C-C Rider Revisited

Tom Clark (W3IWI), Bob McGwier (N4HY), Phil Karn (KA9Q) and Rick Hambly (W2GPS)

Abstract: At last year's AMSAT Annual meeting, W3IWI presented the concept of a C-band in-band transponder[1], dubbed "C-C Rider". This was based on the fact that the C-band satellite frequency allocation has matched pair of 20 MHz wide allocations: 5650-5670 MHz uplink, paired with 5830-5850 MHz downlink.

The status of the 5650-5670 MHz uplink band has changed since last year; the FCC has adopted an industry proposal for expanded 802.11a spectrum, and a world-wide allocation was made at WARC 2003. In this paper we speculate on the QRM level that might exist 5-10 years from now as seen by a C-band receiver on a HEO satellite. We will also discuss the RFI environment to be expected by a typical user at the C-band downlink frequency.

Many of the options that were presented in the previous paper have been considered in the context of a significant part of AMSAT's HEO (High Earth Orbit) EAGLE Project. Recent advances in SDR (Software Defined Radio) technology have led to the concept of a modular transponder that can be easily re-configured in orbit.

Since there is little suitable C-band hardware available for the amateur community, we will discuss the idea that the spacecraft RF and SDR modules can be "dual use" with low-cost compact user terminals developed as a system, in parallel with the spacecraft development.

The C-Band Radio Spectrum: Let us begin by examining the amateur frequency allocations between 1 and 10 GHz in Table 1[1,2]:

Table 1: United States Microwave Allocations			
Amateur Service		**Amateur-Satellite Service**	
Band (MHz)	**Bandwidth (MHz)**	**Band (MHz)**	**Bandwidth (MHz)**
1240-1300	**60**	**1260-1270 ↑**	**10**
2300-2310	**10**		
2390-2450	**60**	**2400-2450**	**50**
3300-3500	**200**	**3400-3410**	**10**
5650-5925	**275**	**5650-5670 ↑**	**20**
		5830-5850 ↓	**20**
10000-10500	**500**	**10450-10500**	**50**
24000-24250	**250**	**24000-24050**	**50**

↑ means Earth-to-space (uplink) direction only
↓ means space-to-Earth (downlink) direction only

With AO-40's S-Band downlink, many amateurs have experienced serious QRM from unlicensed (Part 15) 2.4 GHz wireless devices including cordless telephones, 802.11b/g and Blue Tooth wireless LANs, in-home video monitors and microwave ovens.

These same wireless interests have expansion plans involving the 5-6 GHz C-band spectrum. 802.11a "WiFi" and 802.16 "WiMax" LAN devices and cordless telephones are already on the market. Can we, as

---

[1] see W3IWI paper in AMSAT Space Symposium 2003 Proceedings, also reprinted in AMSAT Journal, August 2004.
[2] Thanks to Paul Rinaldo, W4RI for supplying an early version of this table.

amateurs, build a technology-based “brick wall” to protect these valuable frequencies? In Figure 1, we take a look at the 2004 view of the 5600-5900 MHz spectrum:

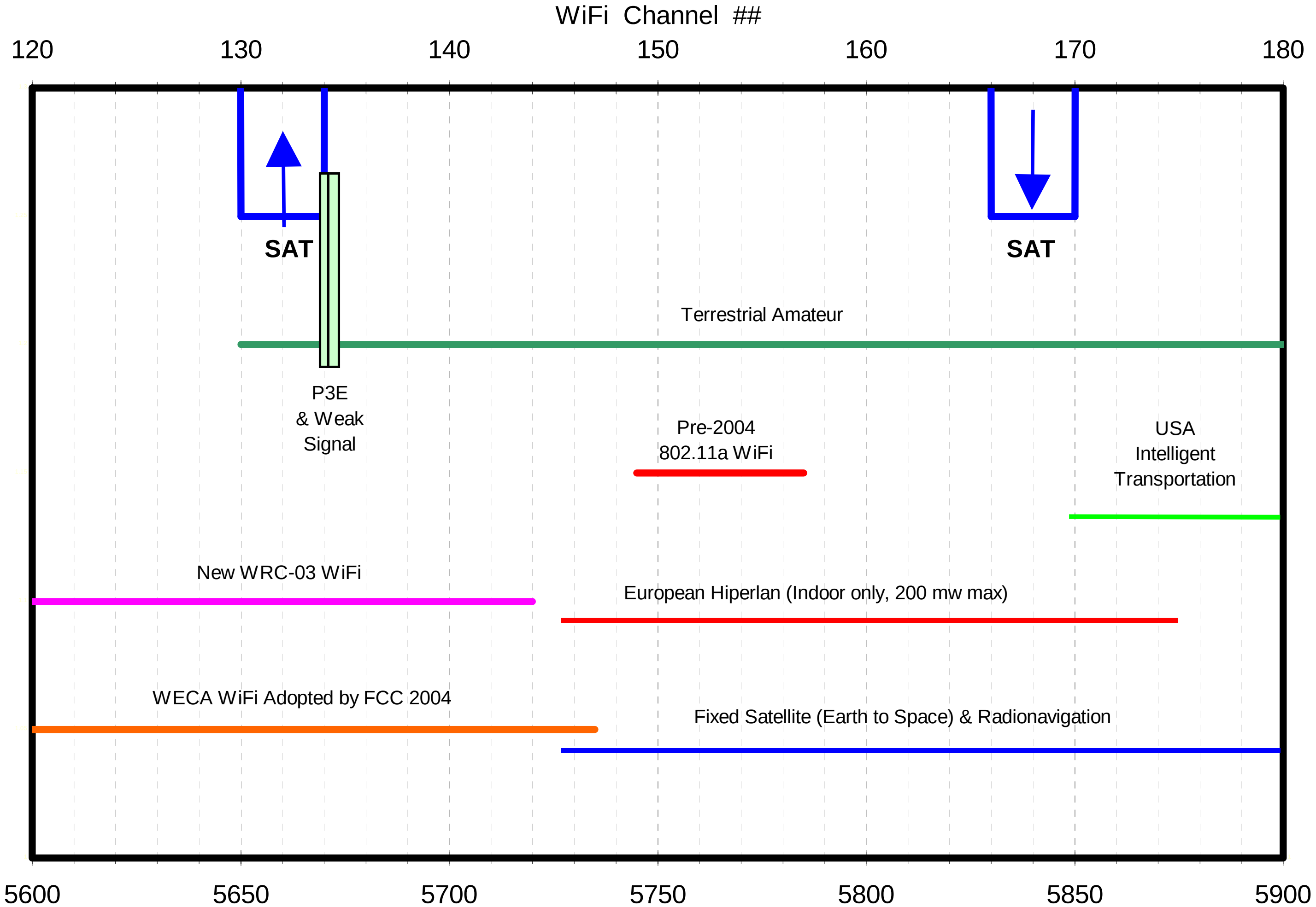

Figure 1

From this figure, we see that the 802.11a WiFi world has moved in to share the 5650-5670 MHz satellite uplink band. Let’s make some estimates concerning the QRM situation that might exist at the satellite.

The WiFi definition calls for the use of CDMA techniques, with a maximum thruput of 54 Mb/sec (just like 802.11g on 2.4 GHz). The total bandwidth available to WiFi is 550 MHz (5150-5350 MHz and 5450-5800 MHz – 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 transmitter per person, operating 16 hours/day. This means that at any time there might be 217 million transmitters.

- 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 217 million transmitters will be a noise-like 217 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:

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

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

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

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

We will return to this topic later when we discuss system link performance.

<u>Some Aspects of System Design</u>: In the previous paper, we outlined some possible design alternatives. In the last year we have refined our thinking on several topics, including:

1. **<u>HEO vs. LEO (Winner = HEO)</u>**: An attractive feature of C-C Rider for Low Earth Orbit (LEO) was the partial cancellation of Doppler with an inverting "bent-pipe" transponder, as well as the sharing of a single antenna for up- and down-link. Link budget calculations for the LEO case indicated the need for ~26 dBiC of antenna gain; this in turn necessitated antenna pointing accurate to a few degrees while the satellite can move at angular speeds up to ~½°/sec. This seems to be a bit beyond the capability of the average amateur.

   However a High Earth Orbit (HEO) satellite offers the user a slow-moving target. Combining this with AMSAT's plans for the HEO EAGLE satellite as it's next project led to our proposing C-C Rider as a main payload at the recent EAGLE design meeting[3]. The concepts presented in the rest of this paper are the result of enthusiastic endorsement of the concept by all the developers present at the meeting.

   The rest of this paper assumes a HEO EAGLE mission with a perigee height ~1000 km and apogee height ~40,000 km.

2. **"<u>Bent-pipe" Transponder vs. Digital Regenerator (Winner = A New Idea!)</u>**: The previous paper described the simple "bent pipe" transponder implementation of the C-C Rider concept reproduced in Figure 2. An addition to the concept was introduced (Figure 4 in the previous paper) discussed the desirability of providing alternative digital "demod-remod" capability as has been espoused by Phil Karn.

   As we prepared for the Orlando meeting, we developed an alternate implementation. The past two years have seen a revolution in amateur radio technique with the use of Software Defined Radios (SDRs). The receiver portion of an SDR is implemented by converting the desired RF signal to a convenient IF, and then digitizing the signal with an analog-to-digital converter (ADC). Final bandpass filters and signal processing is then accomplished in signal processing software. In this paper we will denote the receive side of an SDR as an SDRX.

   The transmit function in an SDR is accomplished by generating the desired signal in software and then converting to analog with a digital-to-analog converter (DAC). This analog signal is then heterodyned up to the desired RF signal frequency. We adopt the notation SDTX for the transmit part of an SDR.

   In most amateur implementations to date, the ADC and DAC functions of the SDR have been implemented in a "Sound Blaster" sound card running in a consumer-grade PC. This includes all the audio baseband PSK31 implementations (like MixW) and real SDR's like LINRAD and SDR-1000. Sound Blaster performance limits these implementations to bandwidths < ~50 kHz.

---

[3] Held in Orlando, Florida in July 2004.

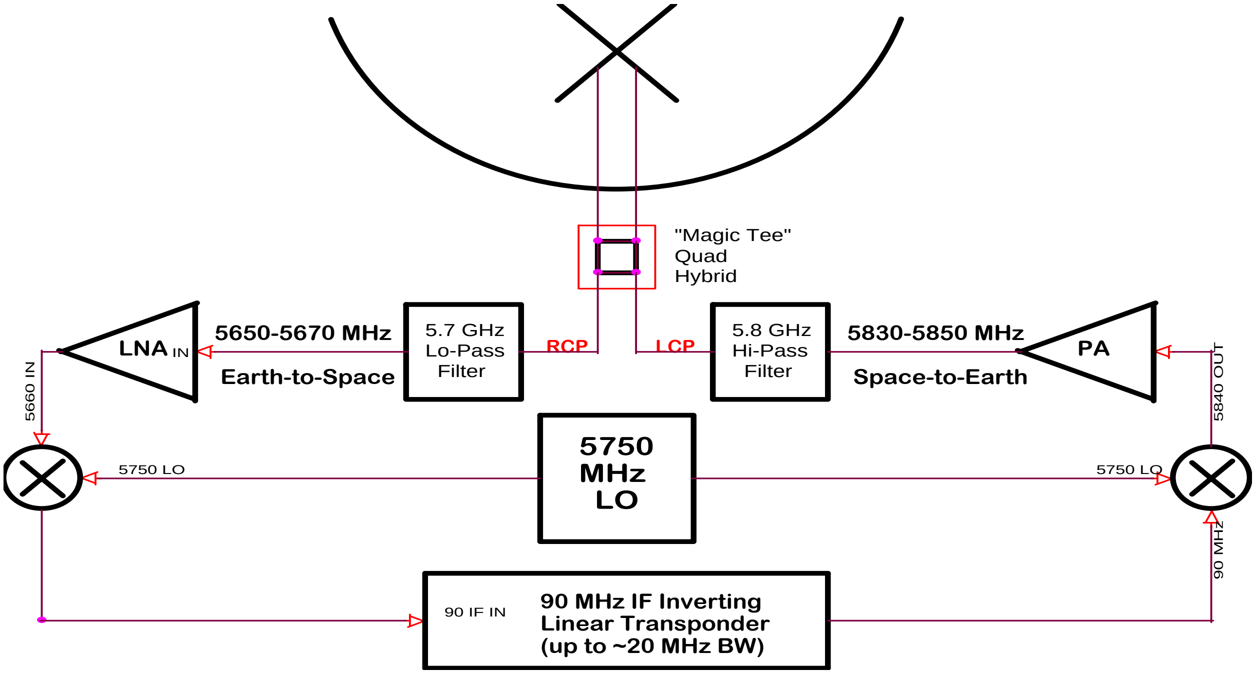

Figure 2: Simple "Bent-Pipe" idea for C-C Rider Spacecraft Transponder

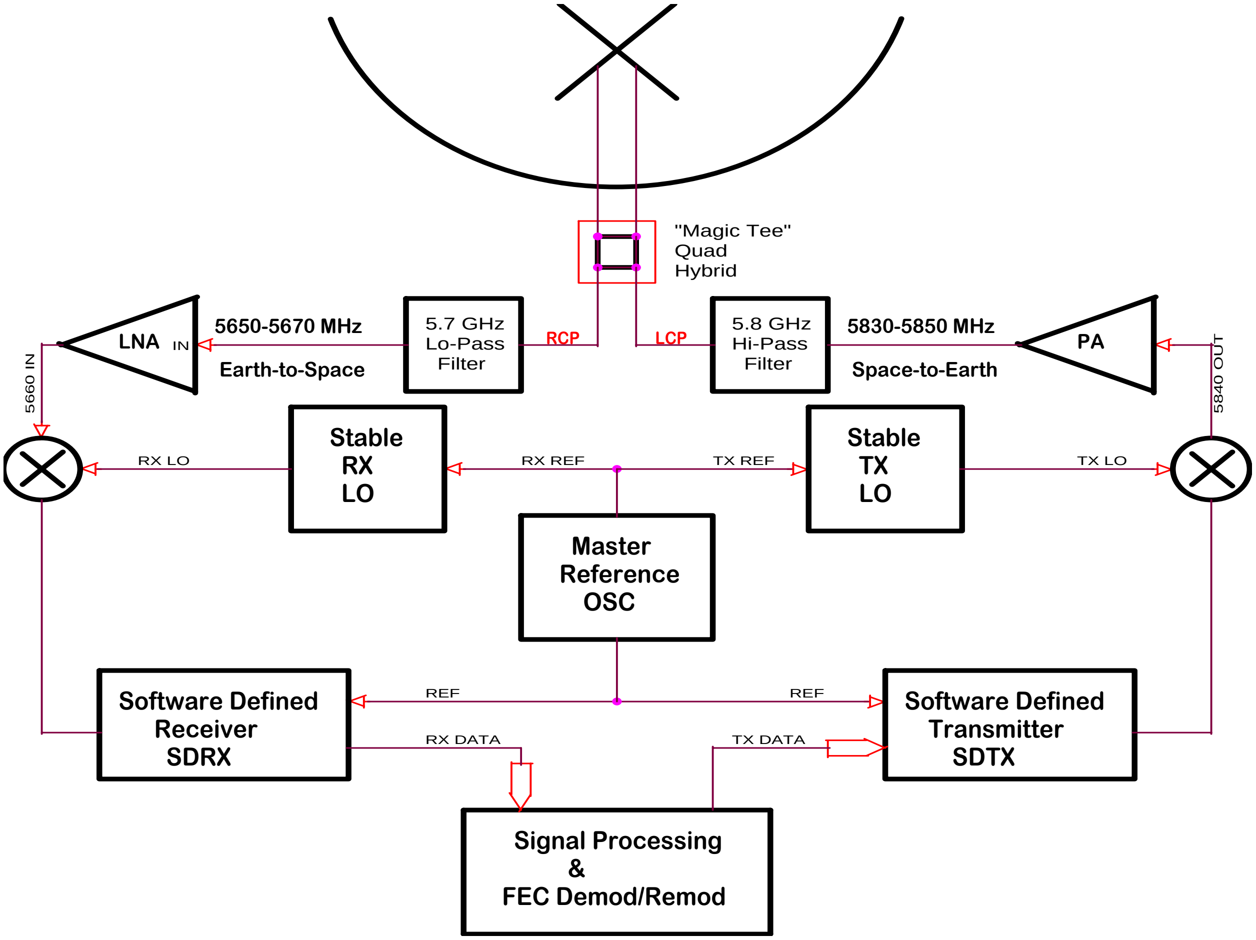

Figure 3: "Universal" Transponder using Software Defined Radio (SDR) Concepts

Thus in Figure 3, we see the C-C Rider concept “morph” into the idea of the universal SDR-based transponder. In order to optimize performance, we see that all Local Oscillators (microwave and SDR) are all derived from a single low-noise master oscillator.

Let’s think about a linear transponder implemented in SDR. The signal processor could

- Remove gross Doppler offsets (less knob twiddling!)
- Apply suitable AGC to each individual signal (no alligators!)
- Optimize band utilization by suppressing unused parts of the band
- Allocate proper user vs. beacon power sharing

If a linear transponder was used for digital signals, the uplink and downlink Signal-to-Noise Ratios (SNRs) would be multiplied (making the link degrade as distance like R^4). Instead of taking this “hit”, we would demodulate the digital signals at the spacecraft, applying error correction. The digital downlink signal get “fresh” FEC coding added and the links perform as a pair of R^2 paths.

3. Dish Antenna vs. Array of Patch Antennas (Winner = Patches): Last year’s paper offered the two possibilities. At the Orlando EAGLE meeting it became apparent that an array of patches has a lot to offer. Dick Jansson, WD4FAB has prepared an extensive drawing package for the ~60 x 60 x 45 cm EAGLE satellite. In Figure 4 we begin with Dick’s drawing of the EAGLE “antenna farm” which shows a large 70 cm patch antenna in one corner. On top of the 70 cm patch is an array of three patch antennas for the 23 cm uplink. In diagonal corners are two separate arrays of four patches each for use on 13 cm.

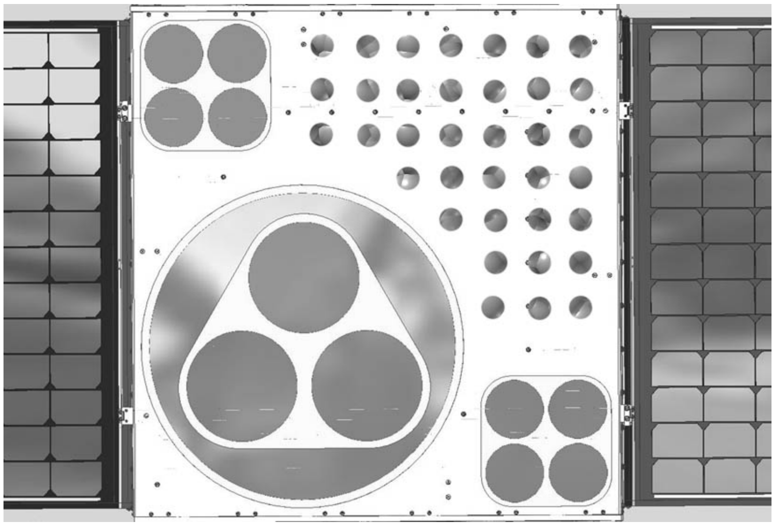

FIGURE 4. Array of 36 C-Band Patches on the EAGLE Satellite.

As seen in this sketch, we fill the remaining area with an array of 36 circular polarized patch antennas for C-Band (5.7 GHz) on a 50 mm (one wavelength) grid. Each patch element would be a complete C-band micro-wave system as shown in Figure 5. This circuitry would be developed using modern microstrip development soft-ware (like Ansoft’s HFSS package.[4])

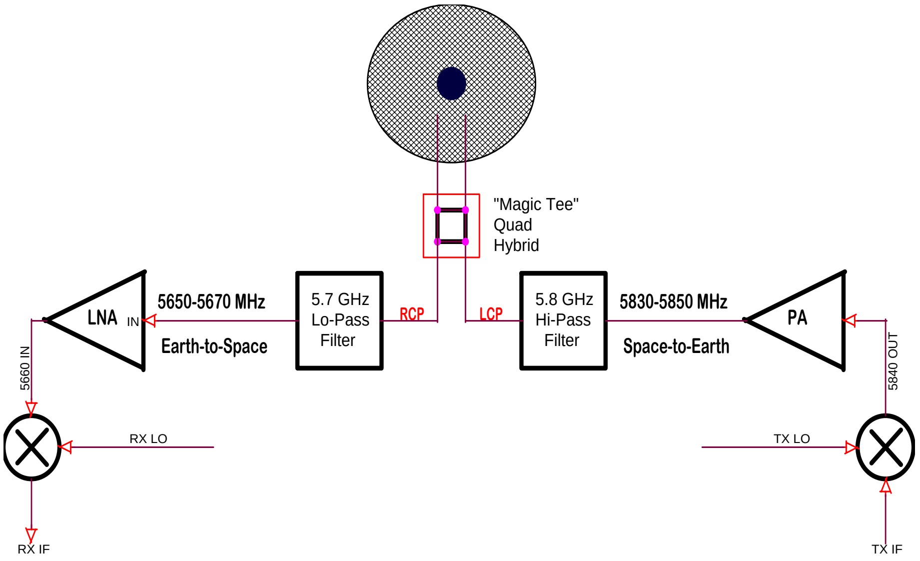

FIGURE 5. Micro-wave components in each C-band array element.

---

[4] See http://www.ansoft.com/products/hf/hfss/.

As mentioned in the first paper, each Power Amplifier would be a ½ - 1 watt output integrated amplifier designed for C-band wireless LAN use [5]. The LNA would be a low-noise PHEMT unit. The use of a distributed array of power amplifiers and microwave front-ends affords a unique level of redundancy. The failure of any one of the N elements would only degrade performance by a factor 1/N.

Let's look at the operation of this array on the receive side first. In Figure 6 we show a ground-based beacon transmitter provides a pointing reference for the C-band system. In this example, EAGLE's spin axis makes an angle α with respect to the signal from the beacon. Onboard the spacecraft, the signal from each of the antenna elements (after conversion to a convenient IF) is digitized in a separate SDRX channel[6].

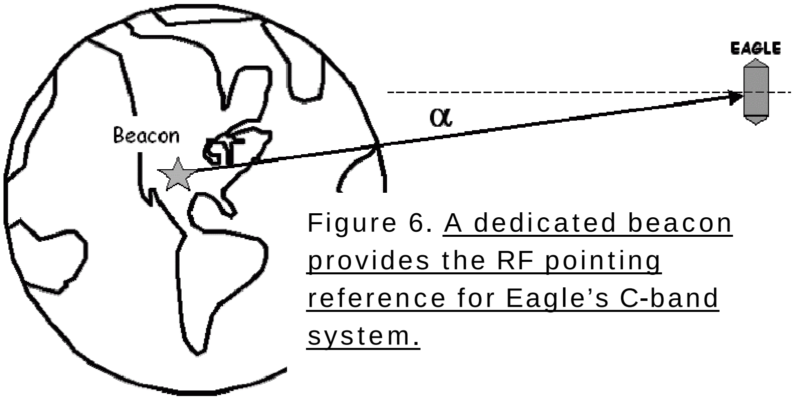

Figure 6. A dedicated beacon provides the RF pointing reference for Eagle's C-band system.

The phase data from pairs of SDRXs are combined to extract the phase difference Φ. As we see in Figure 7, the phase difference is related directly to the pointing offset α.

When projected onto the sky, the phase of the interferometer is periodic, with sinusoidal "fringes" that are spaced $2\pi B/\lambda$. The longer the baseline B, the finer is the scale of the interferometer fringes; but when B is longer than one wavelength, the phase becomes ambiguous. The array sketched in Figure 4 has the patch antennas placed on a one-wavelength grid to resolve so that the close pairs resolve fringe ambiguities, and also has spacings as long as ~9 wavelengths to improve the accuracy of position determination.

We plan that the beacon signal will be strong enough so that the beacon's pointing can be easily determined. Then, knowing the position of the earth relative to the spacecraft, the signals from all 36 antennas can be added to obtain a collecting area equivalent to ~30 cm dish. Since the array "pointing" is done electronically, the dish can be slewed to point at the earth even when the spacecraft's spin vector is off-pointed. This in turn means that the spacecraft will be useful through a larger portion of the orbit.

Once the spin axis is located with respect to the beacon on the earth, the positional data can also be applied to the SDTX transmitter elements so that the transmitting gain is comparable to the receiving gain. The array shown in Figure 4 is a bit larger than is needed to fill the earth at a 40,000 km apogee. The excess can be used to "trim" the shape of the beam to better "light up" the limb of the earth, improving DX performance.

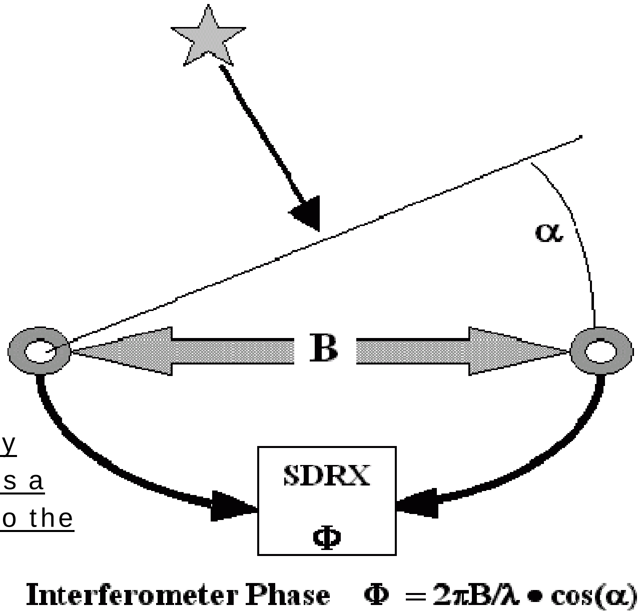

Figure 7. The interferometer formed by combining a pair of elements produces a phase measurement directly related to the pointing reference.

---

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

[6] Lest you become too concerned with the complexity of this operation, realize that your typical 12-channel handheld GPS receiver contains a separate SDRX for each of the 12 channels!

The gain of each individual patch antenna element should be ~5 to 6 dBiC. If the 36 element array is used on-axis, the arraying gain should be about 10 • log(36) = 15.6 dB, the total gain should be in the 20 to 21 dBiC range, corresponding to a beamwidth ~19^0. This nicely matches the size of the earth, 15.7^0 as seen from a 40,000 km altitude.

4. **Some Estimates of uplink performance**: To make estimates of the link performance for C-C Rider flying on EAGLE, we make use of an Excel spreadsheet developed by Jan King, W3GEY/VK4GEY[7].

First, let's consider the uplink; the performance is critically dependent on the noise level that the spacecraft will see. Earlier we made an estimate that the worst-case noise contribution from 802.11a WLANs on the earth would be 57^{0}K. To this we add estimates of other contributions that we may experience:

Sky Noise	3 °K
LNA	40 °K
Antennas and Feedlines	50 °K
802.11a	< 57 °K
Transmitter (est.)	400 °K
TOTAL ESTIMATE	**550 °K**

The dominant term in this estimate is "Transmitter". In order to function as a transponder, the transmitter and receiver need to operate "full duplex" – receiving while transmitting. It is likely that each of the transmitter elements will generate some wideband noise that will be coupled into the receiver through the circular polarizing hybrid and antenna elements. Since the transmitter has not yet been developed, we can only flag this item as a serious worry!

To continue the uplink analysis, we note that we have an earth-to-space one-way path loss of –196 dB. If the user on the ground can develop 30 watts of power into a 20-21 dBiC gain antenna, his signal at the spacecraft will be about –129 dBm. If the spacecraft's antenna has a gain of 20 DbiC, the receiver will see a signal of about –109 dBm. Finally, if the receiver has a bandwidth of 100 kHz, this results in a S/N ratio of +12 dB.

If C-C Rider is used as a digital transponder that employs FEC, this performance implies a usable channel capacity in the 100-200 kb/sec range. Digital voice sounds very good with data rates of 10 kb/sec, so this link could support 10-20 noise-free voice channels. Each channel would support a two-way QSO or an n-way roundtable, so upwards of 50 simultaneous voice users can enjoy the EAGLE/C-C Rider combination.

This number can be increased if more robust uplinks can be developed. This might be done by

- Developing user terminals with transmitters bigger than 30 watts, or
- Developing user antenna systems with more than 20 dB gain, or
- Making the spacecraft transmitter have less noise in the uplink frequency band.

5. **Estimates of Downlink Performance**: Throughout the design, we have assumed that the spacecraft and ground-based user terminals are nearly identical. Microwave hardware developed for the spacecraft could be re-used on the ground by merely swapping the TX and RX ports. The SDRX and SDTX software would be developed with a GNU-like Open Source model; while the actual computer hardware on the ground and in space may be different, much of the intellectual property investment is reused. Therefore it is quite likely that uplink and downlink system performance will be the same, with one major difference. The spacecraft needs to operate full-duplex, so TX noise leaking into the RX becomes a dominant noise contribution. But the user will likely operate half-duplex, turning off the transmitter when not needed. The result is that the large TX noise contribution (estimated above to be 400 °K) doesn't apply. But this may trade off against localized C-band noise sources (cordless phones, "sloppy 802.11a devices, etc) in the downlink band. So, until we know a bit more about the 5830-5850 MHz spectrum, we assume that the downlink can support the uplink.

---

[7] Available at http://www.amsat.org/amsat/ftp/software/spreadsheet/AMSAT-IARU_Link_Budget_Rev1.xls

Some Concluding Comments: As amateur radio enters the 21st Century, we face significant pressure on our most important resource, ***the Radio Spectrum***, especially in the 1-10 GHz range. Our allocations are precious to us, but we ***will*** lose them if we don't use them. And our usage needs to make significant contributions in advancing the state of the art.

AMSAT is now planning its next major satellite in the project that had been dubbed EAGLE which includes the C-C Rider concept discussed in this paper. We hope that it proves to be a challenging project that will inspire the participation of some new, talented people.

The ideas expressed here are far from final. Here are some areas that can challenge new blood:

- Can we really cram a one-watt C-Band PA, patch antenna, circular polarization combiner, bandpass filters and LNA into the 50 mm (~2 inch) space shown in figure 4? What DC-to-RF power efficiency will we able to achieve? How do we get rid of the heat that doesn't make its way into RF energy?

- How quiet will the TX be in the RX band? Link performance is critically dependent on this.

- How much will these modules weigh? Will they upset the spacecraft's 3-axis moment of inertia that allows the satellite to spin smoothly?

- The design of the multi-channel SDRX and SDTX will be challenging! How much computing horsepower is needed? What's the mix between general purpose CPUs vs. DSP CPUs vs. Programmable Gate Arrays?

- What communication protocols will we use (Time slotted TDMA? CDMA? FDMA? ???)? What is the ratio of Error Correction bits to Data Bits?

- How much does all this weigh? How much power is needed? What temperature range can be tolerated by the hardware?

- How do raise enough money to fund the development of the payload, the EAGLE satellite and the launch? Can we find (and afford) a suitable launch?

The way for you to become involved is to volunteer. AMSAT is an **Equal Opportunity Exploiter!**