Lessons Learned from the US Air Force SENSE CubeSat Mission

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Developmental Plans and Projects
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Recap of the Space Environment NanoSat Experiment (SENSE) Program

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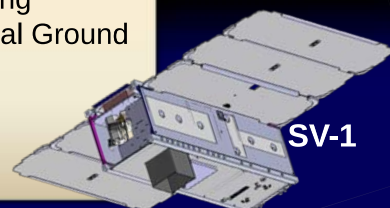
SENSE mission overview

Space, ground and data processing segments

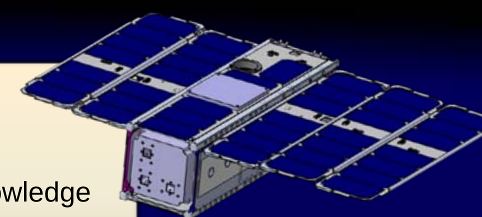
OBJECTIVE: SENSE is a space weather demonstration for evaluating the cost-effectiveness and suitability of CubeSat architectures for augmenting or performing future operational missions. Additionally, SENSE is a risk reduction pathfinder for the Common Ground Architecture (CGA) and the Global Space Telemetry Resource (GSTR) antenna suite.

SENSE Overview:
- Mission: Space Environmental Monitoring
- Architecture: Two 3U CubeSats & Global Ground Sys
- Mission Life: 13 months +
- Launch: 19 Nov 2013, ORS Enabler 3
- Orbit: 500km Alt, 40.5° Inclination



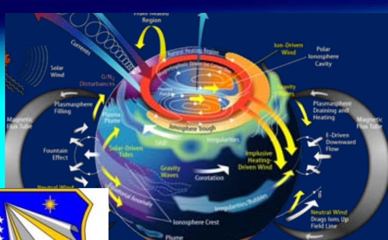
SV-1

Bus Performance:
- Mass: 4kg
- Power: 10W Avg, 37W Peak
- ADCS: <0.5° pointing, <0.3° knowledge
- Data Rate: 1Mbps down, 4kbps up
- Encryption: AES256 Type II



SV-2

GAIM Ionospheric Model



Sensors and Measurements:
1. CTECS: Electron Density (TEC), Scintillation
2. CTIP: Ionospheric Structure
3. WINCS: Temps & Composition of Ions & Neutrals
4. Dosimeter: Cumulative Radiation

Kirtland AFB, NM

Blossom Point, MD

AFSCN

Ground System:
- Sites: Manzano NM, Blossom Point MD, AFSCN
- Common Ground Architecture (CGA) multi-mission, lights-out operation
- Leave-behind asset for future missions

SENSE project objectives

- Develop rapid and affordable access to space for future operational CubeSat missions while satisfying Air Force space program requirements
  - *14 month design, develop, integrate, and test schedule*
  - *Satisfy full complement of mission assurance and regulatory requirements*
    - *Safety and security, mission assurance, spectrum allocation, launch certification*
  - *Develop processes tailored to small satellite missions*
  - *Implement low cost "lights out" satellite operations*
  - *Develop leave behind capabilities for future CubeSat ground architectures*
- Mature CubeSat Technology Readiness Levels (TRLs) and sensor components
  - *Mature bus technologies to increase reliability and duration of on orbit operations by incorporating system engineering best practices for spacecraft design, fabrication and test*
  - *Mature miniaturized sensor capability to satisfy NPOESS IORD-II requirements*
- Demonstrate CubeSat operational utility by:
  - *Utilizing validated data to improve current and future space weather models*
  - *Perform representative mission operations and data analysis to evaluate the applicability of CubeSats to perform similar space environment monitoring missions*

SENSE is an acquisition experiment as well as a technical experiment

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SENSE team and stakeholders

Development Team

Space and Missile Center

SMC/AD

SMC/RS

Air Force Research Laboratory

Stakeholders

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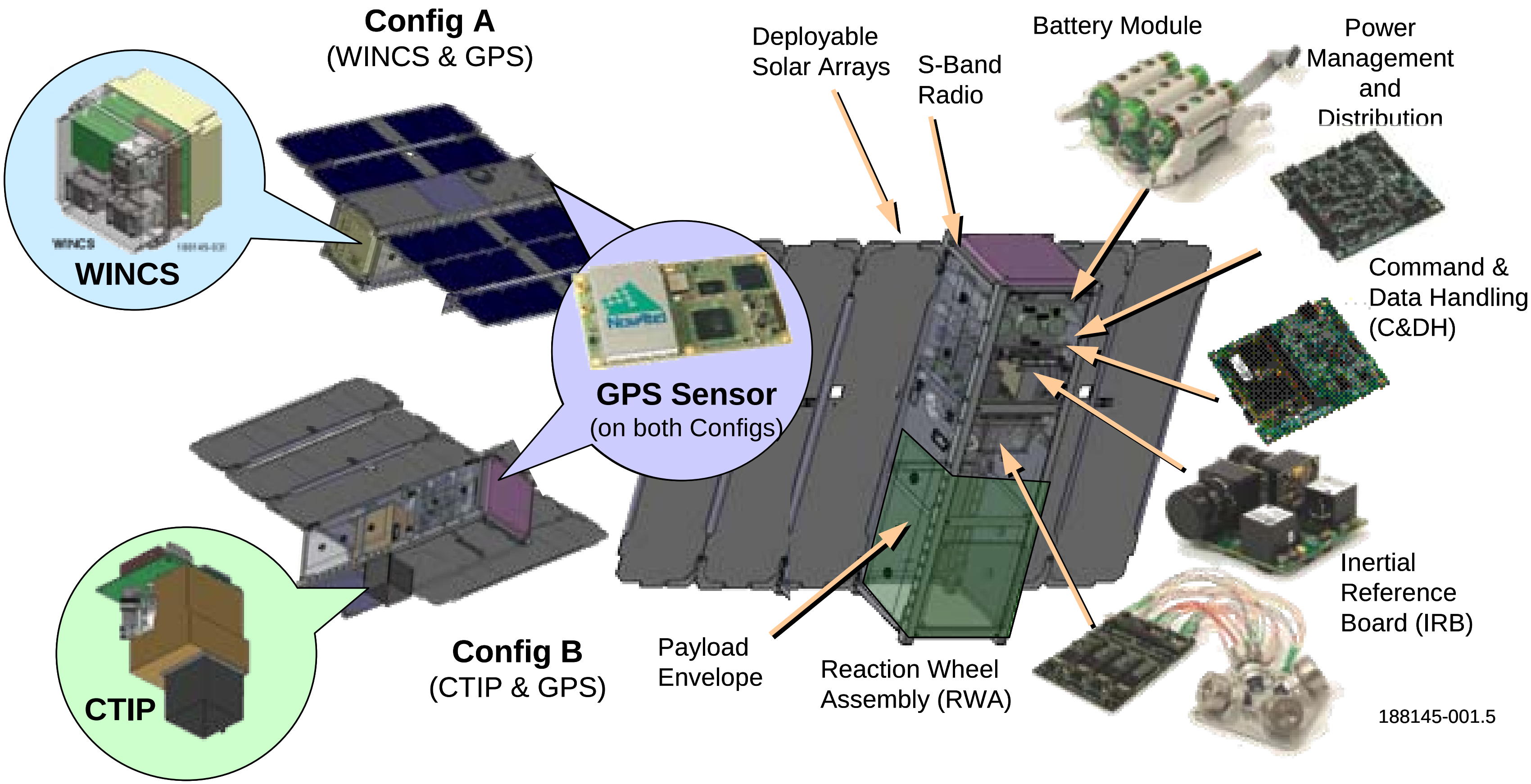
SENSE vehicles



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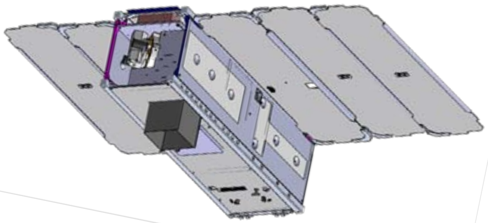
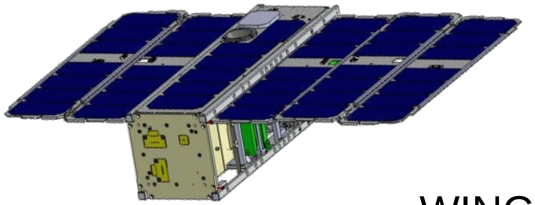
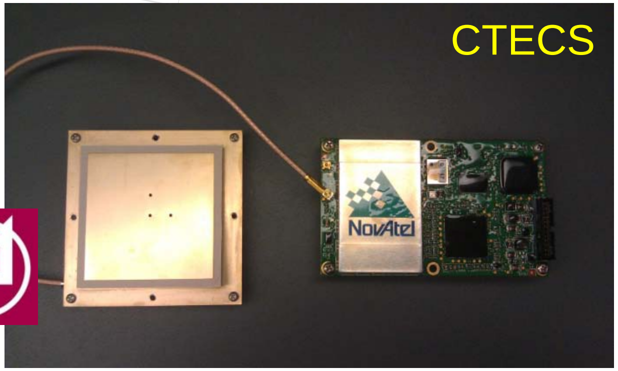
SENSE space weather sensors

SV-1: CTIP + CTECS

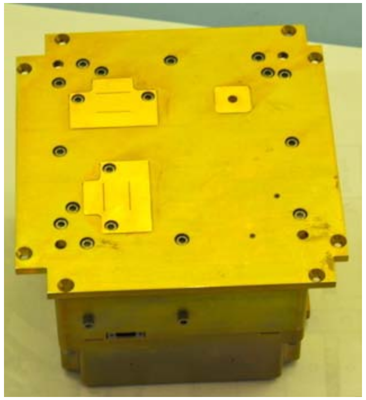


SV-2: WINCS + CTECS





WINCS



Compact Tiny Ionospheric Photometer (CTIP)	CubeSat Total Electron Content Sensor (CTECS) (x2)	Winds Ions Neutrals Composition Suite (WINCS)
Measures 135.6 nm UV nightglow giving ionospheric density variation and structure	Measures amplitude and phase variations of occulting GPS signals giving ionospheric density and scintillation	Measures ram fluxes of ions and neutral particles giving local electric field, densities, neutral winds, and temperatures

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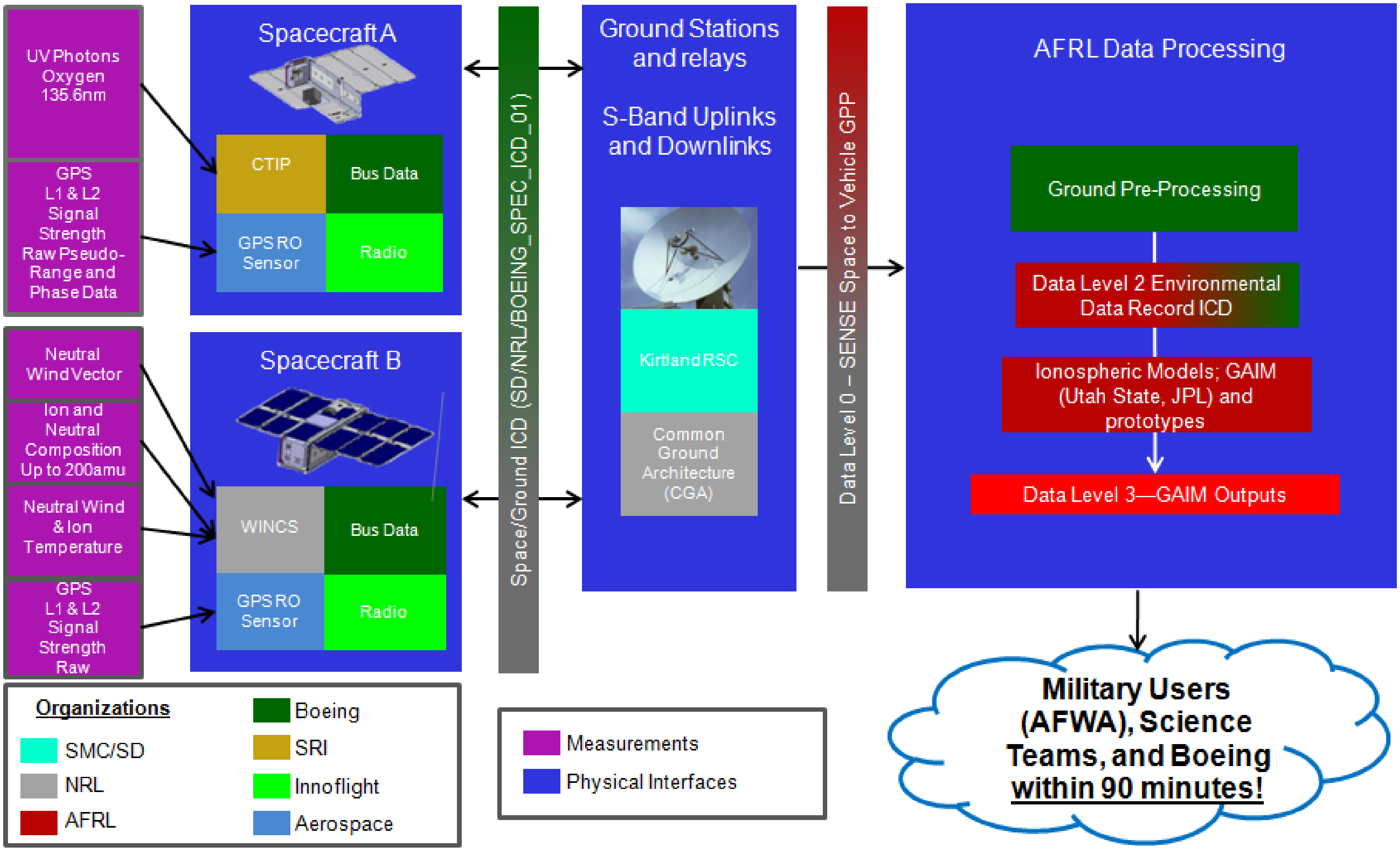
SENSE data flow

From sensors to processor



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On-Orbit History and Accomplishments

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SENSE on-orbit timeline

- Nov 19 2013--Launch and successful orbital injection from the ORS-3 LV
  - *Ground initially unable to differentiate SENSE from other ORS deployed vehicles using JSpOC Two-line Elements (TLEs) and maintain contacts*
- Nov 24—Analysis of limited SV-1 telemetry shows bi-fold solar array not deployed and abnormally high use of control authority
- Dec 6—Use of locally generated TLEs enables contacts and telemetry with radio in beacon mode
- Jan 2014—Completed first fully automated pass using Neptune Common Ground Architecture, tumble rates reduced, all mission payloads turned on. SV-2 collected CTECS data
- Feb to June 2014—Unsuccessful attempts to achieve Local Vertical Local Horizontal (LVLH) attitude on SV-1 without star camera data, SV-2 placed in free drift survival mode
- June to Sept—Attitude control experiments on SV-1 using star tracker—star camera assessed as unusable
- Sept-Dec—Developed and uploaded new flight software to address attitude control and data handling problems
- Feb 2015—Successfully switched SV-1 to new flight software
- March 2015—Deployed CTIP sun baffle and collected photon counts
- March 21—SV-1 reentered, efforts shifted to SV-2

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SENSE Accomplishments

- Very successful vehicle communication using ground antenna network
  - *Implemented Neptune CGA at Kirtland AFB allowing "lights out" automated ground contacts using antennas at Kirtland and Blossom Point MD; data rates near 1 Mbps*
  - *Ground system pathfinder for future missions*
  - *First CubeSat use of Unified S-Band frequencies with NTIA frequency assignment and coordination*
- Developed a distributed ground architecture with leave-behind capability to fly the next minimally-manned satellite mission
- Developed mission data flow to support space weather mission data latency requirements
- Raised TRL and demonstrated reliability of SENSE Innoflight radio, Li-ion batteries, power management system, reaction wheels and many other CubeSat components
- Completed exhaustive root cause and corrective action campaign to address solar array deployment failure
- Successfully uplinked, activated and tested a complete refresh of flight software to mitigate on-orbit problems
- Provided critical on-orbit test and risk reduction effort for identifying and correcting issues with the remaining Colony 2 buses

Many program goals were met and much was learned

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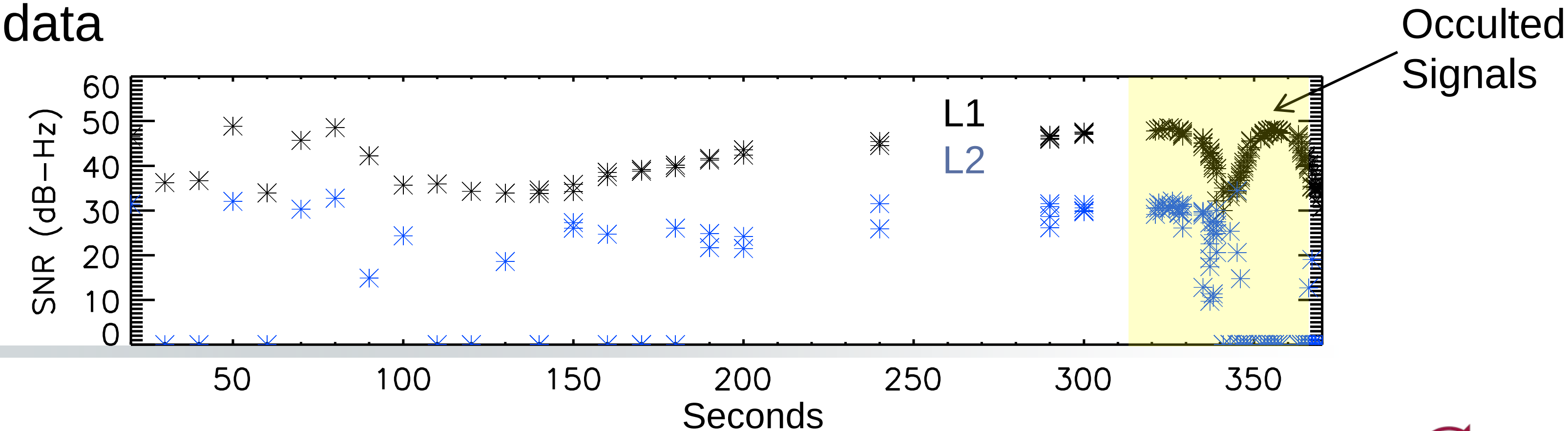
CTECS

Early Orbit Performance

- SV1 sensor initial powered on 12/12/13 (no downloaded data from s/c)
- SV1 sensor 2nd power-on 12/18/13 (7 min period)
  - *Tracking started within 60 seconds*
- SV2 sensor initial powered on 1/21/14 (5 min period)
  - *Tracking began within 60 seconds*
- Total Time CTECS Operated
  - *SV1: 129 days (varying period lengths)*
  - *SV2: ~87 hours over 8 days*
- Both sensors successfully provided Position/Navigation and occultation data



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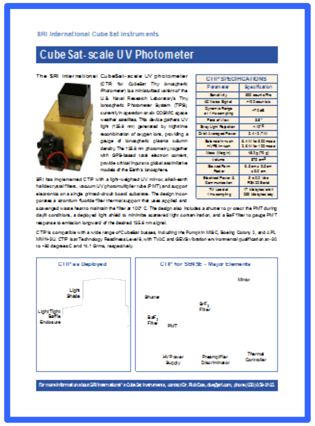
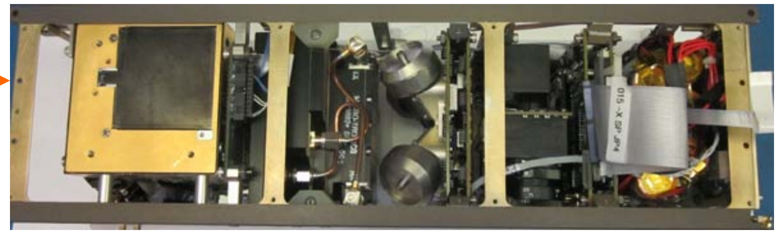
CubeSat Tiny Ionospheric Photometer (CTIP)

EM S/N 012



Delivered Jan 2012

Spacecraft Integration



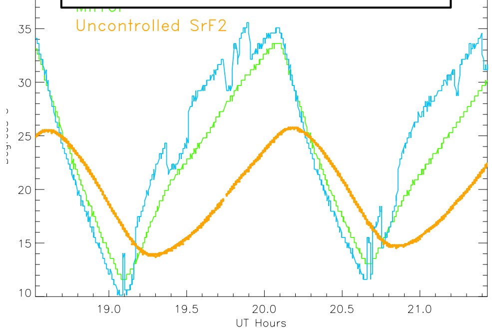
Launch 19 Nov 2013

Spacecraft ADCS Issues

Launch through Apr 2014

Mar 2014

CTIP Readiness



Mar 2015

CTIP Turn On

Date	Time	Board Temp	Mirror Temp	High Voltage	Board Current	Board Voltage	Counts
03-06-2015	20:30:57.841	25.29654	19.91754	-864.7084608	0.14193	5.061468	9833953
03-09-2015	21:05:54.133	26.27454	20.40654	-866.4173708	0.13793	5.053472	9902044
03-10-2015	18:03:46.337	22.36254	16.49454	-866.4173708	0.13993	5.069464	9878774

Chart courtesy of Rick Doe/SRI

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On-Orbit Anomalies and Failures

SENSE on-orbit anomaly “symptoms”

Problems initially ambiguous and strongly interrelated

- Initial difficulties identifying and acquiring vehicles
- Brief contacts
- Low power
- Unable to de-tumble vehicles
- Power drain from excessive torque coil firing to desaturate reaction wheels
- Noisy magnetometer measurements

Added significant delay to anomaly resolution

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Solar panel deployment failure

Dominant mission anomaly

- On SV-1 only the tri-fold solar panel deployed and neither panel deployed on SV-2
  - *Root cause believed to be burn wire mechanism*
- Low power states induced communication “brown outs”
  - *Downlink power draw tripped protection circuits cutting off flight radio in a few seconds*
  - *Increased difficulty of initial spacecraft tracking and continued to adversely affect contacts*
- Un-deployed panel obscured sensors
  - *1 of 2 star cameras blocked*
  - *Some magnetometers out of position and degraded*
- Changed spacecraft mass properties

Eventually able to transition SV-1 to adequate mission power and SV-2 to power positive condition

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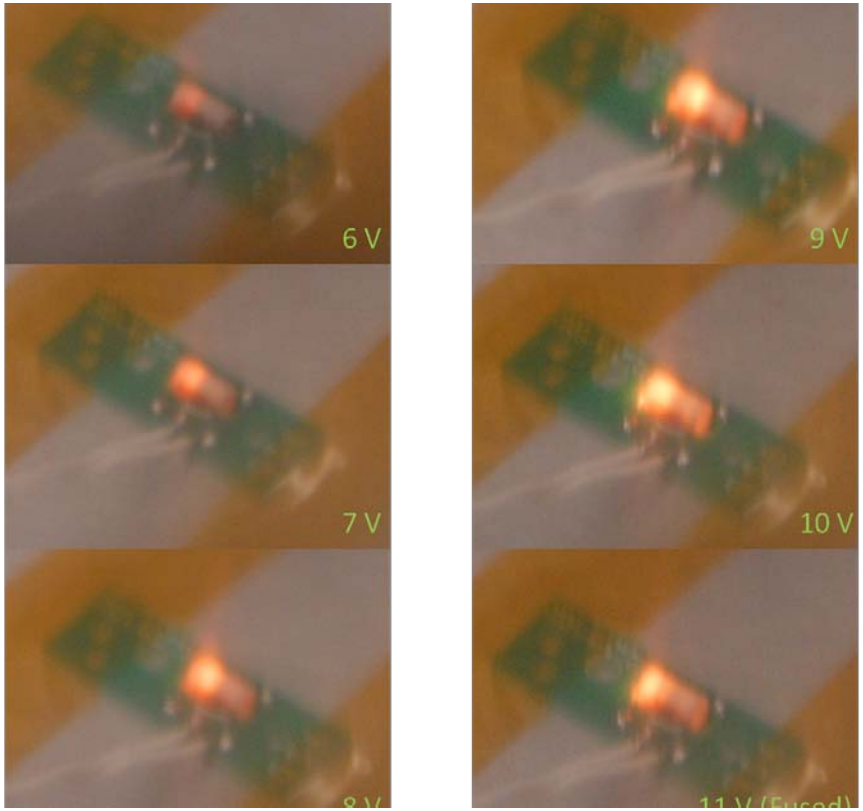
Burnwire mechanism failure

Most probable cause of solar panel deployment failure

- Burnwire had flight heritage with 5V applied
- SENSE burnwire was not tested in vacuum conditions
  - *Risk emphasis was that nylon line would be inadequately heated and fail to melt*
  - *Belief was that ambient conditions would provide a more stressing test*
  - *Non-repeatability a factor in not testing burnwire during TVAC*
- Problem exacerbated by irregularities in heating coil manufacture



SENSE burnwire heater at different voltages in vacuum

Failure analysis led to redesign of Colony 2 deployment mechanisms

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Control system problems

Most caused by deployment failure

- De-tumble initially unable to stabilize vehicles
  - *Fixed using upload of corrected control parameters*
- Reaction wheel firing and desaturation by torque coils attempting to maintain sun safe attitude
- Attitude state progression during initialization was too aggressive
  - *Vehicles were placed in unplanned adverse configurations*
- Magnetometers in wrong orientation or too near torque coils
- Un-obscured SV-1 star camera could not provide attitude solution
  - *Excessive focal plane noise, likely due to overexposure to sun*
- Sun sensors responded to earth albedo—sun safe mode did not point vehicles at the sun

Vehicles stabilized but unable to achieve LVLH attitude

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Lessons Learned and Conclusions

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Lessons learned

- Identification and tracking of satellites launched in swarms is difficult
  - *Problem magnified as higher communication frequencies are used*
- Balance between risk management and agile space acquisition is difficult
- Test critical components in representative space environment
- Avoid components that cannot be repeatably tested
- Take small steps in initial bus deployment and checkout—do not try to do too much “out of the P-POD”
- Many advantages to developing spacecraft in line with ground segment
  - *Better still to have a defined ground system prior to spacecraft design*
- Government frequency allocation process slow and difficult
- Small satellite ≠ low complexity

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Conclusions

- Operationalization of CubeSats for National Security Space missions is possible but requires a “fly-fix-fly” approach
  - *Higher risk must be tolerated as technologies mature*
  - *On-orbit experience is growing and will reduce risk going forward*
- Space vehicle discrimination methods in early operation require enhancement as satellites are deployed in larger numbers
- Lower cost using streamlined, automated ground operations are feasible and highly beneficial for small satellite missions
  - *Ground system complexity and cost must scale with space segment*
- Government frequency management process needs to be tailored for agile space missions

Questions?

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