

Aeneas Mission Overview Lessons Learned

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Aeneas NanoSat mission

1 Satellite Evaluation

Difficulty

- Deploy solar panels
- Deploy dish antenna
- Broadcast Health & Status Beacon
- Recharge Batteries using Sun
- Establish Command Link
- Establish and Maintain Ground Link
- Track a point on Earth's surface

Accomplished

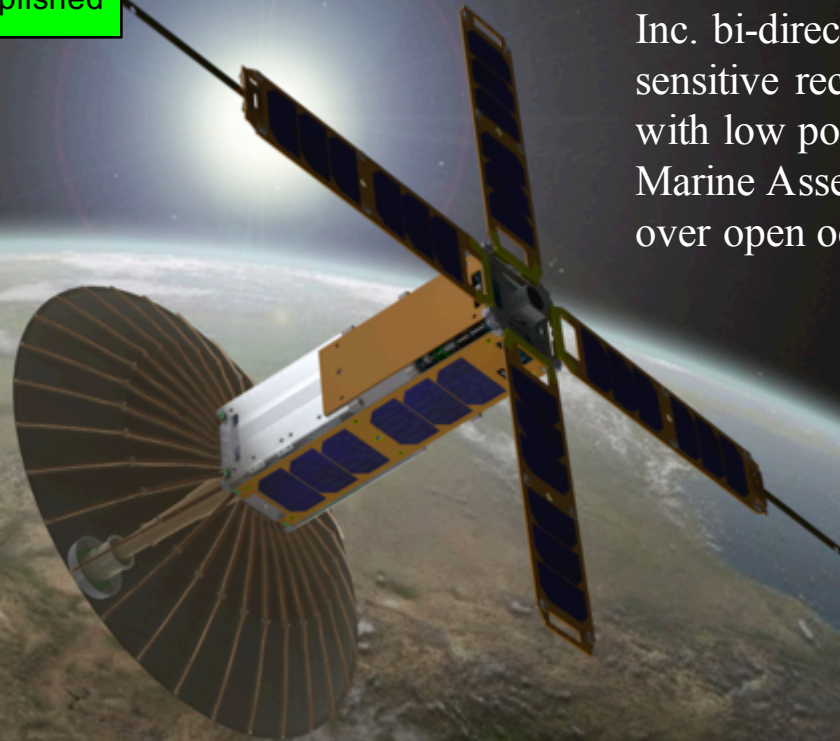
2 Primary Mission

Difficulty

- Schedule a tracking location and time
- Communicate with a large ground asset
- Communicate with a small ground asset
- Relay information between assets
- Track a moving ground asset
- Find an unknown ground asset

Atlas V launch on 9/13/2012 into a 470km – 780km, 64 degree orbit

- Space implementation of iControl Inc. bi-directional 2.4GHz ultra sensitive receiver to communicate with low power, small, earth based Marine Asset Tag Tracking System over open ocean or cross country



World's largest deployable from a NanoSat and first attempt at ground point tracking

L-36 P-POD locations and CubeSat manifest

- P-POD locations and CubeSat manifest on launch vehicle

P-POD	Total P-POD Mass (kg)	CubeSat Name	Organization	Size
1	6.750	SMDC-ONE B	SMDC	3U
2	6.575	Aerocube	Aerospace Corporation	3 x 1U
3	6.335	Aeneas	USC/ISI	3U
4	6.200	CSSWE	University of Colorado	3U
5	6.415	CP5	Cal Poly	1U
		CXBN	Morehead State University	2U
6	5.675	CINEMA	UC Berkeley	3U
7	6.175	Re	LLNL	3U
8	6.175	SMDC-ONE A	SMDC	3U



Mission Visibility

Generated Interest in SERC

- Largest Deployable from Cubesat
 - JPL evaluation for inter-planetary Ka band, Nanosat Yagi for Navy
- System/Bus/CubeSat knowledge and operational flight software and ground station experience
 - Northrop, Boeing
- 23 months on orbit - operational
- First Government Agency CubeSat Rideshare
- Manifest slots into 2014
- Government support services training
- DARPA Phoenix program - Maestro Flight experiment – ATK, Novawurks
- Next Generation Space Processor - Honeywell



KE6YFA

Launch and Orbit

Rocket: Atlas 5
 Payload: NROL-36
 Date: September 13th, 2012
 Period: 13:45 - 16:15 PDT
 Site: Vandenberg AFB, CA
 Altitude: 440 - 880 km

Physical

Configuration: Colony I with Deployables
 Size and Mass: 3U, 30 by 10 by 10 cm | 4 kg

Amateur Radio Beacon

Output Power: 1 Watt
 Antenna: Monopole Whip

Power System

Solar Array: 20 Watt
 Storage: Li-Poly 3.75 Ah

First Reported Contact

Date: _____ Time: _____ Station: _____

Modulation: AFSK 1200 Baud
Frequency: 437.6 MHz
Bandwidth: 20 kHz
Format: AX.25

Email All Contacts To:
aeneas@astronautics.usc.edu

Mission QSL card for amateur radio decodes

Significant mission brings interest

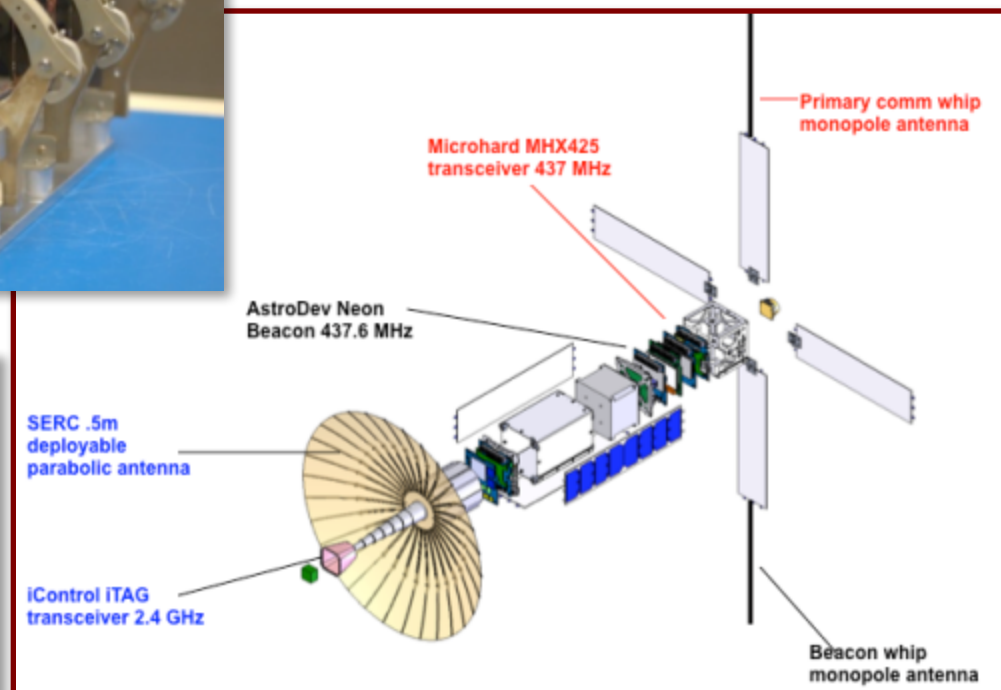
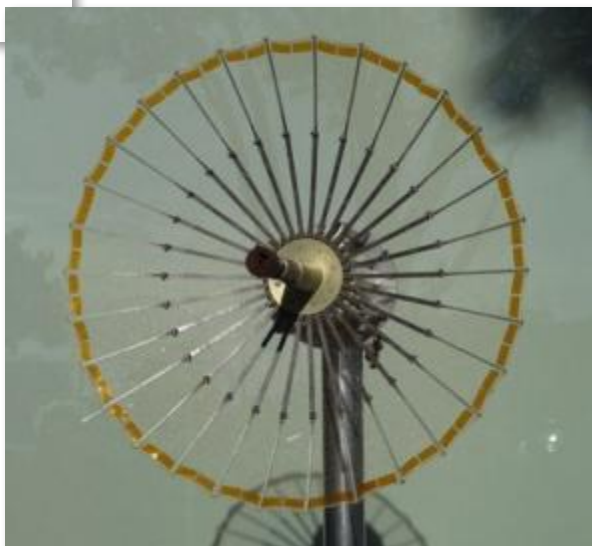
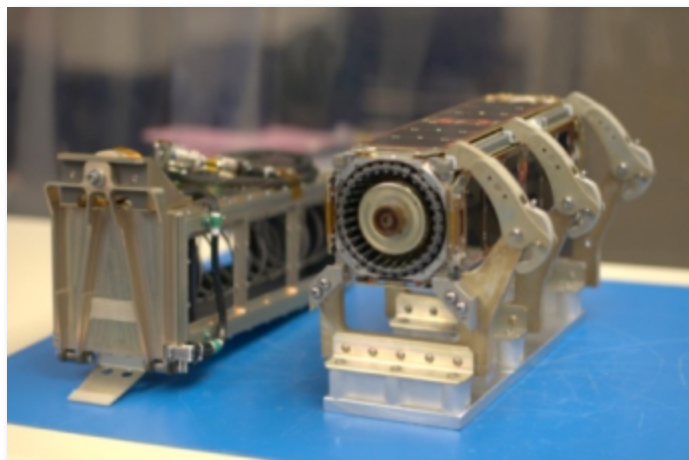
Space Engineering Research Center

Missions to orbit

2 in 3 years, 3 in 5, 4 in 6

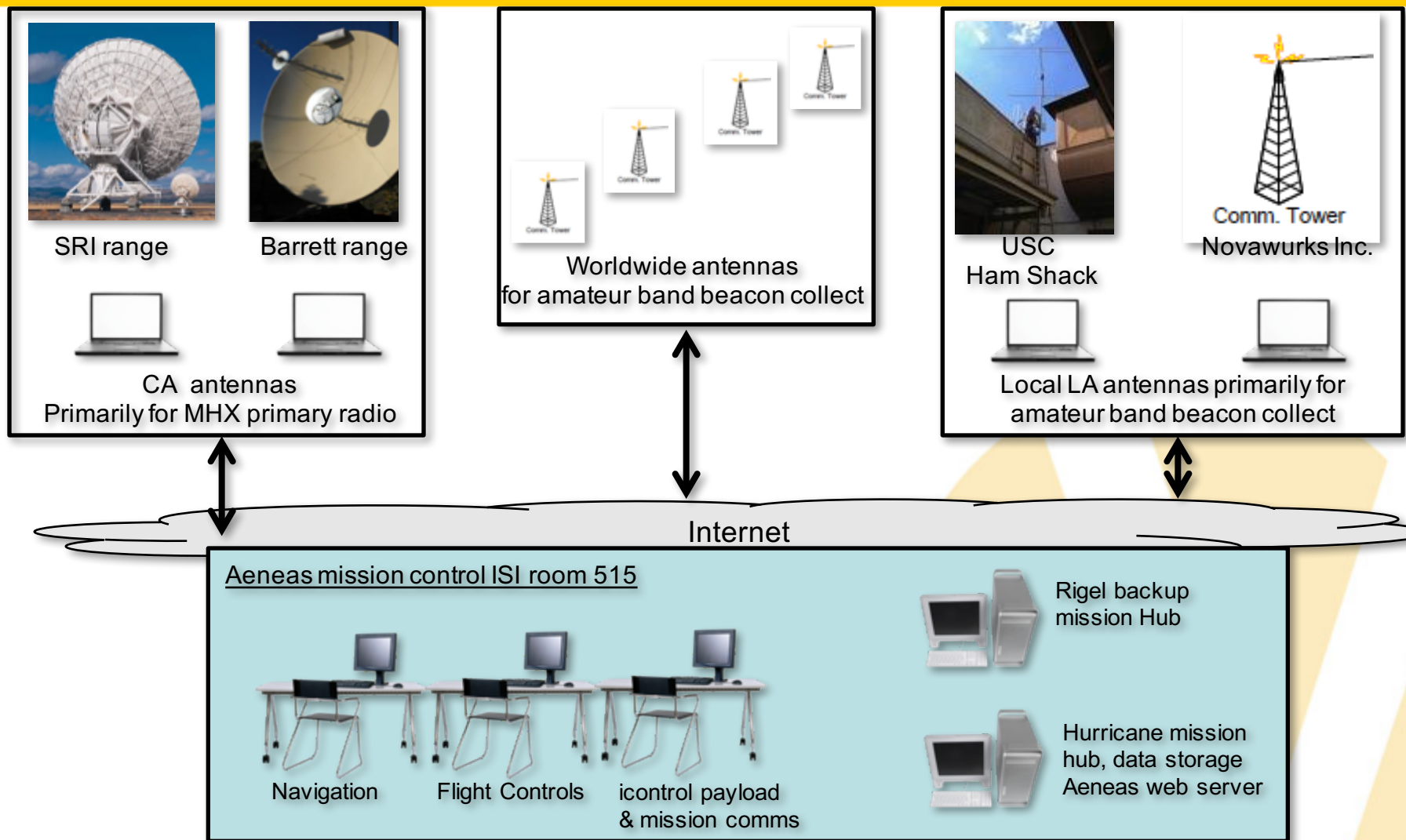
- **Effort – vehicles in space in as many years**
 - A few staff with a bunch of students worked very hard over 8 years
 - Funded by congressional money and some internal ISI funds
 - Designed and executed operational space-like and space vehicles
- **Culmination**
 - Aeneas - on orbit 23 months, still operational
 - Caerus Mayflower mission, Advanced Concepts Northrop-Grumman
 - Ground infrastructure for satellite tracking and operations
 - ½ meter deployable
 - Generating a lot of interest both government and private industry
- **Lessons learned**
 - Design, Testing, Verification and Instrumentation
 - Mission Operations
 - Champion buys Time and Funding

3U CubeSat design: 0.5 meter parabolic antenna; solar arrays; communication antennas deployed



World's largest deployable antenna from a CubeSat, invented in SERC

Spacecraft Control/Data Processing Ground Setup

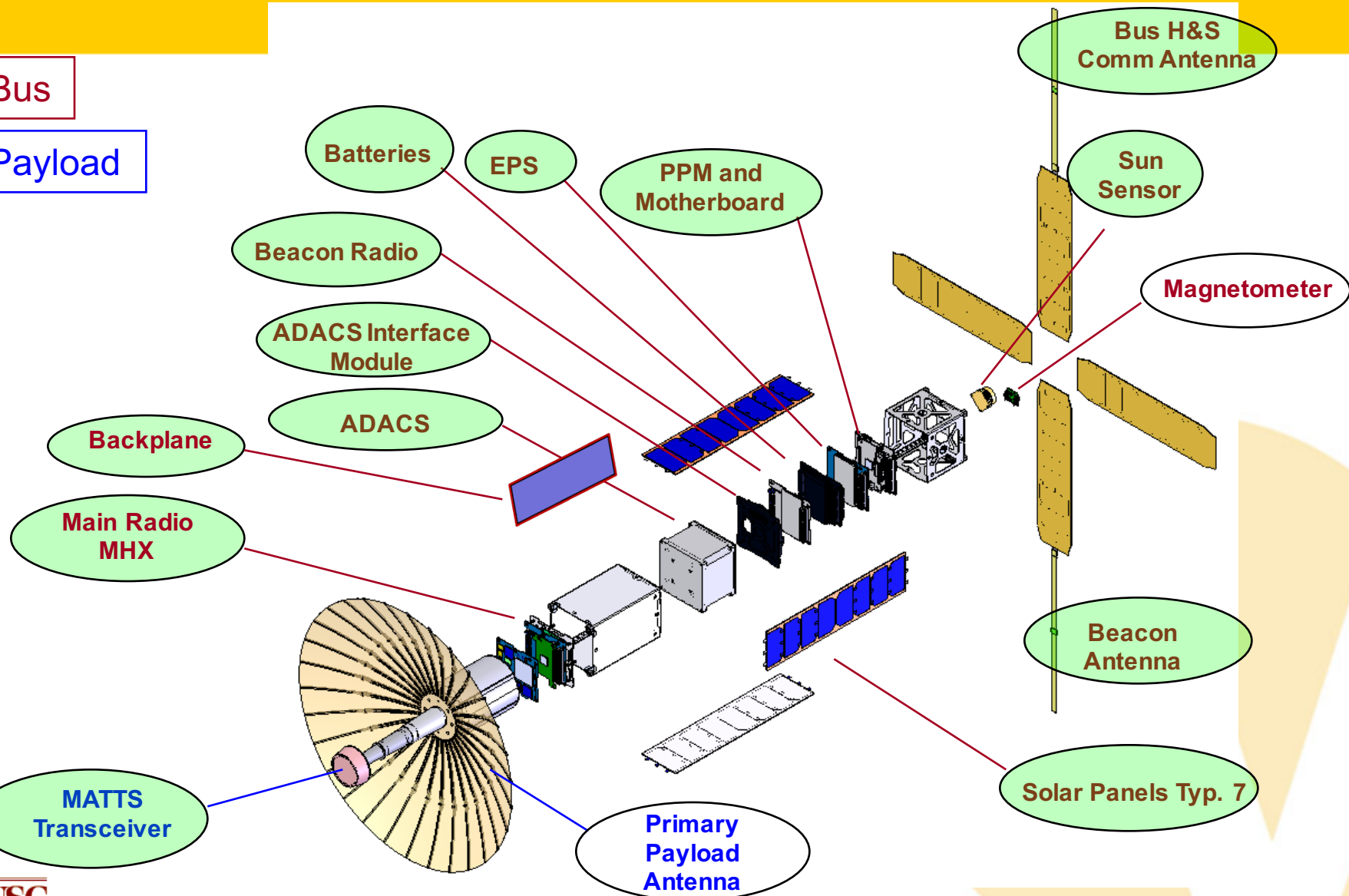


Significant Effort – Remote Command Queue & Data repository

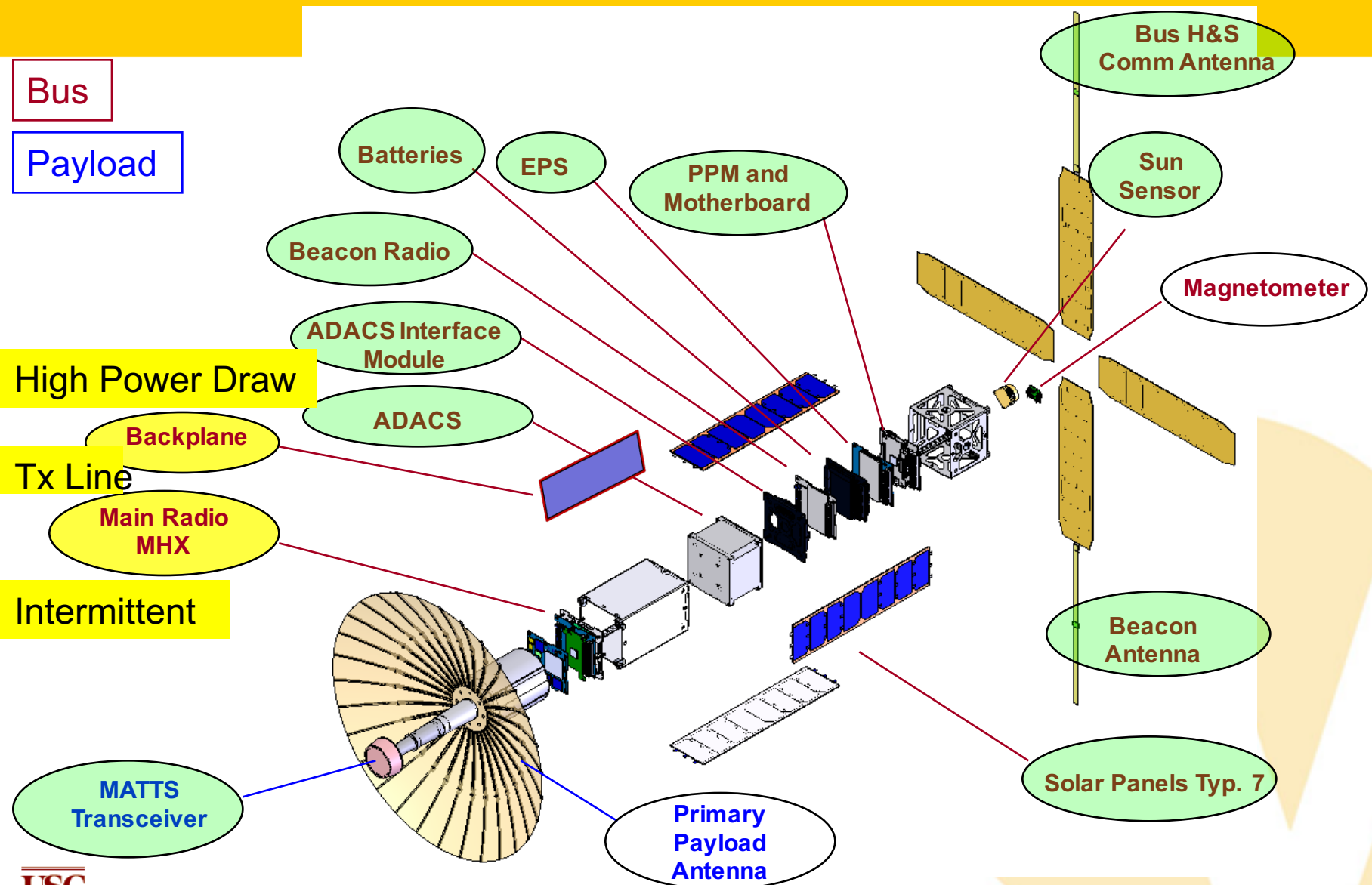
Initial Operational Status - Expanded View of AENEAS

Bus

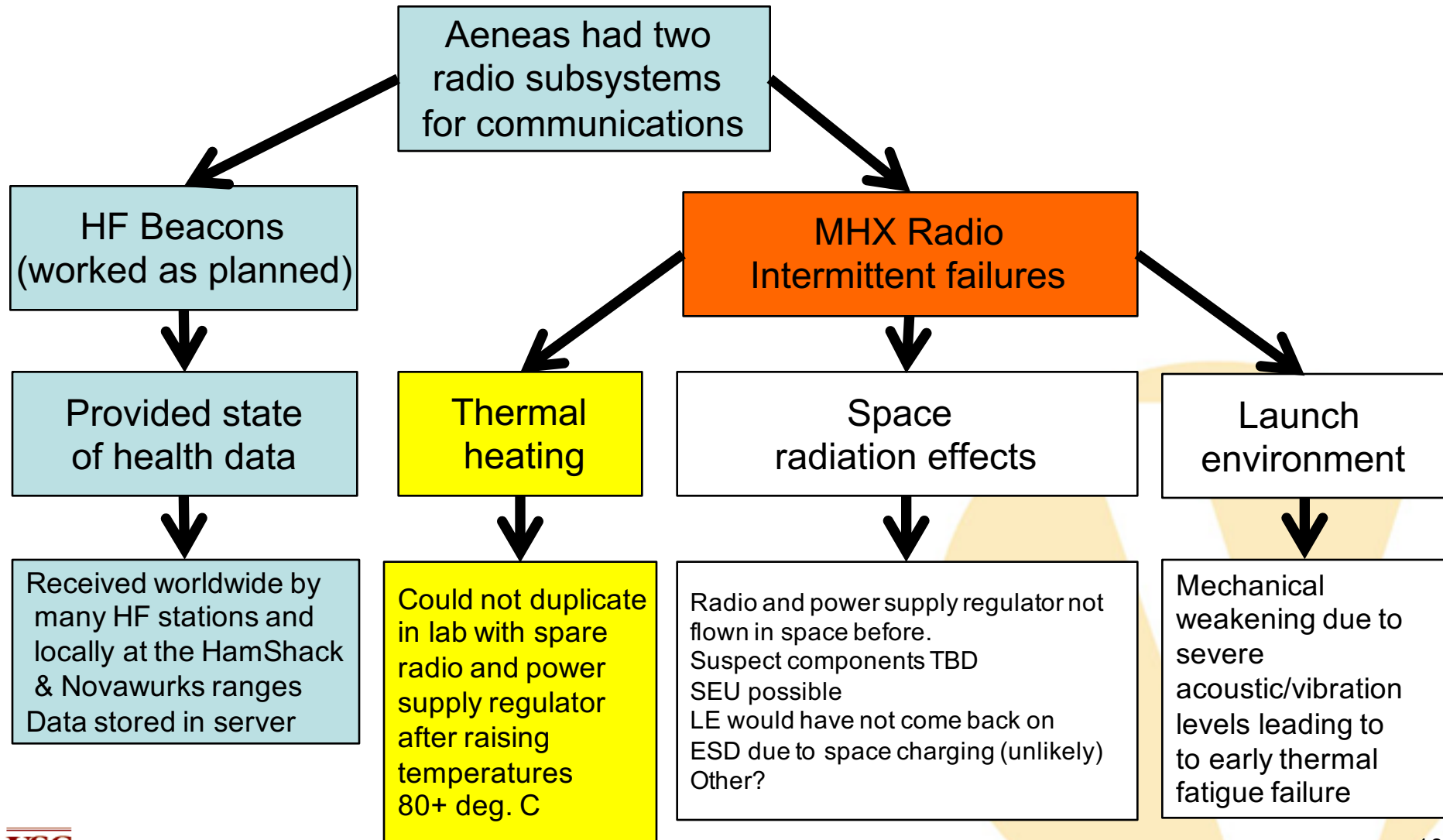
Payload



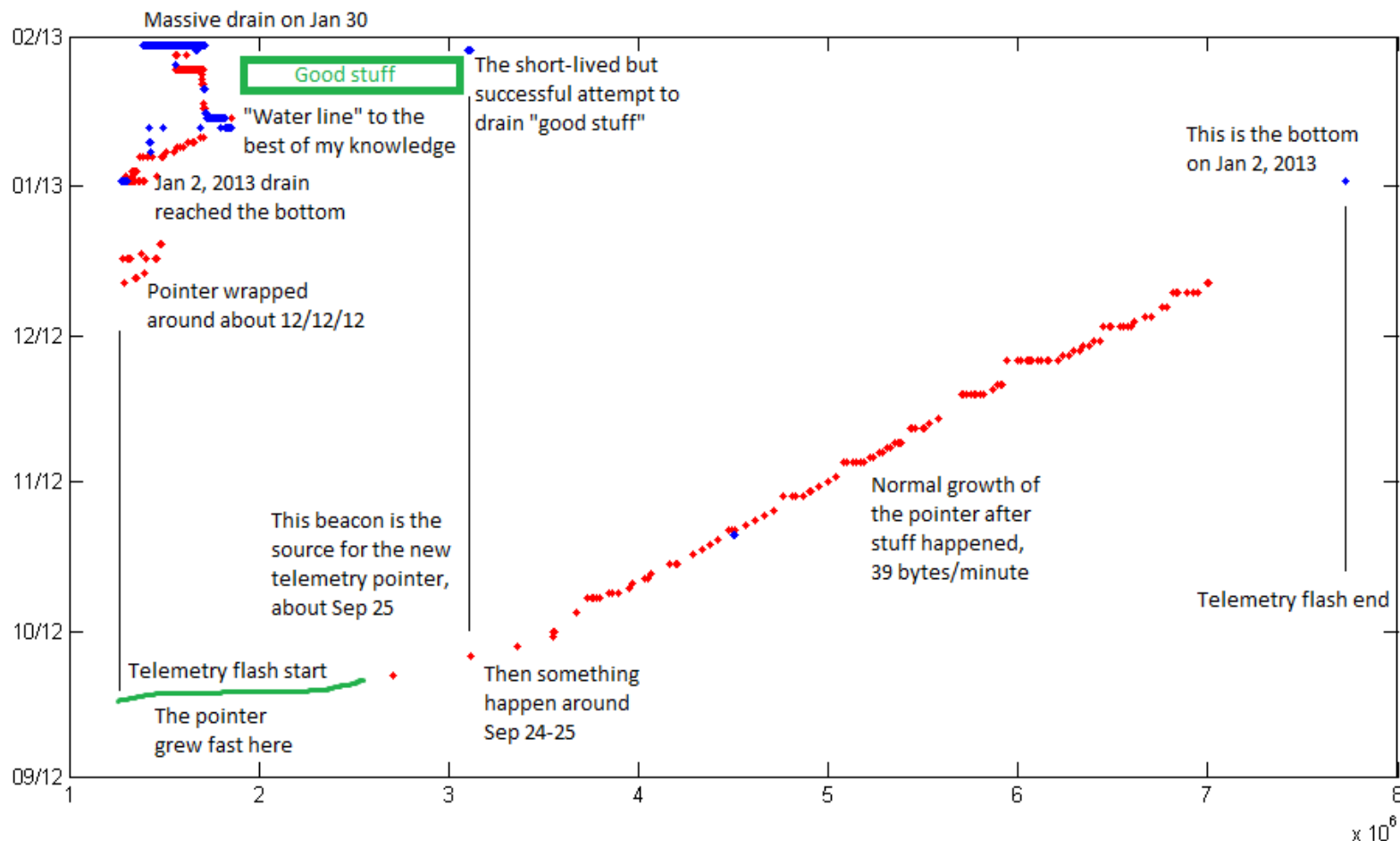
Current Operational Status - Expanded View of AENEAS



Satellite Communication Subsystem Degradation



Telemetry Data in Flash

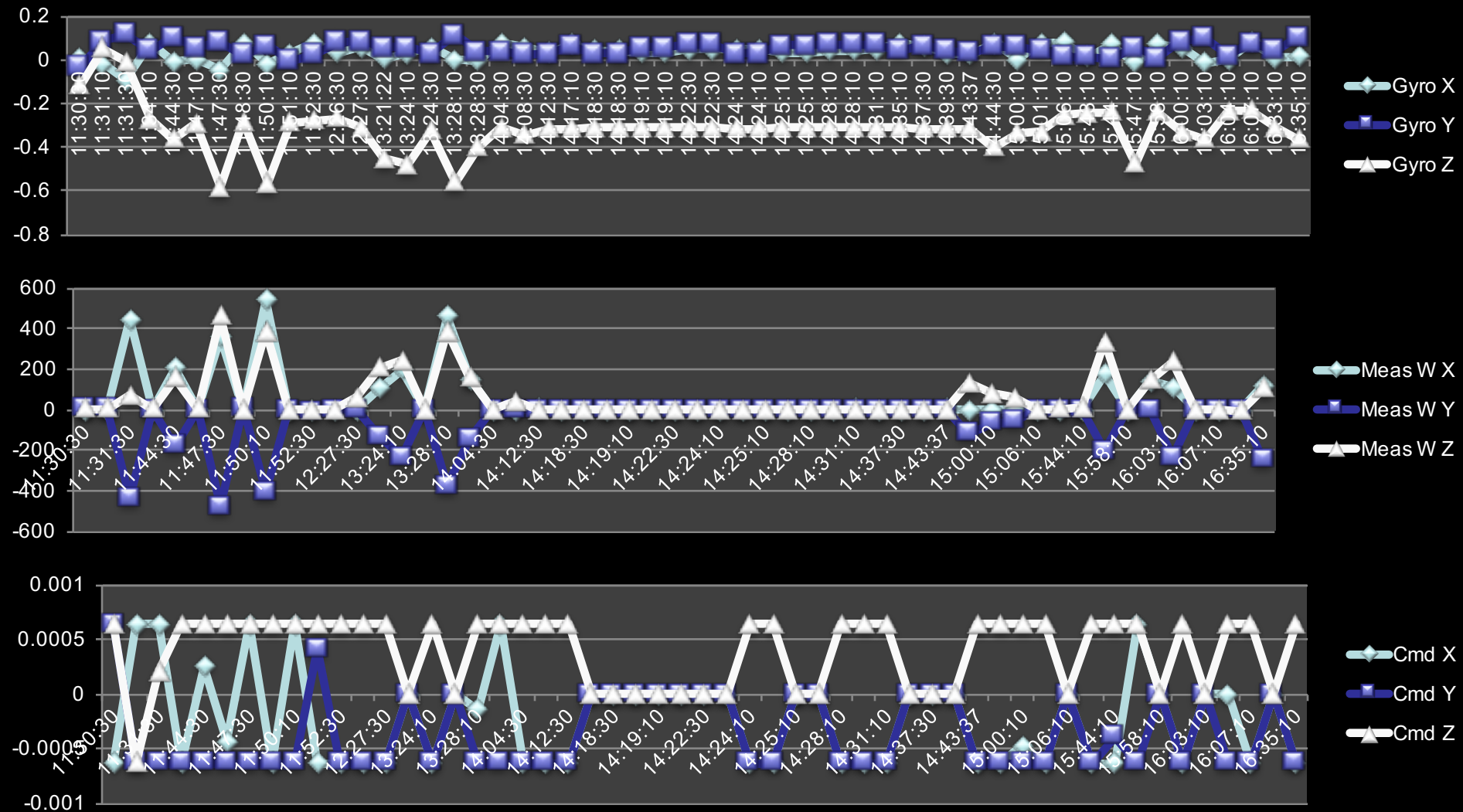


Lower Processor ok until Sept 24-25, then no Inter-processor Tx, Rx ok

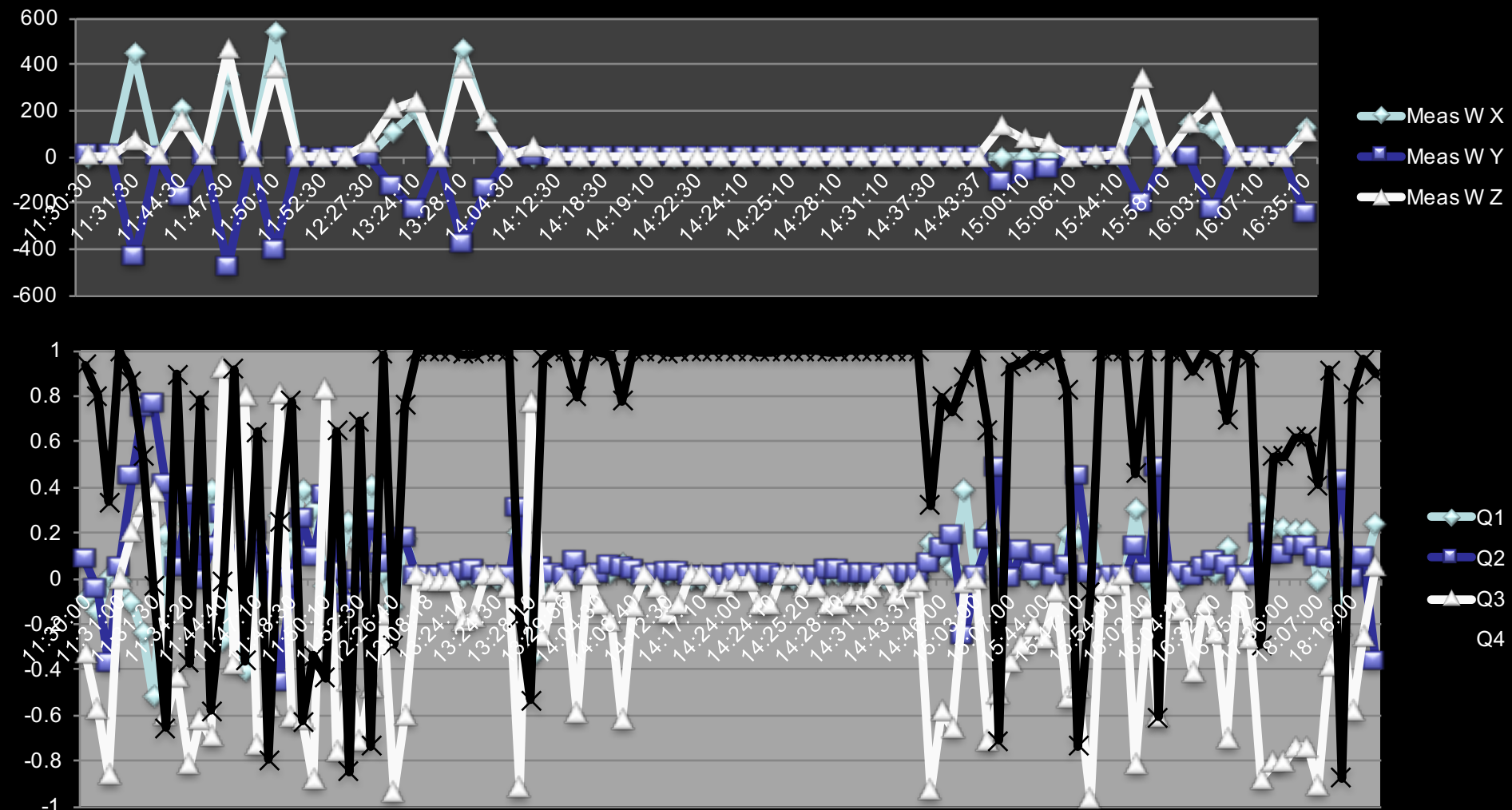
Data Reduction

- 4 Main Telemetry types
 - 61& 62 flight controls, time and time, ephemeris
 - 63 power, time temperature, lower reboots and reboot type
 - 64 upper processor, time, upper reboots, reboot type
 - To ground via main radio and beacon
 - *beacon path stuck at type 64, minimal actionable data*
- Flash filling ~600 bytes/min between wheels off and Sept 25
 - Sept is the cache of full on telemetry to mine
 - Past that slow type 64 growth until Feb 7th ? 2013 shut off beacon to flash
 - Wrapped around flash during first main radio quiet time
- Tatiana's story pins down the rough dates of collect
 - Find it again for the timeline that I'm constructing

Flight Software, Controls



Flight Software Error Quaternions



Power, flight software modes, temperature, sun sensor

- **Power**

- BCRs 1-4 (high power) all operational
 - *at least 4 of 7 panels good*
- BCR 5 (low power) not utilized
 - *Z panels removed and USB not connected*

- **Sun Sensor**

- Detected sun on two time stamps

- **Mode controller**

- Moved from idle to sun search mode

- **Temperature**

- 28-35 deg C, and two inverted sensor mechanisms, but all track
- Reportedly not reliable per Clydespace
- ISI mounted RTDs were not instrumented in fsw

All subsystems were OK, Only the Magnetometer is not directly reportable

Communications Results

107 connects of 290 attempts

Satellite Radios

- Beacons – Stensat Radio Beacon, 1 watt, 20 second intervals, omni whip
 - >47, 848 frames world wide
 - Continuing SOH and signal strength monitoring
- Main Radio – Microhard MHX, 1 Watt, Spread Spectrum, freq Hop, omni whip
 - ½ Megabyte of telemetry data, much was duplicating Beacon data
 - Dozen Command types up
 - wheels off, beacon frequency, move telemetry pointer
 - iTag configuration, execute operational macros
- Itag Payload Radio – 1 watt 2.4 GHz in the 0.5 meter dish

Ground Stations

- Barrett Range, Playa Del Rey, 10 Foot dish 4 turn helix and Auxiliary Beacon
- USC Ham shack, ACB building, 18 foot cross polarized yagi
- Novawurks, Los Alamitos, 18 foot cross polarized yagi
- Stanford Research Inc, (SRI) San Jose, 60 foot dish with cross polarized elements and 100 foot cable.

>47848 Beacon Frames, ½ Megabyte of TT&C data

Ground Station Upgrades

- **Main Helix**
 - 1, 2, 4 turns Z rot. gain within 3 dB
 - Main radio on feed, 1.5 dB 100km
 - Copper shield around radio
 - Tuned with Smith chart Analyzer
 - Cal at 100 feet & Malibu 21 dB
- **Aux 4 turn**
 - Continuous beacon monitoring
 - Main radio measures main feed
- **WiFi**
 - Mounted to Az/EI dish
 - Operated for a time at feed point
- **Az-EI mount**
 - Align with sun, north star
 - Pinned for slippage



Pass Log Spreadsheet

Aeneas Mission Summary
Barrett Range & SRI & Anecdotes from USC, International

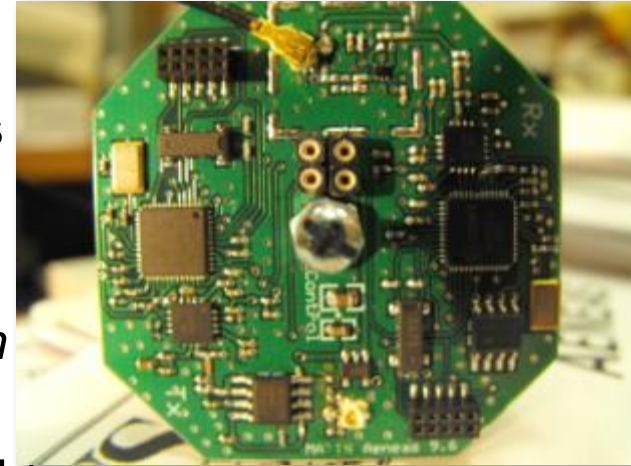
Date	Time	Begin Az	Max El	Alt km	Range km	TLExt	Main Radio MHX	MHX ATS	MHX Connects	Data	MHX Lights	RSSI dbm	Noise Floor dbm	Beacon dbm	Beacon hole	iGate, pwr	Notes	
1-Feb	13:53	200	75	753	794	13032?	Cu on Feed	19	Yes	15 Misc	1.5	-98	-110		yes	no	39	No Beacons under 1300km, CAERUSAMS, CMD set TLM Pointer, 15 iTag packets
31-Jan	23:45	322	89	?	?	13031?	Cu on Feed	19	Yes	100K	1	-100	-110		yes	no	38	MHX 66 to 75, rising, nothing on down side, iTag mics 1 min, 11 hrs, 1 hr
30-Jan	23:26	47	41	688	991	13029	Cu on Feed	19	Yes	3,500	1.5	-99	-109		yes	no	37	1 min connect, 447 tlm 11 misc packets, no iTag
30-Jan	14:52	296	63	756	861	13029	Cu on Feed	19	Yes	10,295	0.5	-102	-111		yes	no	36	5 min beacon stop, tlm 23445-23801 02 958 (855 pkts) +7 itags, cmd Q reset pointer
30-Jan	0:46	231	43	680?	900?	13029	Cu on Feed	19	Yes	371,000	1.5	-98	-110		yes	no	35	3 min connect time, tlm 16068-23359->7291 beacons + 60 iTag packets - Record! All commands up? Kill a beacon?
29-Jan	14:30	90	60	750	850?	13029	Cu on Feed	19	Yes	3859	1.5	-97	-111	-99	yes	no	34	Copper bag MHX on Feedpiece, bknd tests, electric saws running & not iGate & not Bookend 1-29 0812 gate, 1-18tag old, cmd Qset telem ptr upper globals, Wheels start, stop after hard reset., 61,62,63
29-Jan	0:26	90	62	650?	750	13028	Cu Screen Bx	19	Yes	60KB	1.5	-99	-109	-99	yes	yes	33	Bookend 1-27 2008 gate, 1-18tag old
27-Jan	15:30	270	75	750?	790	?	Cu Screen Bx	19	Yes	0	1.5	-97	-109		yes	yes	32	Bookend 1-26 0805 gate, 1-18 tag old, Realterm and audacity fight for time on laptop, kill sound cap, 1 min connect time, tlm #15368-15585 (15591-15586 is dupbeacons (nc doesn't terminate cleanly)
26-Jan	1:06	90	65	680	800	?	Cu Screen Bx	19	Yes	8711	0.5	-99	-110		yes	yes	31	Bookend 1-24 2007, pass, Bknd on Realterm
24-Jan	16:12	270	85	750?	760?	13024	Cu Screen Bx	19	Yes	16K	1.5	-97	-110		yes	yes	30	Argon & 1-24-13 pass
24-Jan	2:06	270	65	686	843	13023	Screen Box	19	Yes	0	1.5	-99	-109	S=2	yes	?	29	No bookend, No data or commands, 1 min in range, Rainy Fade, spec A and recorded beacons Audacity
21-Jan	16:52	270	85	750?	760?	13021	Screen Box	19	Yes	850	1.5	-99	-110		yes	?	28	No bookend, 10501-10530, 54-83 degrees in beam, then Hopelessly lost in Pierouette
21-Jan	2:46	270	72	750?	800?	13019	Screen Box	19	Yes	0	?	-99	-110	-109	yes	?	27	No bookend, but WiFi emitting, No dBase connect, Binary backup is 2012-1-20-433 on Dell (yesterdays date)
20-Jan	18:17	270	26	757	1400	13019	Screen Box	19	No	0		-110	-109	-109	no	?		No bookend
19-Jan	17:52	270	57	757	883	?	Screen Box	19	No	0		-108	-108	-108	no	yes		No bookend, 2 decoded beacons on alt helix
18-Jan	17:34	90	71	740?	?	13018	Screen Box	19	No	0		-109	-108	-108	no	yes		No bookend, no blinks, B team TLE?
18-Jan	3:26	90	85	750?	760?	13014	Screen Box	19	Yes	0	1.5	-99	-109		yes	yes	26	Bookend 2013-1-18 11:2233-49, pass, 12:1646, Q has save upper globals, wheels on, no restart on hard kill, tlm 61,62,63 No Hurricane Connect & BLUE SCREEN, HAND OP DISH
16-Jan	18:36	270	68	754	807	13014	Screen Box	19	Yes	2.5KB	1.5	-97		-102	yes	no	25	Q has wheels on, no restart on hard kill, connect over 60 seconds, telem #10258-10348
15-Jan	4:06	109	63	682	703	13014	Screen Box	19	Yes	72KB	1.5	-97		-103	yes, 5/min	yes	24	Bookend 2013-1-15 11:51-50 dbm, pass, 12:27-48 dbm, Two commands up, debug lower, ask telem 60, connect over 60 seconds, telem #7177-9758
13-Jan	19:13	270	67	746	790	13012	Screen Box	19	Yes	35KB	1.5	-97		-102	yes	yes	23	Bookend 2013-1-14 300-49dbm, pass, 0347-50 dbm, Two commands up (kill a beacon, ask tlm), connect over 13 seconds, telem #5989-7175

Per pass logging aided analysis,
Dish pointing, Feed positioning, Cable lengths, Data collects,
Beacon and TT&C radio signal strength, antenna deployment

Payload Results

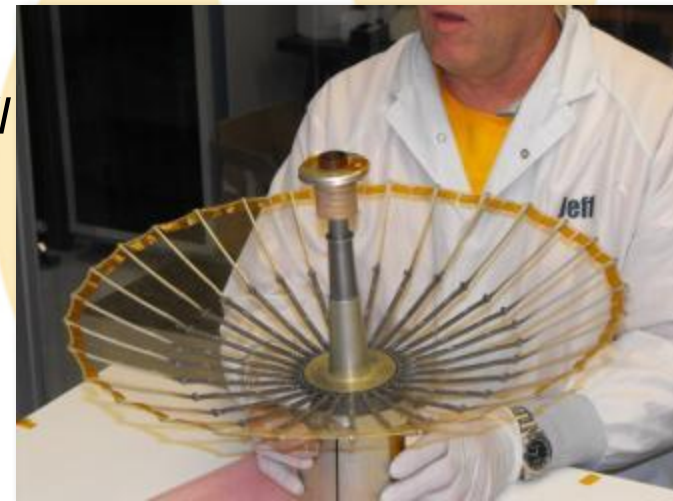
- iTag Wifi Transceiver

- Telemetry shows it has been alive for months straight, without resets
- Commanded it to go CW mode for 8 minutes
 - *Digital control responses indicated it was on for that time*
- Commanded it to stream data to iGate (1/2link)
 - *No reception on ground*
- Commanded to send back its configuration and parameters
 - *Digital control responses indicated it is still setup appropriately*



- Main Dish Deployment

- Working the issue



At least two WLAN LQI Hits during AOS

Payload Results

- Mysql search of 28652 records shows handful of Non-Zero LQI, at least two observations during AOS

Asset	Server Time	Source Time	Count	iGate	Commissioned	State	ADC 0	ADC 1	ADC 2	ADC 3	ADC 4	ADC 5
Lebanon 60	2014-07-01 03:30:47	2014-07-01 03:21:00	203	88	Commissioned	Stored_Data Awake Associated In_Range	13.172275869	0.229372989	0.229774693			
USC 61	2014-07-01 03:30:34	2014-07-01 03:20:59	202	88	Commissioned	Stored_Data Awake Associated In_Range	13.172275869	0.228971285	0.229774693			
iControl 62	2014-07-01 03:30:21	2014-07-01 03:20:58	201	88	Commissioned	Stored_Data Awake Associated In_Range	13.172275869	0.229372989	0.229774693			
iGATE 88	2014-07-01 03:30:08	2014-07-01 03:20:57	200	88	Commissioned	Stored_Data Awake Associated In_Range	13.172275869	0.229372989	0.229774693			
Flight Tag 6	2014-07-01 03:29:55	2014-07-01 03:20:56	199	88	Commissioned	Stored_Data Awake Associated In_Range	13.172275869	0.229372989	0.229774693			
Spare 7	2014-07-01 03:29:42	2014-07-01 03:20:55	198	88	Commissioned	Stored_Data Awake Associated In_Range	13.172275869	0.229372989	0.229774693			
Spare 8	2014-07-01 03:29:29	2014-07-01 03:20:54	197	88	Commissioned	Stored_Data Awake Associated In_Range	13.172275869	0.229372989	0.229774693			
Spare 9	2014-07-01 03:29:16	2014-07-01 03:20:53	196	88	Commissioned	Stored_Data Awake Associated In_Range	13.172275869	0.228971285	0.229774693			
	2014-07-01 03:29:03	2014-07-01 03:20:52	195	88	Commissioned	Stored_Data Awake Associated In_Range	13.172275869	0.229774693	0.228971285			
	2014-07-01 03:28:50	2014-07-01 03:20:51	194	88	Commissioned	Stored_Data Awake Associated In_Range	13.172275869	0.228971285	0.229774693			

Asset	Server Time	Source Time	WLAN LQI	WLAN Channel	Beacon (sec)	Server (sec)	Reboot Counter	ACL (#)	ACL Delta (#)
Lebanon 60	2014-07-05 01:24:15	2014-07-05 01:24:24	0	15	31	0	15	0	0
USC 61	2014-07-05 01:23:15	2014-07-05 01:23:24	0	15	31	135	15	0	0
iControl 62	2014-07-05 01:22:15	2014-07-05 01:22:24	0	15	31	136	15	0	0
iGATE 88	2014-07-05 01:21:15	2014-07-05 01:21:24	0	15	31	135	15	0	0
Flight Tag 6	2014-07-05 01:20:15	2014-07-05 01:20:24	0	15	31	136	15	0	0
Spare 7	2014-07-05 01:19:15	2014-07-05 01:19:24	0	15	31	135	15	0	0
Spare 8	2014-07-05 01:18:15	2014-07-05 01:18:24	0	15	31	0	15	0	0
Spare 9	2014-07-05 01:17:15	2014-07-05 01:17:24	0	15	31	136	15	0	0
	2014-07-05 01:16:15	2014-07-05 01:16:24	0	15	31	136	15	0	0
	2014-07-05 01:15:16	2014-07-05 01:15:24	0	15	31	135	15	0	0

```
mysql> select * from Data_14_0_0_88_27_173_0_0_12 where Source_Time Like '2014-01-13_00:3%';
```

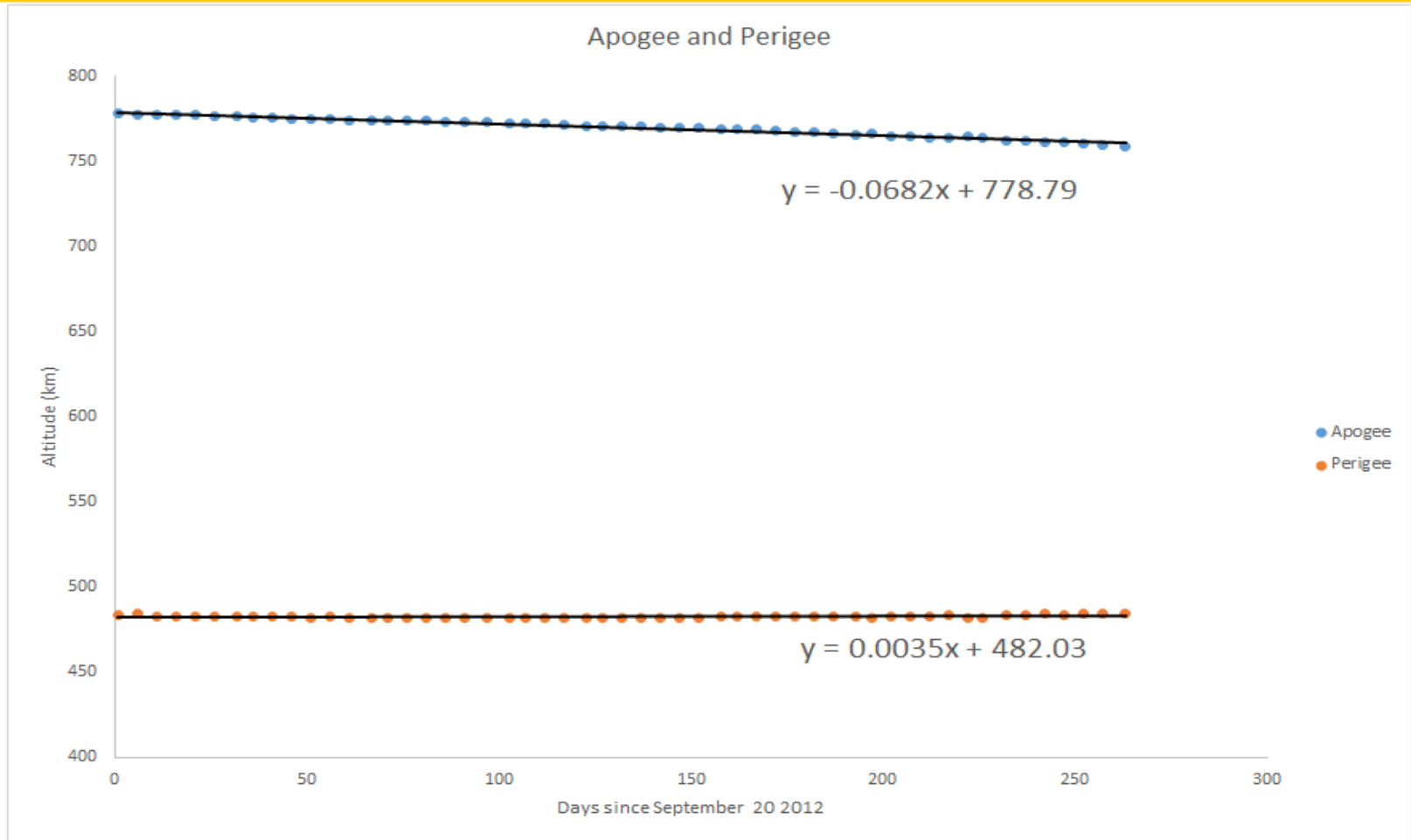
Server_Time	Source_Time	Latitude	Longitude	Altitude	ZigBee_LQI	ZigBee_Channel	Beacon_Timer	Comm_Timer	Reboot_Counter
2014-01-13 00:30:22	2014-01-13 00:30:24	0	0	0	0	15	31	136	15
2014-01-13 00:31:21	2014-01-13 00:31:24	0	0	0	0	15	31	136	15
2014-01-13 00:32:22	2014-01-13 00:32:24	0	0	0	57	15	31	135	15
2014-01-13 00:33:22	2014-01-13 00:33:24	0	0	0	0	15	31	0	15
2014-01-13 00:34:21	2014-01-13 00:34:24	0	0	0	0	15	31	136	15
2014-01-13 00:35:22	2014-01-13 00:35:24	0	0	0	0	15	31	135	15
2014-01-13 00:36:22	2014-01-13 00:36:24	0	0	0	0	15	31	136	15
2014-01-13 00:37:22	2014-01-13 00:37:24	0	0	0	0	15	31	136	15
2014-01-13 00:38:21	2014-01-13 00:38:24	0	0	0	0	15	31	136	15
2014-01-13 00:39:21	2014-01-13 00:39:24	0	0	0	0	15	31	0	15

10 rows in set (0.19 sec)

mysql>

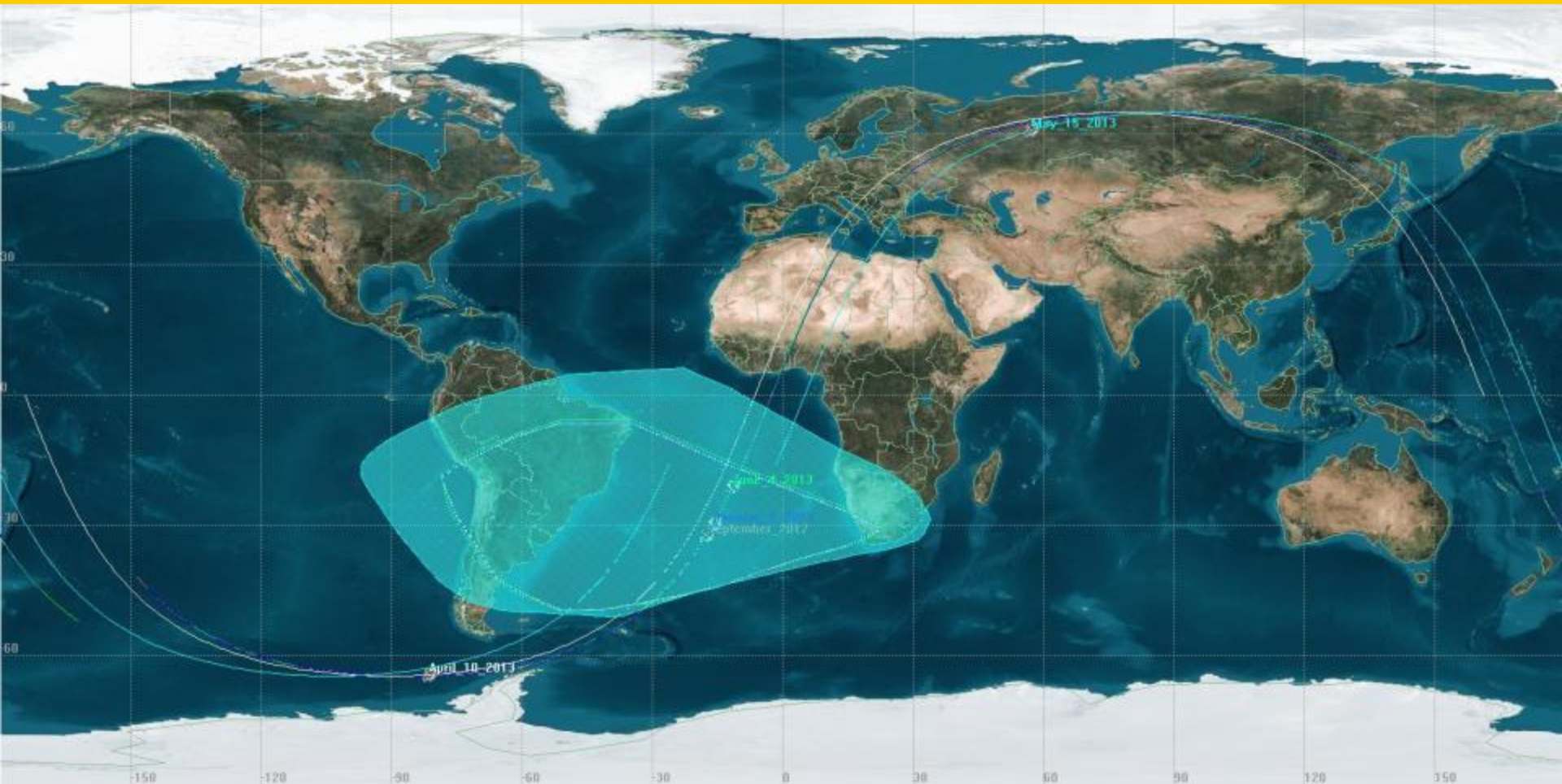
RF Activity consistent with WiFi MATTS Tag Operational

Aeneas Orbit Stability



Orbit degradation is not changing our actual location vs. TLE,
Adjusted timing of sat tracker computer/software - likely not issue

Radiation Belt Crossings



3-4 passes twice daily, 10-15 minutes per day, Flux $O > 0.5$ MeV electrons, 23-94 MeV protons 1-10K /cm² sec str, 1990-1996, 2000-2006, CEASE/TSX-5, LET vs Cross-Section curve starts at 2MeV.cm²/mg, probabilistic, must collide

We can get extra bit flips from SAA

Lessons – Design, Test, Verification

- **Design**
 - Duplicate interconnect wiring
 - *Inter-processor interconnect , one way, went bad at connector, partially cured arathane*
 - B dot controller
 - *Torque coil controller to kill tip off rates, momentum control too great for wheelbox*
- **Testing**
 - Beacon checkout
 - Inter-processor communication interconnect
 - Long range and Doppler Radio tests
- **Verification**
 - Power consumption for ‘functionally identical’ components



Lessons – Agencies, Mission Ops, Champion

- **FCC and IARU**
 - Start early and keep checking and circling back until license in hand
 - Amateur IARU coordination first before FCC, big fan of beacons
- **Mission Operations**
 - Tracking
 - *TLE versus momentarily operational vehicle*
 - *HRD sat track great but can easily stick to old TLE*
 - *Keep a dish near you*
 - Don't wait too long for a test on orbit
 - *Comms may not last forever*
- **Champion to buy Time and Funding**
 - Will buy you more test time
 - Can keep a team together for Mission Operations



Going Forward

- Monitor Aeneas from campus/Millennium Space Systems while beacon, batteries and power continue
 - 1 year inside 2 years outside
- Delivered 3 element Crossed-Dipole Yagi deployed from 10x10x8 cm
- Deliver Maestro Flight Experiment for DARPA Phoenix Program
- Build and Fly PTecSat
 - From lessons learned
 - Rev II of post shock tested antenna
- SERC is a successful concept for:
 - Developing low cost platforms for space science research
 - Evolving from designing and flying short life (< 1 year) CubeSats to long life (~ 36 months) NanoSats to meet customer mission needs
 - Educating undergraduate and graduate students in space systems engineering

Questions?

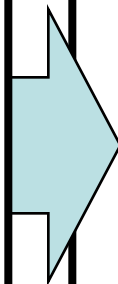
- Thanks to the Cubesat Program office for Colony I bus(es) launch opportunity and support
- Mike Obal for championing the effort to the end
- David Barnhart for providing the mission, initial inspiration and first champion
- Talbot Jaeger for Mayflower/Caerus risk reduction opportunity
- iControl for flight software, Matrix X flight simulation, gyro PPMs, itags and igates and untold extra hours
- Team Aeneas Mike Aherne, Tatiana Kichkaylo, Jeff Sachs, John Smolik, Will Bezouska, Lucy Hoag, Siamak Hesar, Alex Shim, Maria Guzman, Melissa Jawaharlal, and a dozen others that made this happen



Improvements to the baseline Pumpkin Colony I CubeSat design for the AENEAS mission

• Colony I BASELINE BUS

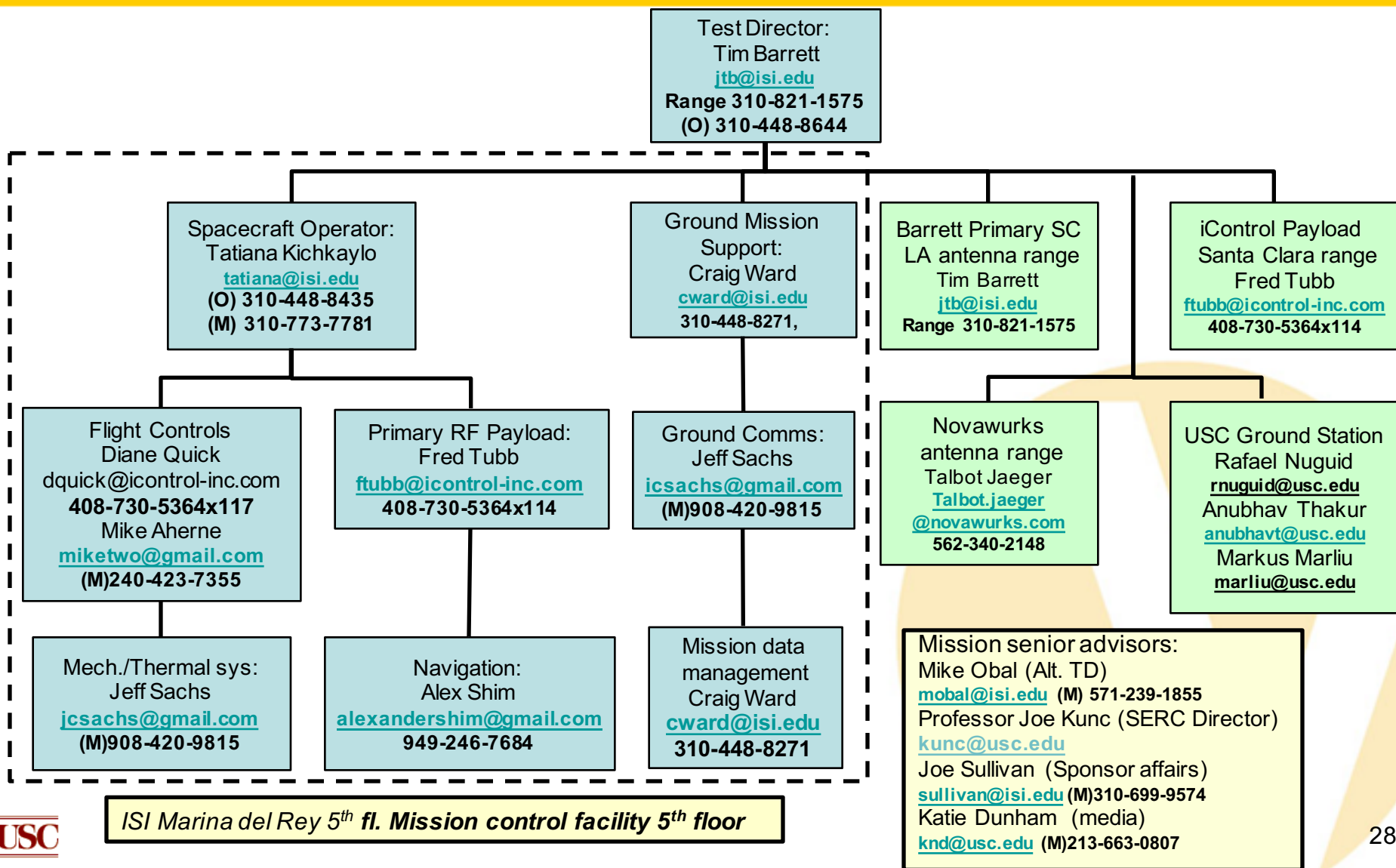
- Attitude determination
 - 3-axis magnetometer on ADACS interface module
 - Coarse sun sensing - requires panels on all 6 faces
- Power
 - Deployable solar panels
 - Fixed cells on Aft, Fwd, and 3 Sides
 - EPS with Li-Ion-Polymer batteries
- Communications
 - None
- Structures & Mechanisms
 - Payload structure plus <1U structure
- CD&H & FSW
 - 8051 Processor
 - Driver software only
- Attitude control
 - Miniature reaction wheels
 - Magnetic torque rods



• USC/ISI MODIFICATIONS

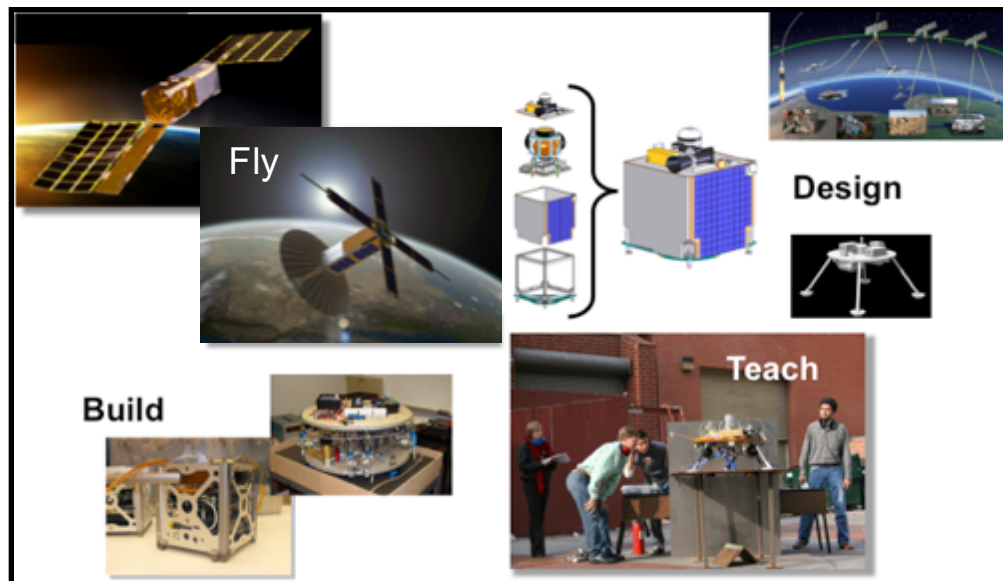
- Attitude determination
 - Relocated magnetometer – reduce field input
 - Added sun sensor – increase pointing accuracy
 - Added MEMS Gyros – increase fidelity of bus for pointing
- Power
 - Changed panel mounting (“flower petal”)
 - Removed aft cells for sun sensor
- Communications
 - 115 kbps Transceiver plus Antenna – for Bus TT&C
 - 9.6 kbps Beacon plus Antenna – for TLE
- Structures & Mechanisms
 - Added Deployment Mechanisms for Solar Panels/Antenna
 - Replaced Payload top plate
- CD&H & FSW
 - Replaced 8051 with PIC-24 Microprocessor
 - Full compliment of Flight, Mission and TT&C Software provided

Aeneas flight mission operations team organization and locations



USC/ISI SERC history of educational programs and rapid growth

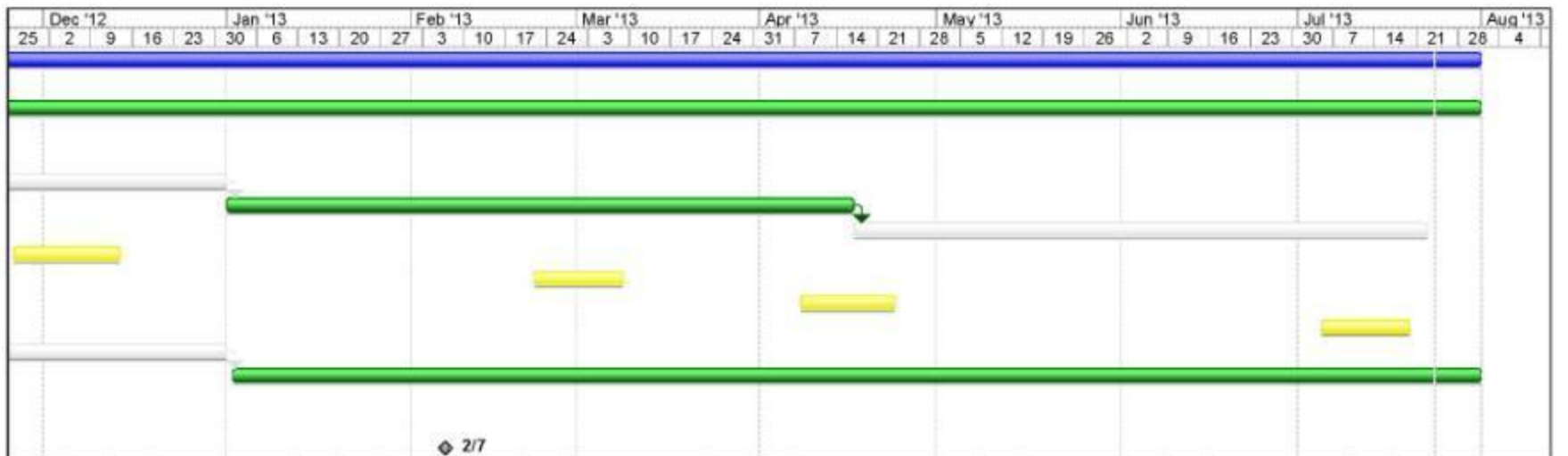
- Dr. Max Nikias, Aerospace Corp. and the USAF initiated the Microsatellite systems center at ISI in 2003 later merged with the Astro dept. into the SERC
- Since 2006 over \$3.8M in sponsorship from USC, government and industry
- ~100 undergraduate, graduate and PhD. students have been involved in all aspects
- Caerus CubeSat payload flown in 2010 and Aeneas CubeSat flown September of 2012 MaVEx manifested for Oct. 2014 launch
- Improved key subsystems to enhance the capabilities of an industry designed CubeSat
- Designed the LOC-Comm Encapsulated NanoSat (Life >24 months) that will conduct a number of advanced “Radio Science” experiments



USC/ISI is evolving from design and flying short life (< 1 year) CubeSats to long life (~ 36 months) NanoSats to meet customer mission needs

Timeline

Microsoft project to collect the arc



Much happened early on, but we may still be on a long arc