Software Defined Transponders, Future AMSAT Missions: Phase 3E and Eagle

by

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Introduction

Heretofore, AMSAT-NA and AMSAT-DL have flown traditional transponders as the analog transponders for their linear orbiting repeaters.   These have served us well so we wish to make the case for a departure from this traditional approach to one where the functions of the transponder are defined in software. The small increase in complexity this will incur is richly rewarded by the increased versatility of the transponder as we will demonstrate.

The linear transponders from Oscar 6's Mode A to AO-40's Mode US have been the staple resource for AMSAT satellites since the earliest years. These linear transponders are necessary to allow multiple users operate the satellite simultaneously in a frequency and power sharing arrangement. To make a linear transponder, one was faced with a design problem in which one had a fixed amount of DC power available, and a known set of antennas.   The design goal was to produce the most efficient possible linear or near linear transponder. In his doctoral thesis, DJ4ZC, Dr. Karl Meinzer wrote about High Efficiency Linear Amplification by Parametric Synthesis (hereinafter called HELAPS). This was adapted for and adopted by the AMSAT Oscar 7 design team for the Mode B (432.1 MHz Up and 145.9 MHz down) transponder. HELAPS has been an integral part of all major AMSAT-DL & AMSAT-NA linear transponder satellite projects since AO-7.
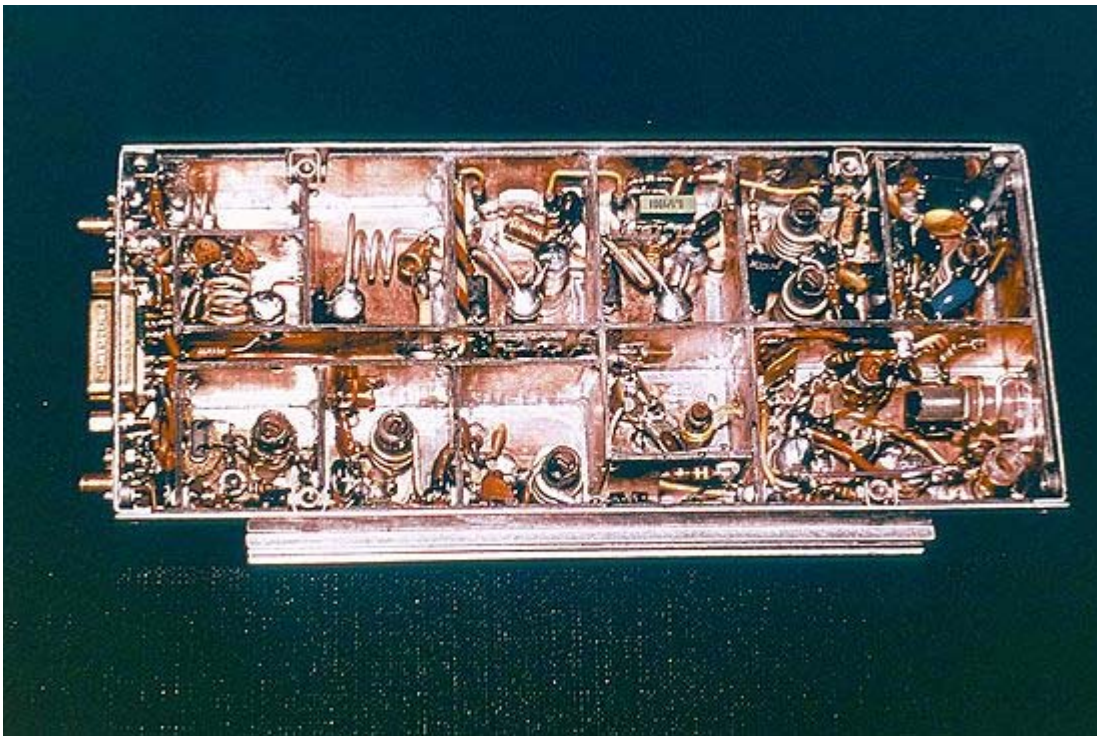

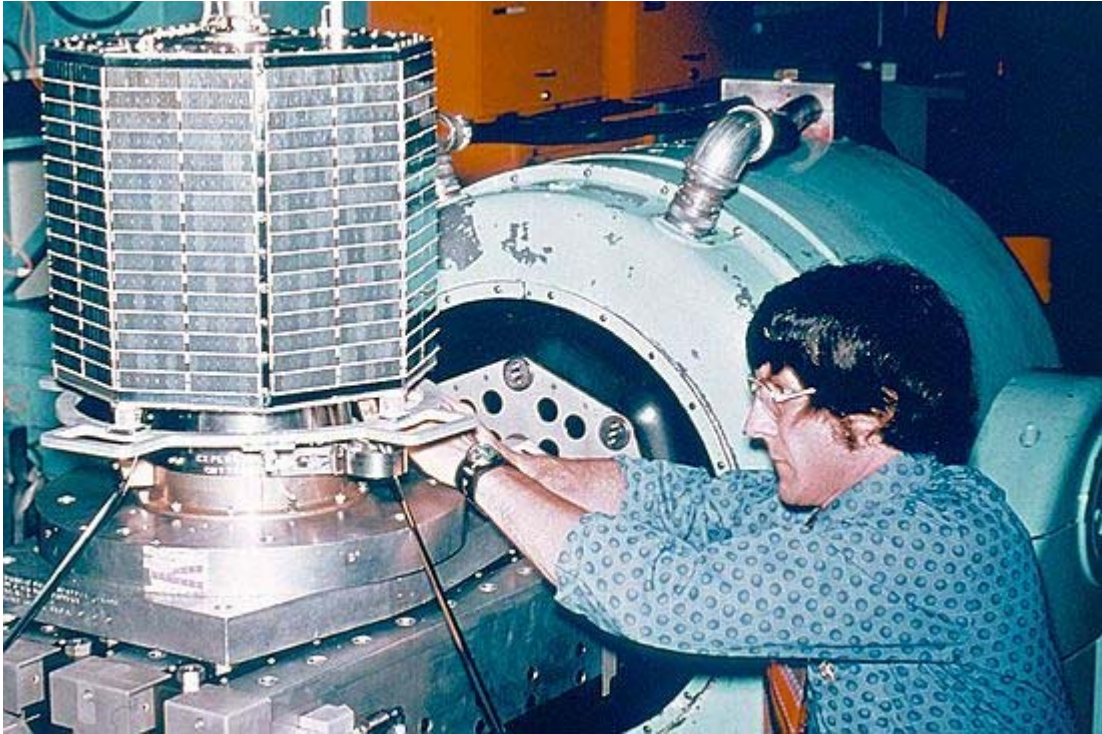Figure 1: AMSAT-OSCAR 7 Mode B transponder

Figure 2: Jan King (W3GEY/VK4GEY) mounts AO-7 for a shake test

Figure 3: The AO-40 Spacecraft and its launch team in Kourou

For AMSAT's Microsats (starting with AO-16), we did channelized digital payloads for the first few and since then "EasySat" FM repeaters have become increasingly popular for these Low Earth Orbit (LEO) satellites. Digital transmissions are mainly used for the transmission of spacecraft telemetry since the advent of the Internet made terrestrial amateur packet radio become the private domain of APRS and DX Clusters.

There have been lots of discussions about linear, FM, digital, etc. and the relative merits, inherent evils, and general characteristics of each. There have been those who decry the cost of using a "Phase 3 bird" and those that deny an FM satellite even belongs in the ham bands. What would you say if you never had to make that decision again except to argue which mode we do tomorrow? Within reason, we are headed in exactly that direction.

The Software Defined Radio and the new SDX Transponders

Software Defined Radio (SDR) is a hot buzzword in amateur radio circles and has been in many technical circles for quite some time. The Department of Defense of the United States, would like nothing better than to have a one-size-fits-all radio. They have called it "Jitters" or JTRS and this acronym stands for Joint Tactical Radio System. Recently the FCC approved the first SDR core for several applications by a company called Vanu (see http://www.vanu.com/technology/softwareradio.html) . Why all of the excitement? DOD wants to be able to have its radios interoperate with any service it might encounter. Vanu wants to be the heart and soul of every cellular telephone irrespective of your brand of service, CDMA, GSM, DAMPS, AMPS, etc. How does one accomplish this technical magic?

Digital Signal Processing has been around for a while. Two of the authors started the TAPR and AMSAT digital signal-processing project in the early 1980's. One of the authors was a designer of the AEA DSP-1232 and 2232. One of the authors has been doing digital music composition, mixing, synthesis, and more since the early 1980's. Now, two of the authors spend a lot of their time doing software-defined radio and we invite you to visit our web page at http://dttsp.sourceforge.net. Why has digital signal processing transmogrified into software-defined radio? It would indeed be humorous if all we did were replace DSP with SDR and thereby turning a small CPU intensive block of code into the proverbial $50,000 hammer for DOD! That is not the case however. SDR is the marriage of DSP with newer hardware. This hardware allows much higher dynamic range analog to digital conversion and analog to digital conversion at IF frequencies which has pushed the digital domain much nearer to the antenna. We have much faster computers and some that can operate at low power with sufficient computational power to do the needed DSP jobs in small battery operated devices.

Recently amateur radio circles have seen a major insertion of SDR technology. GnuRadio, the DCP-1, and the SDR-1000 are major contributors of SDR technology and software for the amateur radio community. We have decided to use all of these pieces of technology in order to conduct serious experiments into the feasibility of applying SDR to AMSAT-NA needs.

The Flex Radio SDR-1000 is based around the Quadrature Sampling Detector (QSD):

Quadrature LO: 4 positions per cycle
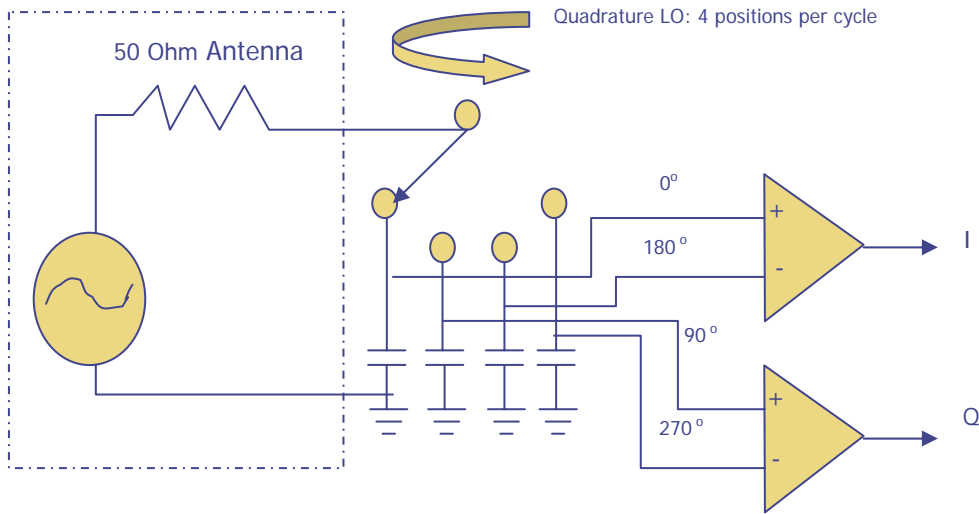
50 Ohm Antenna

0°
180°
90°
270°
I
Q

Figure 4: The Quadrature Sampling Detector (QSD)

As shown in figure 4, this simple idea has really helped SDR take off in a big way in the amateur radio community. Gerald, K5SDR, of Flex Radio is offering the first integrated software-defined HF radio transceiver.   This technology can be directly adapted to giving us several tens of KHz transponders.   The QSD has many properties that recommend its use, including high Q, very good dynamic range, high IP3, and low power consumption.   In our implementation, we would have a differential output for the outputs but the circuit would be very similar to the SDR-1000. In transmit, the signal flow is reversed and the Encoder called a QSE.

Recently, Howard Long, G6LVB, has adapted the QSD from the SDR-1000. Howard chose to use a DSP chip capable of peak rates of 150 MIPS and also low power
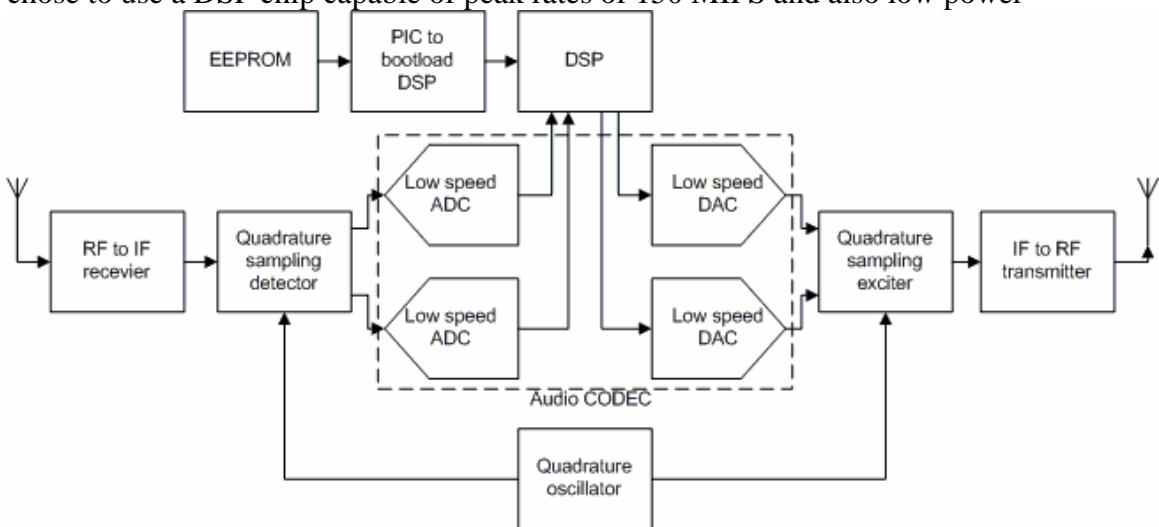

Figure 5a: Block Diagram of G6LVB's QSD/QSE "STELLA" Transponder

consumption from Texas Instruments to process the signal from the QSD (200 mw). This series of chips has flown repeatedly on UOSAT's but to date has not flown in a Phase 3 orbit. Howard calls his QSD/QSE based transponder STELLA (Satellite Transponder with Equalizing Limiting Adapter) which is seen in Figures 5a and 5b. For more details see http://www.g6lvb.com/Articles/STELLA/index.htm

Figure 5b: Howard (G6LVB) showing off some STELLA hardware

Figure 6: Lyle, KK7P discusses SDX with HELAPS with G6LVB (left), DB2OS (top) and AB2KT (seated)

Last December 2005, Howard, Frank Brickle AB2KT, Lyle Johnson, KK7P, and N4HY traveled to Germany to meet with AMSAT-DL concerning their Phase 3 Express (P3E) mission. The SDX was the topic of discussion. Karl Meinzer, DJ4ZC, gave us a series of lectures on HELAPS (High Efficiency Linear Amplifier by Parametric Synthesis).

HELAPS (as you can see from earlier in the paper) has been a part of AMSAT history since the 1970's and Oscar 7 (which it is *still* in operation after 28 years!).   A simple view of how this works is to take the transponder signal you wish to transmit and separate it into two channels. One channel provides a hard limited copy of the "phase" components of the signal. The other channel contains the amplitude envelope. RF power amplification is done by the hard limited "phase" channel in harsh nonlinear amplifiers running high efficiency Class C or Class E amplifiers. Finally, at the final stage, the envelope is modulated onto the signal my means of the final stage power supply (just like an old plate modulated AM transmitter).   In the past, although HELAPS has worked extremely well, it has been difficult to perfect this in analog hardware. The various delays and distortions make this modulation process imperfect. As a result, the transponders were "linear" with fairly high intermodulation distortion that limited the dynamic range of transponders to ~26%.   This was okay for space but not really usable on the ground.

But now, all this has changed. With the digital flexibility afforded by an SDX, we can implement non-linear pre-distortion to compensate for the distortions introduced by "real-world" amplifiers.   In Figure 6, Lyle, KK7P is pointing to a possible implementation of the new HELAPS software modulator and discussing its operation.

We have begun the Software Defined Transponder, SDX, here in concert with Howard Long. Lyle Johnson, Frank Brickle, Howard Long, and Bob McGwier are developing the hardware to be flown on the Eagle spacecraft and hopefully on Phase 3E as well. The current plans call for the DSP engine to be a Texas Instruments TMS320C6713B and the HELAPS modulator will be done in an FPGA.

Figure 7: K3IO, W2GPS, and N4HY after first QSO through our prototype SDX!

As an early development, we wanted to show the feasibility of an SDX, so Frank Brickle (AB2KT), Tom Clark (K3IO, AMSAT BOD, AMSAT Chief Scientist, AMSAT President Emeritus & ex W3IWI), Rick Hambly (W2GPS, AMSAT President, Eagle CTO) and Bob McGwier (AMSAT VP Engineering) used two off-the-shelf SDR-1000's with DEMI transverters. On August 17, 2005, Rick, Tom, and Bob conducted the first QSO through the SDR-based SDX prototype seen in Figure 7 [1]. Since then, we have been concentrating on writing the software and putting together a demonstration project rather than delving directly into spaceflight capable hardware. After the SEVHFS meeting and Dayton, we intend to put a prototype Mode-B (70 cm in, 2M out) transponder on the air in the MD suburbs of Washington, DC.

CC-Rider: A Microwave Payload for AMSAT's Eagle

It may come as a surprise to most amateurs, but when they point their antennas at a satellite in space, the change from operating in the **Amateur Service** to the **Amateur Satellite Service**. And not surprisingly, this means that the FCC and the ITU ordain a different set of rules; in particular, satellite operations mean a different (and more restrictive) set of frequencies. In Figure 8, we reproduce the Microwave allocation tables to show to contrast normal terrestrial and satellite operations.

Figure 8: United States Microwave Allocations			
Amateur Service		Amateur-Satellite Service	
Band (MHz)	Bandwidth (MHz)	Band (MHz)	Bandwidth (MHz)
23 cm: 1240-1300	60	1260-1270 ↑	10
13 cm: 2300-2310 13 cm: 2390-2450	10 60	2400-2450	50
9 cm: 3300-3500	200	3400-3410 *	10
5 cm: 5650-5925	275	5650-5670 ↑ 5830-5850 ↓	20 20
3 cm: 10000-10500	500	10450-10500	50
1.3 cm: 24000-24250	250	24000-24050	50

↑ means Earth-to-Space (uplink) direction only
↓ means Space-to-Earth (downlink) direction only
• the 9 cm satellite band is only available in regions 2 & 3

Let's look at the realities imposed by these differences. At 23 cm, only satellite uplinks are permitted and only 10 MHz of bandwidth is available. For the weak-signal amateur, it means that antennas and transmitters have to be retuned in order to QSY. A much more serious problem may happen in the future. Our 23 cm band is shared with Radio Location services. We had to give up the old 1215-1240 MHz band to make room for the L2 downlink signals from GPS and GLONASS's equivalent signals. The European, Chinese and Japanese each plan for GPS-like systems, and last Christmas, the Europeans launched

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[1] Audio from this QSO can be heard at ftp://ftp.cnssys.com/pub/amsat/Eagle_SDT_1st_Contact.mp3

their first test satellite for their Galileo positioning system. The concern here is that the Galileo E6 signal which has been allocated the 1240-1300 MHz frequency band (along with the Chinese and Japanese systems). Galileo plans to start launching their constellation within the next 2-3 years (with downlink signals ~6 dB stronger than GPS L2). If Galileo, GPS and the other GNSS systems are declared as "Safety of Life" services, it will not be much of a surprise to see the 23 cm band withdrawn from ALL amateur use.

At 13 cm, satellite activity is confined to the "sewer" created by 802.11x WiFi, Bluetooth, cordless phones, microwave ovens, etcetera. The experience with the AO-40 and AO-51 S-band downlinks has shown that all QRM from the "sewer" is certainly a problem. Since the 13 cm activity so far has been receive-only, we have not had much clout in chasing the unlicensed Part 15 users off "our" band. In the future we will see 13 cm used for uplinks, and we can hope that this helps unplug the sewer!

The 9 cm band would be very good for satellite use were it not for the "Region 2 & 3 Only" footnote that excludes Europe and Africa. In the past, amateur satellites have been considered to be a global resource, and there is a strong resistance to "exclusion".

The 3 and 1.3 cm bands will certainly find use in future satellites. This leaves us with the 5 cm C-band allocation. Back in 1979, the WARC allocated the Amateur Satellite Service two 20 MHz wide bands, separated by 180 MHz. In Figure 9 we show the usage of C-band:
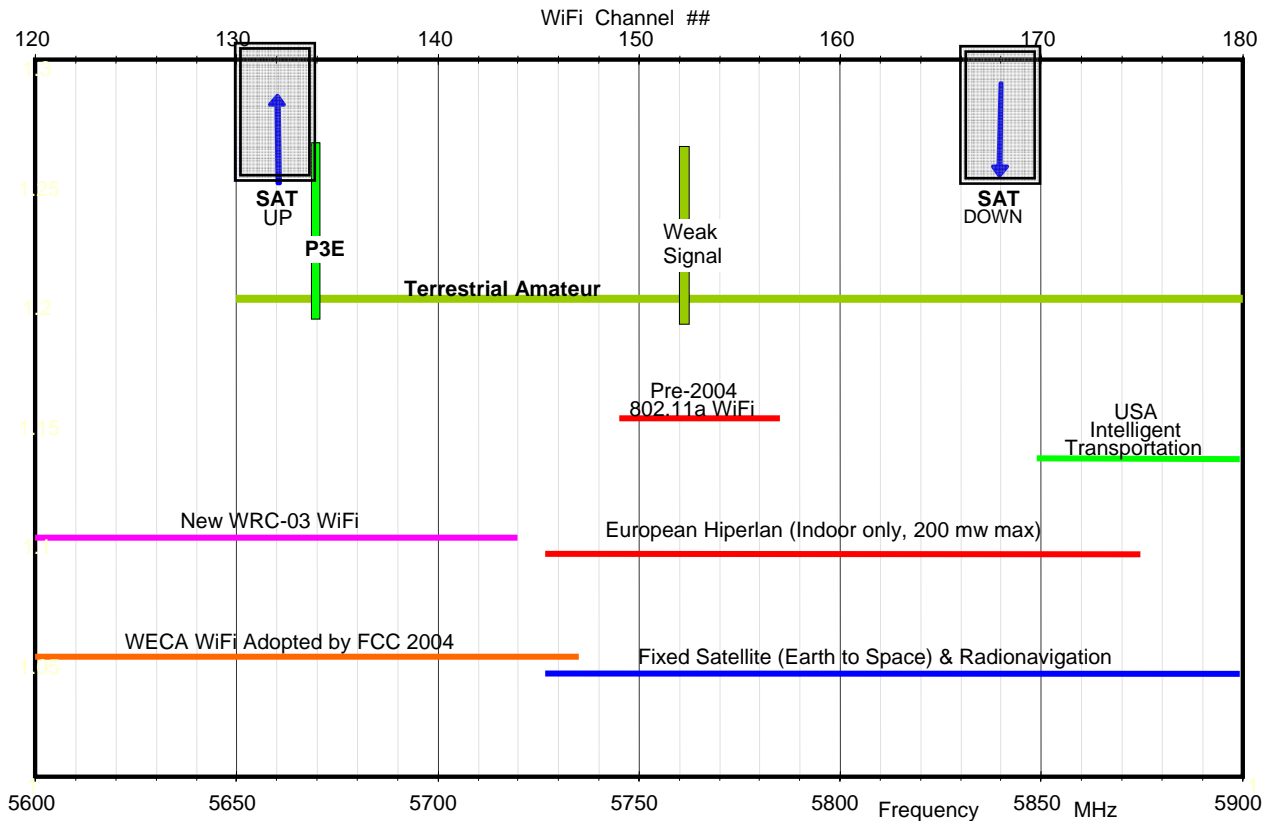

Figure 9: The 5.6 – 5.9 GHz C-band Spectrum.

The CC-Rider development began as a way that amateurs could develop a significant microwave capability to insure retention of a band that is ripe for takeover by Part 15 users. The name shows the main idea – an in-band C-band transponder that capitalizes on the paired C-band allocation [2]; the CC-Rider name is intended to convey the concept of a **C**-band to **C**-band Transponder to **RIDE** on future AMSAT satellites [3,4].

In the past couple of years, the CC-Rider concept has evolved. Figure 10 shows the basic aspects of the current design:
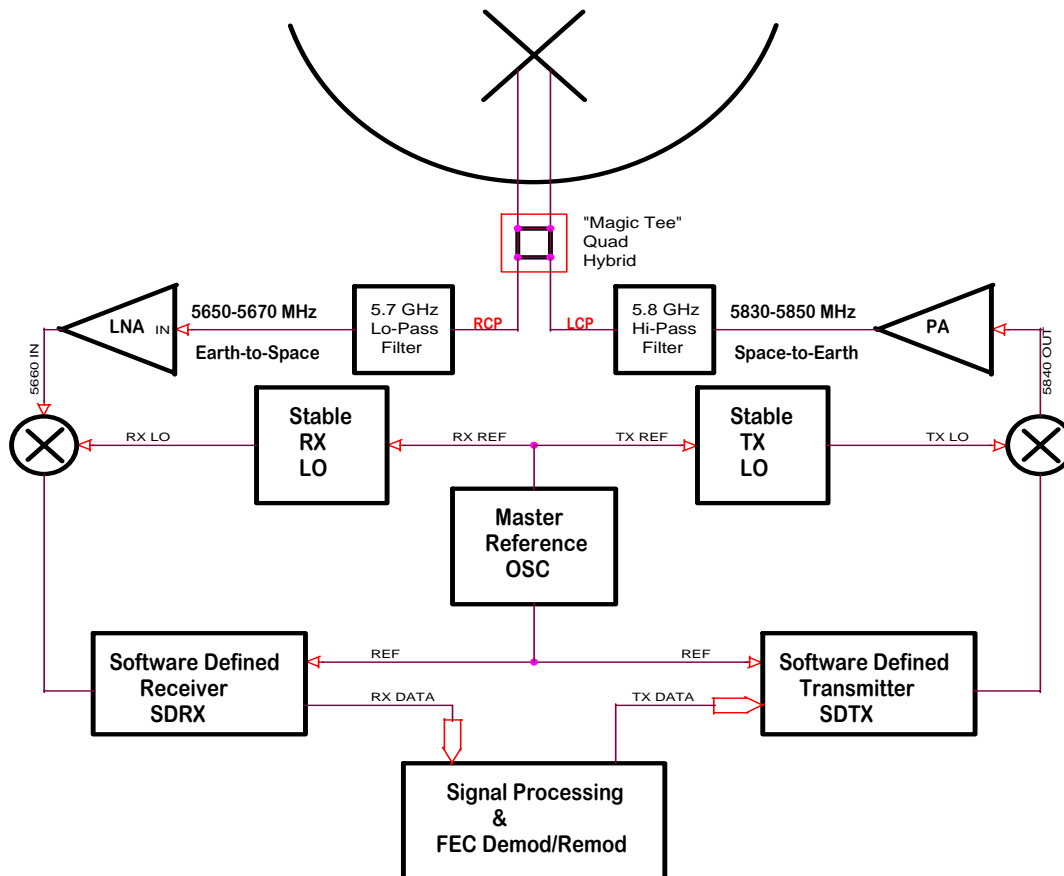
Figure 10: The Basic CC-Rider Concept (circa 2005)

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[2] The CC-Rider concept has been described in papers published in the 2003 & 2004 *Proceedings of the AMSAT Space Symposium*. These papers were subsequently updated in the *AMSAT Journal*. Anyone who does not have access to the papers can also find them available on http://gpstime.com.

[3] The song "*CC Rider*" (sometimes also called *See See Rider*") was one of more than 100 songs written and performed by the great jazz/blues singer, Ma Rainey (http://www.redhotjazz.com/rainey.html) in 1925. In addition to Ma Rainey, it was made famous in versions by Mississippi John Hurt, Big Bill Broonzy, Ray Charles, Bruce Springstein, Elvis Presley, Ian & Sylvia and even the Kingston Trio.

[4] K3IO takes full blame of picking CC-Rider as a name for this project!

The design shown in Figure 10 uses a dish antenna. Link budget calculations have shown that the link will be solid with 30-50 watts RF and a ~30 cm (~6 λ) dish. Such a dish would have a beam that matches the size of the earth (~15°as seen from Apogee) and would have ~20 dBiC gain. In order to have this antenna point at the earth, the entire body of the spacecraft has to have its angular orientation be stable at a level ~5°.

If such stability cannot be achieved, then we consider the use of a phased array of patch antennas, shown schematically in Figure 11:
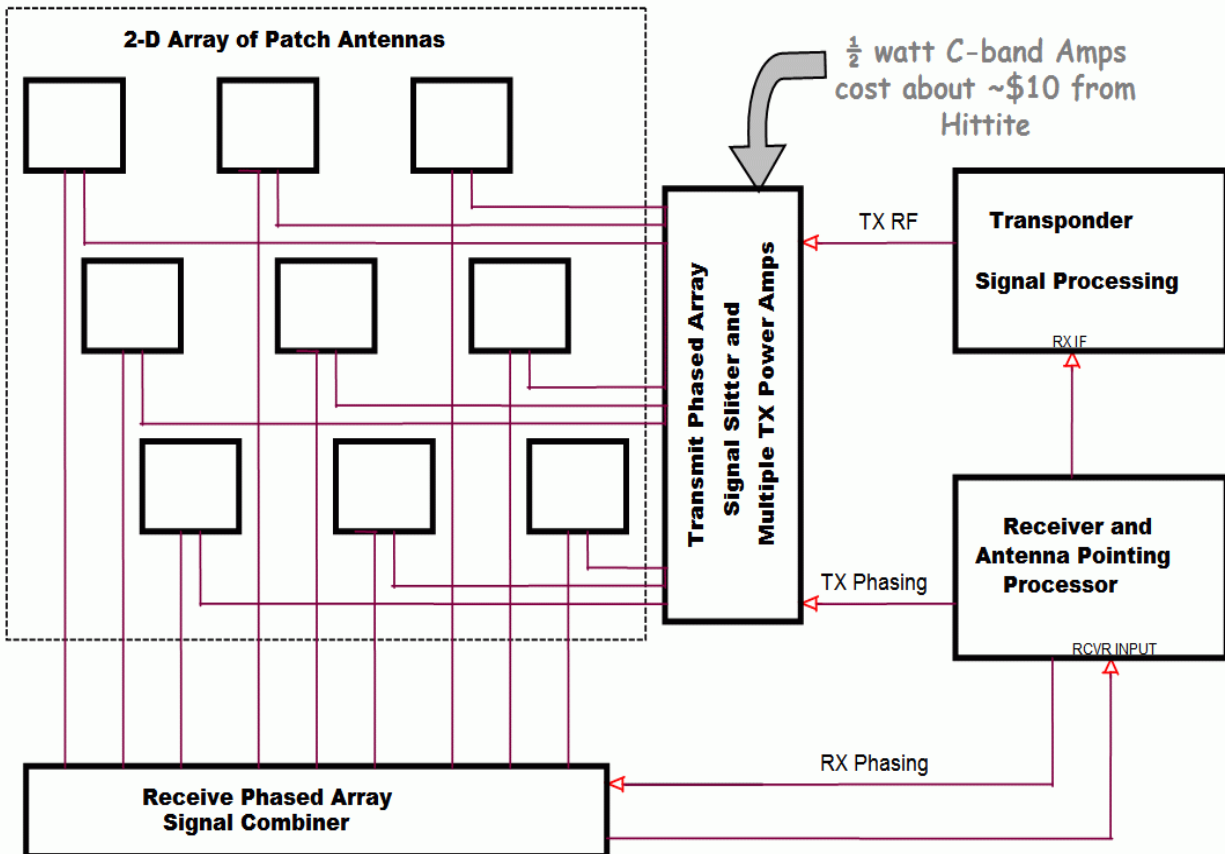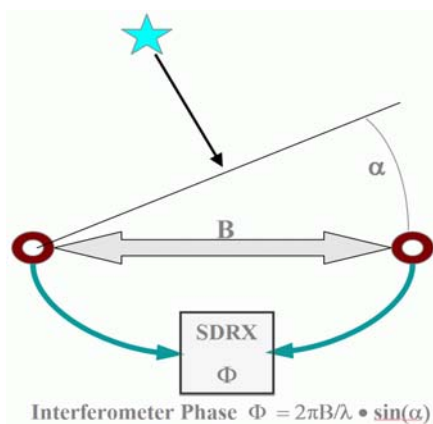

Figure 11: A phased array antenna for CC-Rider

Figure 12: A 2 element interferometer

Interferometer Phase $\Phi = 2\pi B/\lambda \bullet \sin(\alpha)$

If an antenna array is used, the receiver can use any (probably several) element pairs as an interferometer (see Figure 12) to determine the direction that an uplink signal is coming from.

This pointing information can then be applied to phase all the receive elements for maximum uplink signal gain, and can be used to phase the transmitter elements to point the downlink beam.
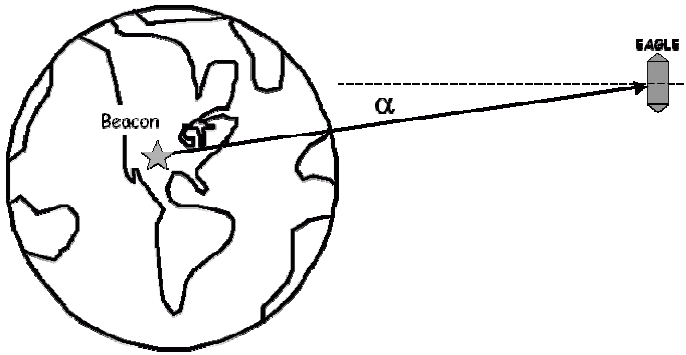
If the satellite is spinning with an axis that does not point at the earth, the phased array could be dynamically steered to keep the beams centered on the earth.

The use of a few dedicated uplink beacons will provide a continuous pointing reference as shown in Figure 13.

Fig 13: Dedicated beacon transmitters used as pointing reference.

Although Figure 11 showed a schematic 3x3 phased array, we will need to use more elements to achieve the desired ~20 dBiC gain even when pointed off the boresight axis. In Figure 14, we show a possible array of 36 patches located on one-λ centers of the 60 cm square face (the Eagle strawman design) along with other possible antennas in the antenna "farm".
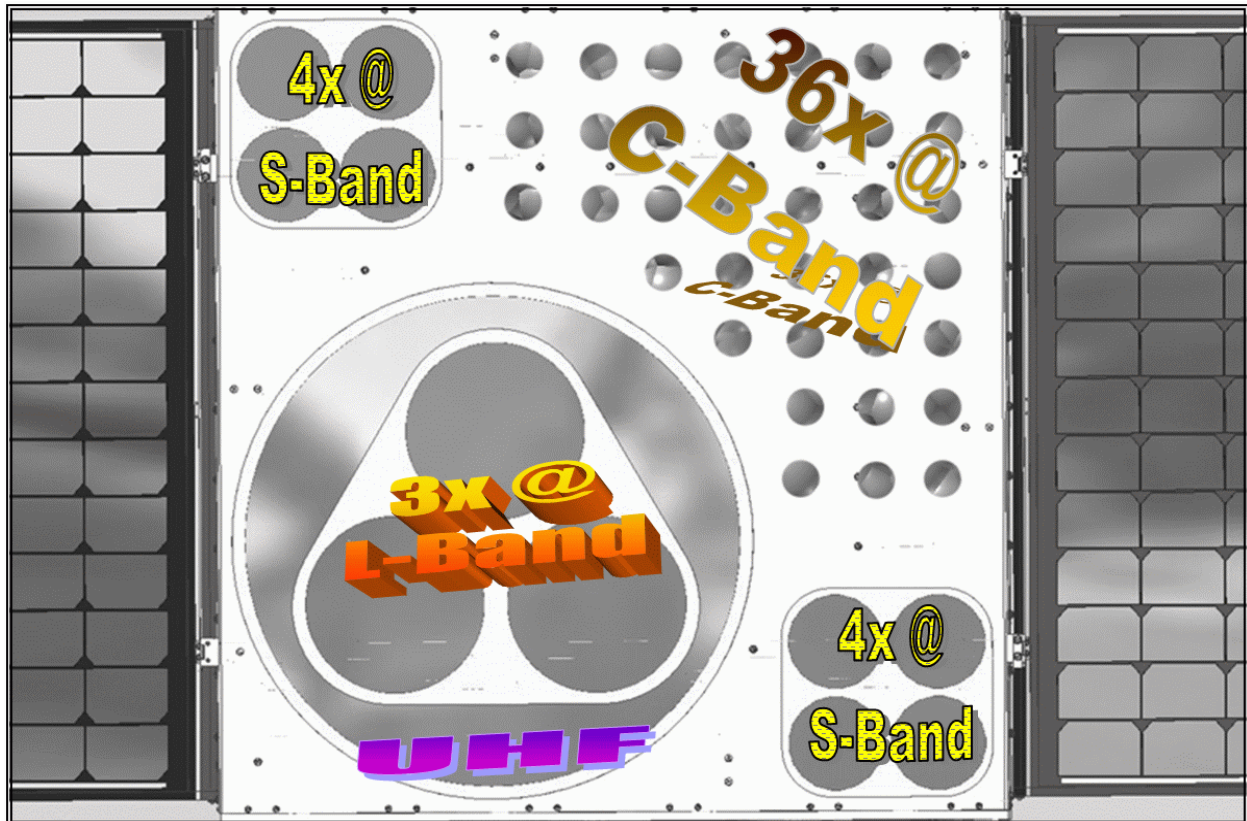

Figure 14: One possible antenna farm for EAGLE

After Figure 14 was prepared, a mechanical redesign increases the "antenna farm" faceplate to ~100x100 cm. The impact of this change on the antenna design is still under study. It is hoped that some real estate can be made available for other microwave bands, especially X-band.

If the phased array approach is used, then we can distribute the C-band transmitter with a ~ ½ - 1 watt power amplifier at antenna each element. We have already located a nice amplifier which, unfortunately, it is a Class-A amplifier that makes more heat than RF [5].

Our current design for CC-Rider allows the SDX shown in Figure 10 to be used as a linear transponder. But a more exciting possibility is to make use of FEC digital links at various bandwidths. In a conventional transponder (as with EME!) the signal undergoes a $1/R^2$ loss on the uplink, and then another $1/R^2$ link on the downlink, leading to the classical "Radar Sensitivity" scaling as $1/R^4$. Assume instead a digital uplink that uses coding to improve accuracy, and is fully decoded at the spacecraft. The spacecraft then regenerates the signal with "fresh" error correction coding. The result is a pair of $1/R^2$ links and no $1/R^4$ problem.

Such a satellite would assign digital voice users to a "channel" slot; multiple users can share a slot for a roundtable. The effect would be operation much like EchoLink. QRP stations could use a narrower bandwidth in a low-speed messaging much like SMS. Finally, amateurs could solve the "DX from an apartment house" problem! This latter possibility would allow amateurs to field small and reliable portable stations to provide the communications that were impossible after the 9/11 attacks and Katrina.

802.11a and Part 15 QRM at C-Band?

One frequently asked question about CC-Rider is "Will C-band be useful with all the 802.11a, cordless phones etcetera QRM? We have already seen that 13 cm is a sewer!"

Take a look at Figure 9. Note that the 802.11a WiFi world has moved in to share the 5650-5670 MHz satellite uplink band (as well as the 5760 MHz weak signal band). The satellite downlink is amazingly well protected. So let's make some estimates concerning the uplink QRM situation that the satellite will see.

The WiFi definition calls for the use of CDMA techniques, with a maximum throughput of 54 Mb/sec (just like 802.11g on 2.4 GHz). The total bandwidth available to WiFi at C-band is 550 MHz (5150-5350 MHz and 5450-5800 MHz. Note that the 5350-5450 MHz chunk is reserved for Radio Navigation).

- Let's assume that the WiFi users fill their allocation uniformly. The signals from the many users will be noncoherent, so their signals add as wide-band noise.

- The population of the USA is 294 million, and Canada is 32 million. As a conservative estimate let's assume one C-band Part 15 transmitter per person, operating 16 hours/day. This means that at any time there might be 217 million transmitters.

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[5] see http://www.hittite.com/product_info/product_specs/amplifiers/hmc408lp3.pdf

- Most 802.11a transmitters have low gain antennas and attenuation through trees and buildings affect the signal seen at a satellite. So we assume that each transmitter transmits 1 mW EIRP. This means that the 326 million transmitters will be a noise-like 326 kW transmitter spread uniformly over 550 MHz, equivalent to

$$(217 \bullet 10^6 \text{ transmitters}) \bullet (1 \text{ mW/transmitter}) / (550 \text{ MHz})$$
$$= 0.39 \text{ mW/Hz radiated}$$

- The path loss from the earth to a HEO satellite at ~40,000 km distance is ~196 dB. Assume an earth-pointing spacecraft antenna gain of ~19 dB. A loss of 177 dB is equivalent to a factor of $2 \bullet 10^{-18}$.

Putting these numbers together:

$$(0.39 \text{ mW/Hz}) \bullet (2 \bullet 10^{-18} \text{ Path Loss})$$
$$= 7.8 \bullet 10^{-22} \text{ Watts/Hz at the input of the receiver.}$$

This worst-case power can be converted into an equivalent 802.11a noise temperature of

$$\mathbf{T_{802.11} = (7.8 \bullet 10^{-22} \text{ Watts/Hz}) /k = 57°K}$$

where k = Boltzmann's Constant = $1.38 \cdot 10^{-23}$ W/Hz/°K.

57°K is not a serious problem compared with the other sources of noise
- ~200-250°K coming from the earth into the main beam
- 3°K transmitted by God
- ~100°K from the LNA
- ~25-50°K coming from ohmic losses in the microwave signal path
- ???? coming from the spacecraft itself
- Etcetera

Some Other Recent SDR/SDX Efforts

In order for the Eagle mission to be a complete success, we must steer the antennas on the spacecraft. We typically shy away from moving parts so we will attempt to steer the beams electrically. The experiments have begun. Last January, Eric Blossom (K7GNU), Frank Brickle (AB2KT), Matt Ettus (N2MJI) and Bob (N4HY) worked together to do phased array experiments using the GnuRadio Radio software and the associated hardware the (USRP). GnuRadio is an extremely large software project. It is led by K7GNU, Eric Blossom and Matt Ettus, N2JMI. Until recently, it has primarily been a computer science project that did radio. Recently, with the introduction of daughter hardware by Matt, the project has taken on real significance to our experimentation. The heart of our experiments using GnuRadio software and the associated hardware are being done using the Universal Software Radio Peripheral, USRP.
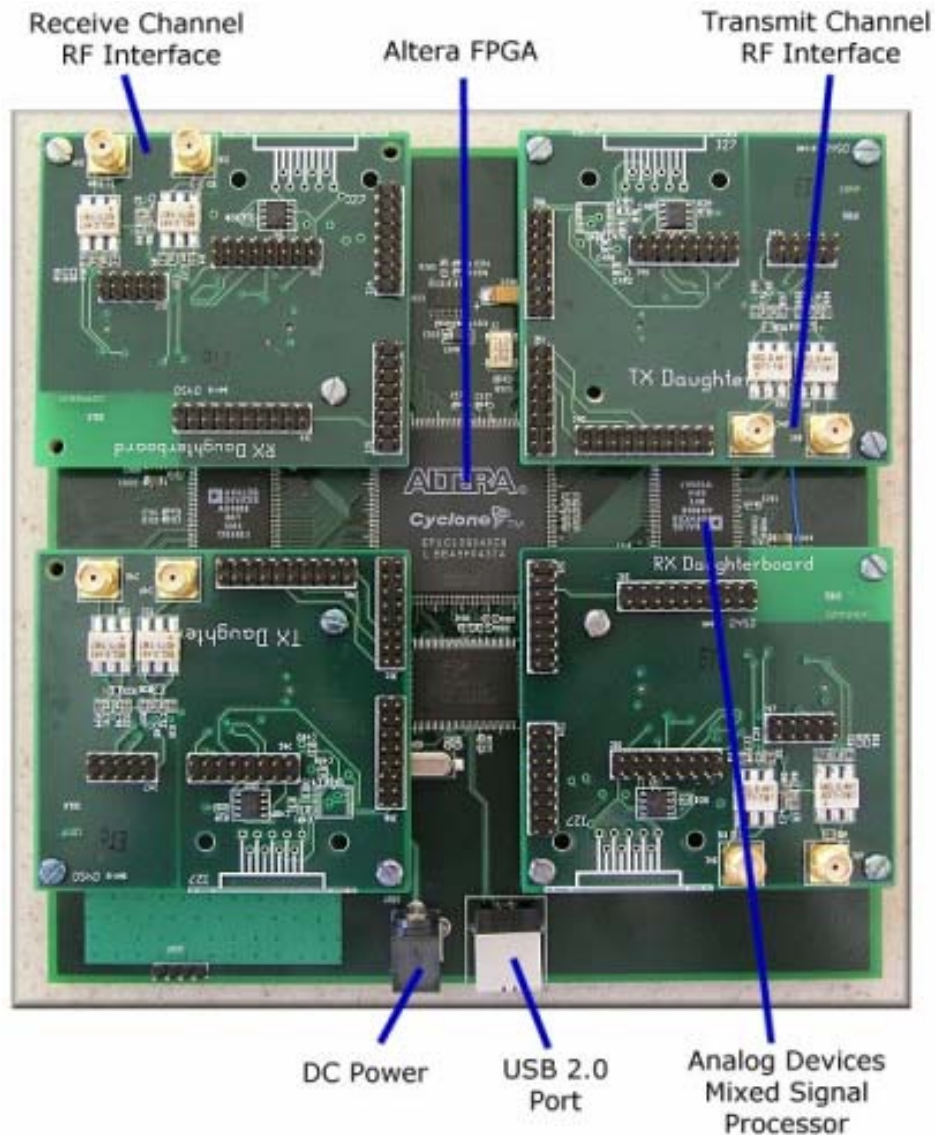
Figure 15. N2JMI's GNU Radio USRP

The salient features for our experimentation are the four input and output ports. These are clearly visible on the TX and RX daughter cards on this board. The engine is an Altera Cyclone FPGA. With this board we can easily do serious phased array tests with four elements. This is made possible by the shared clock and coherence through the entire chain. We will get four digital streams that should allow us to beam steer in software. Since there are other daughter cards, this can be an experimental transponder on a single board with these receiver and transmitter daughter cards. While it was our hope to have this board running LS at the meeting, the L and S modules were not ready as of this paper.

All of this work is being done in support of satellite missions. The first to fly should be the AMSAT-DL P3E. A view of the flight structure is seen in figure 16.

Figure 16: The P3E flight structure with AMSAT-DL's Hartmut Paesler, DL1YDD

The major planned features of P3E are outlined below

Spaceframe Structure, Size and Weight:
- AO-10/AO-13 type triangular star
- Approx.130cm diameter, 45cm height (not including antennas and engine)
- Approx. 150kg

Planned Orbit:
- Highly elliptical 36,000km x 2500km,
- 63° inclination
- 225° - 315° argument of perigee

Uplink Receivers:
- 29.500 (A): multimode
- 436.050 - 436.150 (U): linear passband
- 1268.600 - 1268.750 (L1): linear passband
- 1260.275 - 1260-425 (L2): multimode
- 1260.100 - 1260.225 (L2): linear passband
- 5668.600 +/- 25KHz (C): (linear)

Downlink Transmitters (Main Beacon will use FEC-coded telemetry):
- 145.812 (V): PSK 400 BPS General Beacon
- 145.957 (V): PSK 400 BPS Engineering Beacon
- 145.837 (V): multimode145.845 - 145.945 (V) linear passband
- 2400.250 (S): PSK 400 BPS General Beacon
- 2400.500 (S): PSK 400 BPS Engineering Beacon
- 2400.600 (S) - 2401.000: multimode,
- 2400.275 (S) - 2400.425: linear passband
- 24048.350 (K): beacon
- 24048.300 +/- 25KHz (K): linear passband
- 47088.350 (X): beacon
- 47088.300 +/- 25KHz (X): linear passband
- P5-A MARS Transponder Experiment: 2560 MHz (S) uplink and 10450 MHz (X) downlink. Also usable as a linear transponder with approximately 50 KHz bandwidth.

The AMSAT-NA Eagle spacecraft mission is also very ambitious with our intention to fly:
Orbit:
- Elliptical low-inclination GTO

Transmitters (Hopefully all bands should be capable of being operated simultaneously)
- V band (2M) using SDR techniques (bandwidth configurable up to 50 kHz)
- Two S Band with 100KHz bandwidth
- C band wideband digital which includes telemetry

Receivers:
- U band 100KHz bandwidth
- L band 100KHz bandwidth
- C band wideband digital
- Command uplinks on all receivers

If the possibility of dedicated microwave capabilities on future satellites is exciting to you, please let us know. We need LOTS of help and $$$!

And Remember:

AMSAT IS AN EQUAL OPPORTUNITY EXPLOITER !!