PACE V-R3x
S3VI CoP Webinar

Stanford & Carnegie Melon University REx Lab

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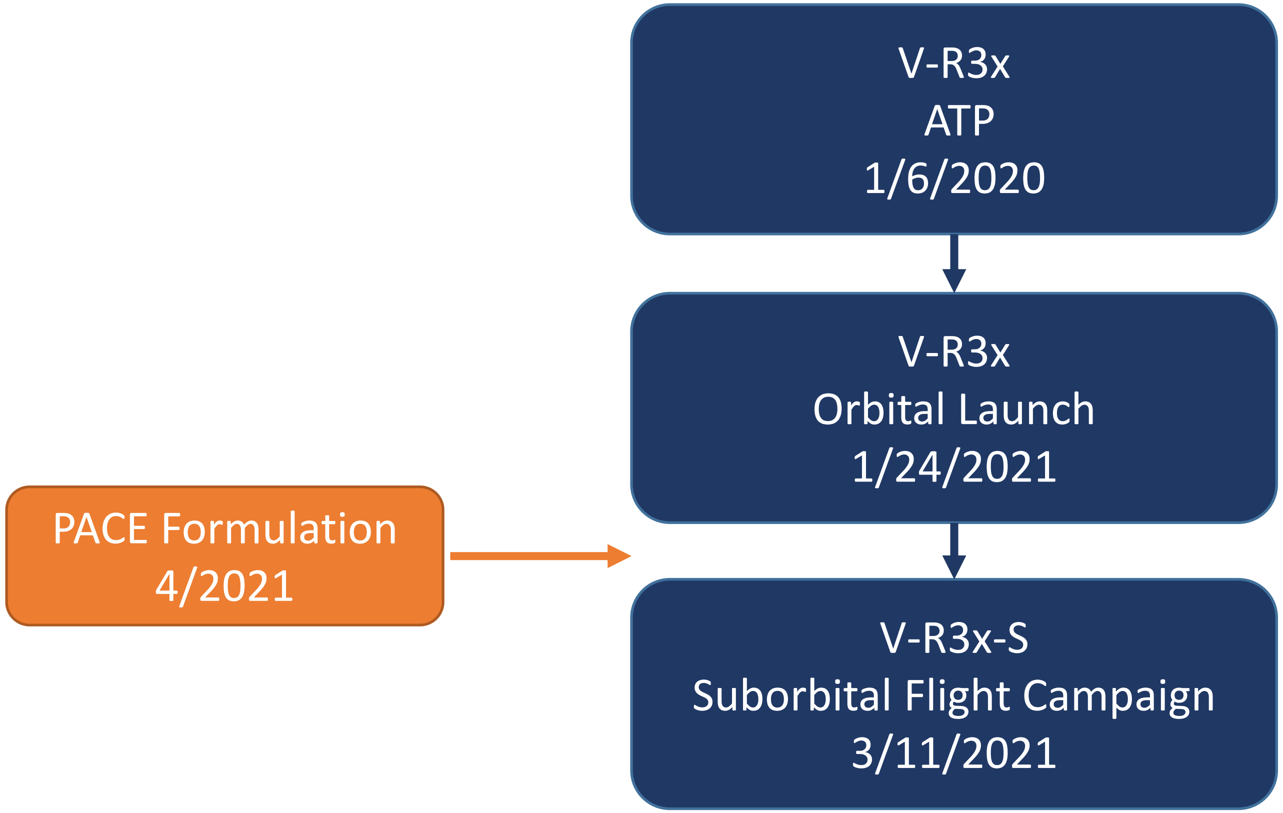
11/10/2021

Agenda

- V-R3x Orbital Summary
  - Tech Demo Overview
  - Objective Tracking
  - Lessons Learned
- V-R3x Suborbital Summary
  - Tech Demo Overview
  - Objective Tracking
  - Lessons Learned
- Overall Summary
  - Lessons Learned for overall PACE pipeline
  - Path forward

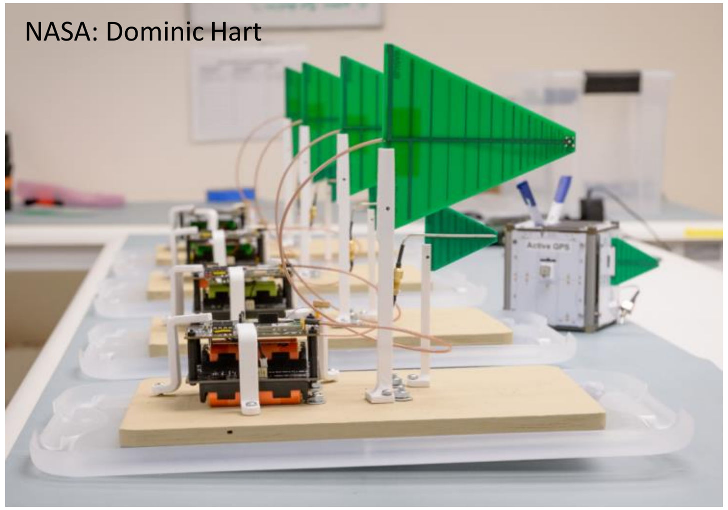
Project Summary



Orbital vs Suborbital Comparison

Description	V-R3x Orbital	V-R3x-S Suborbital
# Units	3	5 (1 Balloon + 4 Ground)
Launch Date	1/24/2021	3/11/2021
Target Altitude	525 km, SSO	30.48 km (100,000 ft)
Mission Ops Duration	6 mo.	2 hrs at float (5 hrs total)
Requirements	• S-band High Precision Ranging • S-band High Data Rate Cross-link • Relative Topology Recovery • Distributed radiation sensor collection	• S-band High Precision Ranging • S-band High Data Rate Cross-link
Networking	Mesh Network w/ 3 nodes	Mesh Network w/ 5 nodes

V-R3x Orbital



V-R3x Suborbital

V-R3x Team

Roger Hunter
SST Program Manager
NASA

Anh Nguyen
Project Manager
NASA Ames

Zac Manchester
Principal Investigator
Stanford/Carnegie Mellon University

Max Holliday
Systems Engineer
Stanford

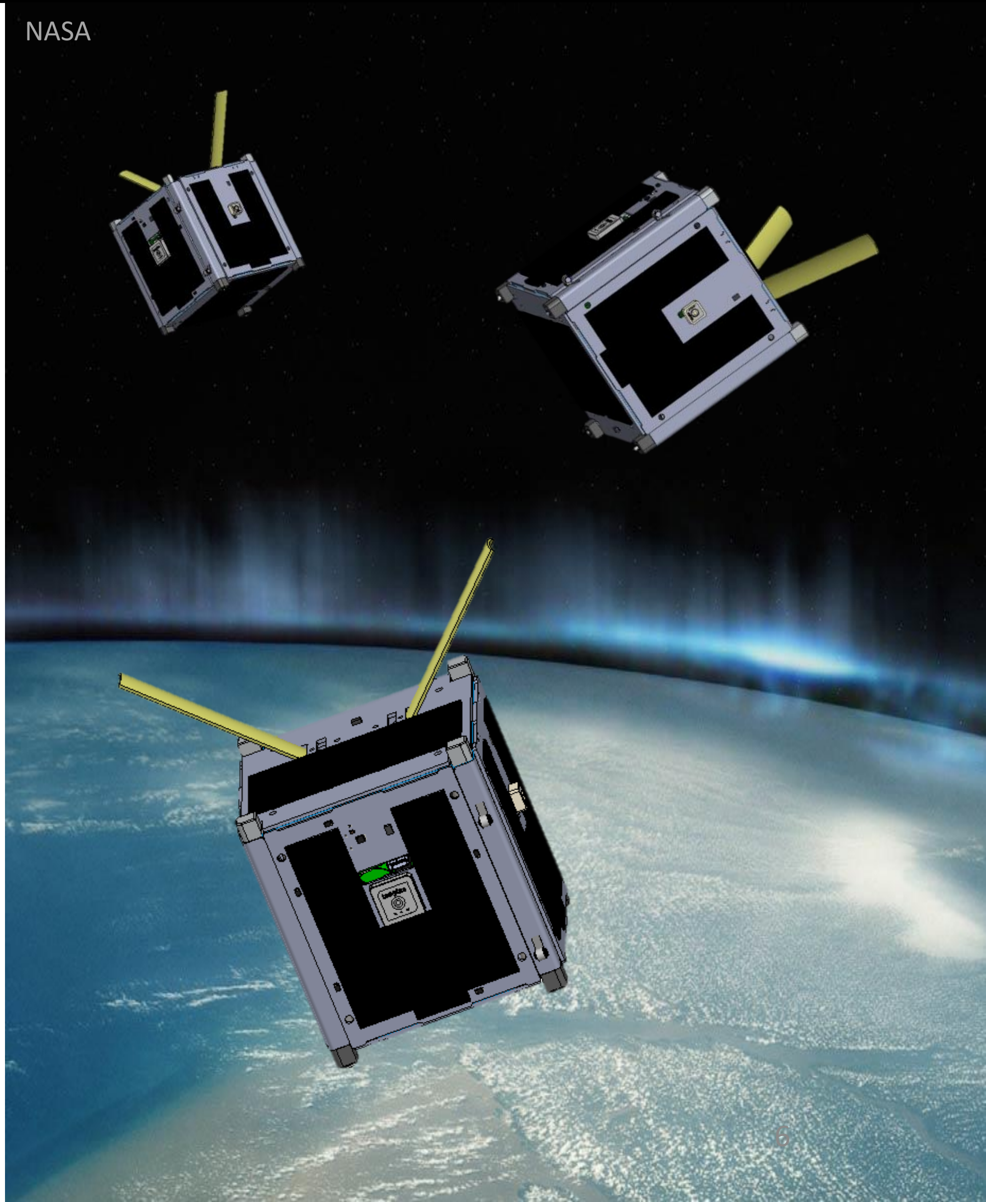
Adam Zufall
Systems Engineer
NASA ARC-MEI

Dallas White
SMA
NASA ARC

Kevin Tracy
Flight Dynamics
Carnegie Mellon University

V-R3x Tech Demo Overview

Stakeholders	NASA STMD-SSTP
Classification	X-Project
NASA Project Manager	Anh N. Nguyen NASA Ames Research Center
Principal Investigator	Zachary Manchester Stanford University
NASA Systems Engineer	Adam Zufall NASA Ames Research Center
Stanford Systems Engineer	Max Alvarez Holliday Stanford University
Project Description	Low-power low-cost spacecraft ranging, topology recovery, and coordinated measurement demonstration for future spacecraft swarm systems
ATP	Dec 20, 2019
Launch Readiness	Dec 14, 2020
Launch	Jan 21, 2021 – Space X Transporter-1 Mission, Florida
Tech Demo Duration	3 mo. threshold/baseline; 11 mo. extended
Total Project Cost	<$500K (including launch)
Status	Launched



Key Milestones

- 12/03/2019: Initial Brainstorming session
- 12/16/2019: SSTP Proposal
- 01/06/2020: ATP - Project Start
- 01/31/2020: Tech Demo Briefing (SPO, ACE, R Mgt, NTIA)
- 03/09/2020: COVID-19 Shutdown Start
- 05/18/2020: PDR/CDR
- 07/06/2020: Return to Site Authorized
- 12/03/2020: FRR
- 12/14/2020: Launch Readiness
- 01/03/2021: LV Integration
- ~~12/18/2020~~ ~~12/30/2020~~ ~~1/14/2021~~ 1/21/2021: Launch
- 1/21/2021: Mission Operations Begin (Nominally 3 mo., NTE 11 mo.)

Concept to Launch Readiness in 12 mo.

Concept Of Operations

NASA

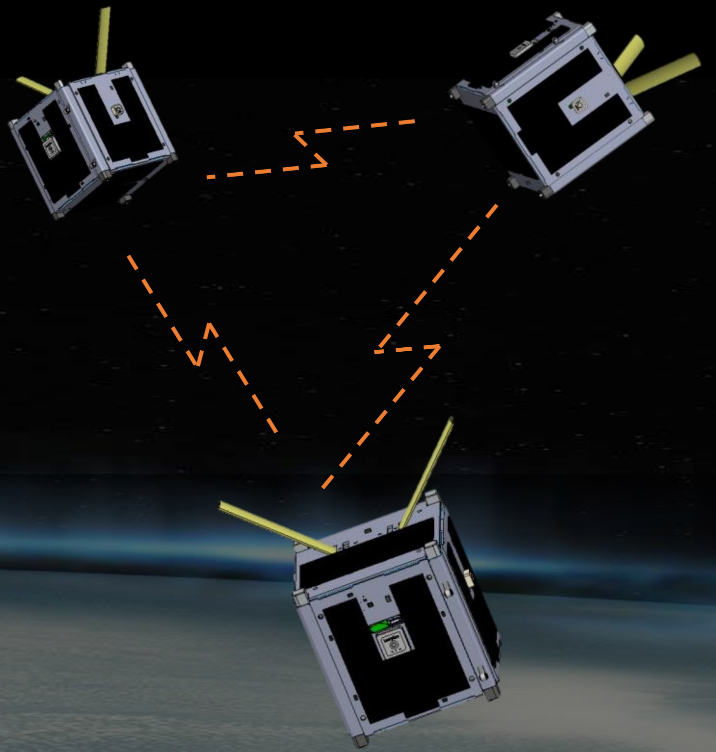
Eject from Dispenser → Separation & Deployment → Nominal Operations

Eject from Dispenser
- SC untethered
- Dipole antenna constrained by dispenser

Separation & Deployment
- Wait 4 sec (launch vehicle requirement)
- Begin RF Transmissions

Nominal Operations

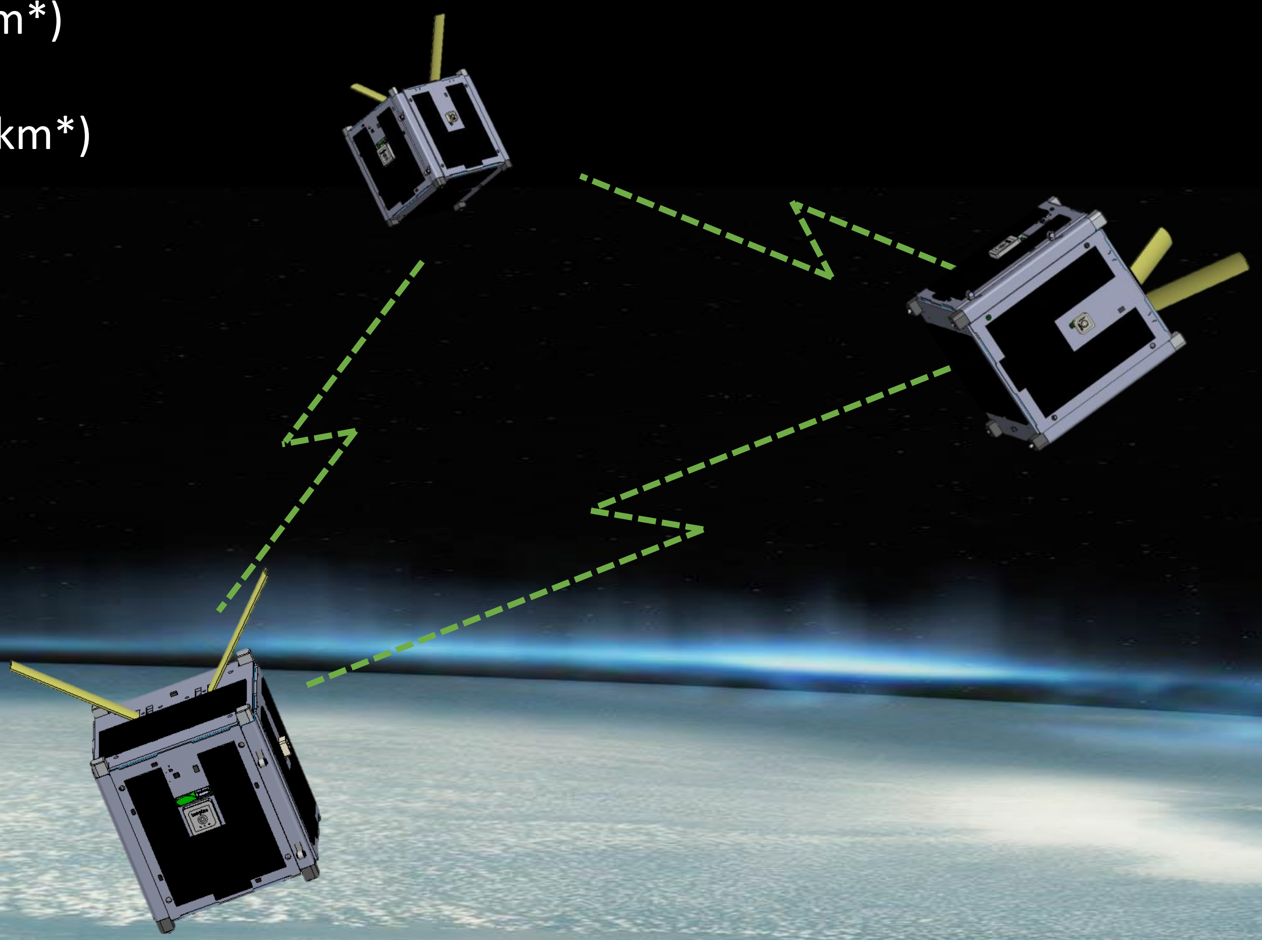




Tech Demo Activities

NASA

- **S-band ranging <1 m** precision (distances >500 km*)
- **Hi-speed S-band cross-link demo** (distances >10 km*)
- **Coordinated radiation measurements**
- **Relative swarm topology recovery**



*link budget dependent

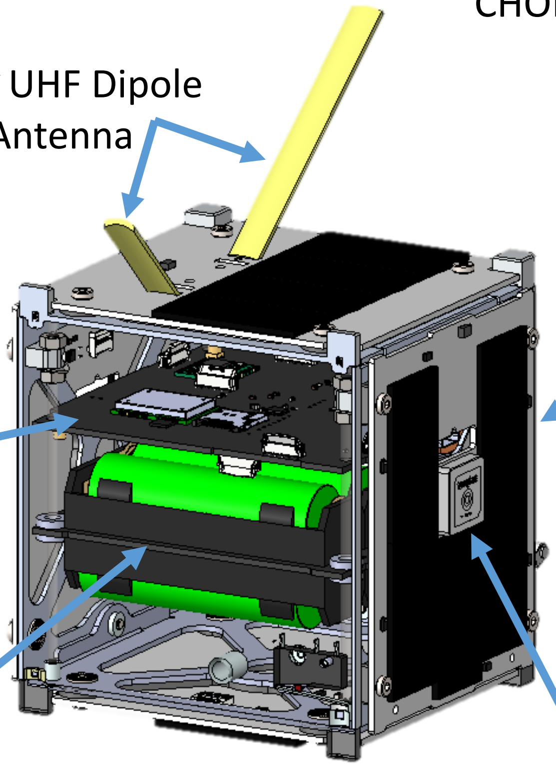
L1 Tech Demo Requirements

ID	Short description	Requirement Description	Verification & Validation	Notes
1-1	S-band High Precision Ranging	V-R3x shall demonstrate ranging with <1 m precision at a distances up to 500 km between at least two satellite nodes	Orbit determination ground tool with inputs from spacecraft GPS and CSPoC TLEs	GPS accuracy limited to ~10 m for verification and validation. Will collect many GPS solutions for filtering to 1 m
1-2	S-band High Data Rate Cross-link	V-R3x shall demonstrate data rates > 50 Kbps (up to 250 kbps) between two satellite nodes at distances up to 10 km between at least two satellite nodes	Spacecraft telemetry downlink	
1-3	Relative Topology Recovery	V-R3x shall demonstrate relative topology recovery between all satellite nodes (post-processed on the ground)	Orbit determination ground tool comparison between SC ranging inputs and inputs from spacecraft GPS and CSPoC TLEs	
1-4	Distributed sensor collection	V-R3x shall Coordinate and collect radiation data from on-board sensors from each satellite node	Compare to simulated + terrestrial sensor data	Verification data already collected. Sensors already built.

Overview

Images: NASA

Description	Specification
No. of SC	3
Class	1U
SC Mass	~1 kg
SC Power	1W Orbit Average
Attitude Knowledge	±10 deg, 3-axis, Sun Sensors, Magnetometer, IMU
Attitude Control	±10 deg, 1-axis, Magnetorquers
Orbit Knowledge	GPS
On-board Data Storage	4 MBytes MRAM 8 Gbytes SD Card
Energy Storage	10.5 Ah, 76 Wh BOL, 49 Wh EOL
Solar Array Power	1.33 W BOL, 1.27 W EOL
UHF UL/DL/XL	1 kbps
S-band DL/XL	20 - 250 kbps
Orbit	LEO, 525 km SSO, mission duration 3-11 mo. deorbit in 13 yrs
Propulsion	None

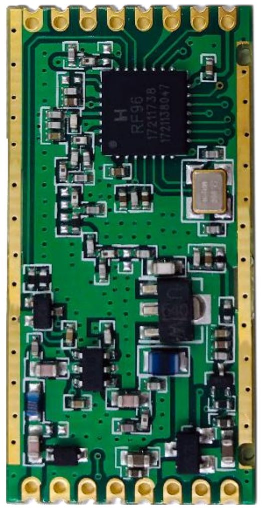


Radios

Low cost, Low SWaP: S-band built-in-ranging

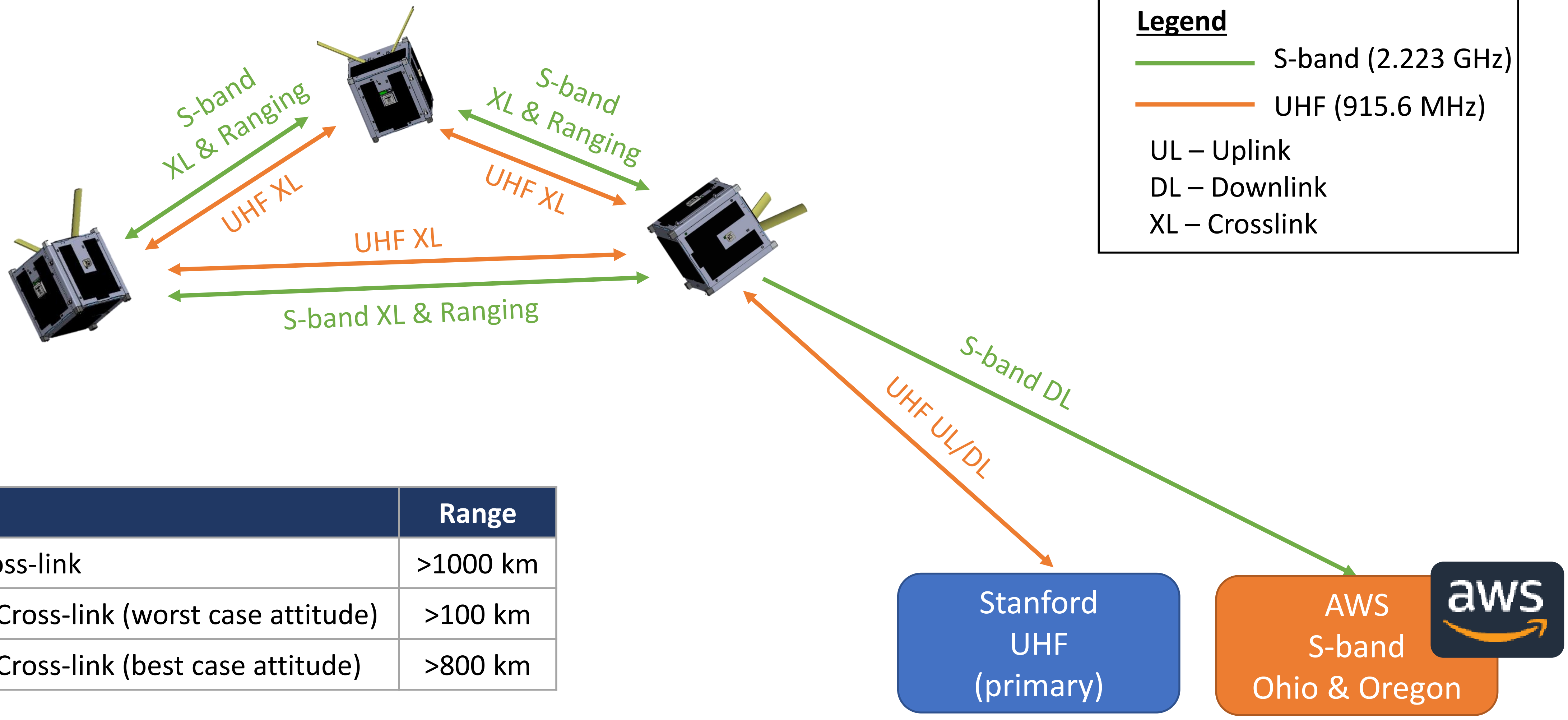
Specification	UHF	S-band
Link	Uplink, Downlink, Cross-link, Beacon	Downlink, Cross-link, Ranging
Center Frequency	915.6 MHz	2.2236 GHz
Bandwidth	500 KHz, SF=12 (selected)	1625 KHz, SF=6 (selected)
RF Output	1 W	500 mW
Manufacturer	HopeRF	Semtech
Part No.	RFM95PW	SX1280
Bit Rate	1.46 kbps	152.34 kbps
Symbol Rate	0.122 ksps	25.39 ksps
Modulation	LORA (CSS)	LORA (CSS)
Encoding	base64	base64
Receiver Sensitivity	-131 dBm	-132 dBm
Ant. Gain	0 dB	2 dB
Designator	500KF1D	1M63F1D

SemTech
SX1280 Transceiver
Credit: SemTech



Hope RF
RFM95PW Transceiver
Credit: HopeRF

Communications Overview



Legend

- S-band (2.223 GHz)
- UHF (915.6 MHz)

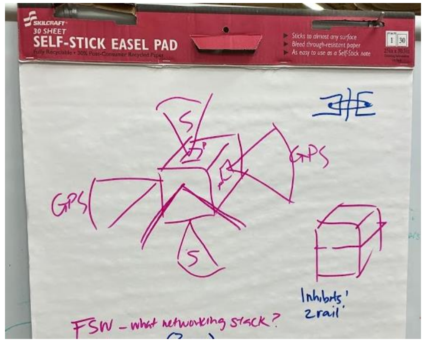
UL – Uplink
DL – Downlink
XL – Crosslink

Link	Range
UHF Cross-link	>1000 km
S-band Cross-link (worst case attitude)	>100 km
S-band Cross-link (best case attitude)	>800 km

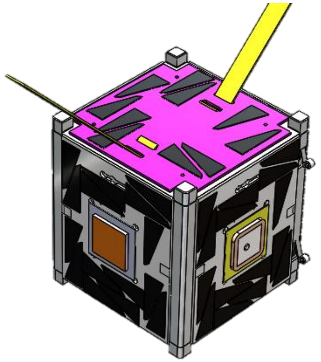
Not able to demo

V-R3x Build

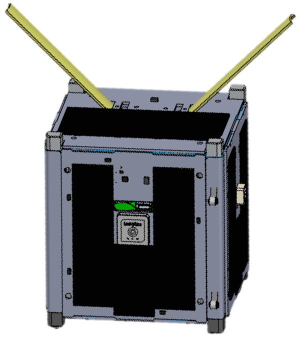
Image Credits : NASA



Brainstorm
12/03/2019



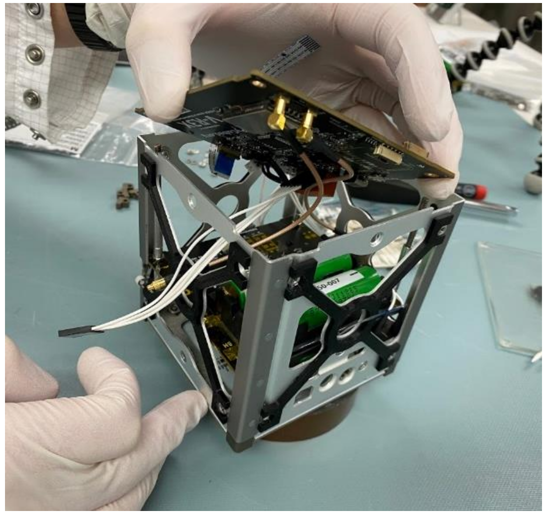
Project Proposal
12/16/2019



PDR/CDR
05/18/2020

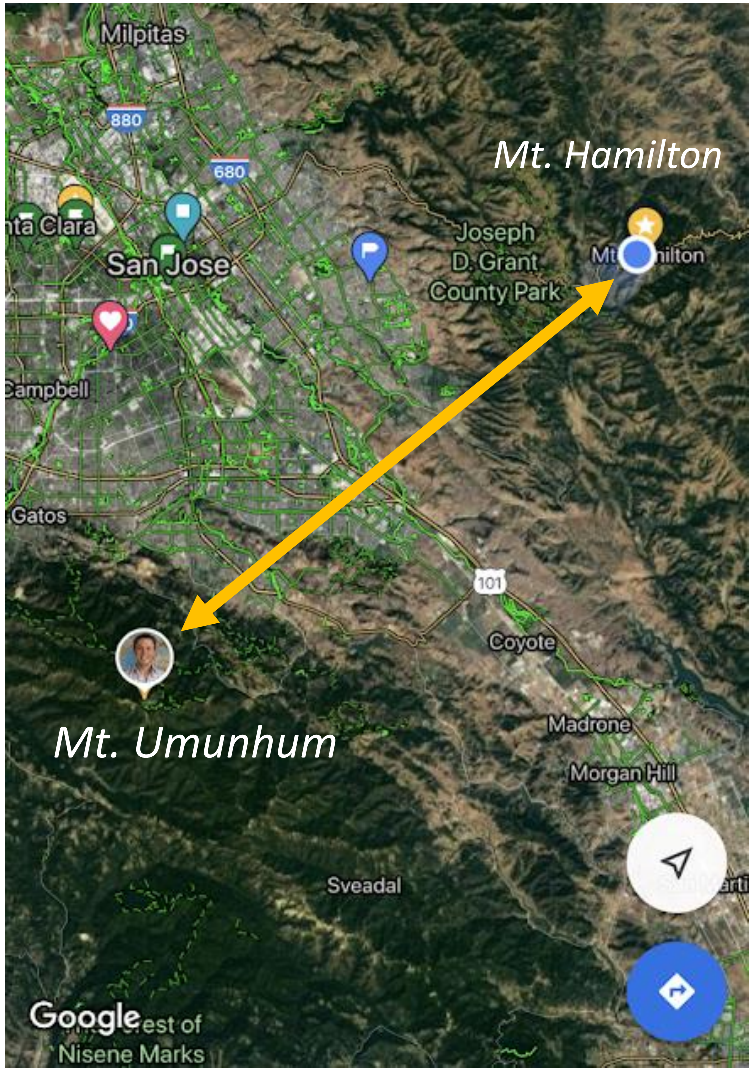
EDU
08/31/2020

FM 09/27/2020

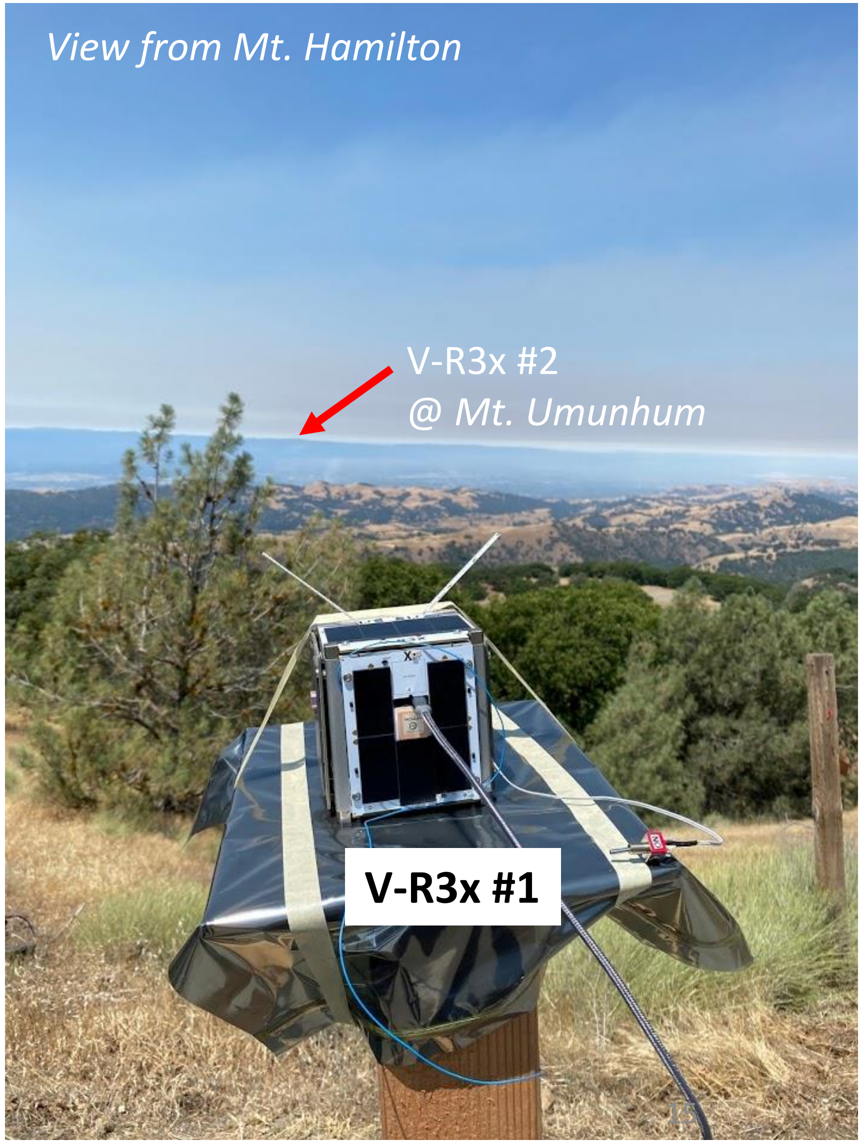


07/19/2020 – Ridge Testing #1

Image Credits : NASA

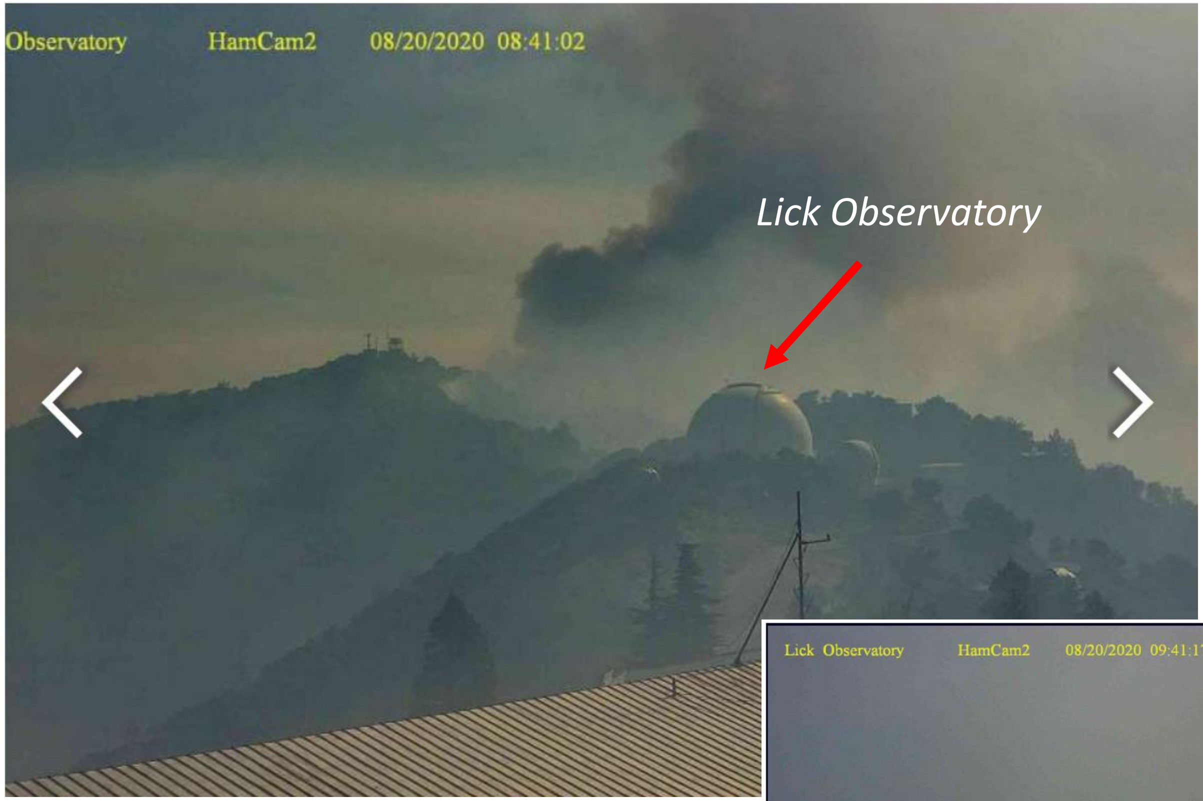


- UHF link closed
- S-band ranging & link didn't close
  - Likely due to valley noise



08/20/2020 – Ridge Testing #2 postponed due to wildfires

Image Credits : NASA

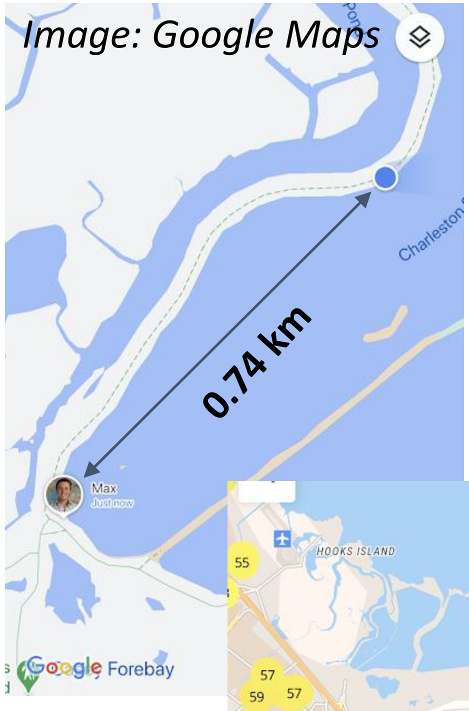


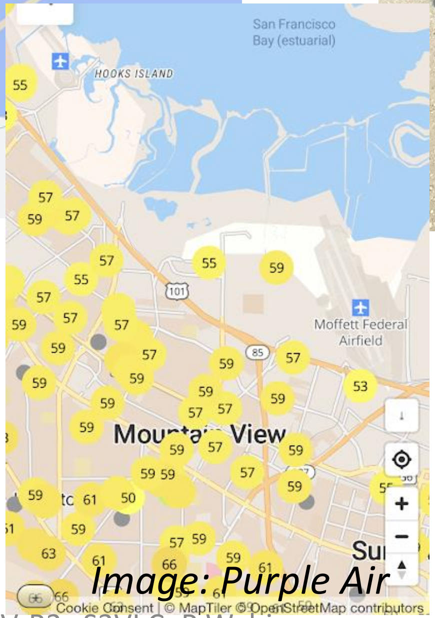
Looking East by Northeast

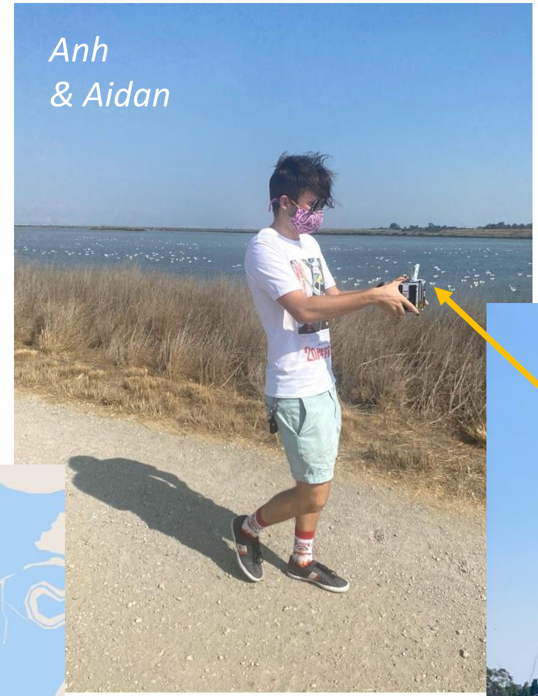
Image (top, right): University of California Observatories/Lick Observatory

Image Credits : NASA

9/20/2020 - V-R3x Range Testing





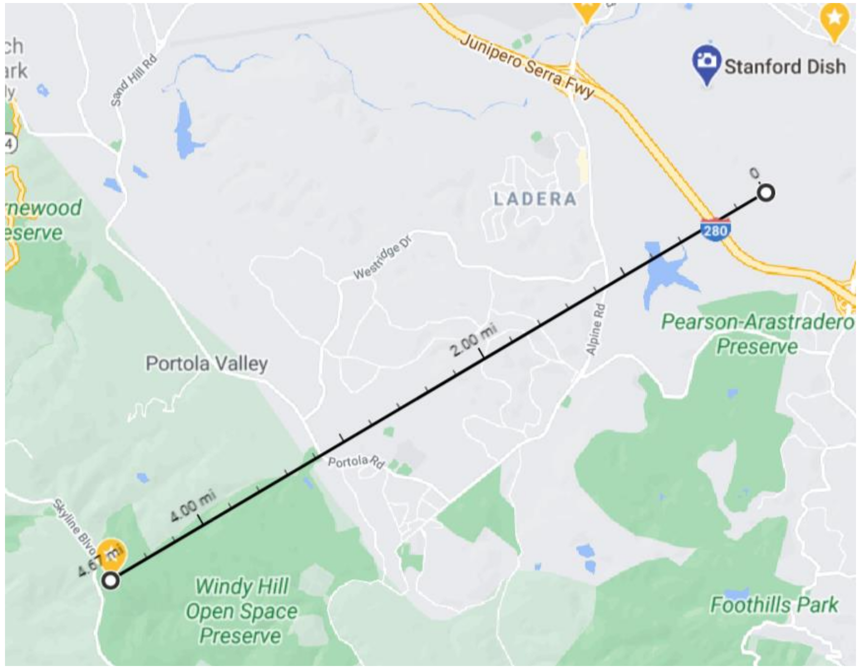


- UHF link successful
- S-band Ranging & Hi-speed link successful

9/26/2020 Ridge Testing

Image Credits : NASA

Image: Google Maps



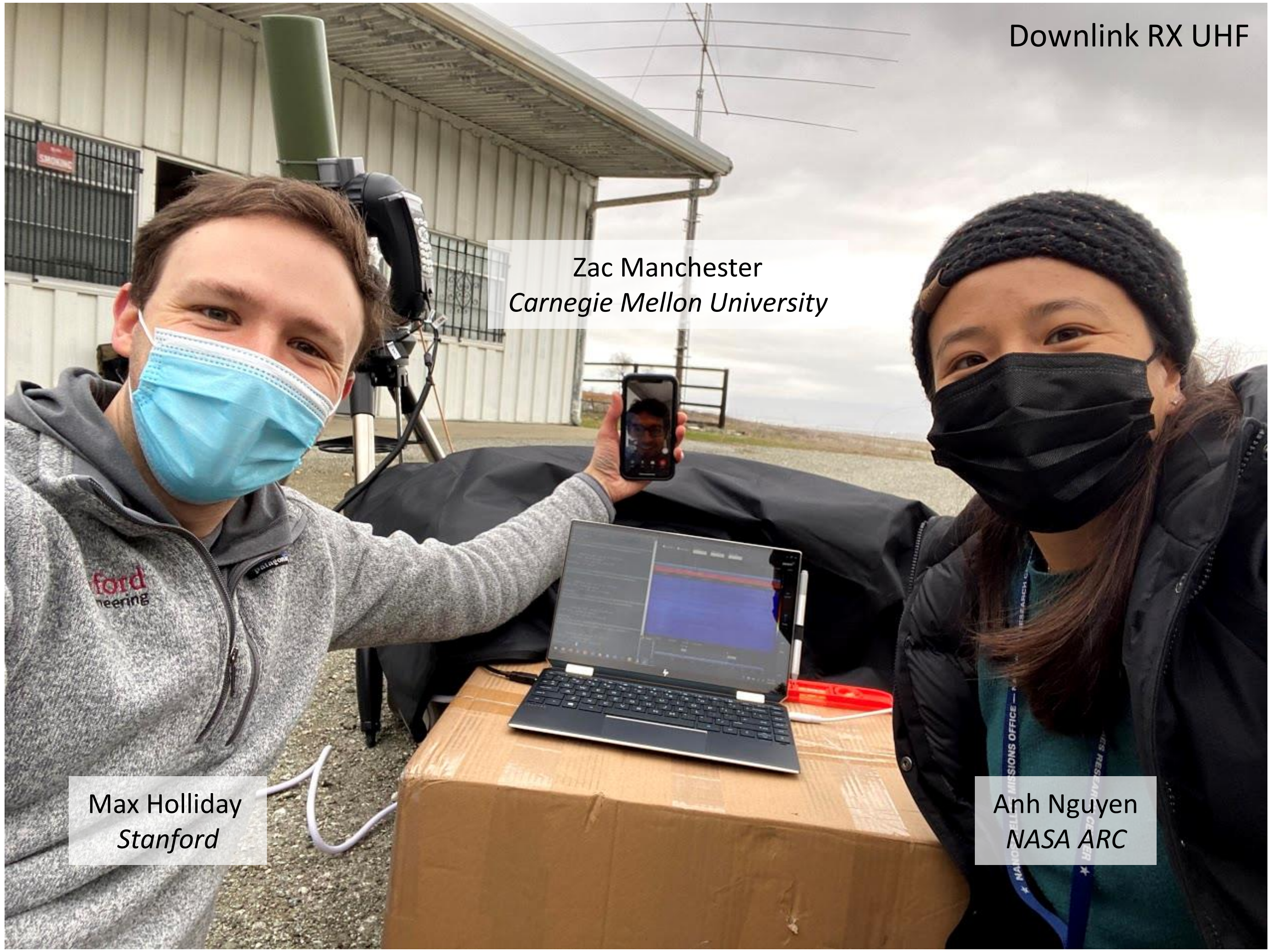
Total distance: 4.67 mi (7.51 km)

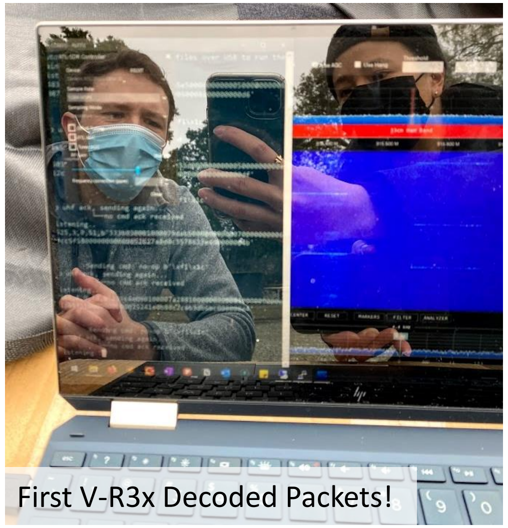
- UHF link closed
- S-band ranging & link didn't close
  - Likely due to valley noise

1/24/2021 10:00A EST Launch

First Spacecraft Packets Recieved

Image Credits : NASA





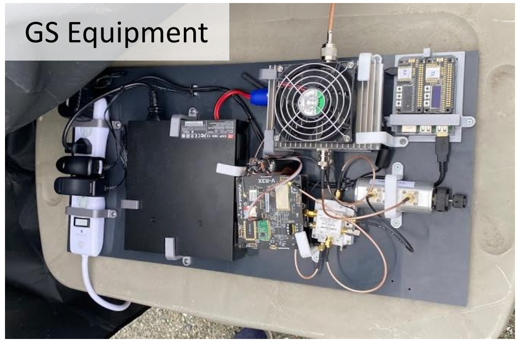
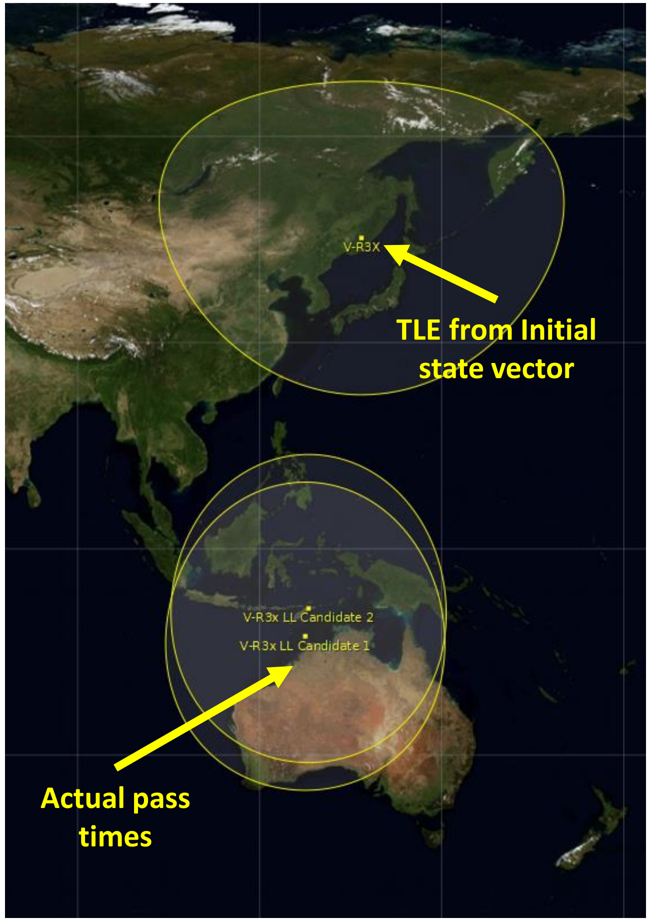
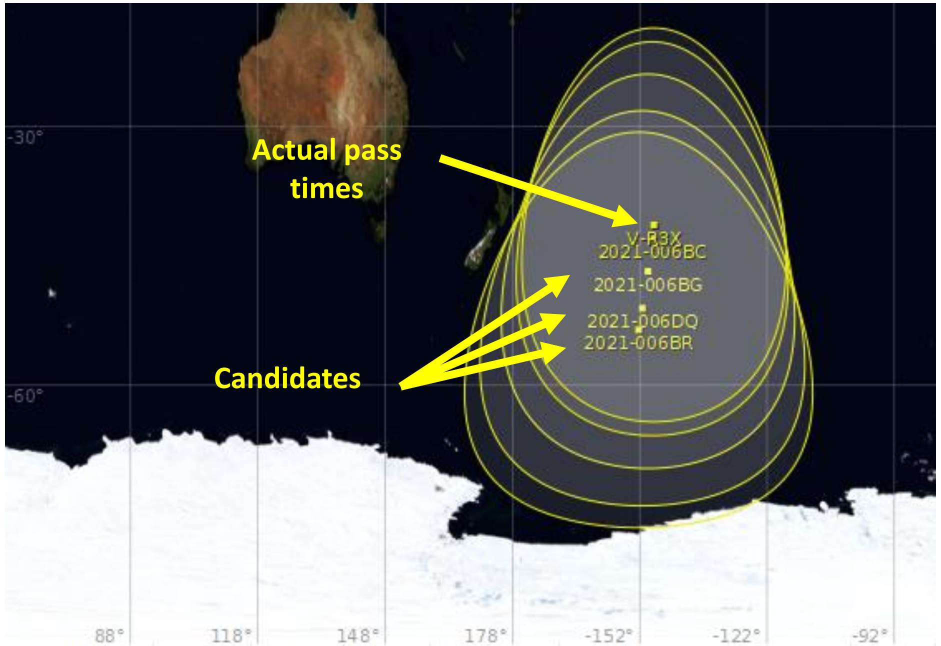


Image Credits : Gpredict

Tracking Issues





Satellite ▲	Az	El	Dir	Range	Next Event	Alt
2021-006BC	199.53°	-39.47°	↓	8878	AOS: 2021/02/09 19:45:16	543
2021-006BG	198.80°	-41.52°	↓	9197	AOS: 2021/02/09 19:44:18	544
2021-006BR	197.48°	-45.20°	↓	9751	AOS: 2021/02/09 19:42:36	548
2021-006DQ	197.97°	-43.85°	↓	9550	AOS: 2021/02/09 19:43:13	546
V-R3X	199.83°	-38.59°	↓	8739	AOS: 2021/02/09 19:45:36	542

- Initial state estimates from SpaceX poor
- LeoLab tracking support for L+7 days poor
- After 2 months, we believe we are objects:
  - NORAD ID 47463 (OBJECT-BC)
  - NORAD ID 47467 (OBJECT-BG)
  - NORAD ID 47524 (OBJECT-DQ)
- Last packets heard from spacecraft on Feb 5, 2021 (2 wks)

Mission Timeline

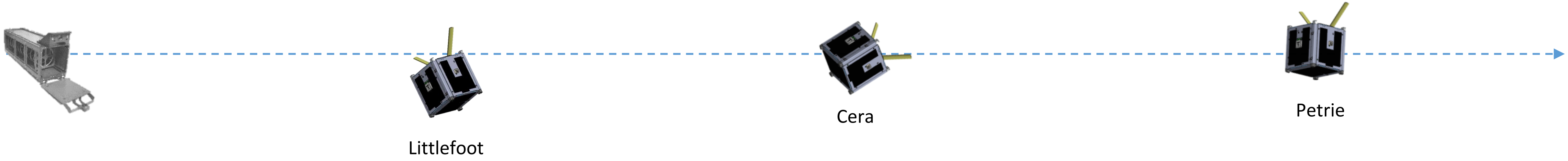
Hour	Detail
0	SC Deployed
2	First community packet
3	First telemetry packets from Stanford GS Jan 24, 10:16AM PST
3 – 77 (1d – 3d)	Gather beacon data from community and Stanford GS Noticed power dropping and tumbling
50 (2d)	First ground station uplink Query battery voltage
50 – 77 (2d – 3d)	More commanding Attempt to downlink datasets, query battery voltage
77 (3d)	Command SC to low power mode SC will stop beaconing (but still listens)
77 – 301 (3d – 12d)	Uplink power tweaks Leverage over-the-air commanding to turn sensors off, reduce processing, etc…
301 (12d)	Last commanding to SC Uplink extended sleep code. Contacted all sats
316 (13d)	Last packet received from SC Cera

Post Launch ops

- Sat beaconed every 30s. beacon could contain 1 of 4 data "types" with ranging being one of them.
- Post launch, V-R3x team and hams around the world collected beacon 114 packets in the first 72 hrs
- Spacecraft beacons reported tumbling > 30 deg/sec and power dropping over time
- Poor initial ephemeris from Space-X, tracking by LEO labs, and tracking by SpaceTrack reduced direct contact time
- Commanded spacecraft to go in ultra-low-power-sleep mode to preserve batteries where beacons stop
  - Hams subsequently stop listening
- V-R3x team shifts focus to balloon units while waiting for orbital units to naturally slow down, get better TLEs, and potentially recharge batteries
- Post-balloon launch, satellites never returned to nominal conditions

Beacon Packet Summary

Image Credits : NASA



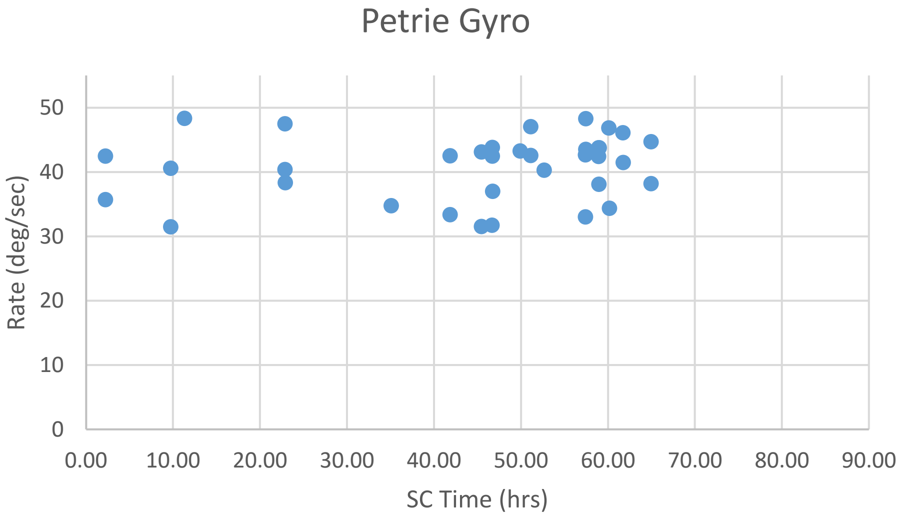
Beacon Packet (45 bytes)

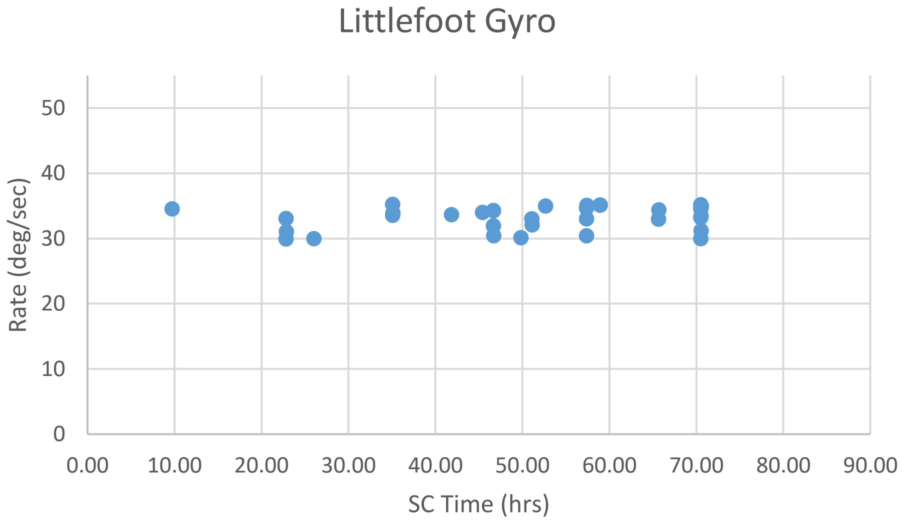
	Header	State of Health + Mission Metrics	Rotating Data Summary	CRC
Bytes:	4	22	18	1

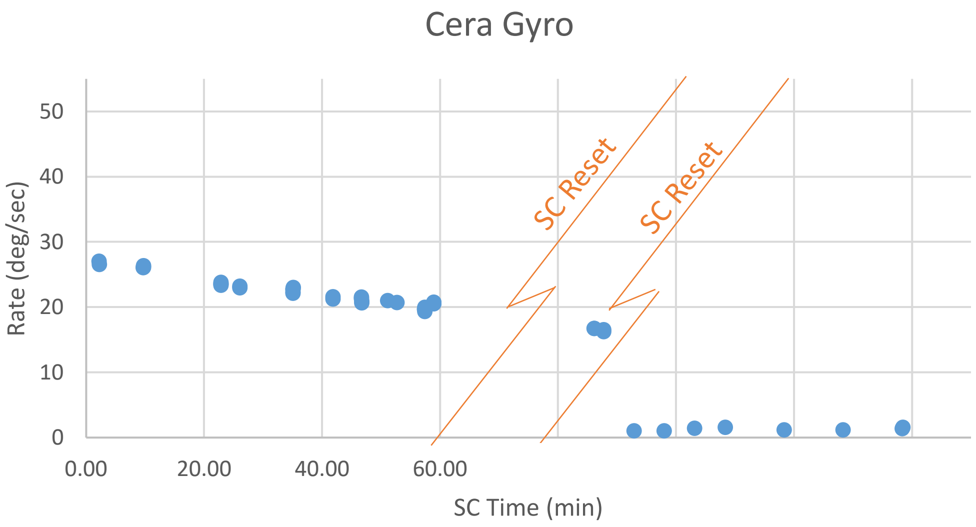
	Ranging (pkts)	Hi-speed X-link (pkts)	GPS Pkts (GPS Locks)	Rad Pkts	Total Pkts
Petrie	Cera (9) Littlefoot (1)	Cera (12) Littlefoot (2)	8 (0)	8	**40**
Cera	Littlefoot (8) Petrie (9)	Littlefoot (11) Petrie (12)	7 (1)	10	**57**
Littlefoot	Cera (8) Petrie (1)	Cera (11) Petrie (2)	4 (1)	9	**35**

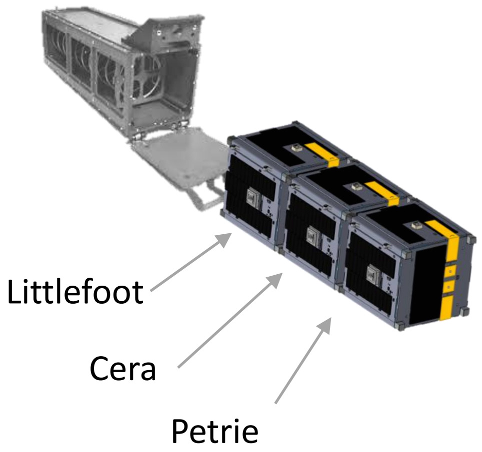
Rates

Image Credits : NASA



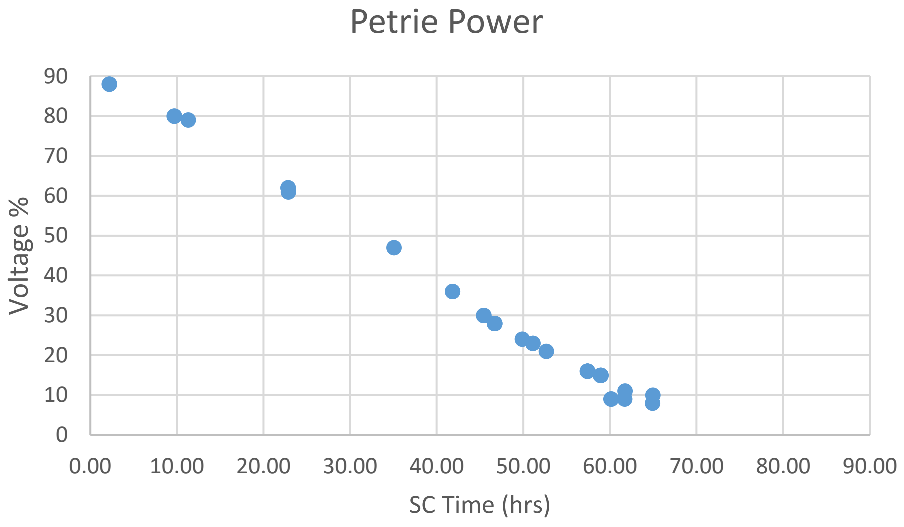


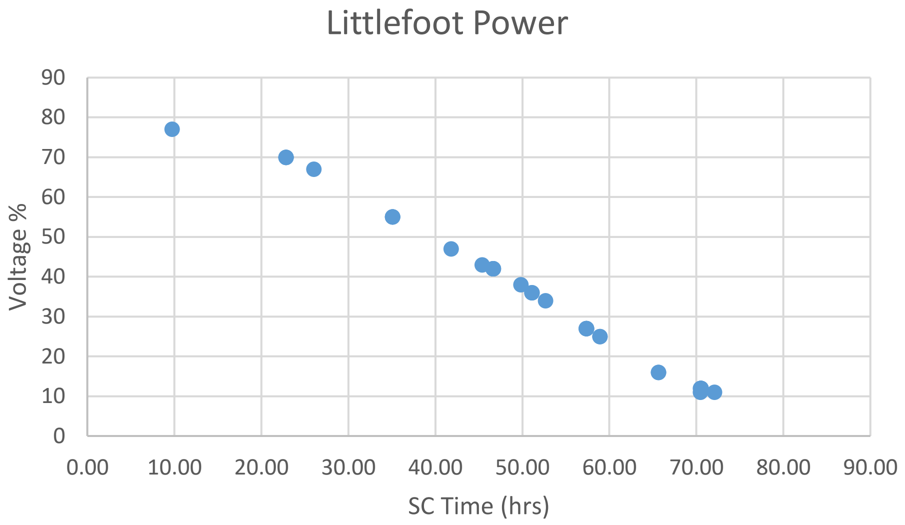


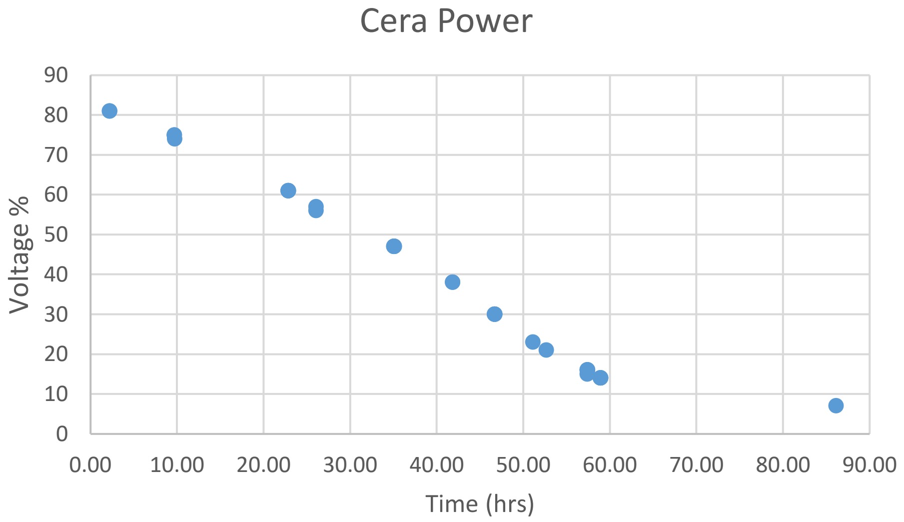


- V-R3x utilizes consumer-grade IMU
- SC tumbled VERY fast upon deployment
  - Likely due to antenna & dispenser
  - Impacts:
    1. Energy harvesting
    2. Communications
    3. GPS lock
- Lessons Learned:
  - Utilize burn wire
  - Initiate MT de-tumble controller
  - Have RTC with independent power line

Power







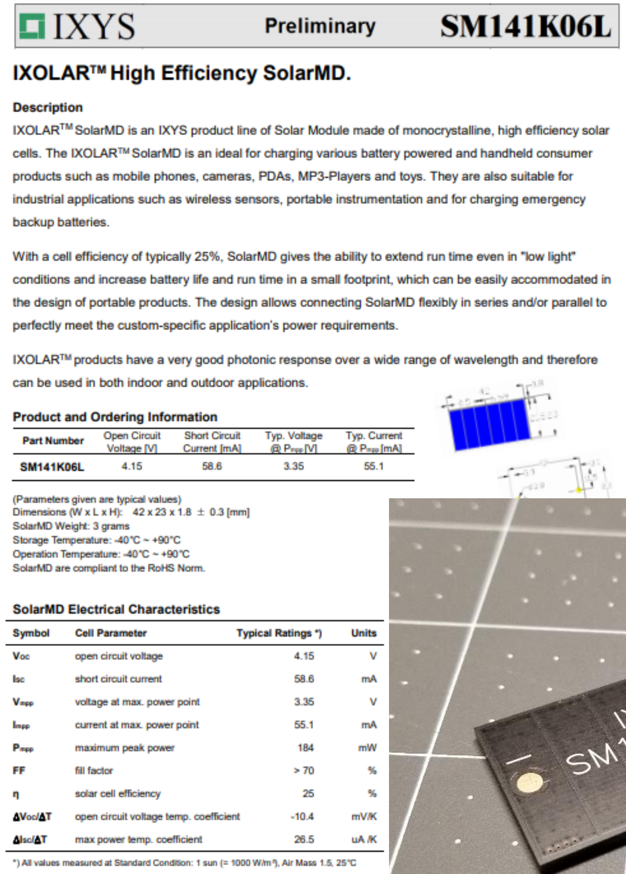
- Over time, power dropped for all three satellites
- Issue likely related to selected solar cells and tumbling (see next set of slides)
- Note: % is non-linear
  - Full (100%): 8.4V
  - Empty (0%) : 4.5V

Solar Cells

- V-R3x selected COTS solar cells (22% efficiency)
  - Readily available
  - Cost-efficient
  - Hoped they'd be easy to work with
- EDU was thermal tested (see next slide)
  - +60C Hot, -15 Cold

Lessons Learned:

- Perform IV Curve at different temps
  - Characterize efficiency drop w/ temp
- Not easy to work with
  - Can't use reflow oven
  - Lots of manual labor needed for staking



IXYS Preliminary **SM141K06L**

IXOLAR™ High Efficiency SolarMD.

Description

IXOLAR™ SolarMD is an IXYS product line of Solar Module made of monocrystalline, high efficiency solar cells. The IXOLAR™ SolarMD is an ideal for charging various battery powered and handheld consumer products such as mobile phones, cameras, PDAs, MP3-Players and toys. They are also suitable for industrial applications such as wireless sensors, portable instrumentation and for charging emergency backup batteries.

With a cell efficiency of typically 25%, SolarMD gives the ability to extend run time even in "low light" conditions and increase battery life and run time in a small footprint, which can be easily accommodated in the design of portable products. The design allows connecting SolarMD flexibly in series and/or parallel to perfectly meet the custom-specific application's power requirements.

IXOLAR™ products have a very good photonic response over a wide range of wavelength and therefore can be used in both indoor and outdoor applications.

Product and Ordering Information

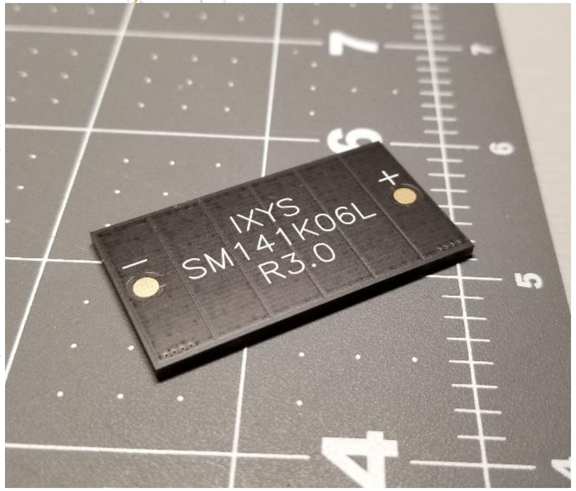
Part Number	Open Circuit Voltage [V]	Short Circuit Current [mA]	Typ. Voltage @ P_{mpp} [V]	Typ. Current @ P_{mpp} [mA]
SM141K06L	4.15	58.6	3.35	55.1

(Parameters given are typical values)
Dimensions (W x L x H): 42 x 23 x 1.8 ± 0.3 [mm]
SolarMD Weight: 3 grams
Storage Temperature: -40°C ~ +90°C
Operation Temperature: -40°C ~ +90°C
SolarMD are compliant to the RoHS Norm.

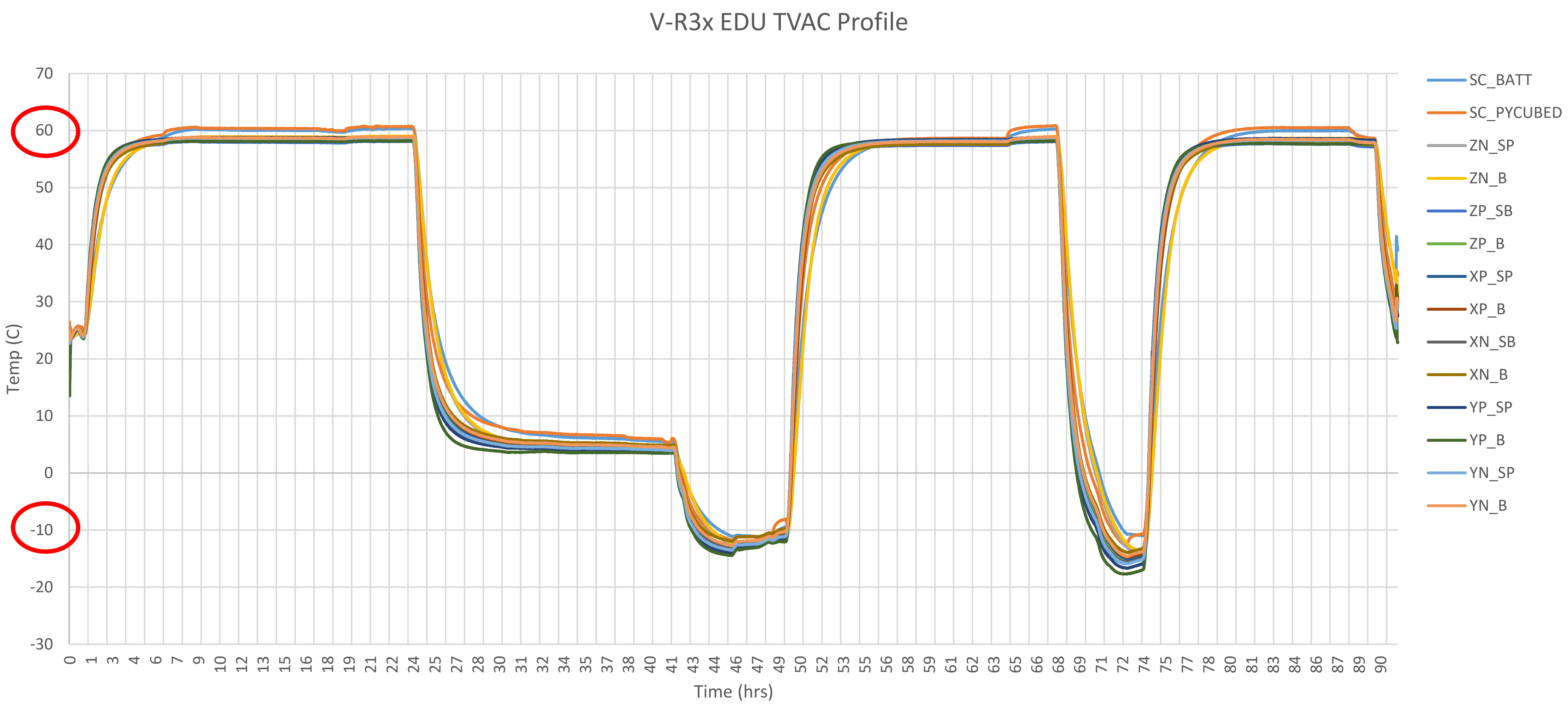
SolarMD Electrical Characteristics

Symbol	Cell Parameter	Typical Ratings *)	Units
V_{oc}	open circuit voltage	4.15	V
I_{sc}	short circuit current	58.6	mA
V_{mpp}	voltage at max. power point	3.35	V
I_{mpp}	current at max. power point	55.1	mA
P_{mpp}	maximum peak power	184	mW
FF	fill factor	> 70	%
η	solar cell efficiency	25	%
$\Delta V_{oc}/\Delta T$	open circuit voltage temp. coefficient	-10.4	mV/K
$\Delta I_{sc}/\Delta T$	max power temp. coefficient	26.5	uA /K

*) All values measured at Standard Condition: 1 sun (= 1000 W/m²), Air Mass 1.5, 25°C

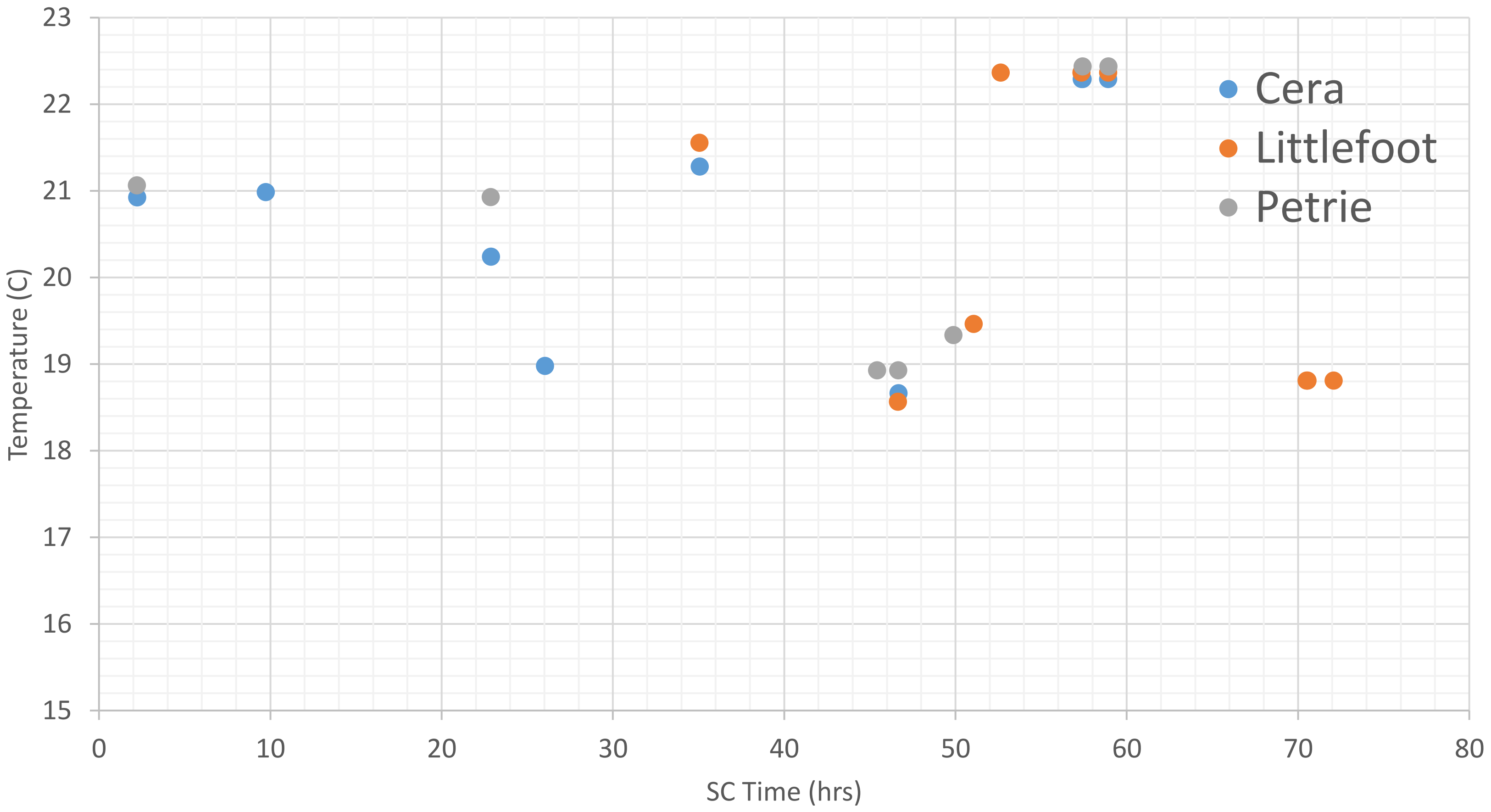


V-R3x EDU TVAC Profile

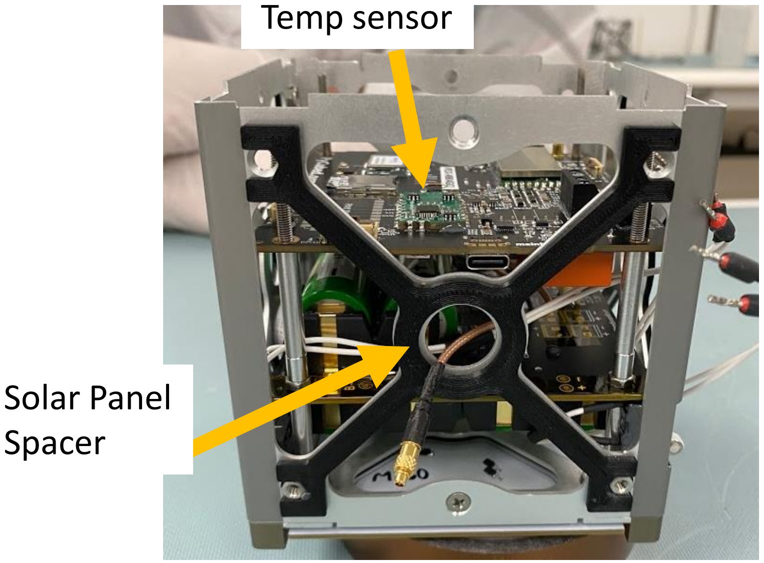


On-orbit Temperatures

Image Credits : NASA



- High precision (28-bit) temperature data from radiation sensors inside spacecraft
    - Min: 18.5C
    - Max: 22.4C
- Panels thermally isolated with spacers



High Precision Ranging

	Full Datasets	Last Good Range
Cera ↔ Petrie	15	701 to 809 meters
Cera ↔ Littlefoot	11	746 to 772 meters

Never able to downlink due to tumbling/power

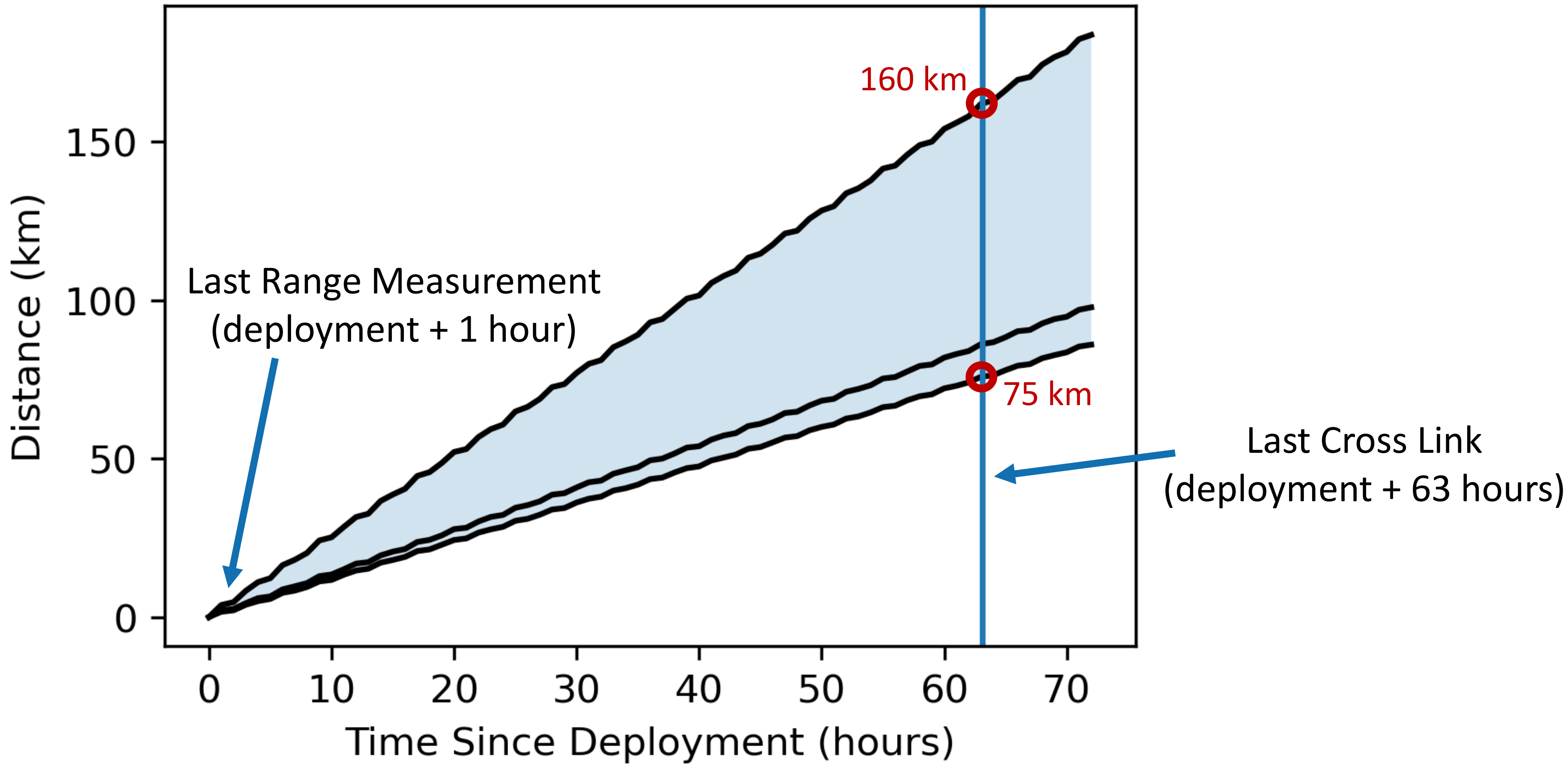
Beacon packets provide "snippets" of range data:

- Ranging measurements stopped at ~1km due to measurement time-out (discovered during balloon campaign post orbital demo)

#	sat	sc-time (sec)	range-with	Range (m)
12	littlefoot	82152.08	cera	
30	littlefoot	126282.30	cera	
39	littlefoot	163430.90	cera	
44	littlefoot	168006.10	cera	
54	littlefoot	179396.60	cera	746
66	littlefoot	206524.10	cera	
87	littlefoot	236348.20	cera	
93	littlefoot	253871.50	cera	
11	petrie	40749.63	cera	
21	petrie	82380.87	cera	
27	petrie	126239.00	cera	
34	petrie	150562.90	cera	701
49	petrie	168094.10	cera	
70	petrie	206607.80	cera	
77	petrie	212041.90	cera	
14	cera	82223.71	littlefoot	
33	cera	126366.50	littlefoot	
48	cera	168074.70	littlefoot	772
60	cera	184042.30	littlefoot	
69	cera	206588.10	littlefoot	
85	cera	212191.50	littlefoot	
5	cera	34910.32	petrie	
24	cera	93803.18	petrie	809
25	cera	126177.50	petrie	
36	cera	150587.10	petrie	
103	cera	103695.50	petrie	

Actual Range After Deployment

Image Credits : Z. Manchester



High-data rate cross-link

	Petrie	Littlefoot
Cera (default mesh leader)	9 UHF 7 S-Band	21 UHF 15 S-band

Cross-link activities always initiated by mesh leader

Frequency	Expected	Actual
UHF (915.6 MHz)	3 – **37 kbps** at distances 50m to >100km* between two nodes	**37.5 kbps** at distance of at least 75 km (up to 160 km)
S-Band (2223.6 MHz)	50 – **250 kbps** at distances 50m to 10km* between two nodes	**253 kbps** at distance of at least 75 km (up to 160 km)

kpbs = kilo bits per second

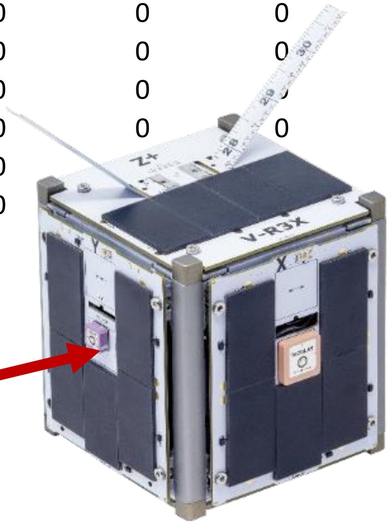
** Link budget dependent*

GPS

Image Credits : NASA

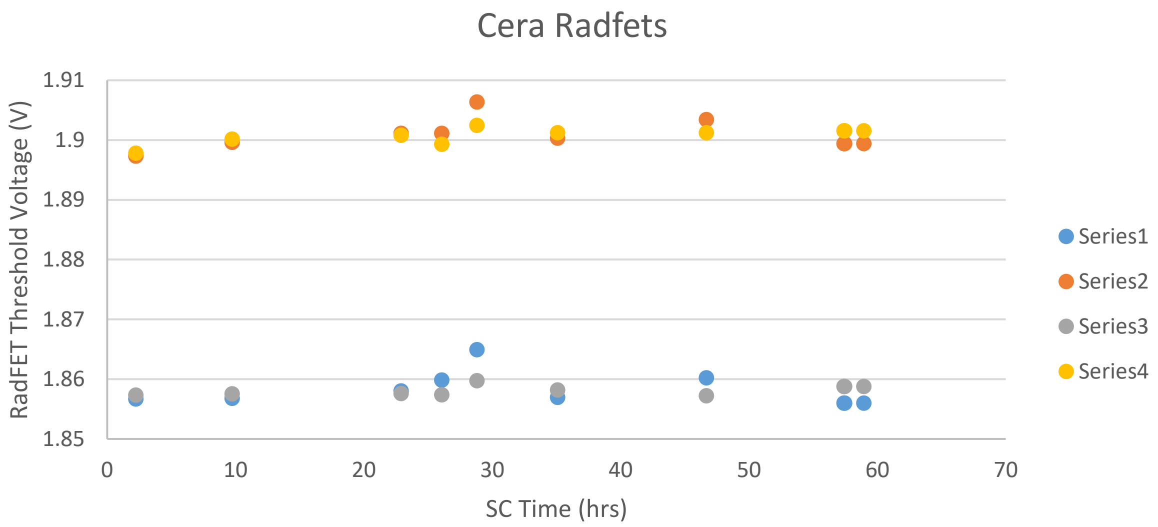
- V-R3x GPS: SkyTraq chip-scale GPS w/ two antennas on opposite faces 180˚ apart
- Nulls in gain pattern edge-on to both antennas
- Tumbling causes severe fading; GPS satellites will drop out when they are in the antenna nulls
- Receivers got partial locks (GPS time, altitude)
- Unable to get a full position + velocity solution on orbit
- **Lesson learned: mitigate tumbling**

#	sat	sc-time	vbatt	boot-cnt	gps-tow	gps-ecef-x	gps-ecef-y	gps-ecef-z	Alt (km)
2	cera	7963.45	81	1	65525	0	0	0	0.00
18	cera	82308.59	61	1	69215	5583.008	3785.889	1514.893	535.50
29	cera	126262.30	47	1	69215	5583.008	3785.889	1514.893	535.50
52	cera	168159.80	30	1	69215	5583.008	3785.889	1514.893	535.50
62	cera	189608.80	21	1	69215	5583.008	3785.889	1514.893	535.50
73	cera	206706.10	16	1	69215	5583.008	3785.889	1514.893	535.50
80	cera	212106.90	14	1	69215	5583.008	3785.889	1514.893	535.50
15	littlefoot	82236.15	70	2	61753	0	0	0	0.00
42	littlefoot	167884.50	42	2	225265	5412.109	4031.982	1500	535.50
64	littlefoot	206439.90	27	2	247611	5412.109	4031.982	1500	535.50
79	littlefoot	212080.60	25	2	247611	5412.109	4031.982	1500	535.50
1	petrie	7943.65	88	1	65397	0	0	0	0.00
9	petrie	35003.26	80	1	92480	0	0	0	0.00
16	petrie	82256.21	62	1	139632	0	0	0	0.00
53	petrie	168193.40	28	1	225675	0	0	0	0.00
59	petrie	183985.60	23	1	241228	0	0	0	0.00
74	petrie	206713.90	16	1	264188	0	0	0	0.00
82	petrie	212130.50	15	1	269330	0	[illegible]	[illegible]	0.00
86	petrie	212349.10	15	1	269330	0	[illegible]	[illegible]	0.00



GPS Antenna

Radiation



#	sat	sc-time	files-rad	rad-R1	rad-T	rad-R2
4	cera	8005.76	0	1.85666	20.9225	1.89733
10	cera	35037.42	0	1.85681	20.9854	1.8996
20	cera	82371.57	0	1.85804	20.2395	1.90113
23	cera	93760.98	0	1.85987	18.9791	1.90113
31	cera	126304.70	0	1.85698	21.2809	1.90032
46	cera	168032.40	1	1.86019	18.6633	1.90343
67	cera	206545.90	1	1.85597	22.2899	1.89941
75	cera	206748.50	1	1.85597	22.2899	1.89941
83	cera	212149.30	1	1.85597	22.2899	1.89941
102	cera	103653.10	2	1.86495	17.2779	1.90635
28	littlefoot	126240.30	0	1.55606	21.5545	1.51404
43	littlefoot	167936.50	0	1.5595	18.5634	1.51898
56	littlefoot	183882.90	0	1.55834	19.4618	1.51898
61	littlefoot	189532.10	0	1.55552	22.3652	1.5132
65	littlefoot	206482.10	0	1.55552	22.3652	1.5132
81	littlefoot	212126.20	0	1.55552	22.3652	1.5132
92	littlefoot	253829.50	0	1.55911	18.8078	1.51883
96	littlefoot	254008.60	0	1.55911	18.8078	1.51883
97	littlefoot	259541.60	0	1.55911	18.8078	1.51883
3	petrie	7985.85	0	1.53829	21.0617	1.53082
19	petrie	82312.22	0	1.53883	20.9268	1.53738
40	petrie	163544.70	0	1.54153	18.9277	1.54068
45	petrie	168017.70	0	1.54153	18.9277	1.54068
55	petrie	179593.40	1	1.54107	19.3337	1.54068
76	petrie	206756.10	1	1.53754	22.4353	1.53509
84	petrie	212179.80	1	1.53754	22.4353	1.53509
101	petrie	4167.85	2	1.53809	18.2167	1.53777

Cera on-board dosimeters indicate dose of ~700 rad(Si).

- Reasonable dose
- Unable to downlink full datasets

Objective Tracking

ID	Short Req.	Long Req.	Orbital
1-1	S-band High Precision Ranging	V-R3x shall demonstrate ranging with <1 m precision at a distances up to 500 km between at least two satellite nodes	IN-PROGRESS Requires complete ranging and GPS data. Beacon data indicates **ranging successful**; no GPS yet.
1-2	S-band High Data Rate Cross-link	V-R3x shall demonstrate data rates > 50 Kbps (up to 250 kbps) between two satellite nodes at distances up to 10 km between at least two satellite nodes	COMPLETE **253 kbps** at distance of at least 75 km (up to 160 km)
1-3	Relative Topology Recovery	V-R3x shall demonstrate relative topology recovery between all satellite nodes (post-processed on the ground)	IN-PROGRESS Requires complete ranging and GPS data. Beacon data indicates **ranging successful**; no GPS yet.
1-4	Distributed sensor collection	V-R3x shall Coordinate and collect radiation data from on-board sensors from each satellite node	IN-PROGRESS Requires full dataset with GPS. Beacon data indicates **radiation data collection successful**.

Orbital Lessons Learned & Path Forward

- Lessons Learned/Challenges
  - Tracking is poor from LeoLabs & SpaceX initial state vector; build into mission ops; beacons extremely helpful
  - Tumbling is an issue: Mitigation either to tie down antenna –and/or– build in magnetorquer-only de-tumble
  - Do NOT use the solar cells we used
  - Plan on CA wildfire season for risk to schedule/testing
  - Severe COVID impacts to staffing for small team & getting services (standing up ground stations)
- Accomplishments
  - First to collect intersatellite range measurement using LoRa radios
  - V-R3x paved way for LoRa 915MHz transmissions with NTIA
  - Valuable lessons learned working with AWS commercial ground station. Configured and ready to go for next mission
  - Entire satellite programmed in Python (no C or assembly), open-source design
- Path forward
  - Continue to continuously listen for beacons over CMU Ground station after stood-up
- Dissemination of Information
  - Lessons Learned Session for SmallSat 2022
  - V-R3x Post-processing GNC Autonomous Navigation Paper - K. Tracy
  - V-R3x Serial Bus Protection Journal – M. Holliday
  - Follow-on PyCubed Paper – M. Holliday

Post-launch Balloon Schedule

Activity	Date	Jan 2021				Feb 2021				Mar 2021				Apr 2021			
		Wk 1	Wk 2	Wk 3	Wk 4	Wk 1	Wk 2	Wk 3	Wk 4	Wk 1	Wk 2	Wk 3	Wk 4	Wk 1	Wk 2	Wk 3	Wk 4
V-R3x Launch Integration	01/3/2021 - 1/8/2021																
Balloon Development	1/11/2021 - 1/24/2021																
V-R3x Orbital Launch	01/24/2021				◊												
Early Mission Ops	1/24/2021 - 2/15/2021																
Balloon Development	2/15/2021 - 3/6/2021																
Backet Drop Test	02/19/2021							◊									
Dress Rehearsal	03/03/2021									◊							
Balloon Campaign @ Raven, SD	3/7/2021 - 3/14/2021																
Travel Day	03/07/2021										◊						
Integration & Indoor EMI/EMC Test	03/08/2021										◊						
Outdoor EMI/EMC Test	03/09/2021										◊						
Ops Planning (Snow Day)	03/10/2021										◊						
Site Planning/Waiting for STA	03/11/2021										◊						
Flight Campaign Day	03/12/2021										◊						
Recovery/Packing	03/13/2021										◊						
Travel Day	03/14/2021										◊						
Lead Eng. Out (Family Emergency)	3/15/2021 - 3/26/2021																
Balloon Data Analysis	3/29/2021 - Current																
Balloon Range Test	04/04/2021													◊			
Balloon Ridge Test	04/09/2021													◊			

V-R3x-S Team

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Alex Mazhari
Rapid Prototyping
NASA

V-R3x-S Balloon Campaign

Image Credits : NASA

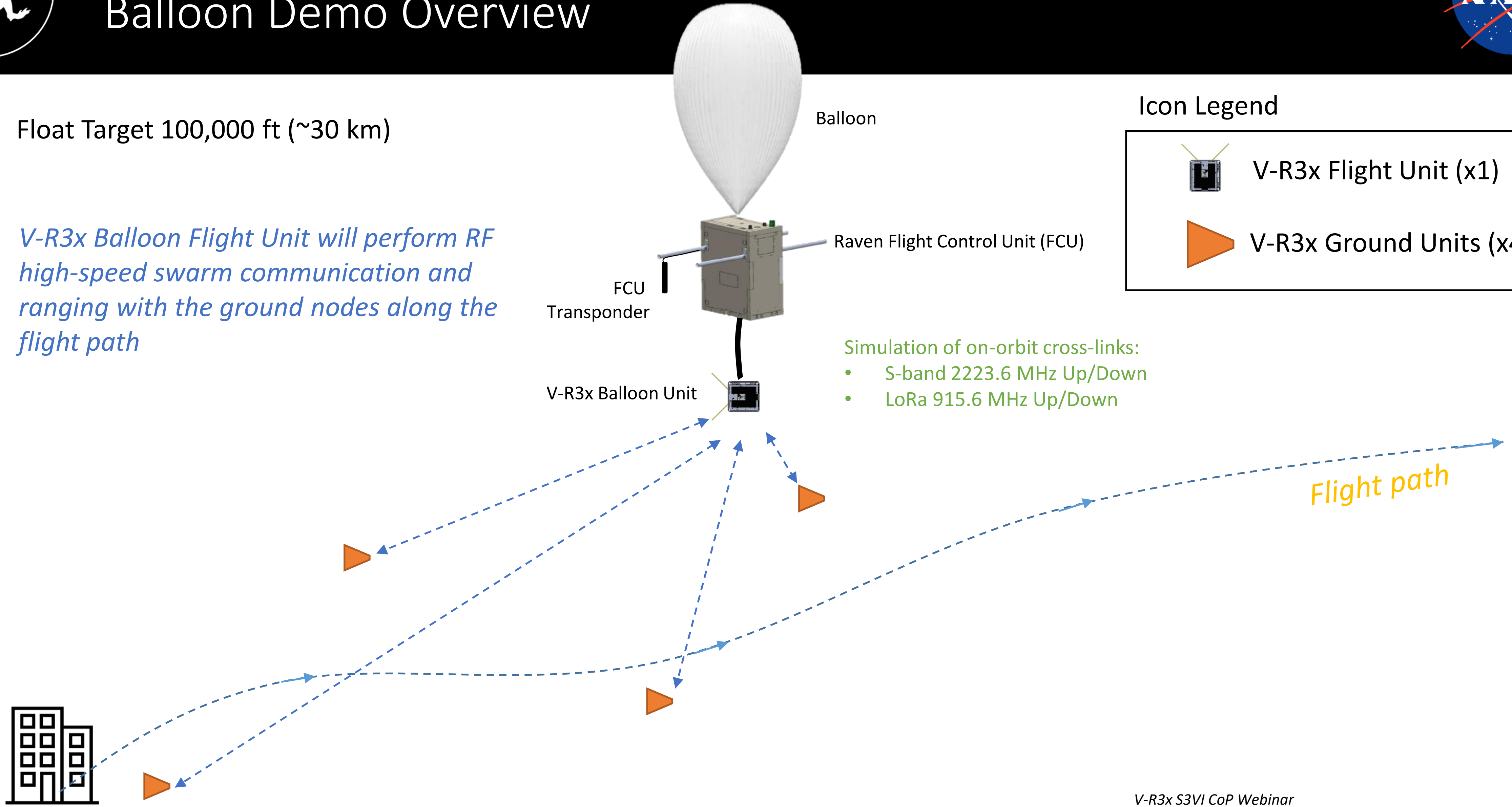
V-R3x-S Balloon Objectives

- ***Objective 1 (O-1): S-band High Precision Ranging***
  - *O-1 Success Criteria: V-R3x shall demonstrate ranging with less than 1 m precision at distances 45 m - 800 km between two satellite nodes. Spacecraft and balloon GPS will be used to validate ranging measurements.*
- ***Objective 2 (O-2): S-band High Data Rate Cross-link***
  - *O-2 Success Criteria: V-R3x shall demonstrate data rates 50 - 250 Kbps at distances 45 m – 10 km between two satellite nodes. Spacecraft telemetry downlink will be used to validate the ranging measurements.*
- *Raven Flight Objectives*
  - *100kft altitude for a minimum of (2) hours*
  - *Transmit and receive data from Balloon unit to four ground units via ISM & S-band*

Balloon Demo Overview

Float Target 100,000 ft (~30 km)

V-R3x Balloon Flight Unit will perform RF high-speed swarm communication and ranging with the ground nodes along the flight path



Simulation of on-orbit cross-links:
- S-band 2223.6 MHz Up/Down
- LoRa 915.6 MHz Up/Down

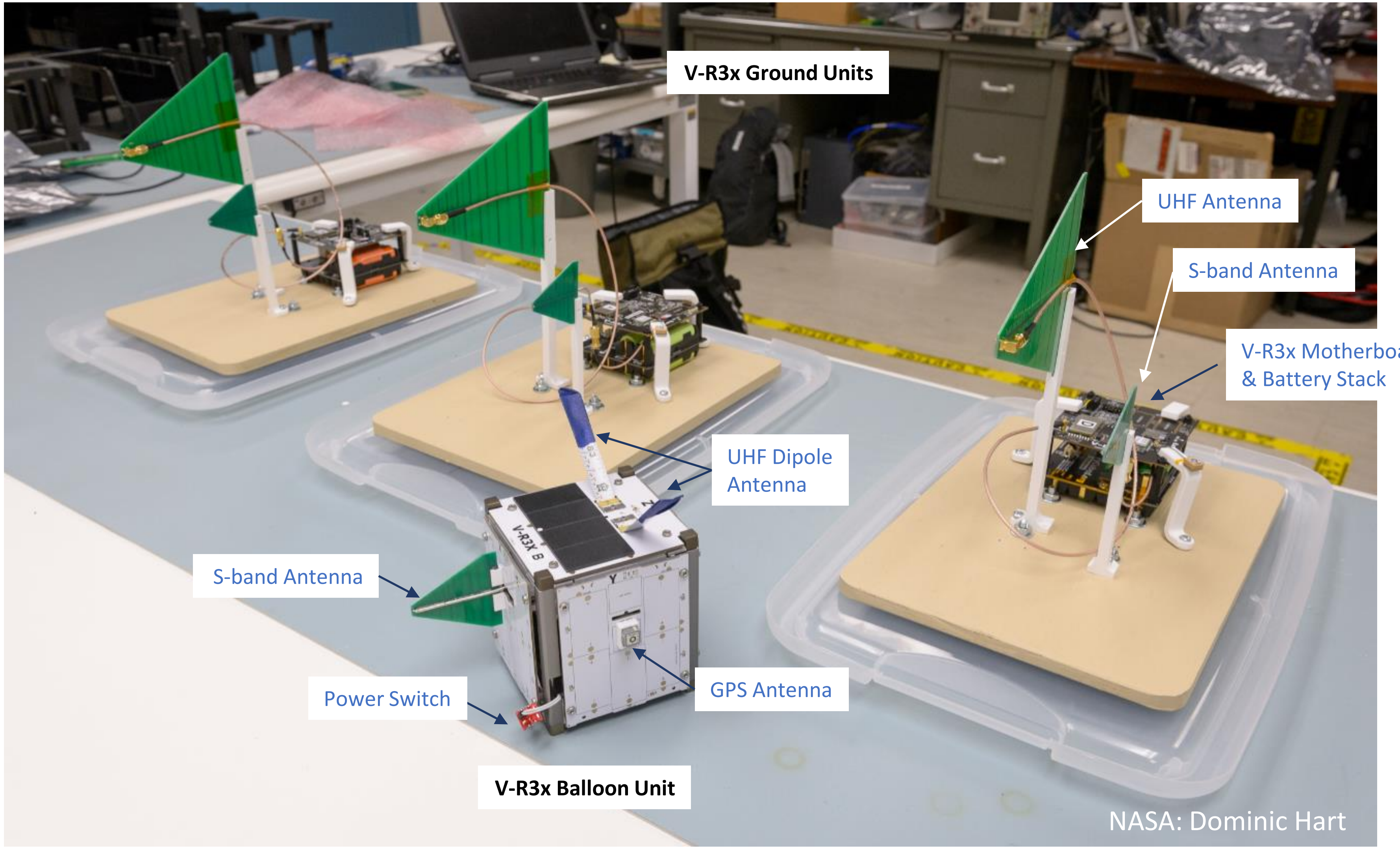
Icon Legend

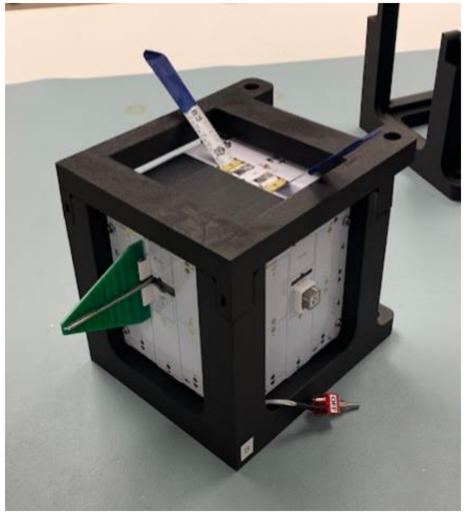
V-R3x Flight Unit (x1)

V-R3x Ground Units (x4)

Image Credits : NASA

V-R3x Balloon Hardware





Mechanical Changes

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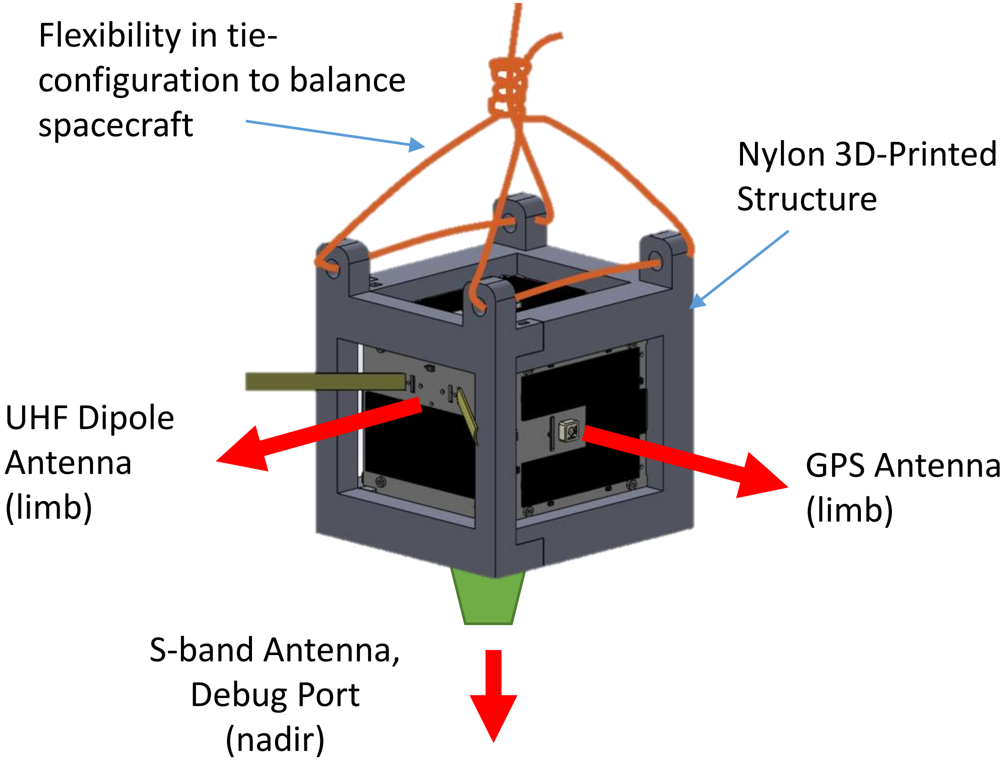
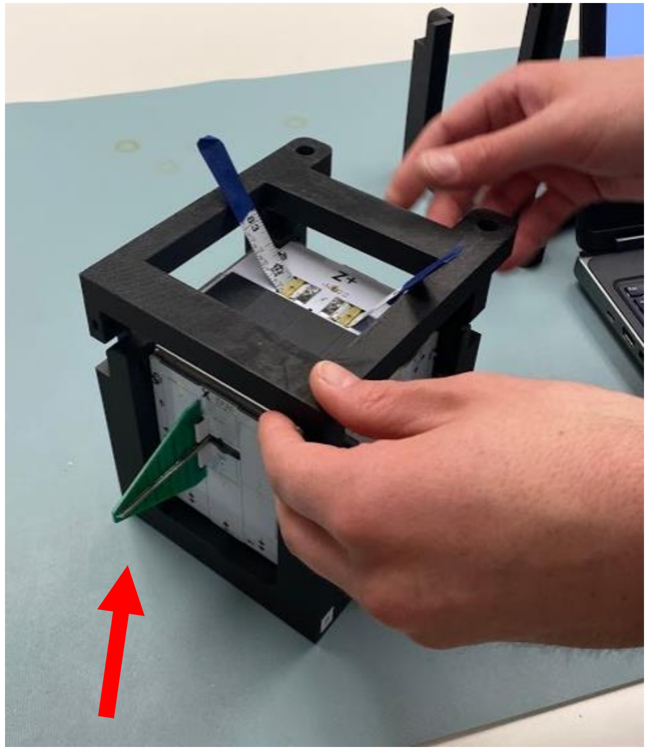


- Change of antenna for improved coverage susceptible to damage upon lift-off
- Intact recovery buys down risk for increased time/LOE in correlating missing data



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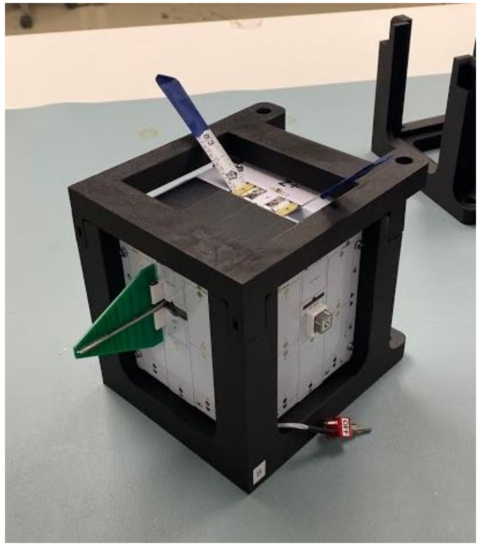
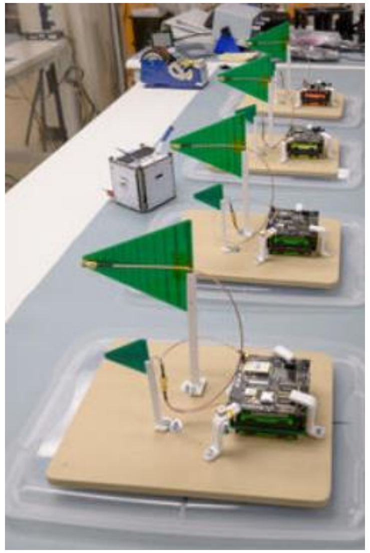
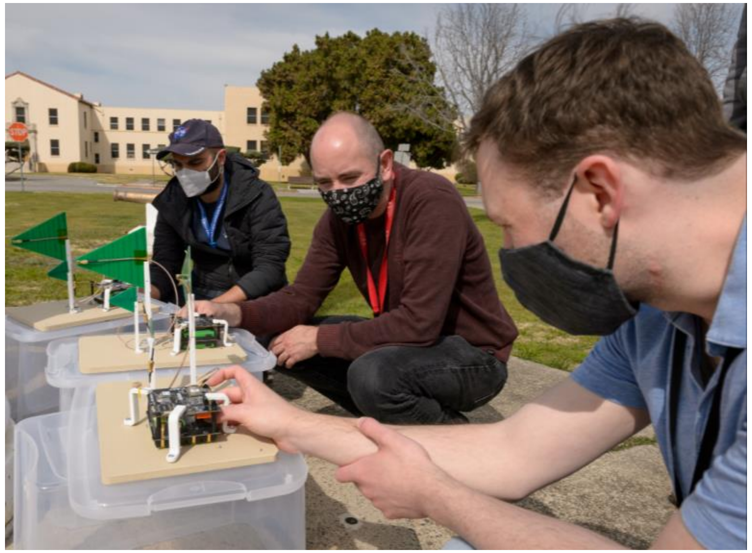
2/19/2021 Bracket Pull/Drop Test

3/3/2021 Field Test/Dress Rehearsal

Image Credits : NASA, Dominic Hart

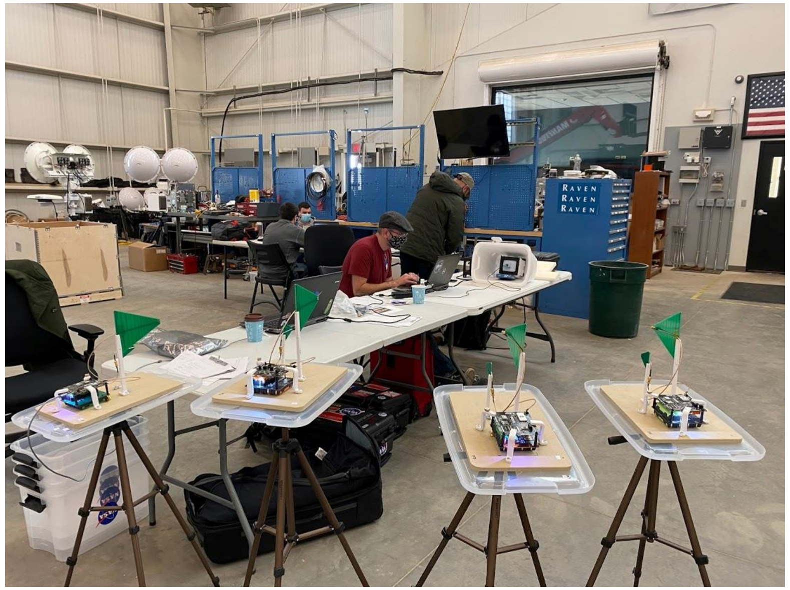






3/8/2021 GS Assembly & Checkout

Image Credits : NASA



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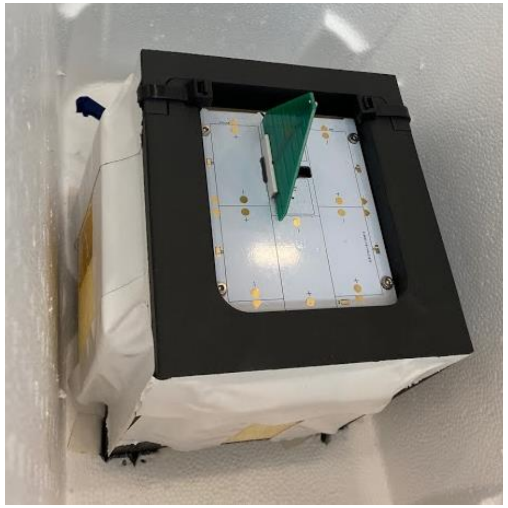
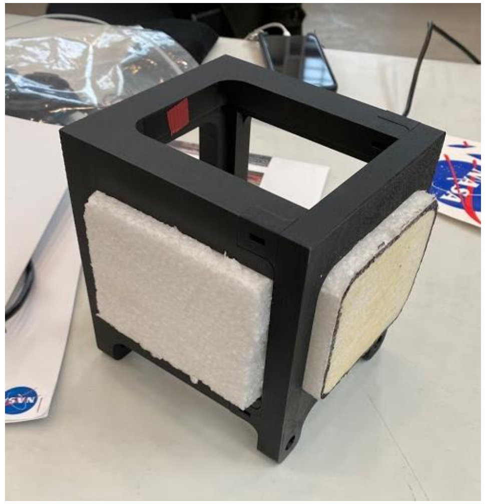
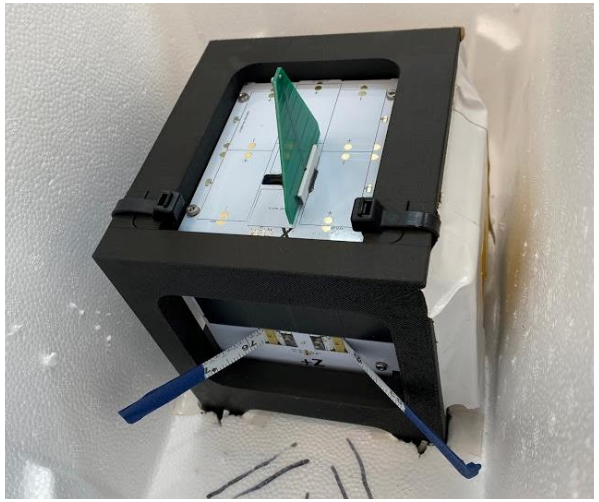
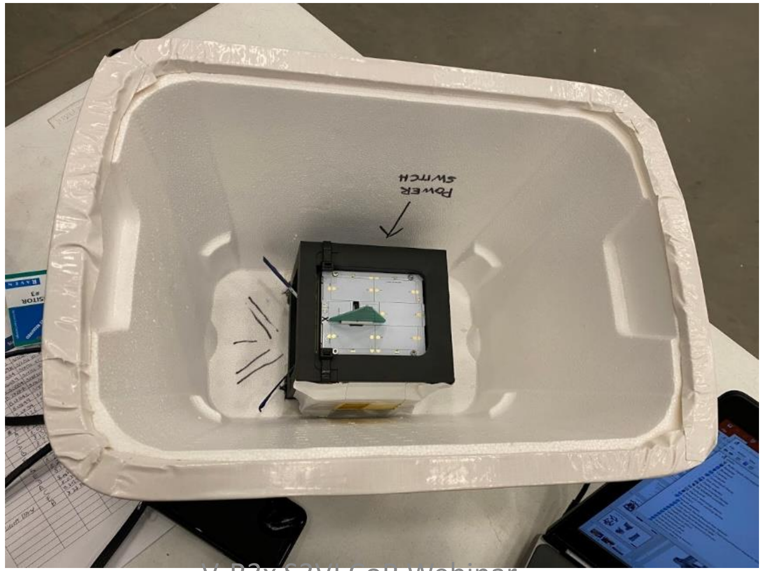
3/8/2021 Assembly, Check-out, Indoor EMI/EMC Test



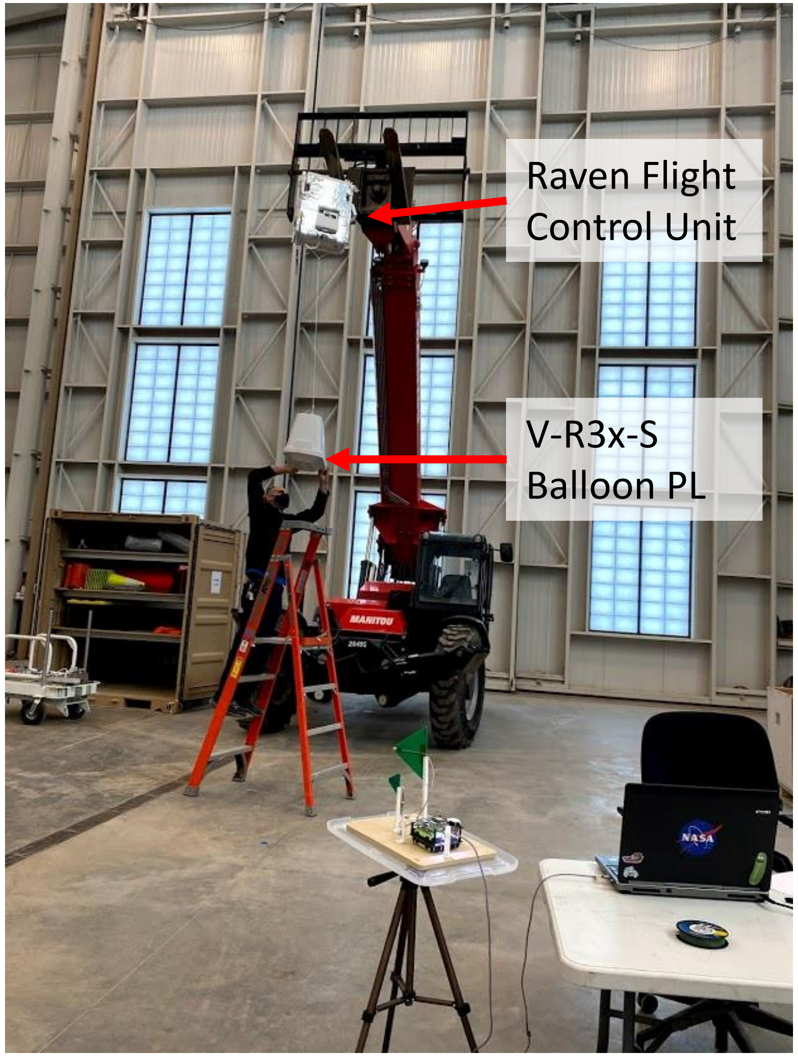


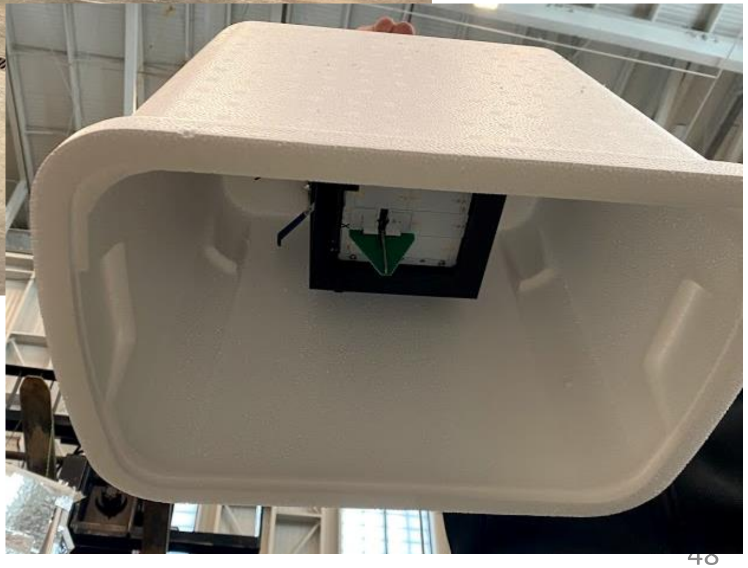




3/8/2021 Indoor EMI/EMC Test

Image Credits : NASA





3/9/2021 Outdoor EMI/EMC Test, Planning

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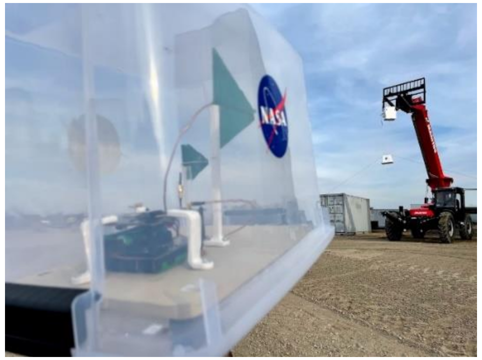

3/10/2021 Planning (Rain/Snow Day)

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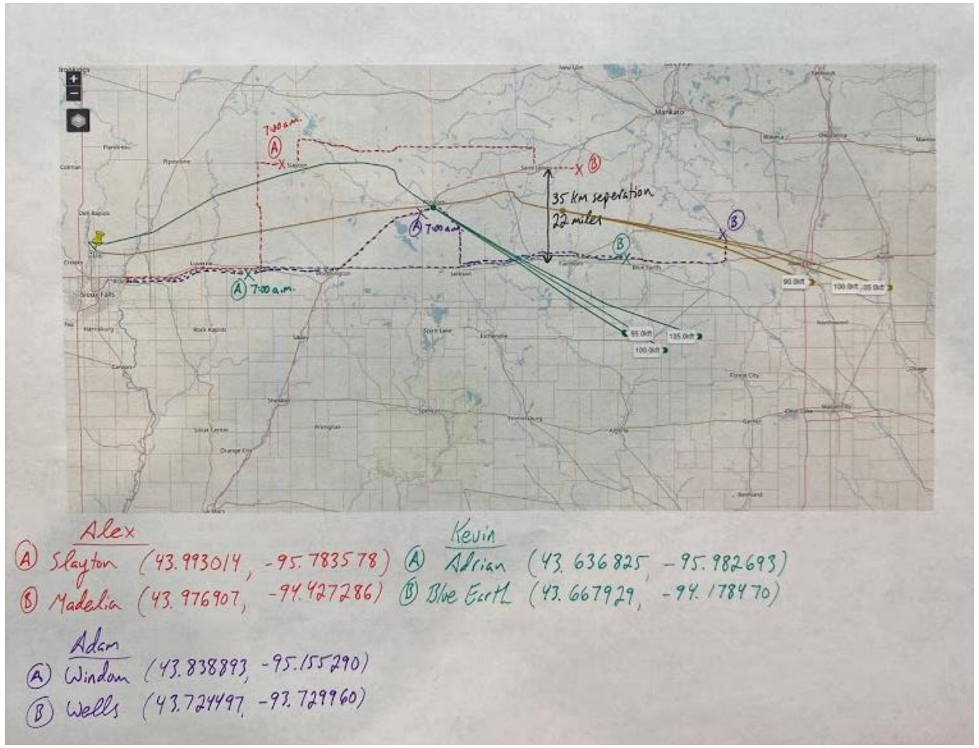

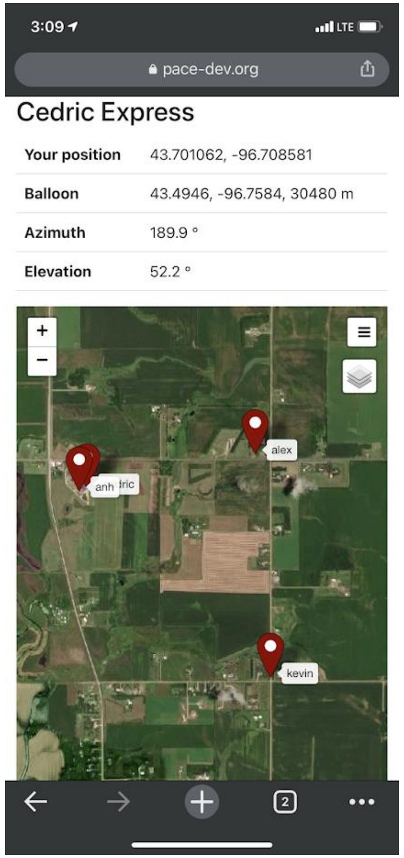

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3/11/2021 Site Scouting/Waiting on STA

3/12/2021 Flight Campaign Day

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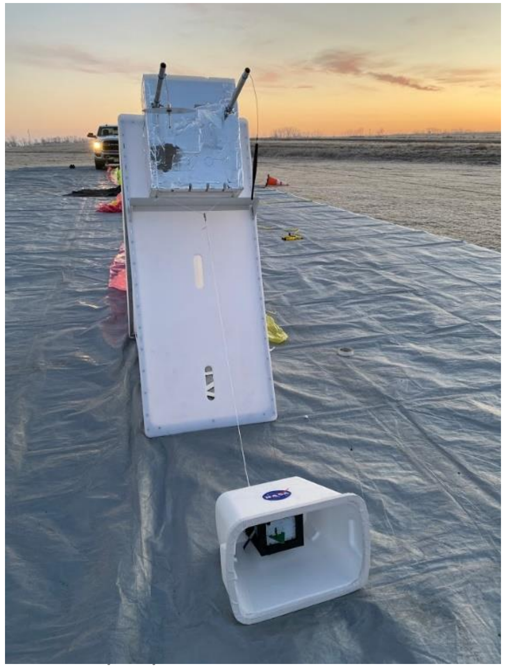
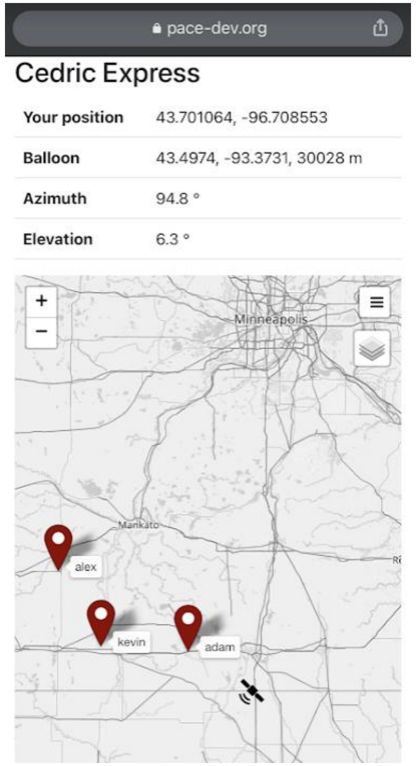
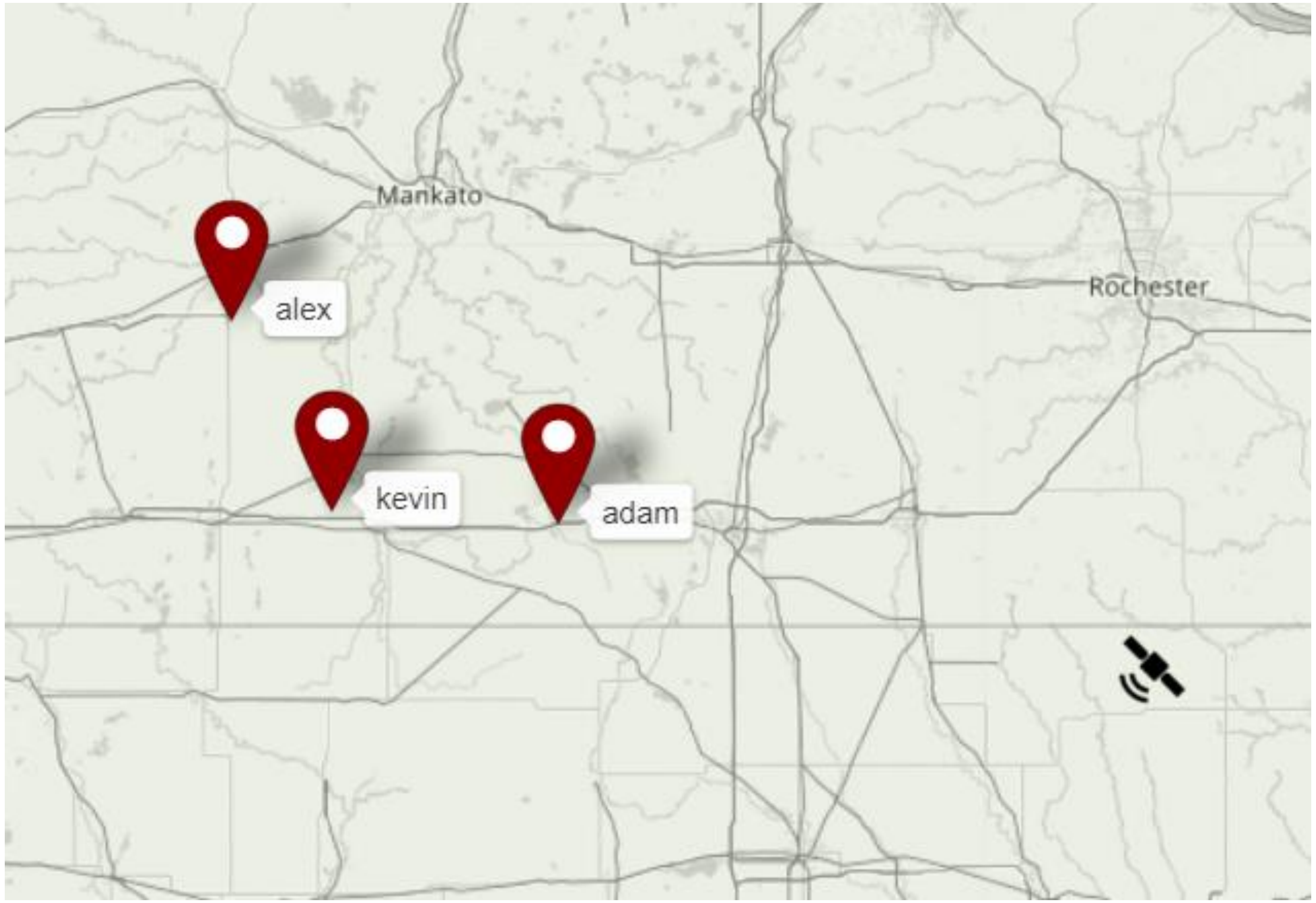


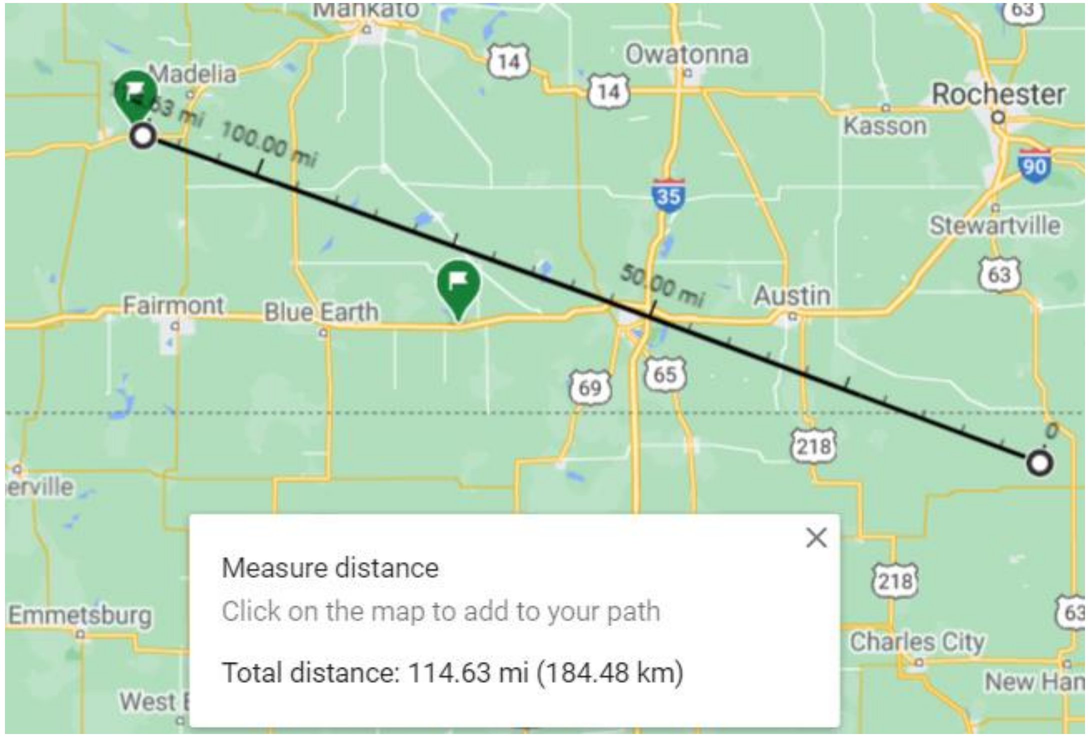


V-R3x S3VI CoP Webinar

Tracking via Cedric Express

Image Credits : NASA



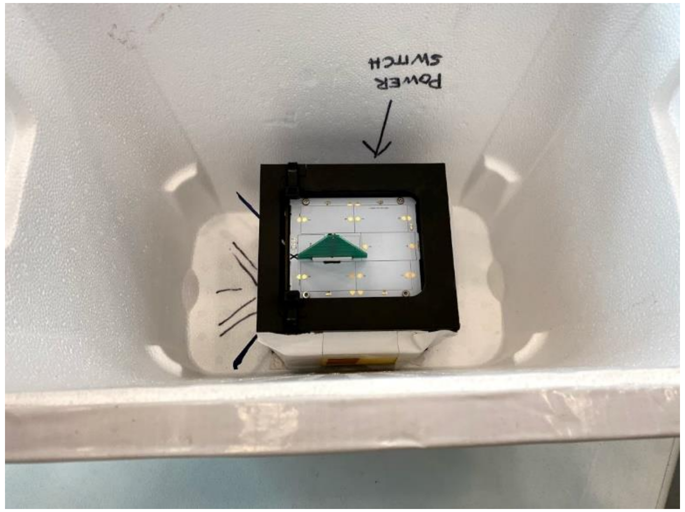


3/12/2021 Recovery

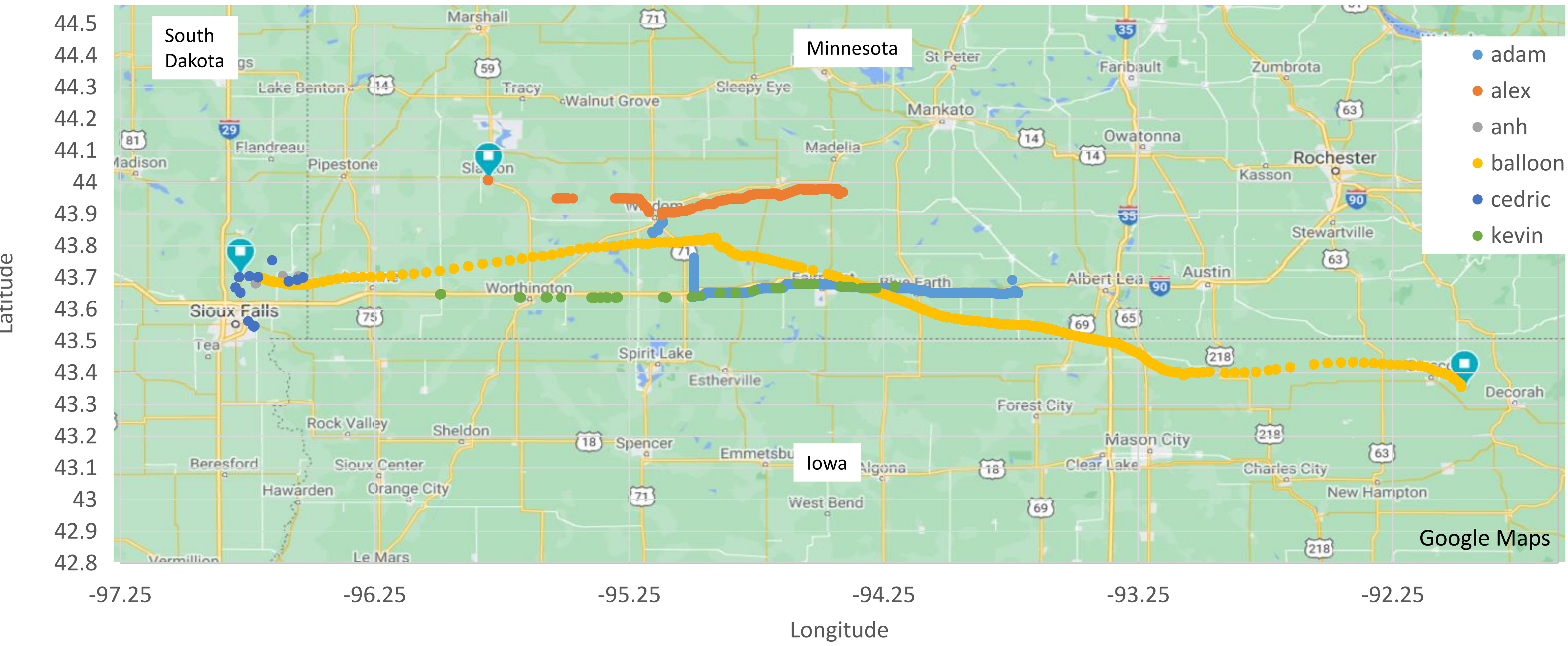
Image Credits : NASA

3/13/2021 Pick-up & Packing

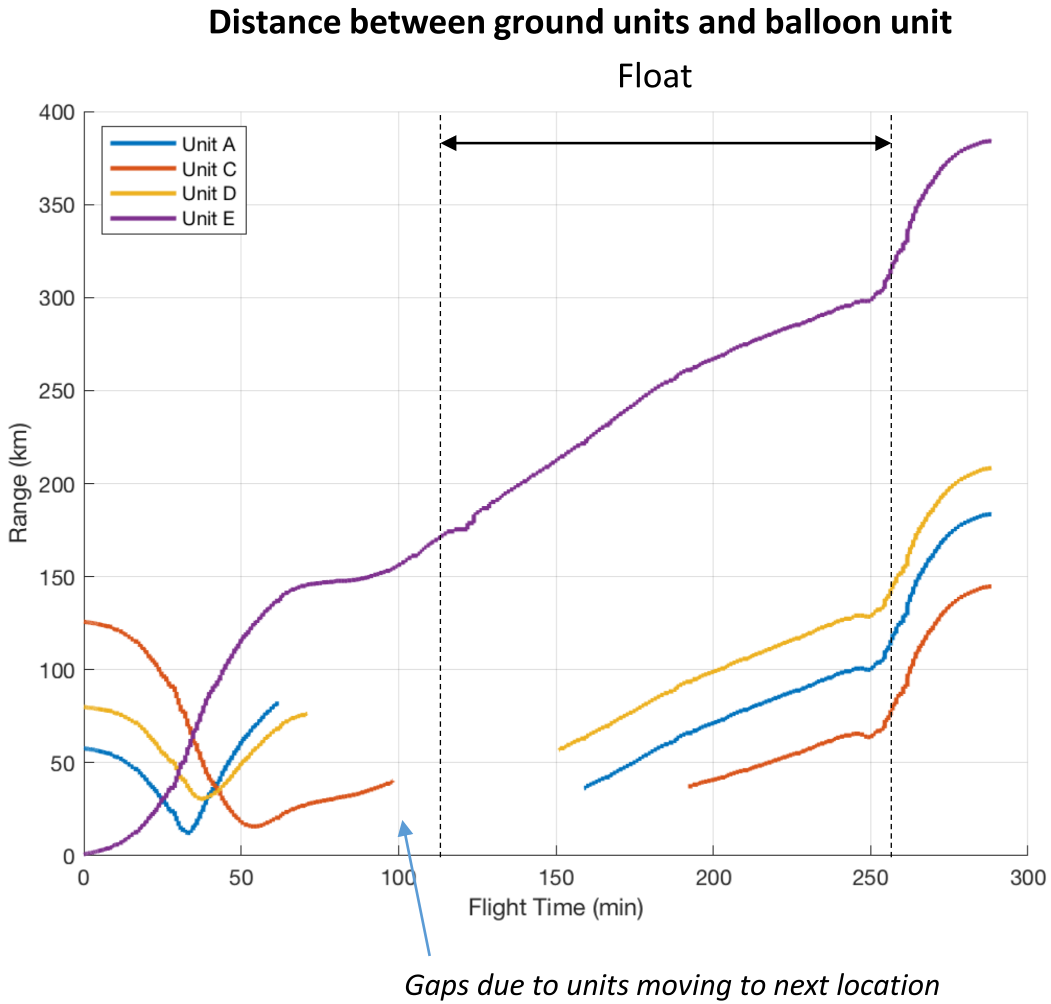
Image Credits : NASA

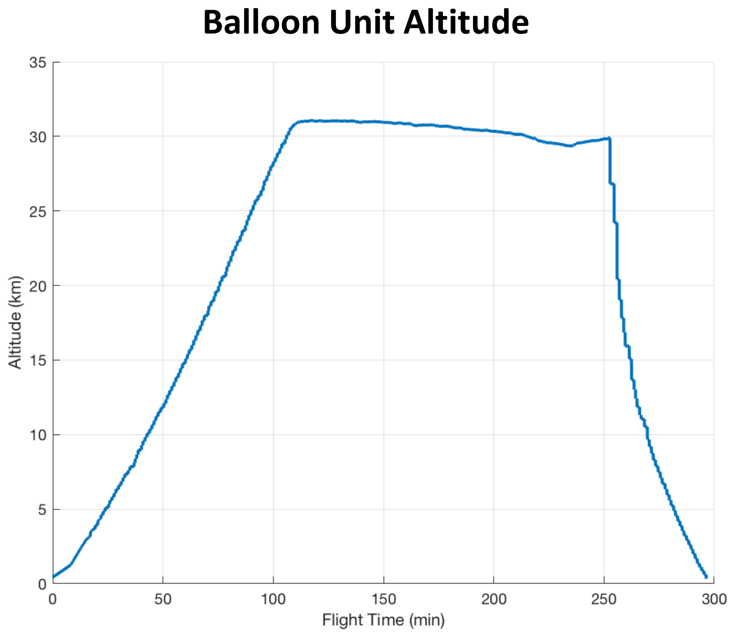



Tracking Summary



Range values from GPS data





Chaser	Unit	Max Range (km)
Kevin	A	183.48
Adam	C	144.69
Alex	D	208.29
Cedric	E	384.01

Experiment Summary

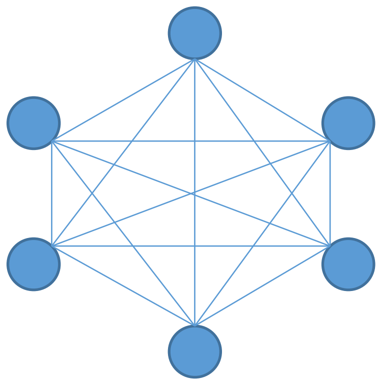
- Balloon unit successfully networked with each of the ground units over a duration of 5.2 hrs
- Successful mesh networking
- Successful high-speed data transfer S-band and UHF
- No S-band ranging data collected ☹
  - Frequency offsets (EFE’s) collected for all links
  - Ranges not calculated
  - Successful GPS lock maintained throughout the duration of the flight

Mesh Networking

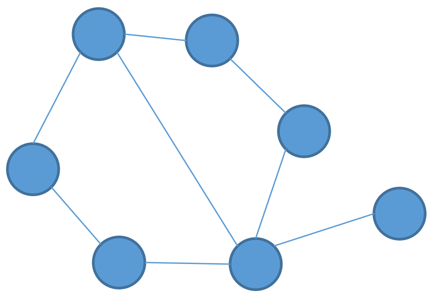
Image Credits : NASA

- V-R3x-S units **successfully** demonstrated **point-to-multipoint, mesh networking**
  - **Point-to-multipoint**: selected given the terrestrial nature of the suborbital experiment
  - **Partial mesh networking**: data was routed between nodes that weren't able to communicate directly via the mesh

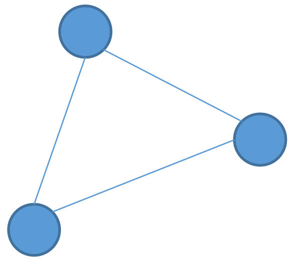
Full Mesh Network



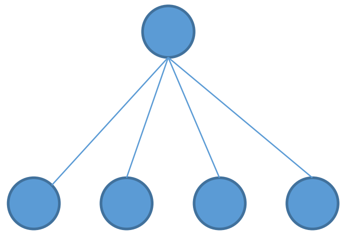
Partial Mesh Network



V-R3x Orbital
Full Mesh Network



V-R3x Suborbital
Point-to-multipoint
Mesh network



High Speed Data Transfer

- Maximum data rates achieved for both suborbital and orbital units
  - Maximum data rates are range independent and limited by hardware

Frequency	Expected	Balloon Actual
UHF (915.6 MHz)	3 – **37 kbps** at distances 45 m – 10 km between two satellite nodes	**37.5 kbps** at distances up to 30 km between two nodes
S-Band (2223.6 MHz)	50 - 250 Kbps at distances 45 m – 10 km between two satellite nodes	**253 kbps** at distances up to 30 km between two nodes

kpbs = kilo bits per second

Ranging Background

- Chirp modulation is ideal for time-of-flight ranging
- Newest S-band LoRa chips (SemTech SX1280 Transceiver) have ranging functionality built into the hardware
- Ranging to be performed between the nodes
- GPS data used for ground-truth

Ranging Packet Format

Preamble	Double Header	Ranging Request	Ranging Silence	Ranging Response
16.25 Symbols	16 Symbols	15 Symbols	2 Symbols	15 Symbols

Ranging process

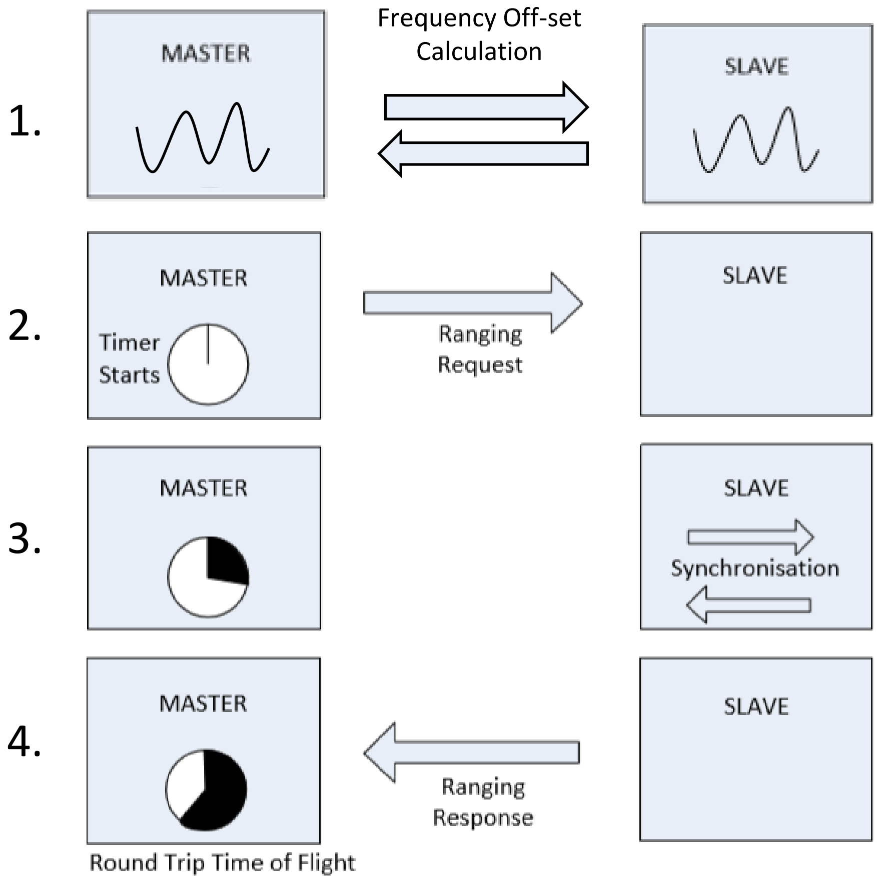
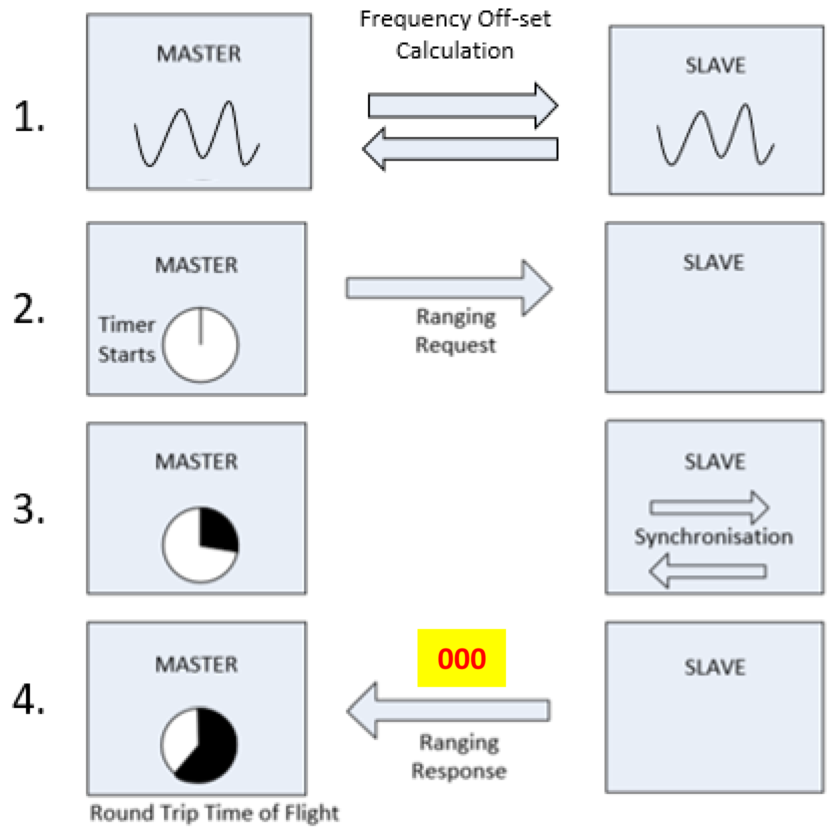


Image Credits : SemTech

Ranging Anomaly Observations

- After 37 minutes, the S-band radio chip started returning 000 for all ranging calculations for the remainder of the flight.
- No usable ranging data was collected
- S-band radio still able close the link and calculate the frequency offset value (EFE) for each ranging exchange throughout the entire flight duration
- No useful data to extract from the EFEs since Doppler shifts were within the noise
- This is NOT the behavior of the on-orbit nodes
  - On-orbit ranging beacon packets logged ranges up to ~80 km



Ranging Anomaly –Investigation

Image Credits : SemTech

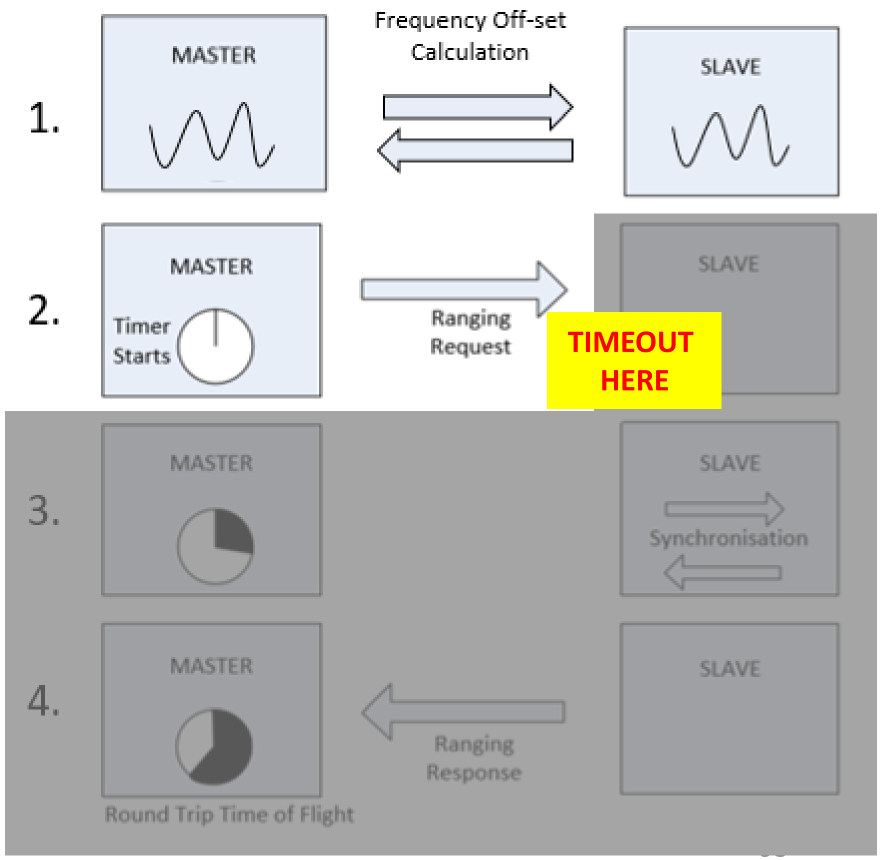
Root cause analysis points to an IRQ routine error:

- Radio parameters changed for balloon flight to optimize ranging distances rather than precision to ensure links close with balloon
- Lower bandwidth means longer TX time per symbol.
- Increasing TX time, revealed an oversight in the way the interrupt controller bit is checked for ranging
- Interrupt controller returned a false positive where an interrupt was fired before the ranging had completed resulting in 000 after the balloon gained some distance from the ground nodes

Path forward

- Fixed the IRQ routine to check for bit-by-bit changes w/ documentation
- Selected new parameters, where Ridge Testing Radio Parameter Selection: Went through the link budget and pick the SF/bandwidth for this scenario; picked the most reliable choice to close the link (trade of closing the link vs accuracy

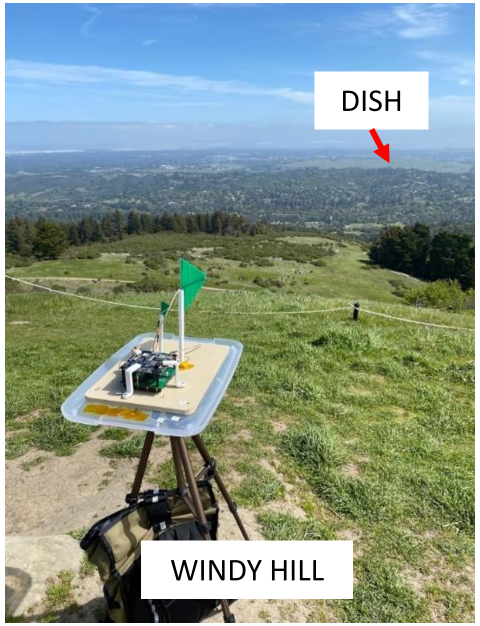
Units	SF	Bandwidth	Ranging Distance	Ranging Precision
Orbit	10	1600 kHz	Short	Best
Balloon	10	400 KHz	Long	Worst



Ranging Anomaly – Testing

Image Credits : NASA

- Fixed the IRQ routine to check for bit-by-bit changes w/ documentation
- Selected new parameters to optimize timing and link budget and pick the SF/bandwidth for this scenario
- Range test 4/4 – All nominal
- Ridge testing 4/9 – Same anomaly observed
- Implemented firmware fixes
- Ridge testing w/ successful ranging 4/30

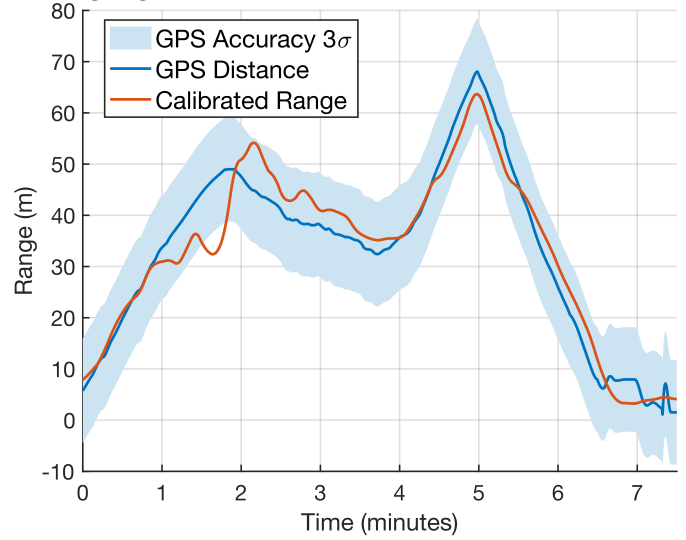


Units	SF	Bandwidth	Ranging Distance	Ranging Precision
Orbit	10	1600 kHz	Short	Best
Balloon	10	400 KHz	Long	Worst
Ridge Testing	10	800 KHz	Medium	Medium

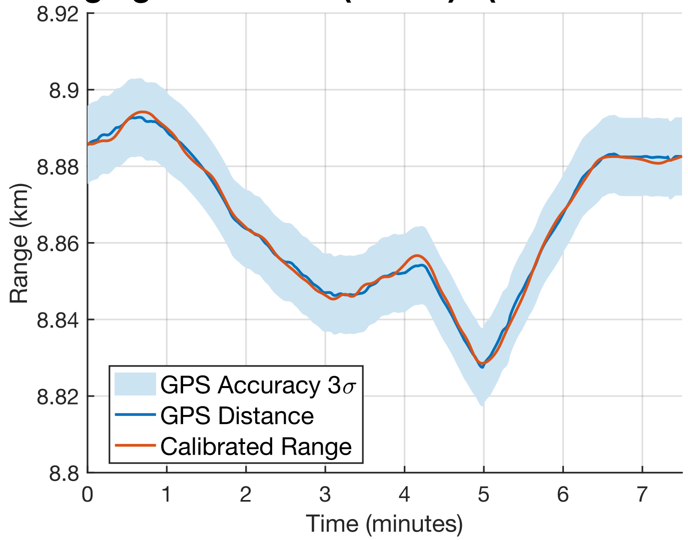
Dataset 1

Calibration coefficients from Selected data set

Ranging Calibration (B + A) (RMS = 4.6725m)

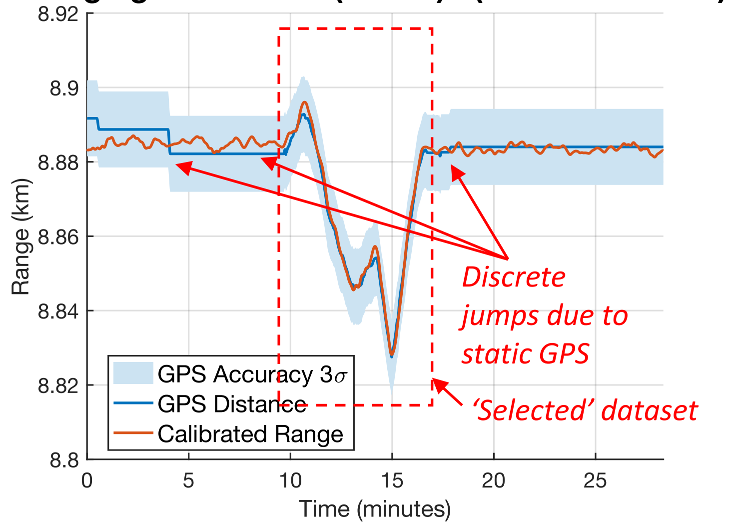


Ranging Calibration (C to B) (RMS = 1.1204m)

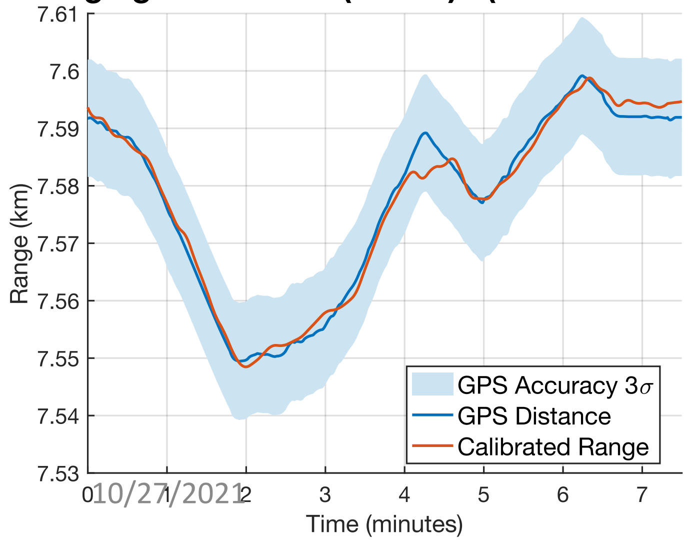


Whole dataset example:

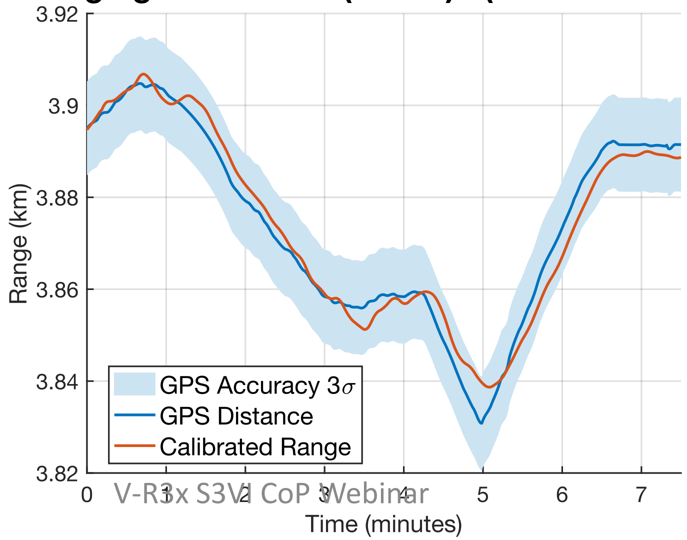
Ranging Calibration (C to B) (RMS = 2.4388m)



Ranging Calibration (D to B) (RMS = 1.8458m)



Ranging Calibration (B to E) (RMS = 3.6266m)

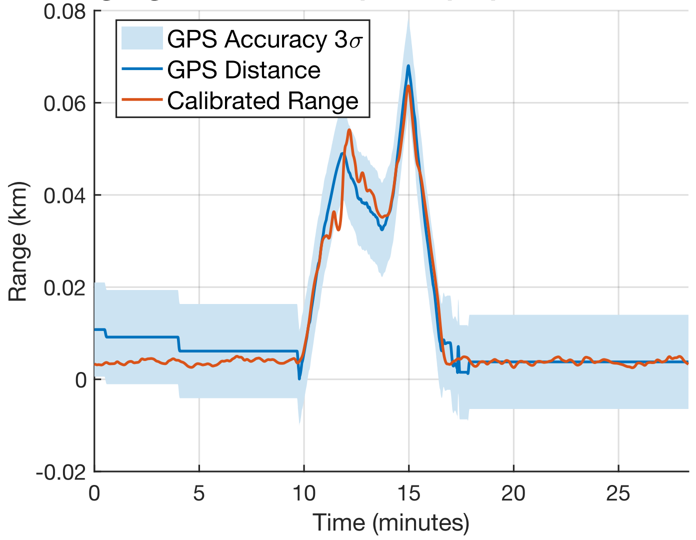


- A = Max (w Balloon)
- B = Balloon (Dish)
- C = Adam (Skyline 9.12 km)
- D = Anh (Windy Hill 7.64 km)
- E = Kevin (Foothills Park 4.15 km)

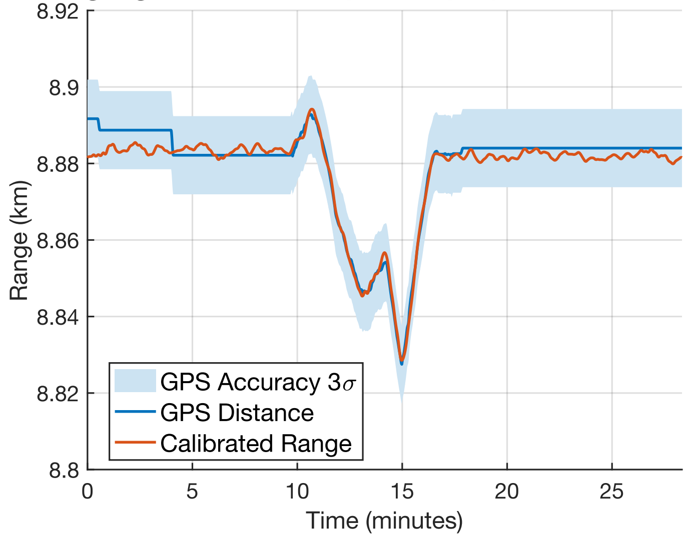
Dataset 2

Calibration coefficients from Dataset 1 and applied to the whole measurement history.

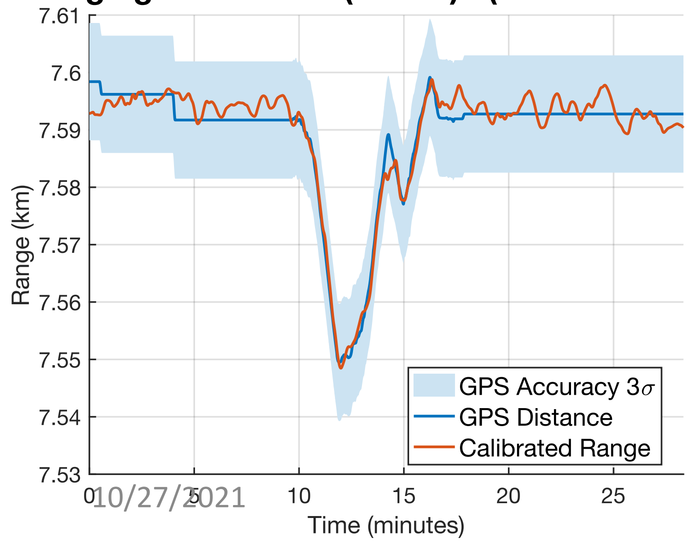
Ranging Calibration (B + A) (RMS = 3.4307m)



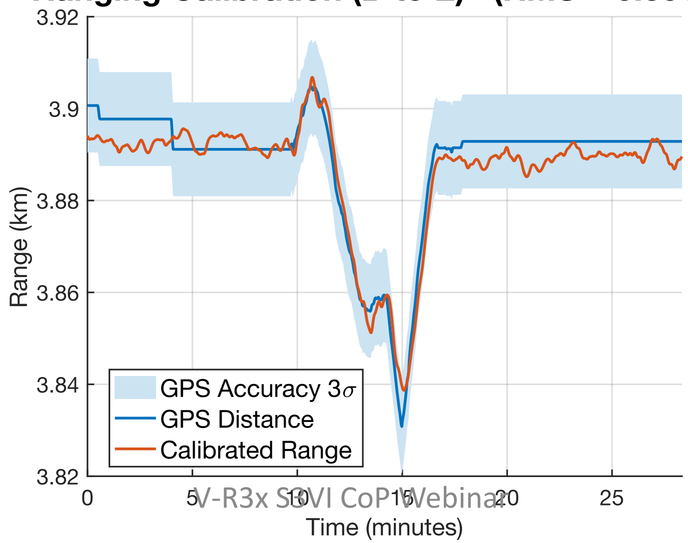
Ranging Calibration (C to B) (RMS = 2.7942m)



Ranging Calibration (D to B) (RMS = 2.3012m)



Ranging Calibration (B to E) (RMS = 3.851m)

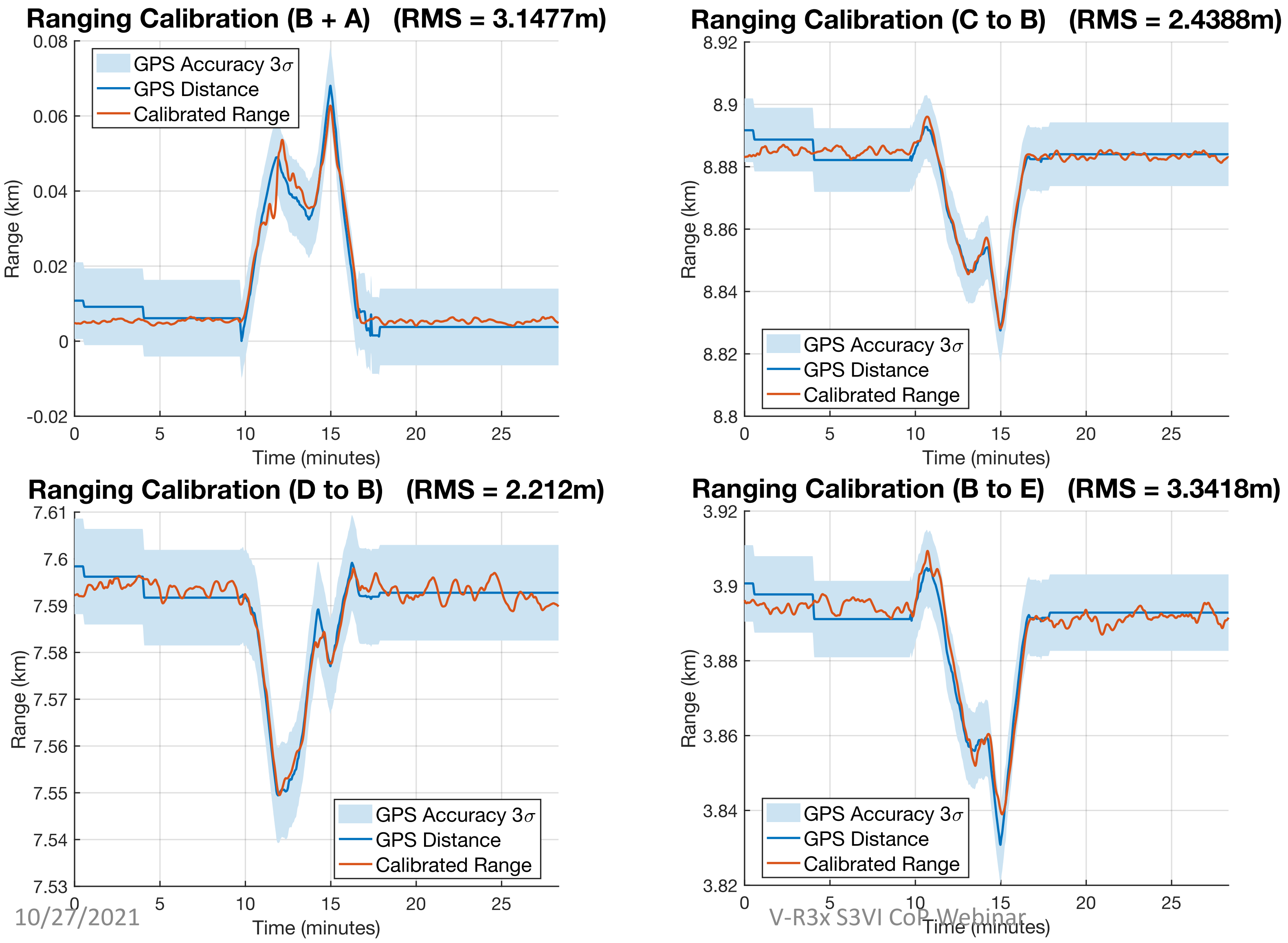


Notes on analysis

- Smoothing of raw range data was done using a sliding window moving average
- Also tried pure matlab smoothing data routine
- Potential to use a kalman filter and model max as a 2-d integrator

Dataset 3

New calibration based on all the data, not just the 'selected' data



Ridge Test Summary

Dataset	Dataset Summary	Range Error between Sats			
		B⇔A	B⇔C	B⇔D	B⇔E
1	Calibration from ‘selected’ dataset	4.672m	1.120m	1.846m	3.627m
2	Calibration applied to whole dataset from ‘selected’ dataset	3.431m	2.794m	2.301m	3.851m
3	All data calibration	3.148m	2.439m	2.212m	3.342m
Average Range Error		**3.750m**	**2.118m**	**2.120m**	**3.607m**

- All errors within the stack-up for the given uncertainty on the GPS receiver and spec from the radio
- Manufacturers advertise numbers as guarantee with unit-to-unit variation
    - 7m for 3-sigma error for GPS
    - 5m is 2-sigma error for GPS
    - Expected error is **3.85m** (1-sigma)

- Take away:
    - Accuracy goes down with sqrt of measurements
    - Orbital dynamics would allow better filter implementation to achieve GPS ground-truth precision of 1m RMS

Suborbital Objective Tracking

ID	Short Req.	Long Req.	Suborbital
1-1	S-band High Precision Ranging	V-R3x shall demonstrate data rates 50 - 250 Kbps at distances 45 m – 10 km between two satellite nodes. Spacecraft telemetry downlink will be used to validate the ranging measurements.	NO BALLOON DATA Supplemental ridge test data indicates **2 m** range precision at distances up to **9 km** between at least two satellite nodes, indicating orbital data **likely** to achieve <1 m at 500 km.
1-2	S-band High Data Rate Cross-link	V-R3x shall demonstrate data rates 50 - 250 Kbps at distances 45 m – 10 km between two satellite nodes. Spacecraft telemetry downlink will be used to validate the ranging measurements.	COMPLETE **253 kbps** at distances up to 30 km between two nodes

Raven Flight Objectives

- *100kft altitude for a minimum of (2) hours - COMPLETE*
- *Transmit and receive data from Balloon unit to four ground units via ISM & S-band - COMPLETE*

Suborbital Lessons Learned

Lessons Learned

- Suborbital demonstration before orbital demonstration would have been useful to address bugs
- GPS, UHF, and S-band Link budget better than expected for terrestrial demo
- High speed comm verified hardware limits
- Expected temperatures very cold
- Gather more data if possible of env. (temp, acceleration, etc.)
- Always get TSA paperwork; carry-on hardware does not fit in overhead cabins of older regional planes
- Check hardware end-of-day; go through debug exercise with everyone during campaign
- Stay on top of your STA
  - Submit with plenty of margin
- Raven has a lot of knowledge, materials, and expertise – lean on them
  - Mechanical, Thermal, and Flight patterns
  - Environment at Raven dustier/drier than expected

- Achievements:
  - Demo'd meshed networking and debugged ranging
  - Valuable lessons learned for future comm mesh networking suborbital experiments

Global Objective Tracking

ID	Short Req.	Long Req.	Orbital	Suborbital
1-1	S-band High Precision Ranging	V-R3x shall demonstrate ranging with <1 m precision at a distances up to 500 km between at least two satellite nodes	**IN-PROGRESS** Requires complete ranging and GPS data. Beacon data indicates **ranging successful**; no GPS yet.	**NO BALLOON DATA** Supplemental ridge test data indicates **2 m** range precision at distances up to **9 km** between at least two satellite nodes, indicating orbital data likely to achieve <1 m at 500 km
1-2	S-band High Data Rate Cross-link	V-R3x shall demonstrate data rates > 50 Kbps (up to 250 kbps) between two satellite nodes at distances up to 10 km between at least two satellite nodes	**COMPLETE** **253 kbps** at distances up to 75 m between two nodes	**COMPLETE** **253 kbps** at distances up to 30 km between two nodes
1-3	Relative Topology Recovery	V-R3x shall demonstrate relative topology recovery between all satellite nodes (post-processed on the ground)	**IN-PROGRESS** Requires complete ranging and GPS data. Beacon data indicates **ranging successful**; no GPS yet.	**NOT SCOPED**
1-4	Distributed sensor collection	V-R3x shall Coordinate and collect radiation data from on-board sensors from each satellite node	**IN-PROGRESS** Requires full dataset with GPS. Beacon data indicates **radiation data collection successful**.	**NOT SCOPED**

PACE Global Lessons Learned

- Suborbital demonstration provides critical data and lessons learned to increase mission success for orbital demonstrations
- Ability to rapidly demonstrate this technology could not be done without University partners and PyCubed architecture
- Lessons learned from rapid V-R3x demo can enable future rapid follow-on missions (<12 mo.)
- COVID-19 impacts severely compressed schedule
- RFA is **always** an issue
- V-R3x provided many lessons learned and valuable experiences for shaping of PACE series of mission on how to technically and logistically bridge FO to SST opportunities

Questions

Robotic Exploration Lab

PACE