Antenna Design For Satellite Communications Aeronautical Application in Ku-Band

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1. INTRODUCTION

During the last few years IFE (In-flight Entertainment) has capture the attention of major airline operators. It seems to be the added-value factor that can create the difference between airlines. IFE services range from canned movies to content provided from ground via the internet. Content offered from ground can offer more flexibility and may be of more interest to passengers. Services offered to aircraft passenger can be e-mail, VPN access and web browsing.

In order to provide content to aircrafts from the ground, airline operators are looking into satellite systems. In order to provide a data link to a satellite, one of the key elements is an antenna that can be mounted on top of a commercial aircraft and that can reduce interference to adjacent satellites 2° apart from the target satellite.

2. DESIGN OVERVIEW

The objective is to design an antenna as small as possible in diameter so it does not represent a considerable increase in weight to the aircraft and that can be installed without compromising the integrity of the fuselage. For aeronautical applications other factors need to be considered such as air drag and aerodynamics. However mechanical factor will not be analyzed in this paper.

3. DESIGN REQUIREMENTS

The antenna will be used in a full-duplex satellite system using geostationary satellites and shall comply with the following requirements:

- Transmit and Receive in Ku-band 11.7- 12.2GHz downlink/14.0-14.5 GHz uplink
- Linear polarization (vertical and horizontal)
- Shall comply with FCC Ku mask
- The antenna shall meet FCC Title 47, Part 25.218 regulation for off-axis EIRP envelopes
- The antenna shall be less than 1 m in diameter
- The antenna shall close the link for at least to a 255 kbps service

4. REGULATORY CONSIDERATIONS

Because the spectrum is a limited resource, regulatory bodies such as FCC and ITU have established policies and rules for its efficient use. The purpose of these policies is to maximize the number of system accessing the resources but minimizing the interference among these systems. The FCC's rules require parties seeking to provide satellite service to submit an application. The Commission's general rules for licensing satellites are contained in Title 47 of the U.S. Code of Federal Regulations, Part 25 (See 47 CFR Part 25.218). These regulations include limitations for EIRP Spectral Density as shown in Table I.

TABLE I

OFF-AXIS EIRP SPECTRAL DENSITY FOR KU BAND

$21–25\log_{10}\Theta$	dBW/4 kHz	For	$1.5° \le \Theta \le 7°$
0	dBW/4 kHz	For	$7° < \Theta \le 9.2°$
$24–25\log_{10}\Theta$	dBW/4 kHz	For	$9.2° < \Theta \le 48°$
–18	dBW/4 kHz	For	$48° < \Theta \le 85°$
–8	dBW/4 kHz	For	$85° < \Theta \le 180°$

We will consider just the 1.5 to 7 degree range, since there is where the two closest adjacent satellites reside.

5. ORBITAL POSITION

The satellite considered in this paper is on geostationary orbit, that is at 36,000 Km above the equator. It is in this orbit where most of the commercial satellites are positioned. At this orbit, the satellite appears stationary with respect to a fixed point on the rotating earth. Using satellites in this orbit, makes the antenna design less complex, since it does not have to track a moving satellite.

Satellites on this orbit are now as close as 2 degrees apart from each other, increasing the probability of interference between systems in adjacent satellites. This brings a limitation on the size of the antenna that can be used, since the smaller the antenna the broader its main lobe, increasing the probability of interference to an adjacent satellite.

6. LINK BUDGET

A commercial off the shelf (COTS) link budget program is used to do the calculations and to validate that the link closes at 255 Kbps. We will not show the calculations here, just the process to derive the minimum antenna size. The COTS program takes in account the parameters mentioned here and more.

The objective is to minimize the size of the antenna. We need to know the performance of the satellite in terms of the ratio of power of the carrier to the power of the noise.

$$\frac{C}{No} = EIRP + \frac{G}{T} - (losses) - k$$

Using a satellite G/T = 8 dB/k for higher gain satellite, and k = Boltzmann's constant.

The losses include the free space loss (FSL) and other atmospheric losses which are not described here but accounted for in the full link budget in appendix A.

$$FSL = \left[\frac{4\pi r}{\lambda}\right]^2$$

We also know that the $\frac{C}{No}$ can also be expressed in energy terms

$$\frac{C}{No} = \frac{Eb}{No} + Rb \quad [in\ dB]$$

Doing the appropriate substitutions in the above equations we can see that the antenna gain is

$$G = \frac{EIRP}{Pt}$$

Where Pt is the power output from the amplifier. From here we solve for D in order to find the antenna diameter that can satisfy the requirements

$$D = \frac{\lambda}{\pi}\left(\frac{G}{\varepsilon}\right)^{1/2}$$

From this process we find that that a 20 cm. antenna could close the link at the specified data rate. However the analysis has to look into the radiation pattern in order to see if such antenna will not interfere with adjacent satellites.

We know that the smaller then antenna, the broader it's main lobe, and therefore more susceptible to interfere.

7. RADIATION PATTERN

A radiation pattern is a three dimensional representation of the distribution of energy. It let us know certain characteristics of the antenna such as the directivity of the antenna, position of the nulls and the beamwidth.

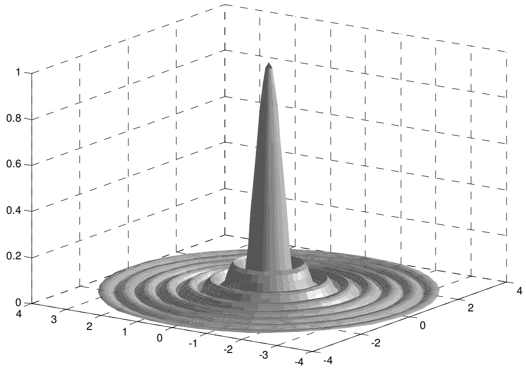

Fig. 1. 3D representation of a radiation pattern

7.1. Taper

The pattern of a reflector antenna depends on how the reflector is illuminated by the feed. The variation of the energy across the aperture is called the taper.

If the feed is designed to cause the electric field to decrease with distance from the canter, then the aperture taper efficiency decreases but the proportion of power in the main lobe increases. Maximum aperture efficiency occurs for a uniform aperture distribution, but maximum bema efficiency occurs for a highly tapered distribution.

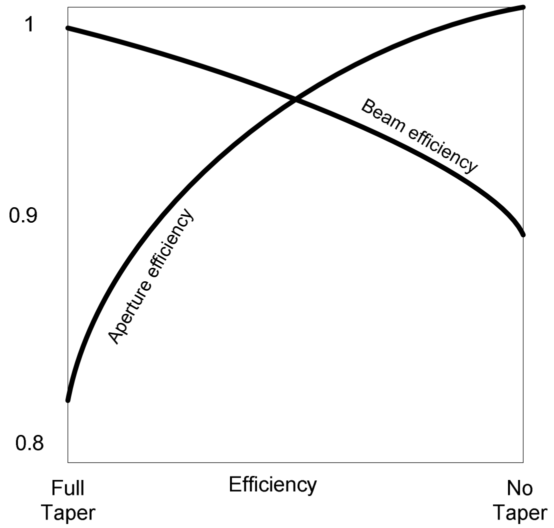

Fig. 2. Beam and aperture efficiency for a 1-dimensional aperture as a function of taper

In general, maximum aperture taper efficiency occurs for a uniform distribution, but maximum beam efficiency occurs for a highly tapered distribution. In other words, as the taper gets larger, the side lobes decrease but the beamwidth increases.

In our design we want a narrow main lobe beamwidth, which can lesser the interference from and to adjacent satellites. Therefore a uniform illuminated reflector with taper zero is selected.

The pattern is plotted using Bessel functions as shown in the next formula

$$G(\phi) = G_{\max}\left[f(\phi)\right]^2 = G_{\max} \cdot \left| 2^{tpr+1}(tpr+1)! \frac{J^1_{tpr+1}(\phi)}{(\phi)^{tpr+1}} \right|^2$$

7.2. First Nulls

In a pattern the lobes are separated by nulls. There is where the radiation falls to zero. This is because the radio waves interfere at different angles constructively or destructively. Where the waves arrive out of phase the radiation is zero and a null is created in the pattern.

We know that adjacent satellites are located 2° apart, so we need the first null to be at 2°, so we minimize the interference to neighbouring satellites.

$$BWFN = 2HPBW$$

And we know that

$$\text{HPBW} = 70\frac{\lambda}{\text{D}}$$

This yields to an antenna with a diameter of 70 cm, which is considerably larger than the 20 cm calculated with the link budget method.

In order to see the difference in the patterns characteristics we plot the patterns using Matlab®. For our analysis we will not use a three dimensional representation but a two dimension plot for simplification.

We can see in Fig 2 that even when the link budget method calls for a 20 cm antenna, when we evaluate the bandwidth between first nulls we can see that the main lobe of a 20 cm aperture would interfere to any satellite 6° apart from boresight's axis. Because of the reciprocity principle in antennas, this station would also receive interference from satellites 6° from boresight.

Making the first nulls fall at 2° from boresight we calculate a 70 cm antenna. This antenna still meets the requirement for a sub-meter aperture. Also having a larger antenna can provide a larger margin in the link budget that can be used to provide a link above the 255 Kbps, exceeding the original requirement.

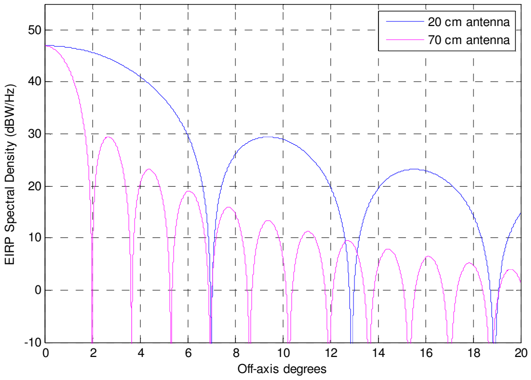

Fig. 3. Pattern comparison between 20 cm and 70 cm antenna

The next step is to see if the proposed antenna meets the Title 47 of the Code of Federal Regulations, which are the FCC rules, part 25 describes the regulations and rules pertaining to satellite communications.

As we can see in Fig 4 an antenna with a 70 cm aperture meets the link requirement and also the FCC emissions regulation for EIRP spectral density

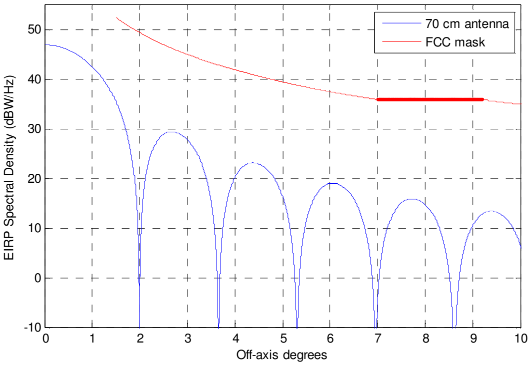

Fig. 4. Comparison of pattern against FCC mask

8. CONCLUSION

An antenna design needs to consider the environment on which the antenna will be performing, as well as the regulatory limitations that may apply in the environment where the antenna will be operating. Considerable attention must be applied in the requirements gathering phase in order to not over look factors that could render the design not usable because regulatory requirements were not met, even when technically the design seems to be a sound one.

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Appendix A

Link Budget

Produced by Hector Velasco

Monday 12 September 2011

Service Name	Middle East
Coverage	Middle East
Uplink earth station	Aircraft
Downlink earth station	Dubai-Teleport
Satellite name	ASIASAT 5
Modcod	Manual

Link Input Parameters	**Up**	**Down**	**Units**
Site latitude	31.2N	25.25N	degrees
Site longitude	34.9E	55.31E	degrees
Site altitude	5.000	0.037	km
Frequency	14.205	12.457	GHz
Polarization	Horizontal	Horizontal	
Rain model	ITU-R	ITU-R	
Rain zone or mm/h	25.4	23.0	
Availability (average year)	99.5	99.9	%
Antenna aperture	.7	6.1	metres
Antenna efficiency or gain (+ or - prefix)	65	65	% or dBi
Coupling loss	.5	.5	dB
Antenna mispoint loss	.4	.5	dB
Other path losses	0	0	dB
LNB noise figure or temp (+ prefix)		4	dB or K
Antenna Noise		5.00	K
Csat/ACIo	72	72	dB.Hz
Csat/ASIo	150.00	100.00	dB.Hz
Csat/XPIo	72	72	dB.Hz
Uplink station HPA output back-off	4.4		dB
Uplink power control	0		dB
Number of carriers / HPA	1		
HPA C/IMo	140		dB.Hz
Required HPA power	MIN		W

Satellite Input Parameters	**Value**	**Units**
Satellite longitude	100.50E	degrees
Transponder type	SSPA	
G/T Reference	0	dB/K
SFD Reference	-95	dBW/m2
Receive G/T	0	dB/K
Attenuator pad (gain step)	14	dB
Effective SFD	**-81.00**	**dBW/m2**
Satellite ALC	0	dB
EIRP (saturation)	52.5	dBW
Transponder bandwidth	36	MHz
Input back off total	3	dB
Output back off total	5.00	dB
C/IM	15.55	dB
Number of transponder carriers	AUTO	

Carrier/Link Input Parameters	**Value**	**Units**
Modulation	2-PSK	
Required Eb/No	-7	dB
Information rate	.255	Mbps
Information rate overhead	68	%
FEC code rate	.43	
Spreading gain	6	dB
(1 + Roll off factor)	1.2	
Carrier spacing factor	1.4	
Bandwidth allocation step size	.1	MHz
Implementation loss	1	dB
System margin	1	dB

Calculations at Saturation	**Value**	**Units**
Gain 1m^2	44.50	dB/m2
Uplink C/No	103.09	dB.Hz
Downlink C/No	103.28	dB.Hz
Total C/No	100.18	dB.Hz
Uplink EIRP for saturation	82.73	dBW

General Calculations	**Up**	**Down**	**Units**
Elevation	12.26	32.27	degrees
True azimuth	103.22	112.96	degrees
Compass bearing	99.14	111.23	degrees
Path distance to satellite	40351.98	38412.26	km
Propagation time delay	0.134599	0.128129	seconds
Antenna efficiency	65.00	65.00	%
Antenna gain	38.49	56.15	dBi
Availability (average year)	99.5	99.9	%
Link downtime (average year)	43.830	8.766	hours
Availability (worst month)	98.440	99.615	%
Link downtime (worst month)	11.393	2.809	hours

Uplink Calculation	**Clear**	**Rain Up**	**Rain Dn**	**Units**
Uplink transmit EIRP	71.65	71.65	71.65	dBW
Transponder input back-off (total)	3.00	3.00	3.00	dB
Input back-off per carrier	11.08	11.79	11.08	dB
Antenna mispoint	0.40	0.40	0.40	dB
Free space loss	207.61	207.61	207.61	dB
Atmospheric absorption	0.22	0.28	0.22	dB
Tropospheric scintillation fading	0.00	0.64	0.00	dB
Cloud attenuation	0.00	0.00	0.00	dB
Rain attenuation	0.00	0.00	0.00	dB
Total attenuation (gas-rain-cloud-scintillation)	0.22	0.93	0.22	dB
Other path losses	0.00	0.00	0.00	dB
Uplink power control	0.00	0.00	0.00	dB
Uncompensated fade	0.00	0.71	0.00	dB
C/No (thermal)	92.01	91.31	92.01	dB.Hz
C/N (thermal)	26.03	25.32	26.03	dB
C/ACI	-5.06	-5.77	-5.06	dB
C/ASI	72.94	72.23	72.94	dB
C/XPI	-5.06	-5.07	-5.06	dB
C/IM	62.94	62.94	62.94	dB
C/(N+I) [= Es/(No+Io)]	-8.08	-8.45	-8.08	dB
Eb/(No+Io)	1.59	1.22	1.59	dB

Downlink Calculation	**Clear**	**Rain Up**	**Rain Dn**	**Units**
Satellite EIRP total	52.50	52.50	52.50	dBW
Transponder output back-off (total)	5.00	5.00	5.00	dB
Output back-off per carrier	13.08	13.79	13.08	dB
Satellite EIRP per carrier	39.42	38.71	39.42	dBW
Antenna mispoint	0.50	0.50	0.50	dB
Free space loss	206.05	206.05	206.05	dB
Atmospheric absorption	0.16	0.16	0.25	dB
Tropospheric scintillation fading	0.00	0.00	0.63	dB
Cloud attenuation	0.00	0.00	0.15	dB
Rain attenuation	0.00	0.00	2.07	dB
Total attenuation (gas-rain-cloud-scintillation)	0.16	0.16	2.56	dB
Other path losses	0.00	0.00	0.00	dB
Noise increase due to precipitation	0.00	0.00	0.82	dB
Downlink degradation (DND)	0.00	0.00	3.22	dB
Total system noise	474.44	474.44	572.85	K
Figure of merit (G/T)	28.89	28.89	28.07	dB/K
C/No (thermal)	90.20	89.49	86.98	dB.Hz
C/N (thermal)	24.22	23.51	21.00	dB
C/ACI	-7.06	-7.77	-7.06	dB
C/ASI	20.94	20.23	20.94	dB
C/XPI	-7.06	-7.77	-7.07	dB
C/IM	15.55	15.55	15.55	dB
C/(N+I) [= Es/(No+Io)]	-10.09	-10.80	-10.09	dB
Eb/(No+Io)	-0.43	-1.13	-0.43	dB

Totals per Carrier (End-to-End)	Clear	Rain Up	Rain Dn	Units
C/No (thermal)	88.00	87.29	85.80	dB.Hz
C/N (thermal)	22.02	21.31	19.81	dB
C/ACI	-9.19	-9.90	-9.19	dB
C/ASI	20.94	20.23	20.94	dB
C/XPI	-9.19	-9.64	-9.19	dB
C/IM	15.55	15.55	15.55	dB
C/I (total)	-12.21	-12.79	-12.21	dB
C/(No+Io)	53.77	53.19	53.77	dB.Hz
C/(N+I) [= Es/(No+Io)]	-12.21	-12.79	-12.21	dB
Eb/(No+Io)	-2.55	-3.12	-2.55	dB
Implementation loss	1.00	1.00	1.00	dB
System margin	1.00	1.00	1.00	dB
Net Eb/(No+Io)	-4.55	-5.12	-4.55	dB
Required Eb/(No+Io)	-7.00	-7.00	-7.00	dB
Excess margin	**2.45**	**1.88**	**2.45**	**dB**

Earth Station Power Requirements	Value	Units
EIRP per carrier	71.65	dBW
Antenna gain	38.49	dBi
Antenna feed flange power per carrier	33.16	dBW
Uplink power control	0.00	dB
HPA output back off	4.40	dB
Waveguide loss	.5	dB
Number of HPA carriers	1	
Total HPA power required	38.0603	dBW
Required HPA power	6397.8176	W

EIRP Density Calculations	Clear	Rain Up	Rain Dn	Units
Flange transmit (up)	-32.82	-32.82	-32.82	dBW/Hz
Flange receive (down)	-176.62	-177.33	-179.84	dBW/Hz

Space Segment Utilization	Value	Units
Overall availability	99.401	%
Information rate	0.2550	Mbps
Information rate (inc overhead)	0.4284	Mbps
Transmit rate	0.9963	Mbps
Symbol rate	3.9663	Mbaud
Noise Bandwidth	65.98	dB.Hz
Occupied bandwidth	4.7595	MHz
Minimum allocated bandwidth required	5.5528	MHz
Allocated transponder bandwidth	5.6000	MHz
Percentage transponder bandwidth used	**15.56**	**%**
Used transponder power	39.42	dBW
Percentage transponder power used	**15.56**	**%**
Max carriers by transponder bandwidth	6.43	
Max carriers by transponder power	9.91	
Max transponder carriers limited by:-	Bandwidth	[6.43]
Power equivalent bandwidth usage	5.6000	MHz