C/X Digital Transponder for Eagle

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The Eagle class 2 and class 3 downlink and class 2 uplinks require bandwidth that is only available in the bands above 1 GHz. Only the microwave bands are considered as the millimeter-wave bands suffer from excessive atmospheric attenuation at low elevations. There are 7 microwave bands allocated for the amateur satellite service on a worldwide basis as shown in table 1, below.

Band	Frequency	Direction	Other Uses
L	1,260-1,270 MHz	Up	Galileo
S_1	2,400-2,450 MHz	Up/Down	WiFi
S_2	3,400-3,410 MHz	Up/Down	(regions 2&3 only)
C	5,650-5,670 MHz	Up	WiFi
	5,830-5,850 MHz	Down	-
X	10,450-10,500 MHz	Up/Down	-

Table 1 – Microwave Amateur Satellite Bands

Wide-band uplinks on L band may cause interference to Galileo receivers operating in the 1215-1300 MHz radionavigation band so it is desirable to avoid use of the L band for wide-band satellite uplinks. Narrow-band signals may fit in the null shown in figure 1 but wide-band signals will cause more interference. L is also not the best band for small antennas as a 2-foot dish is only 2.5λ wide and cannot be fed efficiently.

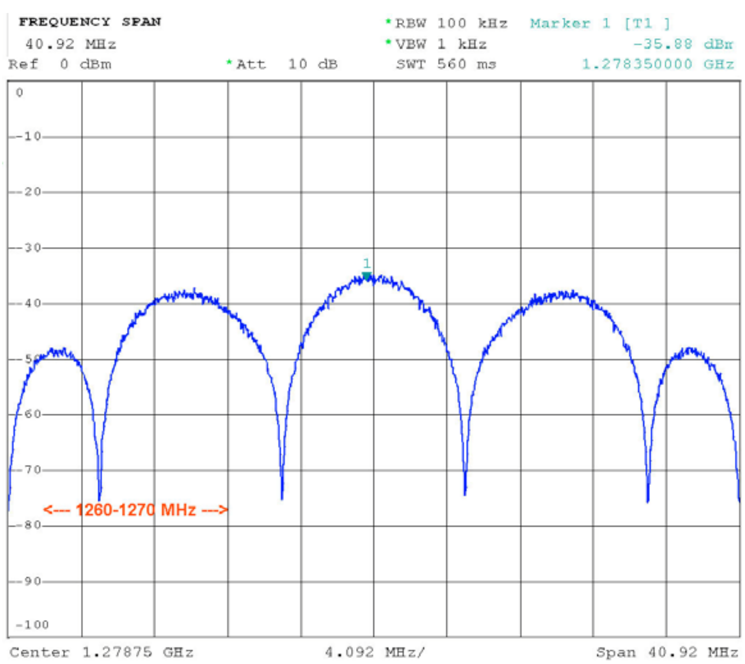

Figure 1 – Galileo Downlink Signal

The WiFi equipment operating in the 2400-2483 MHz ISM band is a source of interference, so it is useful to avoid the S_1 band for satellite downlinks. The S_2 band is not allocated for region 2 (Europe) so it is also undesirable. This results in two potential frequency pairs for digital transponders – S_1/C and C/X.

S_1/C is the best technical solution, but has two political problems – S_1 is unavailable in Argentina and some AMSAT members want S_1 used as a downlink for a L/S_1 or U/S_1 analog (SSB, CW, etc.) transponder. The digital transponder should be available throughout the orbit so sharing S for a digital uplink and analog downlink is not feasible. The uplink problem in Argentina may be solved in the future as licensed commercial users are vacating that band. Either moving the analog S downlink to a quieter band or moving the digital S uplink to another band could solve the L/S_1 transponder problem. This document examines that latter solution.

The lower frequency pair, S_1/C, was deemed to be the most desirable as LNA noise figures are slightly lower and the required antenna pointing accuracy is lower. However, the magnitude of these effects is much smaller today than in the past. C-band LNA ICs are now available with a 1.3 dB noise figure and X-band discrete-component LNA noise figures have been 0.9 dB or less for almost a decade. For a 2-foot dish, the C/X antenna is also more efficient than an S/C antenna. The reflector size at the lowest frequency increases from 4.5λ to 10λ so the feed is smaller. This reduces blockage and increases gain for both the uplink and downlink.

Antenna pointing accuracy is an issue as the -3 dB beamwidth decreases from 6.2° to 3.3°. However, since the pointing accuracy must be much greater than the ±4° of Yaesu rotators used for VHF/UHF antenna arrays, the difference between C and X bands should not significantly affect the cost. The position can be determined to less than 0.5° by counting shaft rotations on positioning motors or a combination of mechanical and electrical steering can be used. The narrower beamwidth has one advantage – the satellite can be lower on the horizon before thermal noise from the earth degrades the system noise figure.

Antenna size is not a problem. The downlink antenna gain cannot exceed 18 dBic, as it must illuminate the earth. 25 elements can provide this gain and 36 elements provide redundancy in case the electronics for some elements fails. Therefore, a 36-element X-band antenna is smaller than a C-band antenna, but the EIRP is the same. The earth-based downlink receiver will have the same aperture on either band, so the gain increases by 5 dB from C to X band, which compensates for the increase in path loss. The gain of the fixed-size earth-based uplink antenna also increases to compensate for increased path loss from S to C band, so moving from an S to C uplink does not require an increase in the number of elements. This frees up space on the satellite for other antennas or for more solar cells. Alternatively, the satellite may be smaller. Figure 2 shows the approximate size of the 36-element C and X arrays along with V and U antennas.

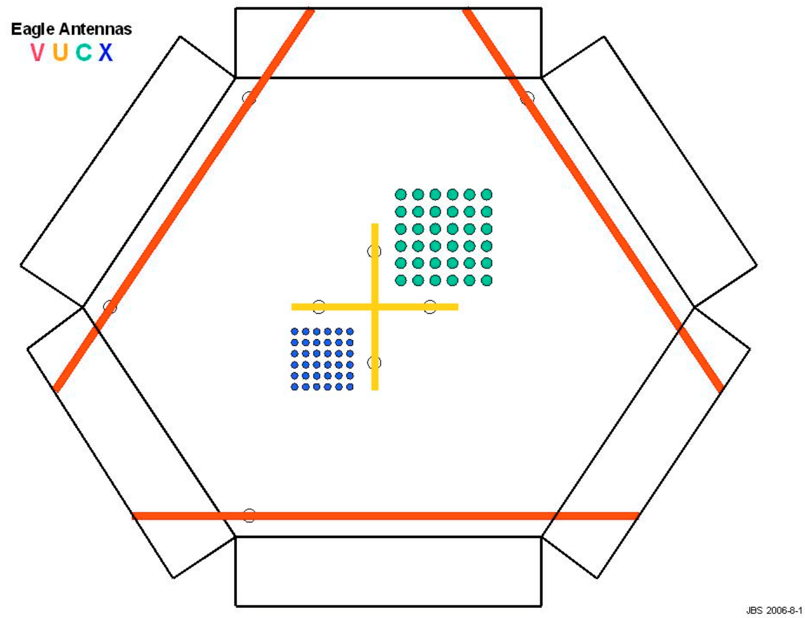

Figure 2 – Antenna Placement on 600 mm per side Hexagonal Spaceframe

Another issue if spin modulation. As the satellite rotates, the distance from the center of the antenna to the earth station changes. A 36-element array is about 4λ square. If it is mounted with one edge ½λ from the spin axis, it will rotate in a circle 7λ in diameter. Given that the satellite spins at less than ½ RPS, the modulation rate will be less than 3.5 Hz. The carrier-tracking loop in the receiver will have a bandwidth of 100 Hz or more, so it will easily track this low-frequency variation and no spin modulation will not appear at the demodulator output.

Power amplifier efficiency remains an area of difference. X-band MMIC PA efficiencies have been below 20% but ICs are now available for X-band with ½ to 2 W RF outputs with efficiencies of 30%. This compares to efficiencies of 50% for C-band.

The receivers and transmitters must have local oscillators with low enough phase noise so as not to significantly affect the carrier tracking and demodulation of the data links. Requirements have not yet been provided by the digital payload designers, but the requirements of class 2 and 3 links at C/X should not be harder to meet than class 1 links at U/V. Since class 1 and 2 downlinks operate at 20 times the data rate of uplinks, the uplink requires the lowest phase noise. The class 1 service is 30-50 bps with an uplink at 435 MHz. The class 2 service is 4800 bps with an uplink at 5660 MHz. Thus the data rate for class 2 is at least 96 times higher than class 1, but the uplink frequency only increases by a factor of 10.7 when going from 436 to 5660 MHz. This should allow the use of relatively simple LOs for C band. This document can be updated once phase noise requirements are available.

The link analyses for the C uplink and X downlink are shown in tables 2 and 3, below. 5 dB of implementation loss is assumed – 2 dB is for antenna pointing errors and 3 dB for miscellaneous losses. The C uplink in table 2 has similar performance to an S uplink. However, an X downlink consumes 67% more power than a C downlink.

	A	B	C	D	E	F	G	H	I
1	Ground:								
2	#Tx Pwr	5.0	W	Carrier	0.19913492	W	3.98%		
3	#Ant Gain	28.009626	dBi	Eb	199.134925	µJ	96.02%		
4	#Impl Loss	2	dB						
5	#Dish diam	0.6	m	(Gain)	28.009626	dBi	Beamwidth	6.17498684	deg
6				EIRP	33.0	dBW			
7	Path:								
8	#Range	40000	km						
9	#Freq	5660	Mhz	Wavelength	0.05300353	m	Path loss	199.5	dB
10	Spacecraft:								
11	#Ant Gain	18	dBi						
12	#Impl Loss	3	dB	Rx Power	-151.5	dBW	G/T	-13.1	dB/K
13	#Noise Temp	640	K	No	-200.5	dBJ			
14				Rx P/No	49.0	dB-Hz			
15	#C loop BW	100	Hz				Mod index	78.4883609	deg
16	#C SNR	15	dB	C/No	35.0	dB-Hz	Mod loss	0.18	dB
17	#Eb/No	5	dB	Data rate	24109	b/s	Carrier loss	14.00	dB
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	A	B	C	D	E	F	G	H	I
1	Ground:								
2	#Tx Pwr	15.0	W	Carrier	0.0221261	W	0.15%		
3	#Ant Gain	37.5520511	dBi	Eb	22.1261027	µJ	99.85%		
4	#Impl Loss	2	dB						
5	#Dish diam	1.8	m	(Gain)	37.5520511	dBi	Beamwidth	2.05832895	deg
6				EIRP	47.3	dBW			
7	Path:								
8	#Range	40000	km						
9	#Freq	5660	Mhz	Wavelength	0.05300353	m	Path loss	199.5	dB
10	Spacecraft:								
11	#Ant Gain	18	dBi						
12	#Impl Loss	3	dB	Rx Power	-137.2	dBW	G/T	-13.1	dB/K
13	#Noise Temp	640	K	No	-200.5	dBJ			
14				Rx P/No	63.3	dB-Hz			
15	#C loop BW	100	Hz				Mod index	87.7989176	deg
16	#C SNR	15	dB	C/No	35.0	dB-Hz	Mod loss	0.01	dB
17	#Eb/No	5	dB	Data rate	676932	b/s	Carrier loss	28.31	dB
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Table 2 – Uplink Characteristics

The satellite receiver is assumed to use Avantek MGA-665P8 LNA ICs and have a noise figure of 3 dB. The typical noise figure of each IC is 1.5 dB with a 1.9 dB absolute maximum. 1.1 dB of PCB and transmission line loss and 60 K of noise from earth-based 802.11 devices are assumed. The class 2 uplink assumes the use of four Hittite HMC408 power amplifier ICs in the ground station. Each produces 1.6 W RF output and after combining and transmission line losses, 5 W is assumed to arrive at the 2-foot dish antenna to create 3.1 kW EIRP. The class 3 uplink assumes a 15 W amplifier and a 6-foot dish for 85 kW EIRP.

Note that the user data rates will be less than half of the rates shown, as there will be overhead for error-correcting codes and communication protocols.

The satellite downlink uses 36 M/A-COM MAAPGM0034 power amplifier ICs. They provide 500 mW saturated output with a 30% power-added efficiency, so an array of 36 provides 18 W RF power output and 1150 W EIRP with 60 W DC power input. The ground-station receiving system has a 1 dB NF LNA, transmission line losses are 0.5 dB and antenna side-lobe levels are -10 dBc. The downlink data rate is almost halved to achieve DC power input similar to a C-band downlink.

	A	B	C	D	E	F	G	H	I
1	Spacecraft:								
2	#Tx Pwr	18	W	Carrier	0.04667225	W	0.26%		
3	#Ant Gain	18	dBi	Eb	46.672248	µJ	99.74%		
4	#Impl Loss	2	dB	EIRP	28.6	dBW			
5	Path:								
6	#Range	40000	km						
7	#Freq	10460	'Mhz	Path loss	204.9	dB			
8				Wavelength	0.02868069	m			
9	Ground:								
10	#Dish diam	0.6	m	Gain	33.3439311	dBi	Beamwidth	3.34134087	deg
11	#Ant Gain	33.3439311	dBi						
12	#Impl Loss	3	dB	Rx Power	-146.0	dBW	G/T	8.6	dB/K
13	#Noise Temp	150	K	No	-206.8	dBJ			
14	#Rx P/No				60.9	dB-Hz			
15	#C loop BW	100	Hz				Mod index	87.081205	deg
16	#C SNR	15	dB	C/No	35.0	dB-Hz	Mod loss	0.01	dB
17	#Eb/No	5	dB	Data rate	384668	b/s	Carrier loss	25.86	dB
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	A	B	C	D	E	F	G	H	I
1	Spacecraft:								
2	#Tx Pwr	18	W	Carrier	0.00518581	W	0.03%		
3	#Ant Gain	18	dBi	Eb	5.18580533	µJ	99.97%		
4	#Impl Loss	2	dB	EIRP	28.6	dBW			
5	Path:								
6	#Range	40000	km						
7	#Freq	10460	'Mhz	Path loss	204.9	dB			
8				Wavelength	0.02868069	m			
9	Ground:								
10	#Dish diam	1.8	m	Gain	42.8863562	dBi	Beamwidth	1.11378029	deg
11	#Ant Gain	42.8863562	dBi						
12	#Impl Loss	3	dB	Rx Power	-136.4	dBW	G/T	18.1	dB/K
13	#Noise Temp	150	K	No	-206.8	dBJ			
14	#Rx P/No				70.4	dB-Hz			
15	#C loop BW	100	Hz				Mod index	89.0274424	deg
16	#C SNR	15	dB	C/No	35.0	dB-Hz	Mod loss	0.00	dB
17	#Eb/No	5	dB	Data rate	3470013	b/s	Carrier loss	35.40	dB
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Table 3 – Downlink Characteristics for Similar RF Power as C Downlink

The data rates shown are prior to error correction and prior to multiplexing of low and high data rates. Each adds approximately 50% of overhead, so user data rates are approximately 25% of the instantaneous raw data rate. The required raw data rates are 4*4800*20 or 384 kbps for 20 class 2 users and 4*3*256 kbps or 3072 kbps for 3 class 3 users so the transponder requirements are just met.

Thus, if more DC power is made available, a digital C/X transponder for Eagle is possible and frees up S_1 for a L/S_1 analog transponder. Generating 18 W of RF for an X downlink requires 60 W and generating 18 W of RF for a C downlink requires 36 W. There will also be more power required for drivers as they will also be less efficient. Assuming 20% goes into drivers, 30 W of additional power must be provided to provide an X band downlink. Of course, the same amount of DC power could be used for other purposes.