Developing Gram-Scale Flight Computers for Free-Flying Light Sail Demonstration in LEO

Joshua Umansky-Castro, Corbin Heywood, and Matthew Hurford

2023 International Symposium on Space Sailing

Mission Context

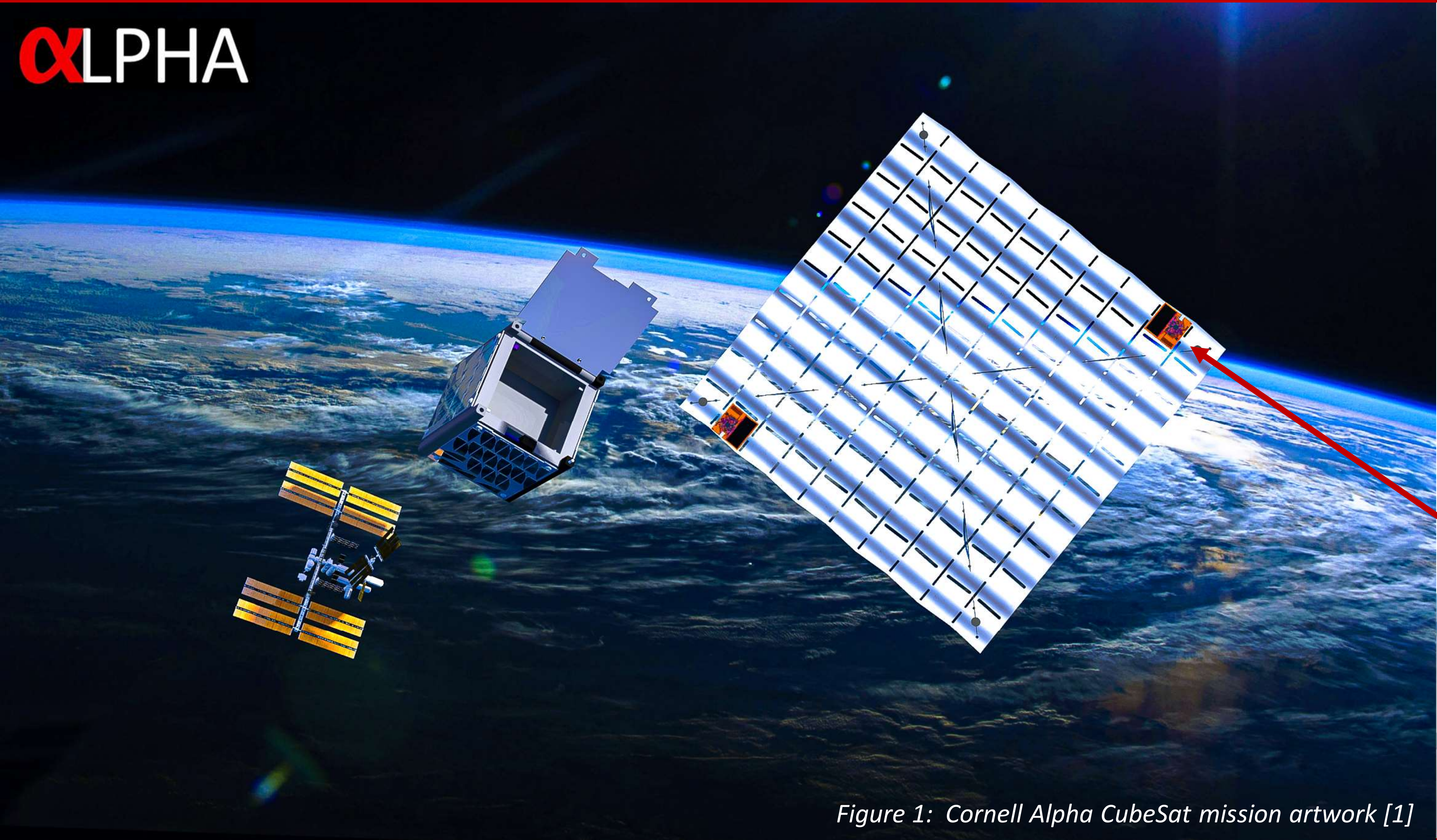


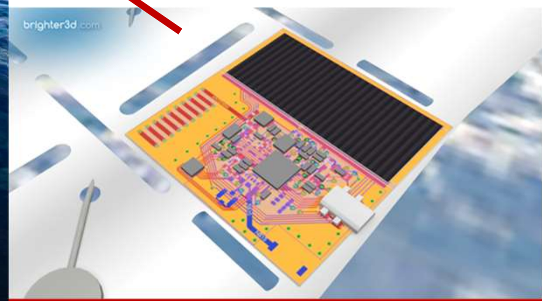
Figure 1: Cornell Alpha CubeSat mission artwork [1]

1U CubeSat deployed from ISS

Light sail unfolds and fully separates from CubeSat

Gram-scale computers, "ChipSats," gather and downlink sail telemetry

Figure 2: ChipSat on Alpha sail [Image courtesy of Andrew Filo]



Mission Context

CubeSat mission technology demonstrations

Light Sail

ChipSats

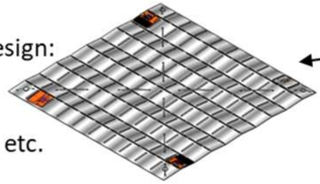
Radio

Attitude Control

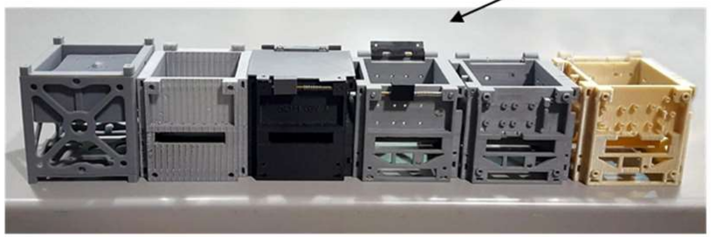
3D-Printing

Holograms

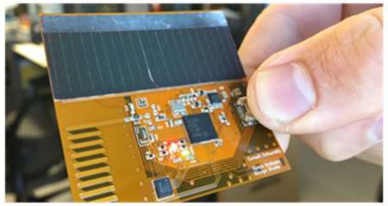
Novel sail design: material, deployment mechanism, etc.



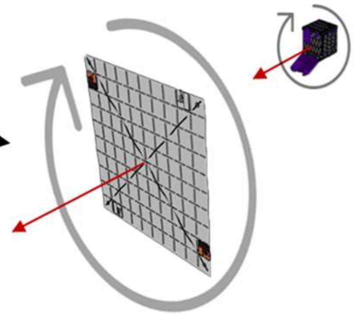
First flight of RockBLOCK Iridium modem. Only transceiver on board



Fully 3D-printed chassis



First flight of newest-generation ChipSat



Full inertial body nonlinear angular rate control and attitude control using magnetorquers only

First demonstration of a holographic message plaque in space; Retroreflective elements for identification in orbit

Also establishing flight heritage for:

- flight computer
- batteries
- several sensors

Figure 3: Primary technology demonstrations onboard the Alpha CubeSat mission

Light Sail Background

A little about the light sail:

It's small...

But very low mass

The result: comparably high acceleration is possible

$$\sigma = \frac{m_{tot}}{A} \quad (1)$$

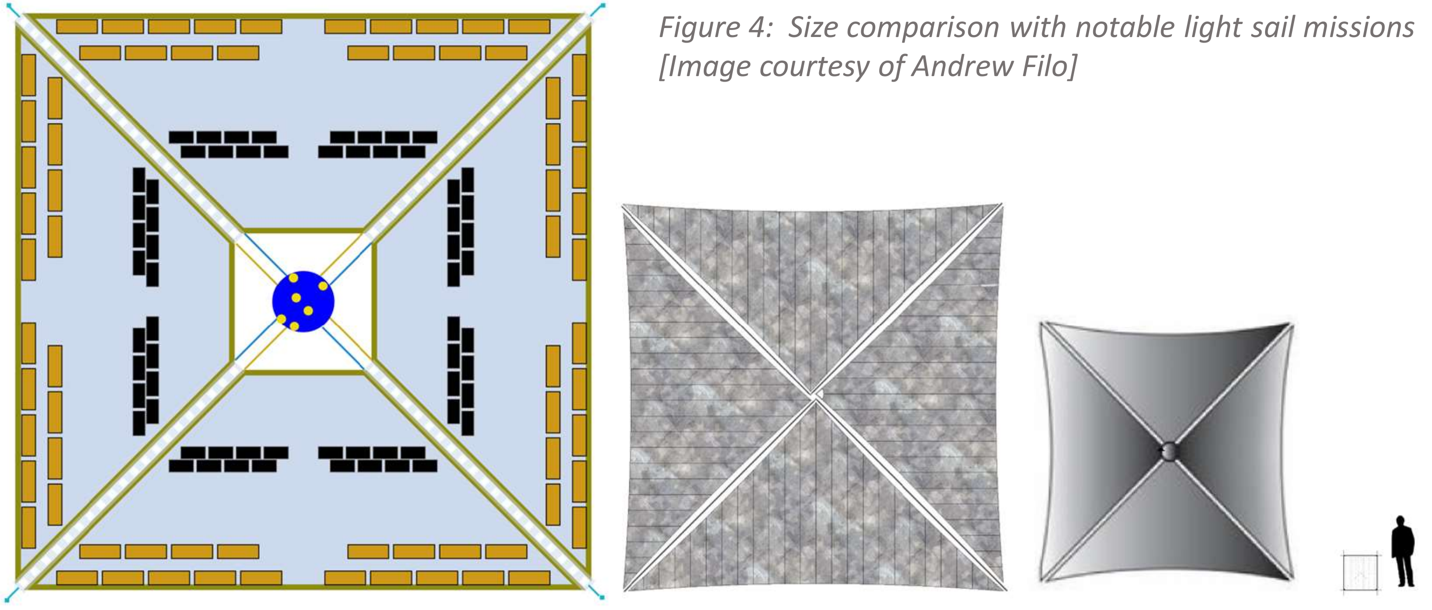


Figure 4: Size comparison with notable light sail missions [Image courtesy of Andrew Filo]

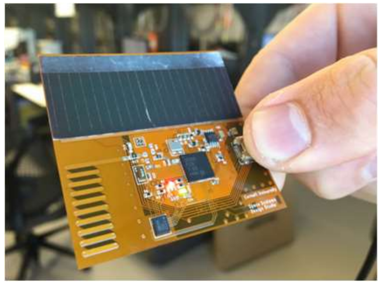
	IKAROS (2010)	NanoSail D-2 (2010)	LightSail-1,-2 (2015, 2019)	CanX-7 (2016)	InflateSail (2017)	CubeSail (2018)	Alpha (2021)
Propelled Mass	315 kg	4 kg	5 kg	3.75 kg	3.2 kg	3.5 kg	93.5 g
Sail Dimensions	14m x 14m	3.05m x 3.05m	5.6m x 5.6m	2m x 2m	3.3m x 3.3m	7.7cm x 250m	0.575m x 0.575m
Sail Area	196 m^2	10 m^2	32 m^2	4 m^2	10 m^2	20 m^2	0.33 m^2
σ (g/m^2)	**1607**	**400**	**156**	**938**	**320**	**175**	**283**

Table 1: Light sail specifications comparison [1]

[1] Umansky-Castro et al. "Design of the Alpha CubeSat: Technology Demonstration of a ChipSat-Equipped Retroreflective Light Sail," *AIAA SciTech 2021 Forum,* January 2021

Alpha Sail Overview

Comparably high acceleration made possible by…



Chip-Scale Flight Computers

0.575m x 0.575m
93.5g

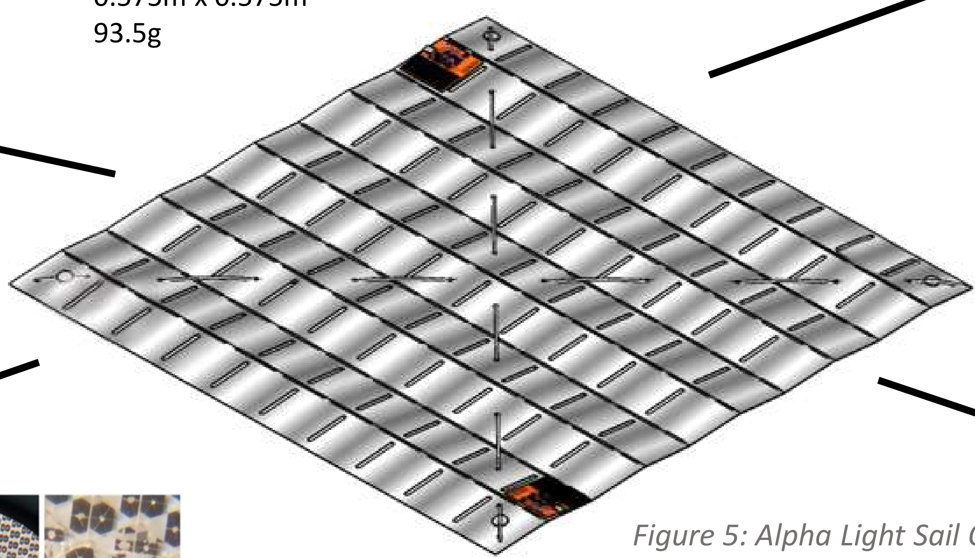
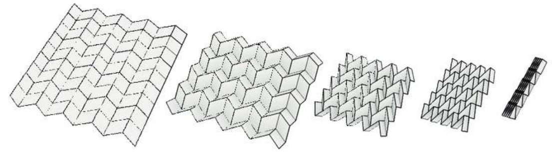
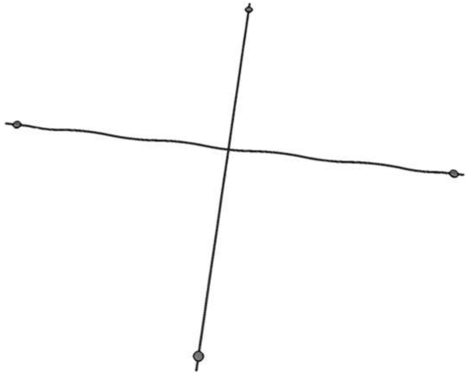


Figure 5: Alpha Light Sail Overview
[Image courtesy of Andrew Filo]

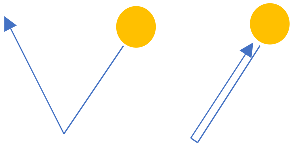


Origami Miura Fold [2]

Shape Memory Alloy Cross-Frame

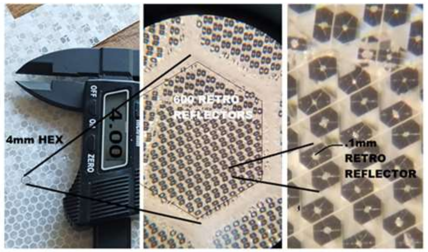


Retroreflective Sail Material



reflective retroreflective

Avery Dennison®
OmniView™ T- 9000

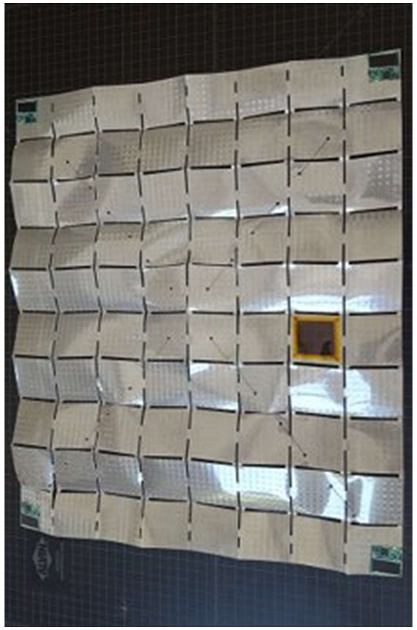


60% OF THE AREA IS RETRO REFLECTORS

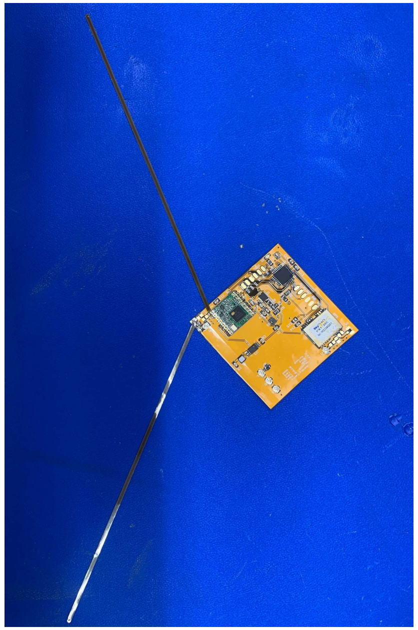
[2] Tachi, Tomohiro. Freeform Rigid-Foldable Structure using Bidirectionally Flat-Foldable Planar Quadrilateral Mesh. 2011.

Current Status

CubeSat complete as of Fall 2022



Light Sail complete as of 2020



ChipSat prototype fully functional as of May 2023

“Sprite” ChipSats

Figure 6: “Sprite” ChipSat developed at Cornell University [Image courtesy of Zac Manchester/Breakthrough Starshot]

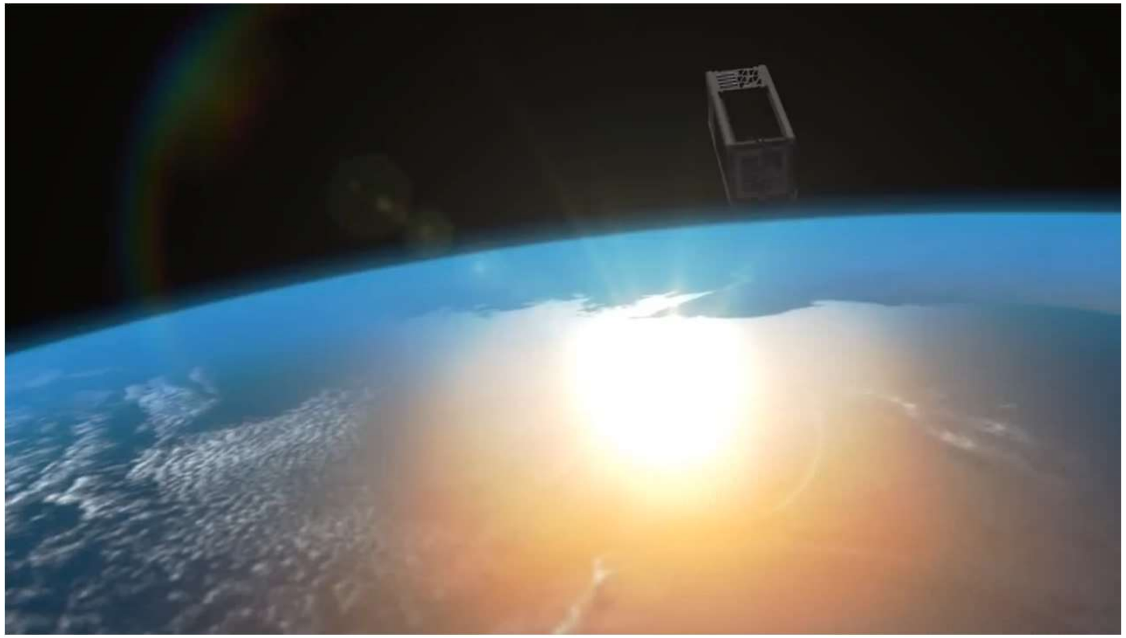


Figure 7: Animation of ChipSats deployed in KickSat-2 Mission [Courtesy of Ben Bishop]

Closing the Comms Link

Main challenge at small scale: RF Communications

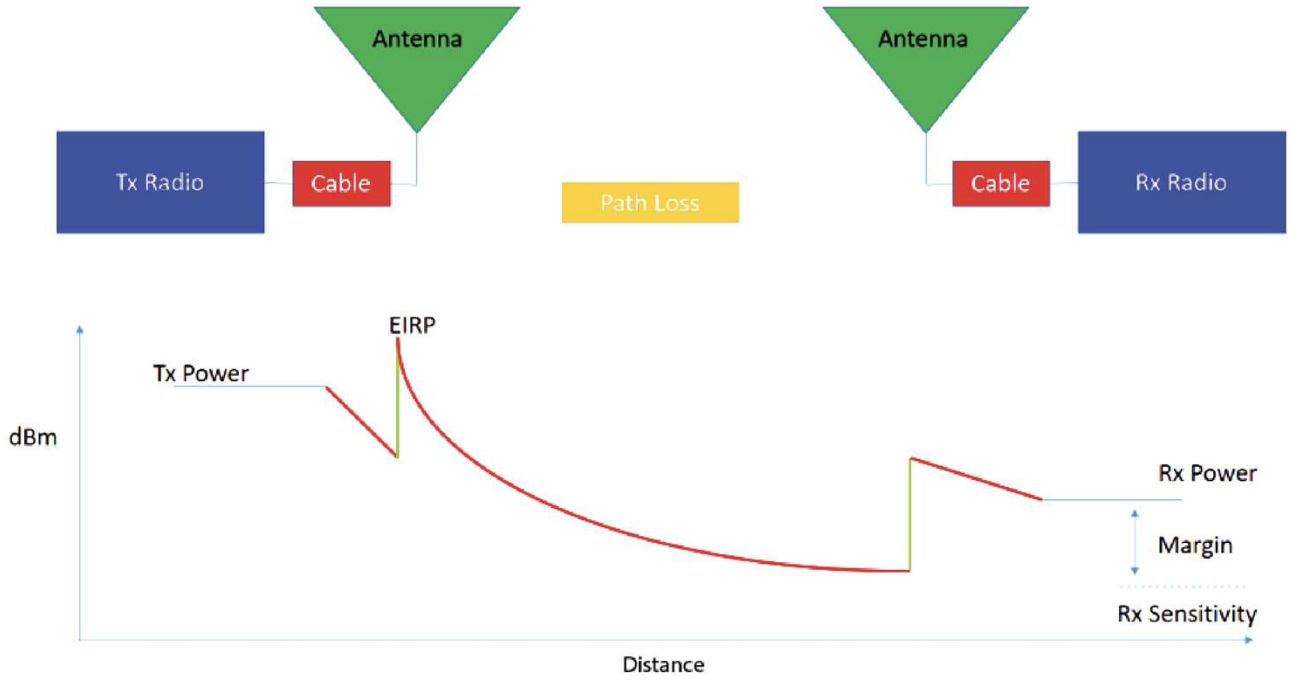


Figure 8: Link budget high level overview [Based on diagram from IITB "Satellite Wiki"]

10mW transmitter needed to be heard over 350km

Well below noise floor

Matched Filter used to extract ChipSat data from noise

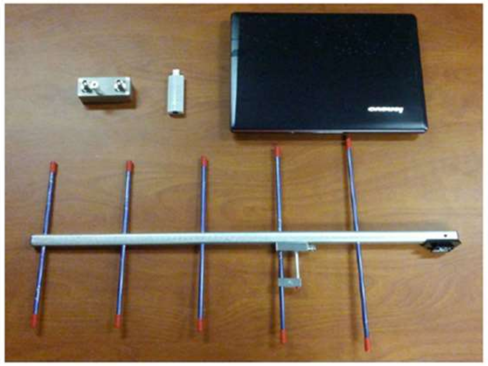


Figure 9: KickSat Ground Station [3]

[3] Manchester, Z., Peck, M., and Filo, A., "KickSat: A Crowd-Funded Mission To Demonstrate The World's Smallest Spacecraft," 2013.

Cornell University

Learning from KickSat 2

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Testing

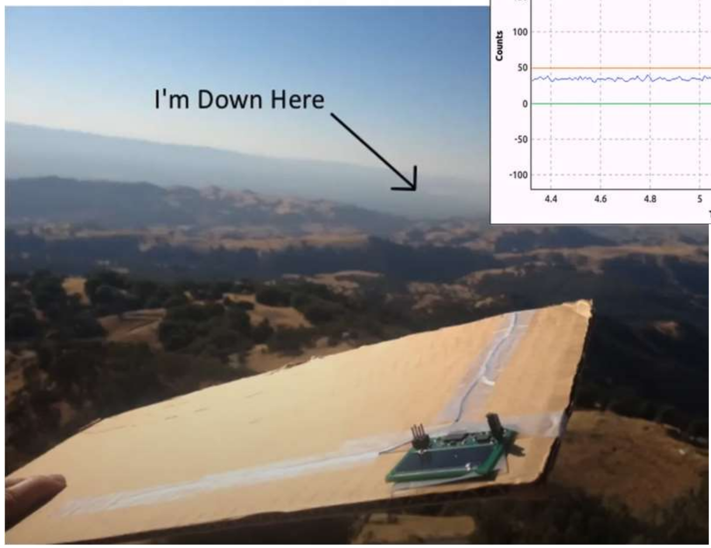


Figure 10: "Sprite" ChipSat ridge test [Zac Manchester]

Figure 11: Correlation spike from matched filter algorithm [3]

30 mile range test

Attenuated further to simulate 1000km

Results

Faint signals detected

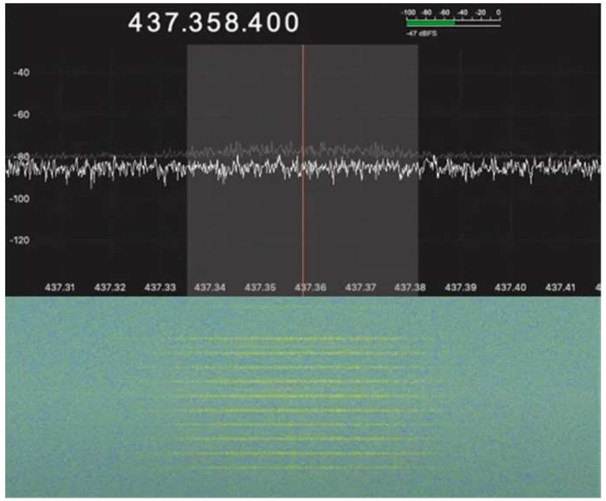


Figure 12: Detected ChipSat signals in LEO

Figure 13: Dwingeloo 25m radiotelescope [Leiden University]

[3] Manchester, Z., Peck, M., and Filo, A., "KickSat: A Crowd-Funded Mission To Demonstrate The World's Smallest Spacecraft," *AIAA/USU SmallSat Conference,* August 2013.

Rethinking ChipSat Comms

New mission profile = new design constraints

Sail in orbit for couple days maximum

Few passes over singular ground station

Transmissions only possible in sun

Solution: wide network of low-cost ground stations

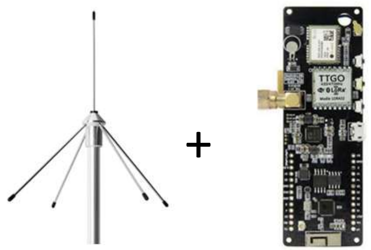


Figure 14: Example ground station equipment for next-generation ChipSats [Alixpress]

Figure 15: TinyGS network of LoRa satellite ground stations [tinygs.com]

LoRa Overview

- Proprietary Modulation Scheme
- Chirp Spread Spectrum (CSS)
- Customizability
- Extremely long range for low power

Figure 17: HopeRF RFM96 LoRa module

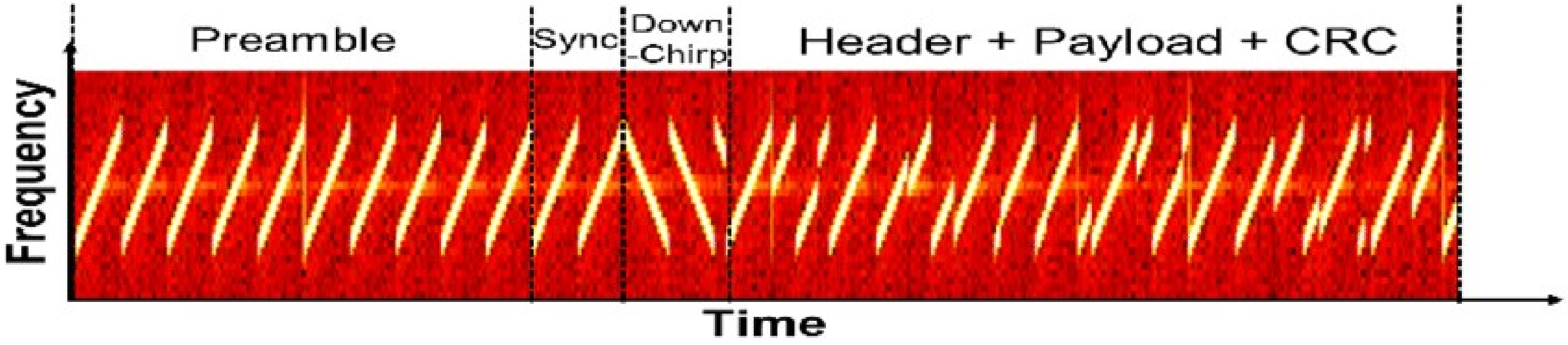


Figure 16: LoRa packet format [4]

[4] Shyamnath et al. (2017). LoRa Backscatter: Enabling The Vision of Ubiquitous Connectivity. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies.

Designing the LoRa ChipSat

- Sources of inspiration:

Figure 18: AmbaSat [5] (LoRa Module)

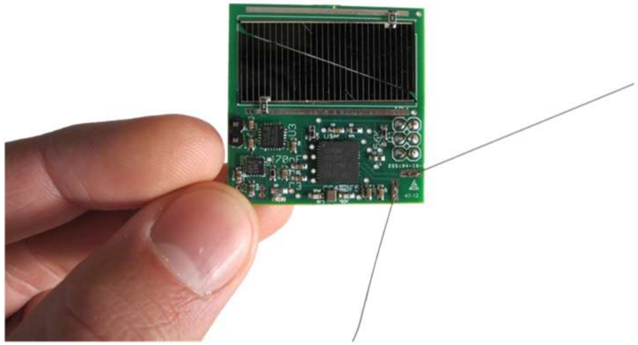


Figure 19: KickSat "Sprite" ChipSat (Dipole Antenna)

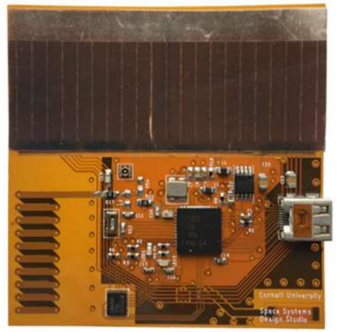


Figure 20: "Monarch" ChipSat (Polyimide substrate, solar cell)

- Key modules:
  - Power: Ubiquity Solar 260mW flex GaAs cells
  - Sensors: Orion B16 GPS, IMU, Temperature
  - MCU: ATMEGA328P
  - Downlink: RFM96 LoRa @ 100mW Tx

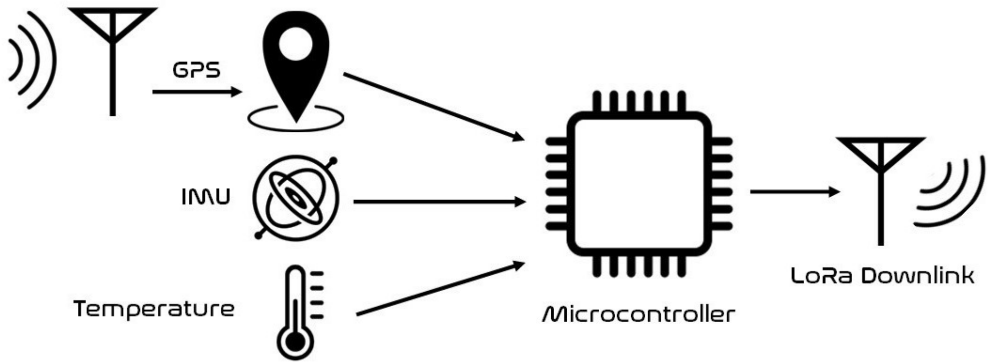
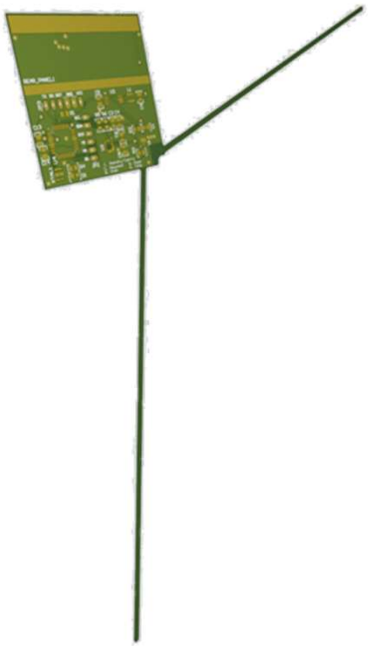


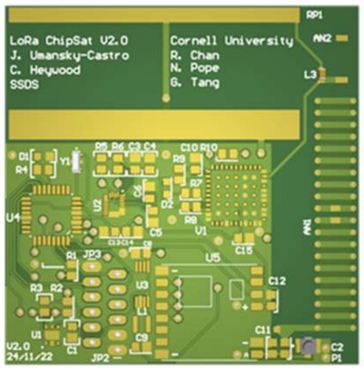
Figure 21: Alpha ChipSat T&C Subsystem Overview

[5] Ambasat Press Release. "Technology start-up creates world's first space satellite kit." May 7, 2019.

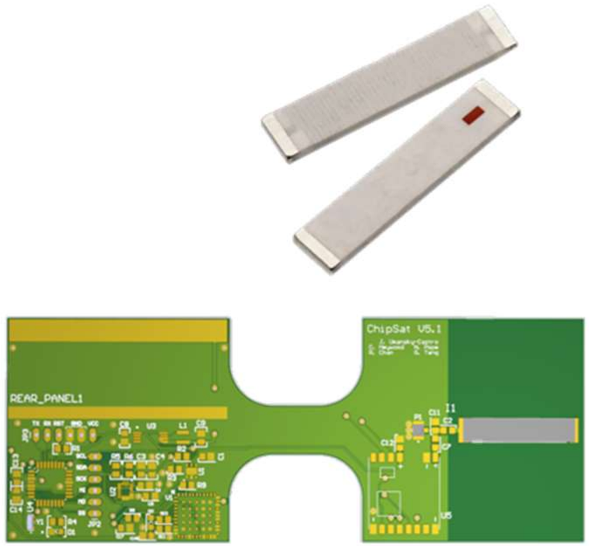
Antenna Candidates



Dipole



Helical



Surface Mount Chip

Monopole

Figure 22: LoRa ChipSat iterations designed and prototyped 2022-2023

Simulation

- CST EM Software
- Modelling
- Optimization

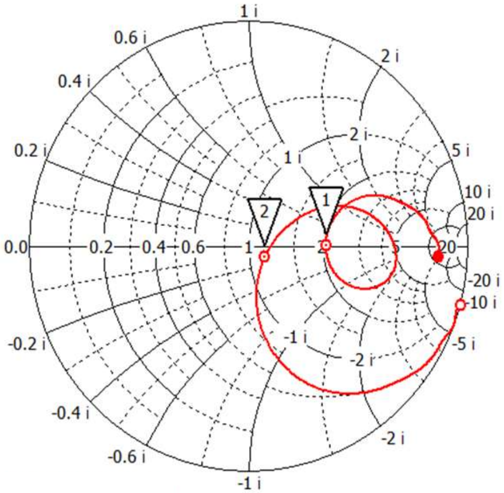


Figure 23: Simulated Smith chart for dipole design

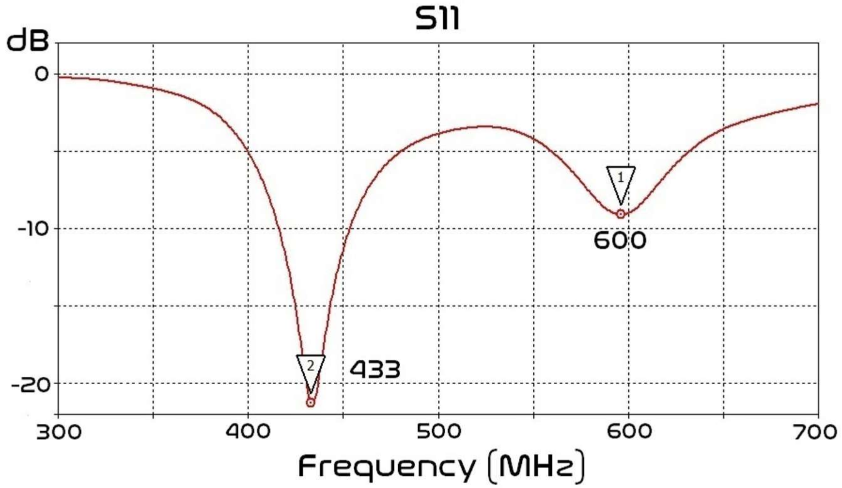


Figure 24: Simulated return loss plot for dipole design

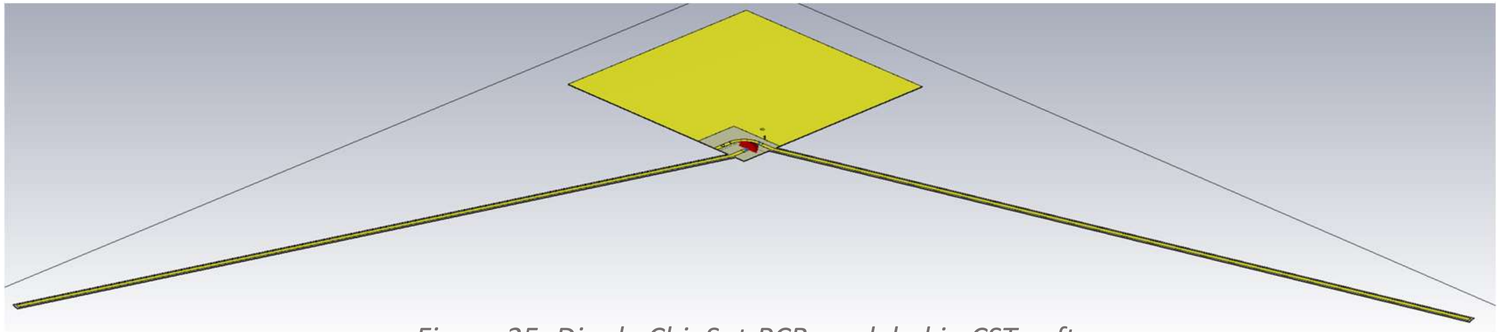


Figure 25: Dipole ChipSat PCB modeled in CST software

Simulation

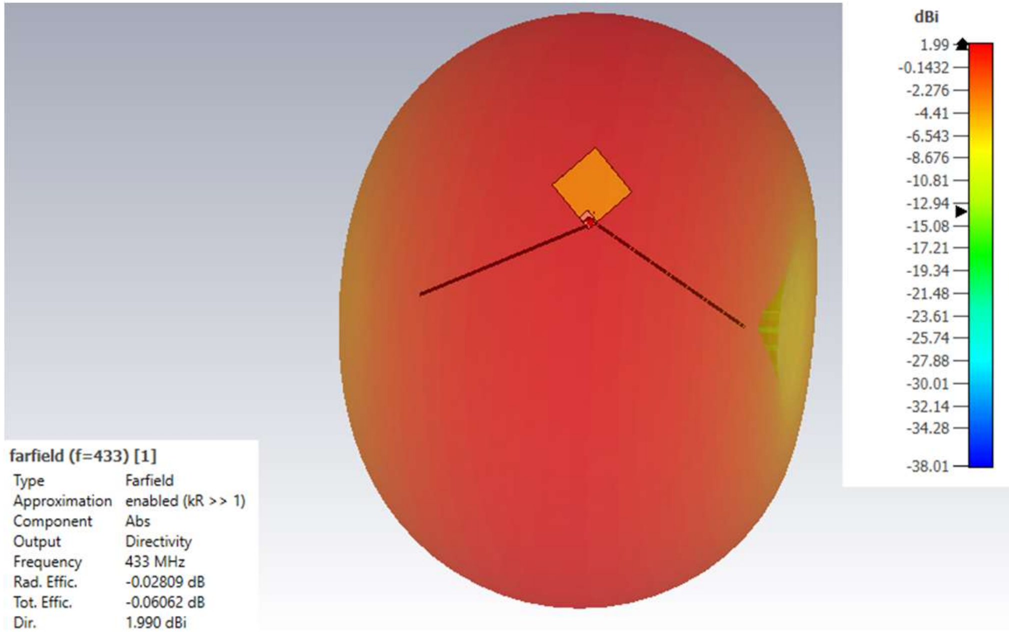


Figure 26: 3D farfield radiation plot simulated for ChipSat dipole antenna

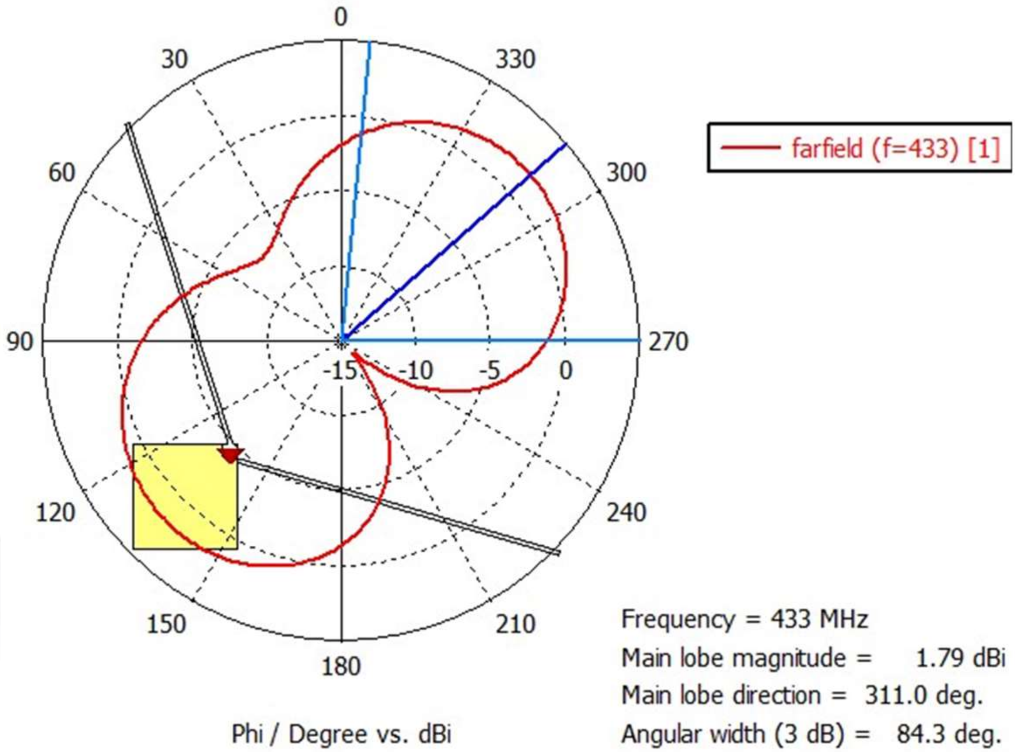


Figure 27: 2D fafield radiation plot simuated for ChipSat dipole antenna

Helical Antenna Investigations

Figure 28: Helical antenna ChipSat on thicker FR4 substrate

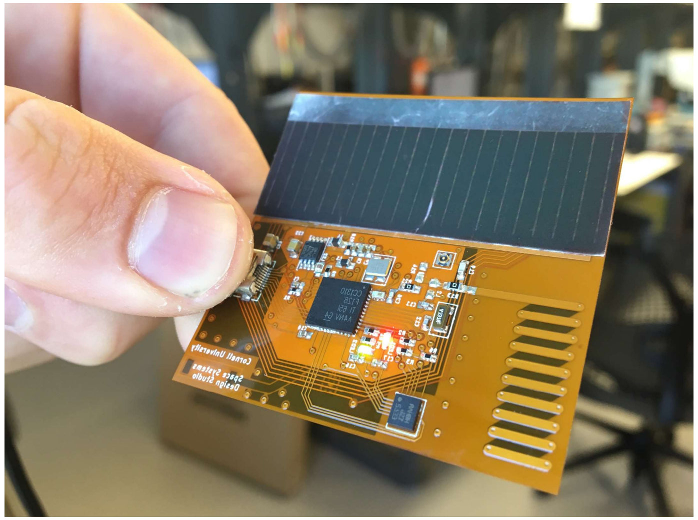


Figure 29: Helical antenna ChipSat on thin polyimide substrate

Figure 30: Side view of thin polyimide ChipSat PCB (no components soldered on)

ChipSat Prototyping

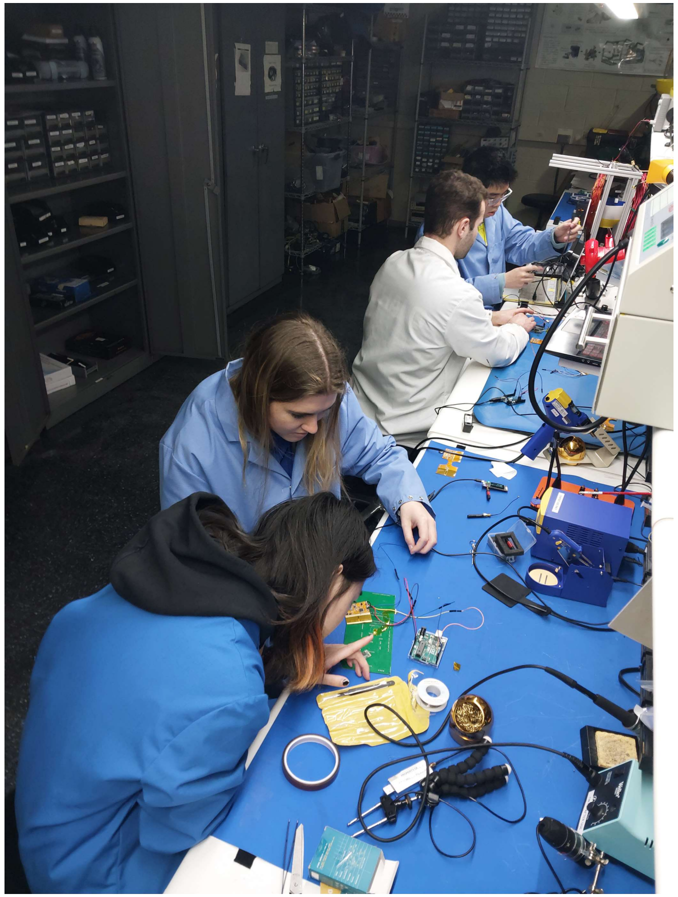


Figure 31: Cornell students prototyping ChipSats

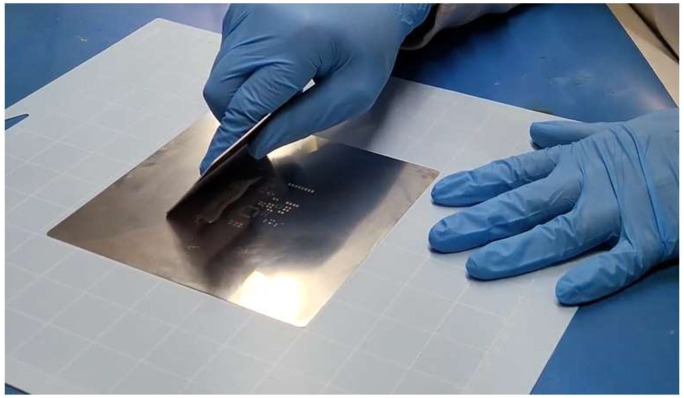


Figure 32: Spreading solder paste over PCB stencil

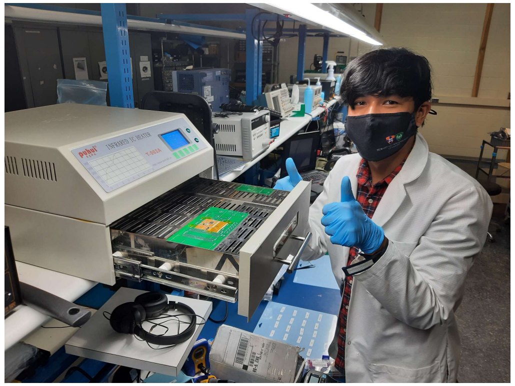


Figure 34: ChipSat placed in reflow oven

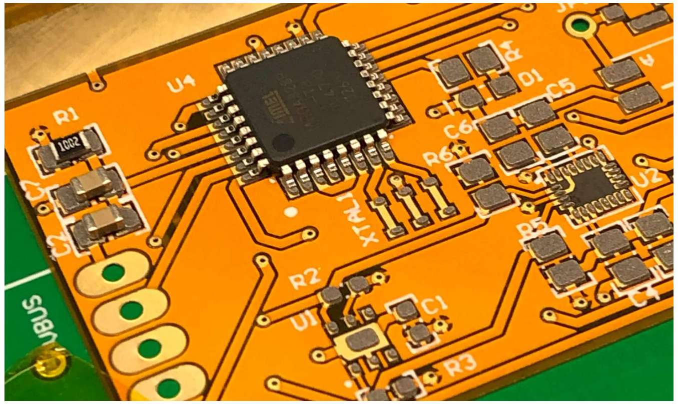


Figure 33: Placing components onto solder paste

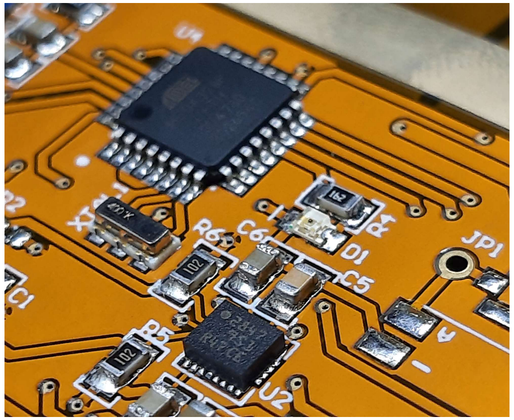


Figure 35: SMD components soldered on ChipSat [6]

Programming & Antenna Tuning

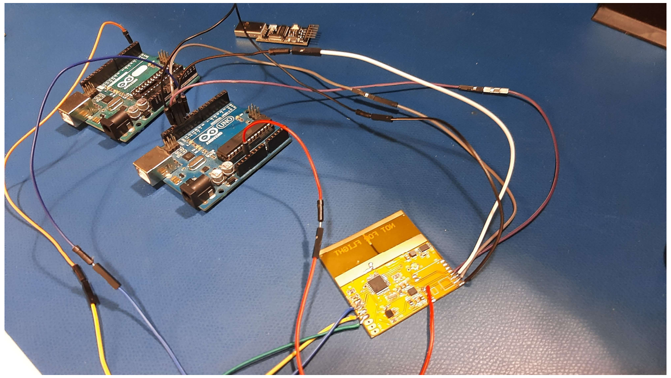


Figure 36: ChipSat wired for programming

Figure 38: Nano Vector Network Analyzer [Aliexpress]

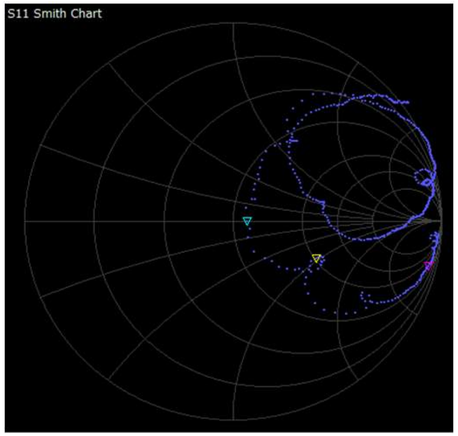


Figure 40: VNA Smith chart for dipole antenna

Figure 37: Reading ChipSat sensors over serial output

Figure 39: ChipSat suspended for antenna analysis

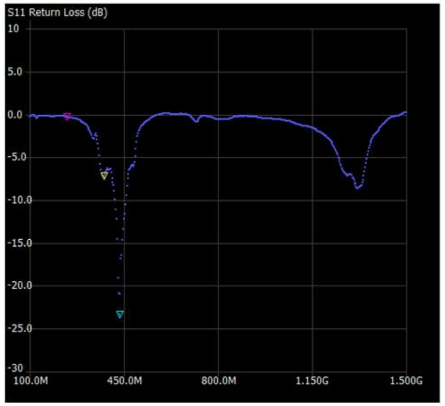


Figure 41: VNA return loss for dipole antenna

Cornell University

Short Range Testing

SSDS
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<u>Antenna comparisons tests (400m)</u>
- Determined best performing antenna

<u>Light sail integration tests</u>
- Quantified light sail interference

Table 2: Antenna comparison test results

For reference,
400m @433MHz = 77dB of path loss
400km @433MHz = 137dB of path loss

ChipSat Testing					
Antenna	**Tx Power**	**Max Atten (dB)**	**RSSI @ Max Atten (dBm)**	**SNR @ Max Atten (dB)**	**Notes**
Monopole	100 mW	44	-138	-16	
Monopole	3.2 mW	36	-137.5	-15.5	Very directional
Chip 1	3.2 mW	30	-138.5	-16.5	Very directional
Chip 2	3.2 mW	30	-136.5	-15.5	Very directional
Dipole 1 (yellow tape on connectors)	3.2 mW	34	-137.5	-15.5	Got one packet at 40, 34 was n
Dipole 2	3.2 mW	40	-138	-17	Very directional at 40 dB atten
Dipole 2	100mW	61	-137	-16	

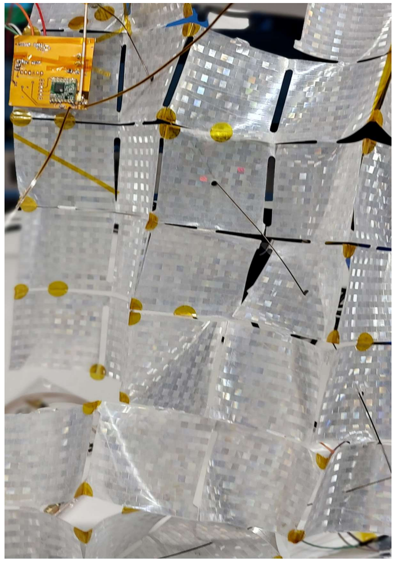


Figure 42: ChipSat-sail integration

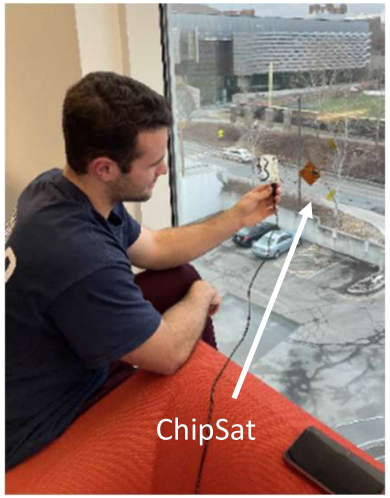


Figure 43: Transmitting ChipSat

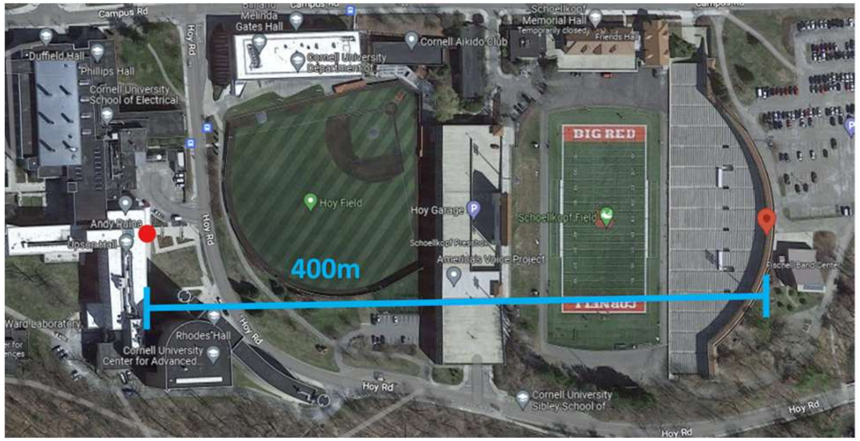


Figure 44: Short-range transmission test

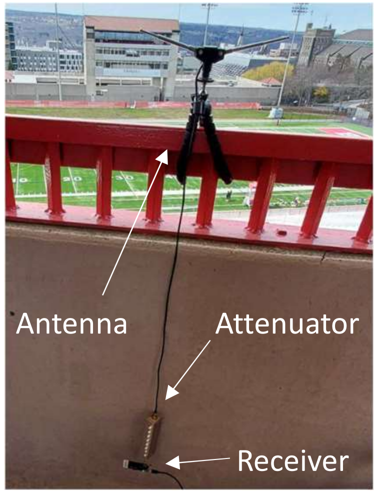


Figure 45: Receiver setup

High Altitude Balloon (HAB) Test

Launched from Maryland; Listening from Cornell

- Distance of 311km
- All receiver antennas able to hear ChipSat transmissions

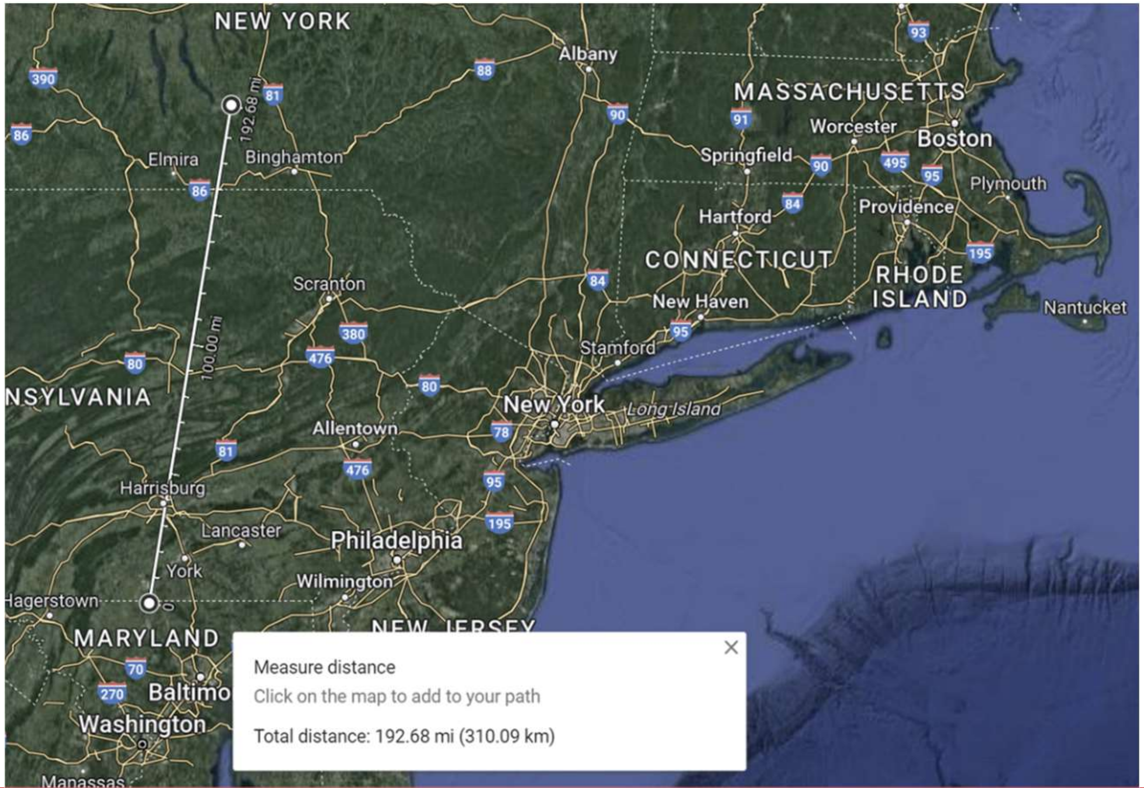


Figure 46: Line of sight distance between ChipSat and ground station during HAB test

Figure 47: Ground Stations near Ithaca, NY

Added over 20dB of additional attenuation to demonstrate link margin.

Feeling confident to launch!

UMD BALLOON PAYLOAD PROGRAM
MARYLAND SPACE GRANT CONSORTIUM

Help track our light sail!

How to get involved:

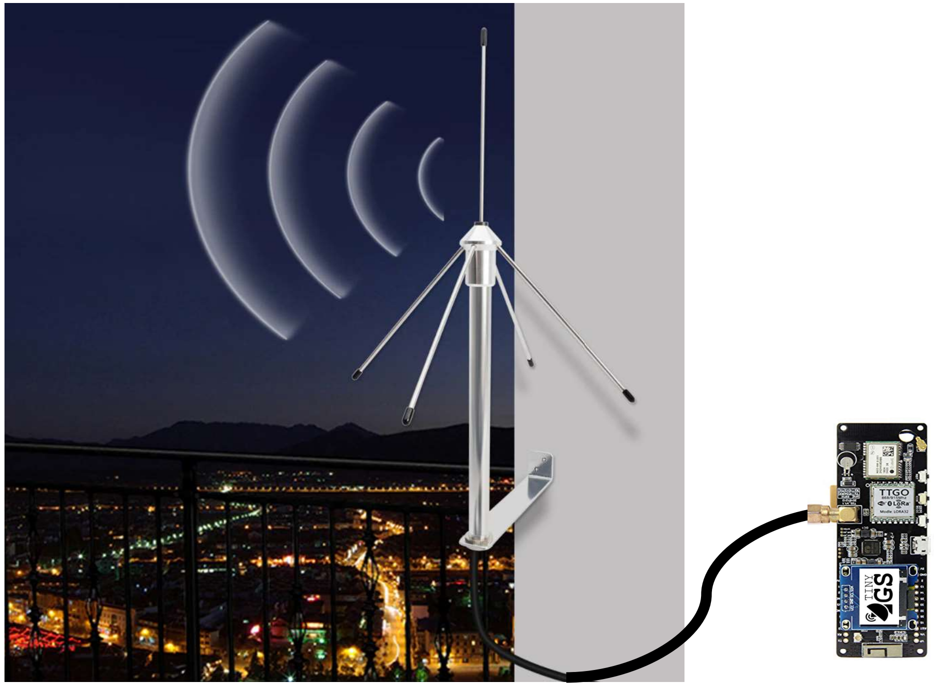


Figure 48: Minimum components needed for ChipSat ground station [Aliexpress]

Set up your own low-cost ground station to track our light sail!

How to learn more:

Visit our exhibit at the Intrepid Sea, Air & Space Museum:

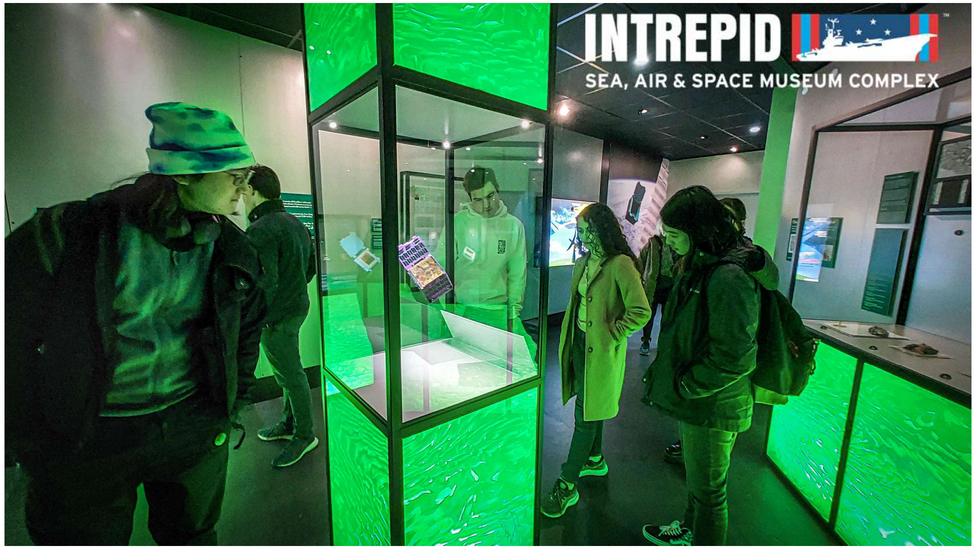
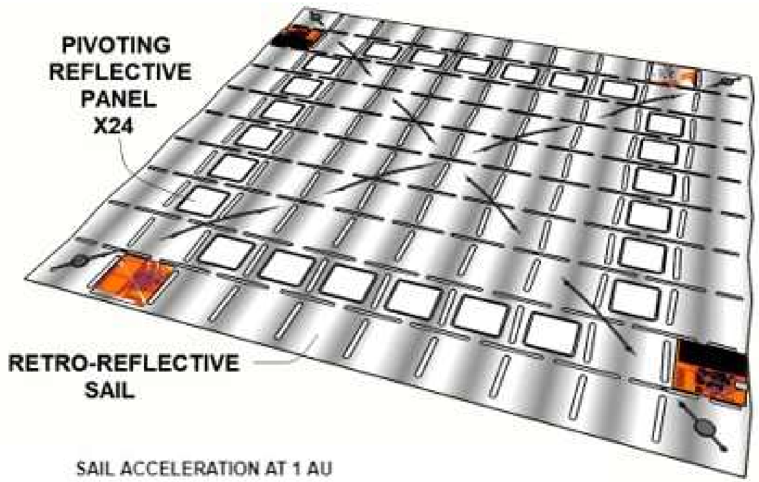


Figure 49: Cornell students visiting "Postcards from Earth" exhibit

New website: alphacubesat.cornell.edu

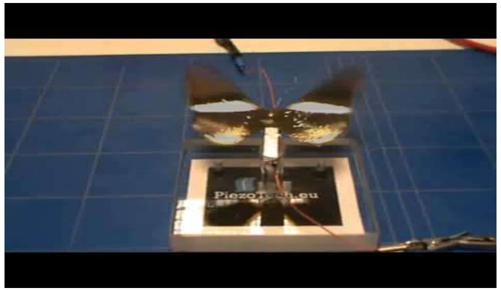
Future ChipSat-Sail Plans

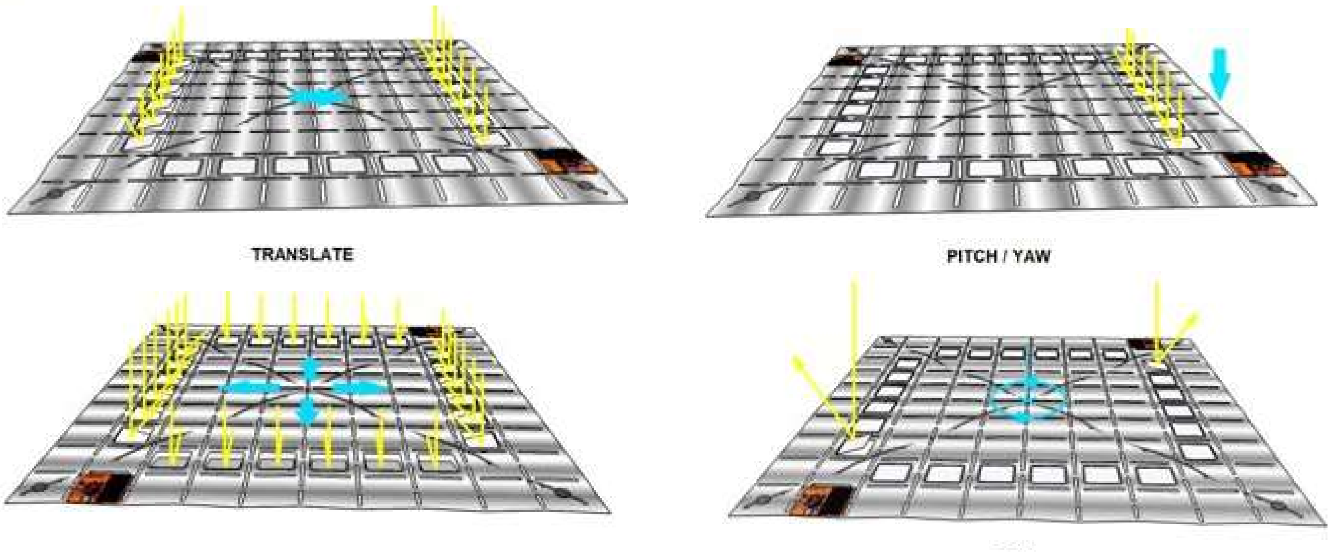


Sails with this mass-area ratio are capable of extremely high accelerations

With more control of the thrust vector, solar system exploration missions may be possible

Piezo-actuated reflective panels enable this control





Conclusions

LoRa communications has proven itself in recent years, and is an excellent fit for the ChipSat form factor.

Simulation tools and **in-house prototyping** equipment were instrumental in rapid and low-cost development of our newest generation ChipSat.

Long-range comms testing on the order of orbital distances is a key step to ensuring mission success.

Join **TinyGS –** we need all the help we can get to track our light sail in orbit!

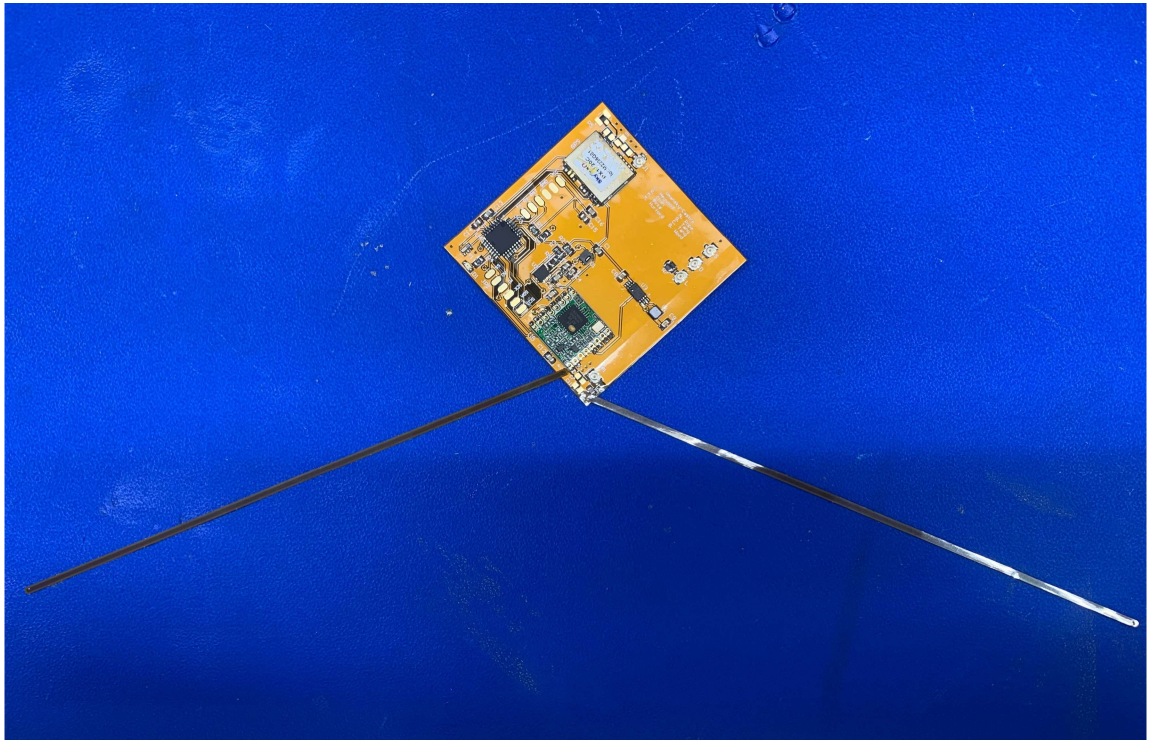


Figure 50: Fully assembled LoRa ChipSat prototype with dipole antenna

Acknowledgements

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Questions?

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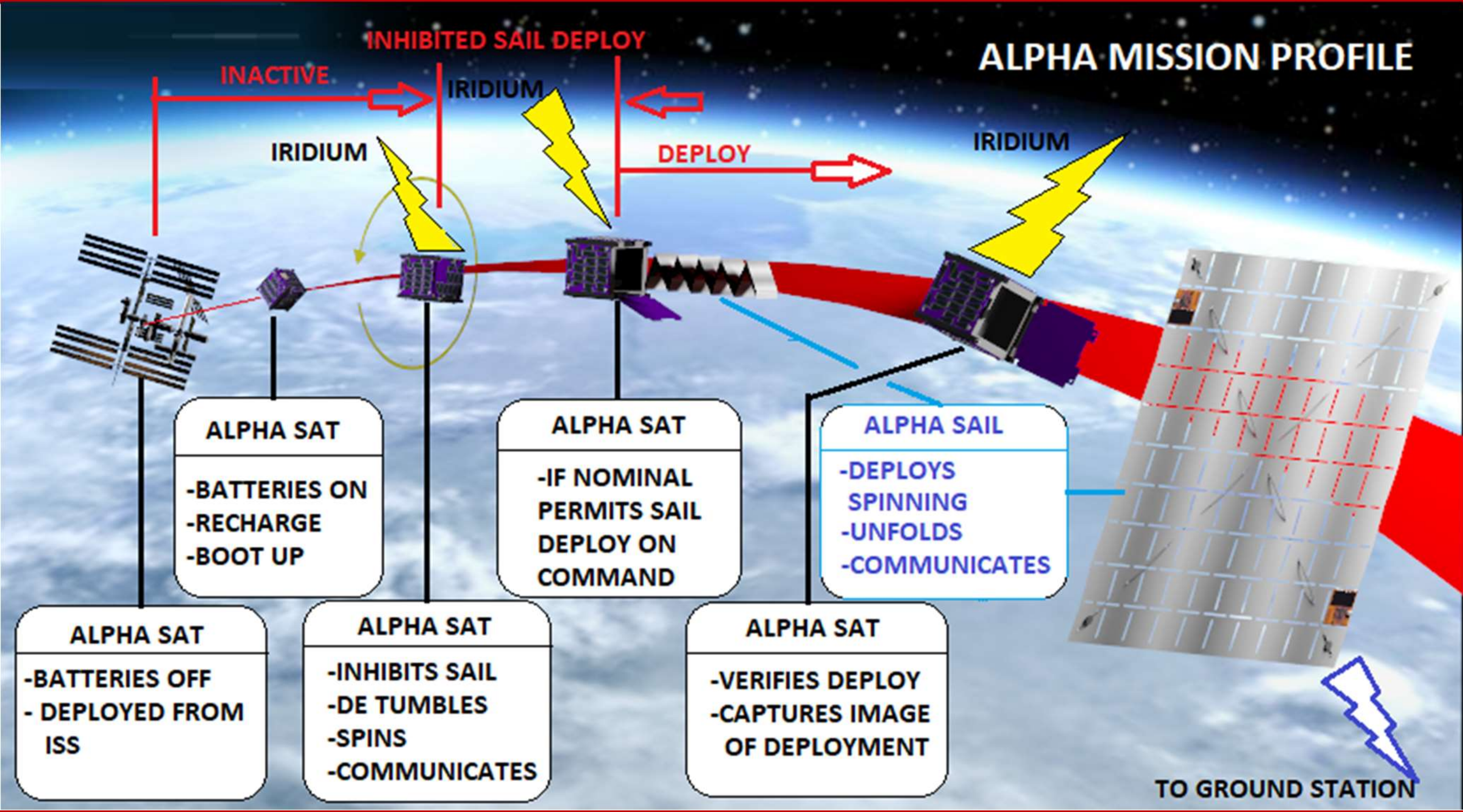
Backup

Mission Profile



Alpha CubeSat mission profile [Image courtesy of Andrew Filo]

Sail Folding & Deployment

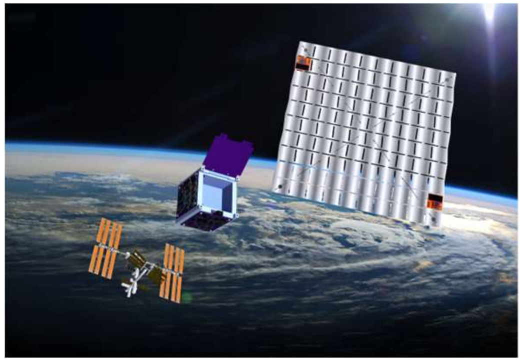
[Video courtesy of Andrew Filo]

Future ChipSat Sail Missions

Images courtesy of Andrew Filo

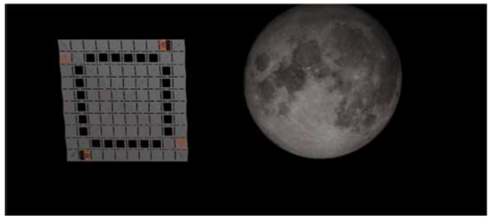
Alpha demonstrates retroreflective sail deployment and ChipSat capabilities

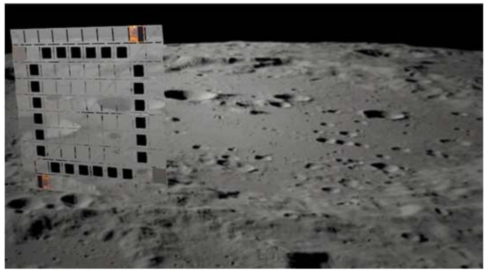
Earth Orbit



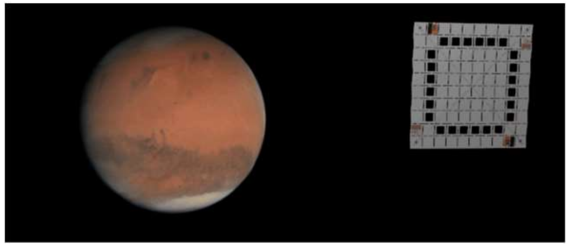
Piezoelectric sails enable steering for interplanetary trajectories

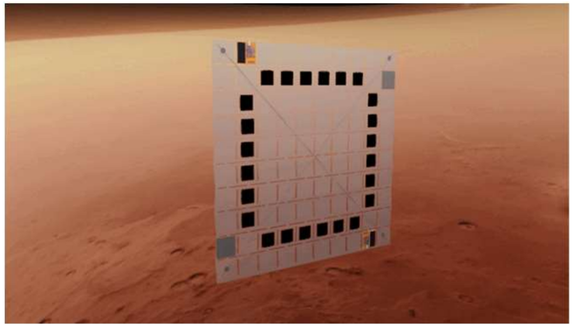
Lunar Flyby



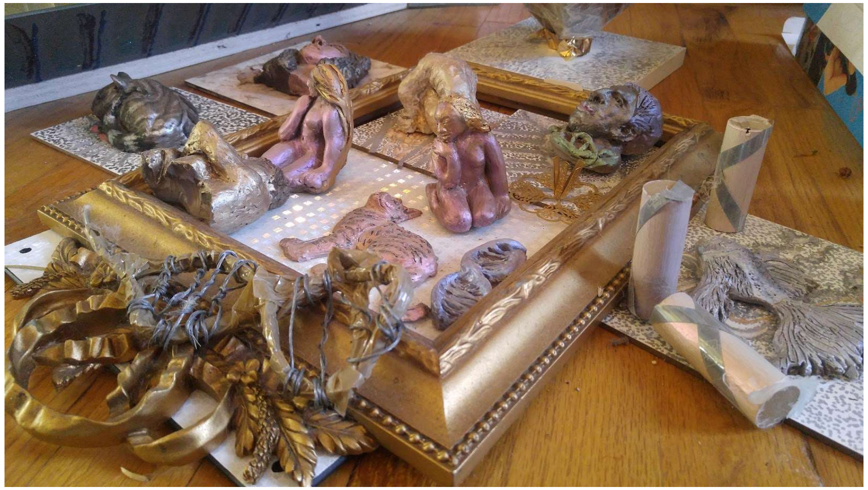


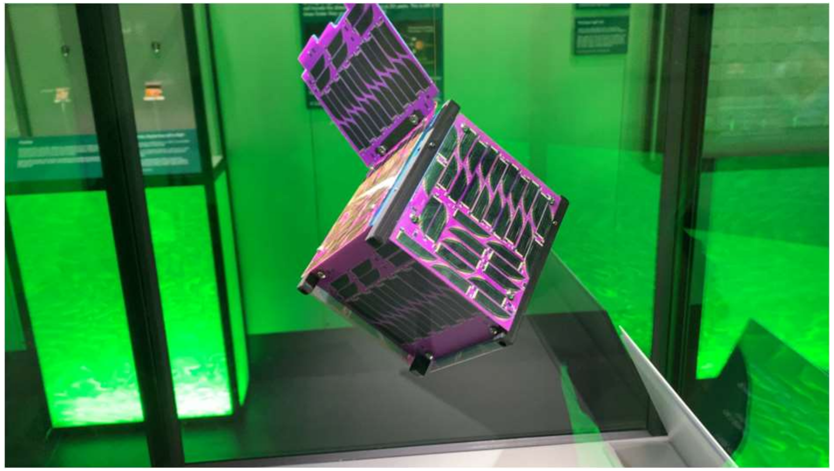
Mars EDL

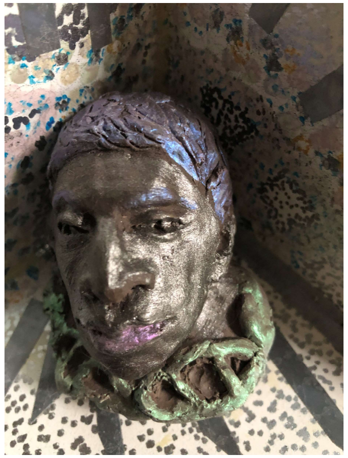


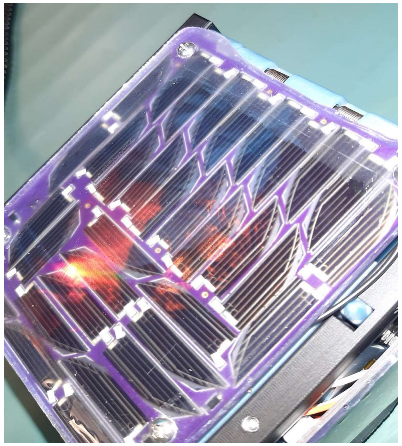


CubeSat Holograms









Link Budget

Figure	Working	Result
Noise Bandwidth	BN=10log500 kHz	57 dBHz
Bit rate (Rb, Bits per Symbol * Symbol rate)	Rb=SF/((2^SF)/BW)=4883 bps 10log(4883)	37 dBbps
Bandwidth to bitrate ratio	BNRB=57 dBHz-37 dBbps	20 dB/bit
Thermal (Johnson) Noise Power	N_thermal=10logkTB =10log1.38×10-23 dBW+30 dB dBm+10log1028+BN	-111 dBm
Carrier-to-noise ratio	CN=P-N =-146 dBm-(-111 dBm)	-35 dB
Bit energy to noise ratio (SNR)	Eb/N0=BN/RB+C/N =20 dB-35 dB	-15 dB
BER Significance level		7.5×10-6

Matched Filtering

- Each data bit encoded as a 512 bit pseudorandom number (PRN)
- Correlated via sliding inner product

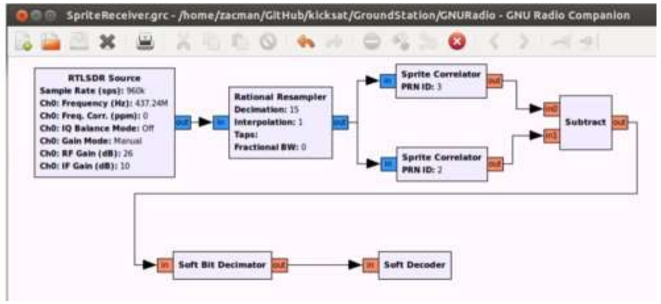
$$x_k = p^{\dagger} \begin{bmatrix} s_{k-N} \\ \vdots \\ s_k \end{bmatrix}$$

- Coding gain is a function of PRN length

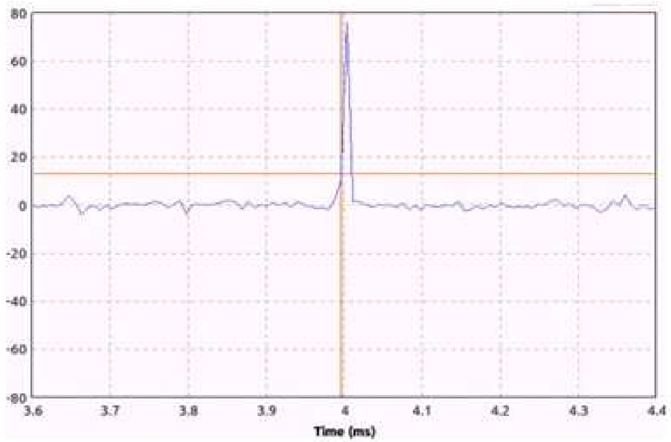
$$G_c = 10 \cdot \log_{10}(511) \approx 27\text{dB}$$

Forward Error Correction (FEC) added in case of cross-correlations between PRNs

Result: 64kbps Tx rate → 62bps data rate



GNU Radio Decoder



Correlation spike from matched filter