# Apophis: Rocket campaign to investigate eclipse induced ionospheric electrodynamics


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AFRL

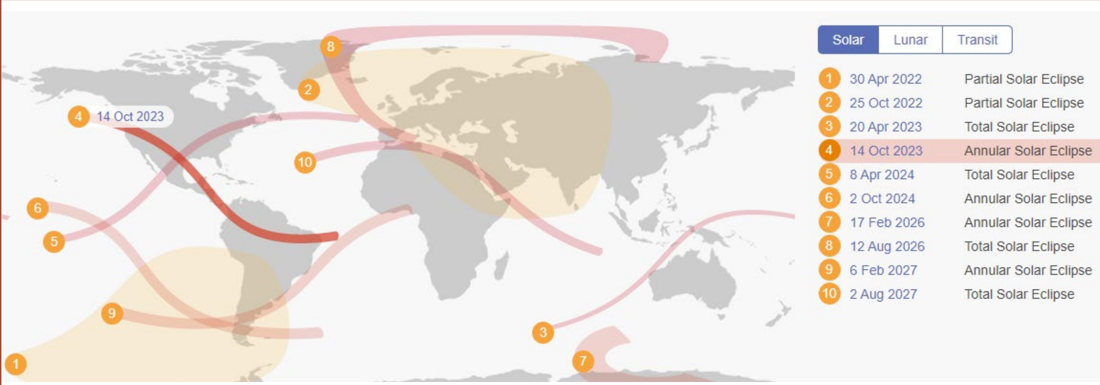
MIT

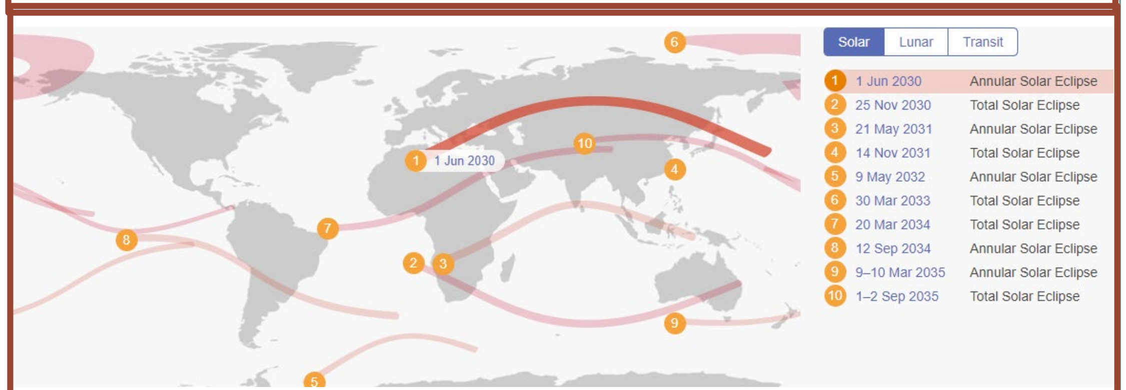
MIT Haystack Observatory

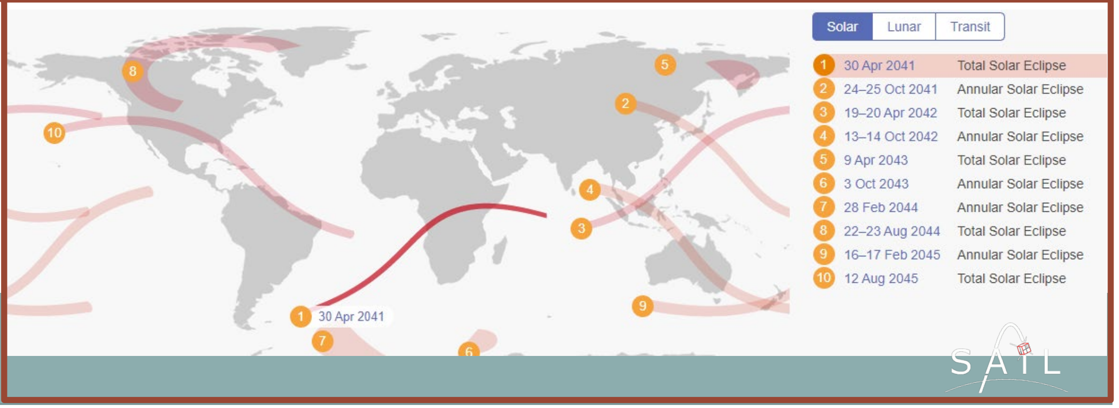
Dartmouth

# Eclipses above/near existing rocket ranges

- Two eclipses
  - Annular, Oct 14, 2023, WSMR
  - Total, April 8, 2024, WFF
- No US Mainland eclipse opportunity until 2044.
- US Mainland affords usage of existing ground-based observation assets.





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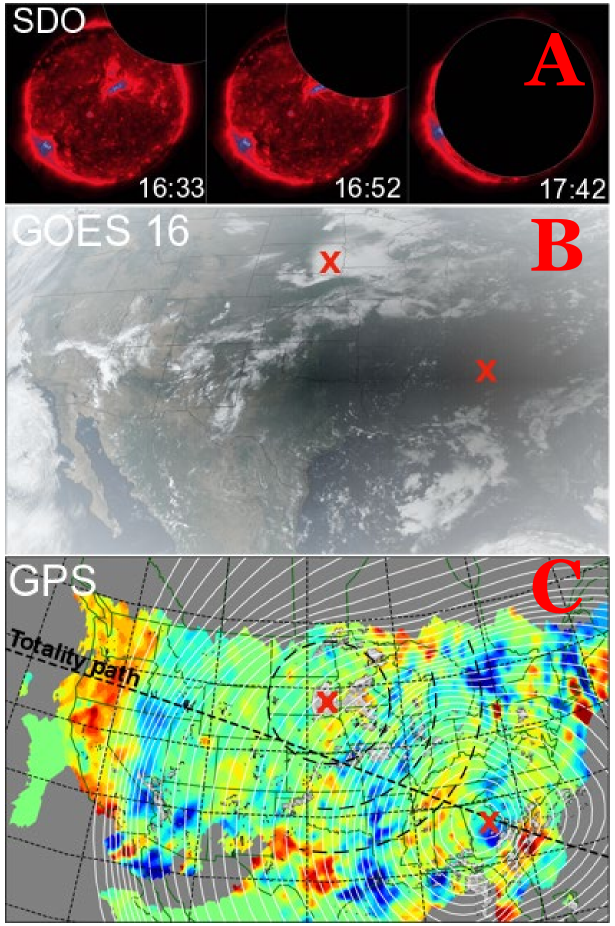
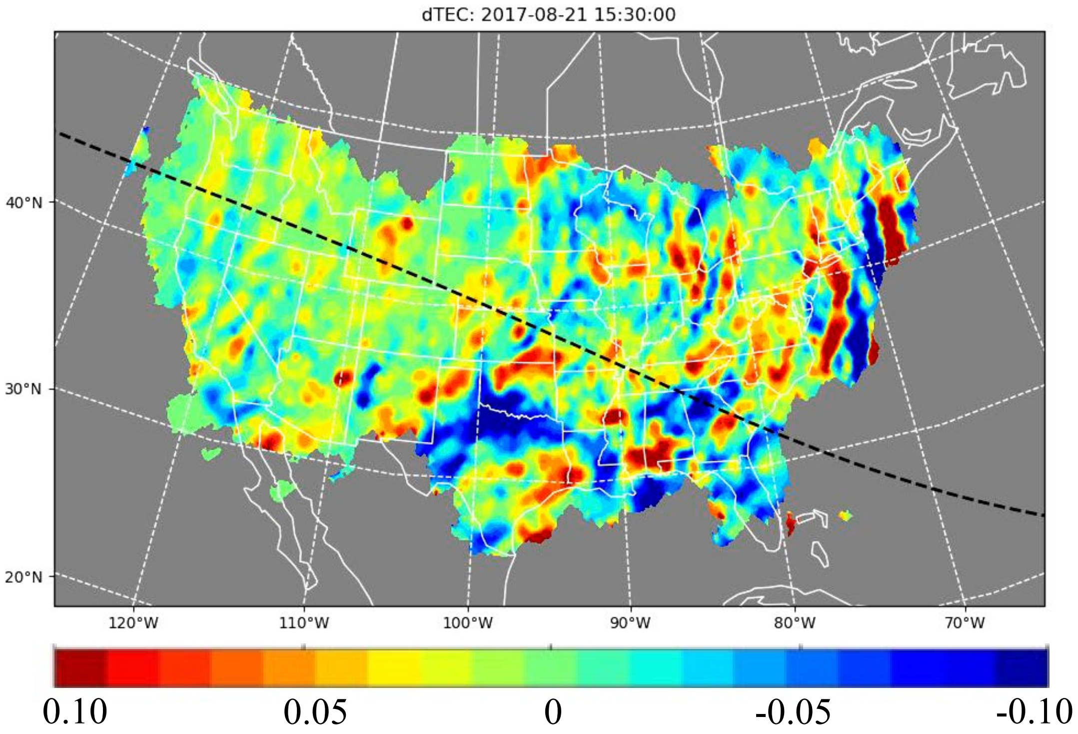
# Eclipses above/near existing rocket range


- **Apophis** - The cosmic world serpent from ancient Egyptian cosmology that pursues the sun god Ra, and every so often, nearly consumes the sun disc, resulting in an eclipse.
- Launch Location – WSMR. Launch North from LC-36 and recover payloads for relaunch later.
- Launch Date - Oct 14, 2023, during annular solar eclipse
- Launch Location – WFF into ocean
- Launch Date – April 8, 2024, during Total solar eclipse

# Electrodynamics induced by eclipse

- Solar active regions can be covered or uncovered as the moon eclipses the sun (A). These regions can be anywhere, depending on the solar corona at the time.
- Gradients in EUV occultation modify the plasma production function and affect the ionosphere even away from totality.
- Along with lower-atmospheric sources of ionospheric perturbations which are commonly present (B), the stunted photoproduction can lead to significant and complex changes in ionospheric electrodynamics (C).




Video shows the perturbations in ionospheric total electron content (TEC) for the 2017 eclipse. Contours represent the non uniform penumbra. Regions with contours bunched together represent bigger EUV gradients – and underneath are the TEC perturbations.



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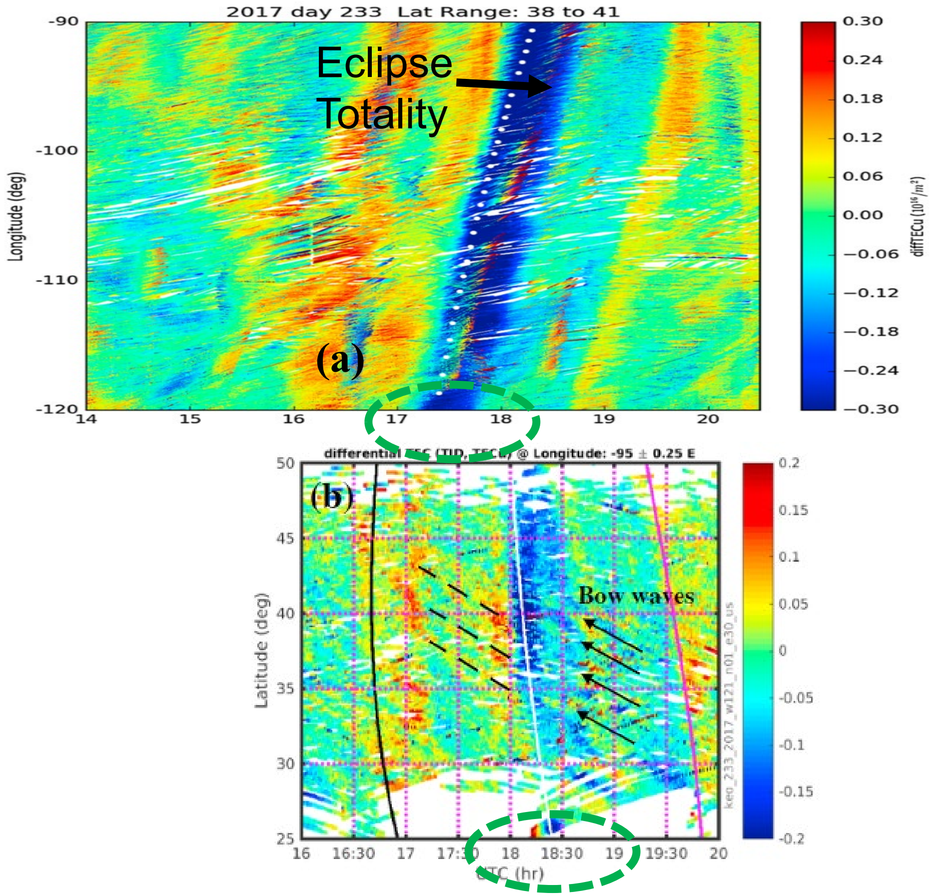
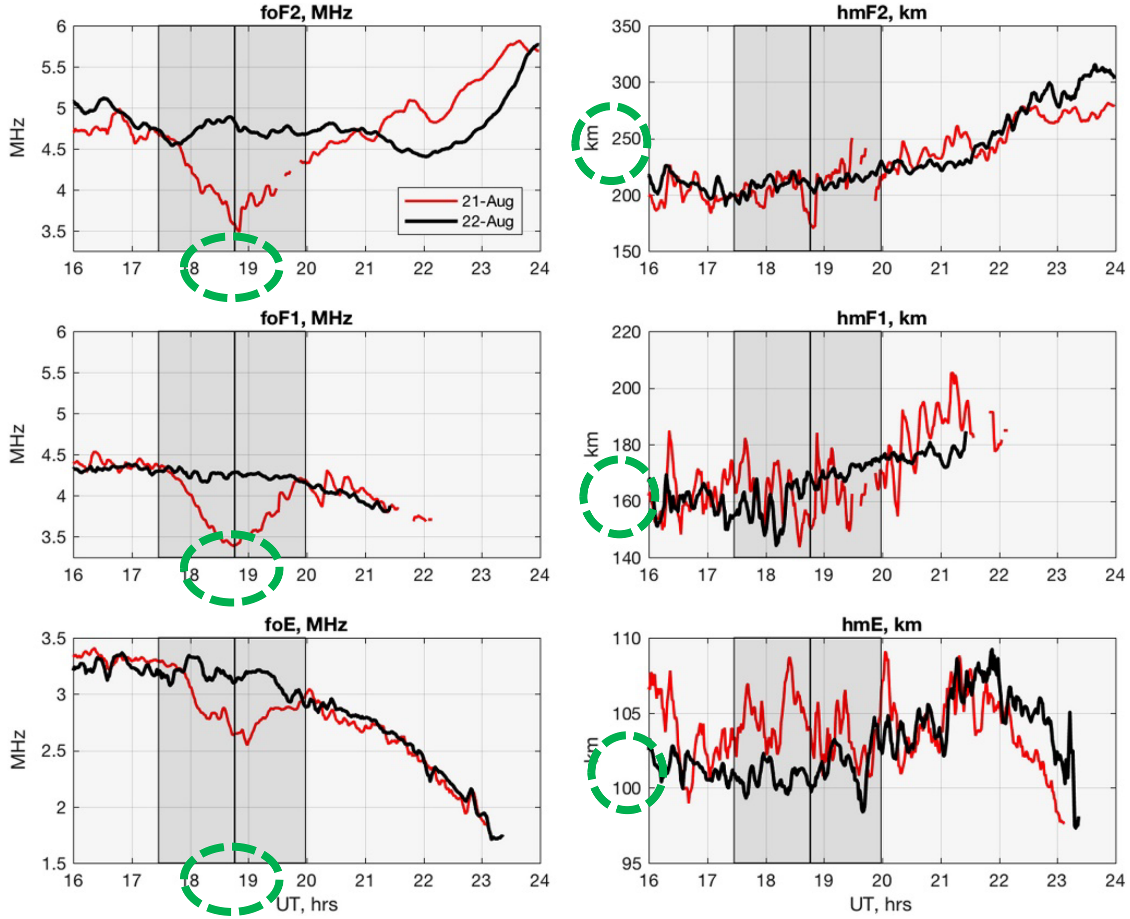
# Ionospheric perturbations induced by eclipse




Differential TEC keograms for the solar eclipse of 2017 showing (a) TIDs [Coster et al., 2017] and (b) bow waves [Zhang et al., 2017]



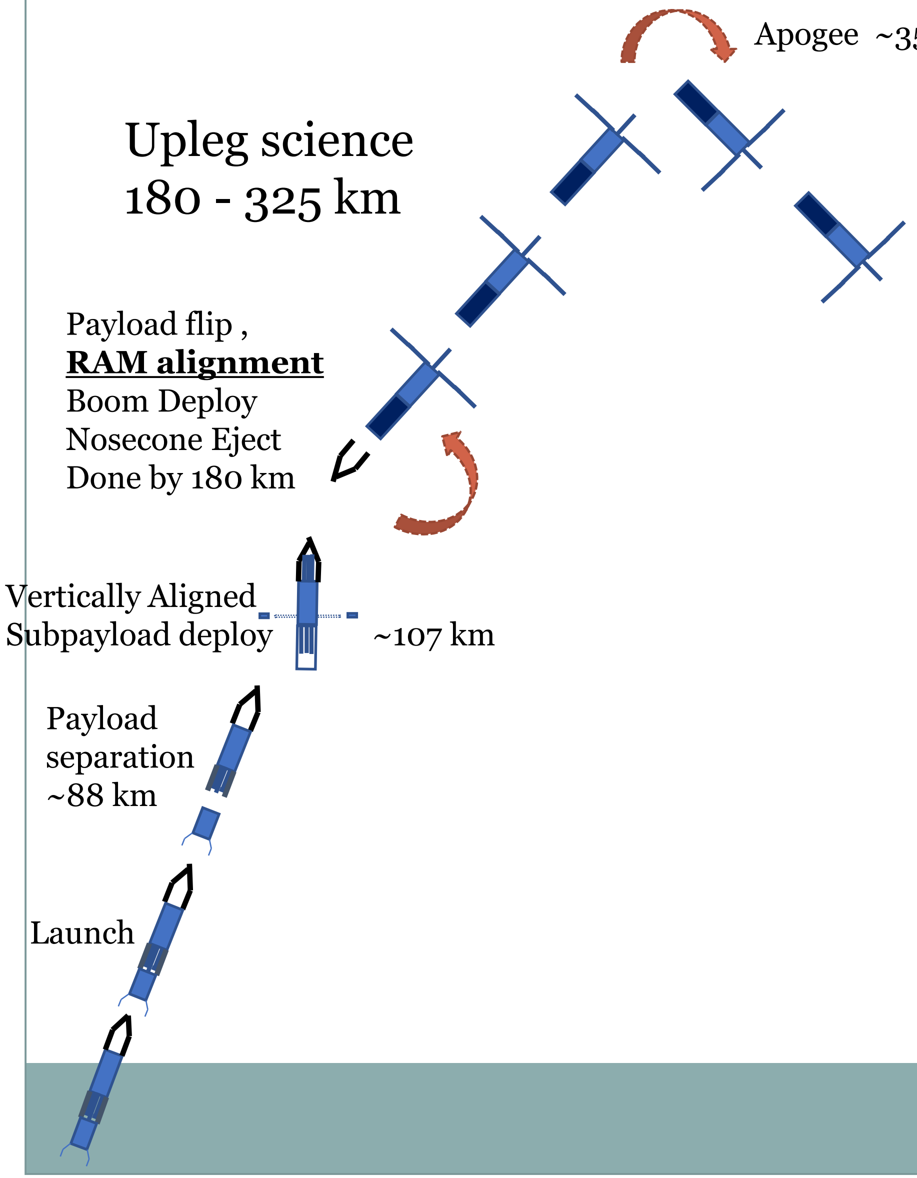

Millstone-Hill digisonde shows increased perturbations superimposed on large scale changes in the different vertical layers of the ionosphere on eclipse day (red) versus a control day (black). [Goncharenko et al., 2018]

# Science Objectives and Questions

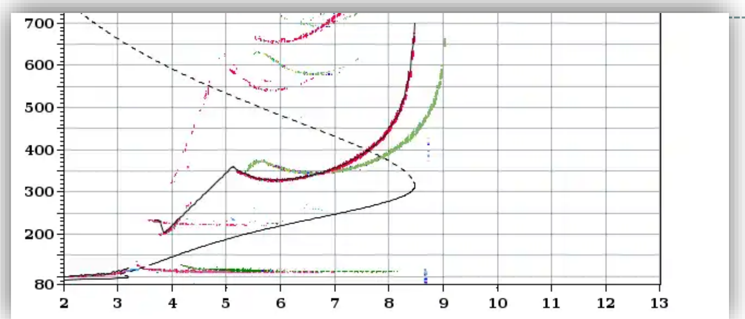
- **First simultaneous multipoint spatio-temporal in-situ observations of electrodynamics and neutral dynamics associated with solar eclipses.**
- Science Questions that can be addressed with these first observations:
  - Does the eclipse shadow directly seed discernible irregularities in the mid-latitude ionosphere? What are the associated vertical length and time scales of these irregularities?
  - What are the impacts of density, temperature, and conductivity gradients in seeding small scale (10s of meters to kilometers) ionospheric irregularities in the presence of solar eclipse?
  - How do the various regions of the ionosphere behave differently at small scales in response to the overall cooling effect of the thermosphere?
- Methodology: Three instrumented rockets; first ~35 minutes before peak eclipse, second at peak eclipse, third ~35 minutes after peak eclipse. The experiment will be supported by ground-based observations from AFRL Digisondes near Socorro for WSMR launch and by VIPIR Dynasonde and Millstone ISR for WFF launch. Furthermore, AFRL is developing a meteor radar from WSMR for neutral winds, and a similar measurement will be made by Haystack Observatory for 2024. Observations will be used to constrain comprehensive modeling during data analysis.

# Concept of Operations

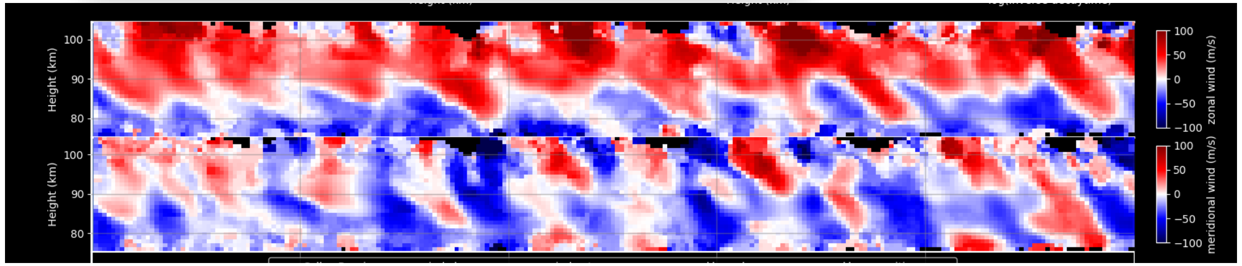
<u>Payload flip at Apogee</u>
RAM realign Target 90 km
Downleg science <u>start at 325 km to 70 km</u>



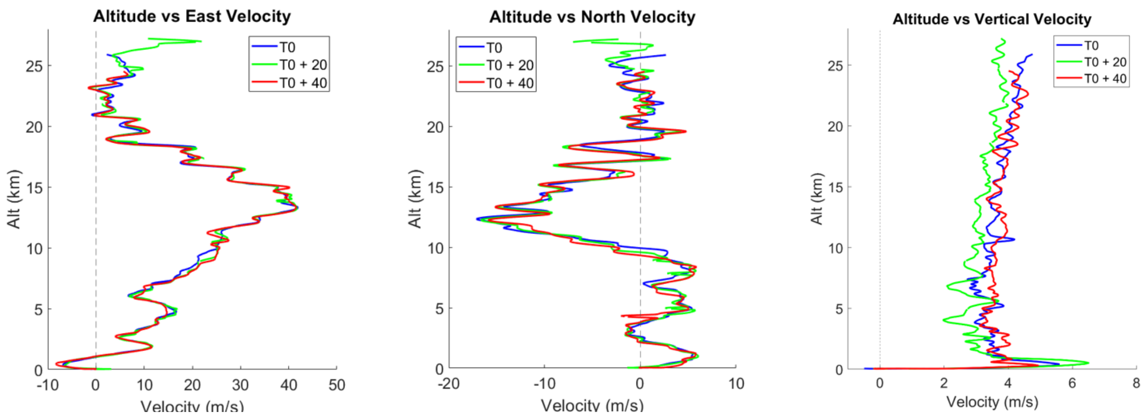

90+ km
Digisonde



75-115 km
meteor
radar winds




0 – 30 KM
Low Cost
Balloon
winds,
temperature
and
pressure




Plus GPS TEC, Opportunistic satellites, HAM radio operators.



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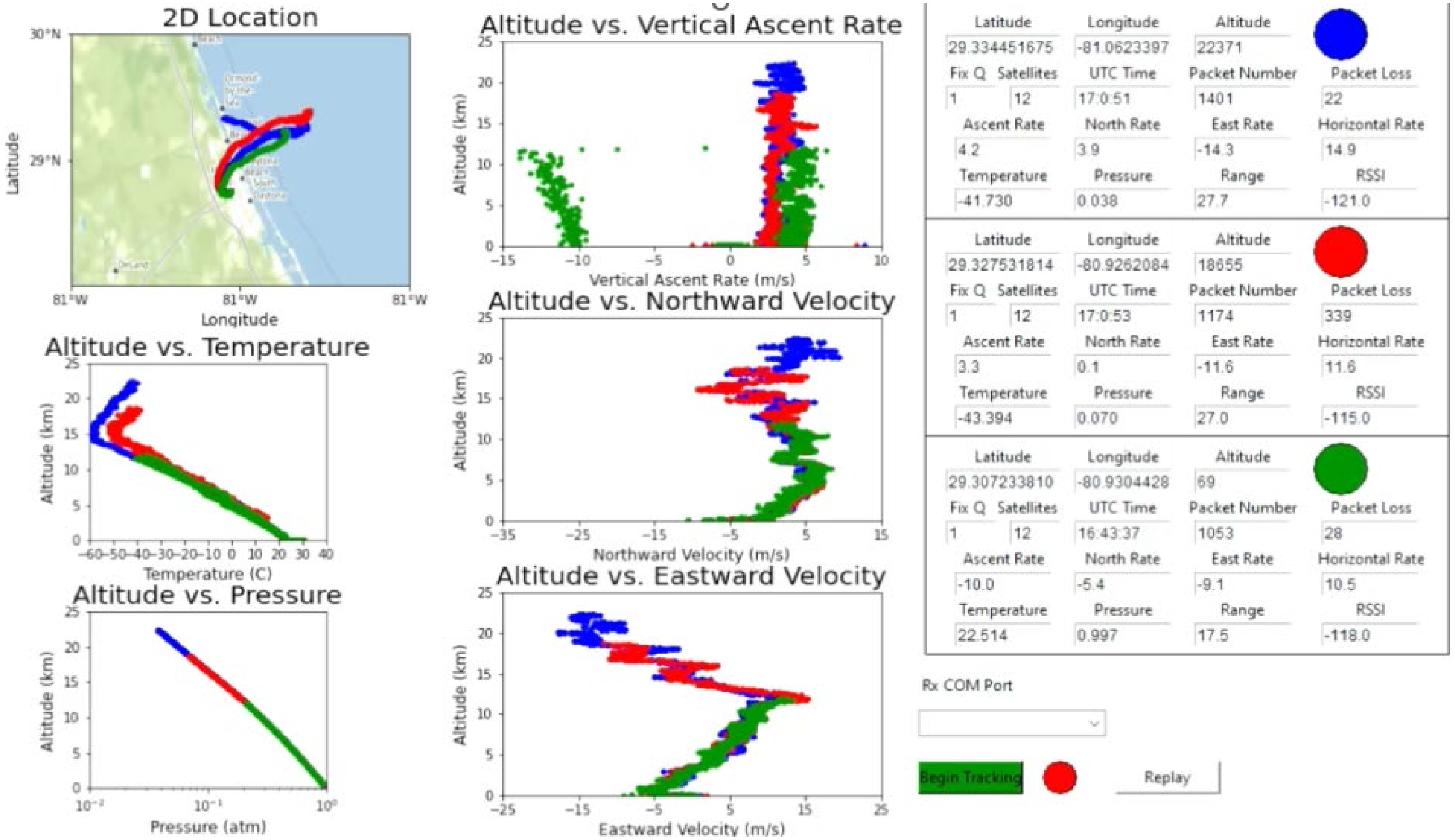
# ERAU Low Cost GPSsondes

- Single man launch; simultaneous multi-point tracking of upto 6 balloons with a single ground station.
- Gives vertical, zonal and meridional velocity, along with pressure and temperature.



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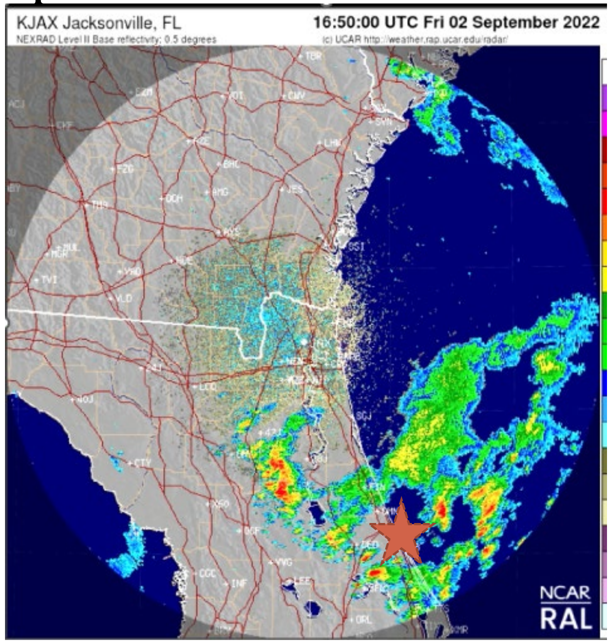
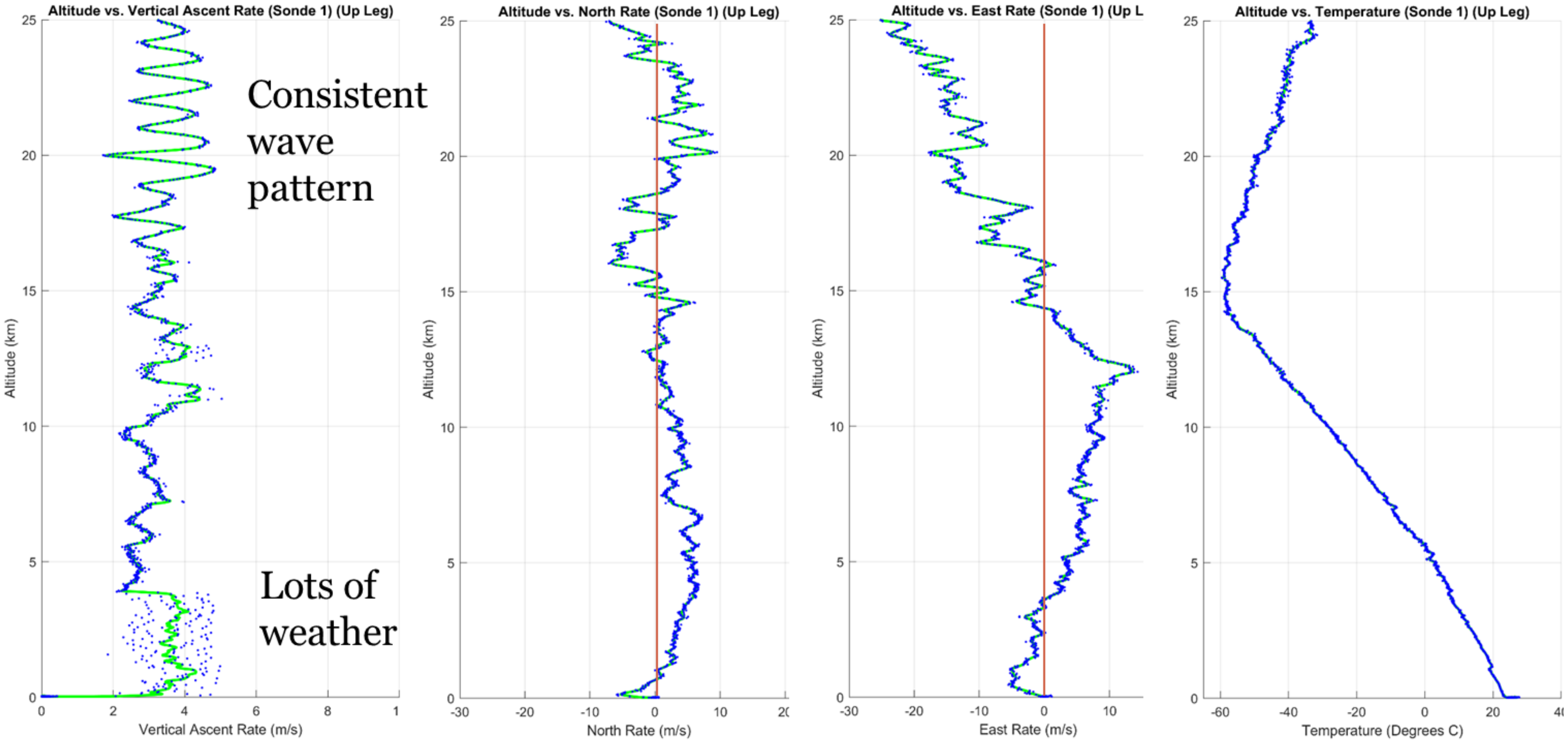
# ERAU Low Cost GPSsondes… contd

- Capable of seeing gravity waves from various atmospheric phenomenon

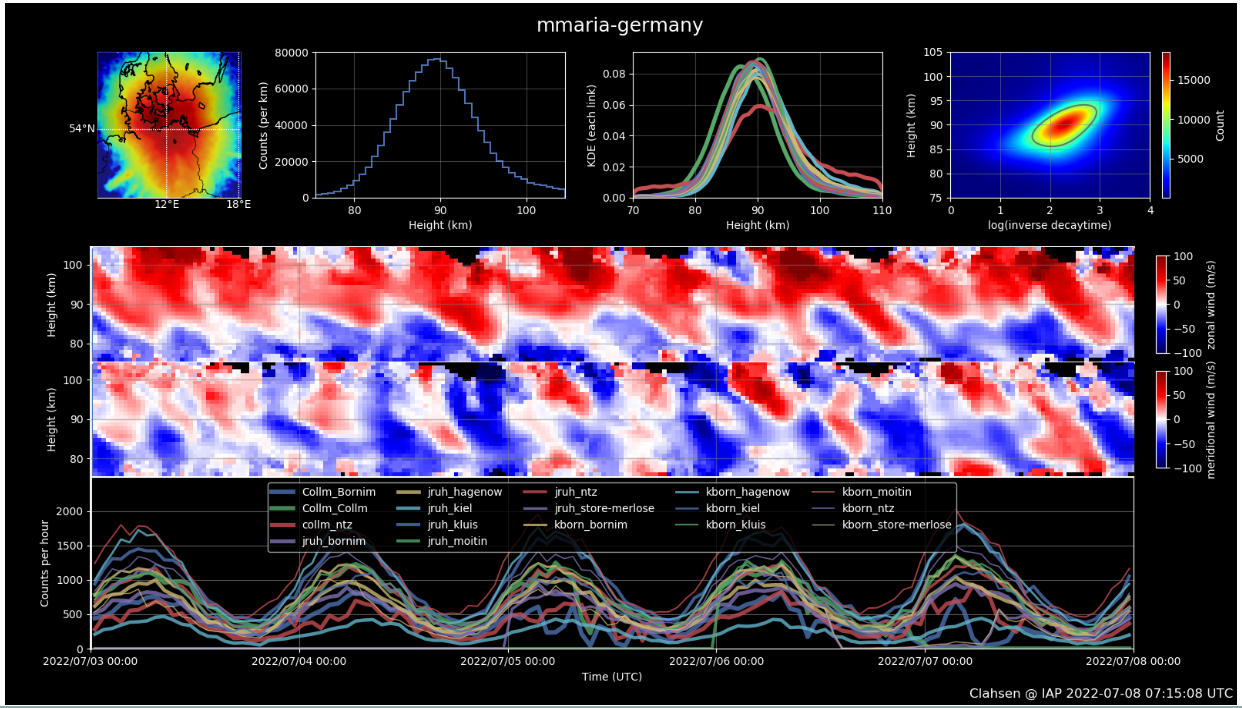



- Launch location

# SIMONe Meteor Radar, in New Mexico

- Spread Spectrum Interferometric Multistatic meteor radar Observing Network (SIMONe) capable of measuring <u>horizontal winds between 75 and 110 km Altitude</u>.
- AFRL - IAP Collaboration to build a meteor radar in New Mexico.





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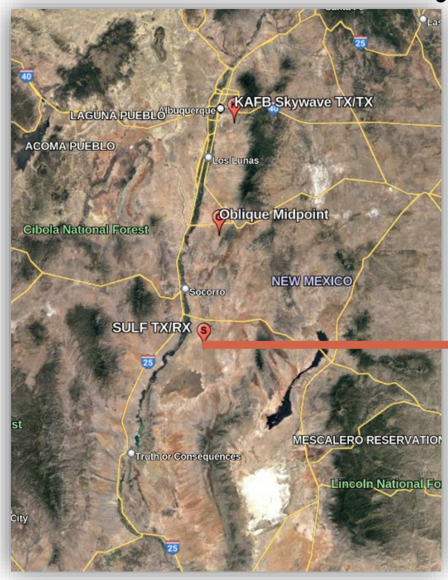
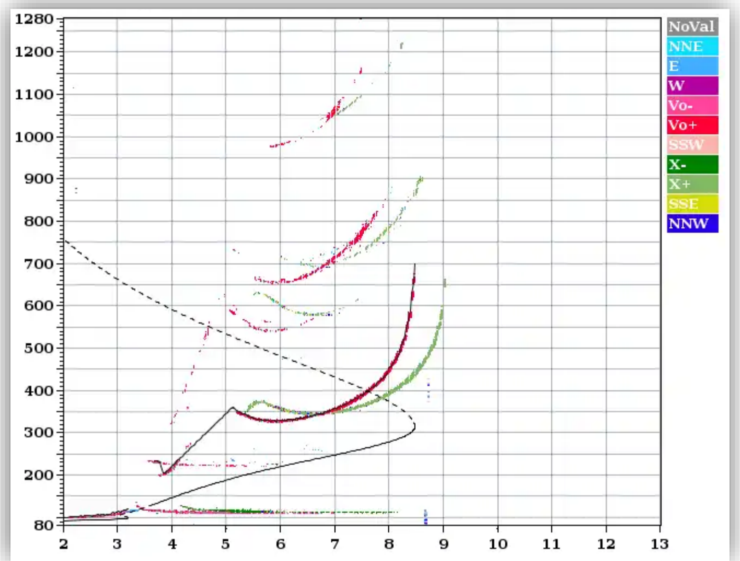
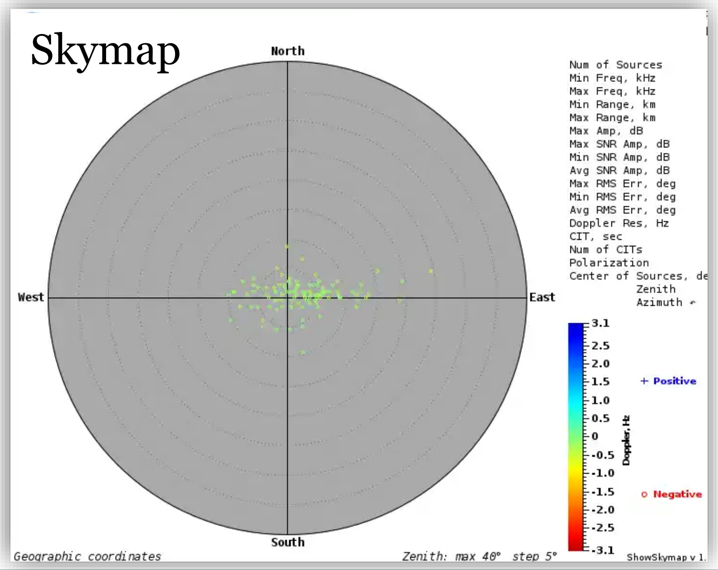
# AFRL Digisonde Support

- AFRL/RVBXC has multiple Digisonde DPS-4Ds that will be operated for Apophis.
- Ionograms can be generated in as little as ~2 minutes for high cadence sampling of the ionospheric E, F1 and F2 layers, including in Oblique mode allowing midway sampling
- Skymaps from the Digisondes can reveal ionospheric layer inclination and the presence of Travelling Ionospheric Disturbances (TIDs), typically on the F-region bottomside
- AFRL has already obtained frequency authorization for both Digisondes







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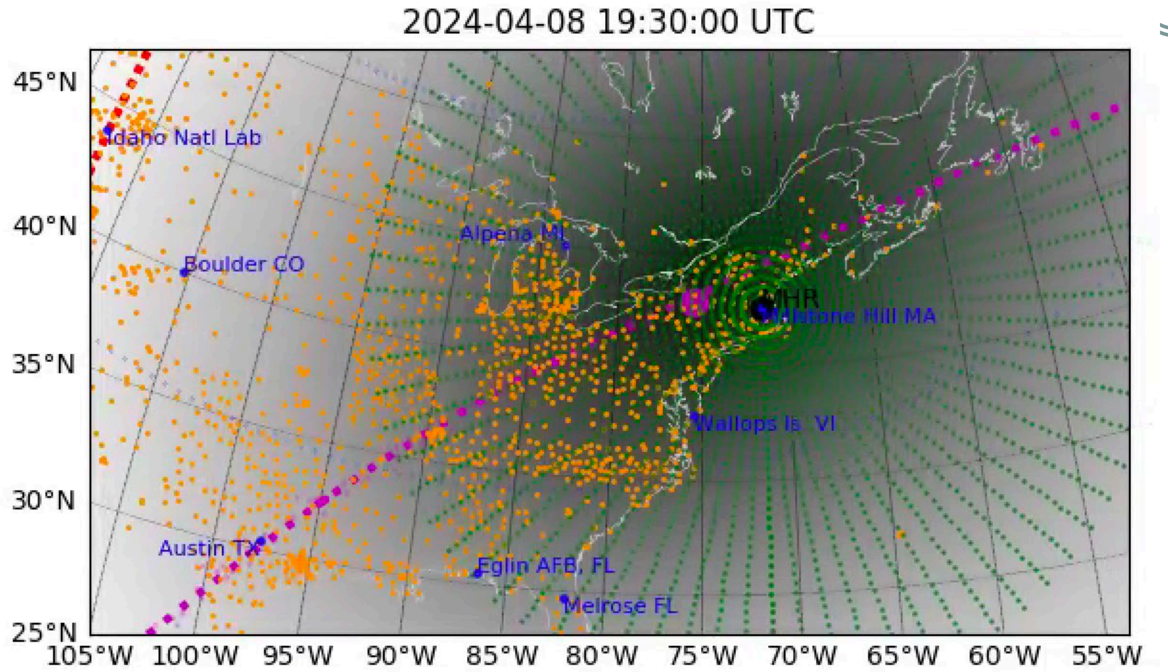
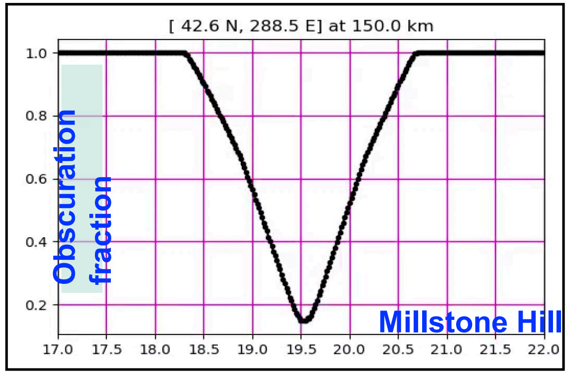
# MIT Haystack Support

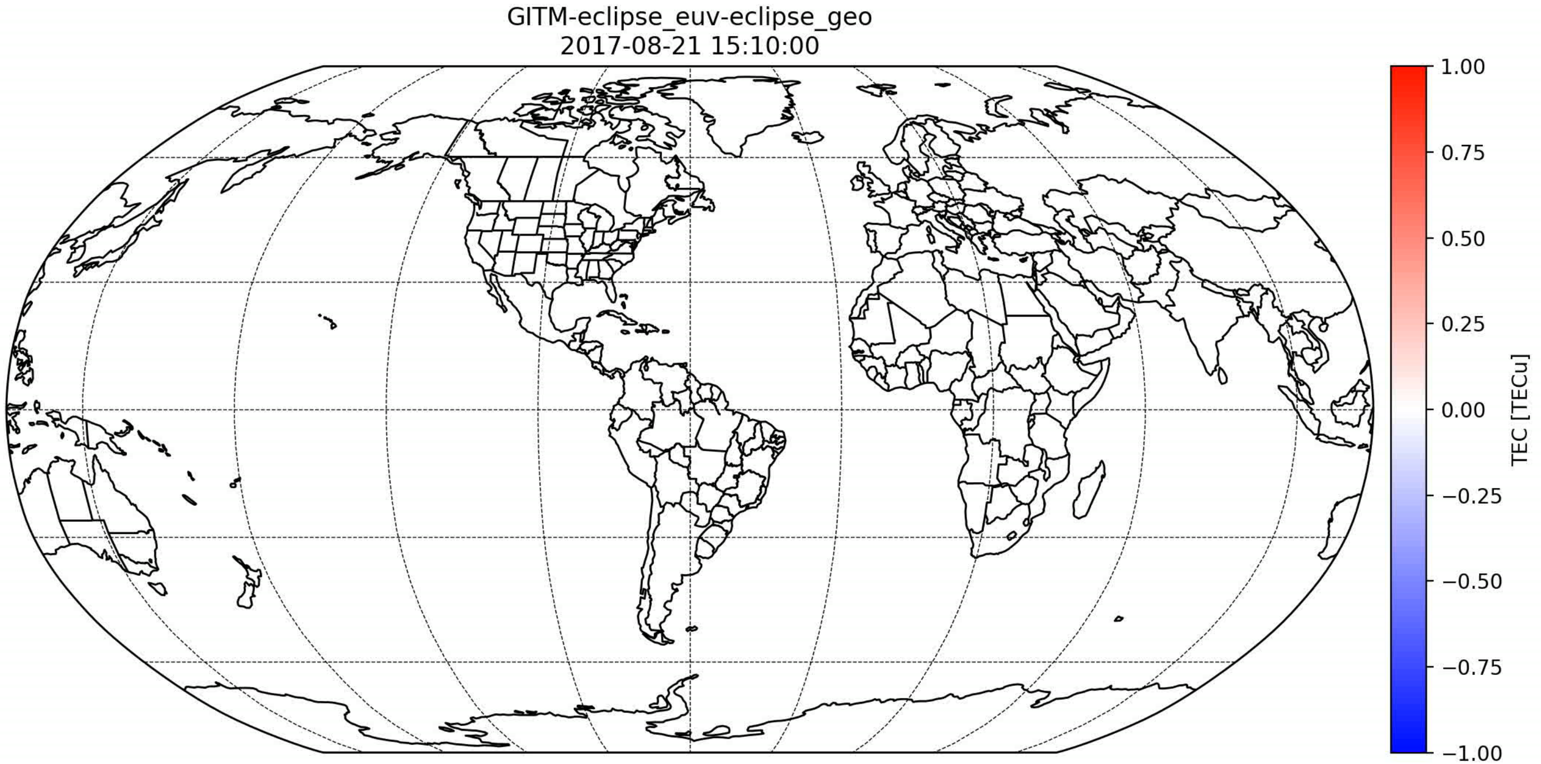


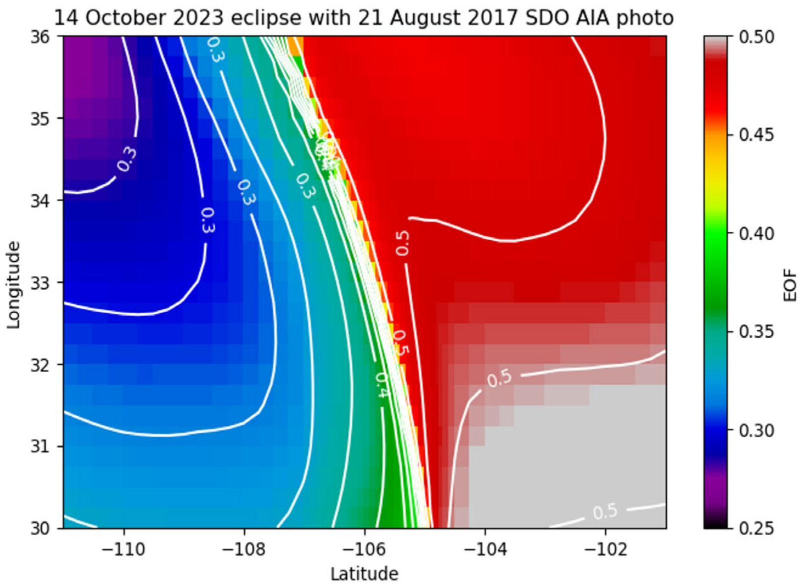




- Mid-latitude ionosphere during Apophis eclipse **rockets from Wallops** [Barjatya / Embry-Riddle]
- Multi-instrument observations: extensive regional data —> **TIDAS** assimilative 3D product

- **MHR** local and regional coverage above 100 km during a long-duration run around the 2024 eclipse
  - **Zenith antenna**: vertical profiles - for vertical coupling studies with joint Zephyr meteor radar mesosphere winds
  - **MISA scans**: regional ionosphere - common volume ionospheric data with EMVSIS network of bottom side ionosondes
- Zephyr meteor wind radar
- EM Vector Sensor Ionosondes
- GNSS receivers
- Digisonde (UML)
- FPI (B Kerr)
- ASI (BU)
- Magnetometer (CPI)

# Coupling the EUV eclipse mask to a physics-based model



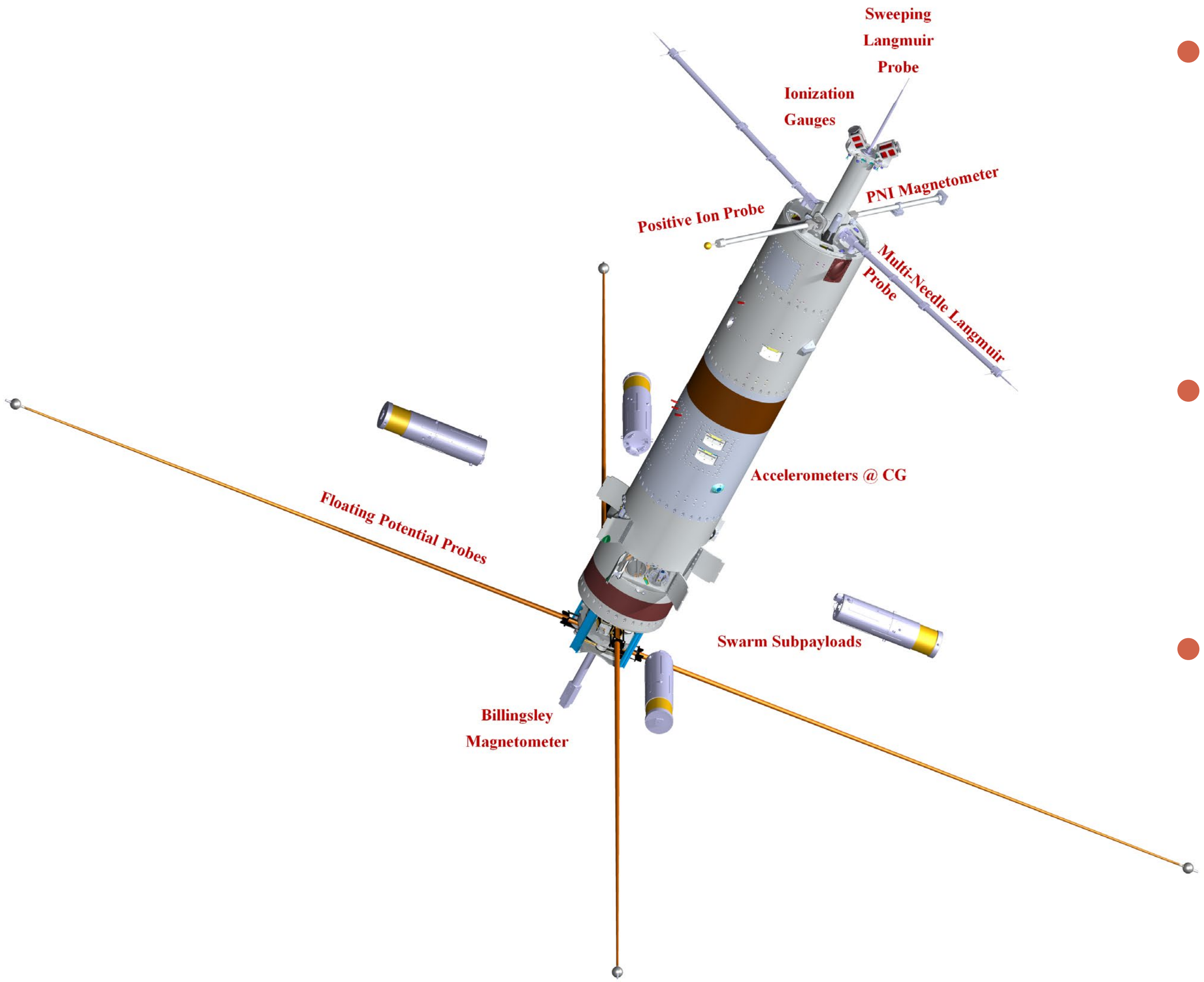




- Video shows GITM global simulation of the TEC perturbations during the 2017 eclipse if an EUV eclipse mask is used. The large scale model perturbations are replicated by observations.
- The global based model GITM will be used to constrain the regional GEMINI simulations for the Apophis campaign

# Traceability Matrix

| Science Questions | Measurement Requirement | Expected Instrument Performance | Mission Functional Req |
|---|---|---|---|
| **(Q1) Does the eclipse shadow directly seed discernible irregularities in the mid-latitude ionosphere? What are their length and time scales?** | Magnetic Fields<br>≤ 1 nT sensitivity<br>≤ 100 m spatial resolution | Magnetometer<br>< 0.1 nT sensitivity<br>≤ 1 m resolution | Three rockets launched in various phases of the eclipse. One before max obscuration, one at peak obscuration and one much later. |
| **(Q2) What are the impacts of density, temperature, and conductivity gradients in seeding small scale (10s of meters to kilometers) ionospheric irregularities in the presence of solar eclipse?** | In-situ Plasma Density<br>1 m spatial resolution<br>1000 – 2x$10^6$ /$cm^3$ range<br>100 /$cm^3$ resolution<br><br>Electron/Ion Temperature<br>300 – 3000K<br>100 K resolution<br><br>E-fields<br>≤ 0.1 mV/m resolution<br>≥ DC to 50 Hz bandwidth | Langmuir Probe Suite<br>≤ 0.2 m resolution<br>1000 – $10^7$ /$cm^3$ range<br>50 /$cm^3$ resolution<br><br>Electron/Ion Temperature<br>300 – 3000K<br>100 K resolution<br><br>Electric Field Probes<br>≤ 0.1 mV/m resolution<br>≥ DC to 500 Hz bandwidth | Each instrumented rocket ejects upto four instrumented subpayloads to measure simultaneous plasma density variations |
| **(Q3) How do the different layers of the ionosphere behave differently in response to the overall cooling effect of the thermosphere?** | Neutral density<br>5 m resolution<br>$10^8$– $10^{12}$ /$cm^3$ range | Ionization gauge<br>Measurements down to 1e-7 torr with a <20% sensitivity in pressure variation | Recovery of instrumented payload in WSMR for relaunch at Wallops |

# SpEED Demon




- SpEED Demon was launched in Aug 2022 from Wallops Flight Facility into a Sporadic E layer as observed by the VIPIR radar.
- It was the first simultaneous multi-point in-situ observation of Sporadic-E layers.
- Observations were:
  - Plasma density
  - Neutral Density
  - Magnetic fields for field aligned currents

# Posters Today

ITMA-5

**In-Situ Rocket Investigation of a Mid-Latitude Sporadic-E Layer**

Conway, Rachel, Embry-Riddle Aeronautical University

ITMA-6

**Simultaneous Multi-Point Ion Density Measurements from a Sounding Rocket Platform**

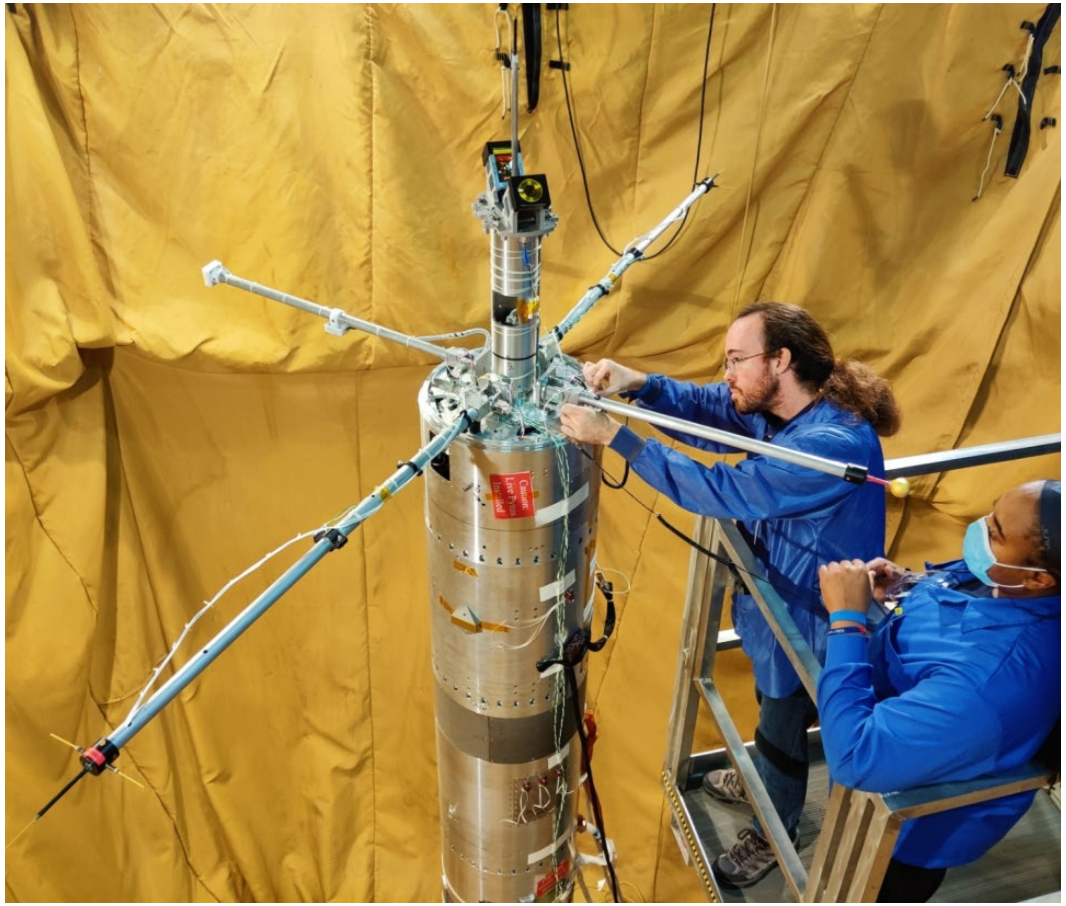
Valentin, Henry, Embry-Riddle Aeronautical University

ITMA-8

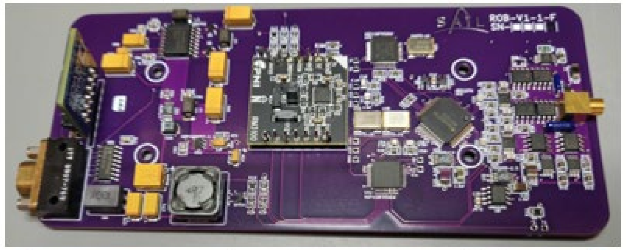
**Mesosphere-Lower-Thermosphere Neutral Density Measurements from Low-cost COTS Accelerometers and Ionization Gauge**

Graves, Nathan, Embry-Riddle Aeronautical University

# SpEED Demon

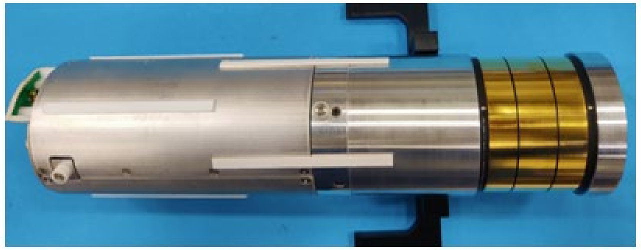


**Subpayload Electronics**



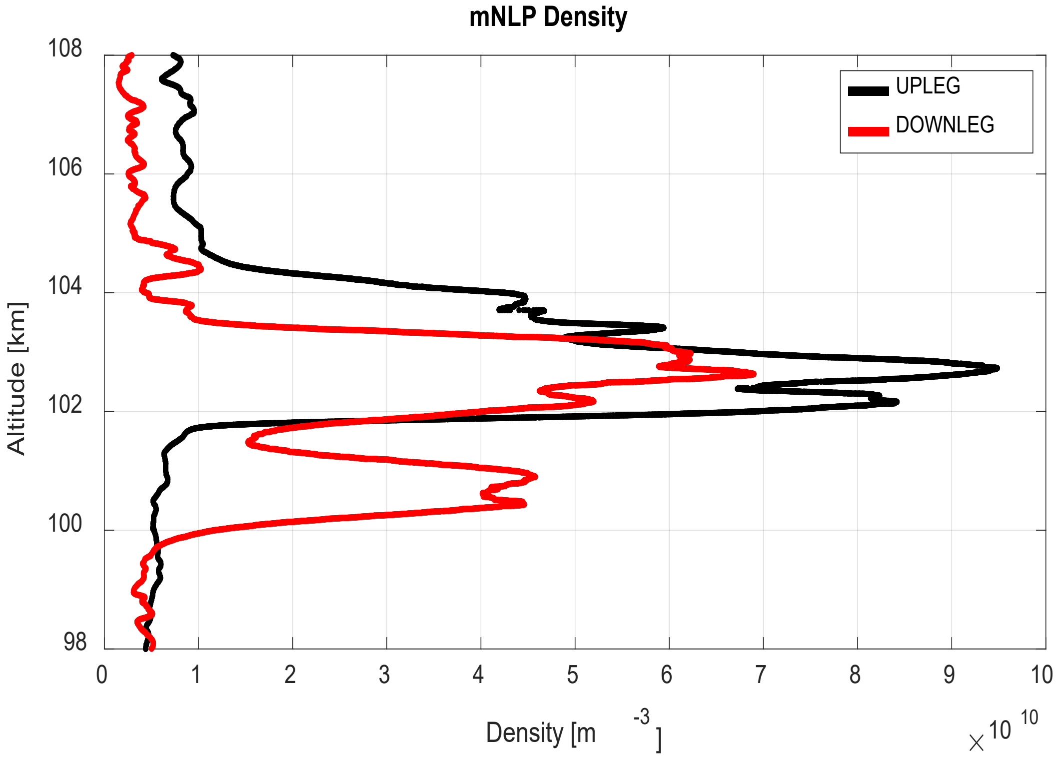
14.5 cm length , 6.5 cm width

**Subpayload Shell**



33.5 cm length, 8.8 cm diameter

# SpEED Demon – Plasma Density




- Payload intersected Es layer both on the upleg and the downleg.
- Spatial separation was ~18 km between upleg and downleg intersection of Es layer.
- Temporal separation was 3 minutes between upleg and downleg intersection of Es layer.
- This was a small rocket with an apogee of 160 km and flight time of 6 minutes.

# SpEED Demon – Multipoint Plasma Density

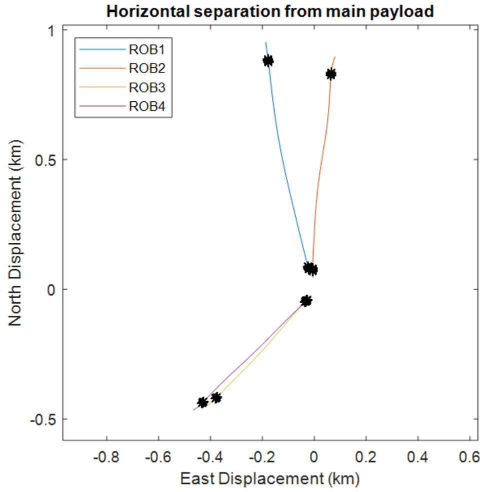
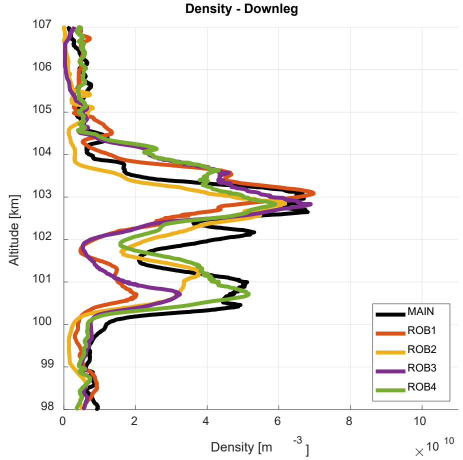
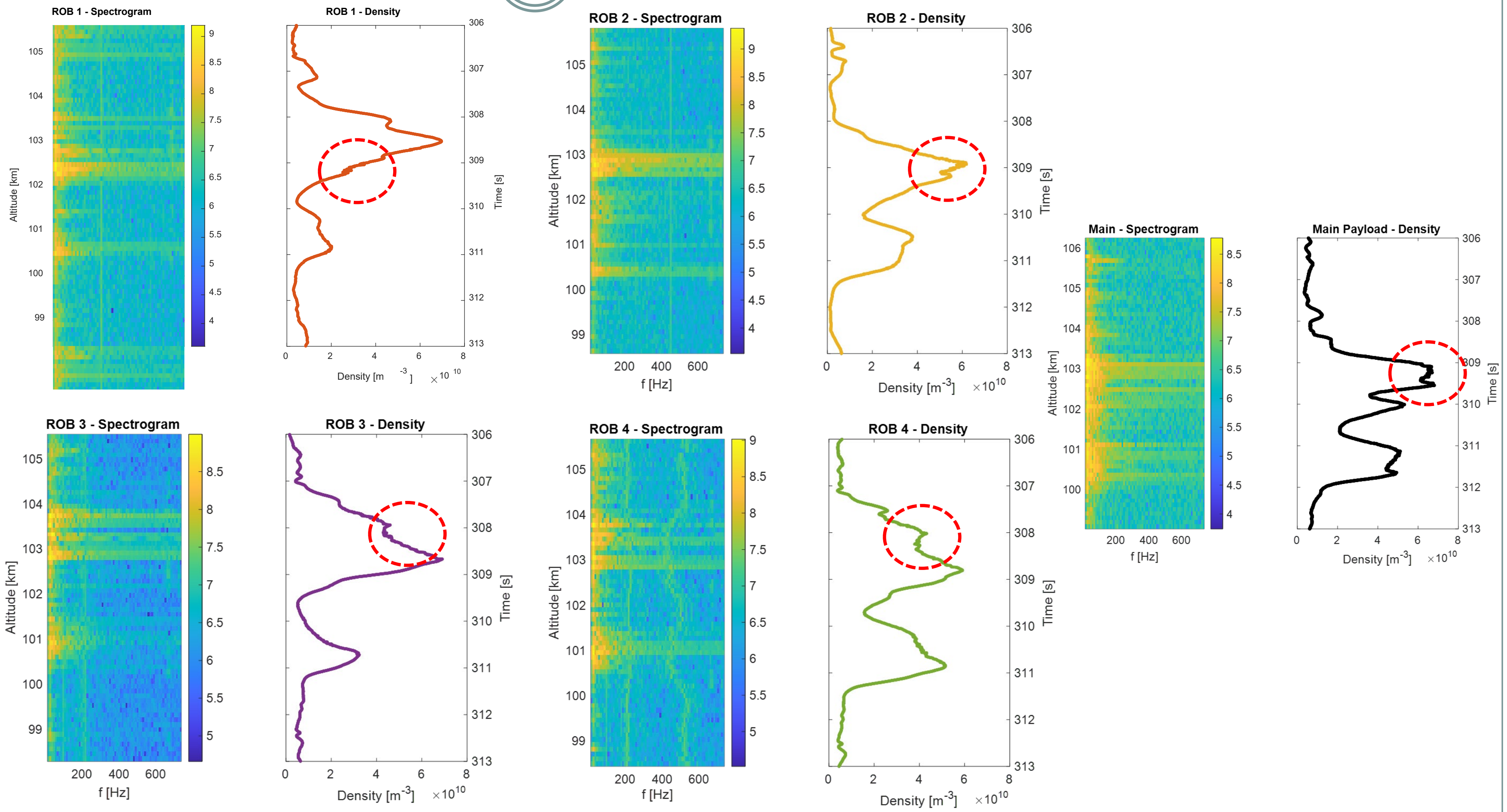
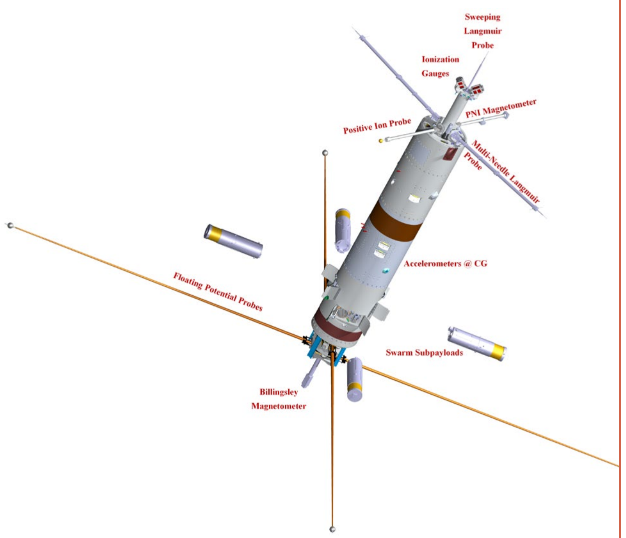


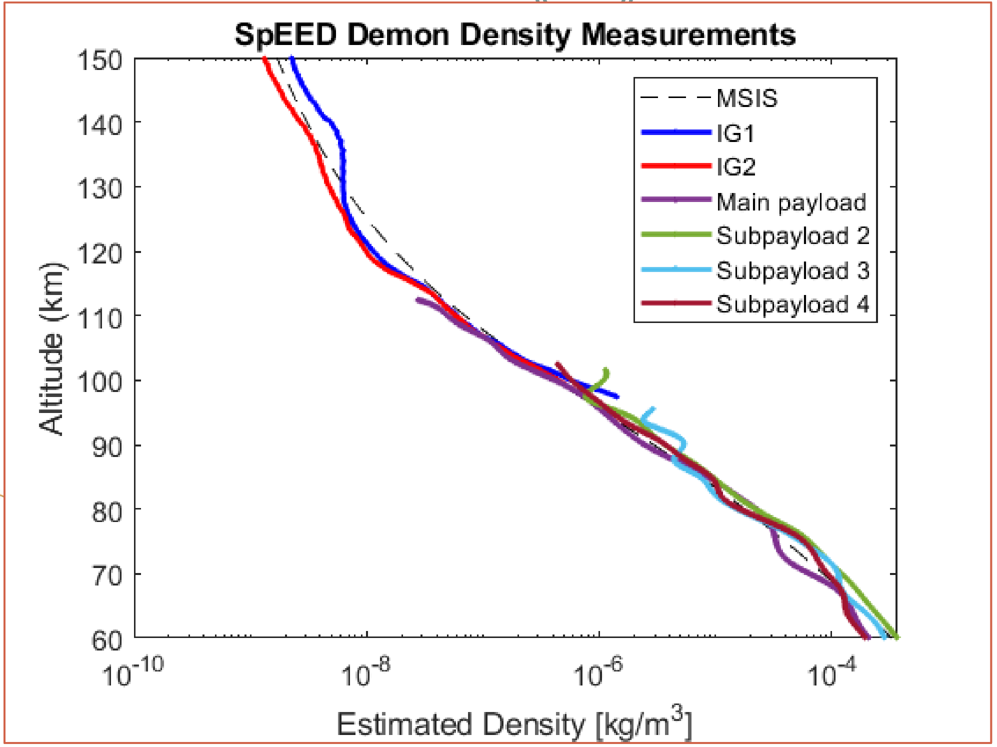

**Figure 11: Horizontal displacement of the ROB subpayloads from main payload. Black marks indicate the Es layer intersections.**

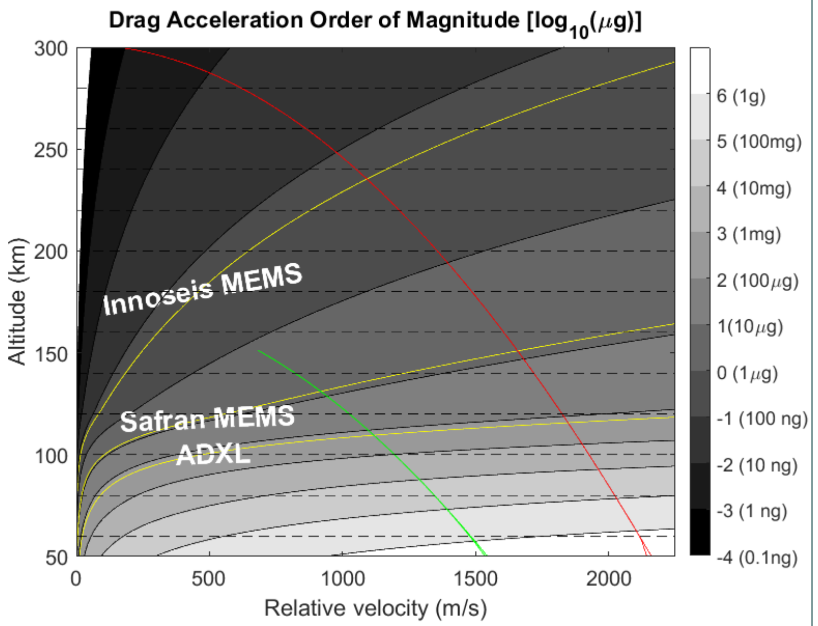


# SpEED Demon – Neutral Density




- Ionization gauges see neutral density fluctuations upto ~150 km.
- The accelerometer-based drag measurements see neutral density fluctuations from 100 km lower down into the stratosphere.
- Work is continuing to (a) attitude solutions (b) derive winds (c) push into high altitudes



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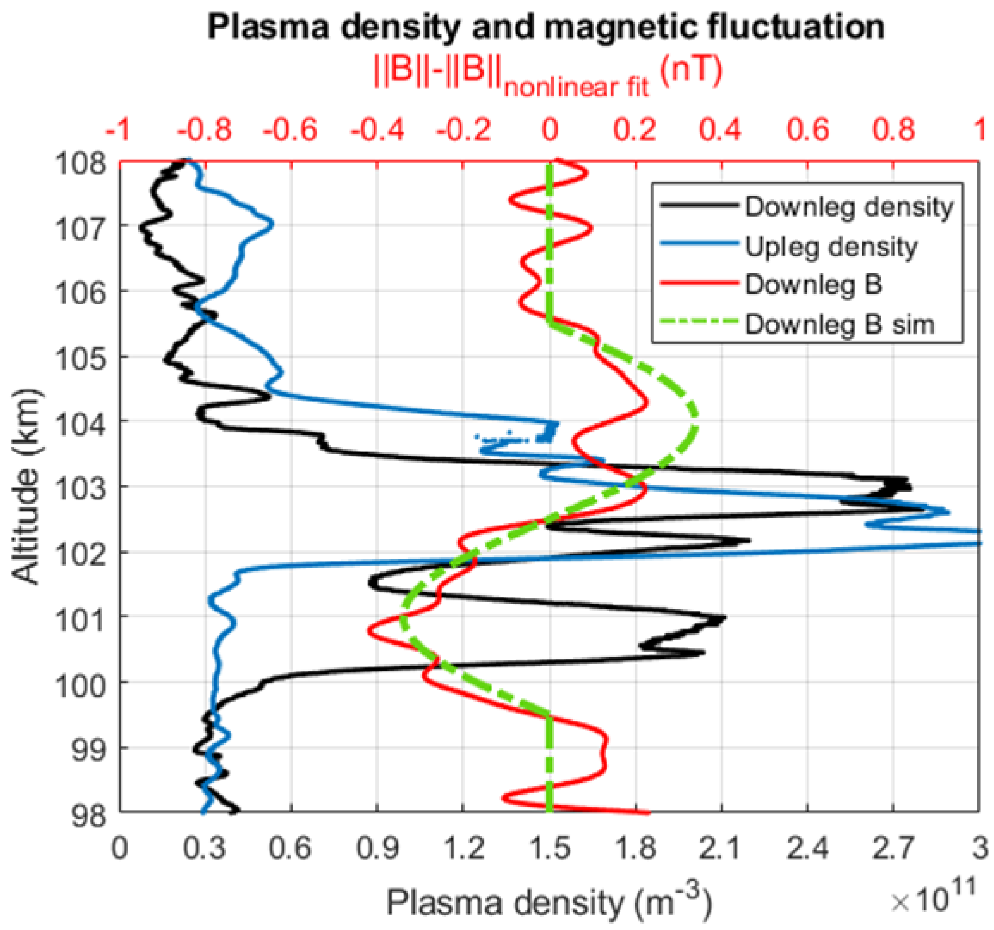
# SpEED Demon – Magnetic Field Measurements




- Main payload magnetometer measurements during Sporadic-E layer crossing on the downleg portion of the trajectory.
- The measured magnetic field fluctuation (red line) coincides with the Es layer (black and blue lines) and is equivalent to simulated field generated by a ~0.1 uA/m2 current density Field Aligned Current.



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