PLANETARY ENTRY VEHICLE PROTOTYPING USING CUBESATS (OR HOW TO PROGRESS ON A SHOE-STRING BUDGET AND HOPE TO PLAY WITH THE BIG GUYS): THE *MI*CRO *R*ETURN *CA*PSULE (MIRCA)

Jaime Esper
Aerospace Technology, Flight Systems Design
Principal Investigator, CAPE/MIRCA
Systems Engineering, Code 592
NASA Goddard Space Flight Center

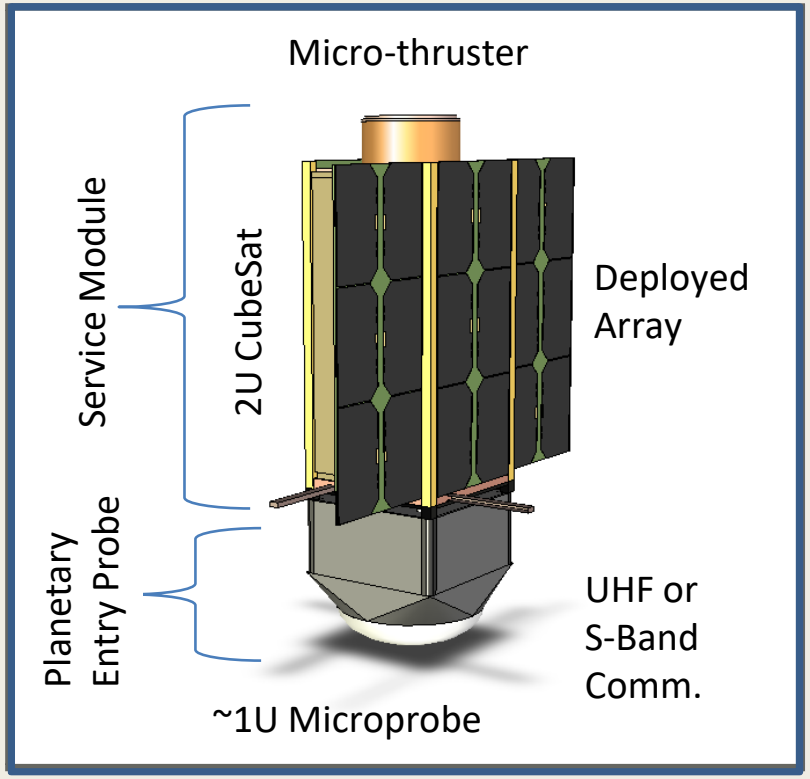
Abstract and Motivation

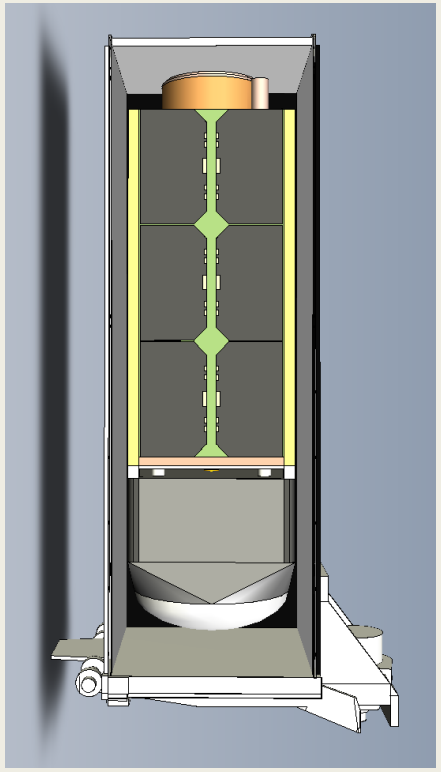
Imagine standing on the surface of an alien planet or satellite. High in the sky, a soft breeze is interrupted by the whistling sound of a tiny probe sent from Earth to study the atmosphere, or to land on some high-value target on the surface. Now imagine that this probe is followed by a dozen others, all entering in distributed locations throughout the geographic landscape. These probes are systematically and methodically being released from an orbiting spacecraft, perhaps having arrived months in advance. Or maybe the probes themselves are released systematically months in advance by and approaching mother-ship. Although probes have been sent to celestial neighbors before, what is unique is that these new vehicles had their genesis on the highly popular Cubesat specification…

My dream is to make spaceflight so mundane, we can actually ***routinely leave the bounds of our planet to explore en masse*** our solar system. For that, we must create systems that allow us to bring space exploration within the realm of our everyday lives. No longer exquisite systems but just good enough, where failure is an option … and a new opportunity.

Introducing a New CubeSat Planetary Entry Vehicle – Original Concept

- **The CubeSat Application for Planetary Entry Missions (CAPE)** concept describes a high-performing CubeSat system which includes a propulsion module and miniaturized technologies capable of surviving atmospheric entry heating, while reliably transmitting scientific and engineering data.
- **The Micro-Return Capsule (MIRCA)** is the first Planetary Entry Probe Prototype.
- First proposed to NASA HQ in 2012.



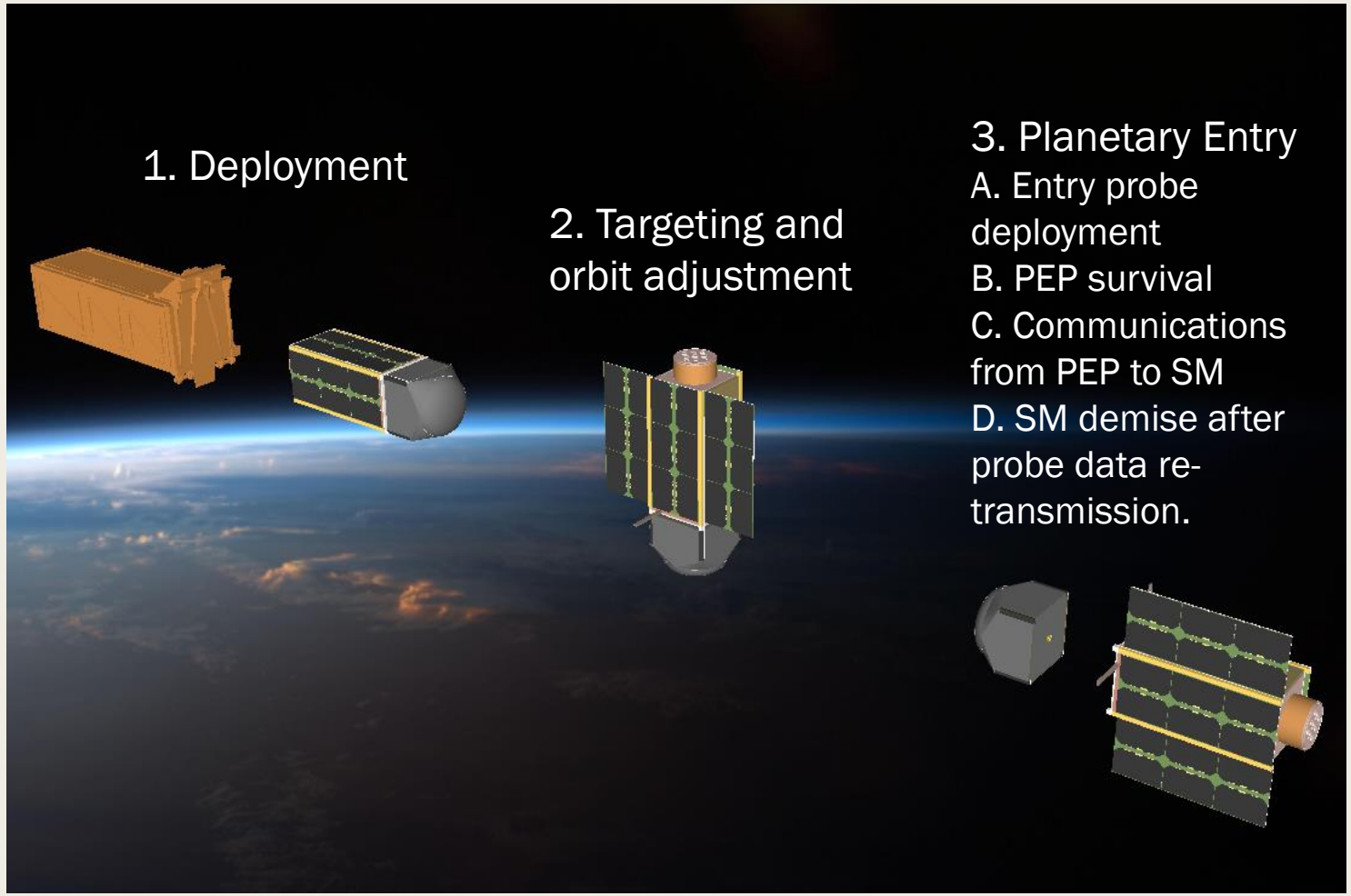


CAPE Components

- The SM contains the subsystems necessary to support vehicle targeting (propulsion, ACS, computer, power) and the communications capability to relay data from the Planetary Entry Probe (PEP) probe to a “mother-ship”.
- The PEP itself carries the scientific instrumentation capable of measuring atmospheric properties (such as density, temperature, composition), and embedded engineering sensors for Entry, Descent, and Landing (EDL) technology monitoring and assessment.

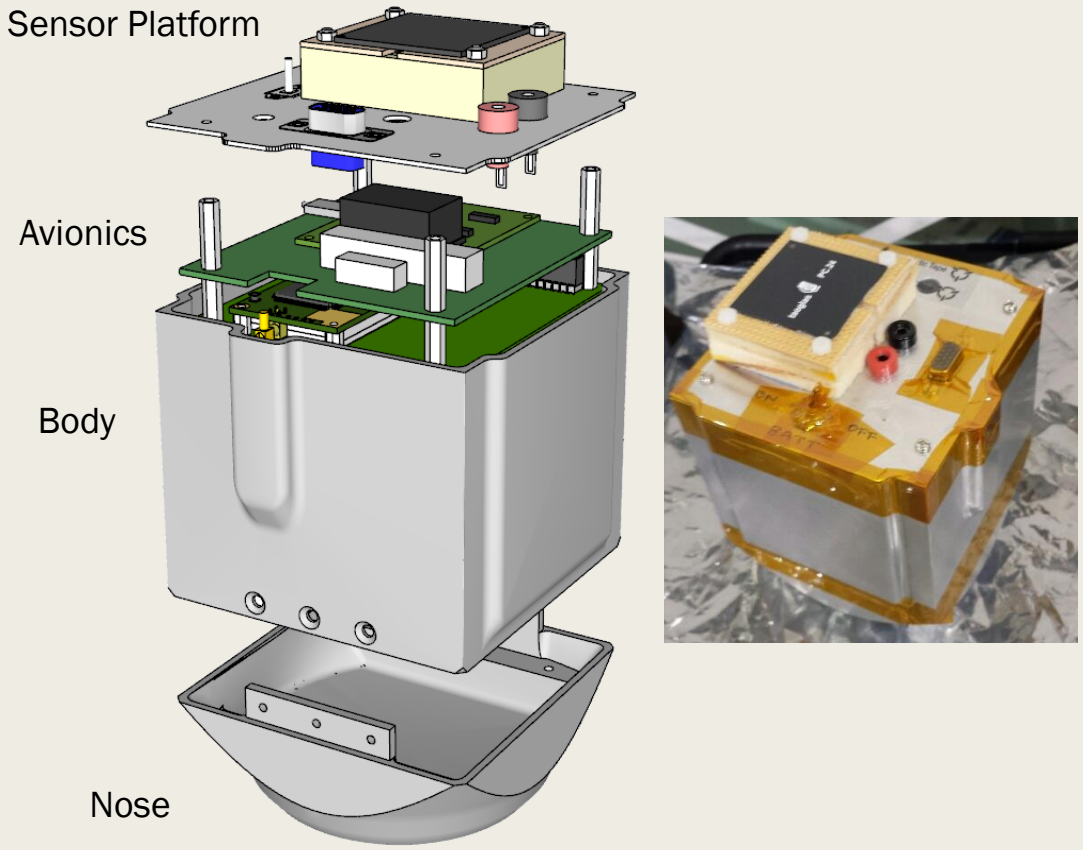
CAPE Operations Concept

- This shows a scenario where CAPE systems are carried by a “mother ship”, and sequentially released to study targets or regions of interest.
- Flexibility is provided by vehicle autonomy.
- Release on approach is another possible scenario.



Micro-Return Capsule 1st Generation (MIRCA-Gen1)

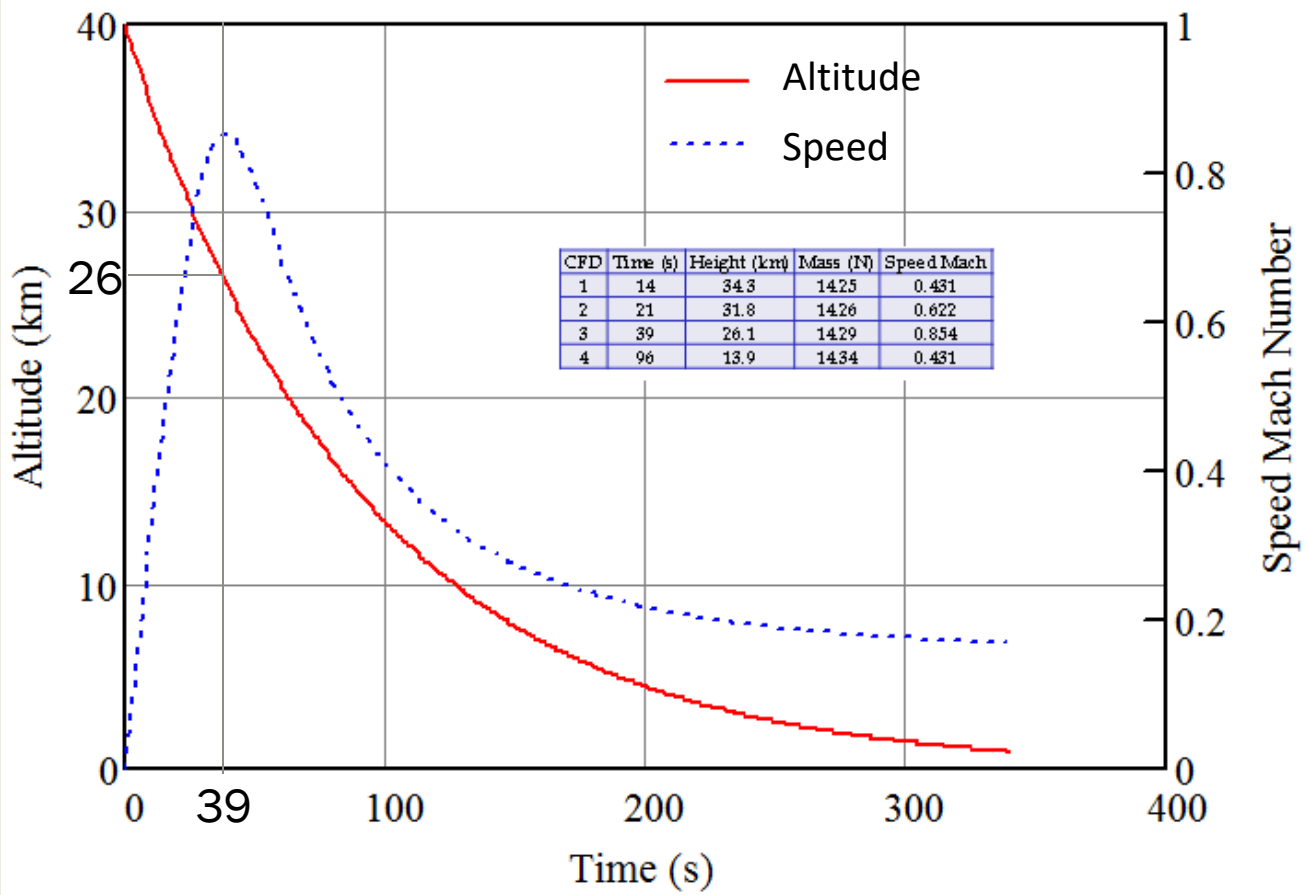
- MIRCA was designed to reduce CAPE's implementation risks, and represents the first PEP prototype.
- MIRCA-Gen1 was meant to be released into the ocean. It was not designed to carry a parachute, and its data was to be transmitted during atmospheric flight.
- It was designed to carry IR and gas sensors, but they were not flown because of budget constraints.
- The avionics contained an Inertial Measurement Unit and thermal sensors to measure dynamic and thermal responses during flight.



MIRCA Gen1

Flight Analysis for Balloon Drop

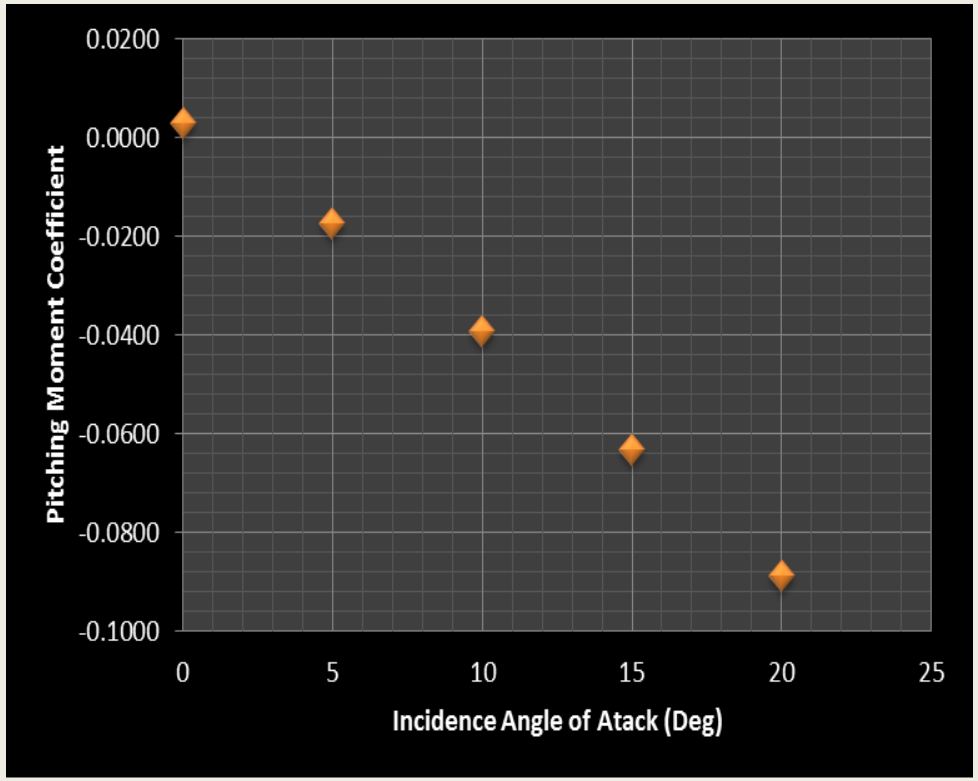
- Analysis of the vehicle in freefall from a starting altitude of 40 km.
- The vehicle reaches a maximum speed of ~267 m/s (Mach 0.854 or 597 mph), about 39 seconds after release.
- The terminal velocity is about 57 m/s (128 mph) at ~2 km altitude.



CFD	Time (s)	Height (km)	Mass (N)	Speed Mach
1	14	34.3	14.25	0.431
2	21	31.8	14.26	0.622
3	39	26.1	14.29	0.854
4	96	13.9	14.34	0.431

Will it Fly Stable?

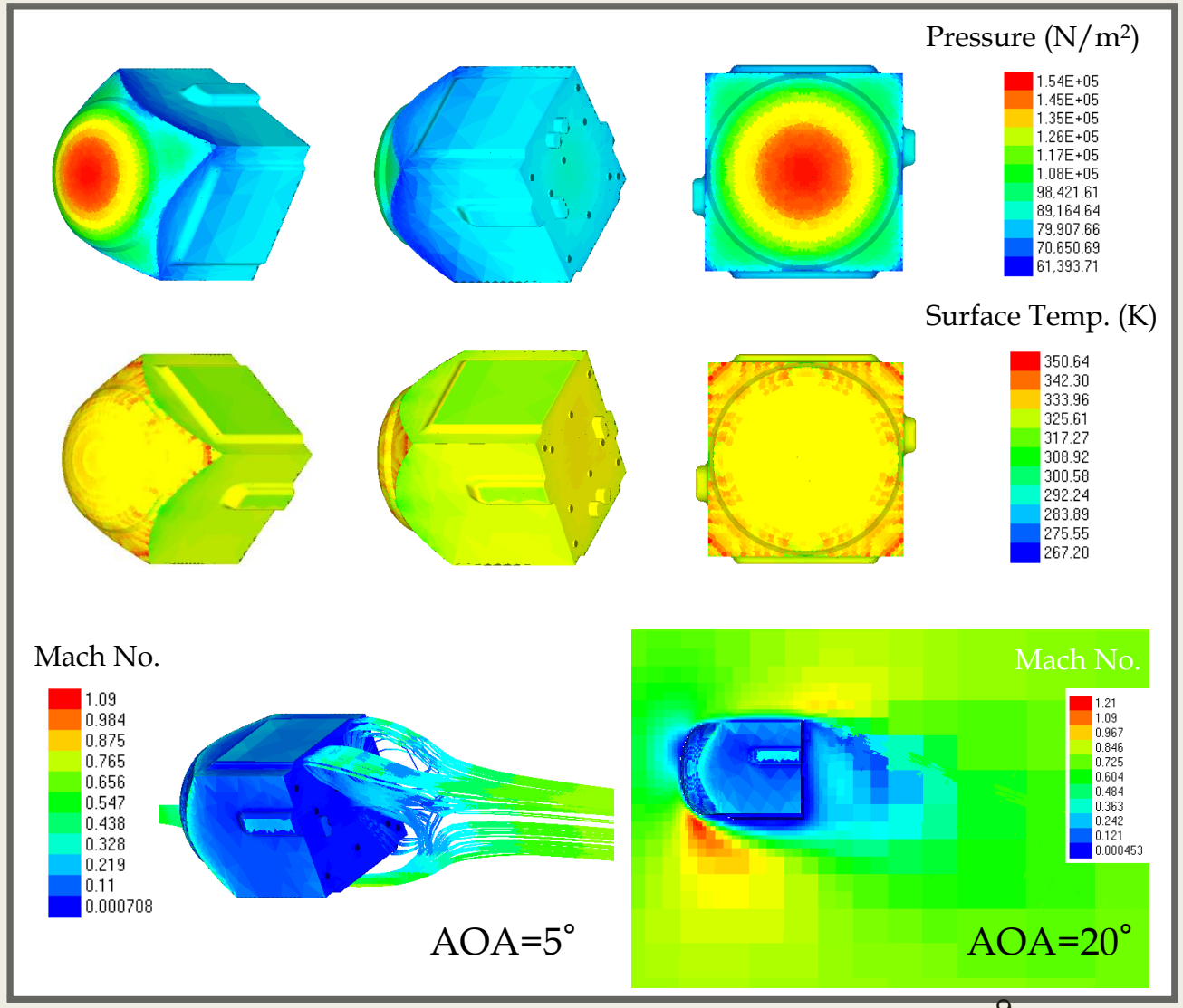
- Vehicle stability is critical in at least two aspects: the ability to survive entry into a planet or satellite's atmosphere at hyperbolic velocities, and the ability to communicate to the SM and/or MS.
- Typical aero-shell configurations are either conical, or of sphere-cone design. MIRCA is unique in that it follows a *sphere-truncated cone-square* design. This design was initially motivated to fit within the CubeSat specification standards.
- … Say what?



Static stability condition is satisfied for MIRCA (from CFD Analysis)

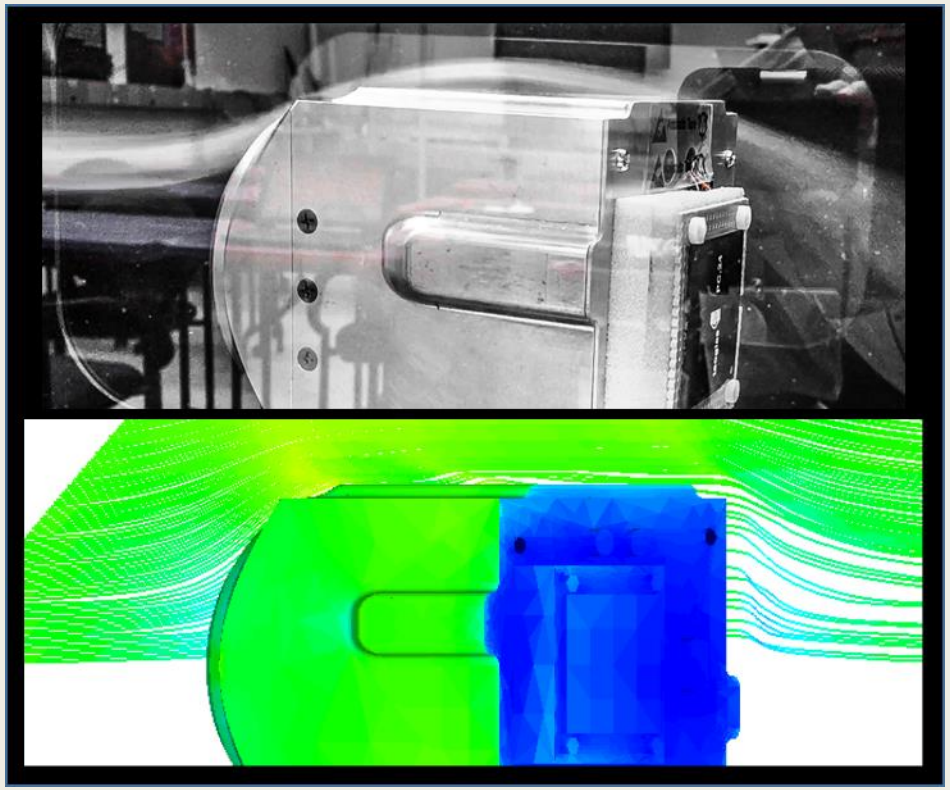
Computational Fluid Dynamics (CFD)

- CFD analysis using 3-dimensional compressible Navier-Stokes equations was carried out at different altitudes and Angles of Attack (AOA).
- Stagnation point pressure at max. speed is ~ 1.5 atm., back pressure ~ 0.8 to 1 atm., and edge minimum pressure ~ 0.6 atm. Maximum temperature is ~ 78.5° C, and average body temperature ~ 45 ° C.
- Vehicle surface parameters were obtained for 0° < AOA < 20°. Wake turbulence was noticeable even for small AOA, and supersonic flow is seen around the flow-field during peak speed (all AOA).



Wind Tunnel Testing

Flight Stability Test



MIRCA in wind tunnel test at NASA WFF (shown at angle of attack ≈ 20°)

MIRCA-Gen1 Flight – 10 October 2015

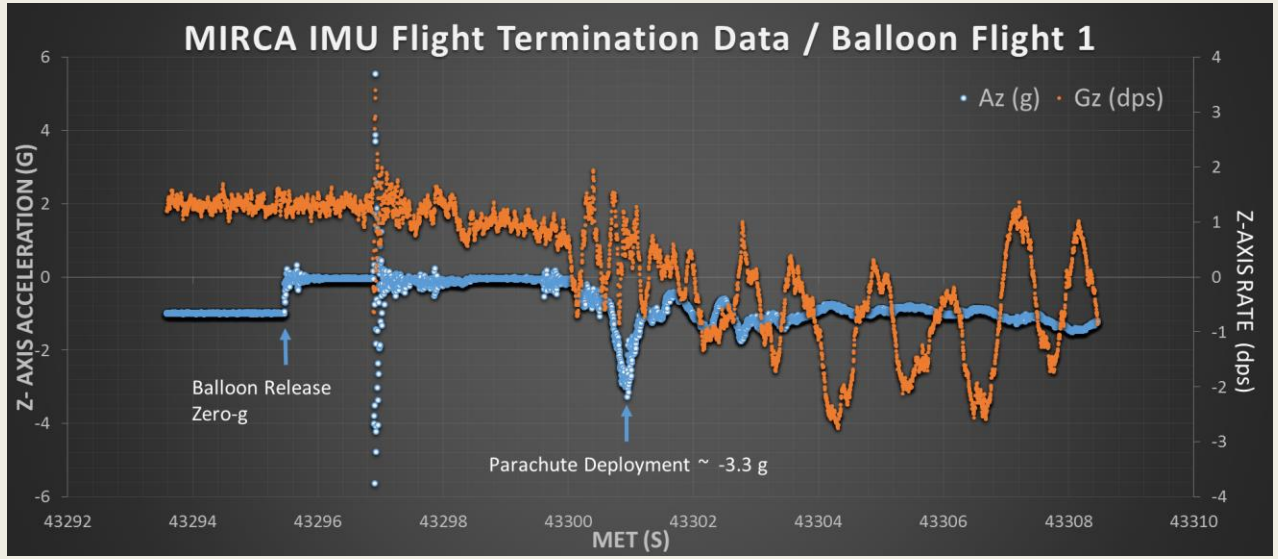
- The first flight of MIRCA was successfully completed on 10 October 2015 as a “piggy-back” payload onboard a NASA Balloon Program Office (BPO) stratospheric balloon launched from the Columbia Scientific Balloon Facility (CSBF) from Ft. Sumner, New Mexico.
- *The vehicle was not to be released from the gondola*.

MIRCA Ground Station – aka "Service Module"

- The MIRCA Receiver/Ground Station plays the role of the Service Module in the CAPE concept. It captures MIRCA's data during its flight.
- The avionics on the receiver box is identical as the one in the MIRCA's flight vehicle, minus the sensors.

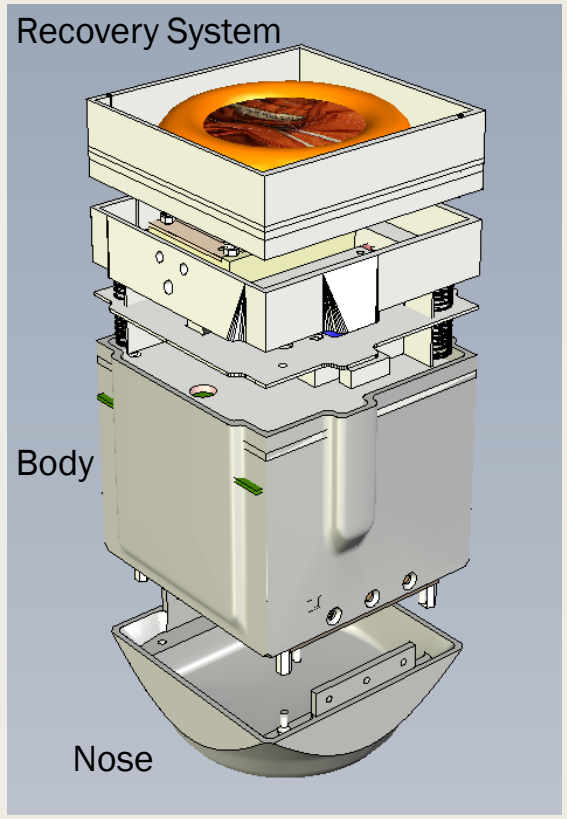
MIRCA-Gen1 Flight Results

- Completed verification of the Inertial Measurement Unit (IMU), single board computer, power conditioning and distribution system, communications transceiver, on-board thermal sensor, telemetry acquisition system, and flight software (cFE).



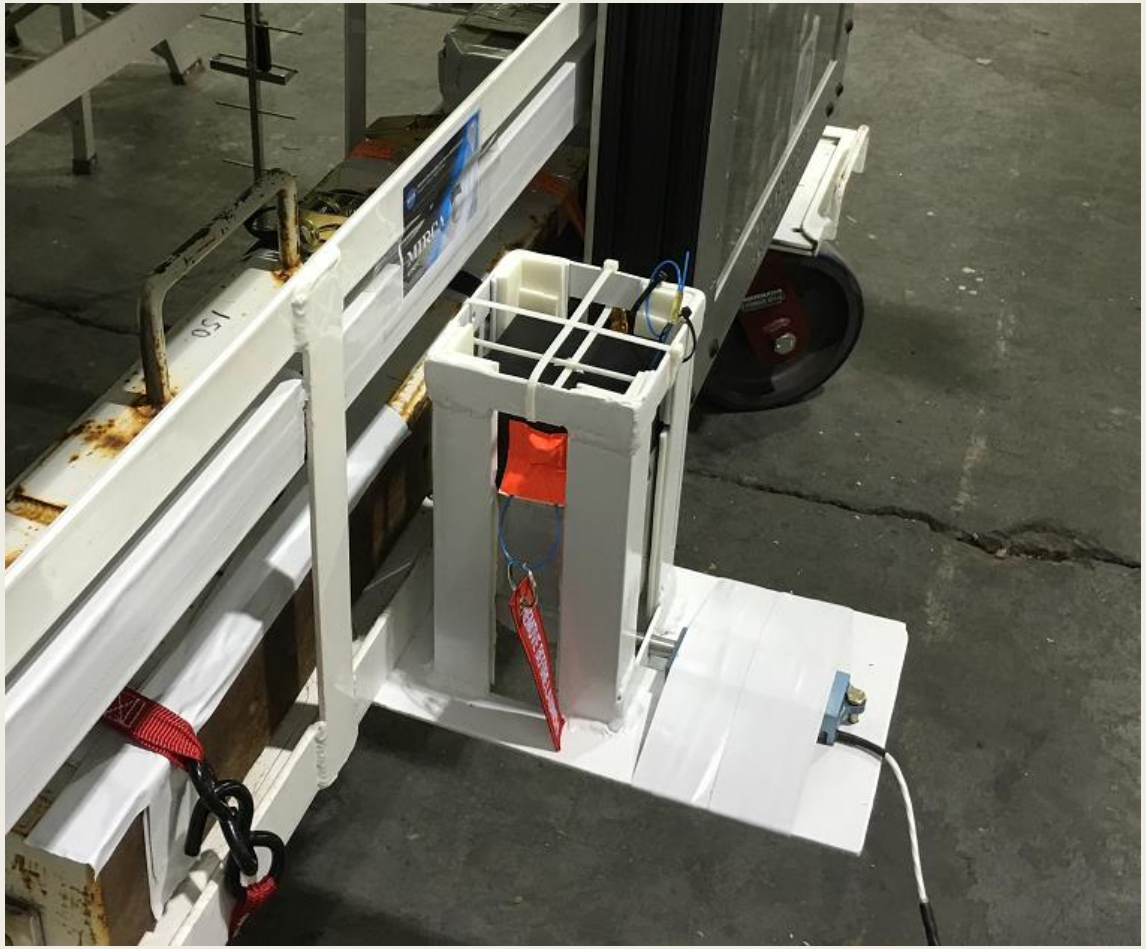
Micro-Return Capsule 2nd Generation (MIRCA-Gen2)

- Given Range Safety concerns with release of an atmospheric vehicle over CONUS, a requirement was levied to modify MIRCA to incorporate a parachute.
- Parachute enclosure was designed and 3D-printed.
- Parachute recovery system was implemented.
- MIRCA Gen2 was born!



Gondola Deployment System

- Best effort design prior to flight.
- A steel cage to hold MIRCA.
- A linear actuator to release the vehicle.
- Gravity was to do the rest.
- However …

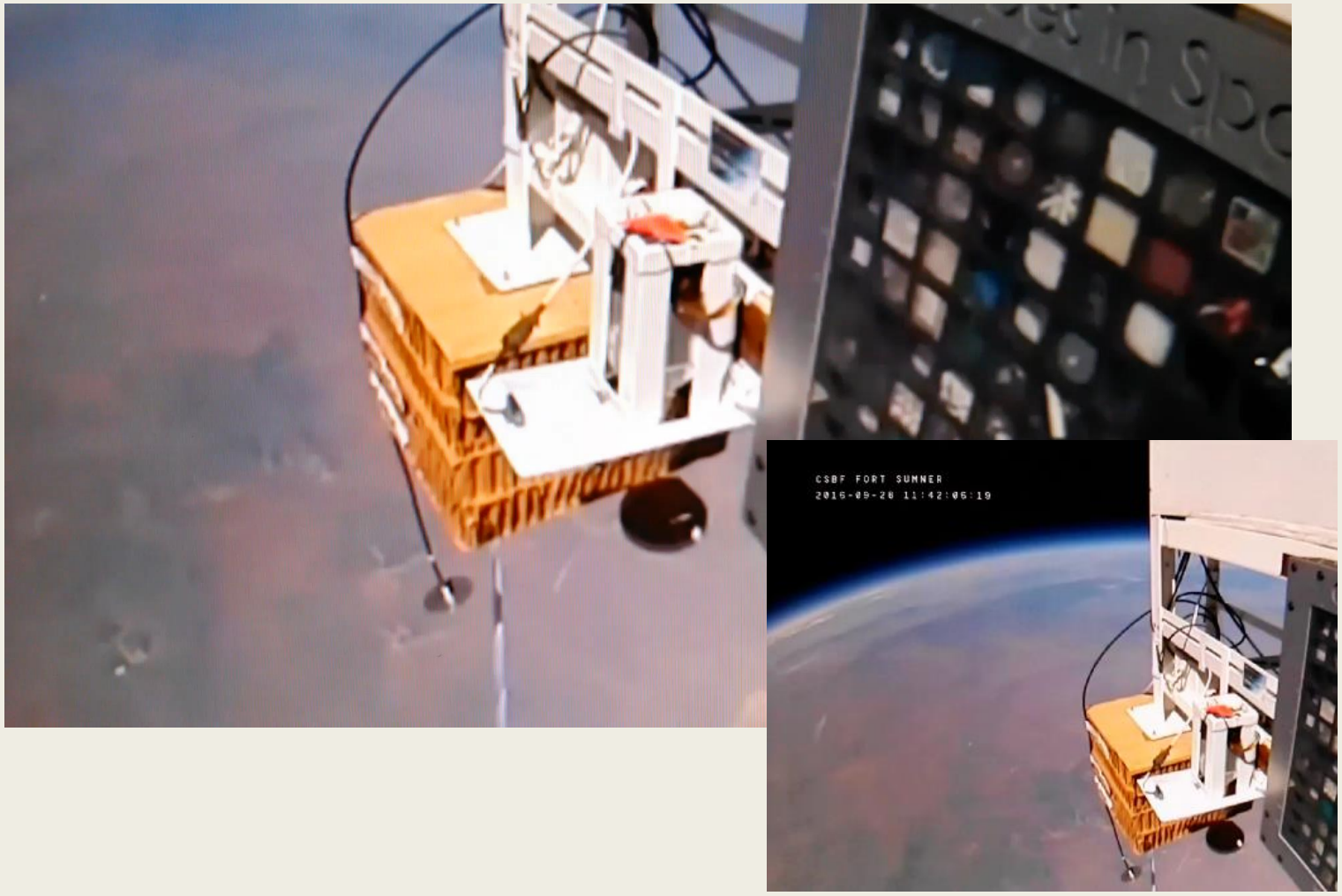


On-Site Release Tests

- In hindsight, I should have acted on something quite obvious here.
- But when time and funding is limited…
- This will be a recurring issue, but not necessarily in a negative way.

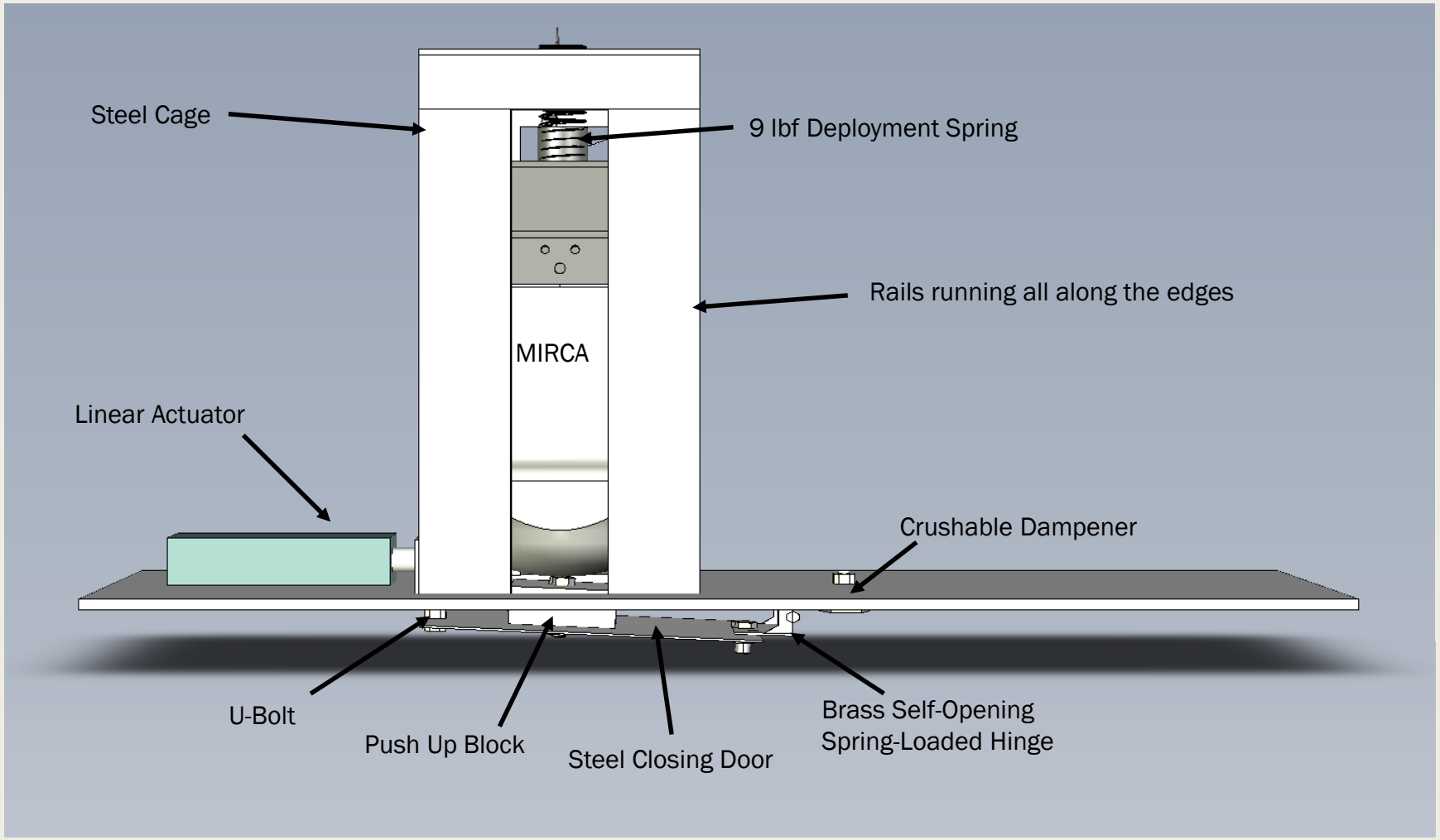
The Moment of Truth – 28 Sep. 2016

- My initial theory was correct.
- Now it seems obvious, but what decisions would you make on-site?
- What do we fear? Is it "failure," or its consequences?
- The "consequences" are human-imposed.
- Failure itself is an opportunity.
- I would have to wait two (2) years to attempt this again!
- Under much more scrutiny.



The Deployment System Must be Redesigned

- Now I had plenty of time to think about the deployment system itself.
- MIRCA was ready, but I could make some improvements as well.
- The new Deployer was tested multiple times under varying environmental conditions.

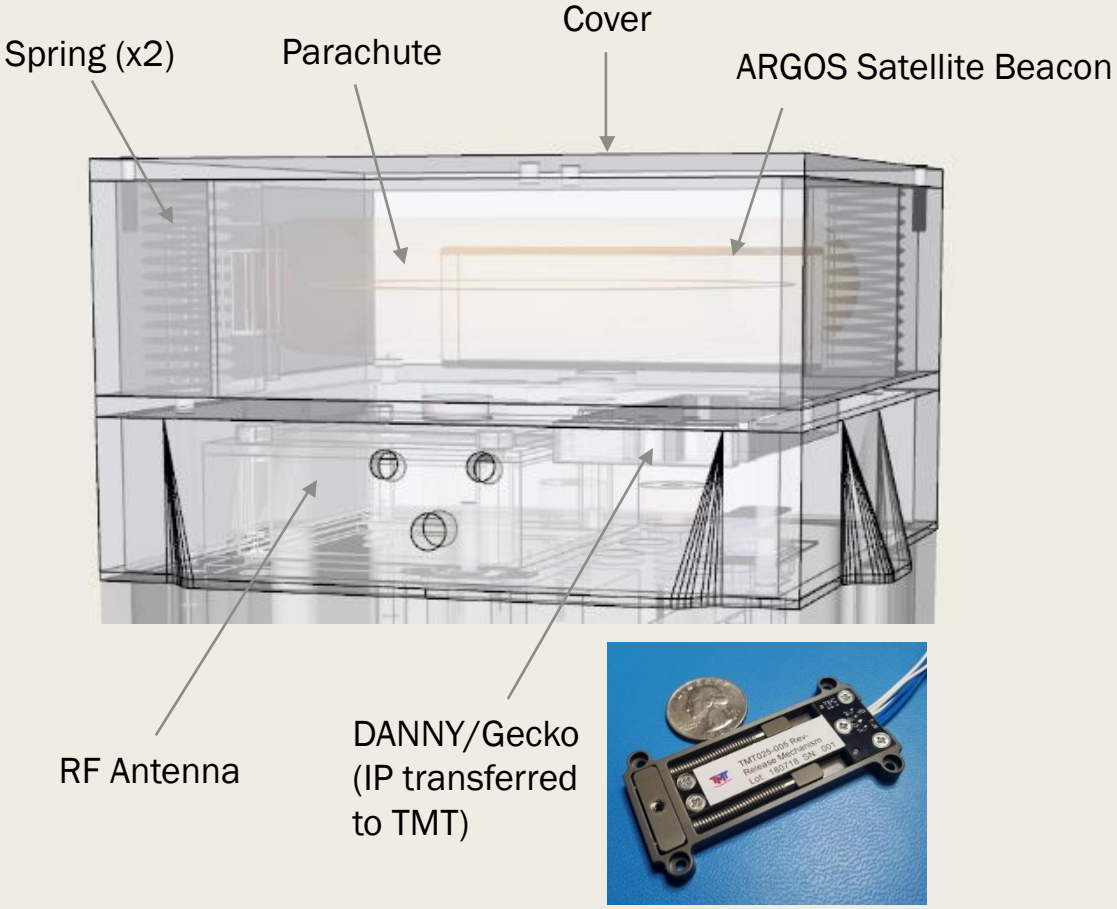


Deployment System Tests

- Deployment tests shot at 240 fps showed consistent, reliable operation.
- Cold test to -74ºC showed deployment was not affected by extreme thermal conditions.

Recovery System

- The parachute was deployed by a lanyard attached to the fabric on one end and to the closing loop on the other. The closing loops was attached to the parachute cover.
- The closing loop was released by the Diminutive Assembly for Nanosatellite deploYables (DANNY).
- Release of closing loop would deploy the parachute cover through a couple of springs. That would in turn pull the parachute out and into the slipstream.
- DANNY is an electromechanical device designed by GSFC (Luis Santos) for Nano-satellites, and used in DELLINGR. Technology was transferred to Thermal Management Technologies (TMT)



Parachute Deployment Tests

- None in flight-like configuration under slipstream conditions.
  - *Reason: Life-limited actuations of DANNY.*
  - *I had already burned the circuit once during testing!*
  - *Even with correct energy, I noticed discoloration of deployment wire after tests, so I used pristine circuit during actual flight.*
- Parachute Top Cover force-release tests were carried out to ensure it would deploy with minimum amount of force.
  - *Spring force was chosen to ~2x required value.*
- Possible outcomes
  - *I estimated an ~80% probability of parachute deployment success.*
  - *My main concerns were ability of parachute to*
    - Deploy from its enclosure (parachute was tightly packed).
    - Clear “dead air” during freefall.

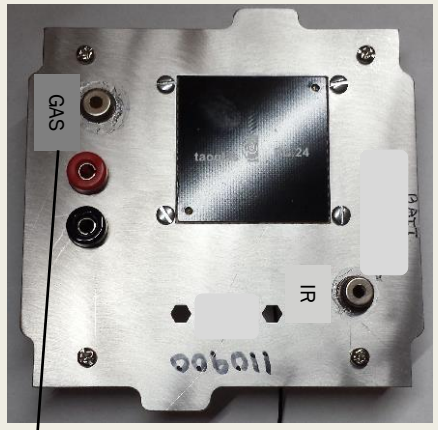
The “Burble” Effect

- Pyrotechnic devices are meant to make sure parachutes are expelled fast and far away from the vehicle to ensure parachute deployment.
- For secondary payloads such as CubeSats, pyrotechnics are problematic: riding along very expensive primary payloads.
- Likely must live with electromechanical actuation and forces to deploy parachutes.

On-Board Radiometer (Spectrometer)

- On-board radiometers can provide in-situ gas analysis.
- MIRCA proposed to test out a simple thin-film thermopile radiometer than could be installed within its resource limitations.
- The baseline sensor has a flat spectral response from 100nm to 100µm, which can be tailored with wide-band optical filters, or narrow-band filters designed to measure specific gases.
- Tailoring would depend on the atmosphere of choice.

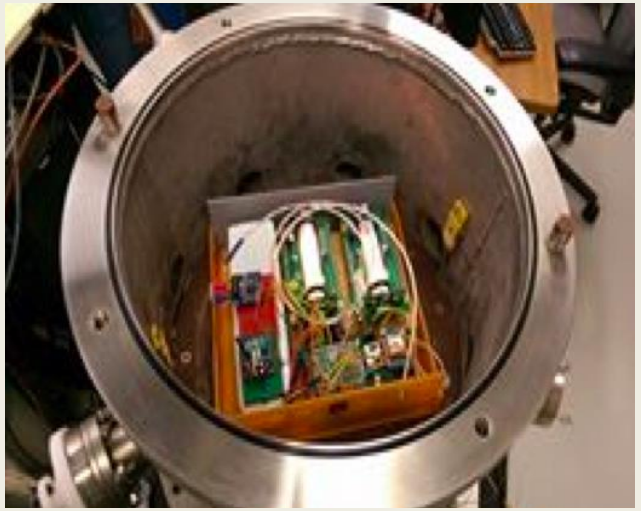
Gas	Center Wavelength (µm)
CH_4	1.66, 2.2, 3.3
CO_2	1.4, 1.6, 2.0, 2.7, 4.3
CO	2.34, 4.67
H_2O	0.72, 0.82, 0.94, 1.1, 1.38, 1.87, 2.7
N_2O	2.87, 4.06, 4.5
O_3	3.3, 4.74
O_2	0.63, 0.69, 0.76, 1.06, 1.27, 1.58



Center wavelength of sample gases within 0.1 to 7 µm (sapphire filter) is shown for Earth's atmosphere.

Gas Abundance Sensor Package (GASP)

- I had my hands full developing the drop vehicle. It became clear development of the sensor package would require a dedicated effort.
- GASP is a "*scientific instrument that has the capability to measure the concentration of target gases based on a non-dispersive infrared sensor system along with atmospheric reference parameters* (*)."
- GASP is currently tuned to detection of CO_2 gas.

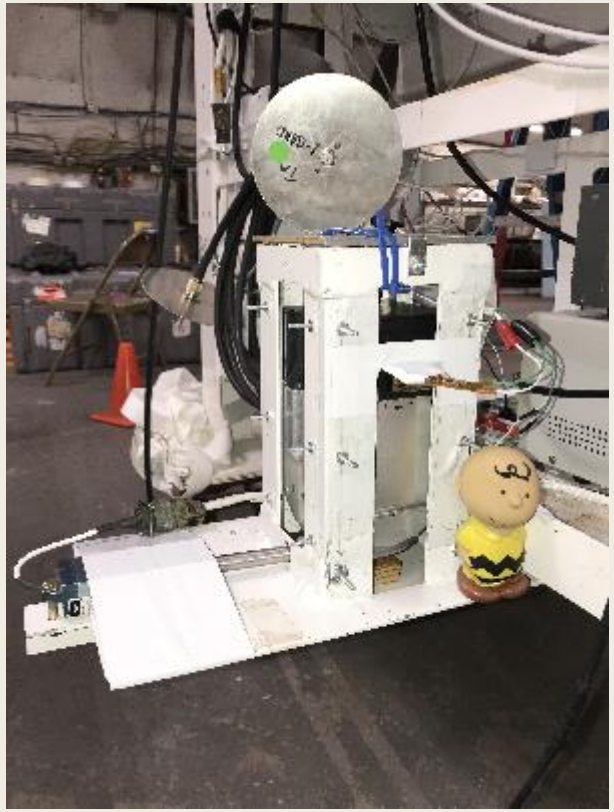


GASP in calibration chamber at GSFC

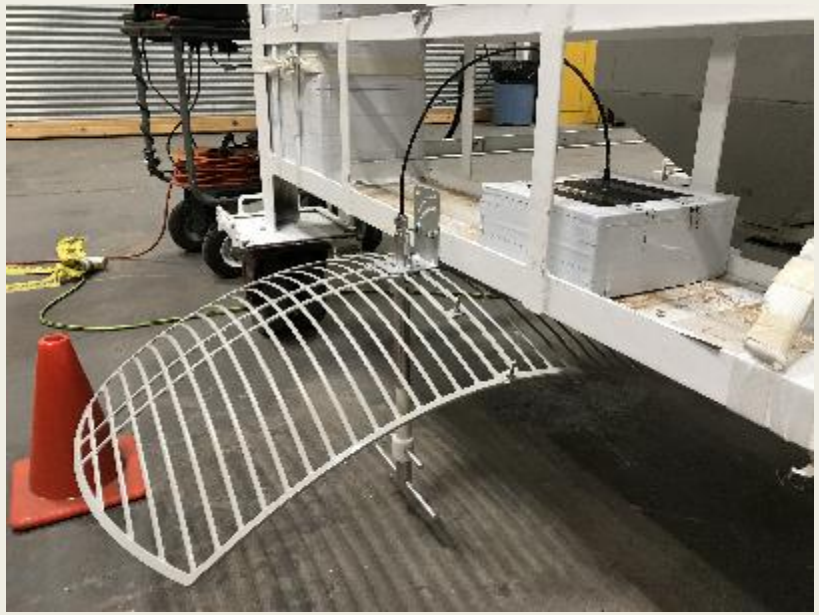
* Dat Tran, George Nehmetallah, Nicolas Gorius, Frank T. Ferguson, Jaime Esper, Natasha M. Johnson, Shahid Aslam and Conor Nixon, "Low-cost, Compact and Robust Gas Abundance Sensor Package," SPIE Defense and Commercial Sensing, Orlando, FL, 2018.

System Integration onto Gondola

- This time, I made sure I had on-board help for MIRCA's deployment (that *guaranteed* a good kick out of the gondola).



MIRCA inside re-designed deployment system



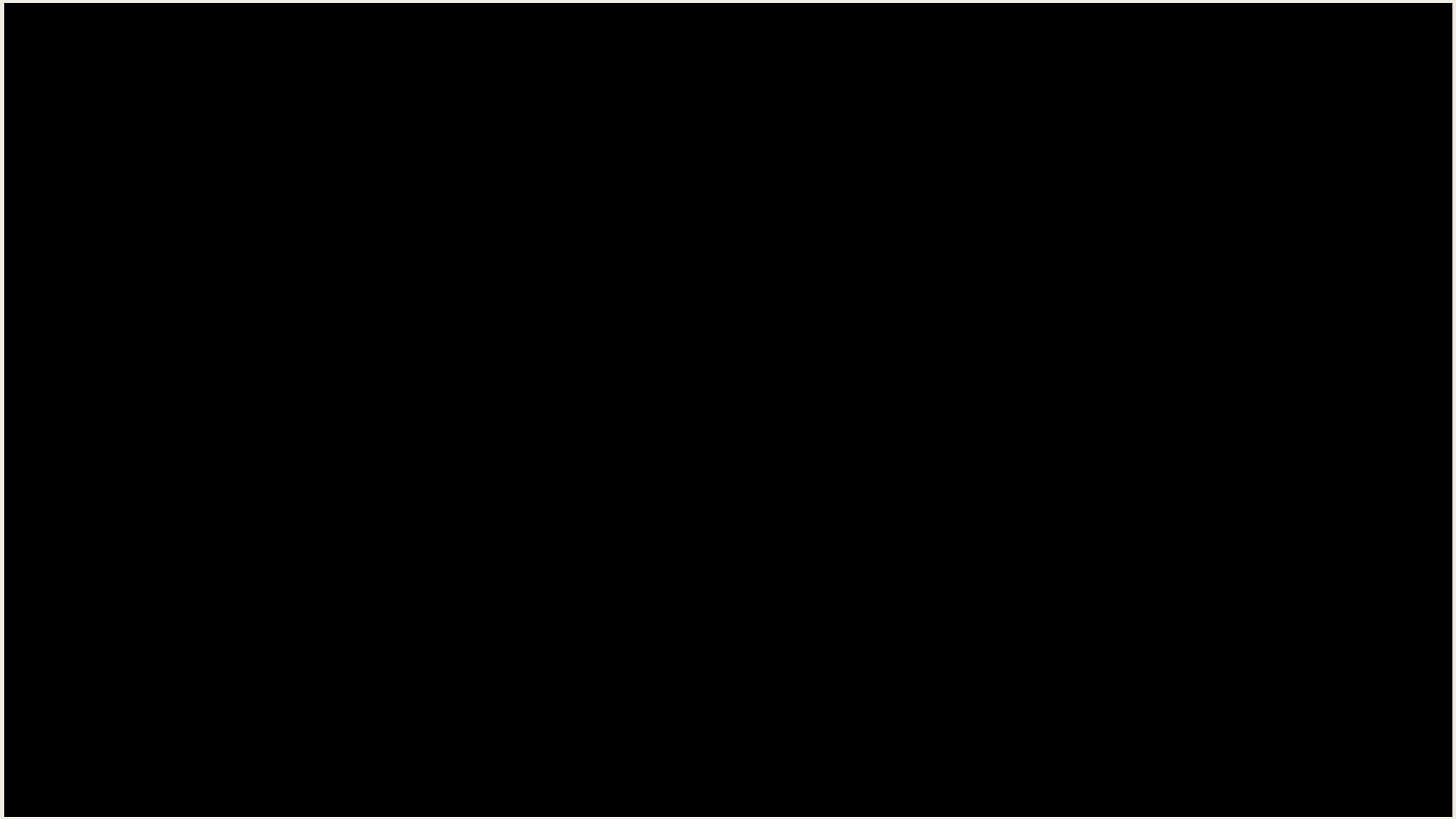
MIRCA receiver and antenna

GASP

MIRCA Gen2 Flight Objectives

1. Test the overall Planetary Entry Probe + Service Module / Mother Ship operations concept.
2. Vehicle aerodynamics and stability.
3. Recovery System.
4. Test potential new sensor package for atmospheric gas sensing (separately this time).

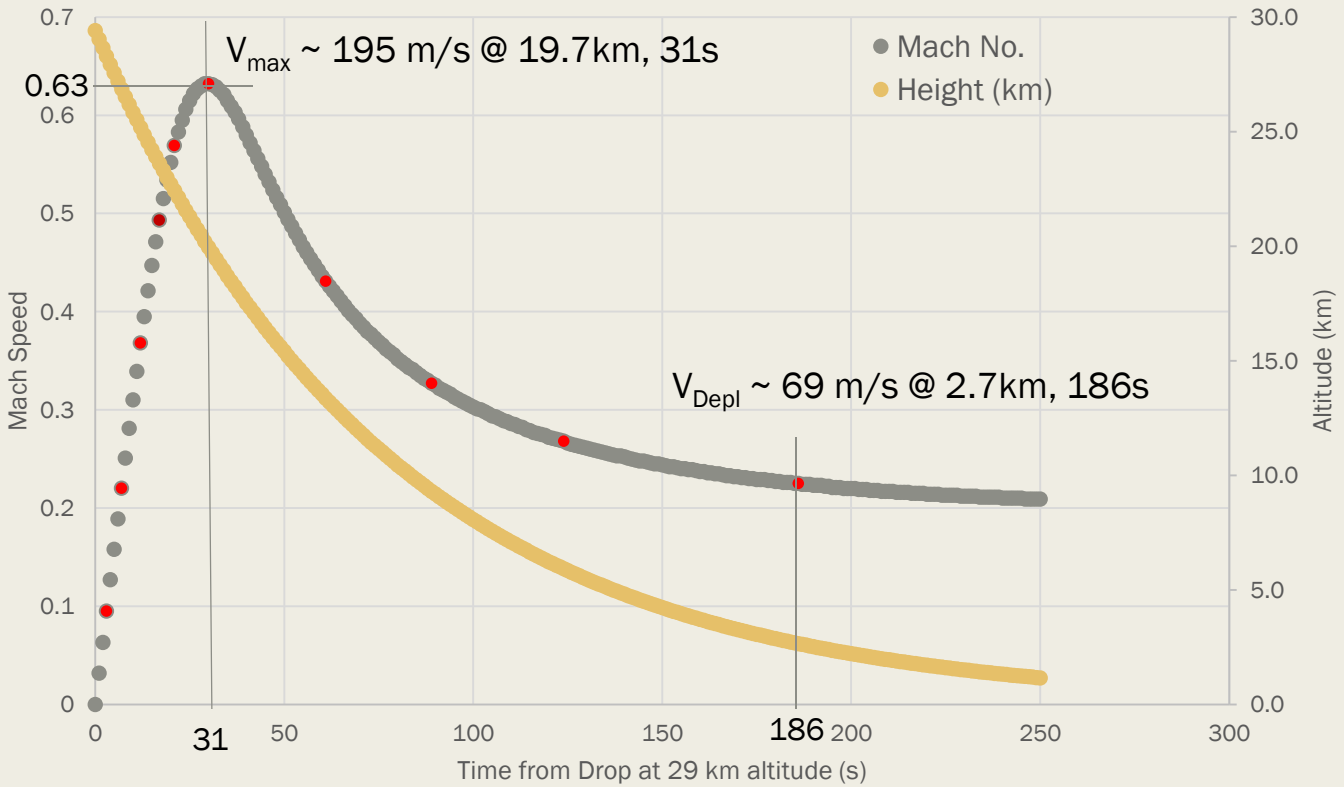
Flight day – 24 August 2018



In Slow Motion

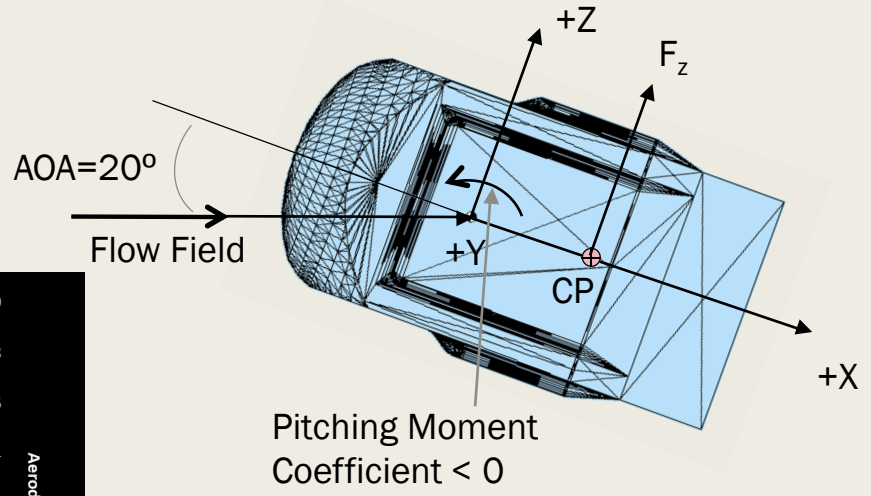
Flight Model for Balloon Drop

- Analysis of the vehicle in freefall from a starting altitude of 29.4 km.
- The vehicle reaches a maximum speed of ~195 m/s (Mach 0.6 or 436 mph), about 31 seconds after release.
- The velocity is about 69 m/s (155 mph) at 2.7 km altitude, 186 seconds parachute actuation time.

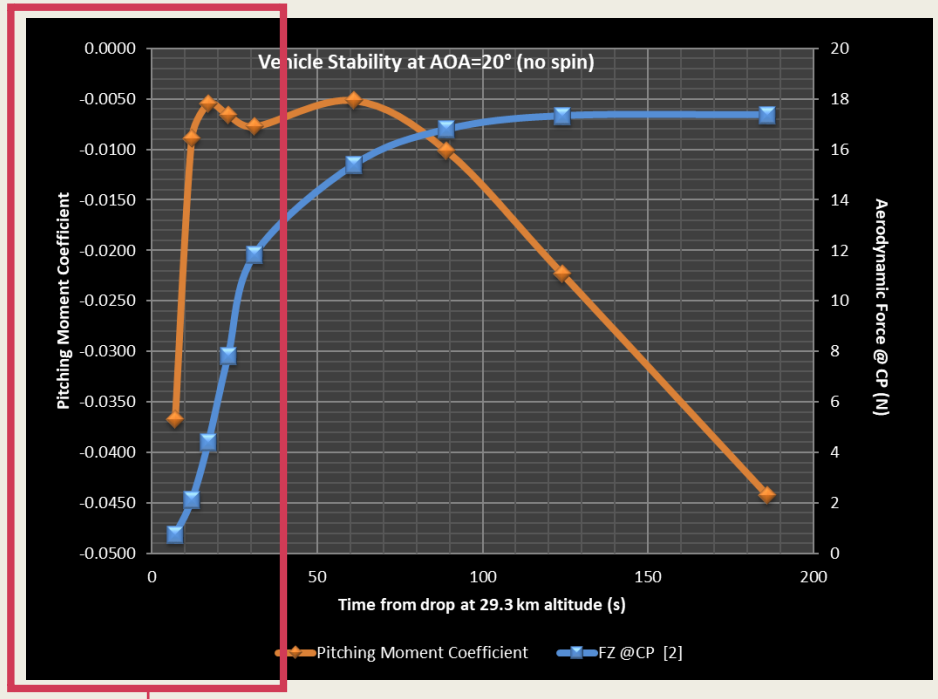


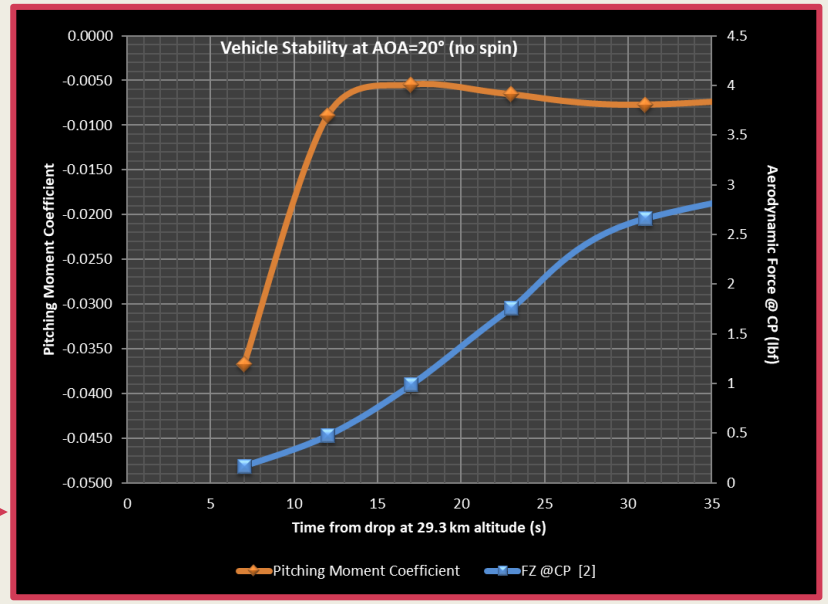
Critical Flight Regime Data: 0 to 31s

- Maximum speed is reached within the first 10 km of flight, from 30 down to 20 km @ ~31 seconds after release.



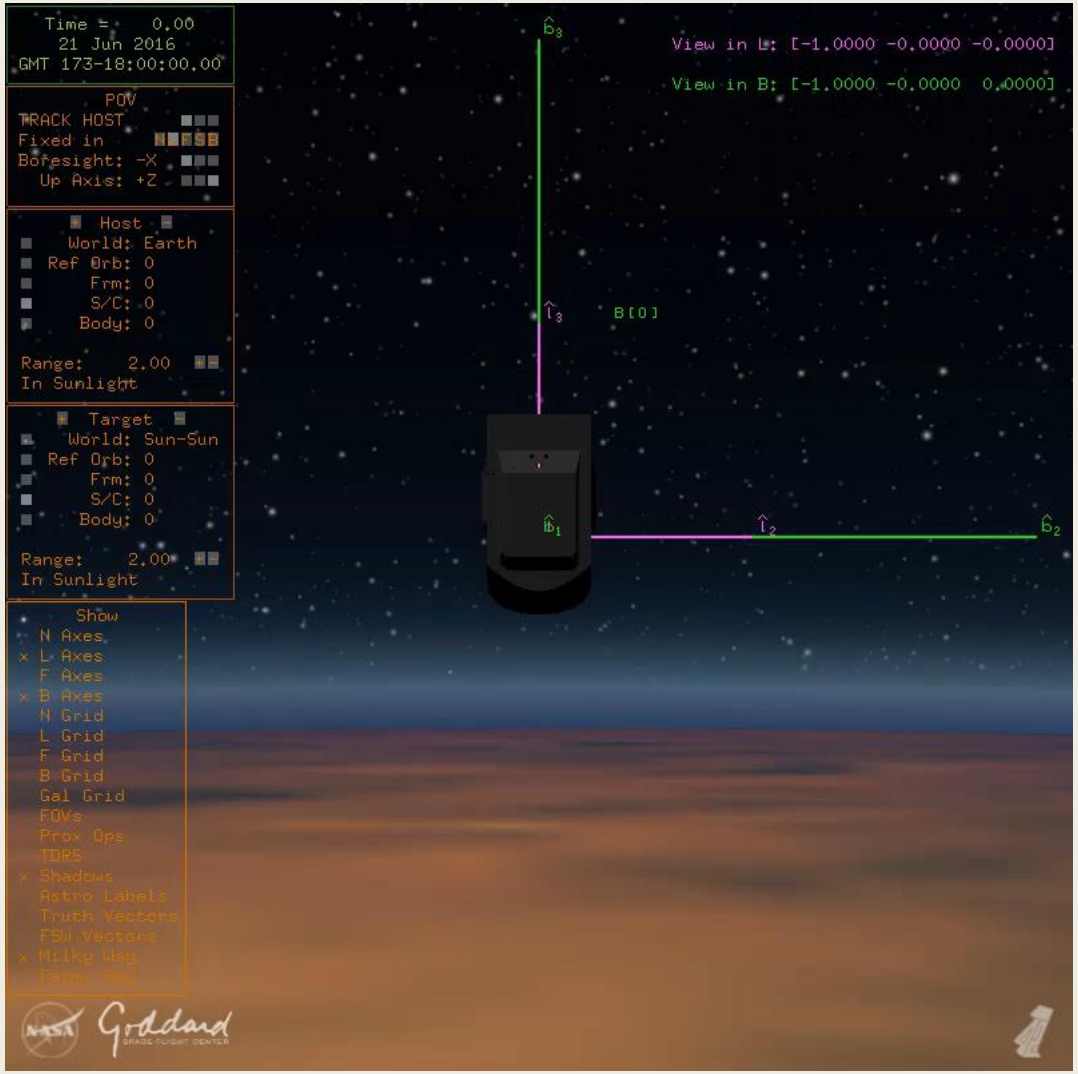
- Vehicle was **predicted** to be stable during this initial flight regime.
- Flight data would
  - *Verify stability as predicted.*
  - *Validate CFD tool.*
  - *Verify trajectory model.*





Attitude Reconstruction from Flight Data – First 31 Seconds

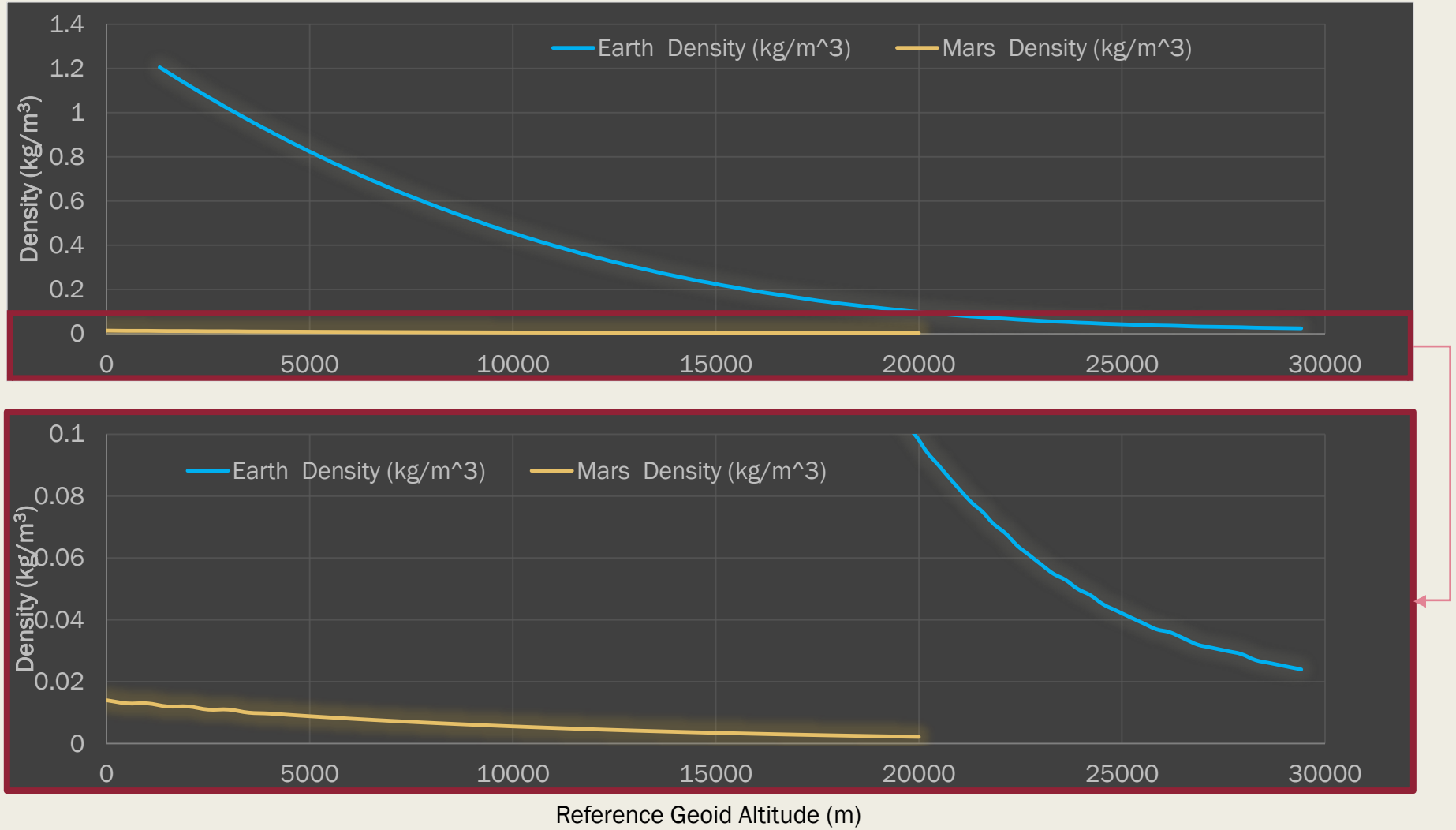
- Receiver flight data shows vehicle dynamic behavior during first 30 seconds of flight from the on-board IMU rate gyros.
- Initial tip-off rate on release is observed.
- Dynamic behavior was as predicted.
- Verification accomplished.



Animation by Eric T. Stoneking (GSFC-591)

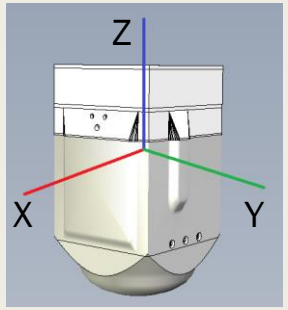
Side Bar: Earth/Mars Atmospheric Models

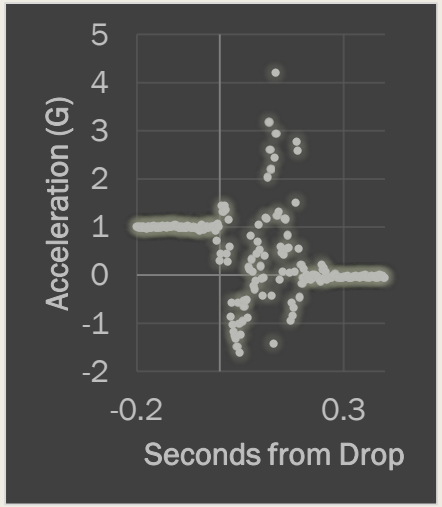
- Yes, we need a space suit!
- + Oxygen
- + Heat
- + Food
- + Return trip back to earth (maybe)
- But what does it mean for MIRCA? Better to spin-stabilize vehicle from start.

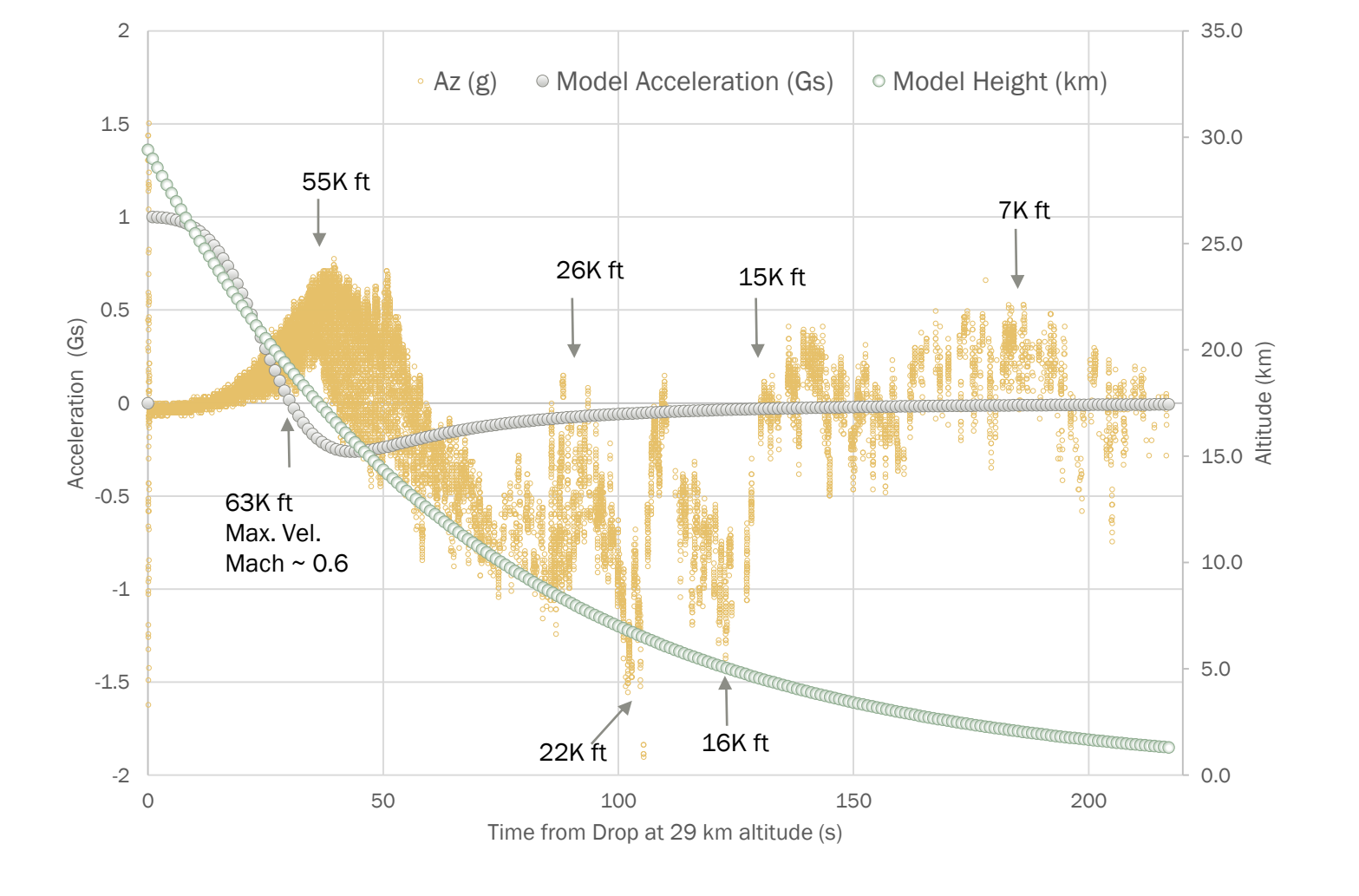


Z-Axis Acceleration

- Data was telemetered back to the MIRCA receiver on the gondola (aka SM/MS) during the entire flight.
- Data reception was expected to deteriorate after about ~15 km separation (Flight #1).







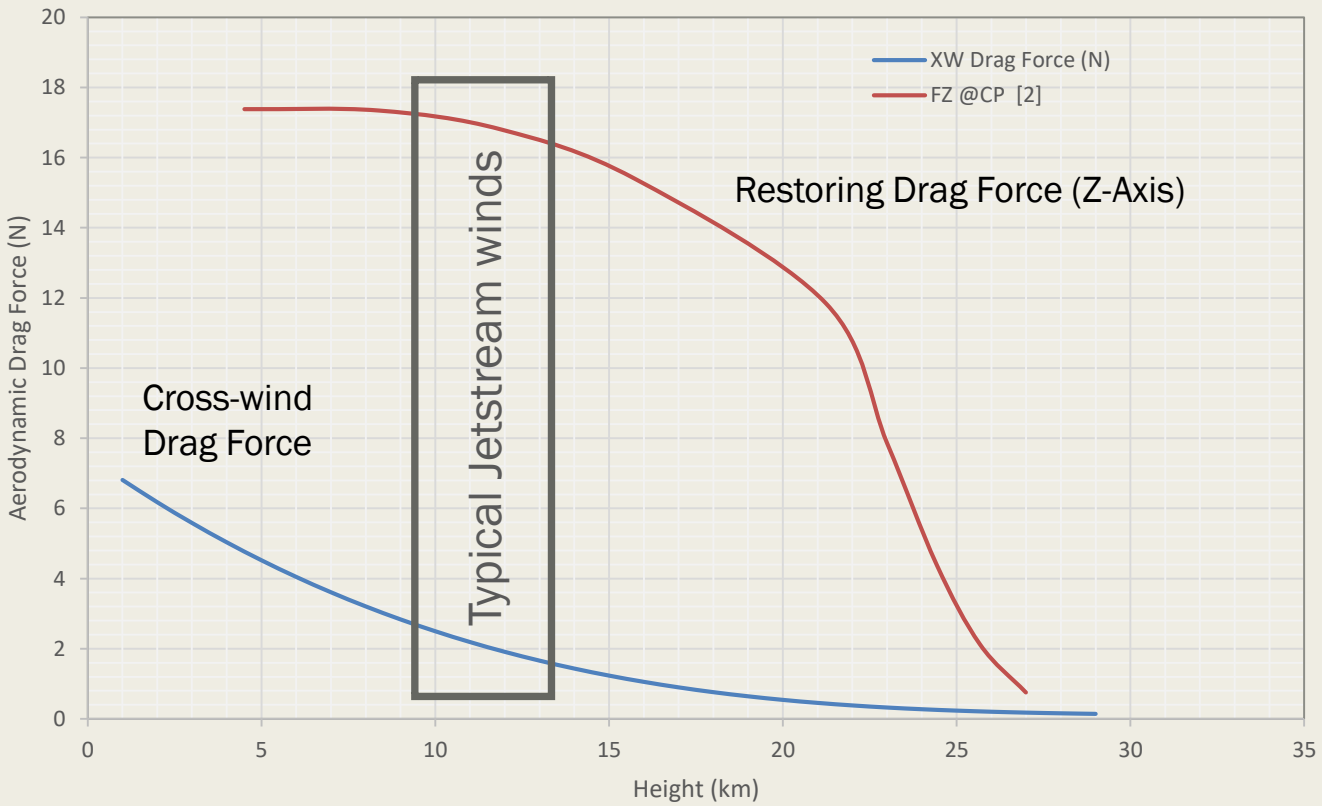
Real-Life Effects: Cross-Winds

- Analysis was carried out assuming the primary wind loading force was solely due to the vehicle's speed.
- This is not the case for real-life flight in the denser parts of the atmosphere. For instance, the jet-streams ranging from 9km (~30K feet) to 12km (~39K feet) in altitude, can blow at speeds greater than 160 km/h (100 mph).
- This is about 1/3 of the calculated vehicle speed at these altitudes, and is a force of instability that cannot be ignored, especially for a tiny vehicle.

Video Source: NASA Visualization Explorer, 7 February 2012

Aerodynamic Forces

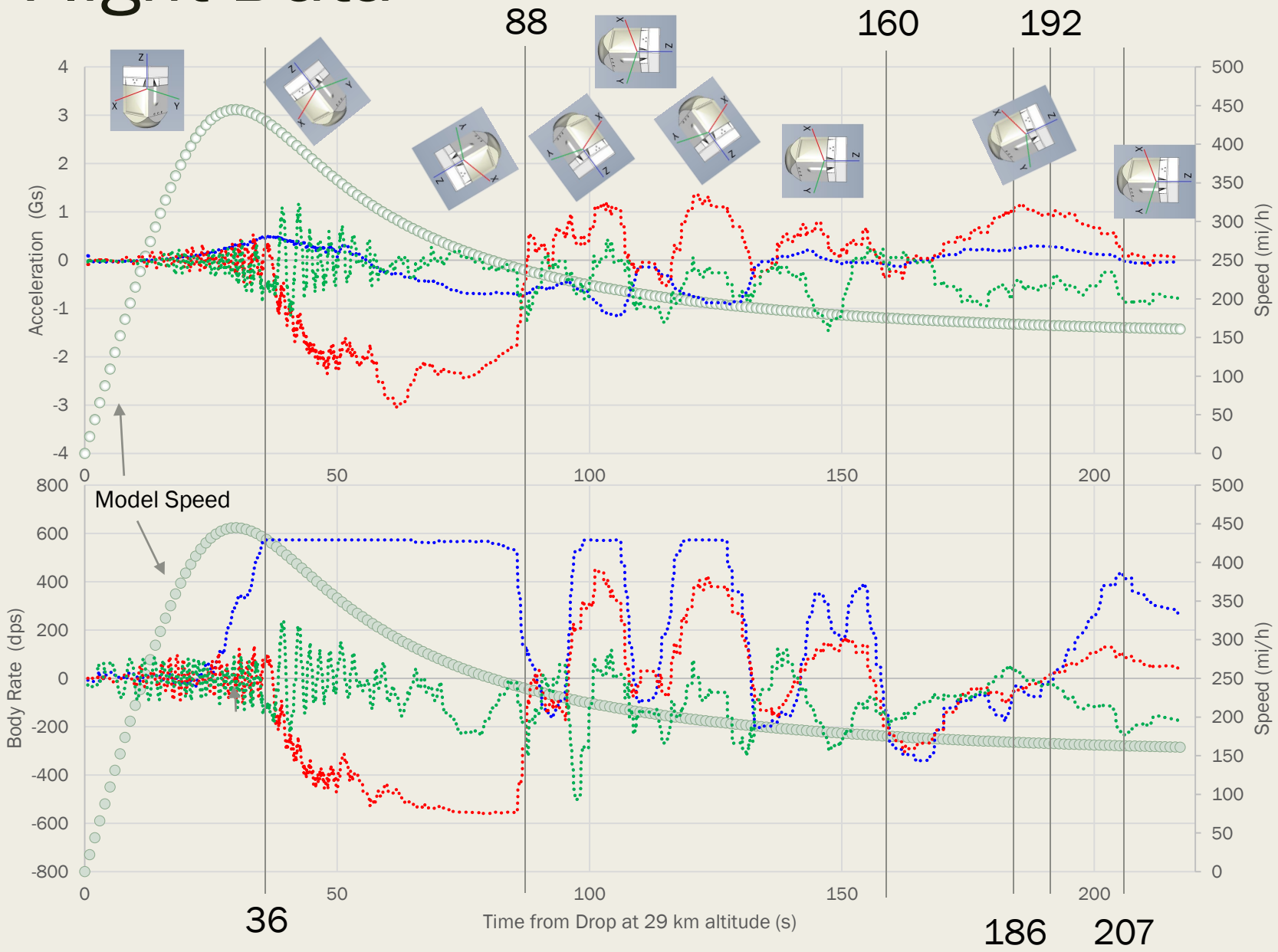
- Aerodynamic forces resulting from cross-winds can play a significant role in vehicle stability, especially at lower (more dense) parts of the atmosphere.
- This is not surprising.

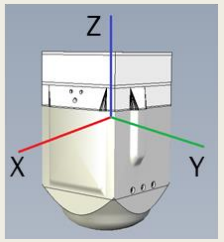


IMU Flight Data

Vehicle dynamics reconstruction from IMU data (acceleration and rate).

255-Point Moving Average Flight Data





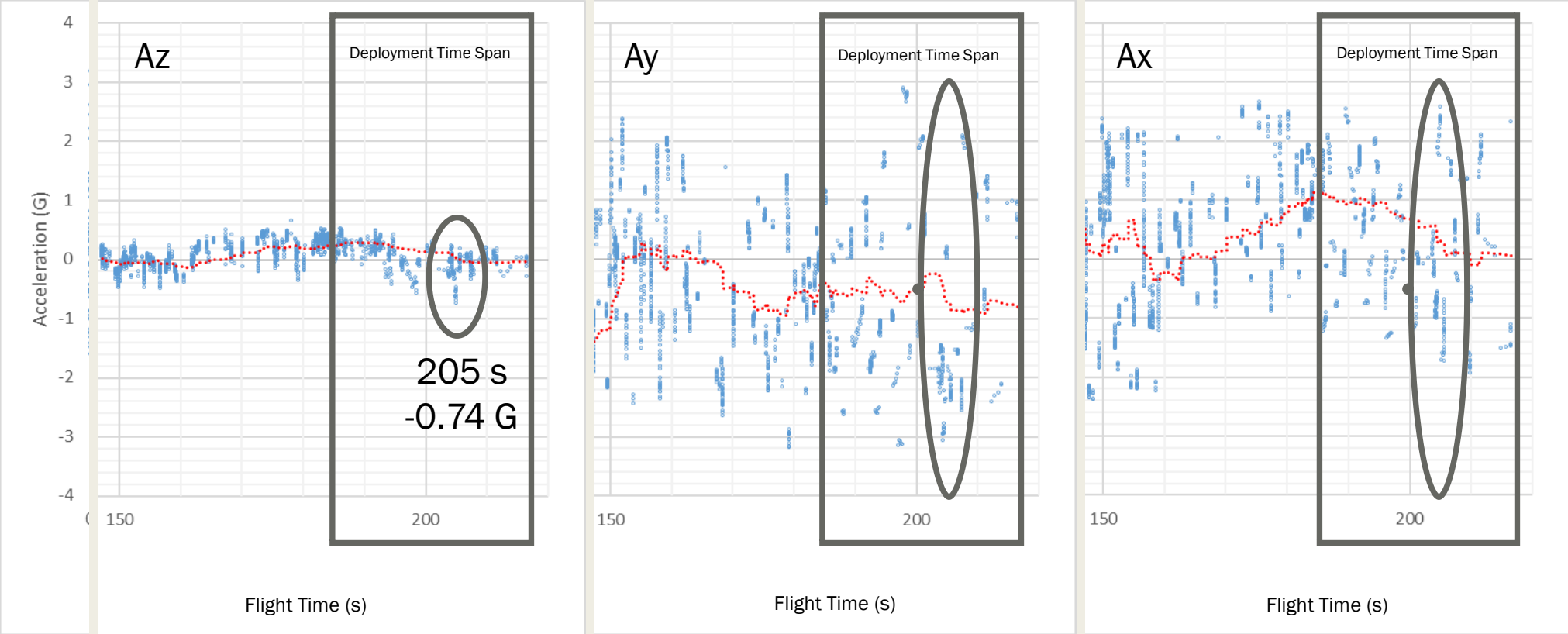
Curves are color-coded to agree with axes colors

Genesis Capsule Return

[redacted]

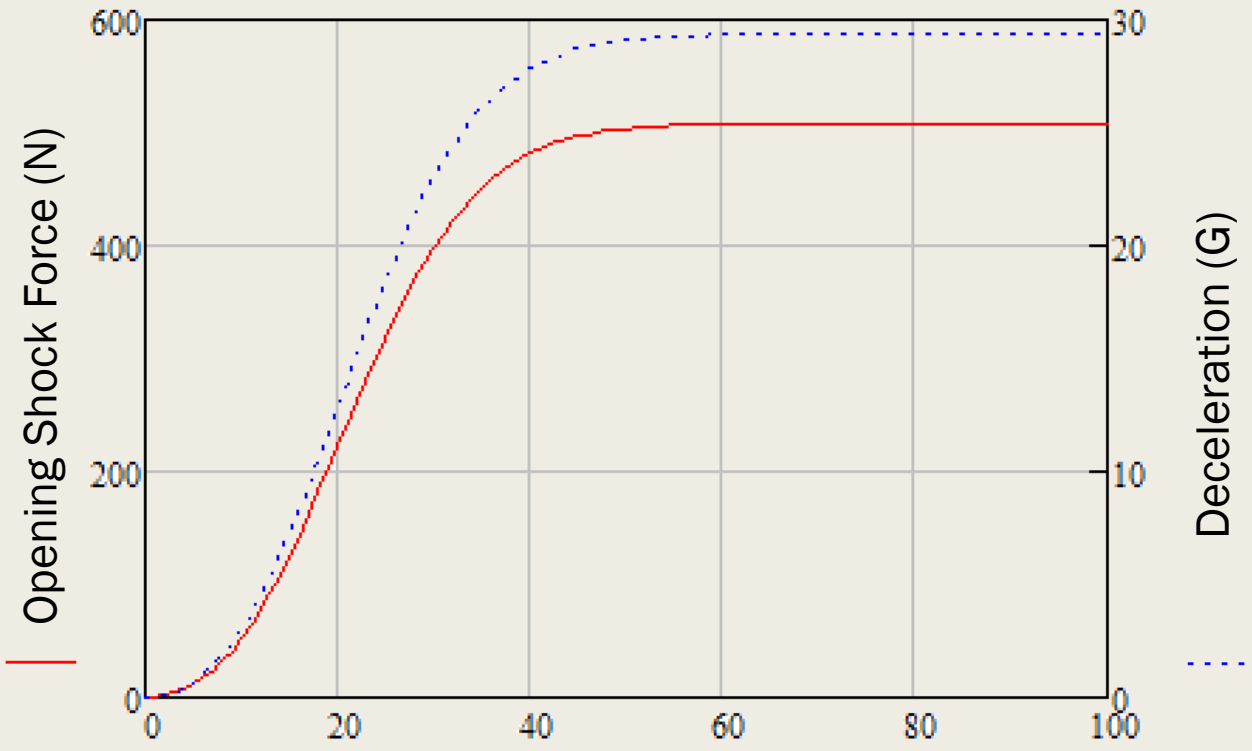
Where is the Parachute?

- Parachute cover actuation time @ 186s from release.
- Circuit energized for 30 seconds thereafter.
- Change in vehicle dynamics noted at ~207 s, and Z-axis deceleration at 205 s.



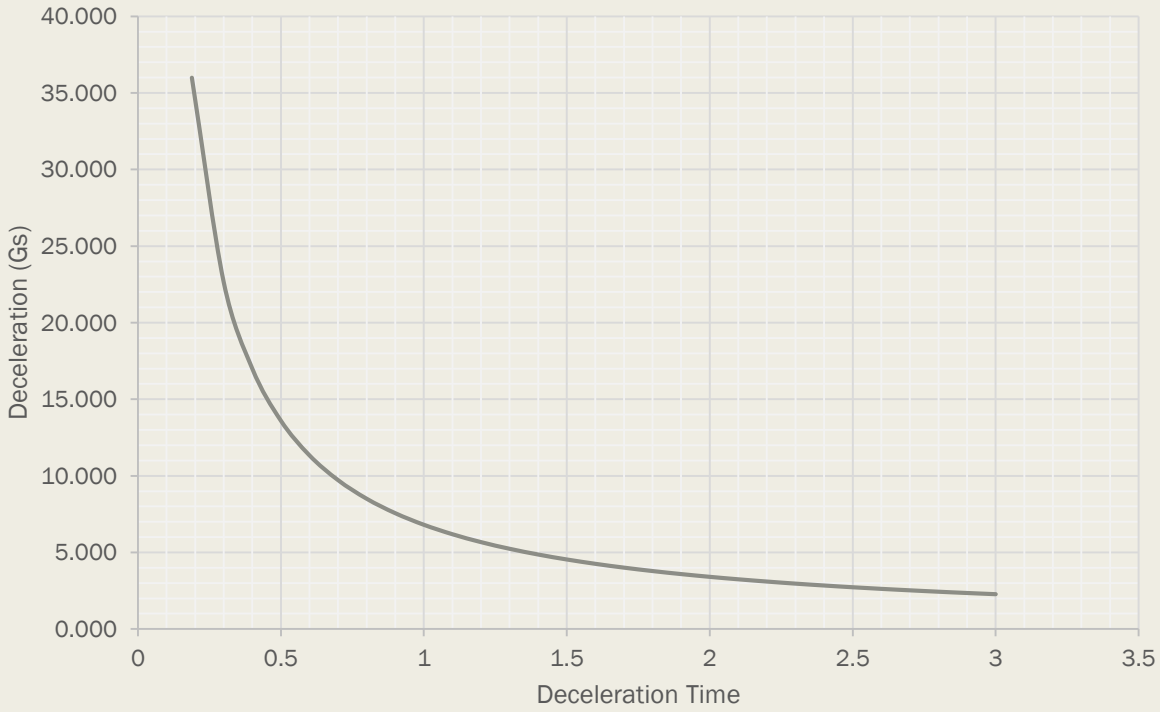
Parachute Opening Shock and Deceleration

- The opening shock force is derived from the finite mass opening shock factor
- Based on a mass ratio defined by the characteristic fluid mass/system mass.



Should I have been able to see parachute deployment from data?

- YES!
- Telemetry update rate every 2.5 ms.
- Calculated deceleration time of 0.189s means that deceleration occurred during a span of ~75 telemetry points.
- Data dropouts during the deployment time span were less than 75 points. Hence at least *one saturation* telemetry point should have been observed.



But …

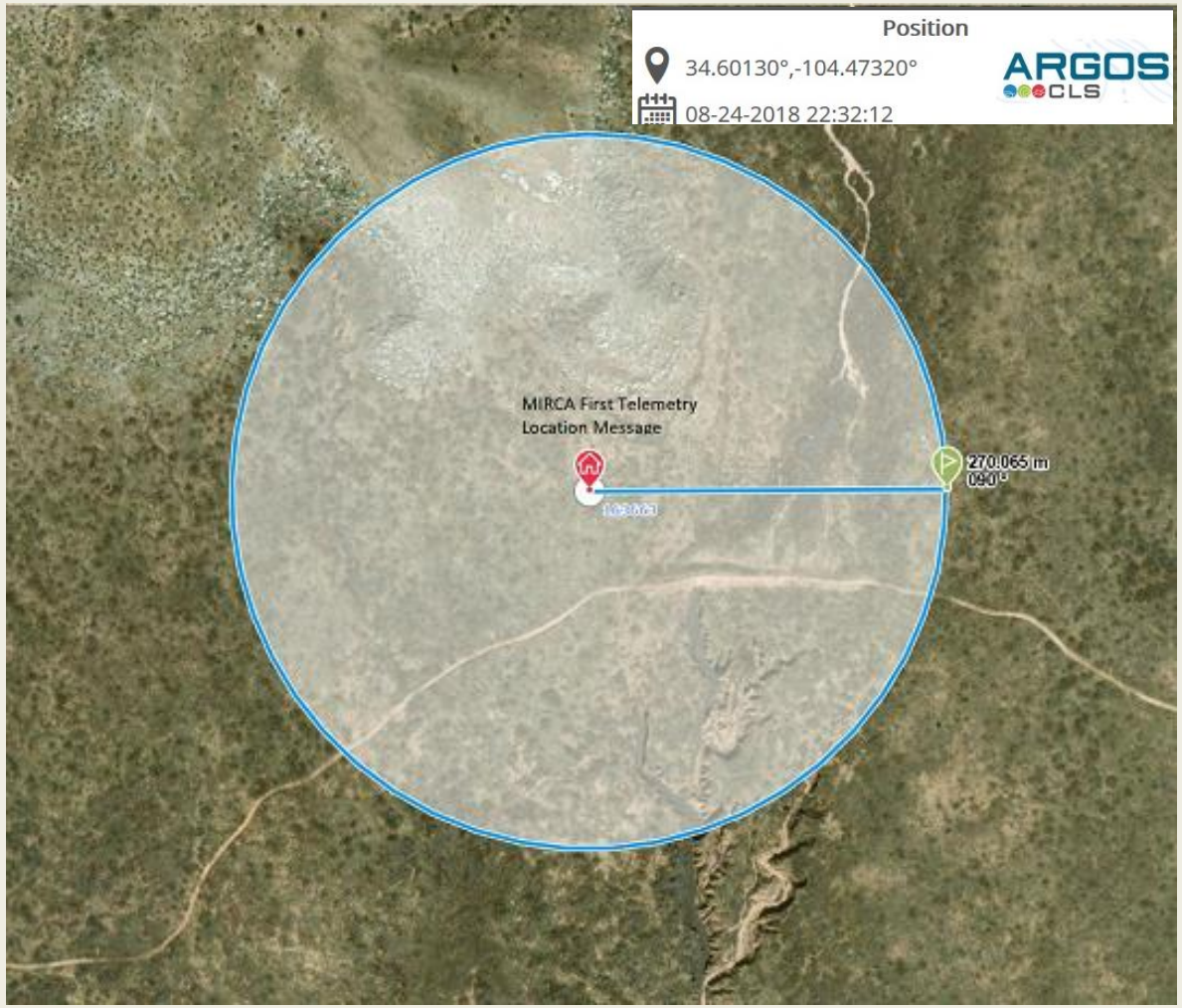
- LOS occurred *exactly* 30.5 seconds from start of energized deployment circuit.
- Deployment command started *exactly* 30 seconds earlier, and ended exactly 30 seconds thereafter.
- Coincidence?
- Could it be the increased Gs essentially “terminated” transmission?
- Unlikely, but all possibilities were to be exhausted.

The Search for MIRCA

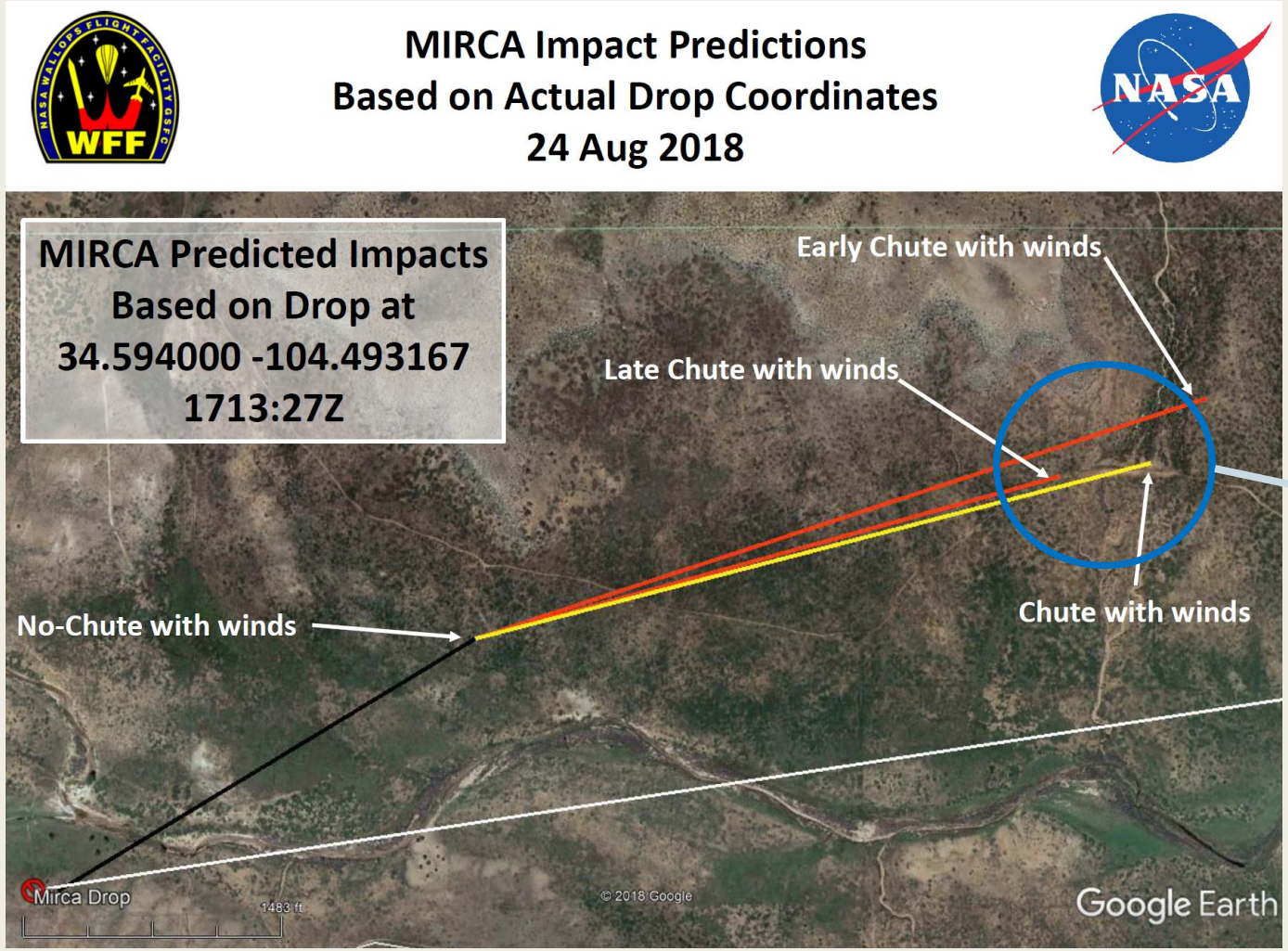
- Onboard recorded data would have an exact account of events.
  - *Mainly, what happened during parachute deployment?*
  - *Had the parachute only partially deployed?*
  - *Had the lanyard responsible for extracting the parachute from its enclosure failed?*
  - *Had the parachute remained completely inside its 5 walls?*
  - *Had DANNY failed to operate (less likely)?*
- The only way to know for sure was to recover MIRCA.
- Physical evidence would be “icing on the cake”.

Satellite Transmitter

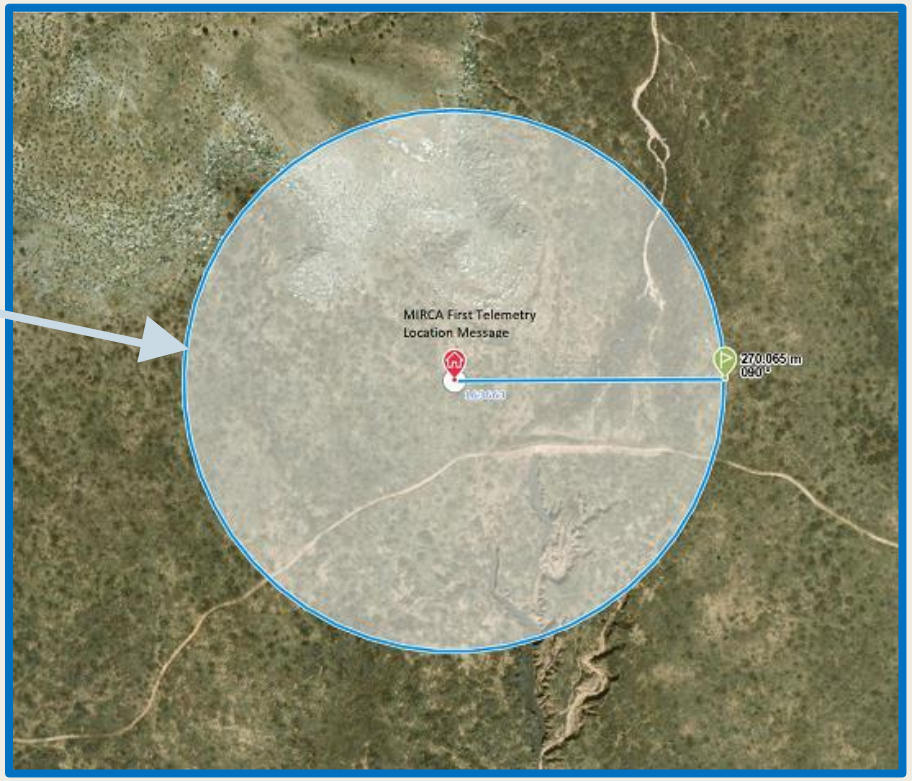
- If MIRCA had impacted the ground, I estimate the shock would have been greater that 3,000 Gs.
  - *We know there was no huge impact detected by telemetry, hence deceleration occurred within 2.5 ms.*
  - *Vehicle was traveling ~ 72 m/s at 216 seconds from release (assumed impact time)*
- The ARGOS satellite transmitter continued to operate!
- First telemetry point agreed *exactly* with predicted location from Range Safety, based on release position, winds at the day of flight, *and a functioning parachute*.



Range Safety Prediction



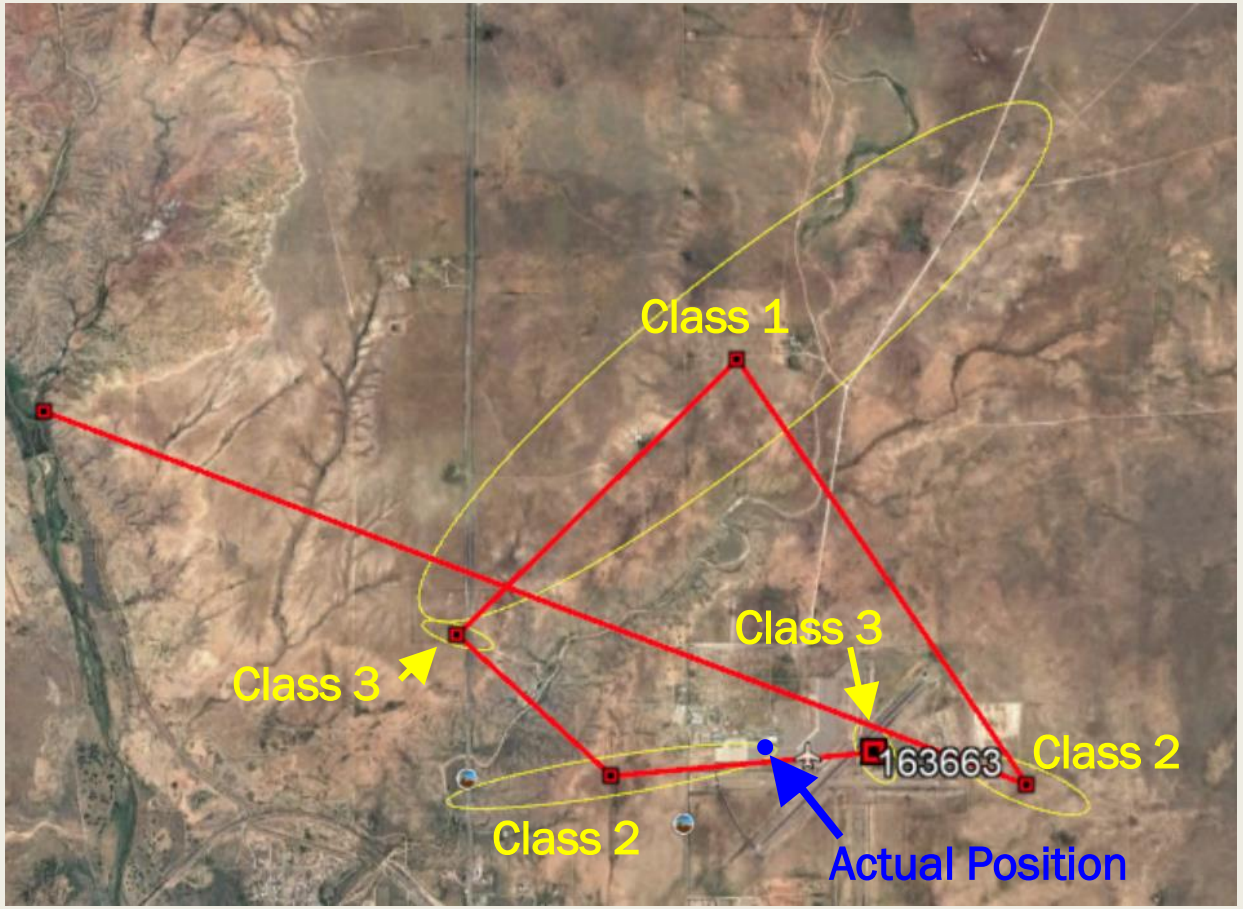
First Satellite Telemetry



Credit: David G. Helfrich (WFF-8030), et. al.

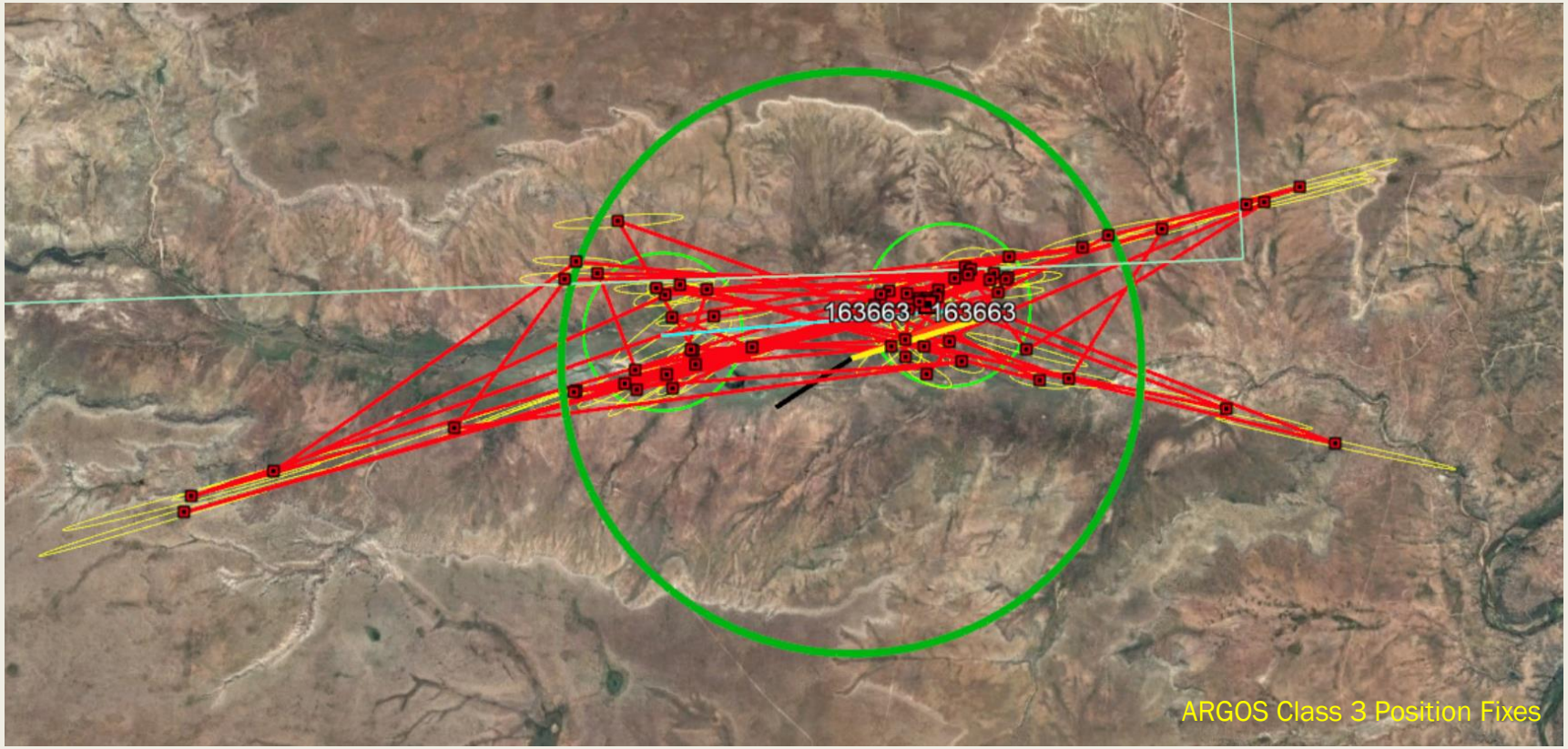
ARGOS Position Accuracy

- Pre-flight tests showed that ARGOS position accuracy was highly variable
  - *From 0.8 to 2 km (for best solutions or "class 3")*
  - *Upwards of 2 km for other classes.*
- No GPS beacon was available at the time of selection.



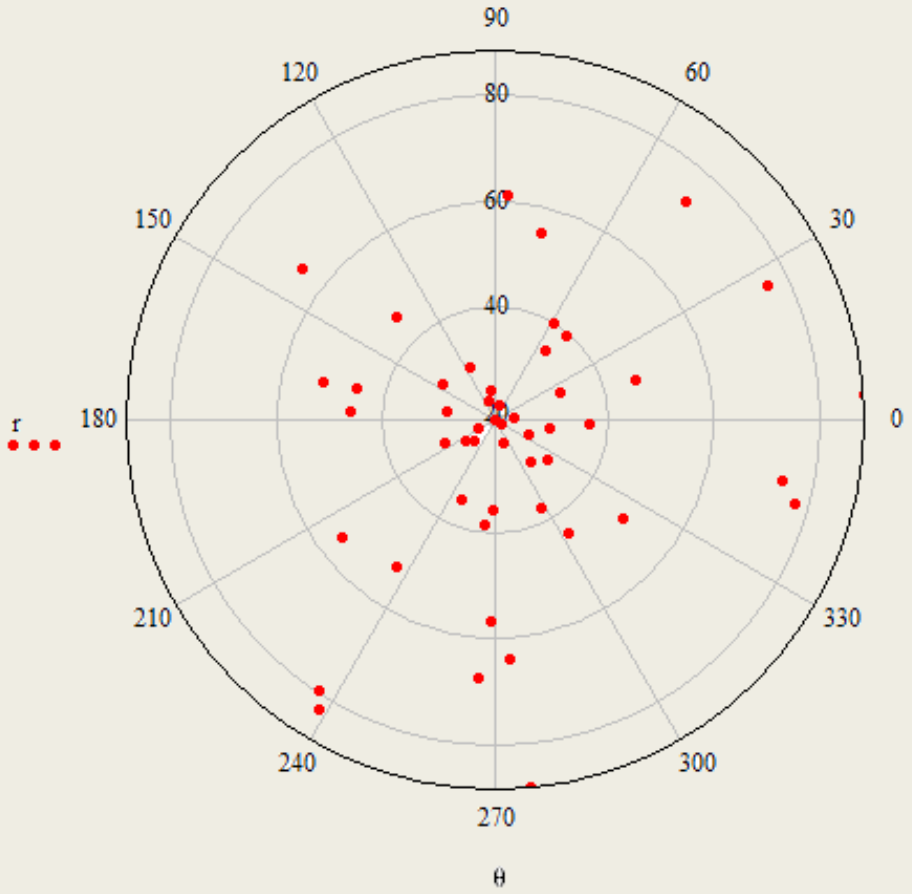
ARGOS Signal Position Map

- There were two major locations where MIRCA's signal was detected.
- On-site RF measurements indicated MIRCA was somewhere between two major circles.



ARGOS Satellite Visibility

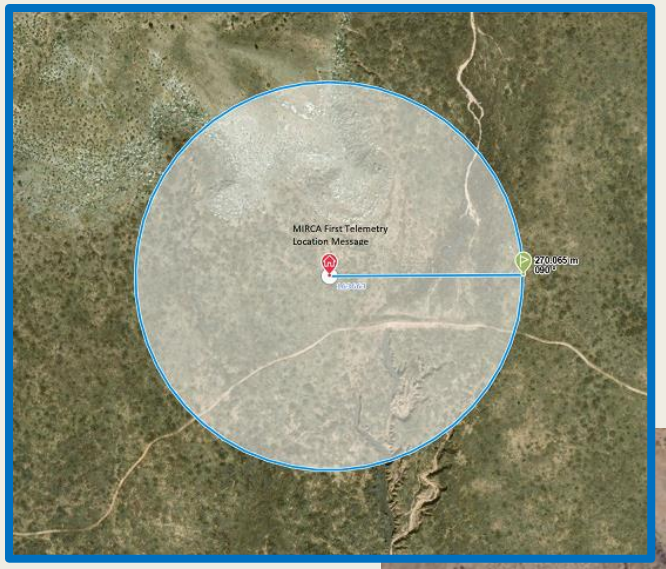
- Data showed MIRCA had a clear view of the sky in all directions.
- Hence it was not on the side of a hill, nor inside of a ravine or dry creek that could obstruct its view.
- Signals below 20º elevation were not detected.

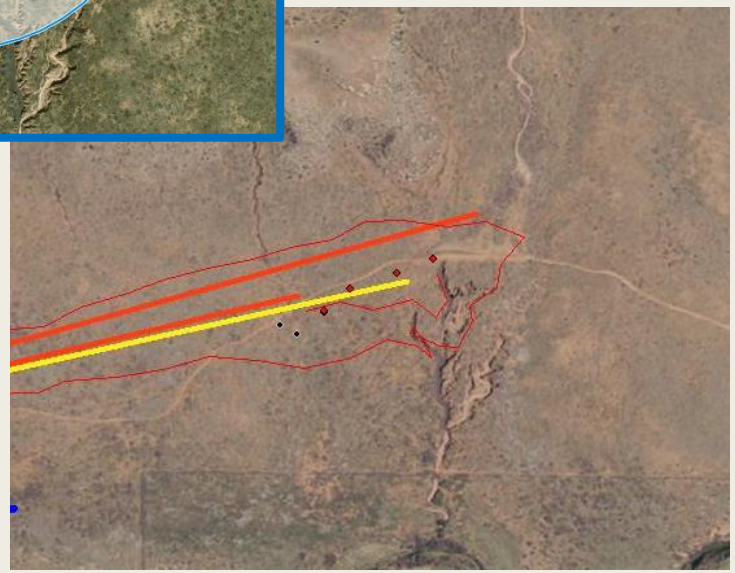


θ is the middle azimuth, and r is the middle elevation of ARGOS satellites observed by MIRCA, irrespective of location quality.

Search – Day 1 (8/25/2018)

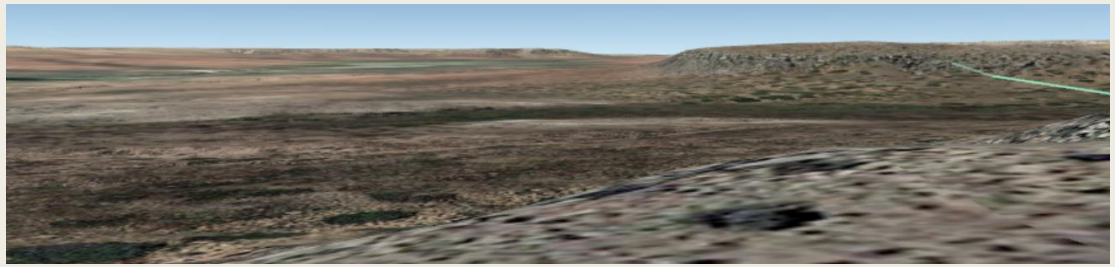
- First search efforts was carried out by Robert Salter the day following the drop.
- Concentrated on first known position for MIRCA.
- Had to secure Rancher permission to enter property, who also provided assistance.
- No ATV's were allowed on the property. Only search by foot.
- There was a single access dirt road.
- Visual search did not find MIRCA.





Search Days 2-3 (8/29-30/2018)

- This time Robert and I headed to the drop site.
- We had RF equipment for triangulation.
- 10 gallons of water.
- Hats.
- And my Chaps to fend-off rattle snakes…

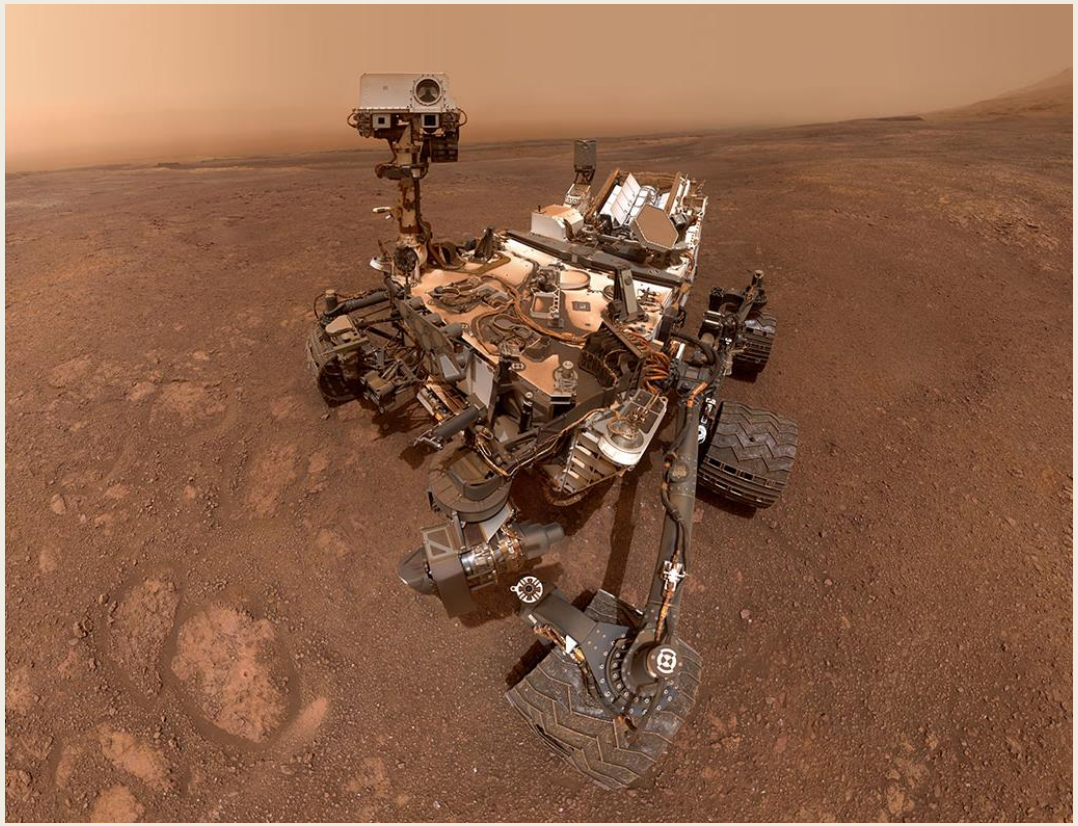


Difficult Terrain

- The terrain was tougher than I imagined.
- Lots of bushes everywhere to hide MIRCA's location.
- Without RF equipment and location beacon it would be like looking for a needle in a haystack

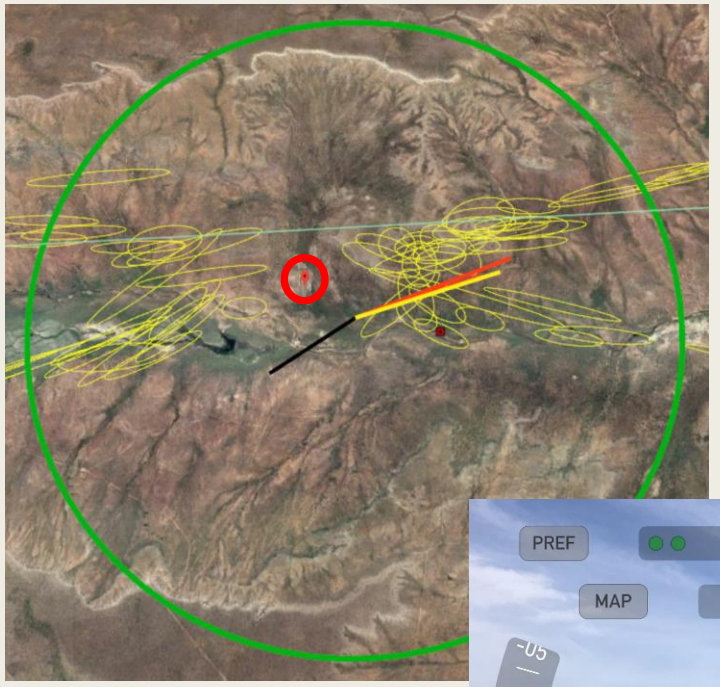
New Mexico Desert is not Mars

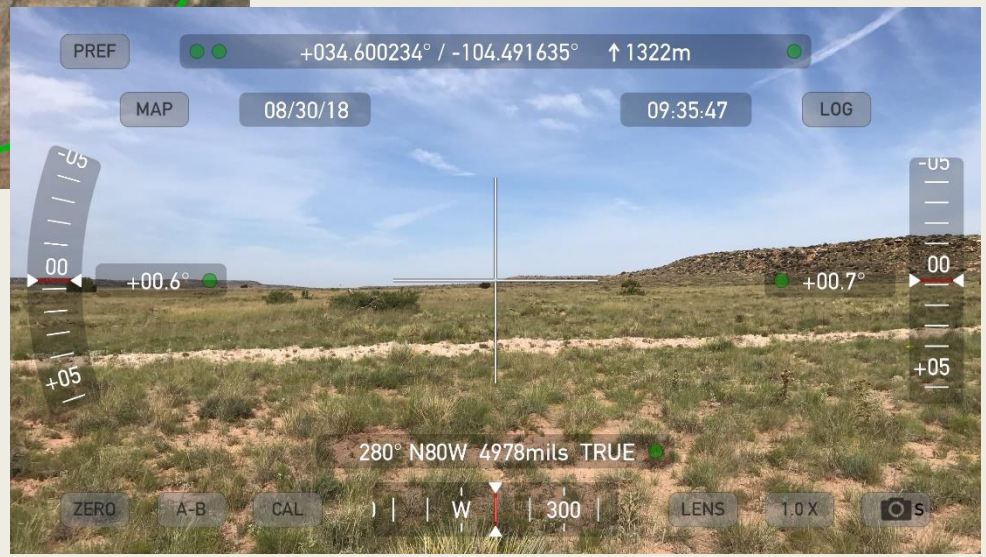
- Just about that time I wished I were in a true desert …



Triangulation – Last Signal Bearing

- We had two types of RF sensing equipment:
  - *A squelch radio receiver*
  - *Spectrum Analyzer (borrowed)*
  - *Receiver antenna (borrowed)*
- MIRCA's beacon operated once every 90 seconds.
- We focused on an area based on signal reception.
- Unfortunately, I run out of time/funding and had to head back home.

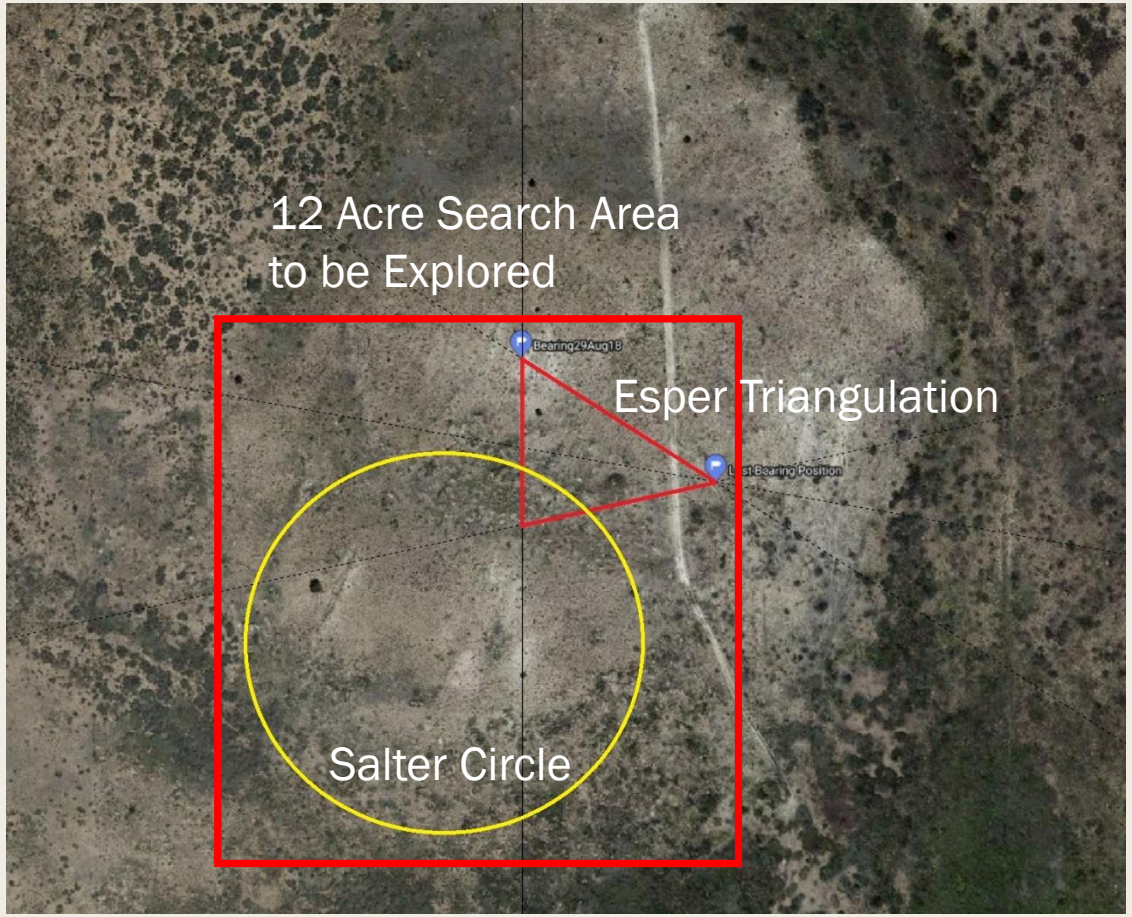




Last signal bearing 30 August 2019

Possible Location

- The likely place where MIRCA had landed was narrowed to a ~ 12 acre area (~47,000 m^2), with a perimeter of ~3,000 feet (869 m).



At the end of the trip

- I found Ernie

34°36′1″ N 104°29′32″ W
4350 ft Elevation

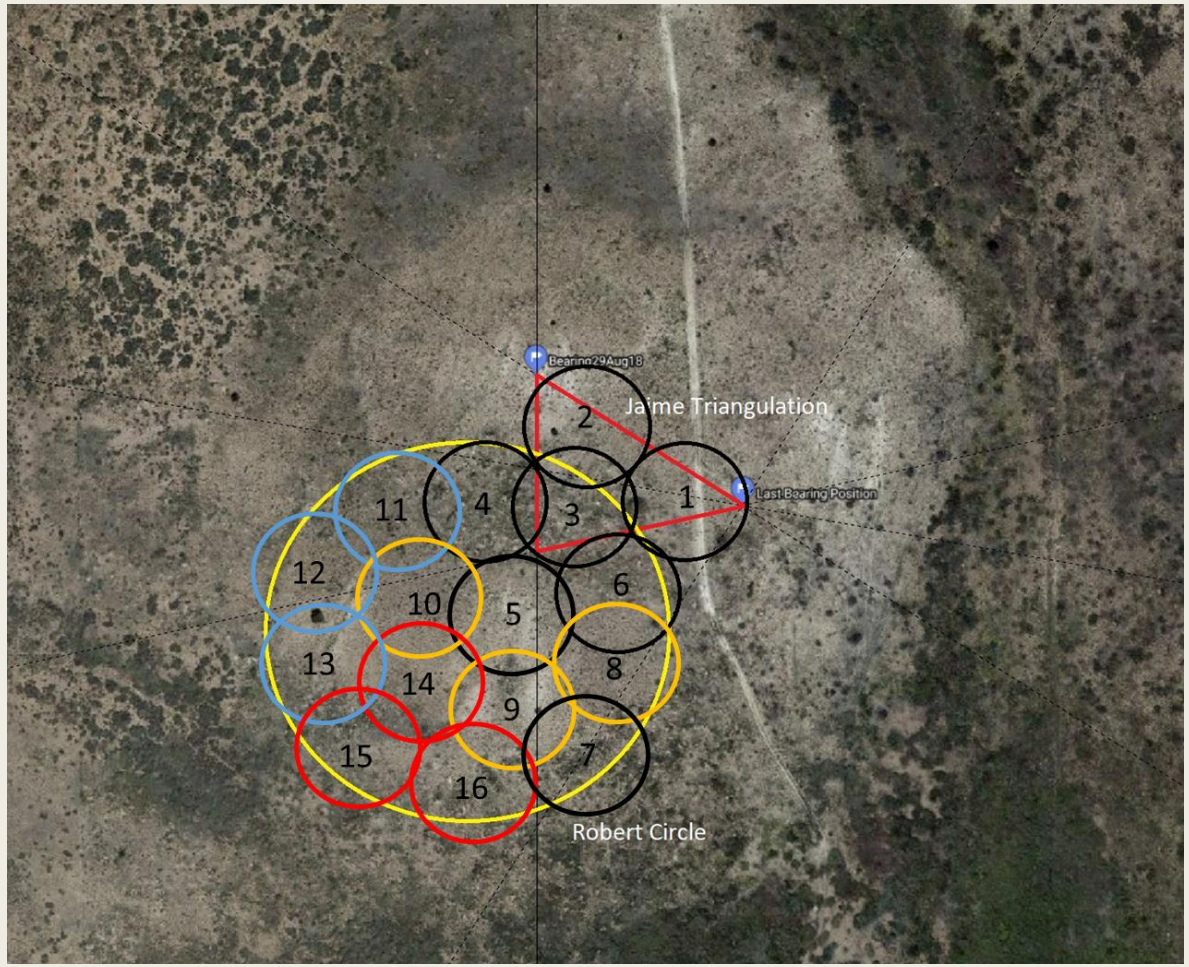
- And lost my boots soles.

Search Days 4-5 (9/10-11/2018)

- The decision was made to return to the drop site and try to recover MIRCA. After all, we were very close to finding its location.
- *The night prior to travel, ARGOS received the last transmission from MIRCA*.
- By this time I had a drone, a kite, a metal detector, binoculars, and a well-calibrated spectrum analyzer.
- I had not lost hope, but I knew the odds had just built against me.

Dead Beacon – On the Visual Search

- MIRCA's beacon had finally run out of batteries, 17 days after its activation.
- The focus was to rule out a deployed parachute by carrying out a thorough visual survey of the area from above ground.



Multiple Drone Flights

- The triangulated search area was covered from above.
- It became evident after the first few flights that finding MIRCA this way was going to be extremely difficult.
- MIRCA's parachute was not seen after reviewing ~ 30 min of drone video.

With John Grunsfeld (center), and Paul Hertz (for scale)

Broad Aerial View

- One last-ditch effort was made to detect the bright-orange parachute.
- Search was expanded to all locations identified by ARGOS signals, east of the triangulated area. No ground-signal was detected west.
- In all, about 20 km were covered on foot.
- Most likely, MIRCA's parachute failed to fully deploy.

Where there is "failure" there is Opportunity

- MIRCA was never found… but it was never designed to be recovered in the first place (Gen-1). Gen-2 was a fair attempt at incorporating a recovery system.

- **What really matters are MIRCA's accomplishments:**
  - *MIRCA successfully demonstrated the first planetary entry probe <u>prototype</u> based on the ubiquitous CubeSat specification.*
  - *Successfully demonstrated CAPE's Operations Concept in a dynamic environment.*
  - *Transmitted its entire flight data to be analyzed.*
  - *Provided valuable lessons on the design of a miniaturized atmospheric probe.*
  - *Set the foundation for improvements.*

MIRCA was a resounding success!

- It has laid the foundation for its generational successor, with:
  - *New Aero-shell design*
  - *New decelerator system*
  - *New parachute deployment system*
  - *New sensor suite*

Miniature Atmospheric and Planetary Probe ExploreR (MAPPER).

- Stay tuned!

Acknowledgements - Alphabetical

- Kathryn Browne (ARC)
- Chuck Clagget (GSFC – 595)
- Carmel Conaty (GSFC – 592)
- Gary Crum (GSFC – 587)
- Debbie Fairbrother (GSFC – WFF – BPO)
- Hugo Franco (CSBF)
- David Helfrich (GSFC – WFF)
- Tupper Hyde (GSFC – 690)
- Conor Nixon (GSFC – 693)
- Robert Salter (CSBF)
- Luis Santos (GSFC – 599)
- Joseph Schepis (GSFC – 544)
- GSFC IRAD FY14-15

"We are still at the Stone Age of space exploration." J. Esper