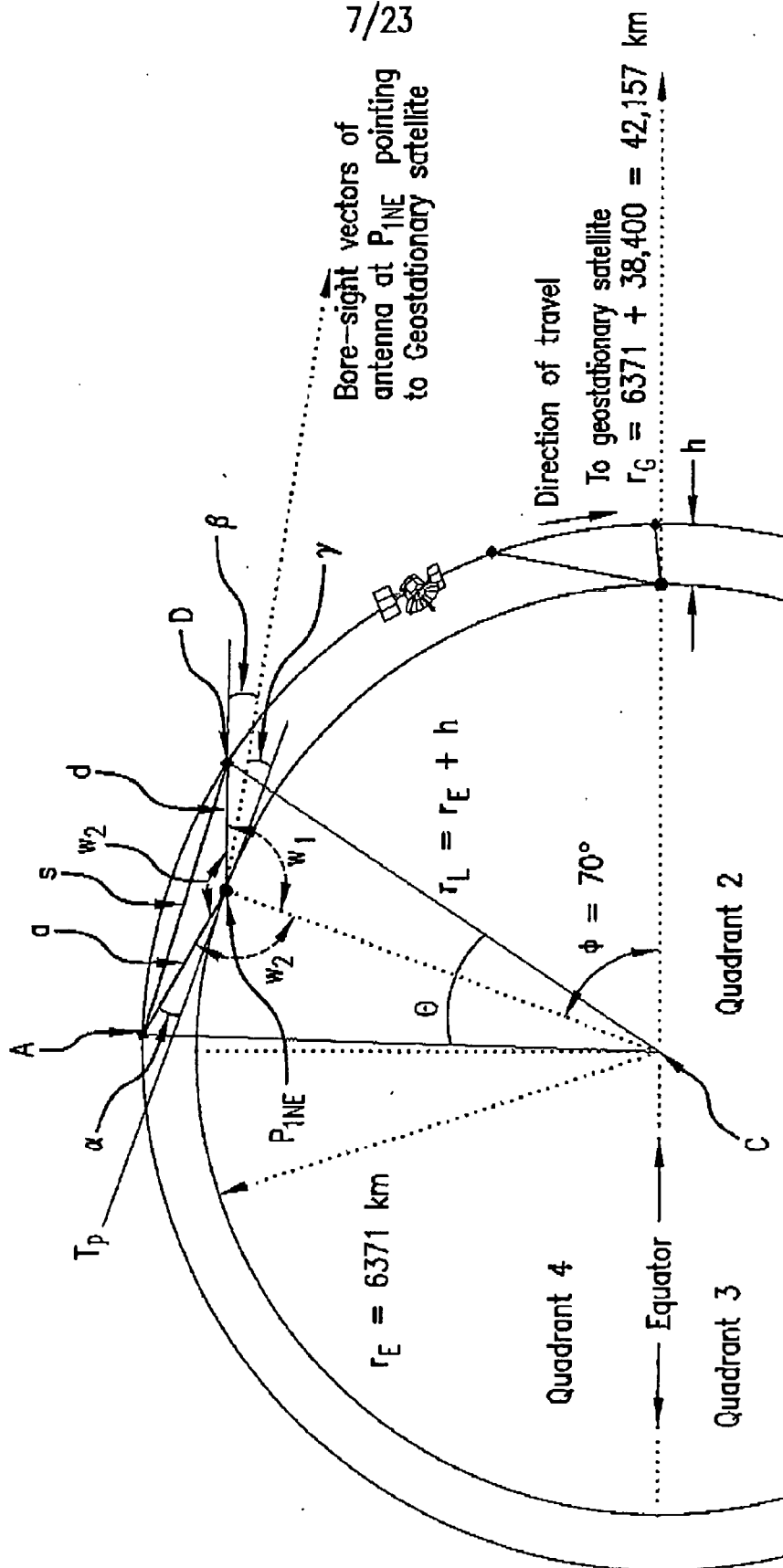


FIG.6B

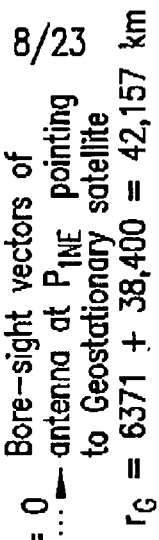


FIG. 7A

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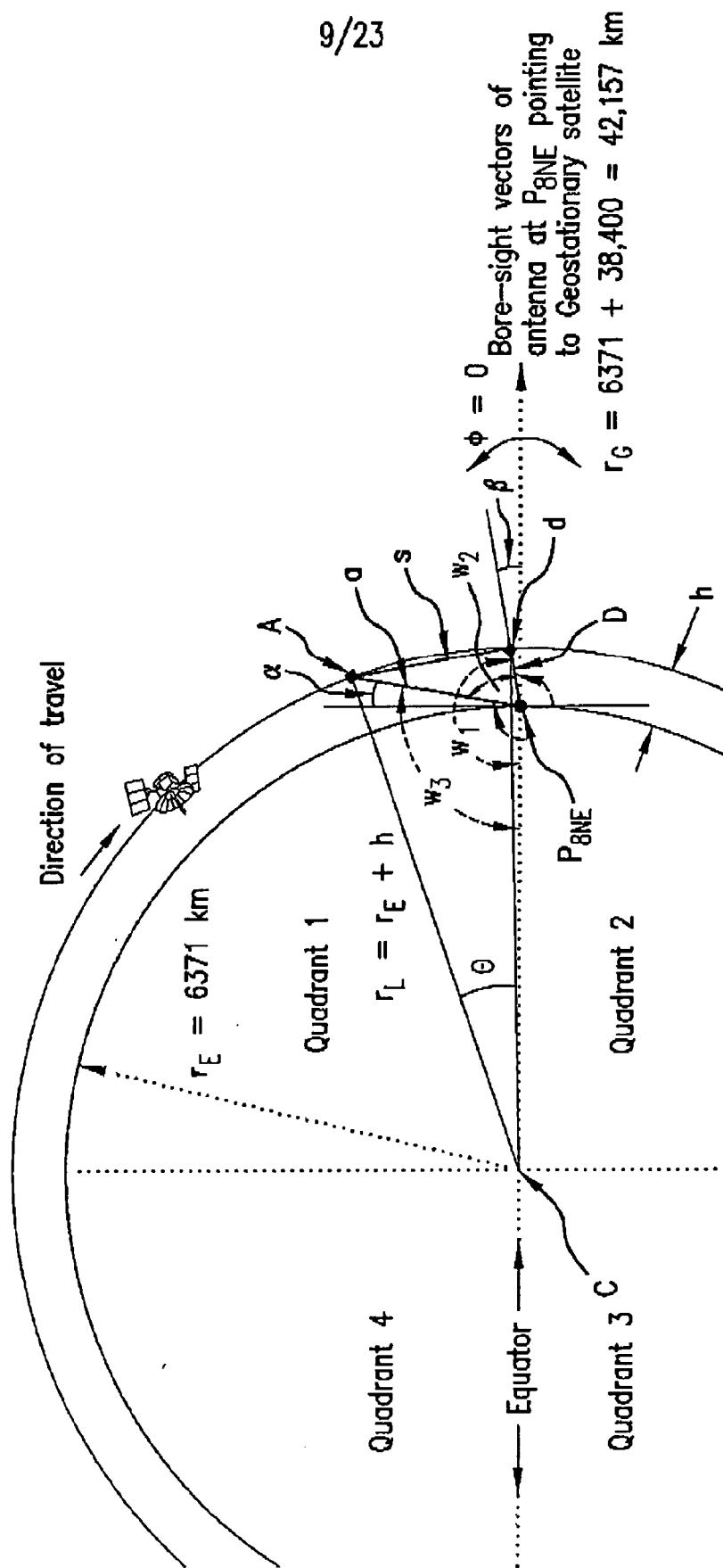


FIG.7B

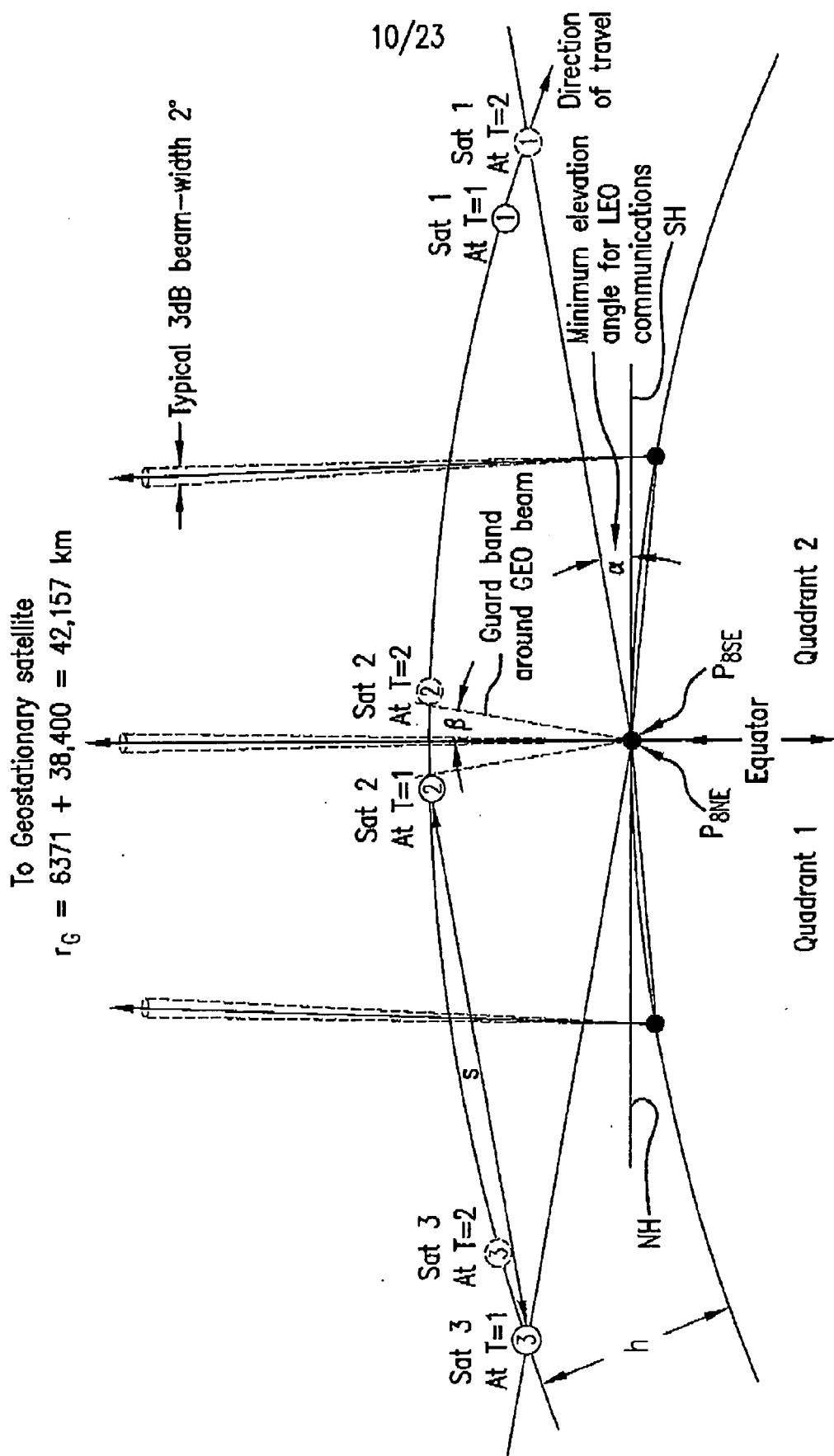


FIG.8

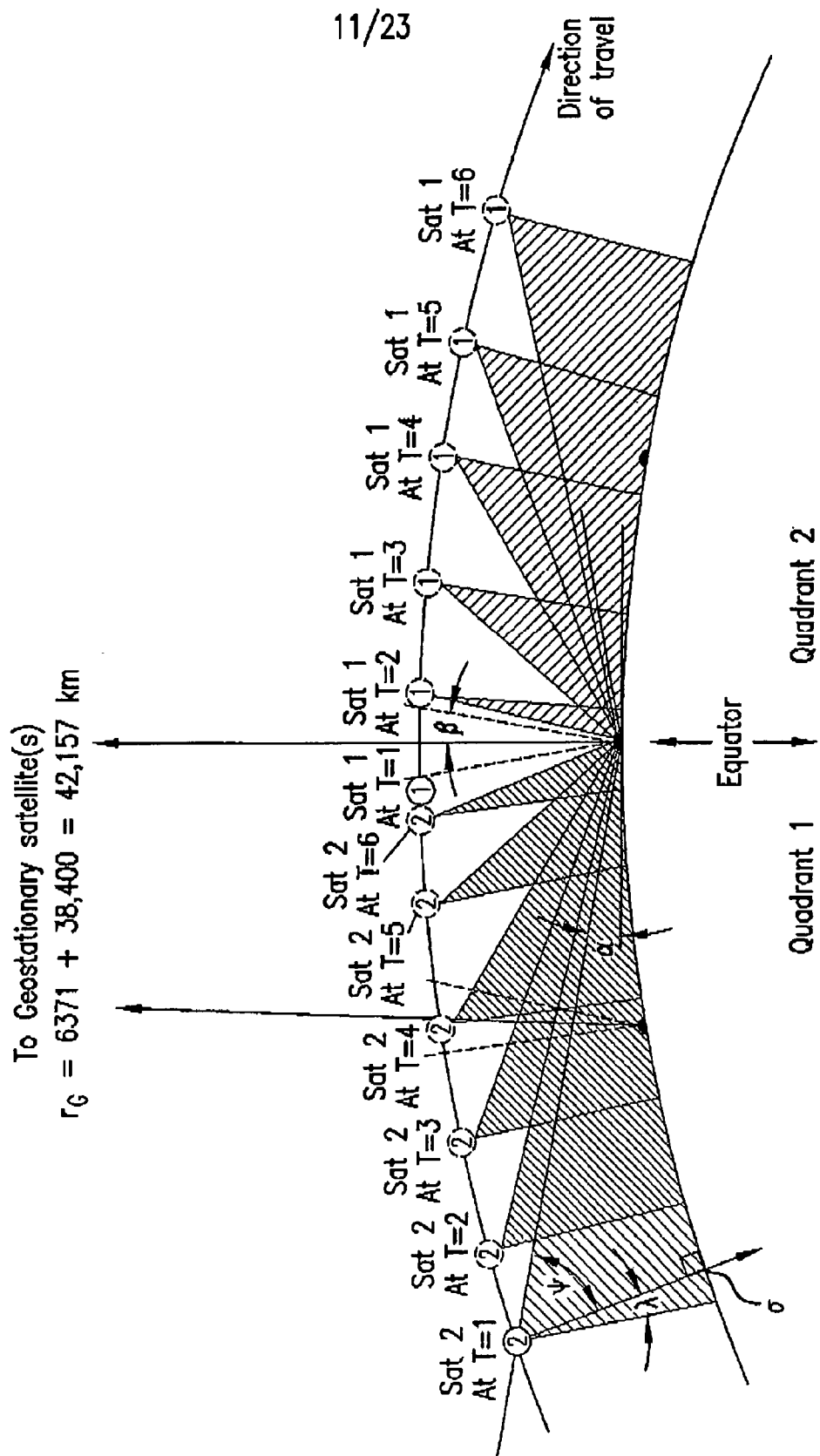


FIG.9

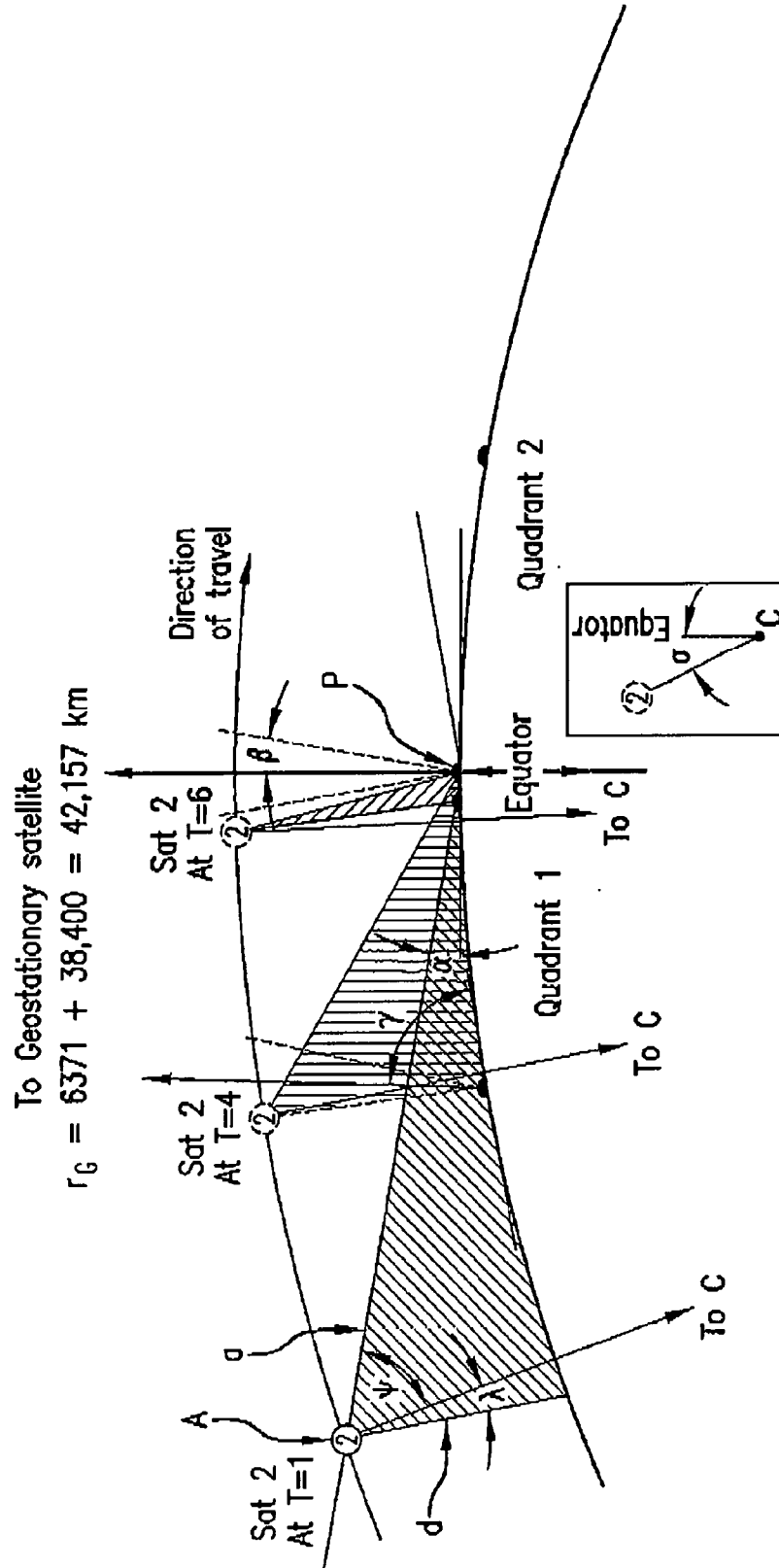


FIG.10A

To Geostationary satellite

$$r_G = 6371 + 38,400 = 42,157 \text{ km}$$

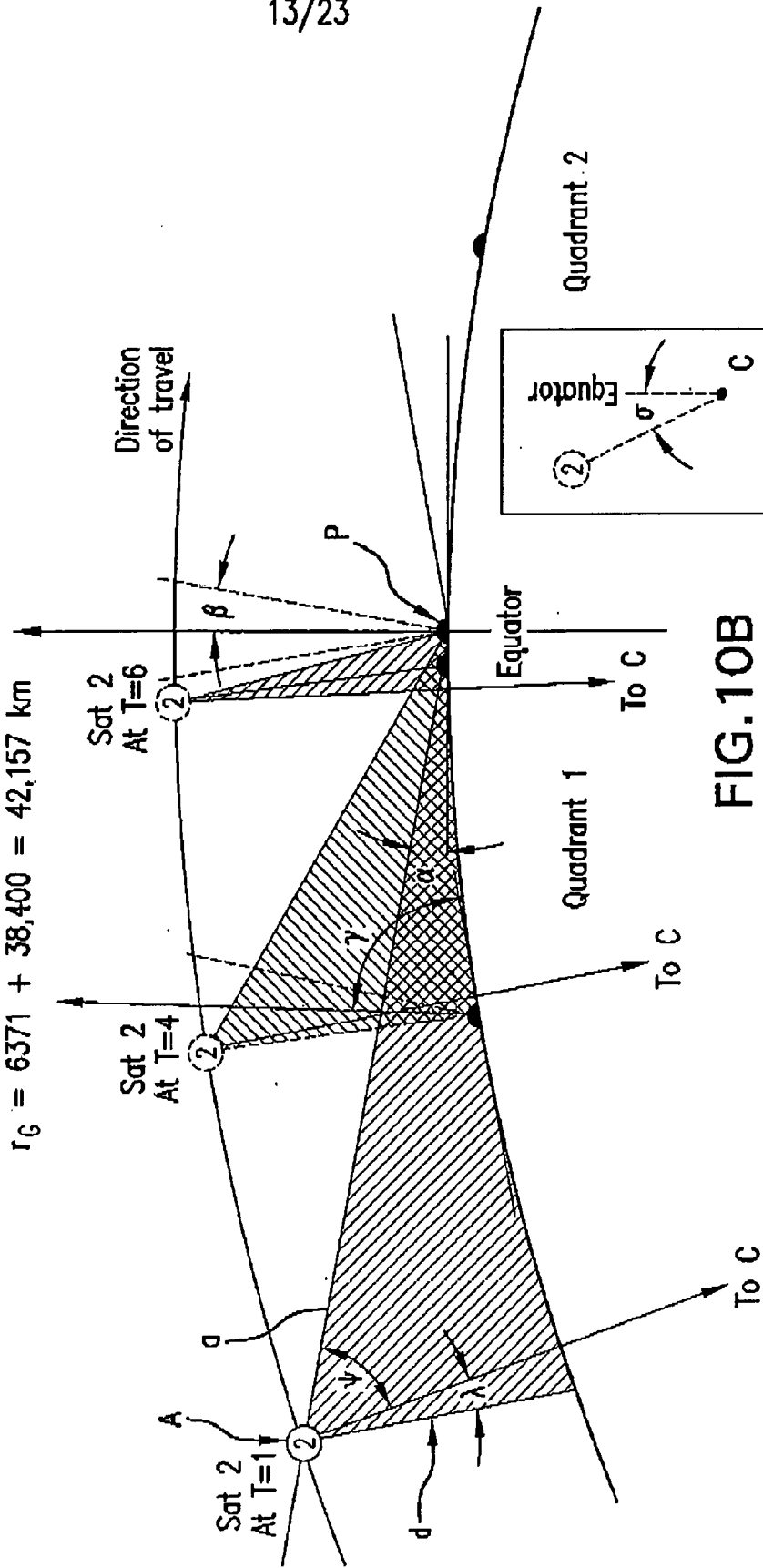
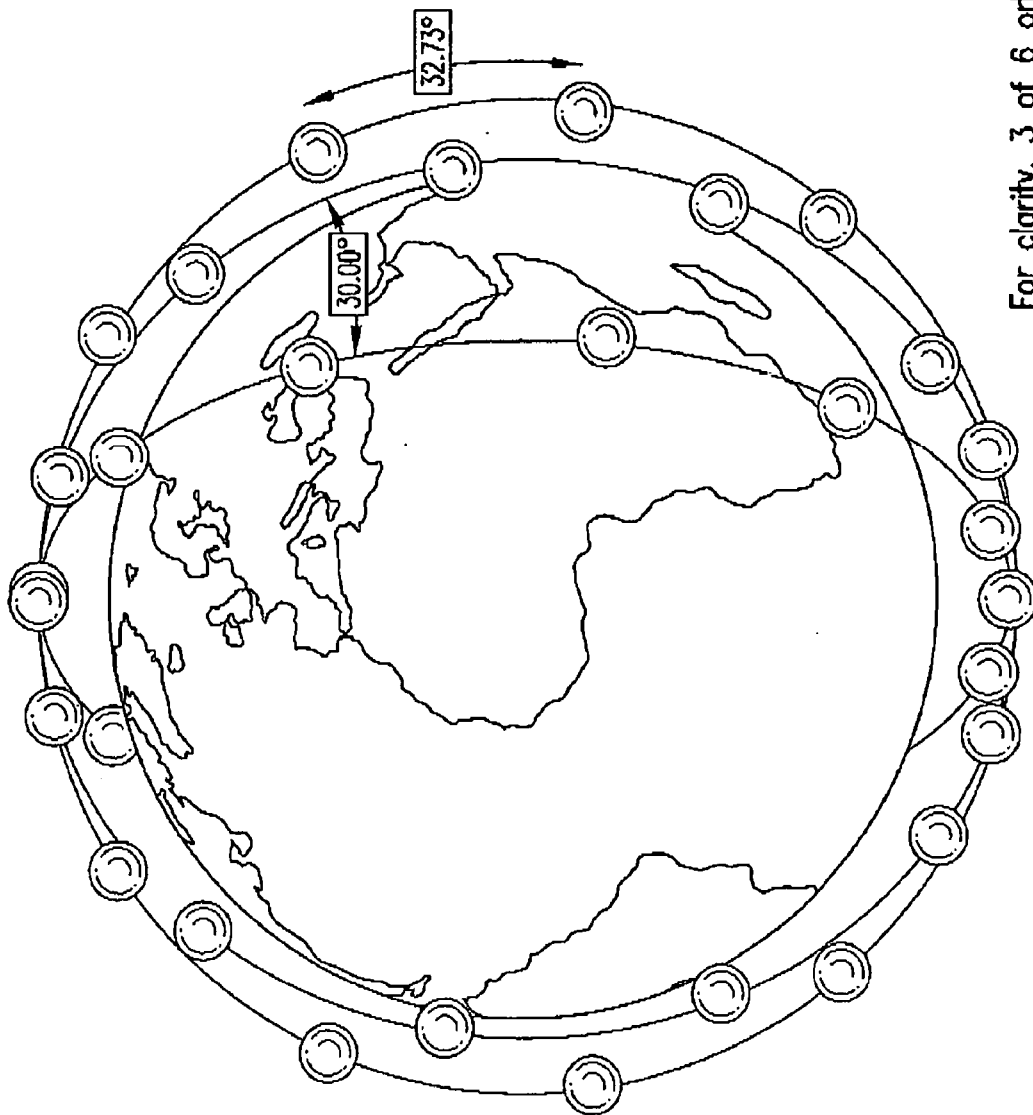
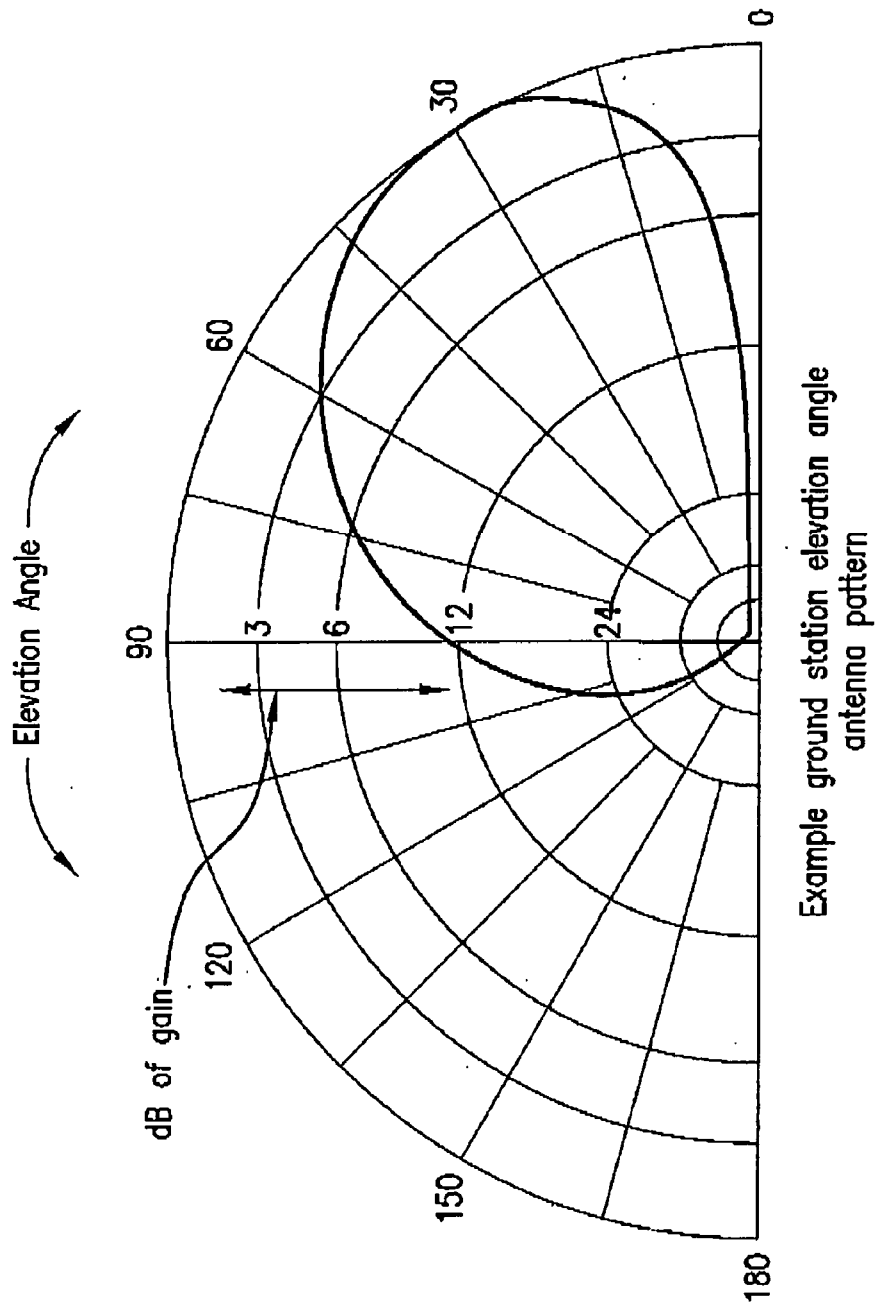


FIG.10B



For clarity, 3 of 6 orbital
planes are shown

FIG.11



Example ground station elevation angle
antenna pattern

FIG.12

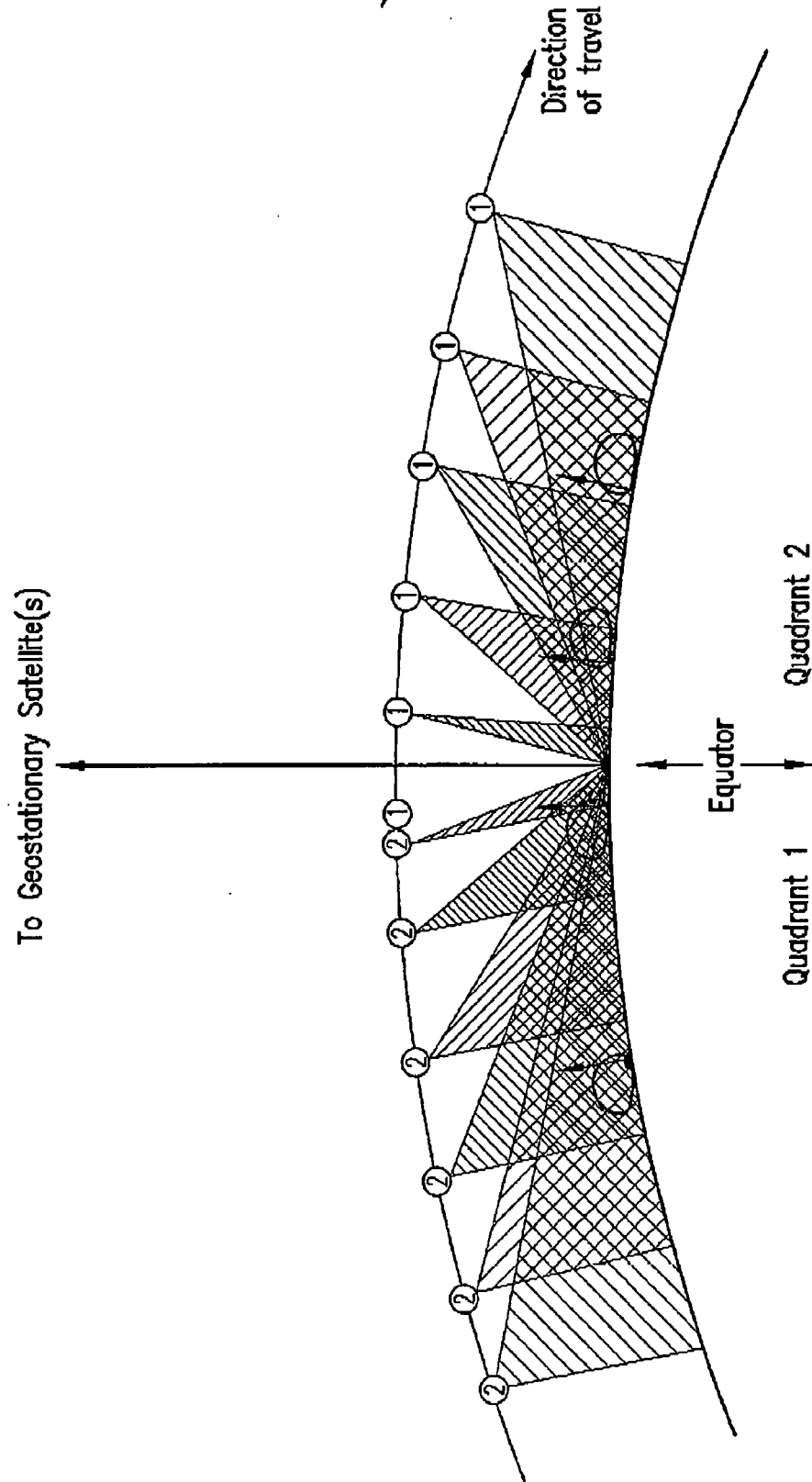


FIG.13

Inputs				Constants			
α	5	degrees	0.087 radians	π	3.1415927		
β	5	degrees	0.087 radians	r_E	6,371 km		
h	1,800	km		r_G	42,157 km		
r_L	8,171	km					

continued
on Fig.14B

Computations											
ϕ	d_G	γ	σ	d	s	θ	N	σ	ψ	λ	σ
Latitude of Earth station P (degrees)	Distance to GEO (km)	Angle to GEO (degrees)	Segment P-A Length (km)	Segment P-D length (km)	Segment A-D length (km)	Maximum Angular sat Spacing (deg)	No. of Sats Req'd per plane (each)	LEO Sat Limit Lat (degrees)	Fwd Beam Angle at Limit (degrees)	Max Back Beam vs Lat (degrees)	Sat Lat. at Indicated Back Angle (deg)
80	41,527	1.31	-	-	-	-	-	-	-	50.80	47.11
70	40,424	11.48	-	-	-	-	-	-	-	48.39	44.87
60	39,360	21.94	-	-	-	-	-	-	-	44.03	40.98
50	38,373	32.69	-	-	-	-	-	-	-	38.10	35.79
40	37,501	43.73	-	-	-	-	-	-	-	30.95	29.68
30	36,778	55.03	-	-	-	-	-	-	-	22.92	22.95
20	36,236	66.55	-	-	-	-	-	-	-	14.28	15.84
10	35,900	78.23	-	-	-	-	-	-	-	5.27	8.50
9	35,878	79.41	-	-	-	-	-	-	-	4.36	7.77
8	35,859	80.58	-	-	-	-	-	-	-	3.44	7.03
7	35,842	81.76	-	-	-	-	-	-	-	2.53	6.29
6	35,827	82.93	-	-	-	-	-	-	-	1.61	5.54
5	35,815	84.11	-	-	-	-	-	-	-	0.69	4.80
4	35,804	85.29	-	-	-	-	-	-	-	-0.23	4.06
3	35,796	86.47	-	-	-	-	-	-	-	-1.14	3.32
2	35,791	87.64	-	-	-	-	-	-	-	-2.06	2.58
1	35,787	88.82	-	-	-	-	-	-	-	-2.98	1.84
0	35,786	90.00	4,591	1,805	4,632	32.93	11	34.04	50.96	-3.90	1.10

FIG.14A

σ Latitude of LEO Sat	ψ Fwd Beam Angle to Equator (degrees)	d Dist. from LEO Sat to PEQ (km)
80	>50.96	>4,591
70	>50.96	>4,591
60	>50.96	>4,591
50	>50.96	>4,591
40	>50.96	>4,591
30	50.21	4,146
20	44.93	3,085
10	30.25	2,196
9	27.95	2,126
8	25.46	2,062
7	22.80	2,004
6	19.95	1,952
5	16.93	1,907
4	13.75	1,869
3	10.44	1,839
2	7.03	1,818
1	3.53	1,804
0	0.00	1,800

continued
from Fig.14A

FIG.14B

Inputs				Constants			
α	5	degrees	0.087	π	3.1415927		
β	0	degrees	0.000	r_E	6,371	km	
h	1,800	km		r_G	42,157	km	
r_L	8,171	km					

Computations											
ϕ	d_G	γ	a	d	s	θ	N	σ	ψ	λ	σ
Latitude of Earth station to GEO P (degrees)	Distance (km)	Angle to GEO (degrees)	Segment P-A length (km)	Segment P-D length (km)	Segment A-D length (km)	Maximum Angular sat Spacing (deg)	No. of Sats Req'd per plane (each)	LEO Sat Limit (degrees)	Fwd Beam Angle at Limit (degrees)	Max Back Beam Angle vs Lat. Indicated Back Angle (deg.)	Sat Lat. at
80	41,527	1.31	-	-	-	-	-	-	-	51.22	42.53
70	40,424	11.48	-	-	-	-	-	-	-	49.83	41.31
60	39,360	21.94	-	-	-	-	-	-	-	46.32	38.26
50	38,373	32.69	-	-	-	-	-	-	-	41.01	33.70
40	37,501	43.73	-	-	-	-	-	-	-	34.29	28.02
30	36,778	55.03	-	-	-	-	-	-	-	26.54	21.57
20	36,236	66.55	-	-	-	-	-	-	-	18.07	14.63
10	35,900	78.23	-	-	-	-	-	-	-	9.15	7.38
9	35,878	79.41	-	-	-	-	-	-	-	8.24	6.65
8	35,859	80.58	-	-	-	-	-	-	-	7.33	5.91
7	35,842	81.76	-	-	-	-	-	-	-	6.42	5.18
6	35,827	82.93	-	-	-	-	-	-	-	5.50	4.44
5	35,815	84.11	-	-	-	-	-	-	-	4.59	3.70
4	35,804	85.29	-	-	-	-	-	-	-	3.67	2.96
3	35,796	86.47	-	-	-	-	-	-	-	2.75	2.22
2	35,791	87.64	-	-	-	-	-	-	-	1.84	1.48
1	35,787	88.82	-	-	-	-	-	-	-	0.92	0.74
0	35,786	90.00	4,591	1,800	4,783	34.04	11	34.04	50.96	0.00	0.00

continued
on Fig.15B

FIG.15A

continued
from Fig.15A

σ	ψ	d
Latitude of LEO Sat (degrees)	Fwd Beam Angle to Equator (degrees)	Dist. from LEO Sat to P _{EQ} (km)
80	>50.96	>4,591
70	>50.96	>4,591
60	>50.96	>4,591
50	>50.96	>4,591
40	>50.96	>4,591
30	50.21	4,146
20	44.93	3,085
10	30.25	2,196
9	27.95	2,126
8	25.46	2,062
7	22.80	2,004
6	19.95	1,952
5	16.93	1,907
4	13.75	1,869
3	10.44	1,839
2	7.03	1,818
1	3.53	1,804
0	0.00	1,800

FIG.15B

Inputs				Constants				continued on Fig.16B			
α	10	degrees	0.175 radians	π	3.1415927						
β	10	degrees	0.175 radians	r_E	6,371 km						
h	800	km		r_G	42,157 km						
r_L	7,171	km									
Computations											
ϕ	d_G	γ	a	d	s	θ	N	σ	ψ	λ	σ
Latitude of Earth station to GEO P (degrees)	Distance (km)	Angle to GEO (degrees)	Segment P-A length (km)	Segment P-D length (km)	Segment A-D length (km)	Maximum Angular sat Spacing (deg)	No. of Sats Req'd per plane (each)	LEO Sat Limit (degrees)	Fwd Beam Angle at Limit (degrees)	Max Back Beam Angle vs Lat. (degrees)	Sat Lat. at Indicated Back Angle (deg.)
80	41,527	1.31	-	-	-	-	-	-	-	60.60	61.91
70	40,424	11.48	-	-	-	-	-	-	-	55.76	57.25
60	39,360	21.94	-	-	-	-	-	-	-	48.93	50.87
50	38,373	32.69	-	-	-	-	-	-	-	40.77	43.46
40	37,501	43.73	-	-	-	-	-	-	-	31.71	35.44
30	36,778	55.03	-	-	-	-	-	-	-	22.03	27.06
20	36,236	66.55	-	-	-	-	-	-	-	11.92	18.48
10	35,900	78.23	-	-	-	-	-	-	-	1.57	9.80
9	35,878	79.41	-	-	-	-	-	-	-	0.53	8.93
8	35,859	80.58	-	-	-	-	-	-	-	-0.52	8.07
7	35,842	81.76	-	-	-	-	-	-	-	-1.56	7.20
6	35,827	82.93	-	-	-	-	-	-	-	-2.61	6.33
5	35,815	84.11	-	-	-	-	-	-	-	-3.65	5.46
4	35,804	85.29	-	-	-	-	-	-	-	-4.70	4.59
3	35,796	86.47	-	-	-	-	-	-	-	-5.74	3.72
2	35,791	87.64	-	-	-	-	-	-	-	-6.79	2.86
1	35,787	88.82	-	-	-	-	-	-	-	-7.83	1.99
0	35,786	90.00	2,366	811	2,223	17.84	21	18.96	61.04	-8.87	1.13

FIG.16A

continued
from Fig. 16A

σ	ψ	d
Latitude of LEO Sat (degrees)	Fwd Beam Angle to Equator (degrees)	Dist. from LEO Sat to P _{EQ} (km)
80	>61.04	>2,366
70	>61.04	>2,366
60	>61.04	>2,366
50	>61.04	>2,366
40	>61.04	>2,366
30	>61.04	>2,366
20	>61.04	>2,366
10	50.97	1,424
9	48.61	1,329
8	45.81	1,237
7	42.49	1,149
6	38.58	1,068
5	33.97	0,994
4	28.59	0,929
3	22.41	0,875
2	15.46	0,834
1	7.90	0,809
0	0.00	0,800

FIG. 16B

Inputs		Constants	
f	12 GHz	π	3.1415927
α	10 degrees	C	299,792 km
β	10 degrees		
h	800 km		

Path Loss LEO Satellite to Earth Station Compared to GEO				
Path LEO to Earth station (km)	FSPL		d_G	
	Free Space	NFSPL	Distance to GEO (km)	GEOPL GEO Path Loss (dB)
2,366	182	-9.06	41,527	206
1,424	177	-4.65	40,424	206
1,329	176	-4.04	39,360	206
1,237	176	-3.42	38,373	206
1,149	175	-2.79	37,501	206
1,068	175	-2.15	36,778	205
994	174	-1.52	36,236	205
929	173	-0.93	35,900	205
875	173	-0.41	35,786	205
834	172	0.00	35,786	205

Table 4

FIG.17