analysis a typical LEO altitude of 400 km is assumed and again a 72° inclination is considered which causes the satellite to pass over the entire CONUS numerous times.

The interference thresholds used in the analysis are shown in Table 6-2 and are based on the conduction testing by JPL last March. Although anechoic chamber testing and live-sky testing have also been performed with these receivers, the conduction testing offers the best accuracy since signal, noise, and interference levels can be carefully controlled and calibrated. In the conduction testing, the primary observable was the degradation in C/No due to simulated LightSquared Phase 1 signal interference (two 5 MHz channels) measured during steady state tracking. (It should be noted, however, that JPL also collected pseudorange, carrier phase, and position solution data. They also collected data for the TRIG using a Phase 0 simulated LightSquared signal.) Table 6-2 shows the interference levels (sum of interference powers in both 5 MHz channels) at the output of the GPS receiver antenna that result in 1 dB, 3 dB, and 5 dB C/No degradation for the four NASA receivers along with the interference level that causes loss of GPS signal tracking. It's apparent that the next-generation TRIG space receiver is the most sensitive of the four receivers.

Terrestrial Receiver Analysis (single base station)

This analysis considers the impact of interference from a single LightSquared base station on the four receivers assuming they are located at fixed positions on the ground. The TRIG/IGOR space receivers are tested on the ground prior to launch and during "burn-in" operations. Receivers #15 & #16 are commonly used in surveying and high precision ground networks such as the IGS (Figure 6-6 and Figure 6-6) and SCIGN (Figure 6-8 and Figure 6-9). Receiver #16 is a standard dual frequency (L1/L2) phase and pseudorange measuring instrument that can track up to 12 GPS satellites. Receiver #15 is a newer 36-channel receiver capable of tracking GPS L1/L2/L2C/L5 and GLONASS L1/L2. Since the closest base station will dominate the aggregate interference, it's useful to estimate the required separation distance between GPS receiver and base station in order that certain interference threshold levels are not exceeded. For this analysis the GPS receiver is assumed to be 1 meter above the ground (e.g. tripod mounted) with a zenith pointed choke ring antenna with gain pattern shown in Figure 6-3. This antenna is designed specifically to reduce multipath effects and consists of vertically aligned concentric rings centered about the antenna element (usually a crossed dipole) connected to a ground plane. The vertical rings shape the antenna pattern such that multipath signals incident on the antenna at the horizon and negative elevation angles are attenuated. The separation distance contours were calculated with MathCAD software for different interference thresholds given in Table 6-2.

Terrestrial Receiver Analysis (multiple base stations)

This analysis considered aggregate interference from the LightSquared deployment in one of LightSquared's planned initial markets. LightSquared provided the locations and height above ground for base stations that it is planning to deploy in one of its initial market areas. The objective is to determine the interference impact to a high precision ground network GPS receiver if it were to be located at different positions in the area (or a similar LightSquared market area). Again the receivers are assumed to use zenith pointed choke ring antennas at 1 meter above ground. For this analysis a MATLAB program was developed which sub-divides

the geographic area into a large number of quadrangles or cells (i.e. 878,628 cells each approx 100 square meters in size) and the aggregate interference calculated at the centroid of each map cell from the base stations within radio LOS of the map cell location. The result is an interference matrix map that shows the aggregate interference over the geographic area. By applying different interference thresholds (Table 6-2) to the matrix map, the % area where interference exceeds the threshold can be determined.

LightSquared Base Station Characteristics

As shown in Table 6-1, for all three analysis types, base station sector main-beam EIRP levels and antenna patterns are the same and based on data provided by LightSquared. The main-beam EIRP per channel is 62 dBm (32 dBW) per (5 MHz) OFDM channel and assuming two 5 MHz channels per sector (i.e. Phase 1 spectrum) this is 65 dBm (35 dBW) per sector.

Spaceborne Receiver Analysis

For the spaceborne receiver analysis the aggregate interference power at the output of the GPS receiver antenna is calculated at one second time steps in the satellite orbit from base stations distributed among certain US cities. Since specific lat/lon locations for the base stations in each city were not available and the GPS receiver in this case is onboard a satellite, it was assumed for the interference calculations that all base stations for a particular city are co-located at the city center. For example, two base stations separated by 10 km will have an angular separation of only 0.7° at 800 km satellite altitude so that the difference in receive antenna gain between the two will be very small. Sector antenna gain towards the satellite is calculated by first determining the appropriate AZ/EL angles from the base-station/satellite geometry; then summing the AZ plane discrimination with the EL plane discrimination; and then subtracting this total discrimination from the max sector gain to get the net sector gain towards the satellite. The maximum interference from a base station will occur when it sees the satellite at low elevation angles. Free-space loss is assumed, but because of uncertainty in the path loss due to blockage and shadowing of base stations on the satellite horizon from terrain or man-made structures, analysis results were generated for two base station mask angles: (1) a 0° elevation mask on the base stations so that all base stations which see the satellite above 0° elevation angle are included in the aggregate interference calculation; and (2) a 5° mask angle so that only base stations which see the satellite above 5° elevation angle contribute to the aggregate interference. For the space receiver analysis, results were also generated for the case when the base station EIRP is increased from 32 dBW to 42 dBW, which is the maximum authorized power under the FCC rules. LightSquared, however, has stated that they plan to operate at a maximum EIRP level of 32 dBW per channel.

Terrestrial Receiver Analysis (single base station)

For this analysis of interference from single base station, a base station height of 18.3 meters (60 feet) above ground is assumed. GPS receiver height is assumed to be 1 meter. Separation distance results were calculated for a number of different propagation models besides free-space

loss (i.e. Hata, Extended Hata, Walfisch-Ikegami, NTIA/ITM). These models are based on extensive measurements of radio propagation losses and used in cellular systems planning. Figure 6-5 shows that there is a significant spread in path loss among these models. For example, for a 10 km distance path loss varies from 115 dB (free-space) to 180 dB (extended HATA in urban area). This leads to a significant difference in separation distances. The issue of which propagation model is appropriate in various terrestrial interference scenarios requires further discussion.

Terrestrial Receiver Analysis (multiple base stations)

As noted previously, this analysis considers aggregate interference from base stations in one of LightSquared's initial market deployments. Again results were generated for different propagation models shown in Figure 6-5.

Analysis Results

(*Editor's Note:* The results presented in the following sections are intended to draw no conclusions or make any recommendations as to what level of interference may be tolerated by the various GPS receivers based on the scenarios for those receivers.)

Spaceborne Receiver Analysis Results

Interference results for the RO GPS RX onboard a COSMIC-2 satellite (800 km/72° orbit) are shown in Table 6-3 and Table 6-4. Table 6-3 assumes a 0° elevation mask on the base stations while Table 6-4 assumes a 5° elevation mask on the base stations. The entries in these tables are interpreted as follows. Consider, for example, Table 6-3 and an aggregate interference threshold of -82 dBm (2nd column). For this row in the Table, the first column indicates that an interference power level of -82 dBm at the output of the GPS receiver antenna will cause a 1 dB drop in the C/No for the TRIG receiver (for both the L1 C/A-code and L1 P-code channels of the receiver). Column 3 indicates that over the 10-day simulation period, the aggregate interference at the GPS antenna output actually exceeds this level about 9% of the time (i.e. since 10 days = 240 hours, the interference exceeds -82 dBm for 0.09 x 240 = 21.6 hours total over the 10-day period). In other words, for 9% of the time, the receiver C/No degradation is at least 1 dB. In the table header, the peak interference level is shown to reach -55.1 dBm (enough for the TRIG to lose lock). Column 4 indicates that over the 10-day period, there are 268 interference events (i.e. 268 separate time intervals during which interference exceeds -82 dBm). Note that these time intervals may be very short or fairly long depending on how many interfering base stations the satellite sees on the particular orbit pass over the US. The sum duration of all 268 interference events is the 21.6 hours. Also, there can be multiple interference events for a single orbit pass as different numbers of base stations pass through the FOV of the receiver antenna. Column 5 indicates that the average duration of an interference event is about 4.9 minutes and the maximum duration from column 6 is 16.9 minutes. Table 6-3 also shows that for a threshold of -67 dBm (where TRIG loses lock), interference exceeds this level about 3% of the time with 152 interference events of average duration 2.9 min and max duration 10.6 min. It should be noted

that the duration of an atmospheric occultation (as the signal path moves from skimming the Earth's surface to an altitude of about 100 km) is only one to two minutes. Table 6-4 with the 5° elevation mask ignores interference from the low elevation angle base stations, but still shows average interference event duration of 3.8 min at the -67 dBm TRIG loss of lock threshold. (Compared to Table 6-3 there are fewer events, 57 vs 152, but the average duration is longer.)

The impact to the IGOR space receiver is seen to be much less. Note, however, that these results are only for the forward looking RO antenna. There will also be an aft pointing RO antenna, so interference will occur both when the CONUS is coming into the forward looking antenna FOV and when it is leaving the aft looking antenna FOV. Further analysis is required to determine the interference statistics when both antennas are included.

For the case of RO receiver onboard COSMIC-2 satellite in the 520 km/24° inclined orbit, the peak interference was found to be -88.2 dBm. This is much lower than for the 800 km/72° inclined orbit since the satellite does not pass over the US, but only sees a few base stations on the southern border. This level of interference is expected to cause less than 1 dB of degradation to the TRIG receiver.

Interference results for the navigation mode GPS RX with zenith pointed antenna onboard a LEOSAT (400 km/72° orbit) are shown in Table 6-5 (0° base station elevation mask) and Table 6-6 (5° base station elevation mask). The majority of GPS receivers used in space are small, lightweight, low-power devices providing spacecraft 3-dimensional position and velocity as well as timing and possibly 3-axis attitude determination. Table 6-5 and Table 6-6 show that compared to the RO case, interference effects are much less due to the backlobes and sidelobes of the receiving antenna facing towards the earth (and interfering base stations). Note also that no satellite body masking is included in this case which will likely further reduce the interference.

Although LightSquared is planning to operate the base stations at a maximum EIRP of 32 dBW per channel, the current FCC rules allow them to operate up to 42 dBW EIRP. Table 6-7, Table 6-8, Table 6-9, and Table 6-10 show the interference results if the base stations were to operate at 42 dBW EIRP.

Terrestrial Receiver (single base station) Analysis Results

Separation distance contours for the four receivers are shown in Figure 6-10 through Figure 6-13. In these polar plots, the base station is assumed to be at the center of the plot with the 3 sector antennas oriented in the 0°, 120°, and 240° azimuth directions. The radial rings show distance from the center (base station) in km. Contours are shown for several different propagation models. The least conservative models are shown on the left side and the most conservative on the right side. Note the different distance scales on the plots. In each case, the contours are associated with the receiver interference threshold that causes 1 dB C/No drop in the C/A-code channel. Referring to Table 6-2, these thresholds are -82 dBm (TRIG); -57 dBm (IGOR); -54 dBm (Receiver #15); and -68 dBm (Receiver #16). Base station height is 18.3 meters and GPS rx height is 1 meter. For these heights the radio LOS distance is 22 km so a receiver beyond 22 km is assumed not to receive interference. There is large variation in required separation distance depending on the assumed propagation model. Free-space loss yields the largest (most protective) separation distances: 22 km (TRIG); 4 km (IGOR); 3 km (Receiver #15); and 14 km (Receiver #16).

Terrestrial Receiver (multiple base station) Analysis Results

The results of this analysis are shown in Table 6-11 (redacted due to competitive sensitive data).

Table 6-1. NASA GPS Receiver Analysis Assumptions

		SPACEBORNE RECEIVER ANALYSIS	TERRESTRIAL RECEIVER ANALYSIS (SINGLE LSQ BASE STATION)	TERRESTRIAL RECEIVER ANALYSIS (MULTIPLE LSQ BASE STATIONS)
GPS CHARACTERISTICS	COMPUTATION METHOD	MATLAB TIME SIMULATION TO COMPUTE AGG INTERFERENCE FROM CONUS BASE STATIONS INTO ORBITING GPS RX (10-DAY SIM PERIOD @ 1-SEC TIME STEP)	MATHCAD CALCULATION USED TO COMPUTE REQUIRED SEPARATION DISTANCE CONTOURS FROM SINGLE BASE STATION	MATLAB INTERFERENCE MATRIX MAP COMPUTATION TO DETERMINE AGG LEVEL OF INTERFERENCE FROM MULTIPLE BASE STATIONS IN LAS VEGAS DEPLOYMENT
	GPS RX TYPE (all dual-frequency semi-codeless)	TRIG (next-gen space/occulation rx); IGOR (current gen space/occulation rx)	TRIG; IGOR; JAVAD; ASHTECH	JAVAD; ASHTECH
	ORBIT	COSMIC 2 HI ALT (800 km/72°) **(FIG 1)** COSMIC 2 LO ALT (520 km/24°) GENERIC LEO (400 km/72°)	N/A	N/A
	GPS RX ANTENNA TYPE	OCCULT 12-ELEMENT ARRAY (15.2 dBic for COSMIC-2 ORBITS) **(FIG 2)**; CHOKE RING (6.8 dBic for GENERIC LEO) **(FIG 3)**	CHOKE RING (6.8 dBic) **(FIG 3)**	CHOKE RING (6.8 dBic) **(FIG 3)**
	GPS RX ANTENNA POINTING	TOWARDS EARTH LIMB (COSMIC-2 OCCULT ORBITS); ZENITH (GENERIC LEO)	ZENITH POINTED	ZENITH POINTED
	GPS RX ANTENNA PATTERN	OCCULT 12-ELEMENT ARRAY; CHOKE RING	CHOKE RING	CHOKE RING
	INTERFERENCE THRESHOLD	THRESHOLDS AS MEASURED DURING JPL CONDUCTED TESTING **(TABLE 2)**	THRESHOLDS AS MEASURED DURING JPL CONDUCTED TESTING **(TABLE 2)**	THRESHOLDS AS MEASURED DURING JPL CONDUCTED TESTING **(TABLE 2)**
	POLARIZATION LOSS	3 DB	3 DB	3 DB
LIGHTSQUARED BASE STATION CHARACTERISTICS	DEPLOYMENT	Redacted for Commercial Sensitivity Reasons		
	SPECTRUM PHASE	PHASE 1: TWO (5 MHz) CHANNELS	PHASE 1: TWO (5 MHz) CHANNELS	PHASE 1: TWO (5 MHz) CHANNELS
	CHANNEL FREQS	1526.3 - 1531.3 MHz/ 1550.2 - 1555.2 MHz	1526.3 - 1531.3 MHz/ 1550.2 - 1555.2 MHz	1526.3 - 1531.3 MHz/ 1550.2 - 1555.2 MHz
	EIRP/CHANNEL STRUCTURE	62 dBm per (5 MHz) channel	62 dBm per (5 MHz) channel	62 dBm per (5 MHz) channel
	CHANNELS PER SECTOR	2 (PHASE 1)	2 (PHASE 1)	2 (PHASE 1)
	EIRP per SECTOR	65 dBm	65 dBm	65 dBm
	SECTORS per BASE STATION	Redacted for Commercial Sensitivity Reasons		
	SECTOR ANTENNA PATTERN			
	PROPAGATION MODEL	Redacted	RESULTS GENERATED FOR VARIOUS PROP MODELS (FREE-SPACE, HATA, EXTENDED HATA, Walfisch-Ikegami, NTIA/ITM) **(FIG 6)**	RESULTS GENERATED FOR VARIOUS PROP MODELS (FREE-SPACE, HATA, EXTENDED HATA, Walfisch-Ikegami, NTIA/ITM) **(FIG 6)**

Table 6-2. Summary of JPL Conduction Testing Interference Thresholds

		NASA GPS RECEIVER SUSCEPTIBILITY TO LSQ INTERFERENCE (BASED ON JPL CONDUCTED TESTING)											
		NOTE: POWER LEVEL SHOWN IS TOTAL POWER AT OUTPUT OF GPS RX PASSIVE ANTENNA (dBm)											
LSQ Signal Spectrum	Interference Criterion	TRIG			iGOR			IAVAD Delta G3T			Ashtech Z-12		
		L1 C/A	L1 P	L2 P	L1 C/A	L1 P	L2 P	L1 C/A	L1 P	L2 P	L1 C/A	L1 P	L2 P
LSQ Phase 1 (two 5 MHz channels @ 1526.3-1531.3 and 1550.2-1555.2)	1 dB C/No degradation	C -82	C -82	C -78	C -57	C -59	C -51	C -54	C -56	C -43	C -68		
	3 dB C/No degradation	C -78	C -80	C -77	C -53	C -54	C -49	C -51	C -52	C -43	C -65		
	5 dB C/No degradation	C -75	C -73	C -74	C -49	C -51	C -48	C -49	C -50	C -43	C -62		
	Loss of Lock	C -67	C -67	C -67	C -45	C -45	C -45	C -43	C -43	C -43	C -38	C -38	C -38

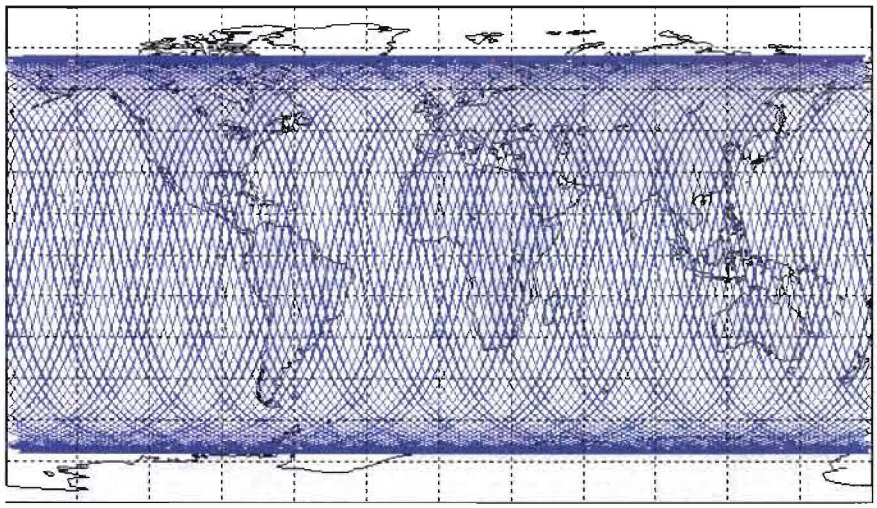


Figure 6-1. Ground Track of COSMIC-2 Satellite in 800 km/72° Orbit over 10-Day Sim Period

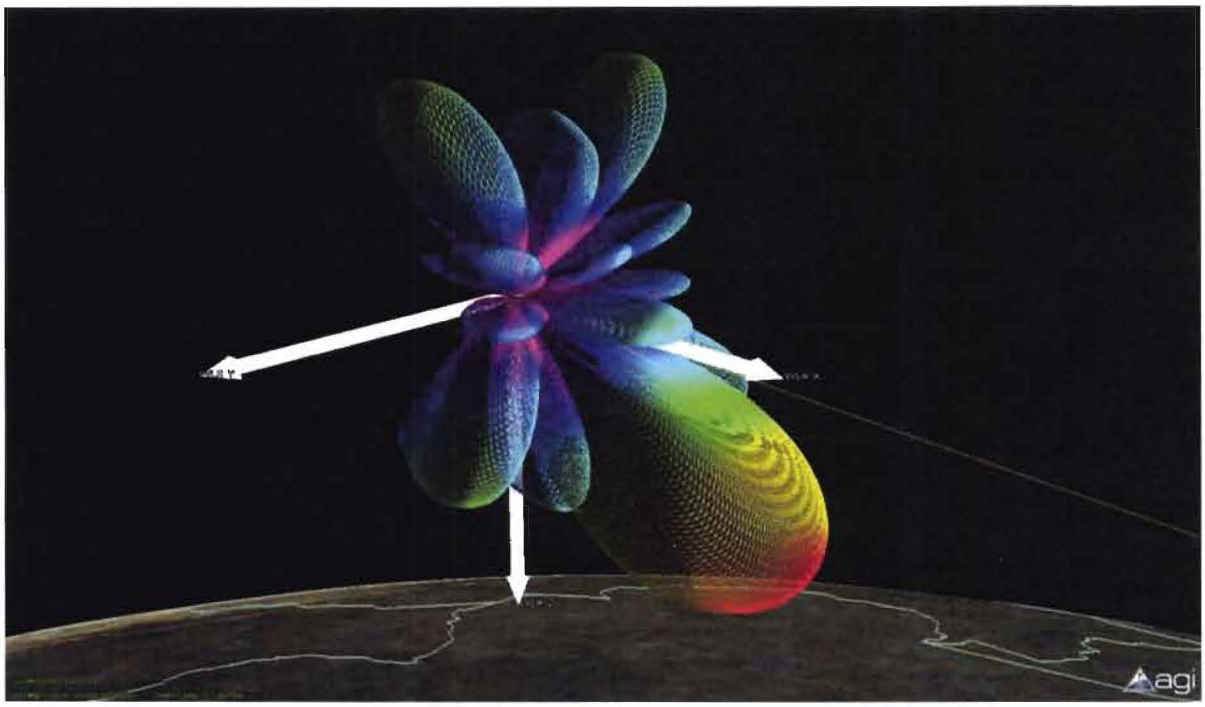
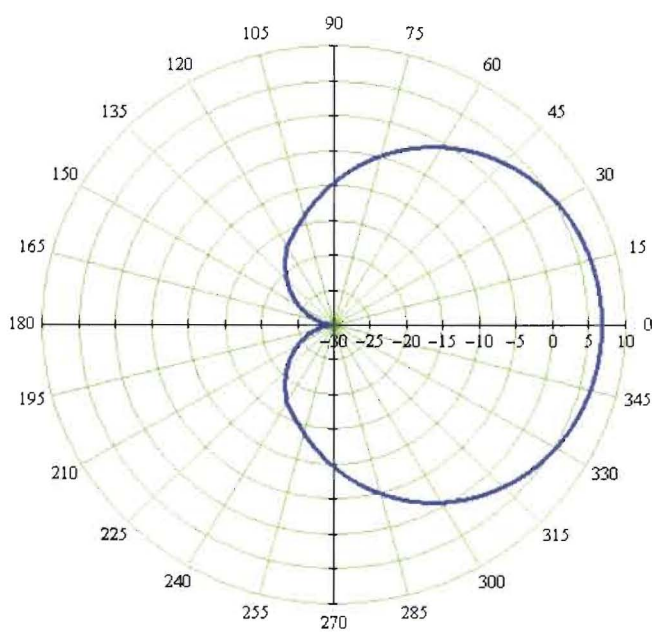


Figure 6-2. Gain Pattern of JPL GPS RX Occultation Antenna (12-element array with 15.2 dBic main beam pointed towards Earth limb)



Off-boresight Angle (deg) θ =	Gain (dBic) Choke_Ring2(θ)
0	6.7537
5	6.7081
10	6.5967
15	6.4016
20	6.1077
25	5.7031
30	5.1787
35	4.5286
40	3.7497
45	2.8421
50	1.8087
55	0.6556
60	-0.6083
65	-1.9709
70	-3.4173
75	-4.9294
80	-6.4863
85	-8.0639
90	-9.6353

Figure 6-3. GPS Receiver Choke Ring Gain Pattern (6.75 dBic gain)

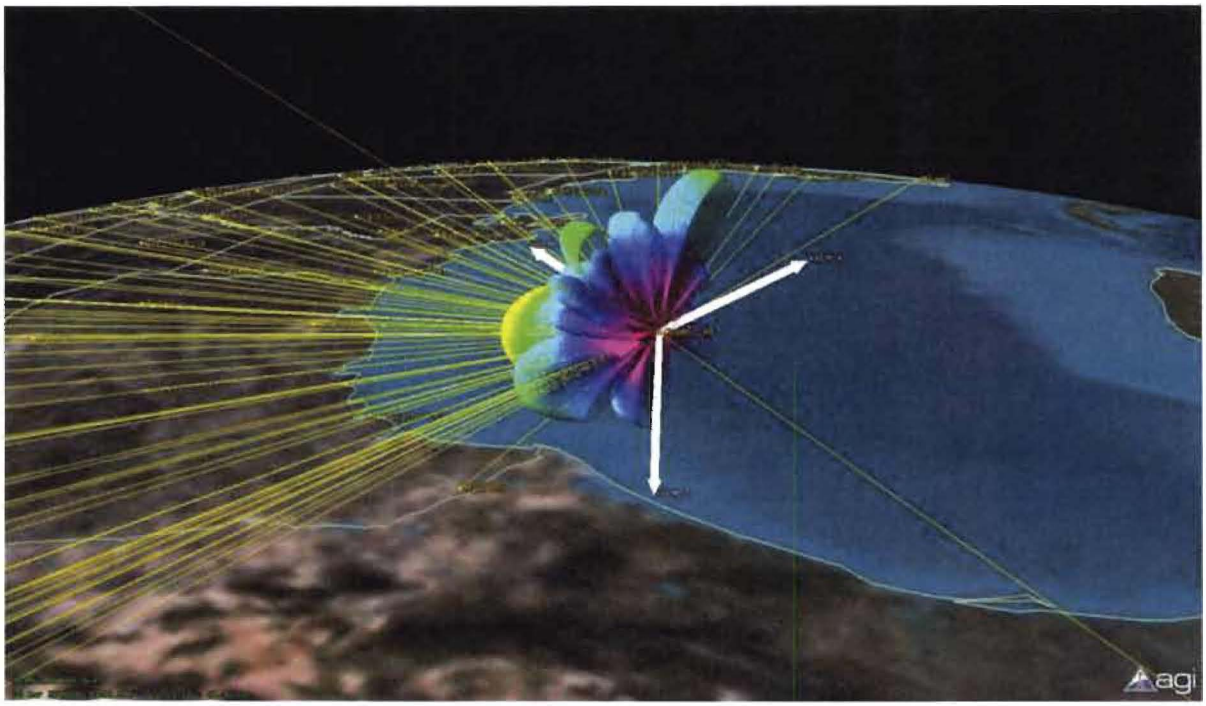


Figure 6-4. Spaceborne GPS RX Occultation Scenario (Main beam of Array Antenna is Pointed 26.2° Below the Satellite Local Horizontal Towards the Earth Limb)

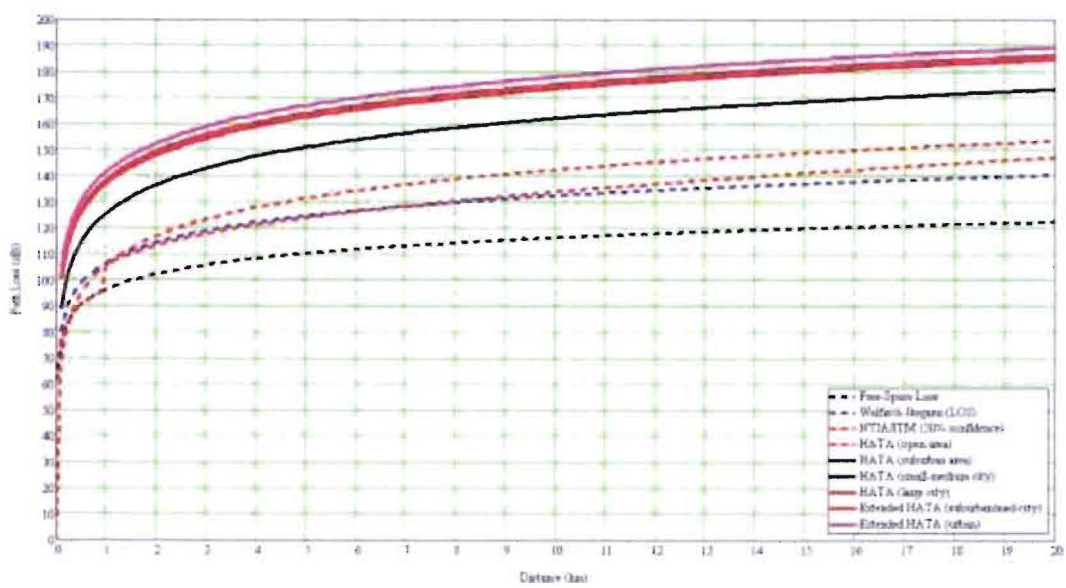


Figure 6-5. Comparison of Various Terrestrial Propagation Models