Using the Band 460-470 MHz for Education Satellites - Some Thoughts -

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Regulatory Basis for This Initiative

- **<u>ITU Footnote 5.289</u>: Earth exploration-satellite service applications, other than the meteorological-satellite service, may also be used in the bands 460-470 MHz and 1690-1710 MHz for space-to-Earth transmissions subject to not causing harmful interference to stations operating in accordance with the Table.**

AND…

<u>US Foonote:</u> US201 In the band 460-470 MHz, space stations in the Earth exploration-satellite service may be authorized for space-to-Earth transmissions on a secondary basis with respect to the fixed and mobile services. When operating in the meteorological-satellite service, such stations shall be protected from harmful interference from other applications of the Earth exploration-satellite service. The power flux-density produced at the Earth's surface by any space station in this band shall not exceed -152 $dBW/m^2/4$ kHz.

Regulatory Basis for This Initiative (2)
International and Domestic (U.S.) Table

International: ITU	Domestic United States: U.S Gov.	Domestic United States: U.S. Non-Gov.	Domestic United States: FCC Radio Regs: (CFR 47)
460-470 FIXED MOBILE Meteorological-satellite (space-to-Earth) 5.287 5.288 5.289 5.290	460-470 Meteorological-satellite (space-to-Earth) 5.287 5.288 5.289 US201 US209 US216	460-462.5375 FIXED LAND MOBILE 5.289 US201 US209 NG124	Private Land Mobile (90)
		462.5375-462.7375 LAND MOBILE 5.289 US201	Personal Radio (95)
		462.7375-467.5375 FIXED LAND MOBILE 5.287 5.289 US201 US209 US216 NG124	Private Land Mobile (90)
		467.5375-467.7375 LAND MOBILE 5.287 5.289 US201	Personal Radio (95)
		467.7375-470 FIXED LAND MOBILE 5.288 5.289 US201 US216 NG124	Private Land Mobile (90)

Interpretation of the Table

- In all 3 ITU Regions the Band 460-470 MHz is allocated on a PRIMARY basis to the FIXED and MOBILE services and to the Meteorological Satellite Service on a SECONDARY basis.
- In the United States US Government stations can use the band for the Meteorological Satellite Service on a SECONDARY BASIS [NOTE: Non-government users are not allowed to do this].
- Footnote US201 allows the band to be used by government and non-government users on a secondary basis for the Earth Exploration Satellite Service. This service is secondary to FIXED and MOBILE services. This use of the band, is secondary (as a satellite service) ,to the Meteorological Satellite Service. Thus, one could say, this is a tertiary use of the band.
- Footnote US201 also places a downlink PFD of -152 $dBW/m^2/4$ kHz on downlink signals emitted by any space station operating in this band.
- In the Domestic U.S. table this band is divided into 5 separate MOBILE and MOBILE/FIXED sub-bands situated across the 10 MHz.
- The Mobile Services are regulated by the FCC regulations under Part 90 (Private Land Mobile Service and Part 95 (Personal Radio Service)

Interpretation of the Table (2)

- Footnotes in the International Table Allow the Band 460-470 MHz to be used selectively in the Maritime Mobile Service.
- International Footnote 5.290 allows certain countries (in the middle and far east) to use these bands on a primary basis for the Meteorological Satellite Service. (NOTE: This is helpful). This minimizes the number of mobile users that might occupy these bands in that very crowded part of the world.
- Footnote US209 allows low power (100 mW) telemetry bio-medical users (both government and non-government) to use this band selectively (i.e., on discrete frequencies around 460 MHz and, again, around 465 MHz. Channel bandwidths are not mentioned in the footnote.
- Footnote US216 allows two small frequency bands around 463 MHz and 468 MHz to be used ON A PRIMARY BASIS for Medical Radio Communications systems (this is for "both Federal and non-Federal government use."
- Footnote NG124 (Non-government footnote) allows police to use low power transmitters on to sub-bands covering most of the lower half of this 10 MHz band on a secondary basis.

Interpretation of the Table (3)

- This band is crowded with many types of terrestrial users and there may be significant downlink (Earth-to-space) use already in progress, particularly in the Meteorological Satellite Service.
- Cubesats SHOULD operate in the Space Research Service. This band is not allocated to SRS. Is a change to the table or a new footnote required? HELP!

- **QUESTION:** **Has anyone investigated the number of transmitters authorized by NTIA and FCC?** These should be in publically available frequency assignment tables.

Given PFD Limits Set by Footnote US201:

- Can Small Satellites Using Narrow Downlinks (as is the current Cubesat Practice) comply with the -152 $dBW/m^2/4$ kHz limitation?

Given PFD Limits Set by Footnote US201:

Cubesat Transmitting 1 Watt at 465 MHz into Omni Antenna at 10 kbps and Occupying 10 kHz Bandwidth.

Power Flux Density for Various Orbit Altitudes and Elevation Angles:										
						Cubesat Spacecraft Tranmitting 1 Watt into an Omni-Directional Antenna i				
Parameter:	Elevation Angle:		Slant Range:		S/C EIRP:		Illumination Level:		Power Flux Density:	
Orbit Altitude (km):	*Value:*	*Unit:*	*Value:*	*Unit:*	*Value:*	*Unit:*	*Value:*	*Unit:*	*Value:*	*Unit:*
600 km	5	°	2329	km	0.0	dBW	-138.3	dBW/m²	-142.3	dBW/m²/4 kHz
	45	°	815	km	0.0	dBW	-129.2	dBW/m²	-133.2	dBW/m²/4 kHz
	90	°	600	km	0.0	dBW	-126.6	dBW/m²	-130.5	dBW/m²/4 kHz
500 km	5	°	2078	km	0.0	dBW	-137.4	dBW/m²	-141.3	dBW/m²/4 kHz
	45	°	683	km	0.0	dBW	-127.7	dBW/m²	-131.7	dBW/m²/4 kHz
	90	°	500	km	0.0	dBW	-125.0	dBW/m²	-129.0	dBW/m²/4 kHz
450 km	5	°	1945	km	0.0	dBW	-136.8	dBW/m²	-140.8	dBW/m²/4 kHz
	45	°	617	km	0.0	dBW	-126.8	dBW/m²	-130.8	dBW/m²/4 kHz
	90	°	450	km	0.0	dBW	-124.1	dBW/m²	-128.0	dBW/m²/4 kHz
400 km	5	°	1805	km	0.0	dBW	-136.1	dBW/m²	-140.1	dBW/m²/4 kHz
	45	°	550	km	0.0	dBW	-125.8	dBW/m²	-129.8	dBW/m²/4 kHz
	90	°	400	km	0.0	dBW	-123.0	dBW/m²	-127.0	dBW/m²/4 kHz
350 km	5	°	1657	km	0.0	dBW	-135.4	dBW/m²	-139.4	dBW/m²/4 kHz
	45	°	483	km	0.0	dBW	-124.7	dBW/m²	-128.7	dBW/m²/4 kHz
	90	°	350	km	0.0	dBW	-121.9	dBW/m²	-125.9	dBW/m²/4 kHz
300 km	5	°	1500	km	0.0	dBW	-134.5	dBW/m²	-138.5	dBW/m²/4 kHz
	45	°	415	km	0.0	dBW	-123.4	dBW/m²	-127.3	dBW/m²/4 kHz
	90	°	300	km	0.0	dBW	-120.5	dBW/m²	-124.5	dBW/m²/4 kHz
250 km	5	°	1331	km	0.0	dBW	-133.5	dBW/m²	-137.5	dBW/m²/4 kHz
	45	°	347	km	0.0	dBW	-121.8	dBW/m²	-125.8	dBW/m²/4 kHz
	90	°	250	km	0.0	dBW	-119.0	dBW/m²	-122.9	dBW/m²/4 kHz

Given PFD Limits Set by Footnote US201:

- Can Small Satellites Using Narrow Downlinks (as is the current Cubesat Practice) Comply with the -152 $dBW/m^2/4$ kHz Limitation?

ANSWER: NO! Not even at the highest practical orbit altitude, at maximum slant range and not even with 10 dB less EIRP.

One Suggested Approach
- Main Sequence Spread Spectrum (CDMA) -

- Use Main Sequence Spread Spectrum on the Telemetry Downlink
- Use a CDMA Spreading Factor/Processing Gain Appropriate for the Satellite Data Class Desired:
  - Higher Data Rate Users Use Lower Spreading (w/R) and a Large G/T Ground Station
  - Moderate Data Rate Users Use a Moderate Spreading Factor and a Moderate G/T Ground Station
  - Low Data Rate Users Use a High Spreading Factor with a High Processing Gain and a Smaller G/T Ground Station.
  - Everyone Uses the Same Chipping Rate: 10 Mbps
  - Everyone Uses the Same FEC or Use an Adaptive FEC –BUT a Common Software Defined Radio.

One Suggested Approach (2) – CDMA Link Budgets

Cubesat CDMA Downlink Link Budgets			Downlink Frequency:	465.000	MHz
Downlink Telemetry Budget:			Wavelength:	0.6424	m
(Worst Case Altitude and Range)			Orbit Altitude:	600.000	km

S/C Transmitter Data Rate: →	Data Rate = 10 Mbps		Date Rate = 1 Mbps		Date Rate = 100 kbps	
Parameter:	*Value:*	*Units:*	*Value:*	*Units:*	*Value:*	*Units:*
Spacecraft:						
Spacecraft Transmitter Power Output:	1.0	watts	0.25	watts	0.10	watts
In dBW:	0.0	dBW	-6.0	dBW	-10.0	dBW
In dBm:	30.0	dBm	24.0	dBm	20.0	dBm
Spacecraft Transmission Line Losses:	-0.5	dB	-0.5	dB	-0.5	dB
S/C Connector, Filter or In-Line Switch Losses:	-0.1	dB	-0.1	dB	-0.1	dB
Spacecraft Antenna Gain:	0.0	dBiL	0.0	dBiL	0.0	dBiL
Spacecraft EIRP:	-0.6	dBW	-6.6	dBW	-10.6	dBW
Downlink Path:						
Spacecraft Antenna Pointing Loss:	0.0	dB	-1.0	dB	-3.0	dB
Antenna Polarization Loss:	-3.5	dB	-3.5	dB	-4.0	dB
Path Loss:	-153.2	dB	-153.2	dB	-153.2	dB
Atmospheric Loss:	-2.1	dB	-2.1	dB	-2.1	dB
Ionospheric Loss:	-0.2	dB	-0.2	dB	-0.2	dB
Rain Loss:	0.0	dB	0.0	dB	0.0	dB
Isotropic Signal Level at Ground Station:	-159.6	dBW	-166.6	dBW	-173.1	dBW
Ground Station:						
------- Eb/No Method -------						
Ground Station Antenna Pointing Loss:	-1.0	dB	-1.0	dB	-2.0	dB
Ground Station Antenna Gain:	35.9	dBiC	25.1	dBiC	18.0	dBiC
Ground Station Transmission Line Losses:	-0.50	dB	-0.75	dB	-1.0	dB
Ground Station LNA Noise Temperature:	95	K	100	K	125	K
Ground Station Transmission Line Temp.:	290	K	290	K	290	K
Ground Station Sky Temperature:	60	K	400	K	450	K
G.S. Transmission Line Coefficient:	0.8913		0.8414		0.7943	
Ground Station Effective Noise Temperature:	180	K	483	K	542	K
Ground Station Figure of Merrit (G/T):	12.8	dB/K	-2.5	dB/K	-10.3	dB/K
G.S. Signal-to-Noise Power Density (S/No):	80.9	dBHz	58.5	dBHz	43.2	dBHz
G.S. Chipping Rate (w)	10,000,000.00	cps	10,000,000.00	cps	10,000,000.00	cps
System Desired Data Rate (R):	10,000,000.00	bps	1,000,000.00	bps	100,000.00	bps
In dBHz:	70.0	dBHz	60.0	dBHz	50.0	dBHz
Processing Gain (=w/R):	0.0	dB	10.0	dB	20.0	dB
Telemetry System Eb/No:	10.9	dB	8.5	dB	13.2	dB
Telemetry System Required Bit Error Rate:	1.00E-06		1.00E-06		1.00E-06	
FEC Coding Type Used:	Conv. R=1/2,K=7 + R.S. (255,223)		Conv. R=1/2,K=7 + R.S. (255,223)		Convolutional R=1/2, K=7	
Tlm System Required Eb/No Using FEC:	2.5	dB	2.5	dB	4.8	dB
System Link Margin:	**8.4**	dB	**6.0**	dB	**8.4**	dB
Maximum Power Flux Density for 600 km Orbit:	-161.1	dBW/m²/4 kHz	-167.2	dBW/m²/4 kHz	-171.1	dBW/m²/4 kHz
(90° Elevation Angle)						
Maximum Power Flux Density for 250 km Orbit:	-153.5	dBW/m²/4 kHz	-159.6	dBW/m²/4 kHz	-163.5	dBW/m²/4 kHz

One Suggested Approach (2) – CDMA Link Budgets (2)

Cubesat CDMA Downlink Link Budgets Downlink Telemetry Budget: (Worst Case Altitude and Range)				
S/C Transmitter Data Rate: →	Date Rate = 10 kbps		Date Rate = 1.0 kbps	
Parameter:				
Spacecraft:				
Spacecraft Transmitter Power Output:	0.10	watts	0.05	watts
In dBW:	-10.0	dBW	-13.0	dBW
In dBm:	20.0	dBm	17.0	dBm
Spacecraft Transmission Line Losses:	-0.5	dB	-0.5	dB
S/C Connector, Filter or In-Line Switch Losses:	-0.1	dB	-0.1	dB
Spacecraft Antenna Gain:	0.0	dBiL	0.0	dBiL
Spacecraft EIRP:	-10.6	dBW	-13.6	dBW
Downlink Path:				
Spacecraft Antenna Pointing Loss:	-4.0	dB	-6.0	dB
Antenna Polarization Loss:	-4.5	dB	-4.5	dB
Path Loss:	-153.2	dB	-153.2	dB
Atmospheric Loss:	-2.1	dB	-2.1	dB
Ionospheric Loss:	-0.2	dB	-0.2	dB
Rain Loss:	0.0	dB	0.0	dB
Isotropic Signal Level at Ground Station:	-174.6	dBW	-179.6	dBW
Ground Station: ***------- Eb/No Method -------***				
Ground Station Antenna Pointing Loss:	-1.0	dB	0.0	dB
Ground Station Antenna Gain:	13.5	dBiC	3.5	dBiC
Ground Station Transmission Line Losses:	-2.0	dB	-3.0	dB
Ground Station LNA Noise Temperature:	125	K	150	K
Ground Station Transmission Line Temp.:	290	K	290	K
Ground Station Sky Temperature:	500	K	550	K
G.S. Transmission Line Coefficient:	0.6310		0.5012	
Ground Station Effective Noise Temperature:	548	K	570	K
Ground Station Figure of Merrit (G/T):	-15.9	dB/K	-27.1	dB/K
G.S. Signal-to-Noise Power Density (S/No):	37.1	dBHz	21.9	dBHz
G.S. Chipping Rate (w)	10,000,000.00	cps	10,000,000.00	cps
System Desired Data Rate (R):	10,000.00	bps	1,000.00	bps
In dBHz:	40.0	dBHz	30.0	dBHz
Processing Gain (=w/R):	30.0	dB	40.0	dB
Telemetry System Eb/No:	27.1	dB	31.9	dB
Telemetry System Required Bit Error Rate:	1.00E-06		1.00E-06	
FEC Coding Type Used:	None		None	
Tlm System Required Eb/No Using FEC:	9.6	dB	9.6	dB
System Link Margin:	**17.5**	dB	**22.3**	dB
Maximum Power Flux Density for 600 km Orbit:	-171.1	dBW/m²/4 kHz	-174.2	dBW/m²/4 kHz
(90° Elevation Angle)				
Maximum Power Flux Density for 250 km Orbit:	-163.5	dBW/m²/4 kHz	-166.5	dBW/m²/4 kHz

One Suggested Approach (3)
- CDMA Summary -

- Using Varying Data Rates with Varying Spreading Factors Depending on the Needs of Each User:
  - PFD Limit is Never Exceeded for All Orbit Altitudes and Elevations
  - Appropriated Ground Station Hardware Can Close Link Budget for Data Rates from 10 Mbps to 1000 bps and lower if required.
  - Link Budgets are Actually Much Better for Small Users than If Narrowband Transmission Technique is Used BECAUSE you can Trade Data Rate for Bandwidth.
  - IF Two or even Three Satellites are in the Same Antenna Field of View, CDMA Sharing will Allow Natural Multiplexing, even if the satellites have different data rates and somewhat different Transmitter Powers.
  - Moderate In-Band Rejection of Narrowband Emitters can be Tolerated.

Rejection of Narrowband Emitters

How Moderate is Moderate?

Potential for Interference from Narrowband Signals

- Assume the SAME big dish system parameters and a 1 watt Cubesat at worst case altitude and elevation angle (2329 km, 5°).
- Signal level from S/C at receiver:
  - S/No = 81 dBHz
  - S/N = 11 dB
  - Signal Level = -95 dBm
  - Noise Floor of Rx = -106 dBm
- Assume a Mobile User 40 dB above the Noise in a Narrowband FM Rcvr at the same location (same noise temp) [i.e. S/N = 40 dB]:
  - NBFM receiver noise floor (kTB) = -134 dBm
  - FM signal level in that receiver = -94 dBm
  - FM S/N in 10 MHz bandwidth = -94 dBm – (-106 dBm) = 12 dB
  - FM User S/N ≈ Satellite Downlink S/N [Within 1 dB].
  - MOST LIKELY: Sidelobe suppression of dish will easily eliminate this signal.
  - BUT: THAT IS ABOUT IT. ANY MORE INTERFERENCE OR EVEN MULTIPLE SIGNALS WILL FAIRLY EASILY OVERWHELM THE SATELLITE RECEIVER.

Another Possible Solution

- Use Frequency Hopping Spread Spectrum -

- For Existing Frequency Hopping CDMA, Channel Bandwidths are ≈ 250 kHz. Data Rates are on the order of 200 kbps peak.
- In a 10 MHz band therefore, there would be 40 defined channels.
- Assuming energy of downlink was spread over 250 kHz we would meet the PFD limitations of -152 dBW/m²/4 kHz by about 10 dB in the worst case.
- If known local interferers channels were eliminated from the "jump list" then there might still be >30 channels remaining to hop to [not occupied] in any reasonable location. The radio is programmed to ignore known interference channels.
- The data throughput for such a system is something like:

$$\mathbf{R_{tp} = R\,(Na - Ni)/Na}$$

Where: R_{tp} is the Throughput in bps

R is the peak data rate of the radio system in bps

Na = Available hopping channels

Ni = Channels that encounter interference per hopping sequence

Another Possible Solution (2)
- Use Frequency Hopping Spread Spectrum -

- This technique has been shown to work with Genesat-1 which used a Microhard Frequency Hopping Radio and a big dish at 2.4 GHz (on Stanford campus. Their throughput was about 50-70 % of peak data rate BUT, it varied from day-to-day significantly. The MAST spacecraft project, also using Stanford as a ground station had similar results.

- We need to better understand the local uses of the band to make or sense out of how it might be used -IF it can be used.

What is the Potential For Interference?

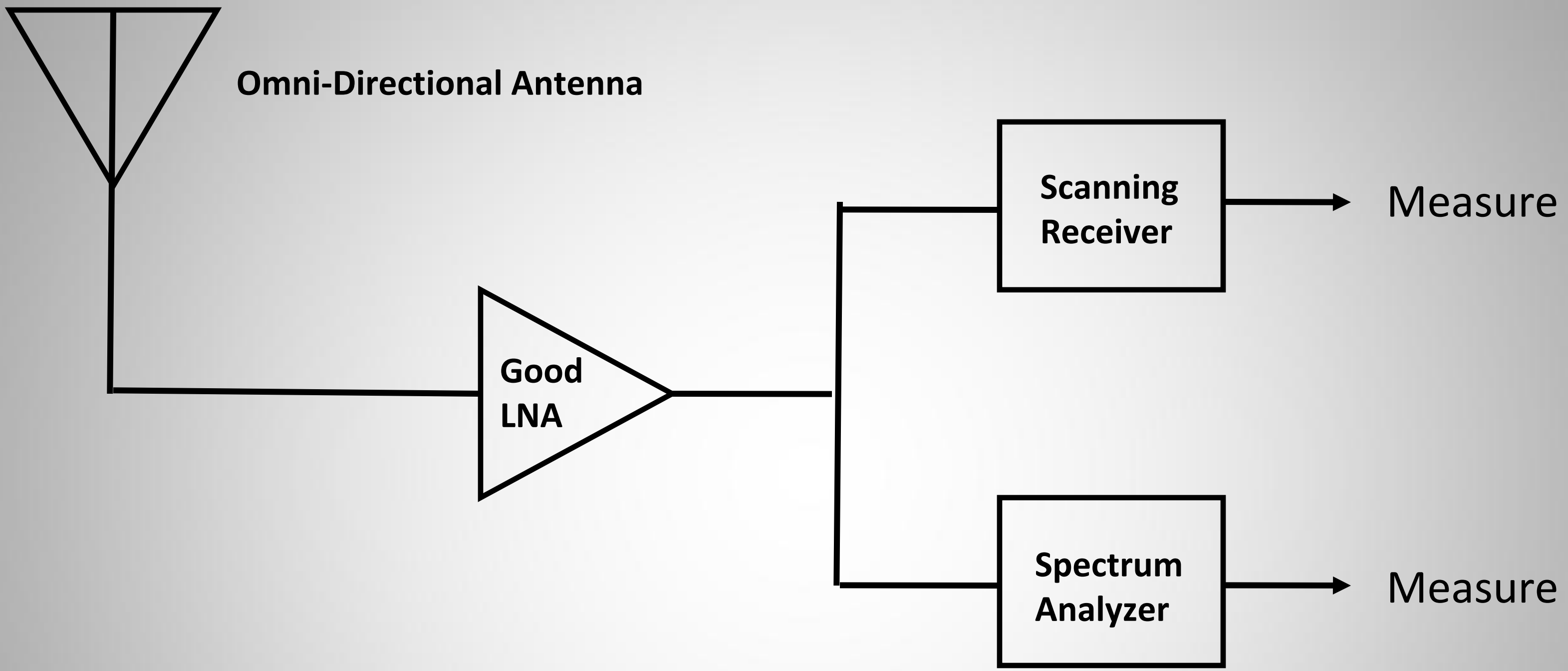
- In North America, for Cubesat Users:
  - The potential for interference is:
    - FROM: Local Mobile and Fixed Users (Mobile is worst)
    - TO: Ground stations receiving satellite Space-to-Earth transmissions
  - The situation is local and will vary from one University or Laboratory to Another
  - The situation can be made naturally better by $1/R^2$ - By getting away from the Fixed and Mobile users operating in towns and cities.
- In the Far East, for Cubesat Users:
  - No Interference potential if your ground station is in North America and you spacecraft is OFF.
  - If you are operating in or near a Footnote 5.290 country:
    - Interference potential is FROM: Your Cubesat downlink
    - TO: A wideband Ground Station Operating in the Meteorological Satellite Service operating in accordance with that footnote.

What Needs to Be Done?

- Form Three Groups:
  1. A technical group needs to define the requirements of all potential users and find solutions to accommodate them in the band (hopefully with one type of radio (SDR) or one with options).
  2. A regulatory group needs to define if we can be accomodated into the ITU/FCC/NTIA regulatory scheme existing for the band or find out what must be changed.
  3. A large group (all universities, potentially) MEASURE the Interference at your potential ground station sites.

  These groups need to communicate regularly together.

Group 3: What To Do?



Measure:

- System Noise Temperature Over Day and Longer Time
- Channel Occupancy Statistics over Many Days/Weeks
- Routinely Occupied Channels
- Identify Police, Fire Public Service Channels – To Be Avoided Later
- Absolute Signal Levels (in dBm or dBW) of Most Common Emitters
- KEEP GOOD RECORDS!