Notes from the Eagle Digital Payload Design Meeting
San Diego, CA
29 – 30 June 2006

Bob McGwier, N4HY and Jim Sanford, WB4GCS

AMSAT leadership and digital experts convened at Qualcomm headquarters in San Diego in late June to hammer out details of the digital payload and the resulting changes to other Eagle features. Attendees were:

Rick Hambly	W2GPS	AMSAT President: w2gps@amsat.org
Bob McGwier	N4HY	AMSAT V.P. Engineering: n4hy@amsat.org
Jim Sanford	WB4GCS	Eagle Project Manager: wb4gcs@amsat.org
Franklin Antonio	N6NKF	Qualcomm E.V.P. and host
Eric Blossom	K7GNU	GnuRadio architecture
Frank Brickle	AB2KT	DttSP, SDX, Suitsat II architect
Tom Clark	K3IO	AMSAT chief scientist and Pres. Emer.
Matt Ettus	N2MJI	USRP designer, GnuRadio architect
Chuck Green	N0ADI	AMSAT Engineer
Lyle Johnson	KK7P	AMSAT Engineer, HPSDR designer
Phil Karn	KA9Q	V.P. Qualcomm, for AMSAT Asst. VP Engineering
Jan King	VK4GEY	Former V.P. Engineering, AMSAT Engineer
John Stephensen	KD6OZH	Eagle 70cm RX designer

AMSAT V.P. Engineering, Bob McGwier, N4HY welcomed the attendees and thanked Franklin Antonio, N6NKF for hosting the meeting. The facilities were excellent and our meeting was a logistical success due entirely to the local hospitality. After stating that the goals were to put together a credible proposal for a digital transponder based on the statement of work for the meeting, the first speaker was introduced.

AMSAT president, Rick Hambly, W2GPS, opened the briefing portion of the meeting with a talk covering the high level objectives of AMSAT, Eagle, and the expectations for this meeting. Rick's presentation can be seen here.

Eagle Project Manager, Jim Sanford, WB4GCS, then briefed the current Functional Requirements (FRD), which can be seen elsewhere on EaglePedia. Jim discussed the history of the FRD. Jim emphasized the importance of some hand-held capability for quick and easy emergency communications, and the strong desire to enable Eagle use by apartment dwellers or others facing severe covenants and restrictions (CC&Rs). Franklin Antonio, N6NKF, had several pointed questions regarding services to be provided by Eagle and averred as to how our functional requirements document was a list of widgets and not services. Jim agreed that the FRD was imperfect and would change, but it lists capabilities and has been a useful focal point to date. Jim stated that the microwave digital payload (and development of the appropriate affordable ground equipment) is a primary objective and discussed the history behind the decisions to fly certain analog payloads. It was recognized that the results of this meeting will lead to changes to the FRD. This exchange was followed by a valuable discussion that our purpose was to decide what services would be provided to how many users and on what bands. This was exactly what the statement of work called for so we got into the rest of the presentations.

Tom Clark, K3IO, presented a discussion of the microwave frequencies under consideration, and the constraints associated with each. Tom included a desire and rationale for flying a C-band uplink and downlink payload and a quick summary of his previous publications on the subject. This led to a protracted discussion, which included concerns regarding the necessary spacecraft filters (many of them) and the proposal that C-C might work if we use a larger structure & separate antennas for TX & RX. This implementation would greatly reduce the filtering requirements without removing them altogether. Later analysis of communications link budgets resulted in this proposal being deemed impractical and it was subsequently rejected. Tom's discussion included comments regarding the vulnerabilities of our L-band uplinks due to the pending European GPS-like (Galileo) deployment. In the extreme, we could very well lose L-band altogether. This fact must be carefully considered in the Eagle design and helped reinforce our design decisions later.

Matt Ettus, N2MJI, made several back to back presentations starting with GNU Radio history and objectives. Matt's presentations included a discussion of the Universal Software Radio Peripheral (USRP) and its applicability to the Digital Transponder, his vision, a preliminary design document and his band proposals for Digital Payload classes of service. The remainder of Thursday and well into Friday was spent looking at all variants and combinations of the microwave bands, required powers, antennas and coding, to see what level of services could be delivered.

We concluded that the handheld digital voice goal is not supportable by a spacecraft we can fly. This capability has been an important goal, but analysis of the communications links revealed it was simply not achievable with our spacecraft– the numerical analysis was unequivocal. We realized that handheld text messaging is possible and after analysis of requirements, link budgets, and power available/required, it was concluded this service is best provided at U/V-band. Trying to do it in the microwave bands would have consumed the majority of all the transmitter power and limited the number of voice grade channels to much less than any desirable level of service. The resulting system will allow a small U/V package that can be parachuted into an emergency area if necessary.

Next, we looked at implementing the digital voice service. To accommodate emergency communications and apartment dwellers or CC&R-limited hams, we considered digital voice services to a ground station with an 18dbi patch antenna or 2 foot (60cm) dish. To accommodate the "big gun" (actually, "big ear") station, we also considered a digital video capability for a station with a 1.8 m dish. The table below summarizes our analysis and preliminary conclusions. The final analysis will be discussed at the end of this document. This table is the conclusions reached while still at the meeting and is included here to demonstrate that all stones were turned.

Classes of service and power required

Class/Signal	Gain	C-band	S1-band	S2-Band
Carrier required for Class 1	6dbi	14W	24W	4W
Data Class 1	6dbi	.042 W/bps	.148W/bps	.016W/bps
Data Class 2A	18dbi	2650υW/bps	62000υW/bps	1181υW/bps
Data Class 2B	28dbi	98.4υW/bps	6009υW/bps	98υW/bps
Data Class 3	38dbi	8.9υW/bps	531υW/bps	8.9υW/bps

This was our initial analysis of the required spacecraft transmitter power to support the link in number of watts of carrier to support the least capable mode, and the number of watts/bps or microwatts/bps OF THE UNDERLYING DATA to close the link from the spacecraft to the ground with a slant range of 40000 km. This table is a headache builder. The spread sheet link analysis has been refined and is much easier to follow and in addition has tentative design details for the U/V class 1 user.

Legend:
Class 1: Low data rate text messaging to hand-held ground station. Notice the amount of carrier power that would have been devoted to the hand-held station just to give them the power needed to acquire and track the carrier of the satellite digital transmitter!

The remaining rows are the power that needs to be ADDED to support the additional service on top of this carrier.

Class 2A: Digital Voice to ground station with coarsely steered and electronically aimed patch array
Class 2B: Digital Voice to ground station with steerable 60cm dish
Class 3: Digital Video to ground station with 1.8m steerable dish

Although several independent spreadsheets were used, a final (and refined/verified) one can be seen here and was provided by KA9Q. The independent spreadsheets served as a real-time peer review.

As an aside, the rule of thumb:

$$\text{3 dB Beamwidth } = (1.22 / D_{\lambda}) \text{ radians or } (57 * 1.22 / D_{\lambda}) \text{ degrees}$$

$$= 20848 / F_{Mhz} \text{ Degrees}$$

Where D_{λ} is the Diameter in wavelengths. The 1.22 is the Airy correction and is due to the size subtended by the first zero's of the J1 Bessel function involved in this piece of geometric optics. $D_\lambda = 299.8/F_{Mhz}$. The pointing accuracy required for us likely to be about 20% of this beam width.

Tom Clark, K3IO, et.al., has previously analyzed and published C-band noise at the satellite due to 802.11a wireless transmitters. We did a quick similar analysis for S-band and concluded that a 2.4Ghz downlink has an equivalent temperature equal to Sun noise at the ground station due to 802.11*x* and that this was growing at an accelerated pace. This coincides with anecdotal evidence from several AO-40 users (or former users) that S-band downlink was unusable due to this noise and the problem has continued to grow worse. The clear implication of our preliminary analysis concludes that ***S band will be unusable as a weak signal downlink over much of the earth and is unusable for a digital downlink as well for the same reasons.*** The spectrum experts in the meeting agreed with this conclusion. On the other hand, a preliminary analysis, with conservative estimates (overestimates based on the reasoning in the Clark, et.al. paper) of the noise floor at the satellite indicated that we ***could*** reasonably generate enough power on the ground to overcome 802.11 noise sources at the satellite and require easily achievable power at S band on the ground station.

Next, discussion moved on to modulation modes for the downlink. Matt Ettus suggested:

Constant envelope (power efficiency)
BPSK vs. m-Ary PSK (power efficiency)
Independent up & down link coding and multiplexing (ease of use)

At the end of the first day, we summarized the following conclusions from 29 June:

1. Shared low data rate text is workable but not on microwave bands. However, this is a good use for V-band, either on beacon or separate beacon-type downlink.
2. Hand-held digital voice is not possible on any band.
3. CC&R users will need a steered 60cm dish. The electrically steered patch array just wasn't quite good enough, largely due to noise captured by side lobes. We need to include affordable steering system as part of the system design and not leave it to users to "figure it out".
4. Hams like to talk and this service should not just be file transfer. Services provided must include excellent voice "conference" (1 to many stations) mode regardless of what else is delivered.
5. While there may be a continuum of varying data rate applications, the spacecraft will have 2 data rates in the initial design for the microwave digital transponder: 4800 bits/sec, 256 kbit/sec.
6. The large data rate requires a 1.8 m dish and is intended to support streaming digital video.
7. We discussed the user service model that will drive the spacecraft design, given the knowledge of link budgets we considered.
8. To support 18dbi ground antenna (patch), spacecraft C-band RF power is 63watts, 33 watts on S-band. These are RF output powers. The DC requirement is exorbitant.

9. To support 60cm ground antenna (dish), spacecraft C-band RF power is 20 watts and 2-4 watts on S band on the ground. This conclusion effectively ruled out the patch antenna.

Modes and satellite transmit power

User class	S1 UserAntenna	S1 Power	C Antenna	C Power
2A	18dbi patch	28W per user	18dbi	63W Eagle
2B	60cm	3W per user	60cm	20W Eagle
3	1.8m	12W per user	1.8m	20W Eagle

(Assuming 20 simultaneous users for class 2 and 2 users for Class 3, these numbers are derived based on the latest spread sheet from KA9Q and done by N4HY)

2A = 18dbi patch
2B = 60cm dish
3 = 1.8m dish

10. Therefore, our analysis appears to dictate a 60cm dish on the ground station for text and digital voice. This system is capable of being easily transported into an emergency area or deployed from an apartment balcony. AMSAT will be required to design the entire ground station system for the Class 2B user in detail to achieve the required performance. The pointing accuracy requirement at 5.8 GHz downlink is particularly demanding given the 5-degree beam width and the close margins we are attempting to hit. We have implementation losses in the spreadsheets that are an attempt to account for some of the losses we might encounter but they need to be refined.

We next considered duplexing options, summarized below. The first three are full duplex modes. The TDD entry is not.

Duplex	Bands	Antenna	Negatives	Positives
FDD	2 bands	Separate antennas	-Area on spacecraft -Dual band ground ant	-Stakes claim to threatened bands -No T-R switch
FDD	1 band	1 antenna	-Complicated, large, and heavy duplexer on spacecraft	-Smallest satellite antenna area
FDD	1 band	2 antennas	-Larger area on S/C	-No s/c duplexer -Single ground antenna -Duplexer on ground
TDD	1 band	1 antenna	-TR switch -Critical timing/synchronization -Duty cycle	-No duplexers -Single antenna

FDD = Frequency Division Duplexing

TDD = Time Division Duplexing

Next, we had a protracted discussion regarding what bands to use, in light of our recently acquired understanding of the link budgets involved and pending usage or other regulatory issues.

This discussion included an implicit assumption of full-duplex usage. It was recognized that the S1 uplink may have interference issues with Wireless Networking (802.11 a & g). Users must employ particular antennas to avoid interference to Wireless Networks.

Alternatives considered are summarized on the next page:

Band usage

Up	Down	Negatives	Positives	Conclusion
L	S1	-S1 "sewer" -Ground ant > 60cm		-Discarded due to possible L-band loss and ground station antenna size. -Discarded due to S-band noise.
L	S2	-Regulatory question with S2 in region 1 -Ground ant > 60cm	Few known interference sources at S2.	-Discarded due to possible L-band loss and ground station antenna size
L	C	-Ground ant > 60cm		-Discarded due to possible L-band loss and ground station antenna size
S1	S1	-S1 "sewer"		-Discarded due to noise
S1	S2	-Legal question with S2 In region 1 -Dual-band feed is difficult	-Easier pointing requirement. -Few known interference sources at S2.	
S1	C		-Reduces filtering requirements in S/C to avoid LNA burnout and desense.	
S2	S1	-S1 "sewer"		-Discarded due to S1 noise. -Discarded due to Region 1 consideration.
S2	S2	-Uplink not avail in Region 1	Better at S/C than S1	-Discarded due to Region 1 consideration.
S2	C			- Discarded due to Region 1 consideration.
C	S1	-S1 "sewer"		-Discarded due to S1 noise
C	S2	-Legal question with S2 in region 1	Avoids WiFi	
C	C	-Many "Ugly" duplexers or two S/C antenna arrays. Poor uplink budget and high power requirments for C up ground stns.		Discarded since S1/C is workable and C uplink requires high power.

We concluded that the best use of L-band was for analog modes since the U/V would continue to support analog users if L band were removed from the amateur satellite service.

Therefore, we considered for the digital payload: S1/S2, S1/C, C/S2 or S2/C.

- S1/S2 includes duplexer loss at ground station and has regulatory questions in Region 1
- S1/C raises noise floor at satellite ("sewage") – need to calculate impact
- S2/C precludes uplink by some Region 1 stations
- C/S2 may preclude reception by some Region 1 stations

S1/C has no regulatory issues. There remains a question regarding interference to WiFi, which must be investigated by further analysis and experiment.

S2/C is technically preferable, regulatory issues aside. Regulatory questions will be investigated by legal inquiry but do not look promising enough to base design decisions on them now.

We therefore concluded to use S1/C, but will continue to explore the regulatory issues with S2 in region 1.

There is no compelling advantage to using CDMA. We therefore chose FDMA for the uplink and TDMA on the single carrier downlink.

Next, discussion moved to uplink characteristics, summarized below:

Multiple uplink access ideas

1. Satellite periodically broadcast position, etc., for use in Doppler correction at the ground transmitter. (open loop)
2. Receiver on satellite calculates offset and transmits Doppler correction to the ground station. (closed loop)
3. We will attempt both.

We suggested a data structure that could be transmitted to implement a channel sharing protocol. Because of the nature of the uplink channels, we can effectively have a huge number of them. They will not all be in simultaneous use.

Example data structure

Channel	**Last Call**	**Last Conference**	**Last Time**	**Last freq corr**	**Eb/No**
0	*NA*	*NA*	*Time since use*	*Channel used longest ago*	
1	N6NKF	A	-18	-5hz	*<as measured>*
2	Etc…				

4. In the data structure for each user will be the last channel user, conference assignment, signal strength, frequency offset, time slot in the spacecraft frame. The satellite will transmit this once per frame using the most robust encoding.
5. Several ways to assign uplink channel:
   a. New user requests an allocation on a “request” channel. Uplink contention may exist on this channel, but ONLY on this channel.
   b. Channel 0 in the data structure tells that channel used the longest time in the past. If there are ties, it picks at random. The spacecraft need only look at the oldest channel to see if there is a new user. Therefore (b.) is preferred!
6. Conferences are assigned by the FIRST person in a conference. The state and users for that conference are maintained in the user conference software on the ground, leaving the satellite stateless.

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Having worked fairly deeply into the overall design, we turned our attention to the spacecraft phased arrays.

Phased array arrangements

1. 2 element interferometers on the spacecraft will locate a beacon on earth. Spacecraft receiver has this information and knows where earth is. Beacon/command is on a private "channel."
2. Receiver then uses direction cosines to electrically point phase arrays.
3. Phasing will be done by digital phase shifters, which are commercial off the shelf devices now. These phase shifters will be in the LO output to a mixer so the narrow band phased arrays are tuned by LO shifts.
4. We will have to know or measure incremental phase difference of each array element or each group of array elements.
5. Spin at a few rpm (except during a motor "burn"). U/V to be used for command during periods of high RPM.
6. Exploit symmetry in antenna array to minimize number of A/D converters and down converters.
7. Looks like array will be 36 elements 1-λ (or less) apart on symmetrical layout.
8. Receive antenna array will calibrate based on a known beacon on the ground. The same calibration constants will be fed to transmitter phase shifters. The beacon will be used to close the loop when available but the spacecraft will maintain a full estimate of its vector orientation in "inertial space" so the antennas may be pointed in open loop when ground beacon is unavailable.
9. Discussion of possibly making measurement on ground of transmit signal to "tweak" transmit phase shifters.
10. Discussion of grouping array elements with relative phase shifts among small group, and are then repeated among groups.
11. Discussion of concentric rings of arrays.
12. Discussion of desense: Filtering C-band TX to keep power at S-band RX below desense/burnout. This argues strongly for the S1/C selection.
13. Add on/off DC control for each TX & RX phased array TX & RX circuit.
14. 2m TX: 20 watts class E, class S modulator, 50 KHz bandwidth. 25 watts DC.

To begin to understand required volume and surface area, we worked out a preliminary power budget for the spacecraft.

<u>Preliminary Power Budget</u>

Item	DC Power	RF Power	Comments
U RX	3 W		
L RX	3 W		
V TX	30W	20W RF	
SDX	5W		
S1 RX array	25W		(may be lower)
C TX array	60W	20 W RF	
SDX	10W		
Spacecraft bus (housekeeping)	24W		
TSFR			
Total	157W		
Required Array	300W		Estimated cost: $360K

Solar array cost information:

$1200/watt for triple junction solar cells 23% efficiency
$900/watt for double junction cells 18% efficiency

We should also measure axial ratio of individual array elements and the full array when prototyped. Qualcomm has offered facilities to be used for these measurements to aid our design. The extra power in the solar generator array will be used to power TSFR modules we are hoping to use to expedite the launch.

TSFR = This Space For Rent, somebody else's experiment in exchange for services.

Our final conversation regarded assignment of future action items and commitment dates.

Action Items

1. Link budget spreadsheet finalization and publish. (Link below for review and critique)
2. Publish decisions. (This report)
3. Revise FRD. (WB4GCS)
4. Simulate phased arrays, build and measure patches. We should also measure axial ratio of patch antennas when prototyped. Qualcomm has offered use of their measurement facilities. (K3IO, N4HY)
5. S1 uplink noise analysis and interference to 802.11. (K3IO)
6. Investigate regulatory issues on S2 uplink/downlink. (VK4/W3GEY)
7. Investigate feasibility of wide/dual band feeds with W1GHZ (K3IO, N4HY, in process, W1GHZ has agreed to do the work)
8. Further investigation of phase shifters and A/D converters for phased arrays.
9. Look at hard limiting C-band devices. (Marc Franco to be asked)
10. Investigate injection orbit, final orbit and pointing sensitivity (N4HY)
11. Design the signals. (N4HY, N2MJI, KA9Q, K7GNU)
12. Detailed uplink link budget and user ground station design for "handheld" Class 1 service on U/V. Find team to define Class 1 signals and design ground segment hardware. AB2KT will do Class 1 signaling. KD6OZH in charge of RX. TX team TBD.
13. Decompose and assign phased array development tasking.
14. Decompose and assign digital "package" tasking.

As stated at the outset, this was a wide-ranging meeting. We made great progress in defining the digital payload, and in supporting the analog payload. More is to be done, but we are clearly heading toward a design.

The Eagle team thanks Franklin, Phil, and Qualcomm for their support and hospitality.