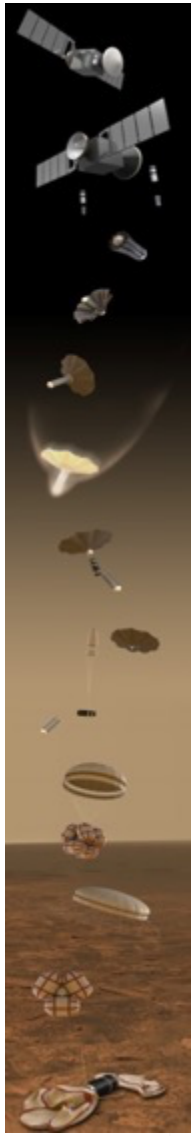
Topics in Advanced Communication and Design in the TES-n Nanosatellite Flight Series

Use of Iridium as a Primary Encrypted Command/Control Gateway

S3VI Webinar

TechEdSat-1:
First off the ISS (2012)
..We were #1..



March 18, 2020

Presented by M. Murbach

T. Stone, R. Alena, A. Guarneros-Luna, C. Priscal, A. Salas, H. Kanniainen, R. Ntone Sike, N. Williams, A. Brock, A. Tanner, S. Mahmood, A. Dono Perez

TES-n/NOW Team

Abstract

Title: Topics in Advanced Communication and Design in the TES-n Nanosatellite Flight 22Series: Use of Iridium as a Primary Command/Control Gateway

Abstract: Since the first Technology Education Satellite (TES) in 2012, the team from NASA Ames has flown an iterative series of nano-satellites with a variety of evolving experiments. The most recent, TES-10, will launch to the International Space Station (ISS) on February 9, 2020, and be subsequently jettisoned. TES-10's attributes include having the highest power density of current NASA nano-satellites while incorporating eight microprocessors (including an NVDIA GPU), eight transmitters, and a unique, targeted, de-orbit system (known as an Exo-Brake). The flight series has successfully used the Iridium SBD modems for rapid command/control and is presented as a potential 'TDRS for nano-sats.' The presentation will include a detailed description of the COM subsystems, including the upcoming Iridium and Globalstar comparison tests. In addition, the 'Lunar' and 'Mars' radio will be discussed, which may help enable future interplanetary nano-sat missions.

Outline

Part 1

1. **TES-n Summary**
    - Balloons to Suborbital missions (SOAREX) to nanosats
    - Matrix of past, present, future flights
2. **Why TES-n?**

How we design and build
- Avionics core
- High Power Subsystem
- Microprocessors

How we manage
- Dot xX [part of Ames 'menu']
- Approach to SMA [We hate risk…]

How we collaborate

How we manage risk
- Approach to S 'AND' MA
- TES-10,7 Upcoming

Part 2

1. **Approach to Avionics Stack.**
2. **Approach to Power Subsystem**
3. **Exo-brake**

Part 3

1. **Approach to COM**
    - NOAA Experiment/
    - Mars Radio/ Lunar Radio
    - Use of Iridium
    - Use of Globalstar
2. **Approach to Encryption**
    - Future Experiments
    - TES2, 2u, 3u, 6u, 6u-Wide, SPQR
    - Mars and Sample Return

Future experiments

Summary

The Small Spacecraft Systems Virtual Institute's

Community of Practice Webinar Series

Join us on

Wednesday, March 18, 2020

10:00AM-11:00AM PDT for a webinar by

Marcus S. Murbach

NASA Ames Research Center

Topics in Advanced Communication and Design in the TES-n Nanosatellite Flight Series: Use of Iridium as a Primary Command/Control Gateway

Abstract

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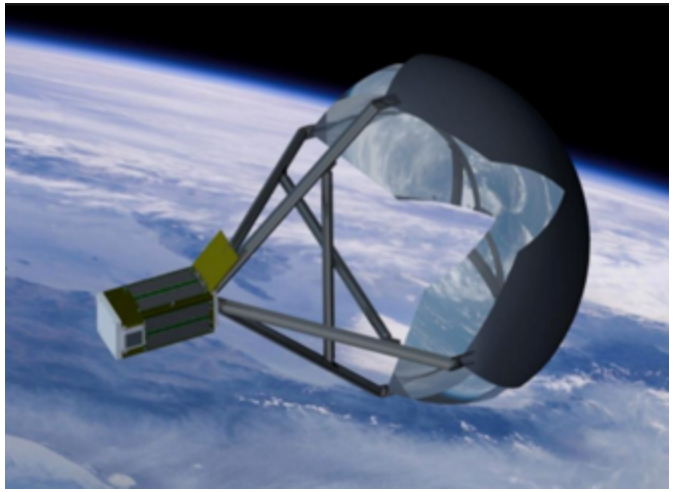
S3VI encourages the community to submit questions before the webinar to enable more directed responses. Please send questions to raquel.l.redhouse@nasa.gov.

Learn more and connect to this webinar

Please contact Julianna.L.Fishman@nasa.gov if you experience issues with the audiovisual connection to this webinar.

TES-10 *On ISS now… Jettison Date TBD*



TES-7 *Waiting on Virgin Orbit*
First commercial launch after 'test launch'

PART 1

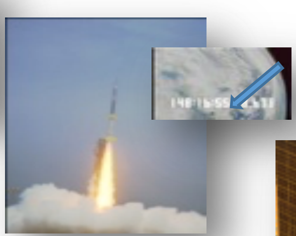
How we design, build, manage, and collaborate

Relevant Flight Experiments

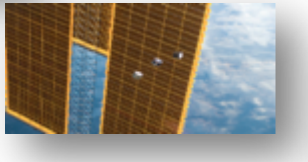
SOAREX/TechEdSat-N Team

Flight Experiments of Recent Years
(2008-2020): 15+ Flights

SOAREX-6
(2008)



SOAREX-7
(2009)

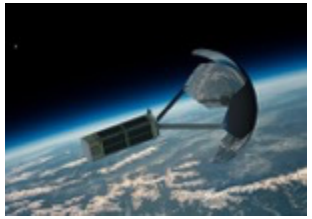


TES-1
Oct 4, 2012

TES-2
PhoneSat
Iridium-test
Aug 21, 2013

TES-3
Aug 3, 2013
(6 wk de-orbit)

TES-4
Mar 3, 2015
(4 wk de-orbit)



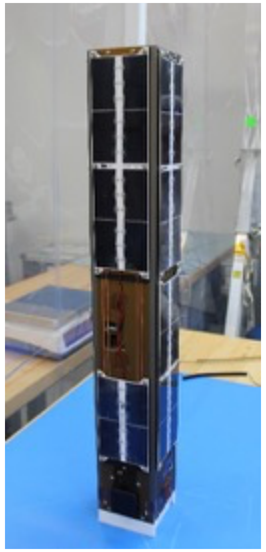
T5/P5
Mar 6, 2017
(19 wk de-orbit)

T8/P8
Jan 31, 2019

…here before

SOAREX-8
(2015)

SOAREX-9
(March 7, 2016)

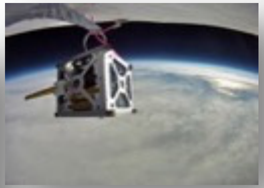


T10/P10
Feb 15, 2020

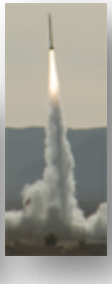
PhoneSat Team

Flight Experiments of Recent Years
(2009-2015)

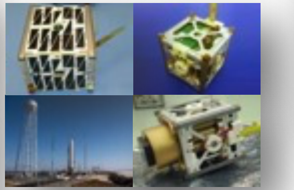
Intimidator-5
July 29, 2010



Balloon
June 9, 2011



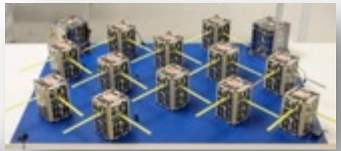
SpaceLoft-6
Apr 5, 2012



PhoneSat 1a, 1b, 2.0
Antares A-ONE
Apr 21, 2013

PhoneSat 2.4
ORS-3 Minotaur 1
Nov 20, 2013
(still in orbit)

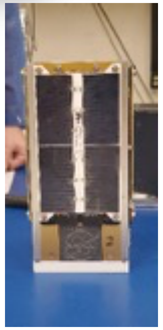
PhoneSat 2.5
CRS-3 Falcon 9
Apr 18, 2014



EDSN
Super Strypi
Oct 29, 2015

Nodes
Orb-4 Atlas V
Dec 3, 2015

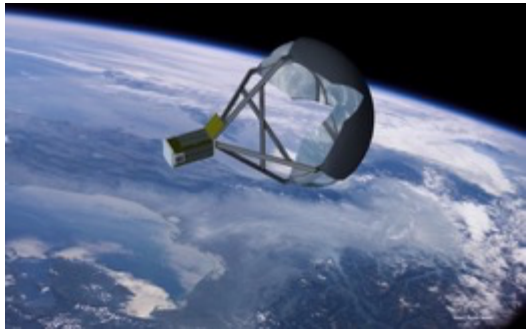
SOAREX-8
Terrier/Black Brant
July 7, 2015



T7/P7
TBD

TES-n Team Accomplishments 2019

TES-8 Delivery/OPS:
Nominal Success
Launched:
December 5, 2018
Jettisoned from the ISS:
January 31, 2019

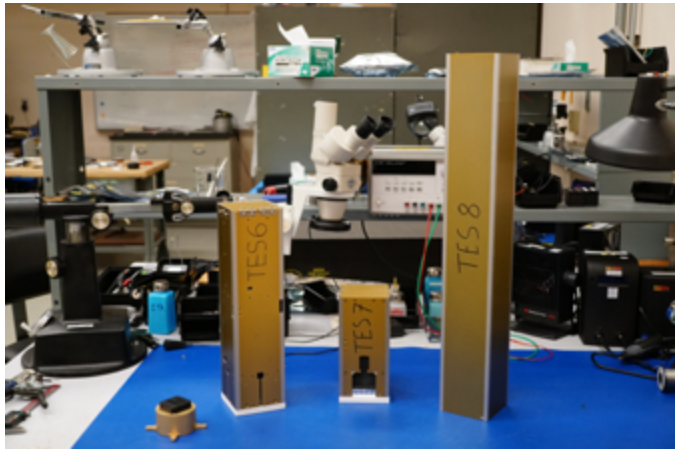


TES-10 Delivery/OPS:
Delivered to ISS
Launched:
Feb 15, 2020 NG-13
Jettisoned from the ISS:
TBD, 2020

TES-7 Development:
Completed
Launch:
First Virgin Orbit Commercial Flight (Projected June 2020)

BEST-1 [Balloon Experiments for Smallsat Technologies]
NVIDIA-TX2 hyperCAM development
Launched form Sioux Falls, SD on
August 29, 2019
Comprehensive Success

Currently in Execution/Planning
TES-7 (Built, waiting for VO)
TES-10 (Built/Delivered to ISS)
TES-9,11,12 (In dev)
SPQR SmallSat Exp (in Dev)



Flown

On ISS

On deck

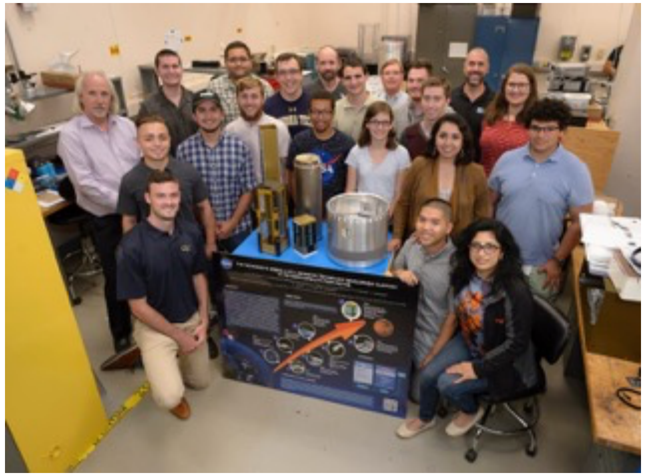
In Dev/ Proposed

Flight	Date	Size	Launched	Main Experiments	Note	Success
TES-1	10-4-2012	1U	ISS	PnP architecture Radio Experiments	1st off the ISS	Nom Success
TES-2	7-21-2012	1U	Antares I	Iridium SBD exp.	1st Iridium exp	Comp Success
TES-3	7-3-2013	3U	ISS	Arduino architecture I Fixed Exo-Brake	Exo-Brake I; Start of unique structural design; Command uplink statistics	Nom Success
TES-4	3-3-2015	3U	ISS	Arduino architecture I.5 ; IoT; Improved tracking 9603 experiment; Phonesat element; email COM control	Pre modulated Exo-Brake; dual Iridium SBD	Comp Success
TES-5	3-6-2017	3U	ISS	PWR/Crayfish; IoT-b; Crayfish/GPS I; fixed drag disposal	Improved GPS tracking; IoT Crickets	Nom Success
TES-6	11-21-2017	3U-L	ISS	PWR/Crayfish; IoT Wifi to the ground/WFF De-orbit targeting (ground control loops)	1st De-orbit targeting with modulated drag device; ground target control; Wifi to the ground record	Comp Success
TES-8	1-31-2018	6U-L	ISS	Dual Omni-board architecture I; IoT; WiFi to the ground De-orbit targeting; Iridium vs Globalstar Lunar Radio Mars Radio/NOAA-I; Vorago Omni Mini-GPS module; ;	8 Microprocessor/ 8 transmitters First NASA long 6U	Nom Success
TES-10	(May2020)	6U-L	ISS	Dual Omni-board; IoT; WiFi to the ground; De-orbit targeting; Lunar Radio Mars Radio/NOAA-II; Vorago Omni Mini-GPS module; LASER tracking exp; heat pipe	READY (On ISS)	TBD
TES-7	(May2020)	2U	Virgin Orbit	Iridium COM Tardigrade/Vorago II; Drag device	READY (1st CSLI flight)	TBD
TES-9	(Jan2021)	6U-W	L9-EFS Jan2021	Compact HIGH-PWR system; CALsat; disposal Exo-Brake II; encryption I; SPAWAR reflector; Auto-ID Laser tracking II; NEN Lunar radio test	Proposed (slot accepted)	
TES-11	(Jan2021)	6U-W	L9-EFS Jan2021	Compact HIGH-PWR system II; NOAA III/ Mars SDR Test; NEN Lunar radio III; encryption II Propulsion I; NVIDIA/GPU III	Proposed (slot accepted)	
TES-12	(Jul2021)	3U	ISS/ CSLI	Hot Exo-Brake; autonomous guidance Encryption II; Encryption III; mini-dual GPS	Proposed (slot accepted)	
TES-13	(Aug2020)	3U	Virgin Orbit Aug, 2020	DISA Iridium SBD+ Data module; Encryption II Hot Exo-Brake II; guidance; ablator II; backup-GPS	Proposed/Negotiating slot	
TES-14	(Aug2020)	180	ISS/ Mar2020	SPQR/ ARCxSAT: Full M-Exo-Brake; propulsion; Mars probe re-entry test flight	Proposed	

Our Team and Sponsors: Who We Are

TES-n / NOW Team:

- ❑ Over 25 years of Dot-x type of rapid flight development
- ❑ Upwell experience/ technologies into other ARC or NASA projects
- ❑ Combining different levels of experience
- ❑ Summer program – from undergrads to Professors/ PhD students



Typical Sponsors:

- ❑ **ARC Discretionary**
- ❑ **USGOV** (Exo-Brake modulation/targeting)
- ❑ **STMD/ESM** (Initial Exo-Brake development/modelling; control strategy)
- ❑ **SSTP** (COM architectures, Lunar/Mars radios- NEN, rad-tolerant systems, NVIDIA GPU performance in orbit rapid, encryption, proto-flight techniques, …)
- ❑ **NOAA** (DCX UHF radio evaluation; Mars Radio; 5G radiometer proto-study)

Universities:

SJSU, U of Idaho, Cal-Poly/SLO, Stanford, UC-Davis, U of Florida, Emry-Riddel, U of Georgia, Smith college, ISU

Dot xx [NASA Ames] Project Class

Classification:

- ❑ Double .xx (highly experimental; do-no-harm)

  Typical expense is of that of a sub-orbital payload
- ❑ Due to the early ISS interaction, the Safety aspect appears more as a **7120.5**

  All ISS UHR (Unique Hazard – as expressed in the Unique Hazard Reports) are mitigated

  Example: Battery packs, RF transmit power, structural integrity (mitigations)

Rolling and Evolving Requirement Set:

- ❑ **Rapid incrementalization allows for the requirement set to evolve and 'roll' into the next experiment**

  Example: The Vorago rad-tolerant architecture (no dependency on new systems)

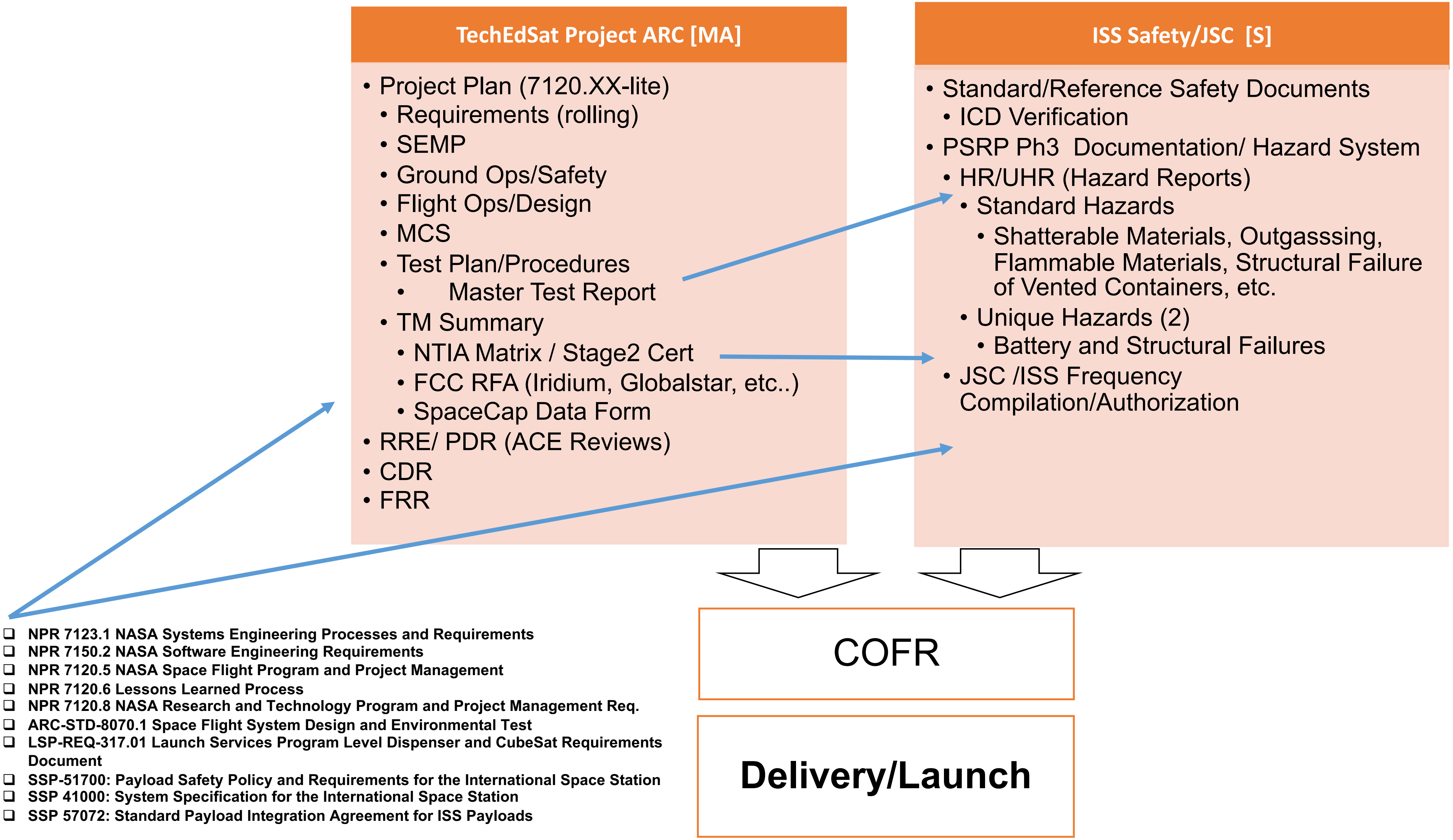
Success Criteria Layers:

- ❑ Typical Minimal, Nominal, Comprehensive. (and if too risky, not included!)

<u>Note:</u> Not all projects should be handled as such (given investment), but this should be part of a portfolio

In $equation\ form: minimizing\ \left.\frac{\partial TRL}{\partial \$}\right|_{Time}$

Approach to S&MA- TechEdSat-n Process Tree



TechEdSat Project ARC [MA]

- Project Plan (7120.XX-lite)
  - Requirements (rolling)
  - SEMP
  - Ground Ops/Safety
  - Flight Ops/Design
  - MCS
  - Test Plan/Procedures
    - Master Test Report
  - TM Summary
    - NTIA Matrix / Stage2 Cert
    - FCC RFA (Iridium, Globalstar, etc..)
    - SpaceCap Data Form
- RRE/ PDR (ACE Reviews)
- CDR
- FRR

ISS Safety/JSC [S]

- Standard/Reference Safety Documents
  - ICD Verification
- PSRP Ph3 Documentation/ Hazard System
  - HR/UHR (Hazard Reports)
    - Standard Hazards
      - Shatterable Materials, Outgasssing, Flammable Materials, Structural Failure of Vented Containers, etc.
    - Unique Hazards (2)
      - Battery and Structural Failures
  - JSC /ISS Frequency Compilation/Authorization

COFR

Delivery/Launch

☐ **NPR 7123.1 NASA Systems Engineering Processes and Requirements**
☐ **NPR 7150.2 NASA Software Engineering Requirements**
☐ **NPR 7120.5 NASA Space Flight Program and Project Management**
☐ **NPR 7120.6 Lessons Learned Process**
☐ **NPR 7120.8 NASA Research and Technology Program and Project Management Req.**
☐ **ARC-STD-8070.1 Space Flight System Design and Environmental Test**
☐ **LSP-REQ-317.01 Launch Services Program Level Dispenser and CubeSat Requirements Document**
☐ **SSP-51700: Payload Safety Policy and Requirements for the International Space Station**
☐ **SSP 41000: System Specification for the International Space Station**
☐ **SSP 57072: Standard Payload Integration Agreement for ISS Payloads**

Part 2

Approach to Design and Hardware Overview

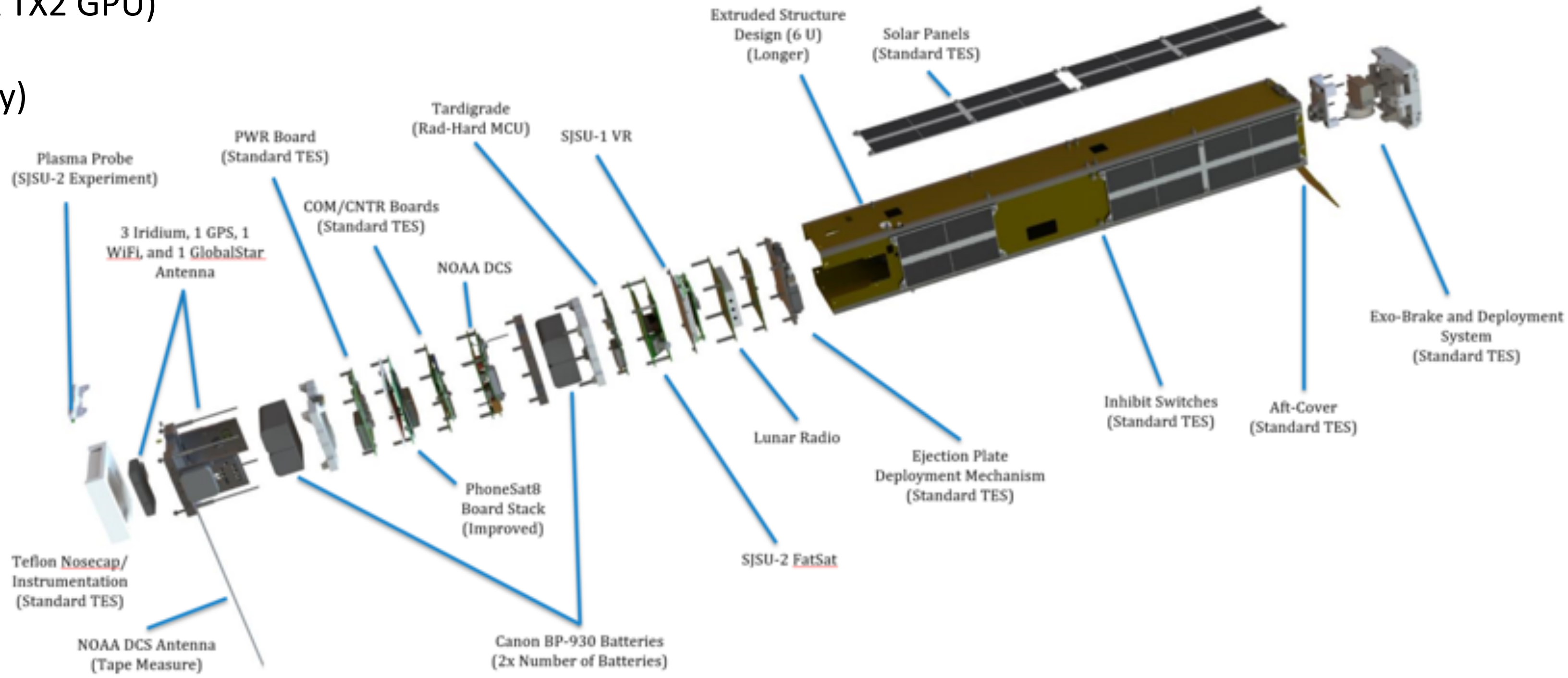
Example Avionics Stack - TES8,10 [Long 6U]

System Layout and Complexity

Nano-Orbital Workshop:

☐ **Most 'powerful' NASA 6U** (150W-hr)
☐ **Most 'vociferous'** (8 radios – UHF, L, S, ISM bands, WiFi mesh network)
☐ **Most 'brains'** (8 processors incl: Tardigrade, NVIDIA TX2 GPU)
☐ **Most cameras** (4 incl VR experiment)
☐ **Most Exo-Brake** (largest to-date; targeting capability)

☐ Also: first heat-pipe, internal WiFi data transfer, mini-GPS… and much more



TES-8,10 Exploded View

Looks easy without the cabling…

☐ **Integration Challenges**
    Split stack (UL certified battery packs 4" apart)
    Distance of power bundle to first inhibit is 6"
    Shielded **USB3** flight cabling
☐ **Effort to simplify and improve integration is on-going**

TES-N Processors

Processor	Specifications	Rad Tol	Payload	Additional Notes
Arduino Pro Mini*	16 MHz ATmega 328, 32KB Flash, 2KB SRAM	~Yes SEU rate:	Powerboard	Flight tested, main control board, radiation testing data available
Vorago 10820	50 MHz ARM Cortex-M0, 128KB Flash, 32KB RAM	Yes	Tardigrade	next-gen control board, radiation hardened, data available
Teensy 3.2	72 MHz ARM Cortex-M4, 256KB Flash, 64KB RAM	No	Crayfish, AttSat	Flight tested, secondary control board
Intel Edison	500 MHz Intel Atom, 4GB Flash, 1GB RAM	~Yes SEU rate:	PhoneSat	Flight tested, COM board, radiation testing data available
TI CC2538	32 MHz ARM Cortex-M3, 128KB Flash, 32KB RAM	No	Cricket	Flight tested, sensor board
Digi ConnectCore 6UL	528 MHz Cortex-A7, 1GB Flash, 1GB RAM	No	Lunar Radio	High data rate COM board
NVIDIA Jetson TX2**	256-Core Pascal GPU, Dual-Core NVIDIA Denver CPU Quad-Core ARM Cortex-A57 32GB Flash, 8GB RAM	No	VR	Radiation testing data available

*http://microelectronics.esa.int/conferences/mesa2010/06_S2_1120_ASTRIUM_GmbH_Andreas_Schuettauf.pdf
*https://nepp.nasa.gov/workshops/eeesmallmissions/talks/11%20-%20THUR/1430%20-%202014-561-%20Violette-Final-Pres-EEE-TN17486%20v2.pdf
**Proton Testing of NVIDIA Jetson TX1 E.J. Wyrwas

Solar Panel Evolution

- ☐ **Limited supply of cracking-prone, outdated but flight-proven monocrystalline silicon cells prompted new solar panel design**

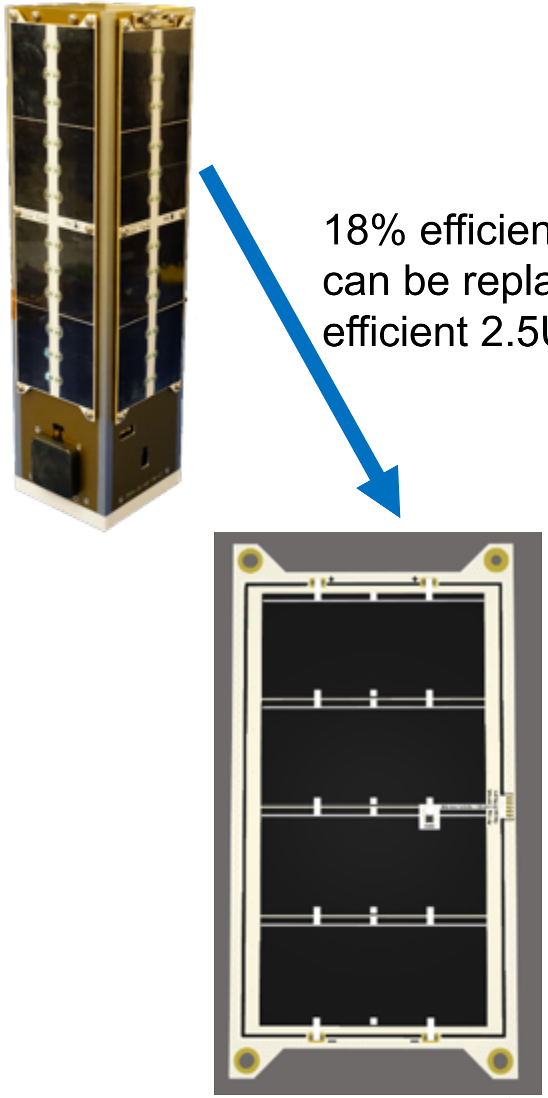
- ☐ Gallium arsenide cells offer improved efficiency and <u>flexibility</u> over silicon and have dramatically decreased in cost over the past several years

- ☐ MicroLink Devices Inc. (MLD) produce NREL-licensed triple-junction GaAs 32% efficient cells that have been tested on the ISS under FTSCE as part of MISSE-5, but have never flown for power production in space (UAV target use)

- ☐ 2U (132x75mm 4-cell) panel with MLD GaAs cells produces 3.12W, **69.5% more power than same size silicon panel**

- ☐ New panels can be prepared using the same ISS safety procedure of wrapping the panels with optically clear, UV-stable Teflon

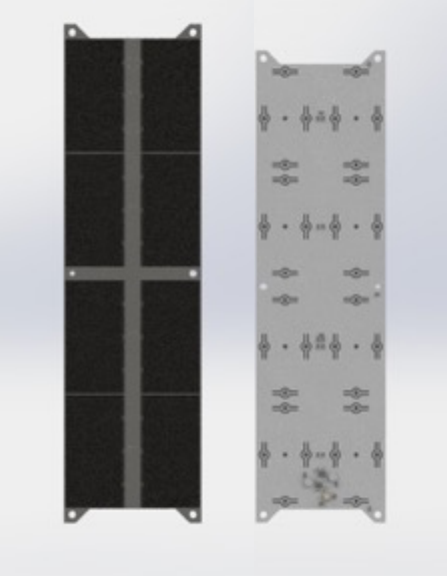
- ☐ **Flight demonstration of rigid static panels will allow development of reliable, inexpensive flexible deployable panels**



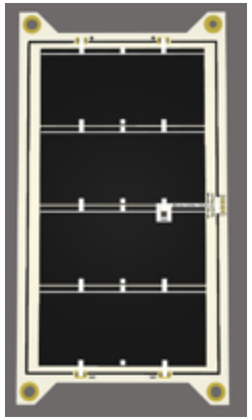
18% efficient 3U panels can be replaced by 32% efficient 2.5U Panels

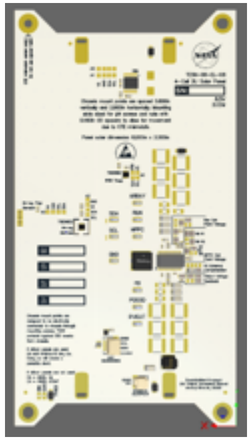
A. Brock

Solar Panel Comparison



	TES-4 to TES-10	**TES-N (2020→)**
Cell Type	Monocrystalline Silicon Single-Junction MFG: NREL	Gallium Arsenide ELO Triple-Junction MFG: MicroLink Devices, USA
Cell Performance (AM0)	69x36mm **18.5% Eff**, 0.46W: 0.52V, 880mA	66x31mm **31% Eff**, 0.78W: 2.51V, 311mA
‘U’ Panel Power (AM0)	**2U: 1.84W** 3U: 3.68W	**2U: 3.12W** ‘2.5U’: 3.90W
Panel Topology: 2U (2.5/3U)	2S(4S)2P MPPT Boost SPV1040 Based	4S(5S) MPPC 4-SW Buck/Boost LTC3119 Based
Sensors	None	• Solar array output V/I/P • Array top and bottom surface temperatures • PCB temperature

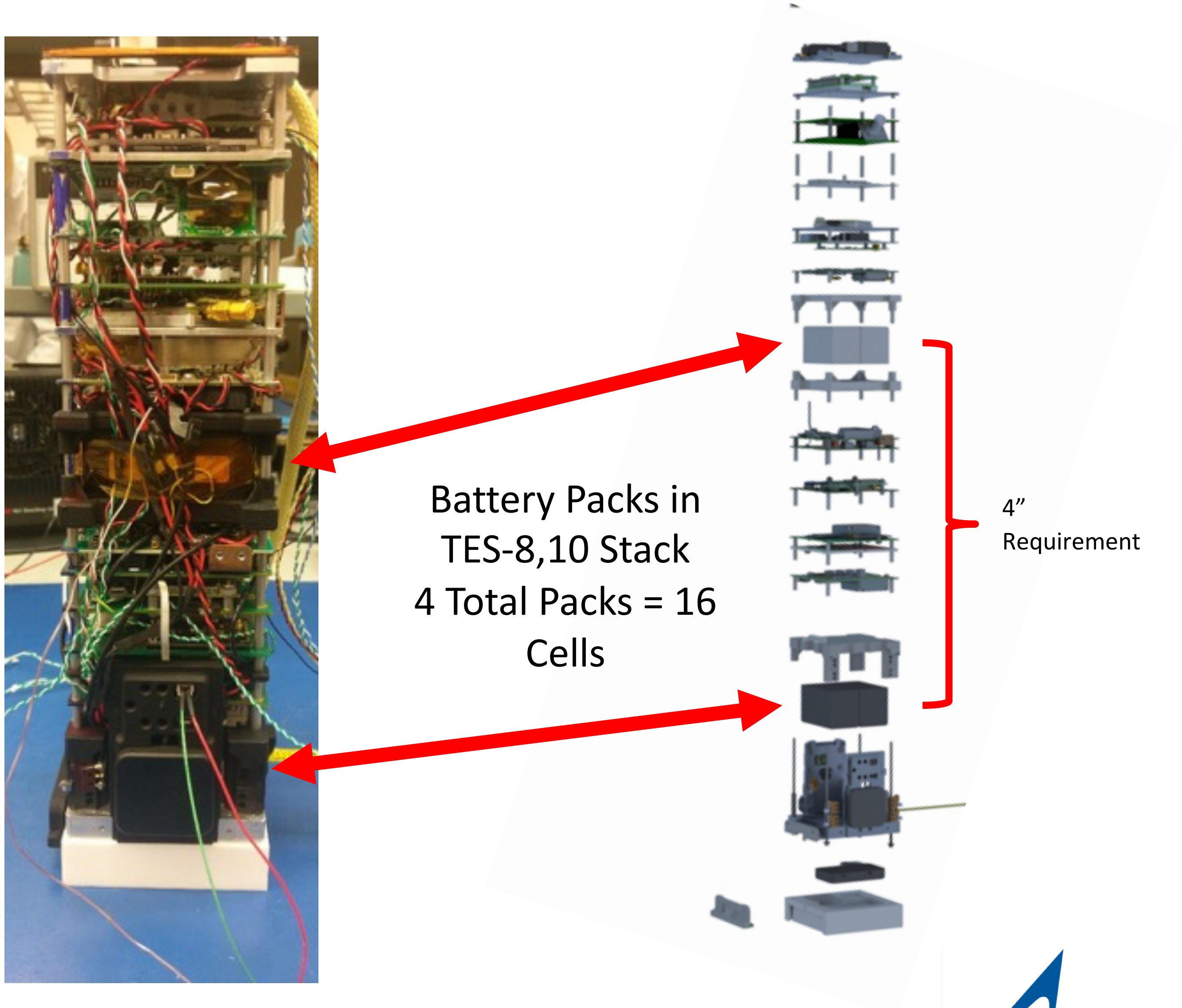




A. Brock

Advanced Power Storage System (APSS)

- **TES-8 and TES-10 both flew four Canon BP-955 battery packs, each containing four 18650 lithium-ion cells (1225 mAh each)**
- Total system capacity: 19.6 Ah, 150 Wh, 16 18650 cells
- NASA ISS safety regulations require every 80 Wh worth of storage to be spaced 4” apart to reduce thermal runaway chain reaction chance, which limits the capacity of each satellite
- Development of a thermal containment system will allow for pack density to be increased, allowing six to eight packs per 6U satellite
- **Even without containment system, existing architecture exceeds commercial 6U systems using UL certified battery packs**



APPS will improve system integration

A. Brock
H. Kanniainen

Advanced Power Storage System (APSS)

Satellite Design	3U	Long 6U	6U	12U
Power per panel [W]	3.12	**3.9**	3.9	3.9
Panels per side 'A'	1	**2**	2	2
Panels per side 'B'	1	**2**	1	2
Solar power [W]	6.24	**15.6**	11.7	15.6
Orbit time [min]	90	**90**	90	90
BP-955 Packs	2	**4**	6	8
18650 Cells	8	**16**	24	32
System capacity [Wh]	72.52	**145.04**	217.56	290.08
Full recharge time [hrs]	11.6	**9.3**	18.6	18.6
Full recharge orbits	15.5	**12.4**	24.8	24.8
20W Thruster run-time [min]	109	**218**	326	435
40W Thruster run-time [min]	54	**109**	163	218

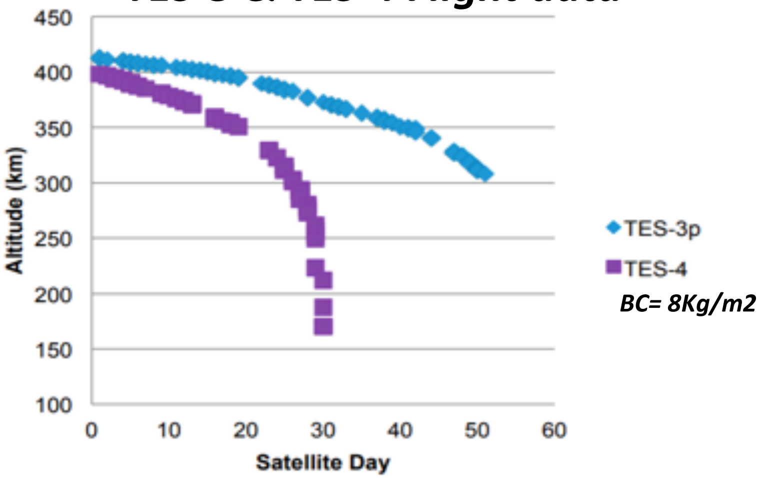
Expandable APSS system offers a unique path forward to long-duration propulsion experiments

- ☐ 3U design uses 2U GaAs panels
- ☐ 6U design uses 2.5U GaAs panels
- ☐ No other loads considered besides thrusters
- ☐ Thruster run-time based on running batteries to 50% capacity

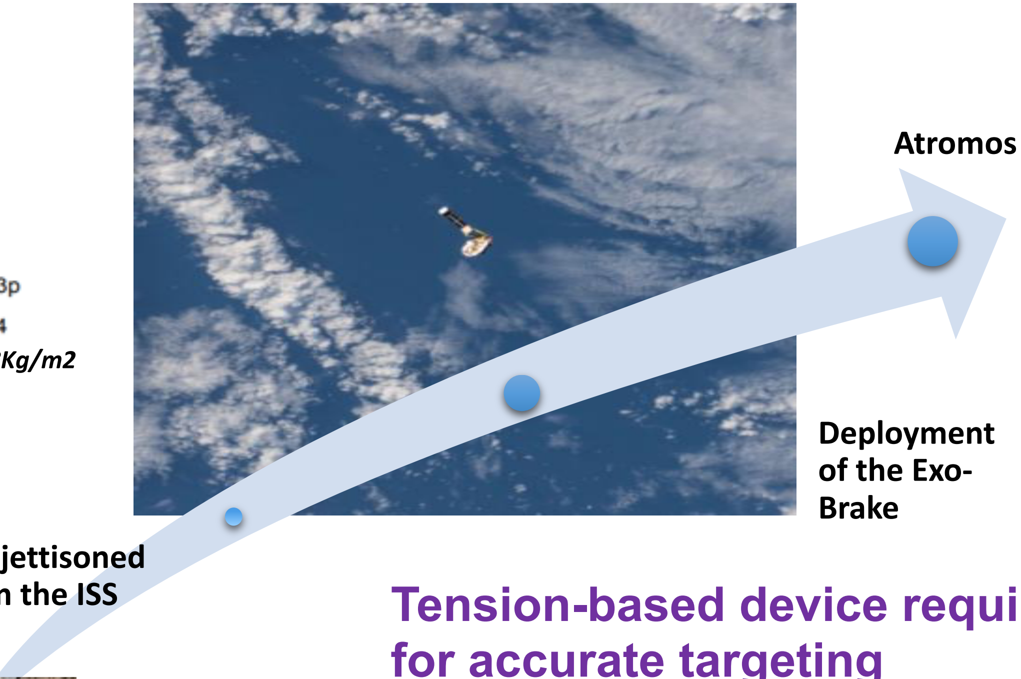
Exo-Brake

Simple, drag-modulated de-orbit system based on tension elements

TES-3 & TES-4 Flight data

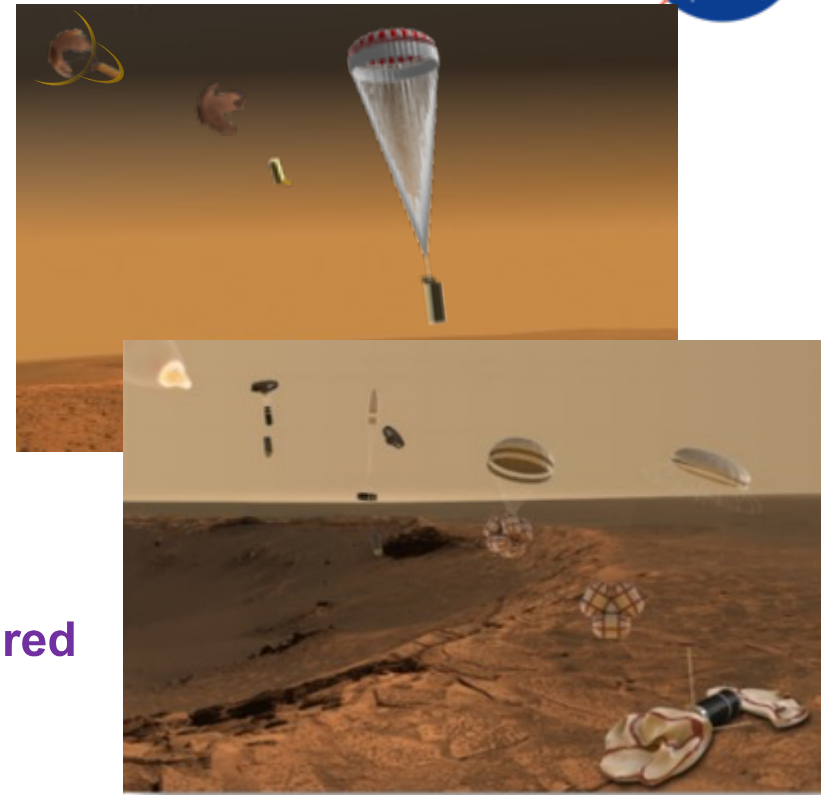


BC= 8Kg/m2

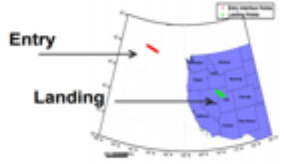


TES jettisoned from the ISS

Deployment of the Exo-Brake



Tension-based device required for accurate targeting



Theoretical targeting of UTTR.
S. Dutta, A Dwyer-Cianciolo

TES-6 target actual navigation
TES-n Team, S. Omar

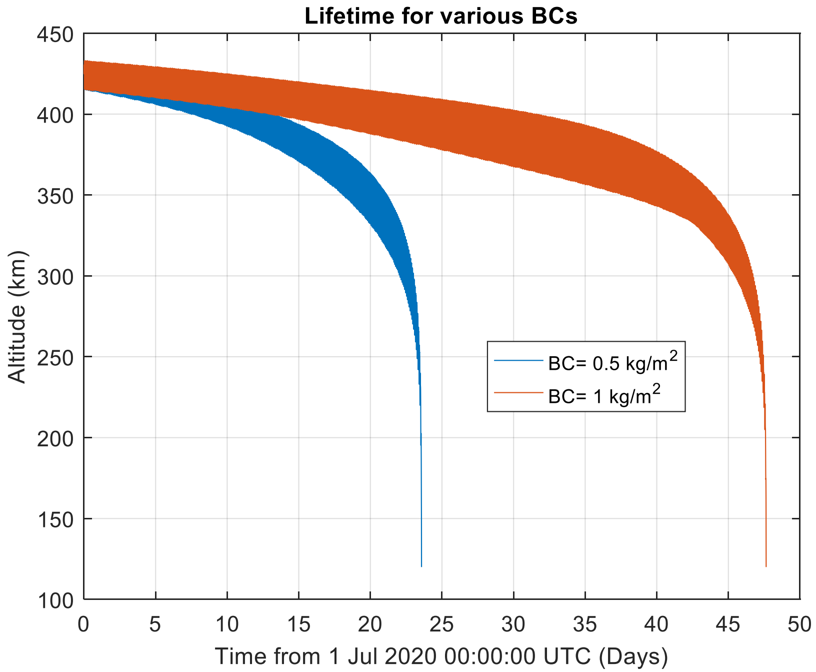
Return/Re-entry targeting with modulated Exo-Brake

- ☐ **TES-6 demonstrated successful drag-modulation experiments**
- ☐ **Development of 'disposal' and 'HOT' Exo-Brake, and autonomous de-orbit navigation in progress**

Thermosphere Test Probe Study

- ❑ Assumptions:
  - ❑ Deployment from ISS on the 1st Jul 2020 00:00:00.000 UTC
  - ❑ Assumed deployment: 1.2 m/S in the anti-velocity direction.
  - ❑ Initial altitude= **424.94** km
  - ❑ Different BCs: 1 kg/m2 and 0.5 kg/m2

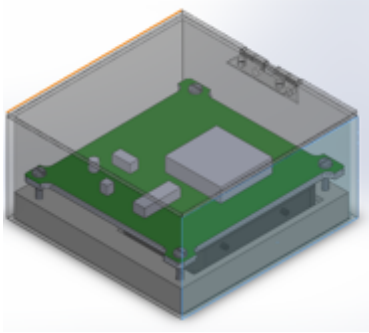
  - ❑ Earth HPOP propagator 21x21
  - ❑ Spherical SRP enabled
  - ❑ NRLMSISE00 atmospheric model with updated F10.7 coefficients



BC=0.5 kg/m^2 Cd=2.2
BC=1 kg/m^2 Cd=2.2

Notes:

- ❑ 0.5 U spacer enclosure
- ❑ Fixed Exo-Brake
- ❑ Single board system design
- ❑ Data can be used to determine Thermosphere structure in detail



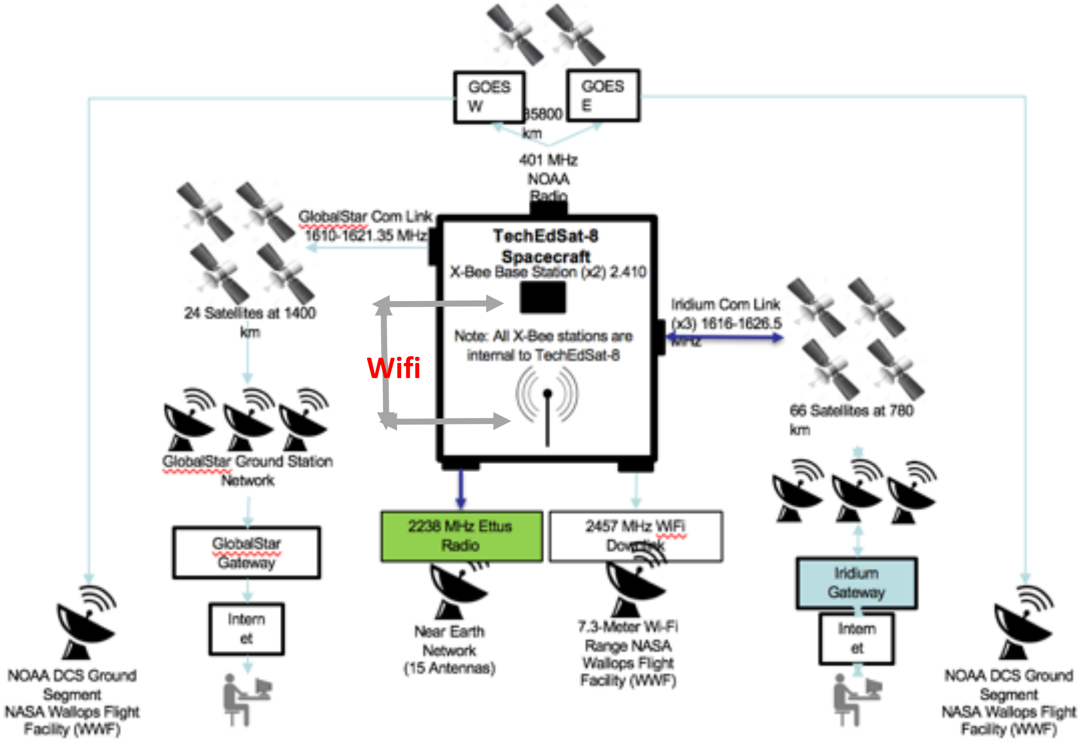
S. Mahmood
A. Dono Perez

PART 3

Communications and Encryption

NASA TechEdSat-8,10 COM Diagram

TES-8,10 COM Architecture (8 emitters; Lunar/Mars Radio Test)



***Also – internal WiFi test**
(transfer of large compressed file from Nvidia to Edison)

- ❑ **NEN-compatible S-band**
  - Uses SDR transmitter (ETTUS) intended for use in one of the EM-1 nanosat payloads
- ❑ **LEO applications**
  - ~15 ground antennas scattered over the globe
  - Increase of the downlink capability of current generation nano-sats
- ❑ **TechEdSat-8,10,-n experiment**
  - Transmit data gathered from the VR (Virtual Reality) experiment, during which >200:1 compression techniques would be used
  - Validate the COM system of a 'pathfinder' EM-1 payload
  - High volumes of optical data would be processed on-board with the NVIDIA TX2 system, compressed, and downlinked.

TES-n Frequency Table

TechEdSat- Radio Frequency Transmission Table Rev B 12/3/19

Transmitter	Frequency Band	Transmit Frequency	Device Model	Maximum RF Power (W)	Manufacturer	Antenna Type	Manufacturer/Model	Maximum Gain (Ant)	Coverage Angle	Polarization	Notes
	GHz	GHz		Watts				dBi	degrees		
Wireless Sensor network	ISM (2.4 - 2.5)	2.410 (ZB CH 12)	Atmel ATZB-RF-233-1-C	0.1	Atmel	stub antenna	used on Atmel ATZB…	1.5	360 omni	linear	One unit - used within payload - does not transmit, receive only. FCC ID: VW4A091729
Wireless Sensor Module	ISM (2.4 - 2.5)	2.410 (ZB CH 12)	TI CC2538	0.005	TI	chip antenna	Cricket v1.3 (Wheless)	2.2	360 omni	linear	Two total - used within payload, FCC Part 15 compliance verified. FCC ID: ZAT2538EM (802.15.4 IEEE/Zigbee Protocol)
Wireless Sensor Module	ISM (2.4 - 2.5)	2.410 (ZB CH 12)	XBee Series 1 Pro	0.1	DIGI	wire lead	XB24-AWI-001	1.5	360 omni	linear	One unit - coordinator/receiver on Crayfish within payload, monitor only, does not transmit - FCC ID: OUR XBEE
Iridium Transceiver 1	L-band (1-2)	1.616 to 1.6265	9602	1.6	NAL Research	Patch	NAL Research SAF7352-IG	5	180 hemisphere	Right Hand Circular Polarization	Transmit and receive, front mounted dual Iridium/GPS antenna, modem tested to FCC CFR47 Parts 2, 15, and 25
Iridium Transceiver 2	L-band (1-2)	1.616 to 1.6265	9602	1.6	NAL Research	Patch	NAL Research SYN7391-C	5	180 hemisphere	Right Hand Circular Polarization	Transmit and receive, side mounted Iridium only antenna, modem tested to FCC CFR47 Parts 2, 15, and 25.
Iridium Transceiver 3	L-band (1-2)	1.616 to 1.6265	9603	1.6	NAL Research	Patch	NAL Research SYN7391-C	5	180 hemisphere	Right Hand Circular Polarization	Transmit and receive, side mounted Iridium only antenna, modem tested to FCC CFR47 Parts 2, 15, and 25.
ISM-Band WiFi Downlink	S-Band (2-4)	2.45 (WiFi CH 10)	SI-G5000UGL	0.72	Alpha/Etekcity	Patch	Taoglas WLP.2450.25.4.A.02	5	180 hemisphere	RHCP	Transmits for downlink only, Alpha product FCC ID: UQ2AWUS036H
NOAA Radio-MARS Radio	VHF (402Mhz)	402Mhz	NOAA/DCS	10.0	NOAA	Measuring tape	ADVANCED TECHCOM INC. / GTX-2.0SS	3	360 omni	Linear	This is an experimental Radio from NOAA
Cubit ISM (902-928)	UHF (0.3-1)	0.915	MSP430	0.01	Texas Instruments	Helical	Pulse Electronics/W3112A	0.9	360 omni	Linear	One unit - externally mounted
LUNAR RADIO	S-band (2280 MHz)	2280 MHz	B200 Mini	5.0	ETTUS	Patch	L-3 SPACE COMMUNICATIONS	4.9	180 hemisphere	Right Hand Circular Polarization	Lunar radio
GlobalStar	1616.25 MHz	1616.250 MHz	Globalstar STX-2 Simplex Modem	0.1		Patch	Globalstar STX-2 Simplex Modem	3	90	Left Hand Circular	**Global Star-FatSat**

NOTE: Cubit will not be integrated on TES10; in future, X-band radio will be added

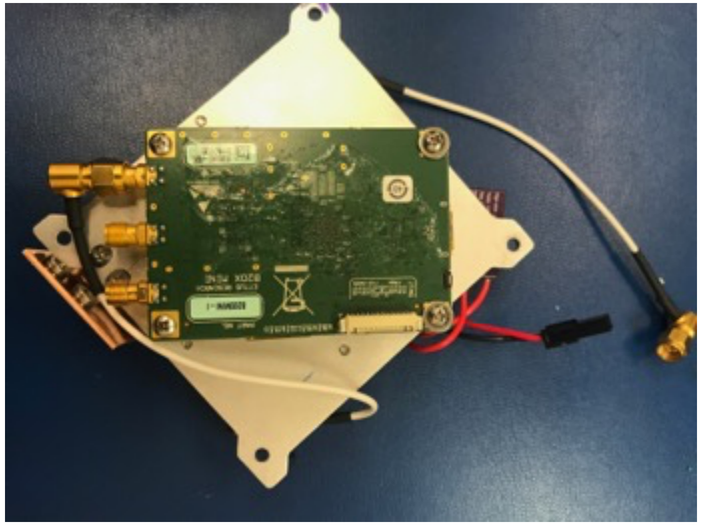
Lunar Radio

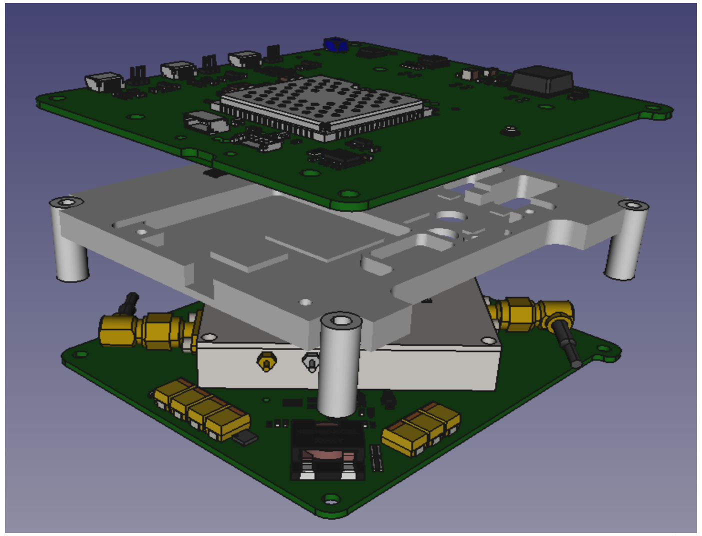
❑ TES-10 – Revision 1

- 3 Mb/s QPSK transmitter, 5W RF output power
- Support for NEN (CCSDS AOS), Compatibility testing postponed due to travel restrictions
- Requires external USB 2.0 or 3.x for signal generation (Intel Edison)

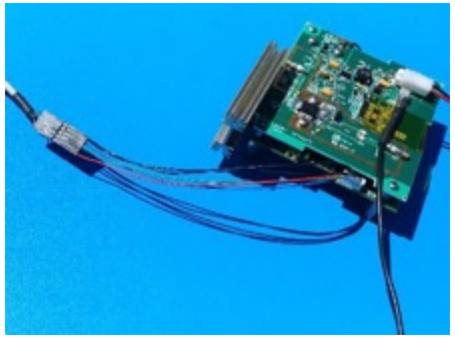
❑ TES-11 – Revision 2

- Better thermal management through aluminum shielding and temperature sensors
- Onboard processor for signal processing and house keeping (current, voltage and temperature sensors)
- Modular amplifier design: support for multiple Wenteq amplifiers footprints (UHF 6W, S-Band 5W)
- **Receiver** hardware included (80MHz to 6GHz), pending software developments for full support.

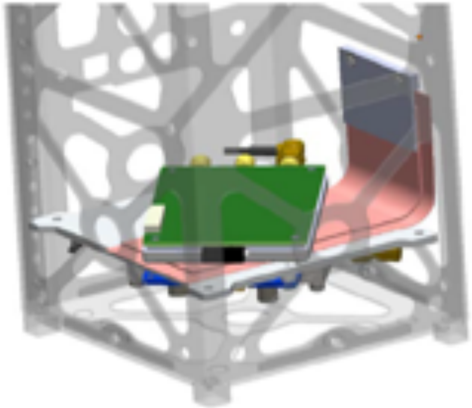




Lunar / NEN Compatibility Radio Rev1



NOAA DCS: Payload Reduction
(A. Salas)



Lunar Radio/ ETTUS
(C. Priscal)

Mars Radio:

401Mhz at 4sec pulses. [Microcom/Bretsill]
300-1200 baud (demonstration of link)
10W RF Amplifier stage
LEO to GEO transmission (GOES-E/ GOES-W)
Doppler effect correction
Transmitter preparation commands– Latitude Entry

- At Mars **401**Mhz ‘downlink’ and **437**Mhz ‘uplink’
- 2W Transmitter BPSK modulation
- Compatible with L3 Electra relays
- Return data rate 32kbps with 9dB margin

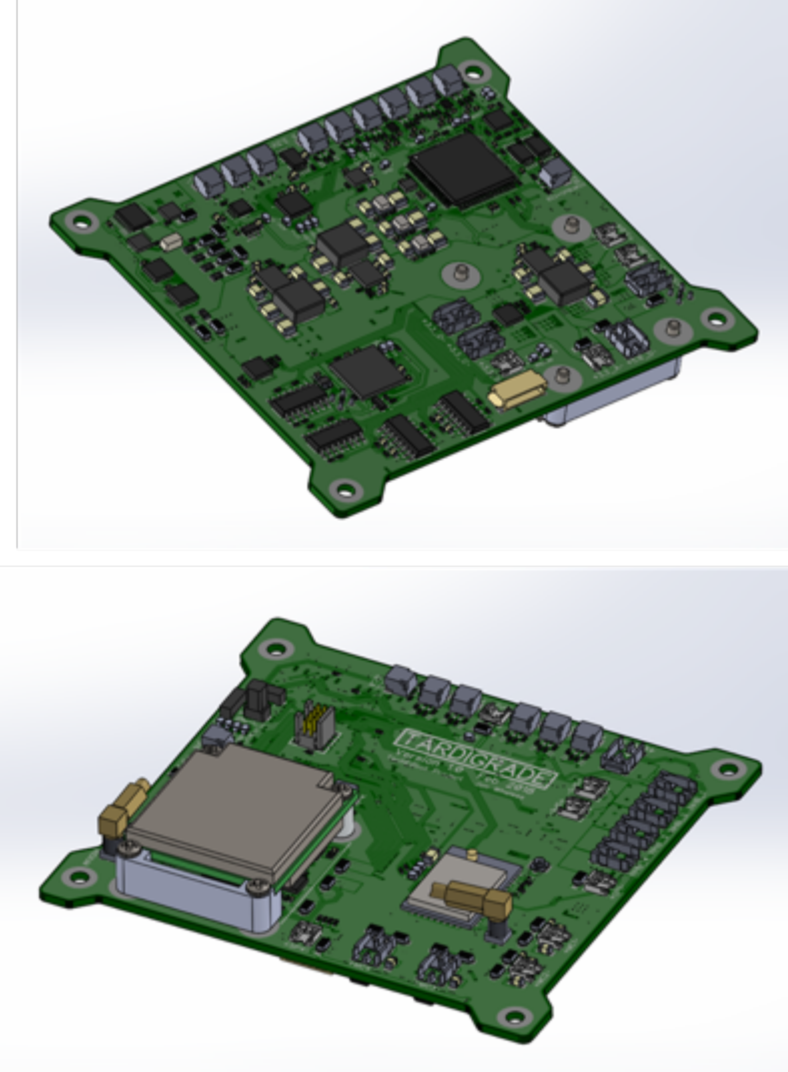
Lunar Radio:

2280 Mhz at 125Kbs. 5W Amplifier stage (ETTUS SDR)
NEN Compatible (possible alternate to DSN at 4x Lunar distance)
LEO test of EM1 payload COM
Reduces pointing requirements (S-band)
Not rad-tolerant but used as dual or back-up

- Next: **5Mbs** to 15Mbs (LEO); 125Kbs at Lunar Transceiver

Tardigrade (REV 2) – ’Rad-tolerant’ Omni-Board

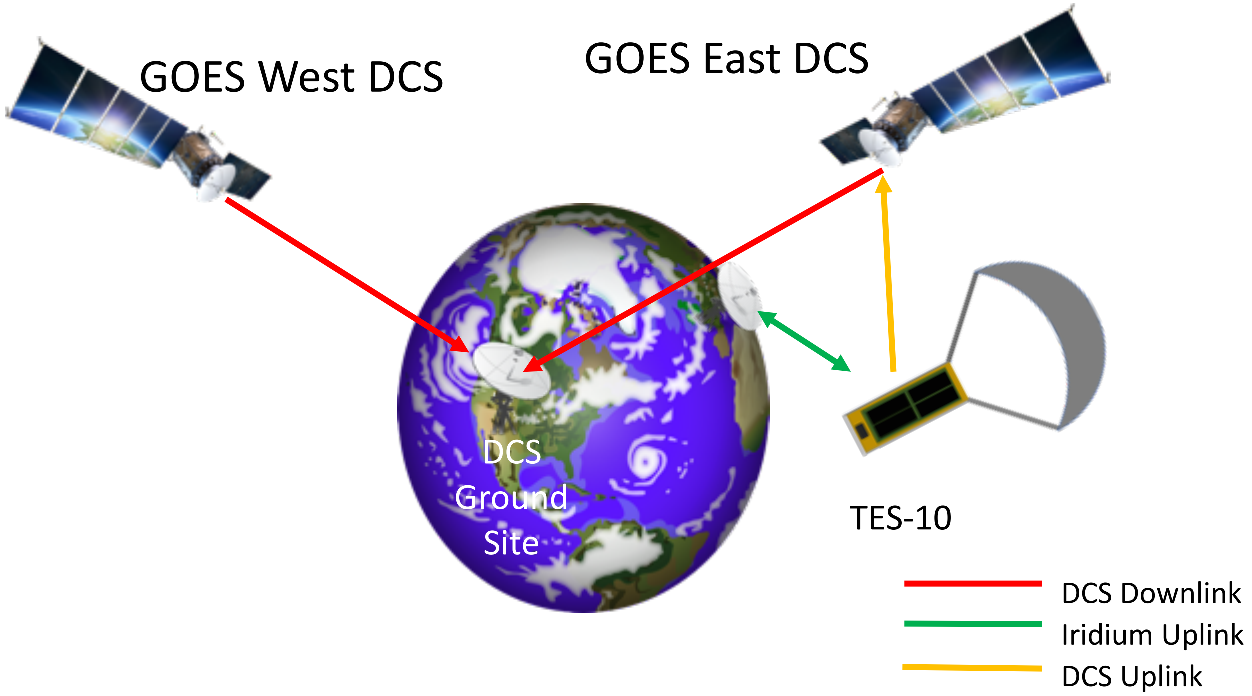
- ☐ Designed to replace current two-board solution
- ☐ Includes VORAGO Rad-hard Cortex M0 microprocessor
  - Running FreeRTOS
- ☐ Communication
  - Back-Up Iridium modem, XBee (2.4GHz)
- ☐ Power
  - 8 regulated, switchable power outputs
  - 4 high-current H-Bridge modules
  - Battery and solar panel current monitors
- ☐ Sensors
  - Back-Up GPS, Magnetometer, 4 thermocouples
  - 16-bit ADC (recession rate sensing, etc.)



J. Wheless (designer)

NOAA Experiment/Mars Radio

Concept: Use the NOAA Data Collection System (DCS) for satellite telemetry and tracking



Mars Radio Option:
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10W RF Amplifier stage
LEO to GEO transmission (GOES-E/ GOES-W)
Doppler effect correction
Transmitter preparation commands– Latitude Entry
    At Mars **401**Mhz ‘downlink’ and **437**Mhz ‘uplink’
    2W Transmitter BPSK modulation
    Compatible with L3 Electra relays
    Return data rate 32kbps with 9dB margin

Note:
TES8,10 Testing in ISS orbit plane (51°)
TES-11 proposed for polar orbit

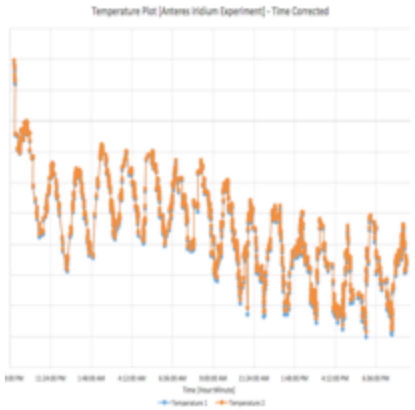
Iridium: Primary Satellite Communication

- ❑ Iridium Network allows for on demand uplink and downlink of data

- ❑ TES-n utilizes Short Burst Data (SBD) modems
  - 340-byte downlink, 270-byte uplink message sizes
  - 9602-I, and 9603-I Iridium modules
  - Goal to utilize the 9523 SBD/Voice modem

- ❑ Successfully used on all missions since TES-2
  - 6 completed missions, 2 upcoming missions

- ❑ **Modems also have firmware to utilize the DISA SECURE network**

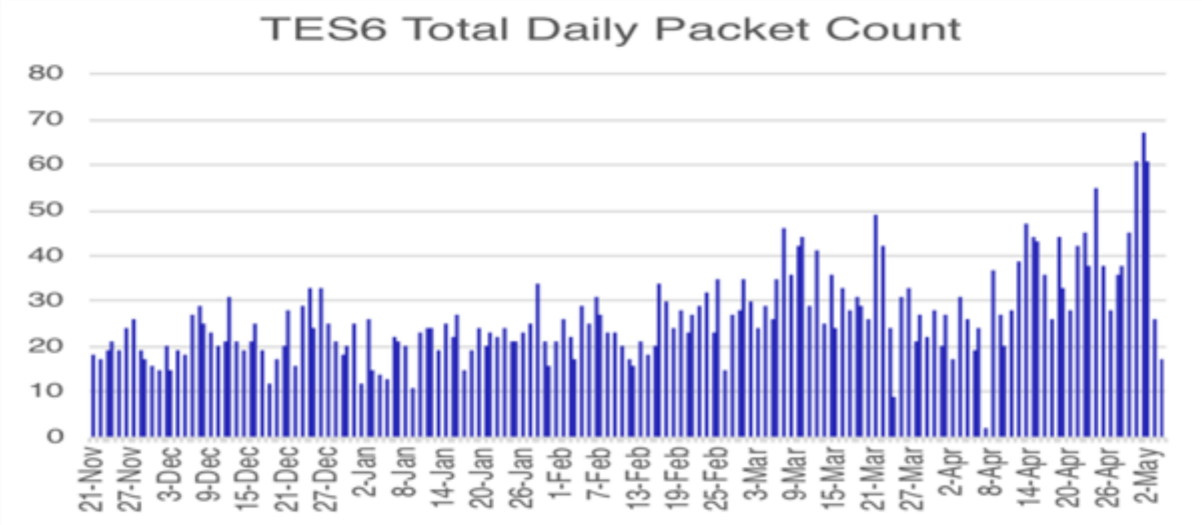


TES-2 Iridium Data

Iridium Statistics

TES 6 – ISS Orbit (51 deg)

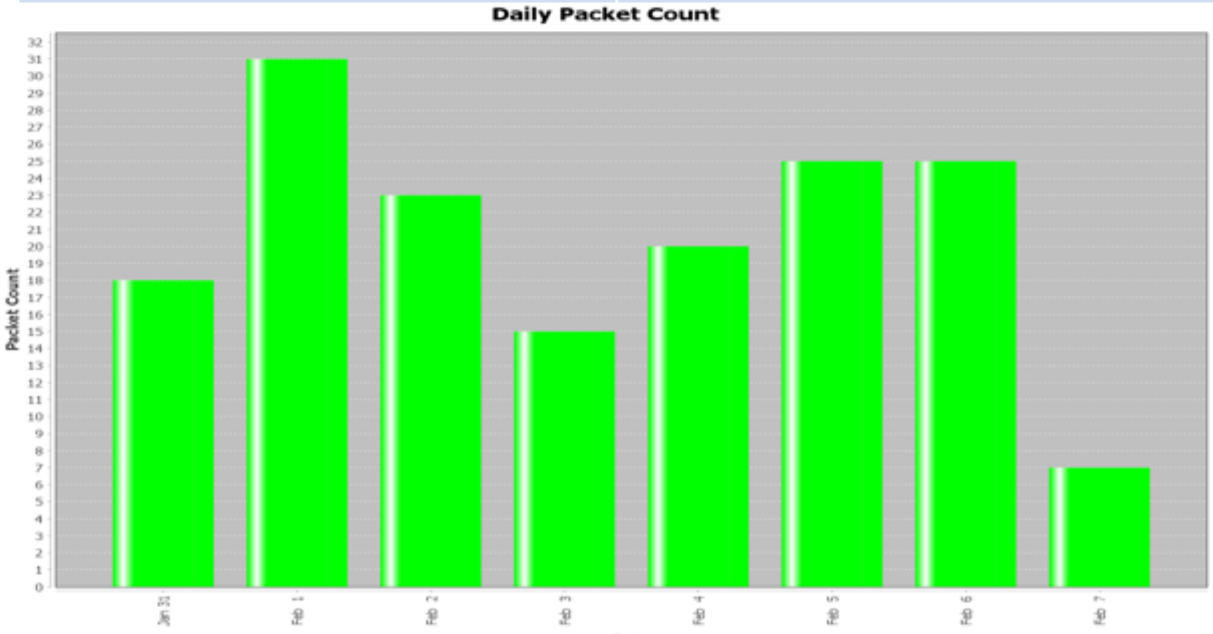
Packet Counts	Powerboard
Total Packets	5168*
Comm Errors	164
Packets/Day	29.5**


TES6 Total Daily Packet Count

*Packets recorded over a 175-day period
**by default a packet was sent once a minute

TES 8 - ISS Orbit (51 deg)

Packet Counts	Powerboard
Total Packets	164*
Comm Errors	3
Packets/Day	20.5**


Daily Packet Count

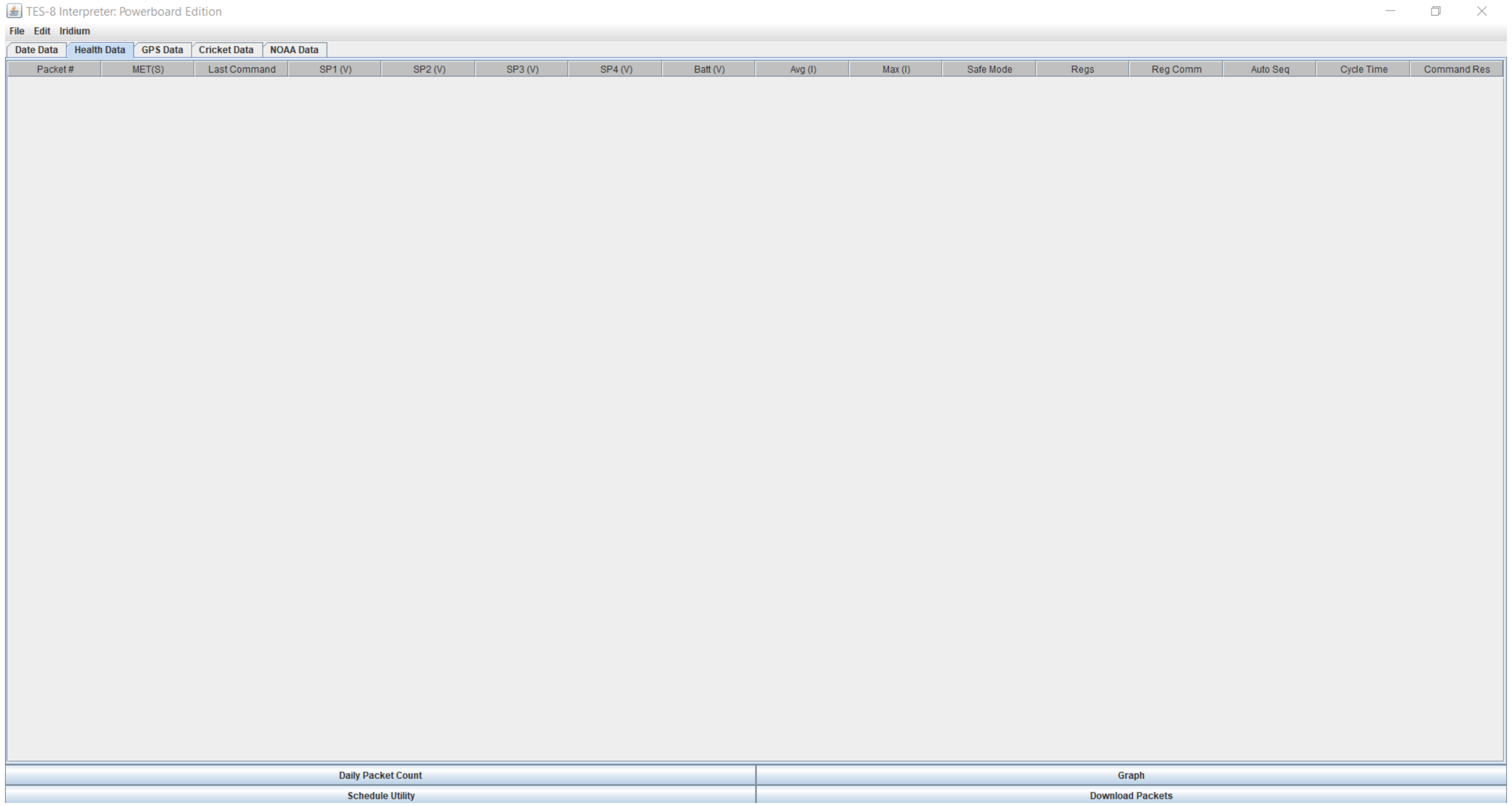
*Packets recorded over an 8-day period
**by default a packet was sent once a minute, but most packets were sent with 20-minute delays

Future flights will be in a polar orbit

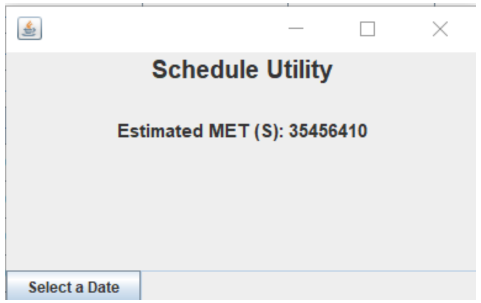
- Expect better signal and completed handshakes

Iridium Telemetry Dashboard

- ☐ Telemetry packets were sent through currently through email
  - Averaged about ~50 bytes per packet
- ☐ Dashboard downloads, parses and displays the telemetry data
- ☐ Contains useful utilities for managing the TES Missions
  - Helps schedule commands
  - Graphs telemetry data
  - Exports data for further inspection

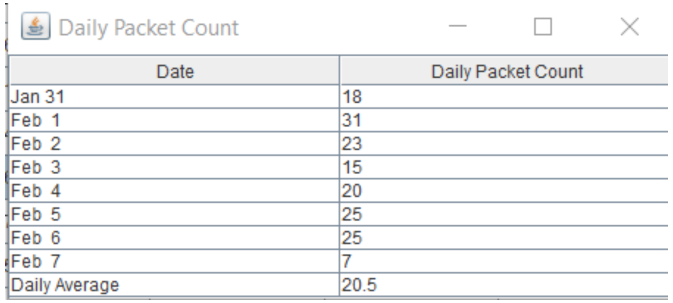


Packet #	MET(S)	Last Command	SP1 (V)	SP2 (V)	SP3 (V)	SP4 (V)	Batt (V)	Avg (I)	Max (I)	Safe Mode	Regs	Reg Comm	Auto Seq	Cycle Time	Command Res



Schedule Utility

Estimated MET (S): 35456410

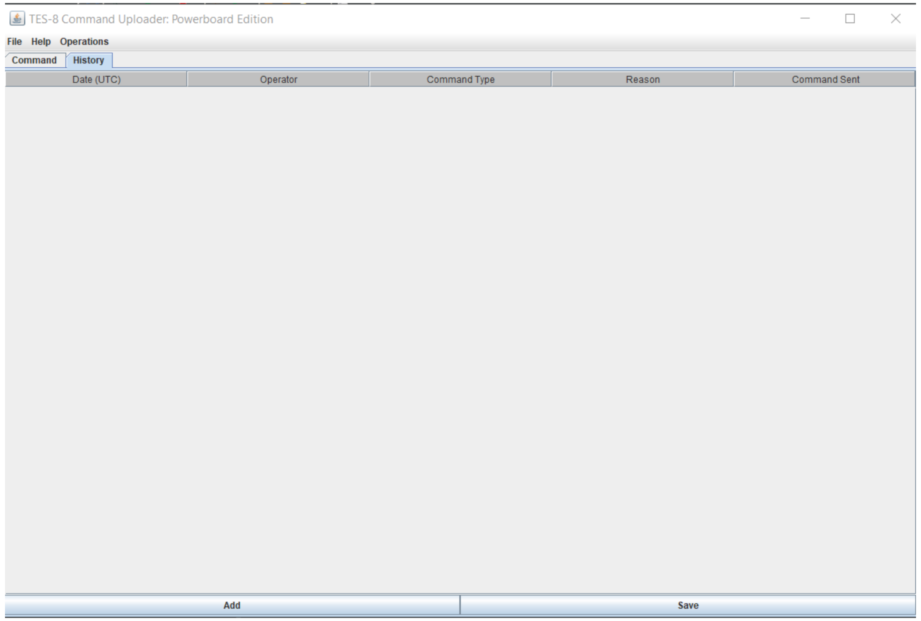


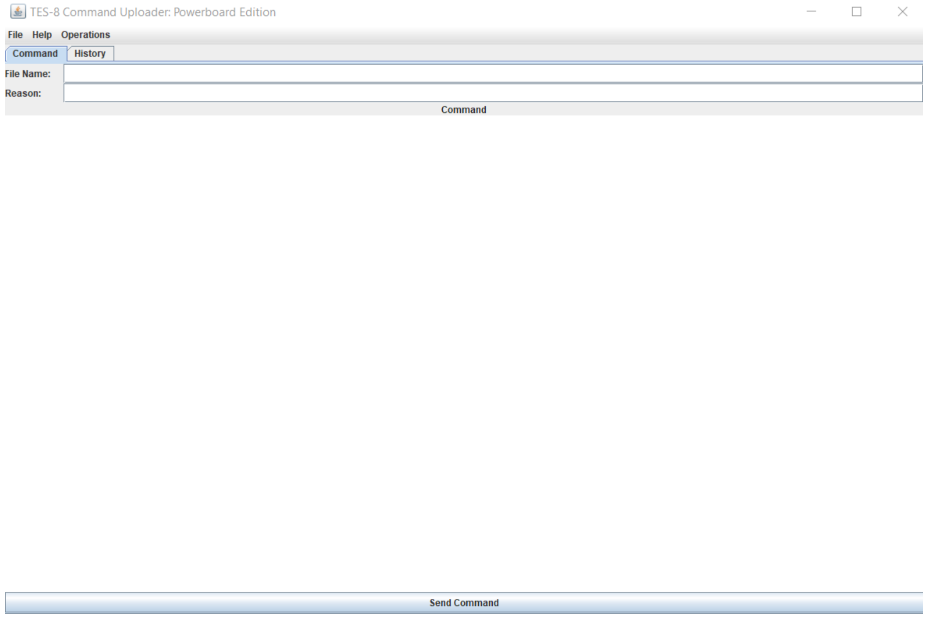
Daily Packet Count

Date	Daily Packet Count
Jan 31	18
Feb 1	31
Feb 2	23
Feb 3	15
Feb 4	20
Feb 5	25
Feb 6	25
Feb 7	7
Daily Average	20.5

Iridium Command Uploader

- ❑ Iridium allows for Command Uplink
- ❑ The command uploader handles the creation of an iridium packet and sends it to the satellite
- ❑ Contains several useful utilities for sending commands
  - Command builder lets the user create commands without needing to know specific command formats
  - Command documentation lets the user determine what each command does
- ❑ Documents each command sent so the mission has a complete command log

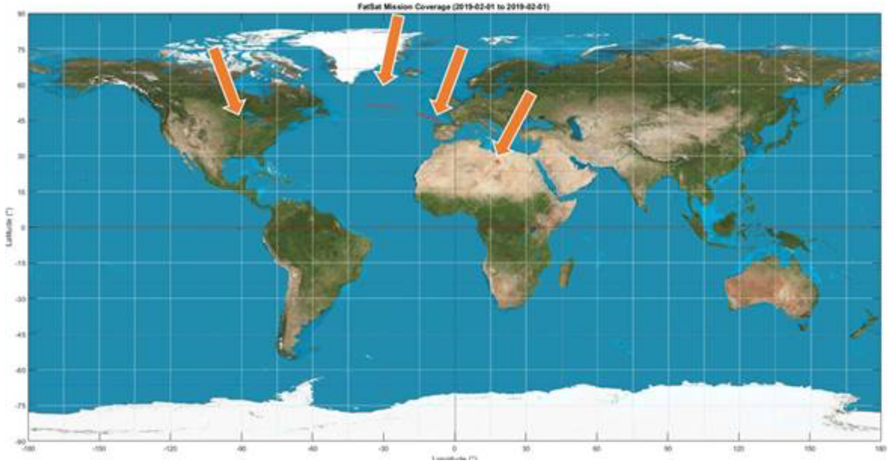




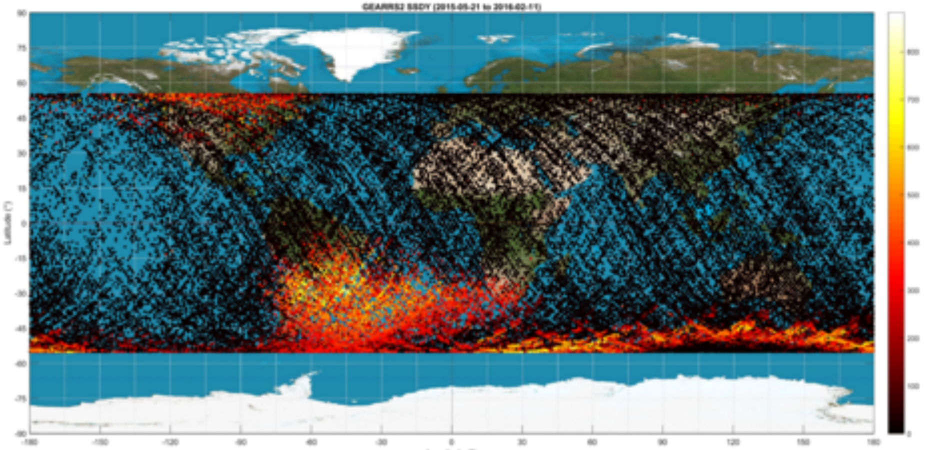
Globalstar Network

- ❑TES-8 was the first TES mission to contain a Globalstar experiment
- ❑Second iteration of the experiment will fly on TES-10
- ❑Comparison of data to Iridium from same s/c surface (transmit only)
- ❑Eventual comparison of duplex Globalstar transmitter

SIMPLEX transmitter results on TES-8 flight



SIMPLEX transmitter example (courtesy: NearSpace Launch Inc)



NSL Satellite mapping of the energetic particles (E>100 KeV) for some orbits. Note the SAMA region and the auroral oval in the south and north. The data is broken up (duty cycle) to save power.

TES 8 Globalstar Results	
Radio On Time (Minutes)	45
Packets Collected	35
Data Collected (Bytes)	630

Iridium and Globalstar Comparison (TES-10)

☐ One of the experiments for TES-10 is to compare the Iridium and Globalstar networks.

- The Globalstar payload will be turned on at the same time as the secondary Iridium payload.
- The Iridium patch antenna and global antenna will be facing in the same direction.
- Each radio will be left on to see how many successful handshakes are completed.

☐ Note:

- GlobalStar does not have duplex modem that can easily be integrated into a cubesat (10x10cm form factor), unlike Iridium that offers multiple small duplex modems.
- **Iridium has a a SECURE path through the DISA network, but Globalstar has no such option.**

Other COM Experiments

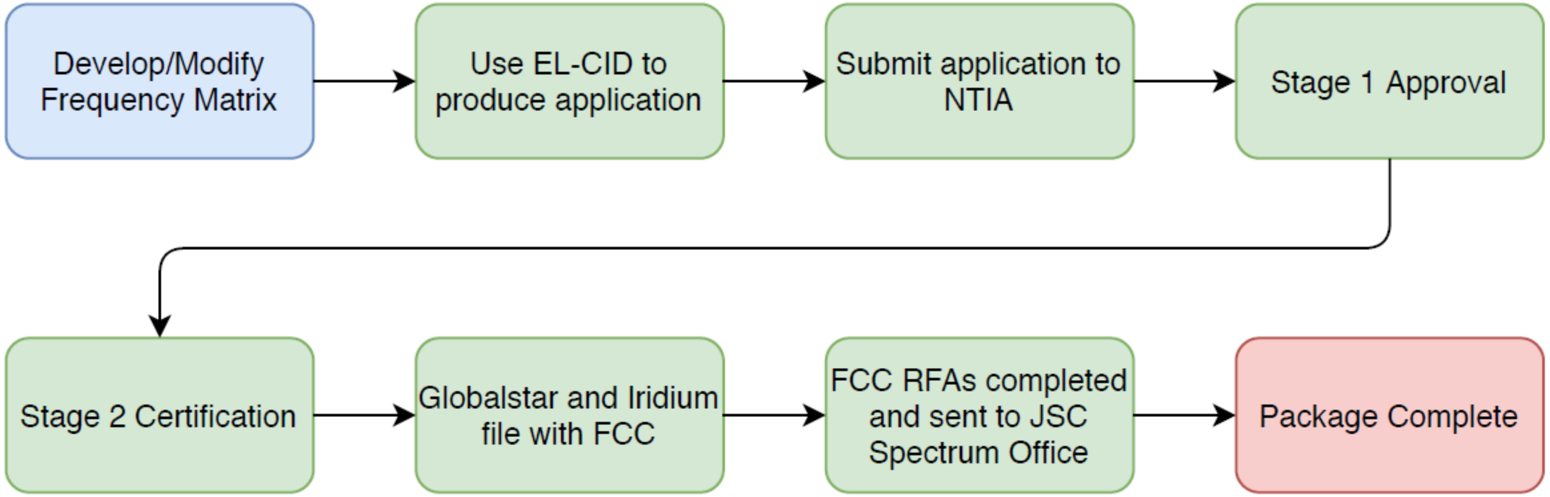
- ☐ Mars Radio Paths (1,2): 402 Mhz Uplink/ 436Mhz Downlink
  - Micro-Com modification
  - SDR experiment (version of Lunar Radio/Priscal)

- ☐ X-band
  - Use of TES-n as higher energy test-bed
  - High power supply and heat-pipe in development

- ☐ Laser-com tracking experiment (DENI diode experiment)

- ☐ Various nano-sat identification systems
  - CUBIT-3 (RFID)
  - Radar-based

NTIA/ FCC Process Diagram



Develop/Modify Frequency Matrix

Use EL-CID to produce application

Submit application to NTIA

Stage 1 Approval

Stage 2 Certification

Globalstar and Iridium file with FCC

FCC RFAs completed and sent to JSC Spectrum Office

Package Complete

Notes

- Once the NTIA Stage 2 certification is complete, the commercial constellations can then submit a request to the FCC for an experimental temporary license

- Effort is being made to further **streamline** the NTIA process for the TES-n series. Once the frequency matrix is set, and the NTIA authorization is in place – the other entities can refer to the previous submittal directly.

Encryption Strategy

1. Secure Iridium DISA (Defense Information Systems Agency) Gateway
   - ☐ Utilize the encrypted version of the iridium modems that already in use on TES COMM boards
     - Encryption Service requires a firmware update on the modems, and coordination with DISA
   - ☐ Easiest path as the DISA network will handle the secure/encryption process
     - Will not require new hardware or software to integrate
2. Simple Encryption
   - ☐ Utilize a lightweight encryption algorithm that can run on every TES microcontroller
     - Speck Algorithm: block cipher, developed by the NSA, well suited for IOT devices
     - Every core payload can encrypt/decrypt without depending on other processors/boards
   - ☐ Allows us to quickly and efficiently encrypt/decrypt the small amounts of data we send through iridium

     Note: that the algorithm will not meet the NIST FIPS140-2 standard
     - Meant to be an initial step toward our encryption plan, and eventually combined with other strategies
3. Dedicated Encryption Payload
   - ☐ Develop a payload that to encrypt and satellite data using approved encryption algorithm (AES-256)
     - Either utilize one of the existing higher end microprocessors, or develop a new payload for this task

Ames Research Center

Encryption Roadmap

Phase 1

- Integrate **Secure Iridium** Network with existing modems
- Implement Simple Encryption
- Quickly tests the ability of the TES system handle encryption with uplink commands, and downlinked packets

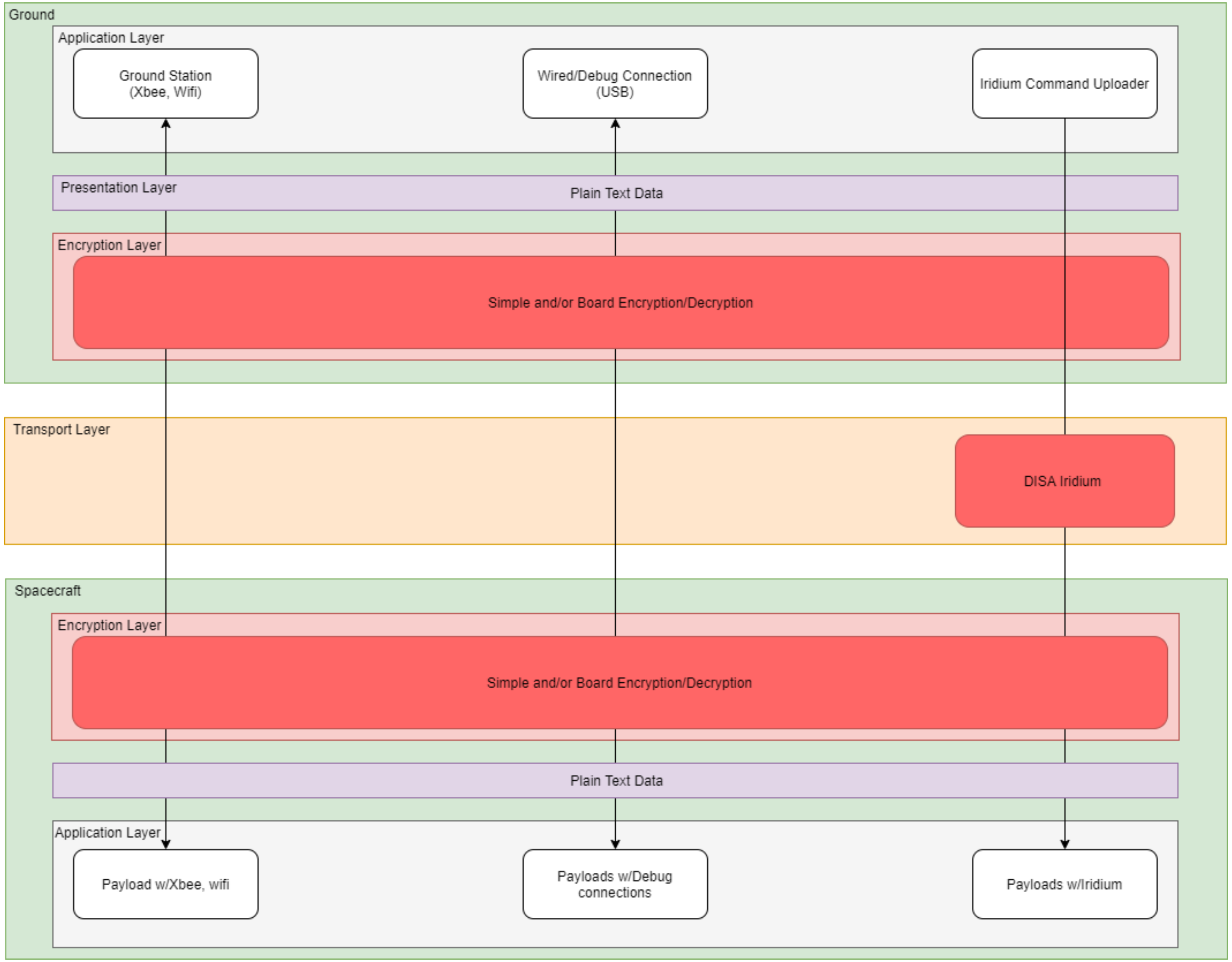
Phase 2

- Continue to use **Secure Iridium** network
- Test an encryption payload with options; collect statistics

Phase 3

- Utilize a combination of **Secure/Encrypted Iridium** with either simple encryption or encryption payload
- Combine final encryption with other experiments (e.g., propulsion)

Satellite Con-Ops with Encryption



TES-7,10: On Deck!

❑TES-10 will be jettisoned as early as April – but could be May/June

- Relevant objectives: Demonstrate the DCS link and baseline [power subsystem fully demonstrated], NVIDIA, heat-pipe thermal, WiFi demo, Lunar radio, modulated Exo-Brake..

❑TES-7 will be on the Virgin Orbit CSLI launch in ~ May/June (TBD). **

- Relevant objective: Demonstrate the use of the Iridium SBD in polar orbit, mini-GPS.
- Will require a Pre-Shipment Review ~April 15?
- Status: Could deliver 'next week'; FCC/Iridium re-authorization (2yr); high-efficiency solar panel

**Note: This was a next important experiment. Greater improvement is expected than at the 51deg inclination – which is still FAR better than depending on ground stations. Also – if successful, it would obviate the 'OPS-trap' of other nano-sats [this is a KEY advantage of the multi RF links that the TES-n use as critical back-up]

Ames Research Center

Upcoming Confirmed/Potential

☐ **TES-9,11:** W-6U on L9EFS (Landsat-9). **(Slots Confirmed)**
- Wide form-factor; known interface
- 500-550km Polar
- TES-9 CALSAT
- TES-11 Propsat

☐ **TES-12** **(Slot Confirmed)**
- Launcher/date TBD
- CSLI Award 3U slot expandable to L-6U (like TES-8,10)
- Flight in 2021 and/or as possible ‘hot’ spare

☐ **TES-13** (Not Confirmed)
- Virgin Orbit flight #2; 500km Polar orbit
- 3U

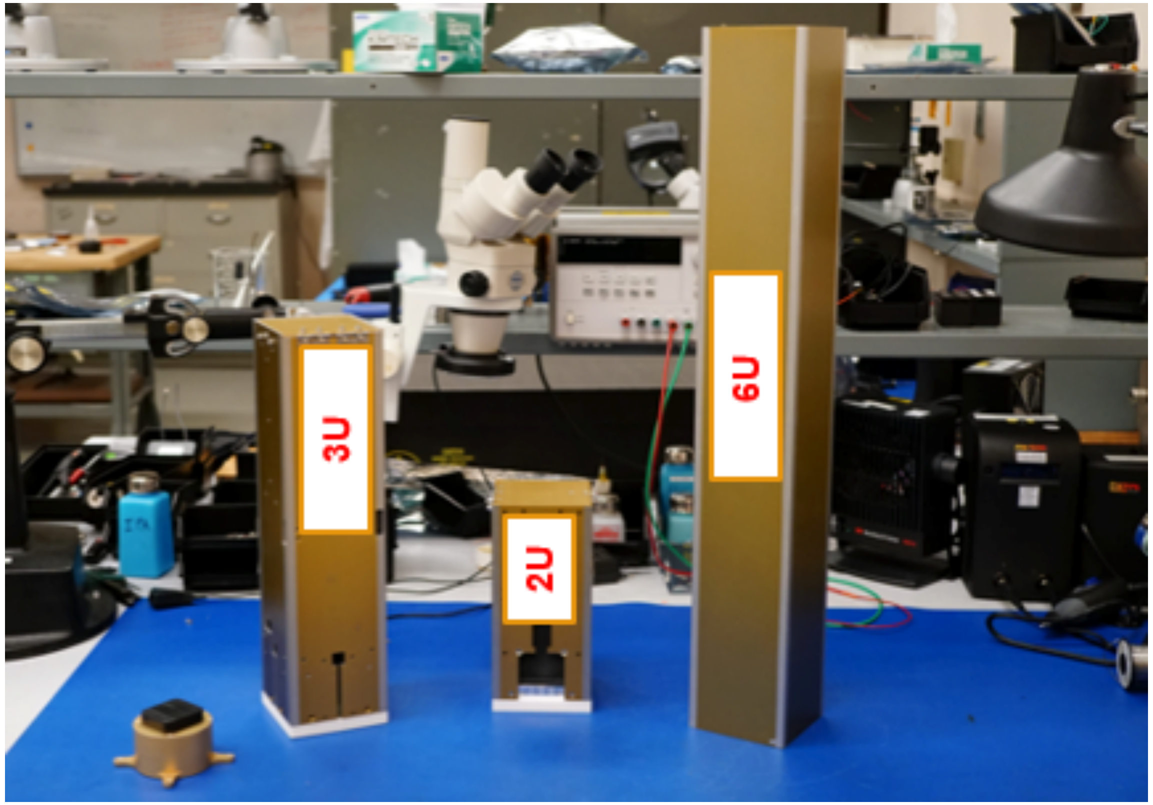
☐ **TES-14** (Not Confirmed)
- 0.5U Thermosphere Test Probe (TTP)
- Launch of opportunity 2020-2021 (a ‘spare’)

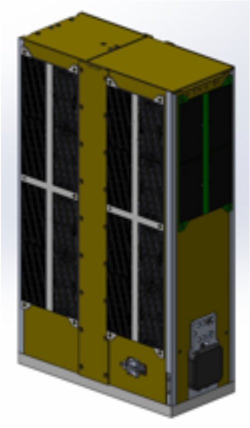
☐ Other: ARCxSAT (SPQR deployed from ISS/NanoRacks Bishop Airlock)

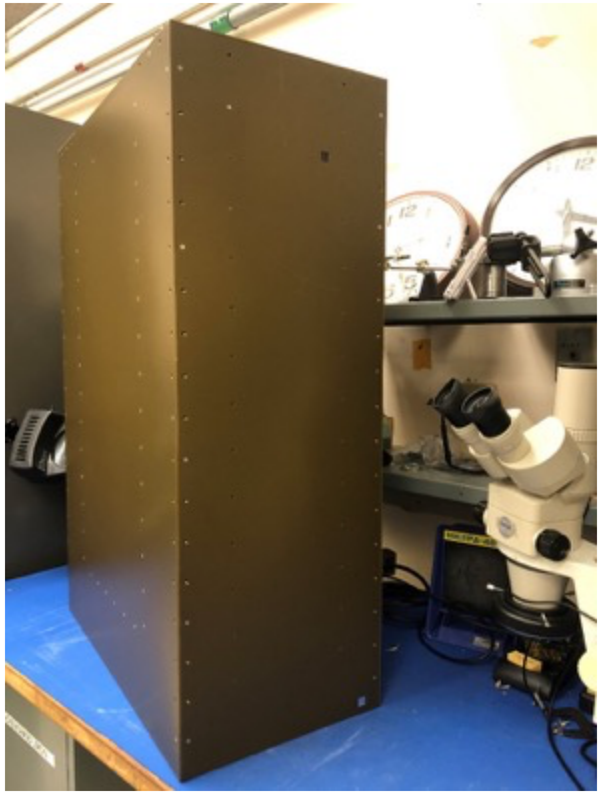
New Directions/Innovation:

Encryption techniques
Nano-sat identification systems
Compact High Energy Power System
Advanced Solar Panels/Cells (32%; flexible)
Tardigrade II (Rad-tolerant Vorago Omni-board
Lunar Radio II (NEN demonstration)
Mars Radio II (two paths)
Exo-Brake III (Autonomous de-orbit navigation)
Higher computation capability / AI exp (NVIDIA)
Heat-pipe II
Propulsion test bed
Etc.
NOW (Nano Orbital Workshop) generic platform

Future Experiments: Optional Sizes







Adaptability-
Sizes: Cup (TES2), 3U (TES3-6), 2U(TES7), 6U(TES8,10),Double Wide 6U (TES9,11), TES-SP (140U)

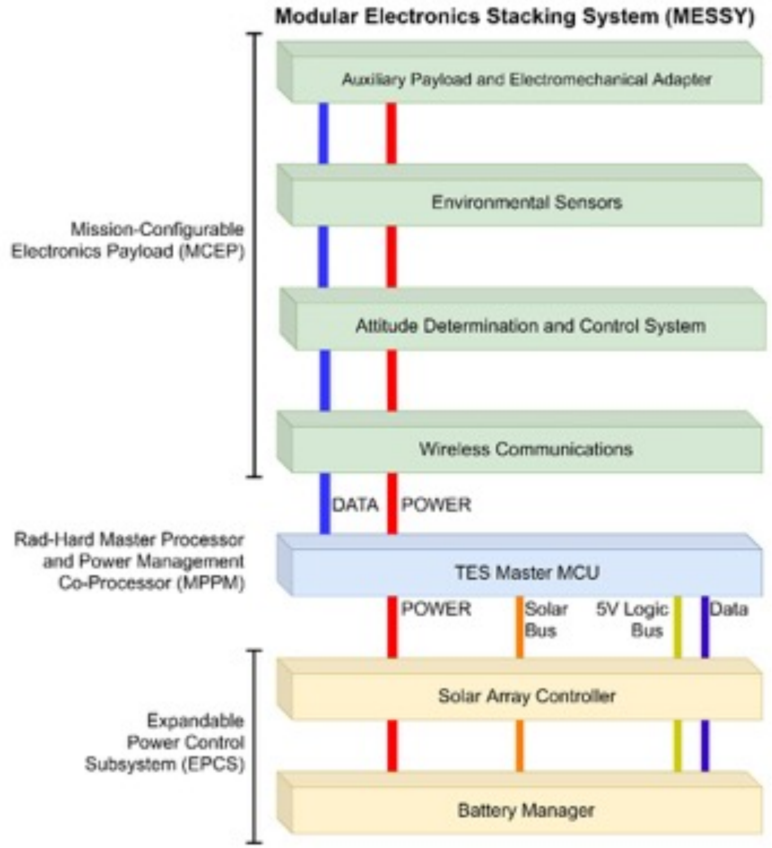
Future Experiments: NanoSat Architecture Options

A. TES Internal Network

- Enables the TES payloads the ability to communicate with each other using a new standard network packet
- Establishes a more redundant system by allowing commands and telemetry packets to be sent to any board in the stack, and routed to their destination
- Eventual goal is to develop a wireless satellite and eliminate the need for data wiring

B. Modular Electronics Stacking System (MESSy)

- New electronics architecture to replace current hand-wired stack with a backplane-less modular stacking architecture
- Robust power system and 12V system bus allows for 750 watts of payload power
- Radiation-hardened system processors and critical systems redundancy to improve craft survivability
- Will allow for rapid stacking and customization of electronics for each satellite



M.E.S.SY. Full System Stack Diagram
Avery Brock
NASA ARC Code RE
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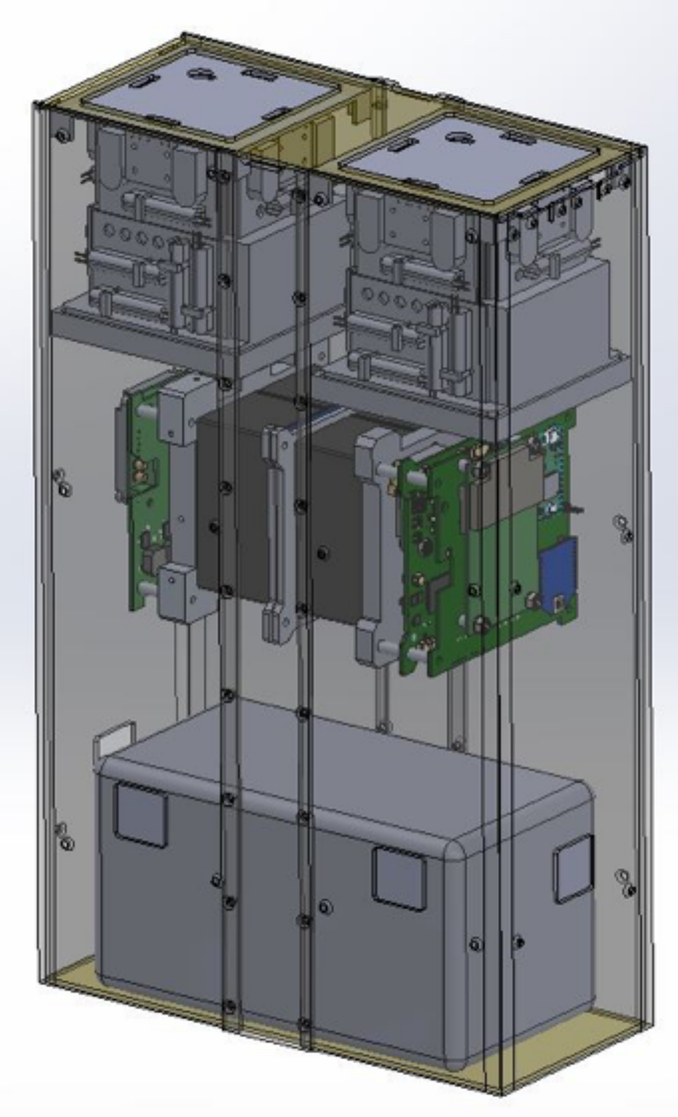
Generic Propulsion Platform Effort



Under study:

- ☐ Unique W-6U layout
- ☐ Candidate for TES-11 opportunity
- ☐ Dual water-based propulsion experiment
  - Miles-Space/EM1 experiment*
  - 4 mN/sensor head (8mN total)
  - >90 mins of operation (1 orbit)
  - High energy-density power system (150Whr)
- ☐ Encryption uplink for command/control
- ☐ Dual omni-board for redundancy
- ☐ L-band (Iridium) and s-band to NEN downlink
- ☐ NOAA DCS polar orbit experiment

- ☐ Panel shapes and stack elements are subject to design changes
- ☐ Magnetorquers will be integrated

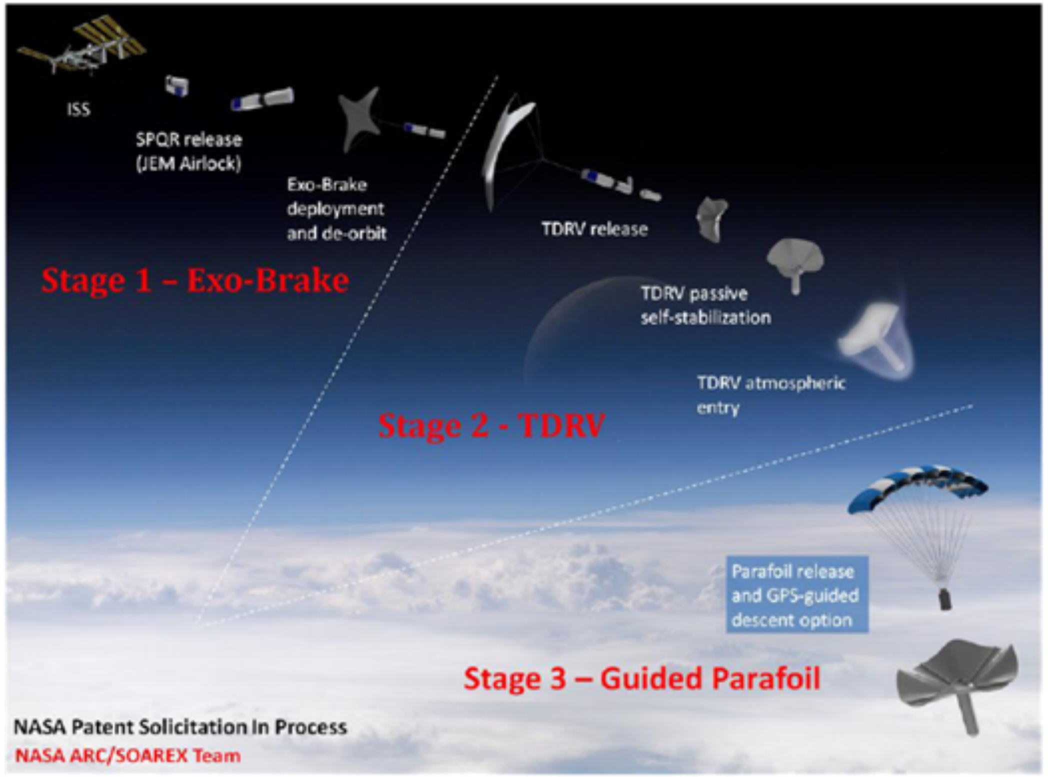
*Reference: Constant Q thruster, (W. Faler) US patent 9,856,862

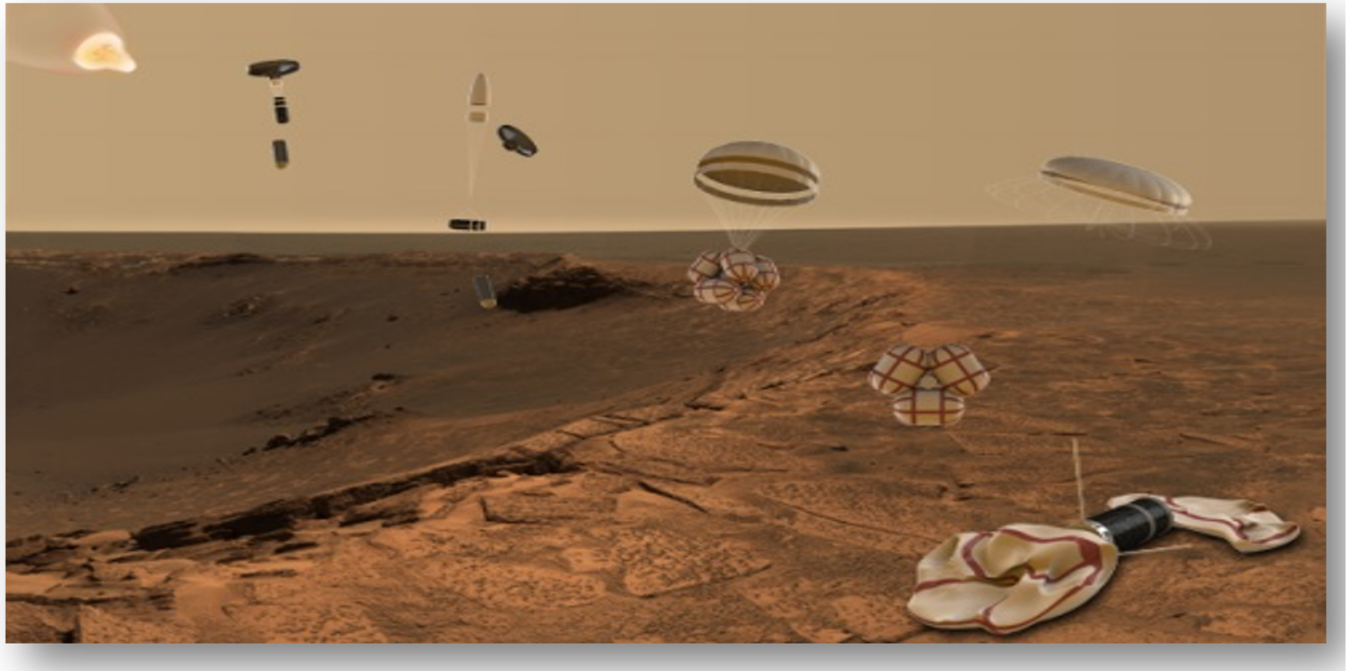
Other Applications: MARS/ Sample Return

ISS EDL Capabilities For Future Missions

SPQR-Small Payload Quick Return

- ❑ **3-stage concept**
- ❑ **Develop and test inexpensive deep-space and Mars surface science technologies/missions**





Atromos: Cubesat Mission to the Surface of Mars (SALMON)

Mission Attributes

- ❑ Self-stabilizing re-entry probe (TDRV-Tube Deployed Re-Entry Vehicle)
- ❑ EDL technique for small probes
- ❑ Radio-isotope option for mission longevity

Summary

- **TES-n/Nano-Orbital-Workshop (NOW) TEAM**
  - 25 years of balloons, sub-orbitals, orbitals…
  - Educational/Tech advancement tool – yet advancing numerous key technologies
  - Variety of sponsors, collaborators, universities involved
  - High level of rigor due to ISS Safety aspects (MA follows S – but closely!)

  YET, we are FAST because we *design, build and incrementalize* our own designs/equipment (hence, **no long procurement cycles!)**
- **General Hardware Design**
  - Fast- increment development due to in-house board designs
  - Unique suite of micro-processors (Arduino to NVIDIA TX2) with known performance to heavy-ion beams/ time-in-orbit (SEUs)
  - Development of an 'ISS-safe' compact high energy power subsystem will enable high power experiments (radios, propulsion, etc.)
- **COM Advances**
  - Both Constellations (Iridium, Globalstar) are to be used/ compared in a future flight [both 'may' be a ''TDRS for nano-sats']
  - Lunar and Mars Radios (LEO – GEO NOAA DCS experiment)
  - External and internal use of WiFi, IoT, and RF-ID/ Optical devices are being investigated
- **Encryption**
  - Several paths being investigated – with different levels of difficulty in implementation
  - Encrypted Iridium SBD path may be easiest to implement
- **Upcoming flight experiments**
  - **Finished:** TES-10 (ISS now); TES-7 (Virgin Orbit polar launch)
  - **Development:** TES-9,11 (Polar orbit),12, 13 in planning (3-4 flights in subsequent 8 months)

Basketball Team!!

Images courtesy of NASA Ames

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