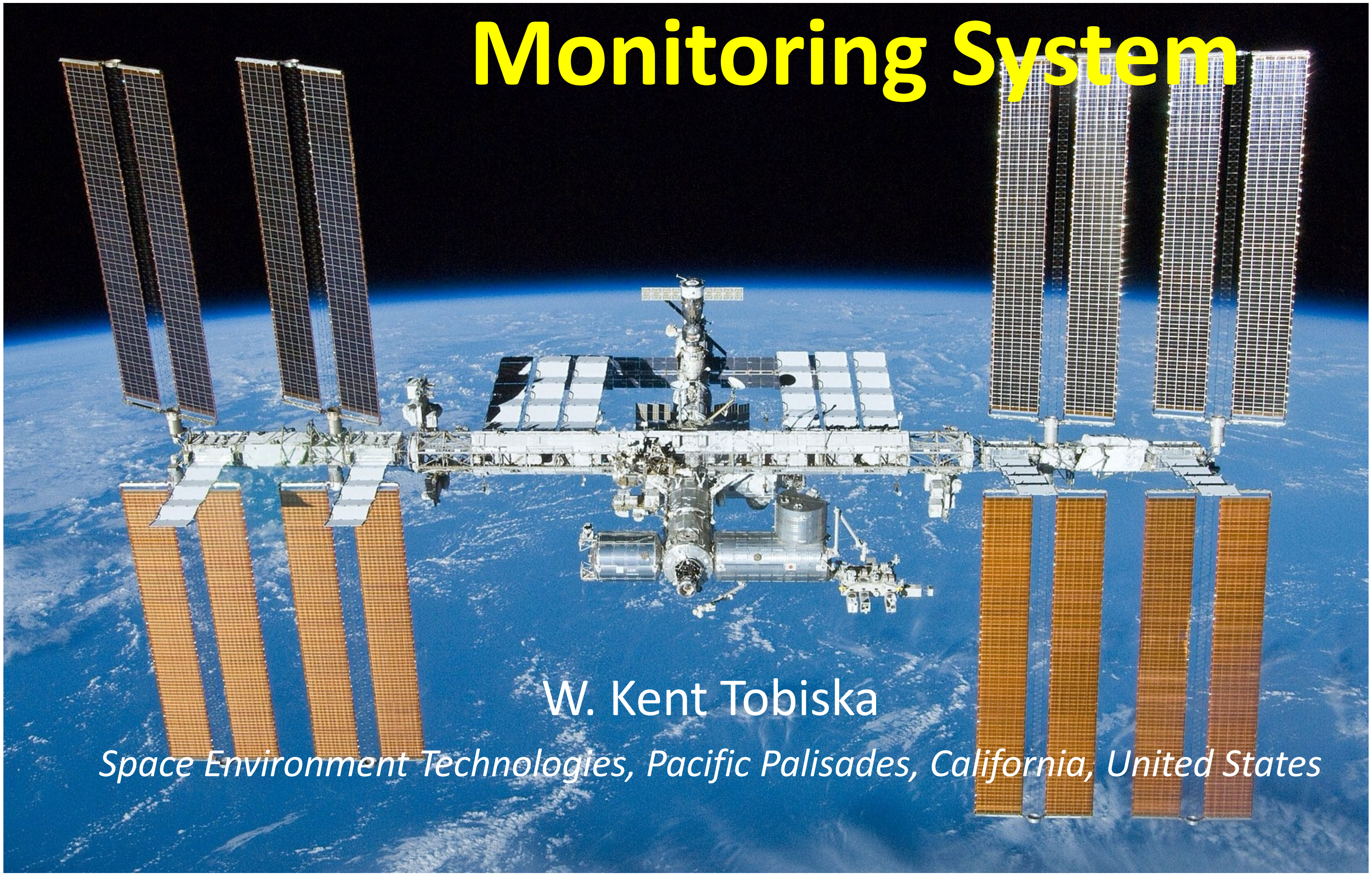
ARMAS Radiation Monitoring System



W. Kent Tobiska
Space Environment Technologies, Pacific Palisades, California, United States

Where are we today? Progress towards aviation radiation nowcast & forecast

- **DETECTORS**
  - ✓ Geiger counters
  - ✓ Bubble detectors
  - ✓ TEPC
  - ✓ Liulin
  - ✓ RaySure

1950-1990

Step 1: Discovery

- **DETECTORS**
  - ✓ Bubble
  - ✓ TEPC
  - ✓ Liulin
  - ✓ RaySure
  - ✓ ARMAS
- **MODELS**
  - ✓ CARI-6
  - ✓ NAIRAS
  - ✓ PANDOCA

1990-2016

Step 2: Validation

- **DETECTORS**
  - ✓ **ARMAS**
  - ✓ ATED
- **MODELS**
  - ✓ **NAIRAS v1**
  - ✓ **CARI-7**
  - ✓ PANDOCA
  - ✓ KREAM

2017-2022

Step 3: Monitoring

(occasional flights; tech demo regional monitoring; demo data assimilation)

- **DETECTORS**
  - ✓ **ARMAS**
  - ✓ ATED
- **MODELS**
  - ✓ **NAIRAS v3**
  - ✓ **CARI-7**

2022-present

Step 4: Nowcast & forecast

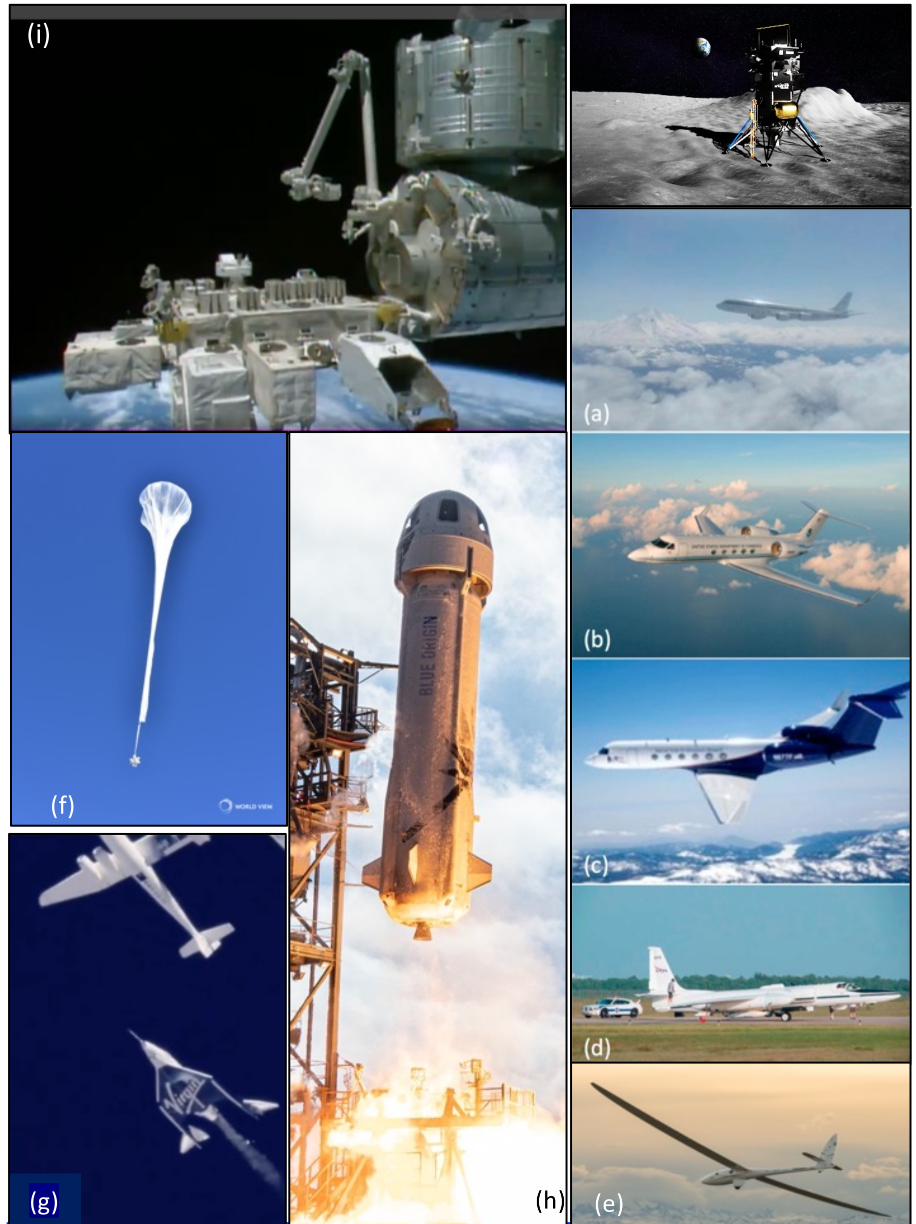
(daily flights for track truth, hi-alt/long endurance regional monitoring, orbital monitoring; operational data assimilation and ensemble modeling)

Fall 2025

1338 ARMAS flights from 0-550 km 2013–2025

- ✓ **Agency and Commercial Aircraft**
  - ✓ **AFRC:** DC-8 (a), ER-2 (d), G-III, SOFIA (B747)
  - ✓ **NOAA**: G-IV (b)
  - ✓ **NSF**: G-V (c)
  - ✓ **FAA**: Bombardier Global 5000
  - ✓ **DoE**: B350
  - ✓ **Commercial**:
    - Boeing 737, 747, 757, 767, 777, and 787
    - Airbus 319 and 320
    - Bombardier Q200
    - CRJ 200, 700 and 900; Embraer 135, 145 and 175
- ✓ **Balloons**
  - ✓ **World View Enterprises:** Stratocraft (f)
  - ✓ **NearSpaceLaunch:** balloons
  - ✓ **World View Enterprises:** Stratollite
- ✓ **NASA space stations**
  - ✓ **ISS JEM EF** (Low Earth Orbit) (i)
  - ○ **Gateway** (Lunar Orbit)
- ✓ **Proprietary vehicles**
  - ✓ **Perlan** Stratospheric glider (e)
  - ✓ **Raytheon** Corporate Jets
  - ✓ **Virgin Galactic** SS2 and WK2 (g)
  - ✓ **Blue Origin** New Shepard (h)
  - ✓ **SpaceX/NSL** Transporter-2/TAGSAT-2
  - ✓ **Intuitive Machines** Mission 2
  - • **SpaceX/NSL** SWAP-E
  - ○ **AXIOM**

✓ Flown
• In progress
○ Potential



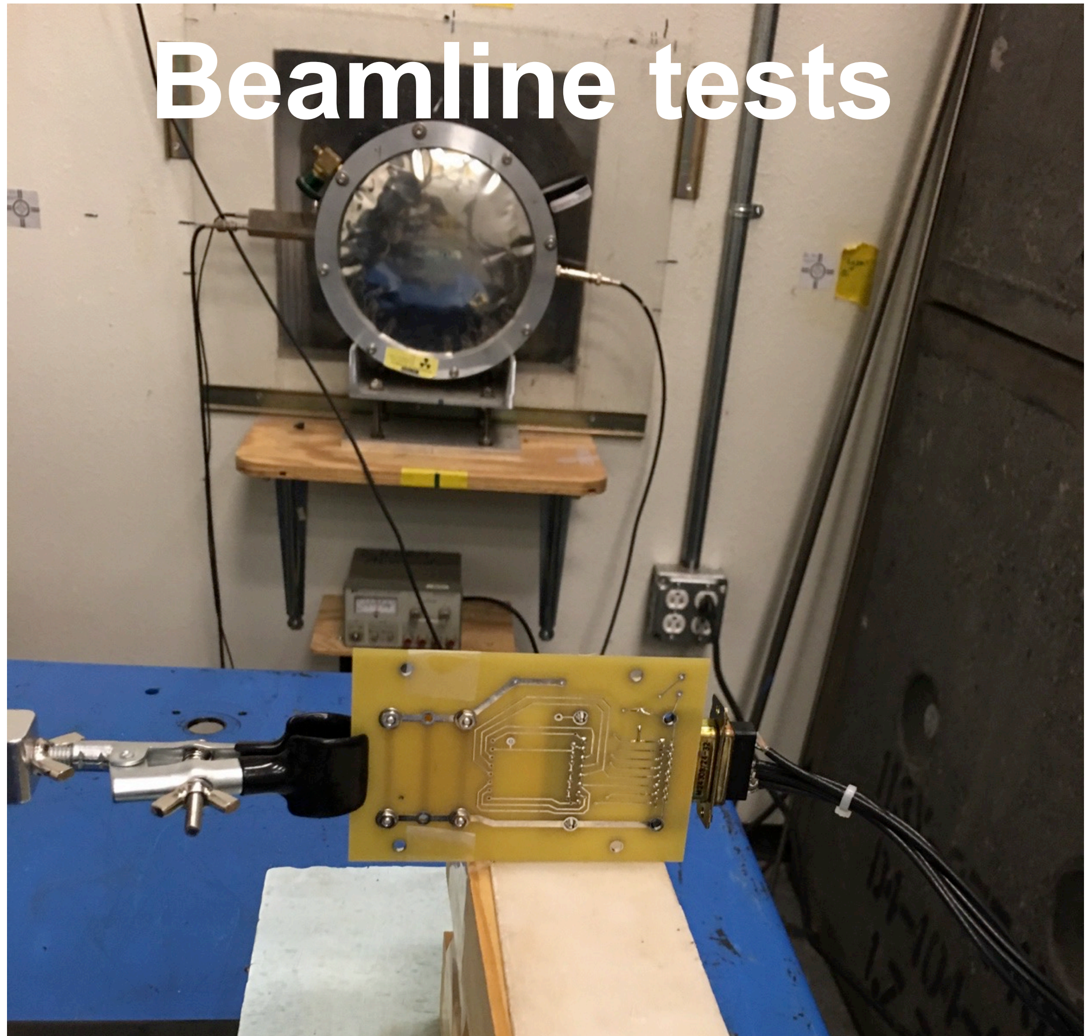
Largest database of aviation radiation data

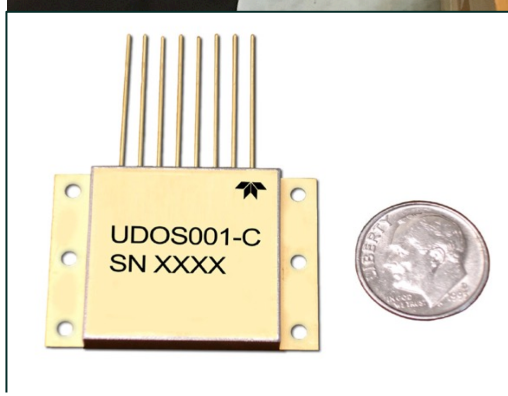
4 million 10-s data records and counting

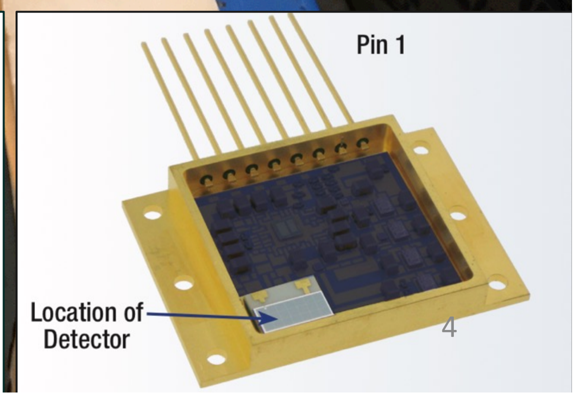
Calibrations & Facilities:

- Los Alamos Neutron Science Center (LANSCE)
  - 1–800 MeV neutrons
- Loma Linda University Medical Center (LLUMC)
  - 200 MeV protons
- Lawrence Livermore National Laboratory (LLNL)
  - MeV electrons
- Brookhaven NASA Space Radiation Laboratory (NSRL)
  - MeV Fe^{+}
- In-flight HAWK/TEPC & ARMAS
  - Absorbed dose rate (Si) at cruise for TEPC was 2.37 μGy/h and for ARMAS was dynamic in latitude with 1.3–2.9 μGy/h

Beamline tests







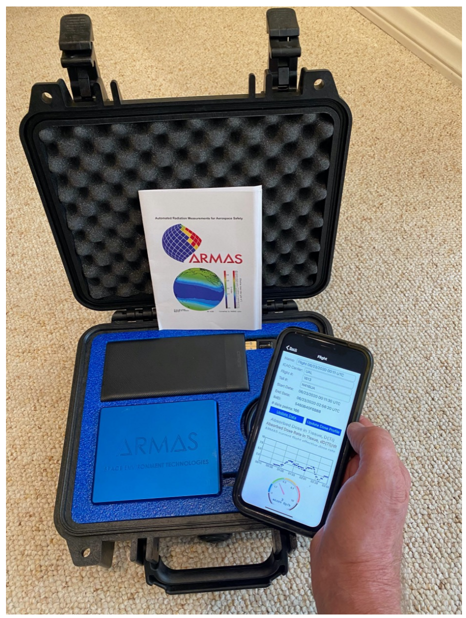
Improved state-of-the-art radiation monitoring:
ARMAS Flight Module 7 (FM7) pairs Bluetooth with iOS devices using the ARMAS app

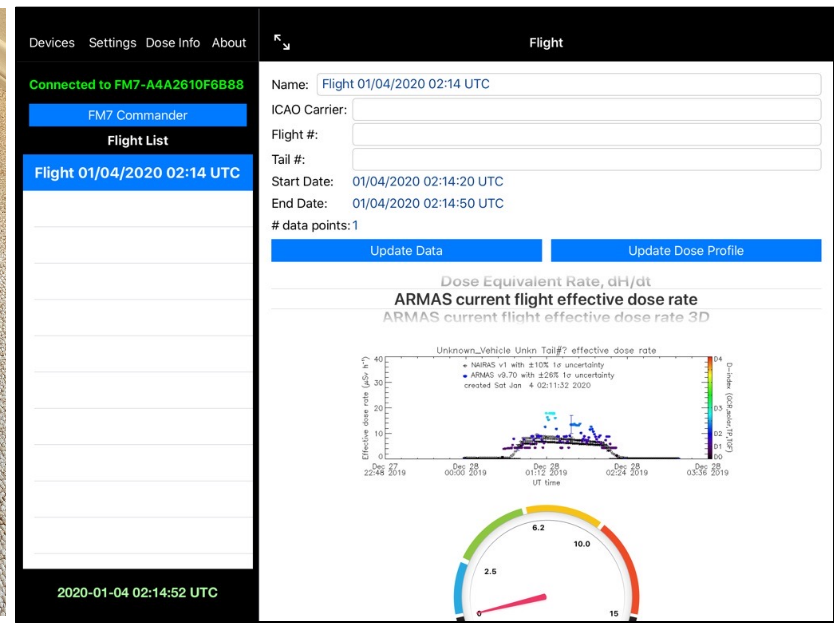
Features:

- ✓ Measures absorbed dose in silicon
- ✓ Small size, mass, and power
- ✓ Data retrieval using Bluetooth to pair with iOS ARMAS app available from Apple Store
    - Current and post-flight dose rate status displayed on app that is paired with FM7
    - Dose rate can be transmitted to ground using WiFi
- ✓ Real-time dose rates: measured absorbed (Si) and derived absorbed (Ti), dose equivalent, ambient dose equivalent, and effective

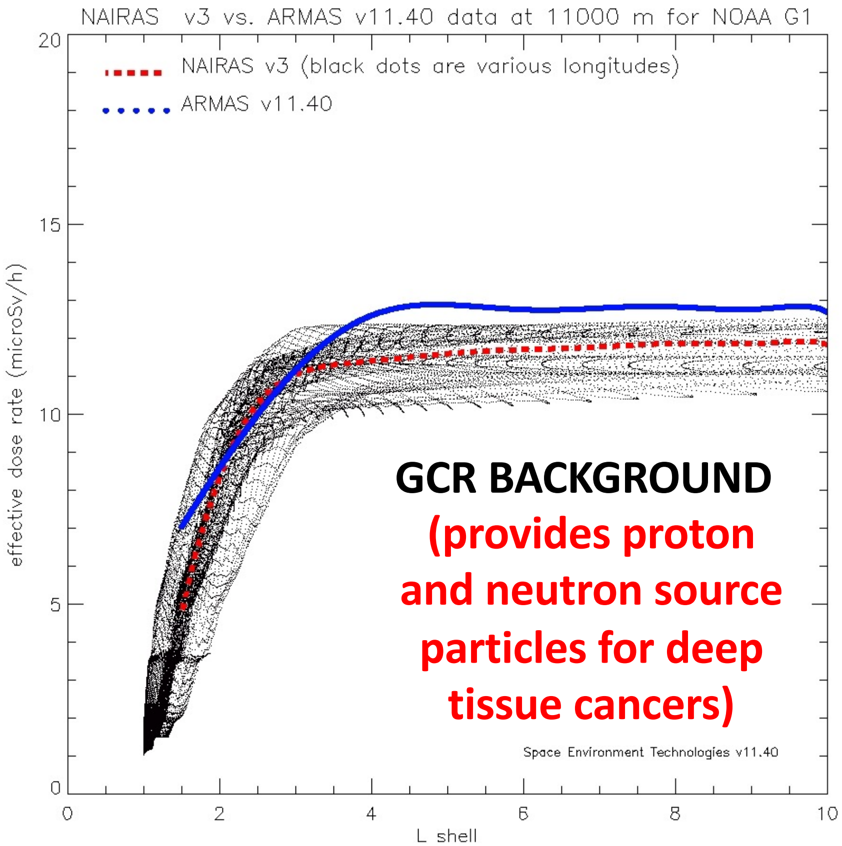
Availability:

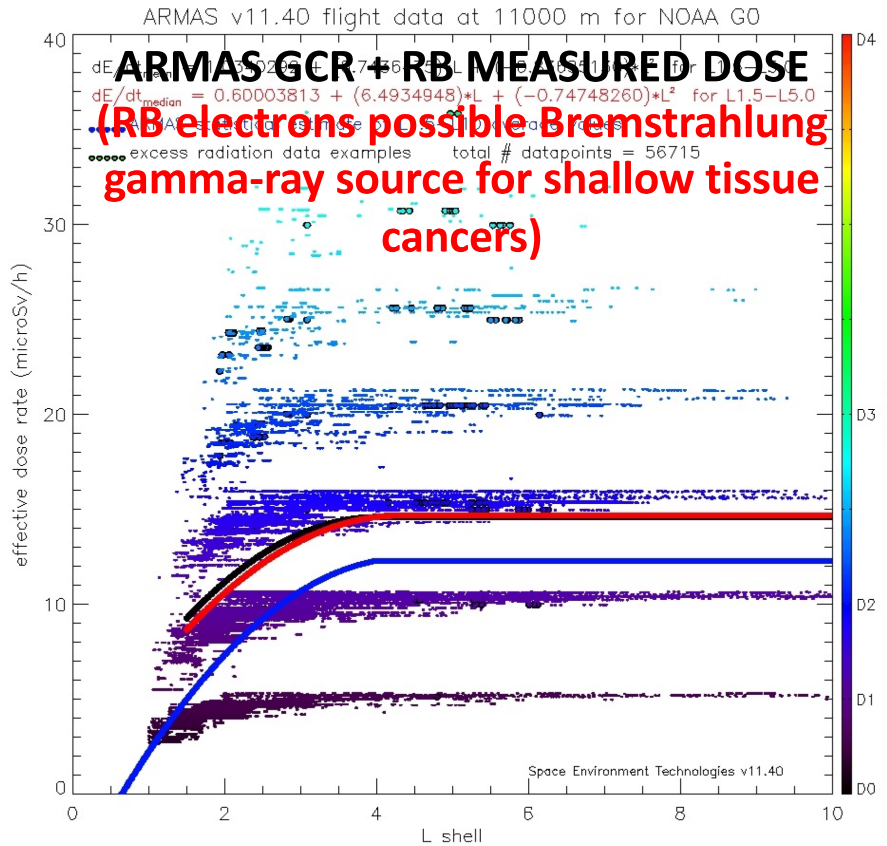
- ✓ 5th production run Oct 2025





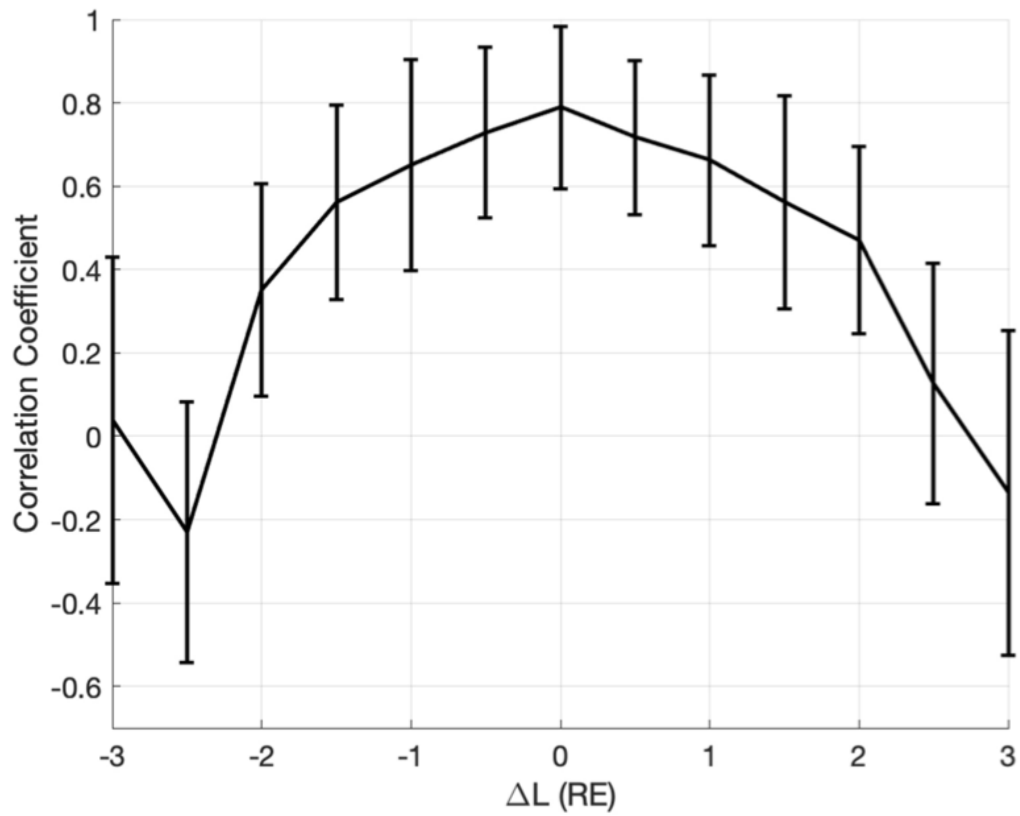
Long term results: Dose rates at 2<L<7 and 11 km during NOAA G0 conditions are more than GCR background





Where does excess dose come from? UCLA Collaboration provides insights into its source

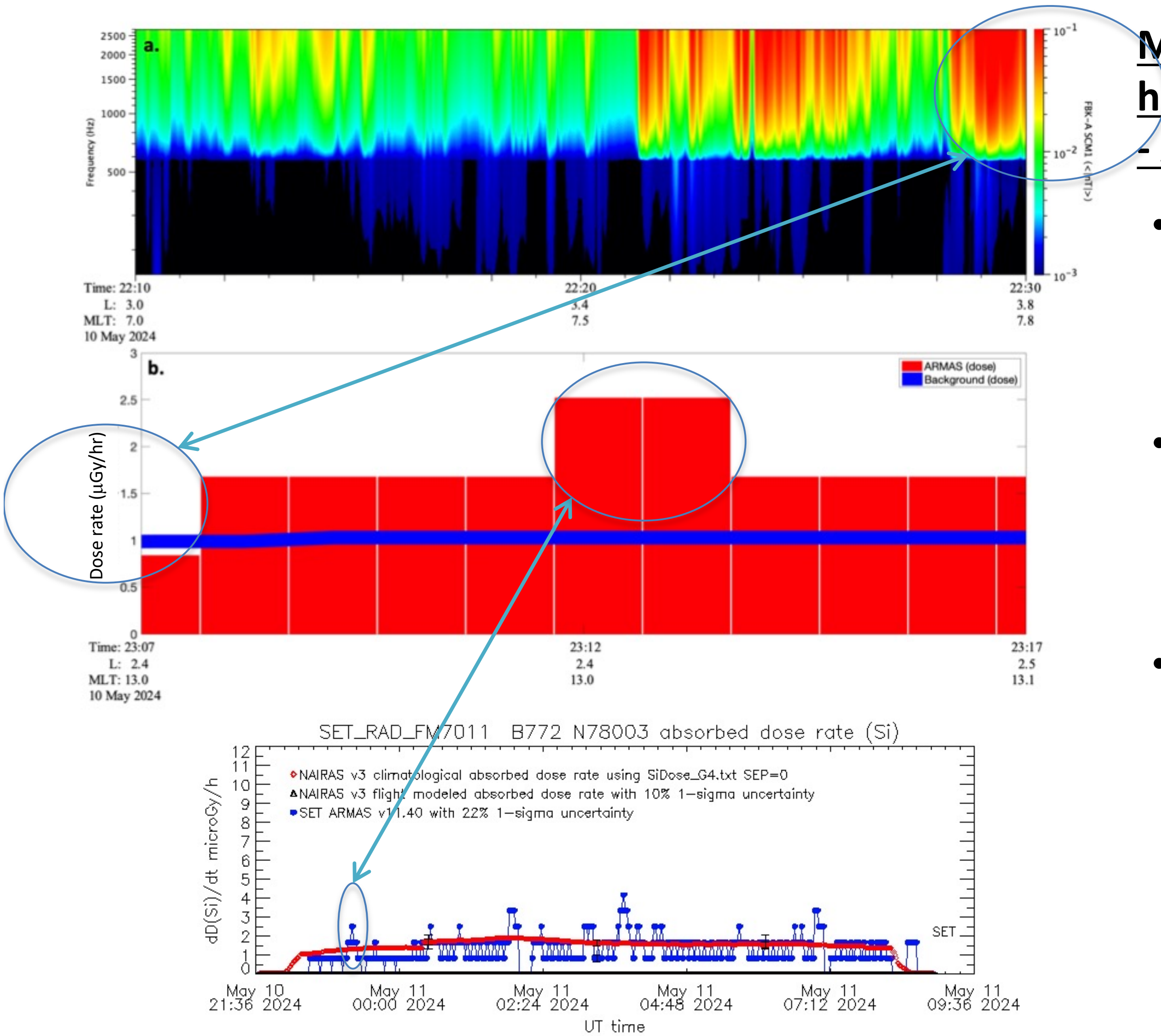
Generalized across the ARMAS dataset



<u>HISS waves measured by VAP correlate highly in location with ARMAS excess dose - Aryan et al., 2023</u>

- The excess ARMAS dose rates above the GCR background and not SEP induced are <u>related to precipitation of radiation belt electrons due to plasmaspheric hiss waves in the inner equatorial magnetosphere</u>.
- ARMAS-VAP conjunctions between were confined to within 1 L (L-shell) and 1 h MLT.

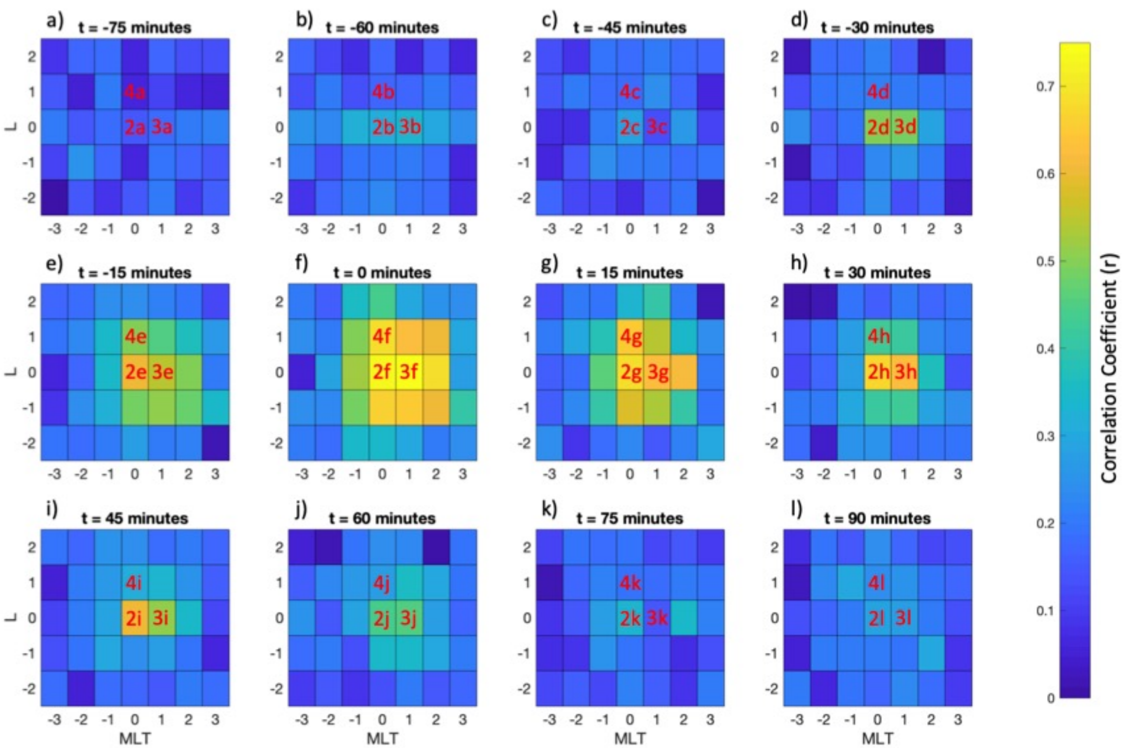
UCLA researchers provide insights into the source of excess dose



<u>Measured HISS waves correlate highly with ARMAS excess dose - Aryan et al., 2025a</u>

- A close conjunction event between ARMAS and THEMIS-A satellite on 10 May 2024.
- THEMIS-A plasmaspheric hiss waves observed in inner equatorial magnetosphere.
- Background dose rate (blue line) and the observed dose rate (red bars) measured by ARMAS onboard the deviated United Airlines flight (SFO-CDG).

UCLA Collaboration provides insights into the source of excess dose



<u>HISS waves measured by VAP correlate highly in time with ARMAS excess dose - Aryan et al., 2025b</u>

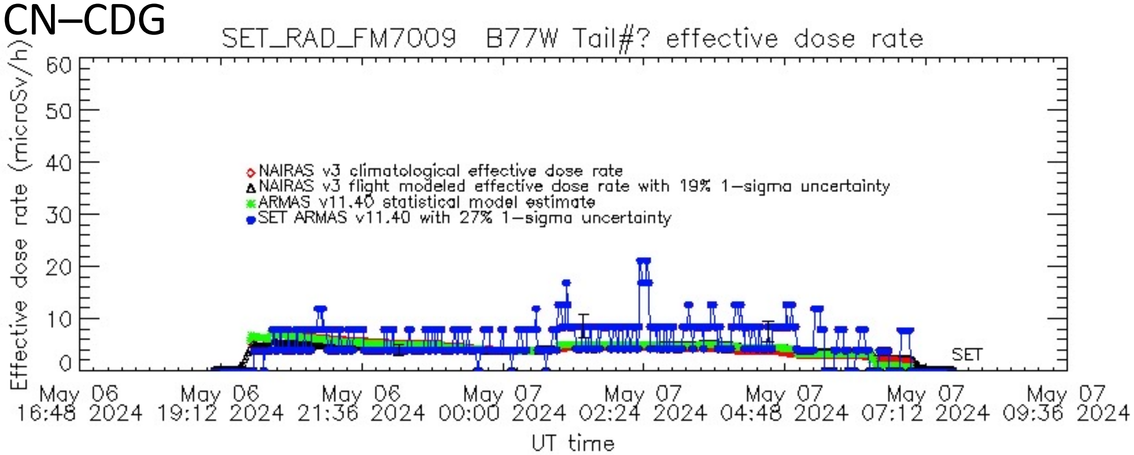
- Symmetry around L = 0, indicating that the correlation does not preferentially degrade when the Van Allen Probes are either inside or outside of ARMAS's L-shell range
- plasmaspheric hiss waves continue to have a <u>significant influence on ARMAS radiation dose rates for up to 45 minutes</u> after the initial measurement

ARMAS Dual Monitor Project: Goals Accomplished

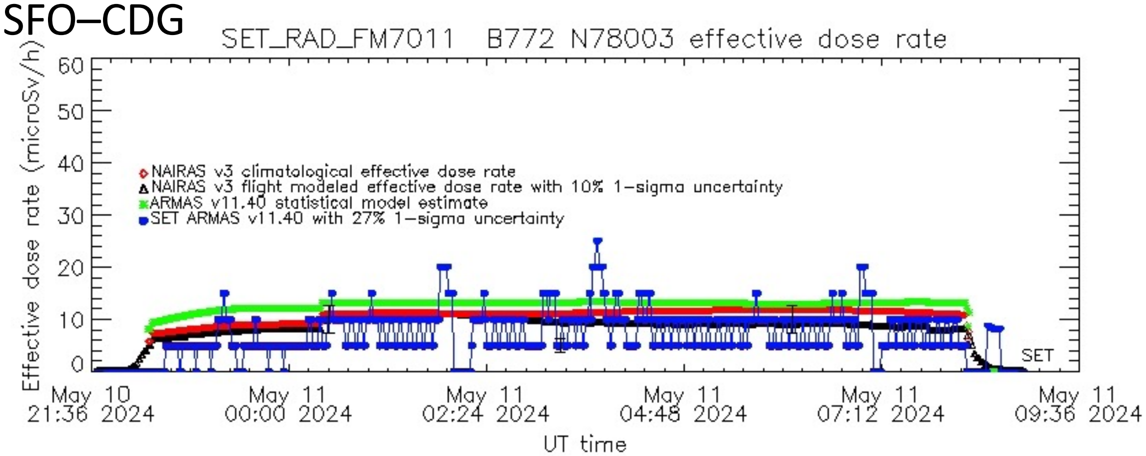
1. Demonstrate real-time **regional ionizing-radiation monitoring** at aviation altitudes using all vehicles
2. **Specify the radiation environment consistently** from the surface to high altitudes for space tourism and access to space operations as well as aviation safety
3. Better **understand the dynamic and variable radiation environment** due to all sources by measuring both total ionizing dose and gamma-rays
4. Validate **ALARA strategy** for aerospace radiation safety
5. Provide **MANY observations** for assimilation into the physics-based radiation models
6. Evolve **ground-breaking measurement** strategies

Goal 1: Radiation measurements at similar latitudes in Eastern and Western hemispheres differ by up to a factor of 2

ICN–CDG



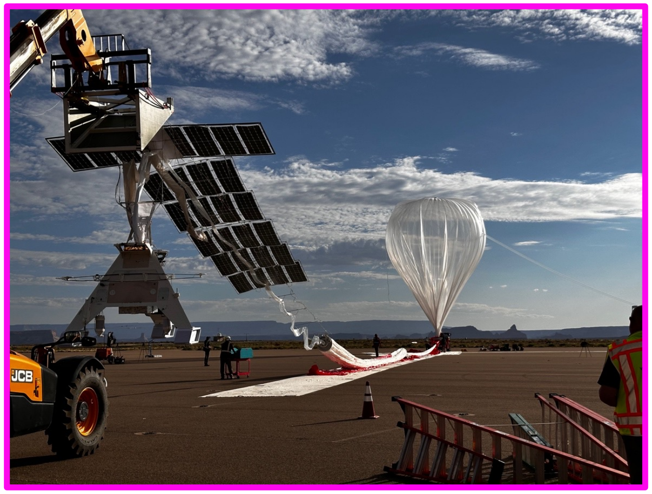
SFO–CDG

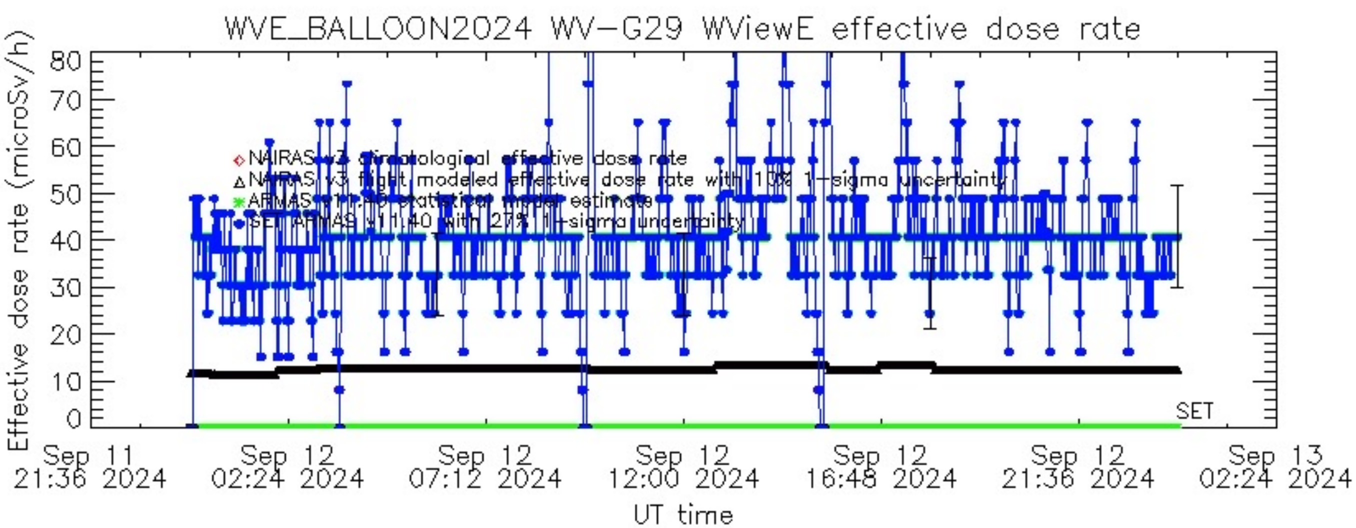


<u>**Flight details**</u>: 11 hours at mid latitude routes in each hemisphere

1. During similar flight times at similar geographic latitudes, the North America – Europe sector had <u>doubled dose rates</u> compared to the Korea – Siberia – Europe sector
2. This is consistent with <u>North American sector having lower cutoff rigidities extending to lower latitudes.</u>

Goal 2: 28-day stratospheric balloon flight (Aug 31 – Sep 27, 2024) – storm effects & high radiation





Flight details: mid latitude crossings of the western U.S. at 16–22 km and during the peak of solar cycle 25

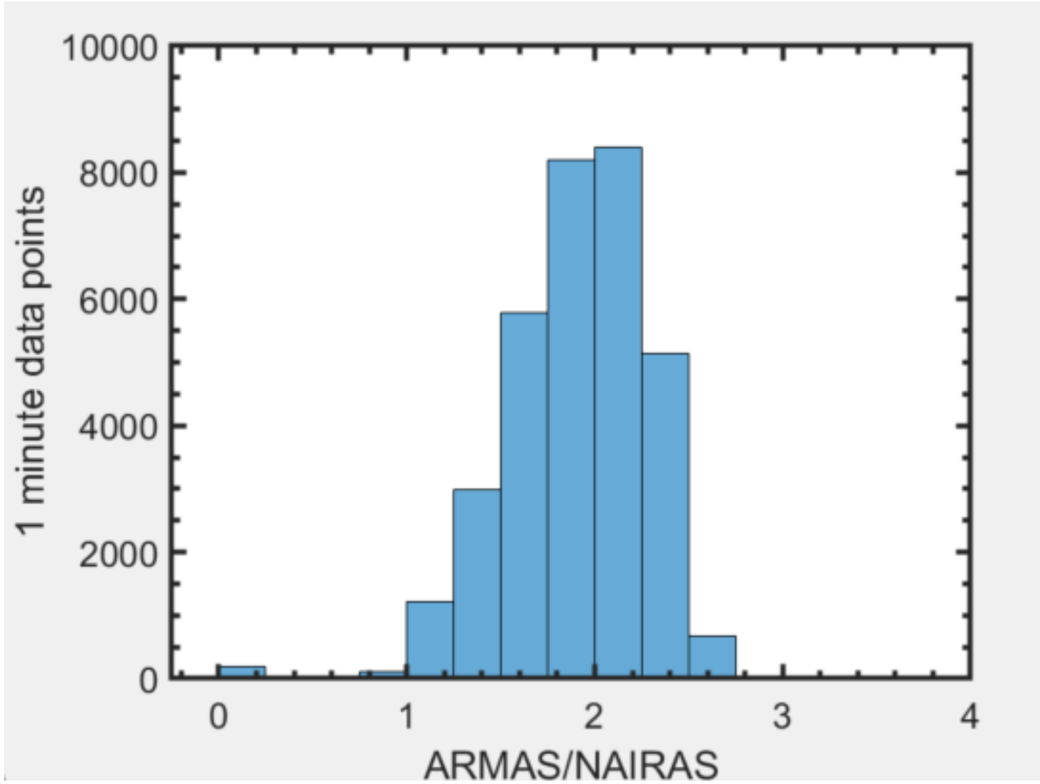
1. Continuous operational monitoring 24/7 at TRL 9 demonstrated above air traffic corridor
2. 4 conjunctions recorded with commercial flights

Goal 2: ARMAS balloon – aircraft conjunctions

Blue indicates balloon location during flight

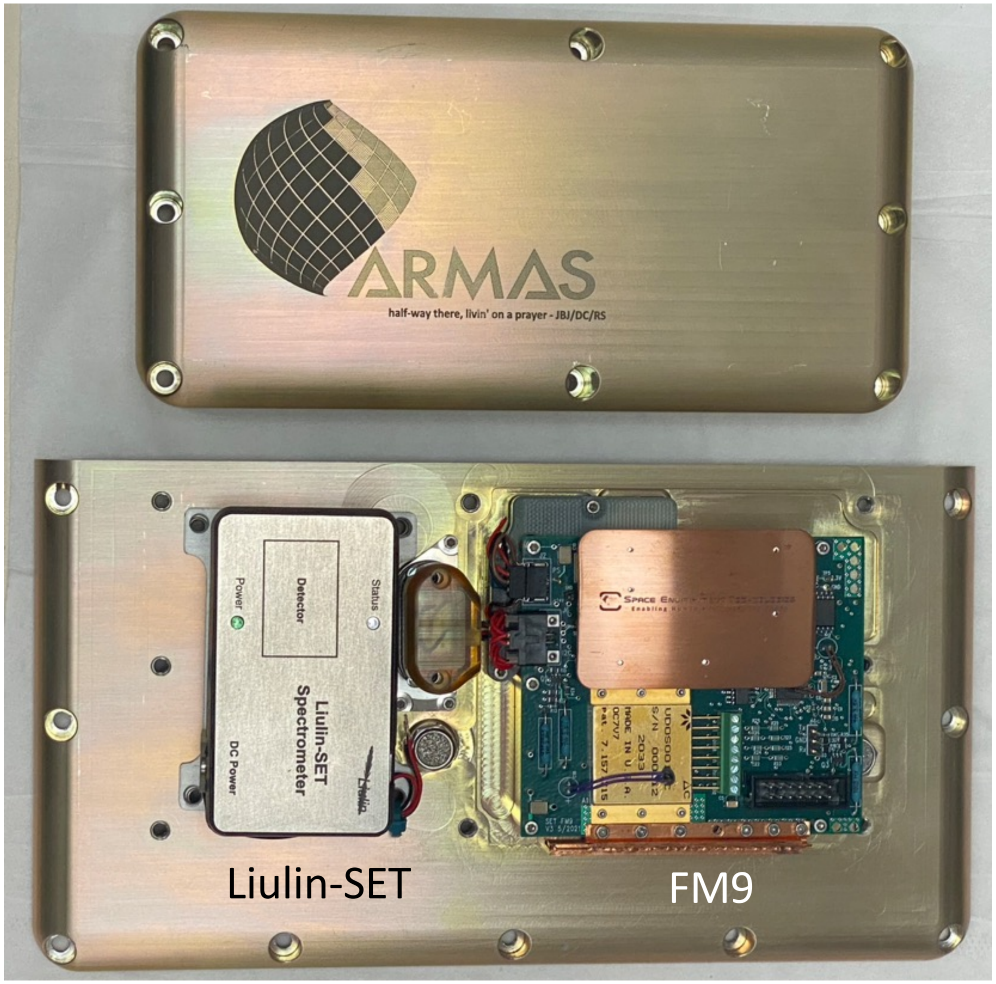
Red indicates airplane flight path

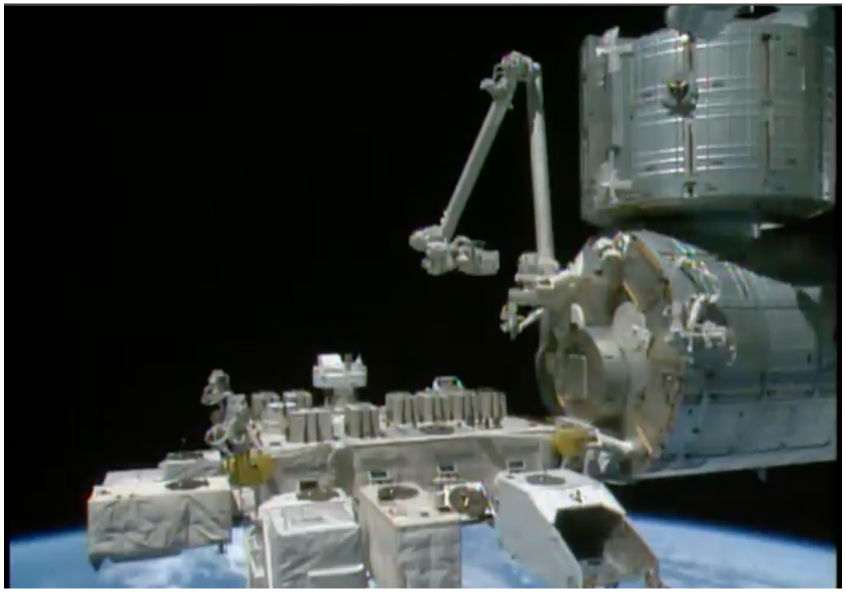
Goal 2: ARMAS/NAIRAS ratios



- While different from 8–11km tropospheric ratios (NAIRAS and ARMAS are close to unity for the GCR background level), the majority of ARMAS data for the 20 km lower stratospheric region are around a factor of 2 greater than NAIRAS dose predictions
- ARMAS/NAIRAS:
  - 99% > 1
  - 86% > 1.5
  - 43% > 2
  - 2% > 2.5
  - 1.1% < 1

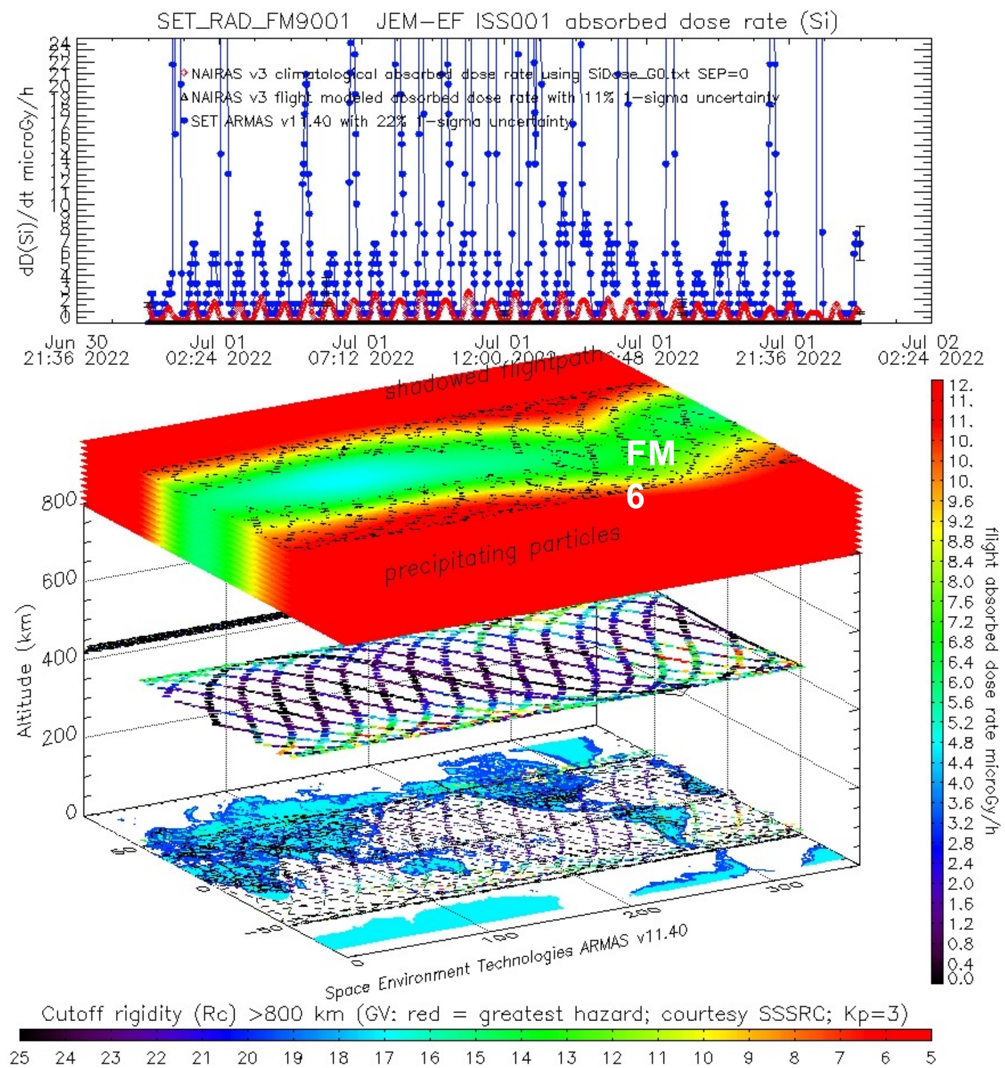
Goal 2: Top of the atmosphere continuous monitoring in 2022 (and 2024): ARMAS ISS



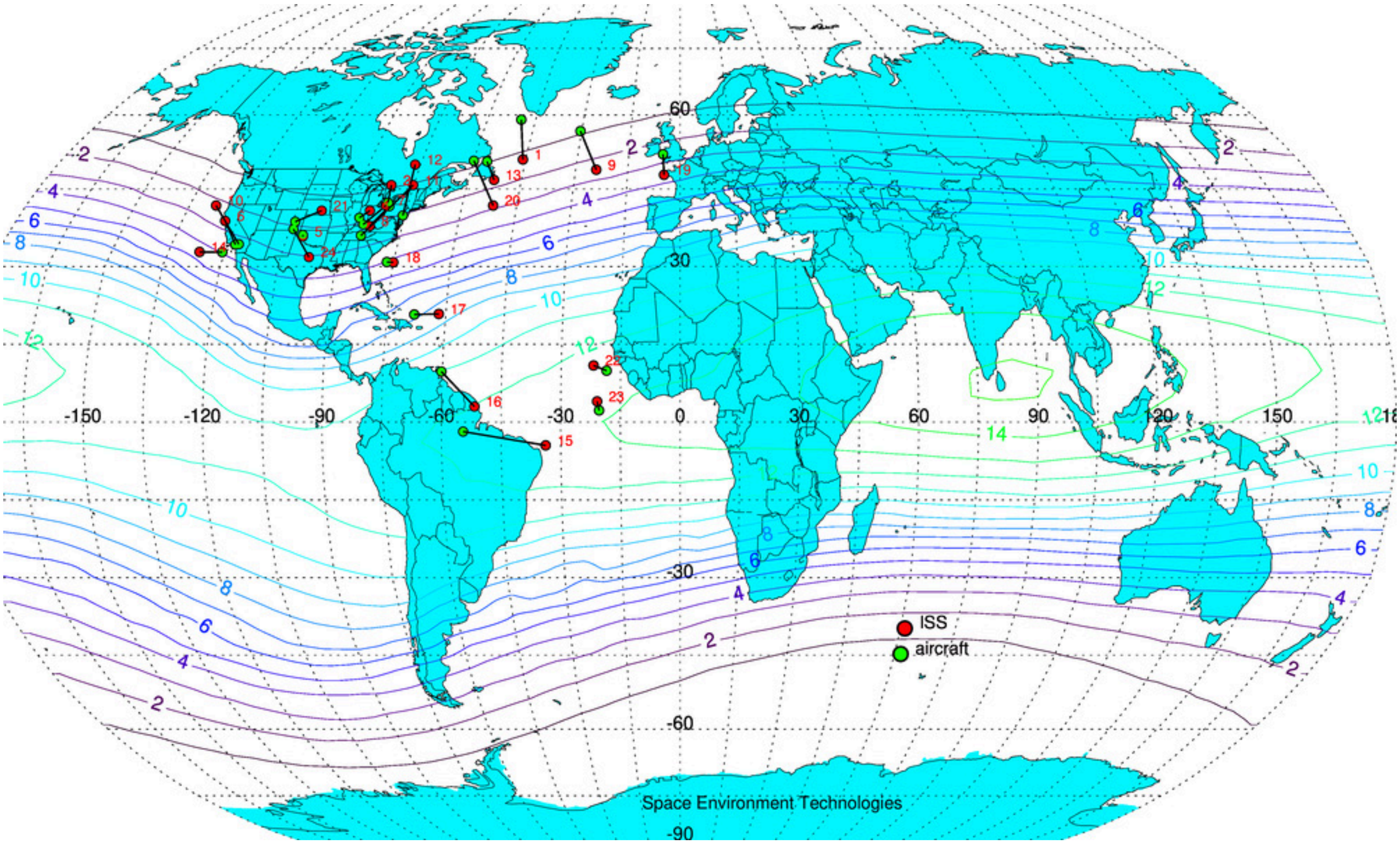


Goal 2: Top of the atmosphere continuous monitoring in 2022: ARMAS ISS

- ARMAS FM9 and Luilin-SET launched February 19, 2022
- Nearly continuous 1-sec data between March and December 2022
- Measured total ionizing dose and LET spectrum for 216 days
- ARMAS FM9 measured total ionizing dose
- Liulin-SET measured linear energy transfer ionizing radiation



Goal 2: ARMAS ISS &B aircraft July – December 2022 conjunction map



Goal 2: July – December 2022 ISS and aircraft conjunction summary

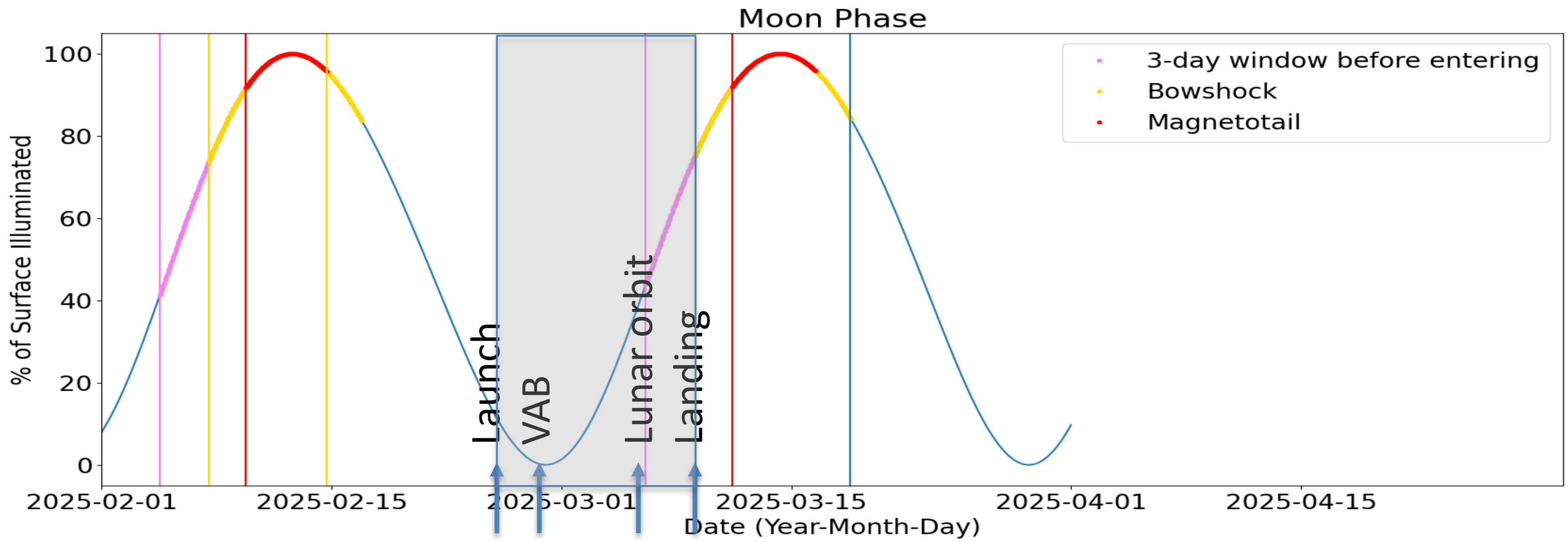
Northern hemisphere	Observed comparisons between pairs of ISS and aviation dose rates	Conjunction pair
High-latitudes Geo (>60) Mag (>65) Rc (<1)	• Insufficient number of conjunctions for comparisons	• N/A
Mid-latitudes Geo (30–60) Mag (40–65) Rc (4 to 1)	• **Higher dose rates than equatorial region overall** o Large variability in time & space o More particle fluxes occur in lower cutoff rigidities • **Regions of highest dose rates** o Areas where there is <5° latitude and <15° longitude separation o Cutoff rigidities have greater shielding as one moves toward equator • **Altitude differences** o Higher dose rates in LEO (thermosphere/top of atmosphere) than at aviation altitudes (troposphere/lower atmosphere)	• 4–5, 6–7, 10, 11 • (all except 15, 16, 22, 23) • 12–13 • 17–18 • 6, 7, 10, 11
Low-latitudes Geo (00–30) Mag (00–40) Rc (13 to 4)	• **Lower dose rates than mid-latitudes overall** o Low variability in time & space o Less particle fluxes in higher cutoff rigidities • **Altitude differences** o Similar dose rates measured in LEO (thermosphere/top of atmosphere) and at aviation altitudes (troposphere/lower atmosphere)	• 15, 16, 17, 22, 23 • 15, 16, 22, 23 • 15, 16, 17, 22, 23

Goal 2: ARMAS lunar flight – February 27 to March 6, 2025

Flight details: ARMAS Flight Module (FM) 11 was installed on Intuitive Machines Mission 2 lunar lander and launched by SpaceX from Cape Canaveral on Feb 27, 2025. It was deployed in first half orbit at 800 km above Indonesia, traversing through the Van Allen Belts, deep space, lunar orbits, landing, and to the surface, arriving March 6 for a landing near the south Pole.

1. The measurements from the Earth to Moon can serve as a radiation baseline for human exploration to the Moon and, later, to Mars
2. Mature sensor was demonstrated as a commercial payload of opportunity
3. Rapid development cycle over 10 months start to delivery leveraged ARMAS FM9 technology used on the ISS in 2022

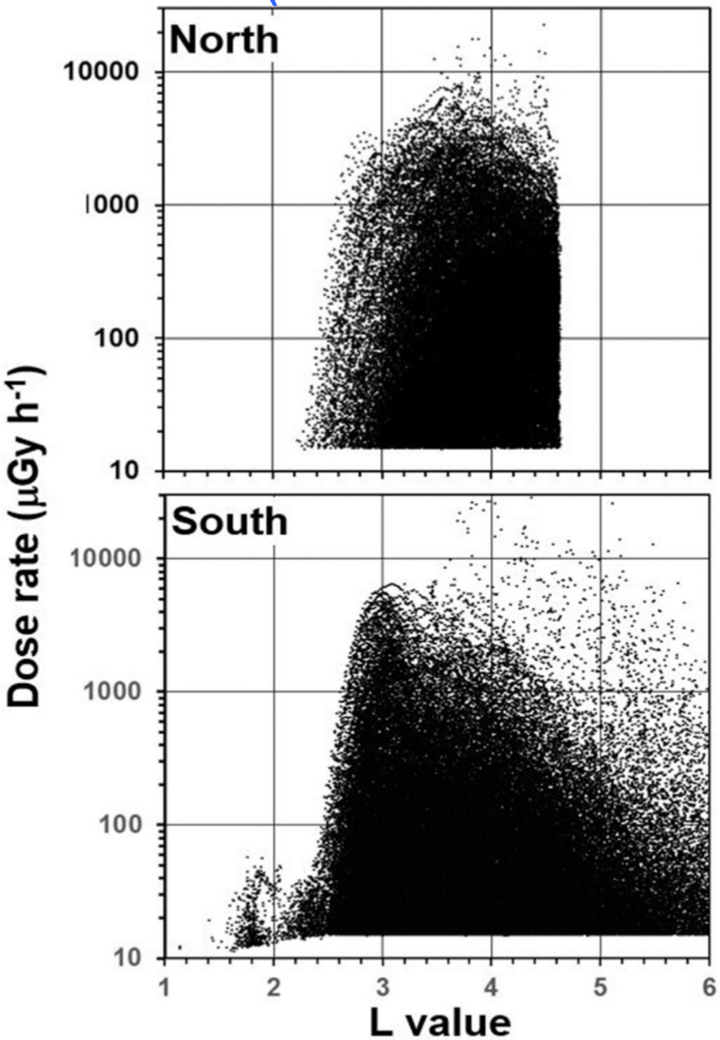
Goal 2: ARMAS Lunar magnetotail crossing



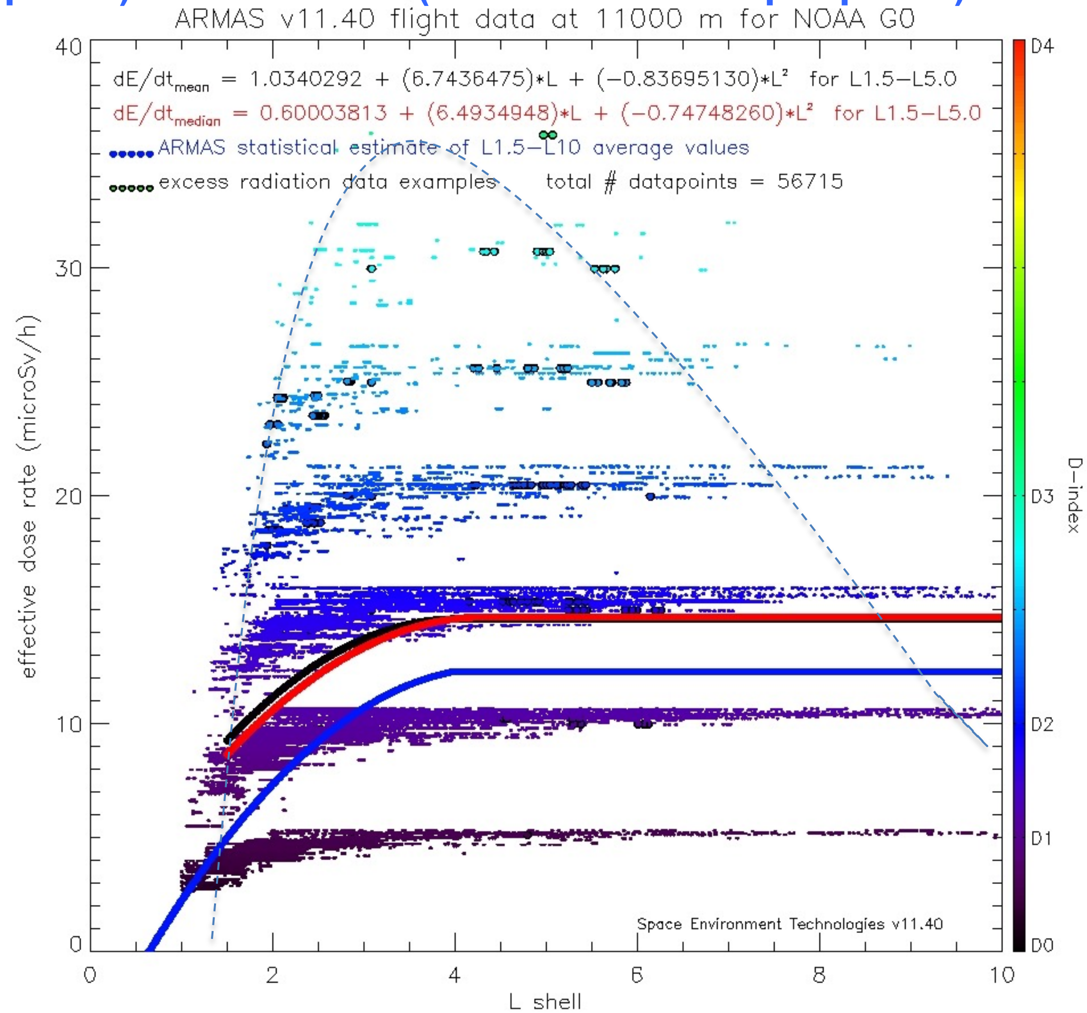
1. This is a human exploration radiation baseline to the Moon and, later, to Mars
2. IM2 and ARMAS FM11 experienced a magnetotail crossing during the mission
3. Multiple conditions expected: pure GCR environment and magnetotail dose
   - Thermosphere above ISS altitudes (800+ km)
   - Van Allen Belt transit (2000 – 36,000 km)
   - Deep space (40,000 – 384,000 km)
   - Lunar orbit (400 – 100 km)
   - Landing (100 – 0 km)
   - Surface (85 S)

Goal 3: Excess radiation is L-shell dependent all altitudes

Dachev (ISS – LEO[1] mid thermosphere)

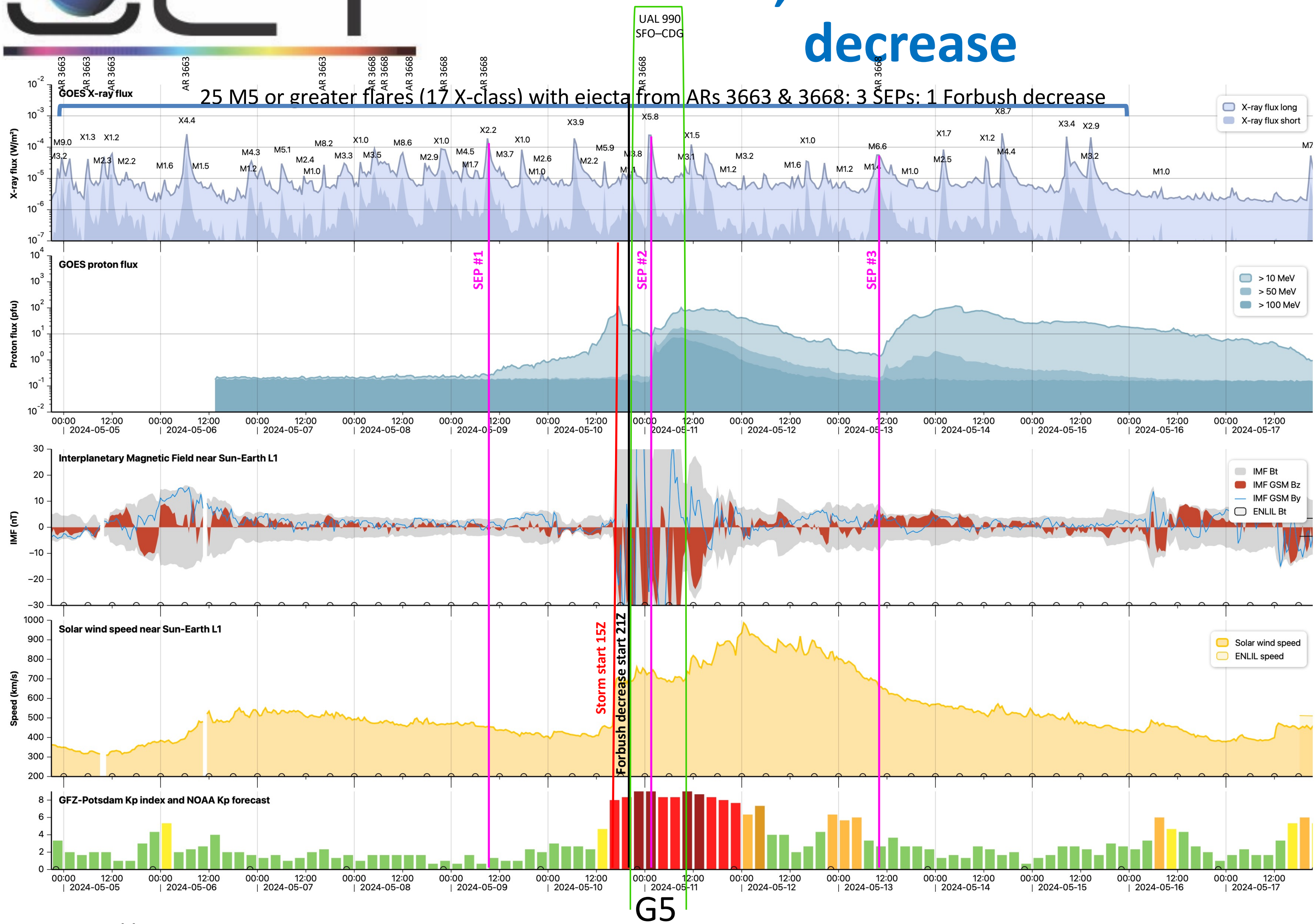


ARMAS (aircraft – mid troposphere)



[1]LEO = low Earth orbit and ISS = International Space Station

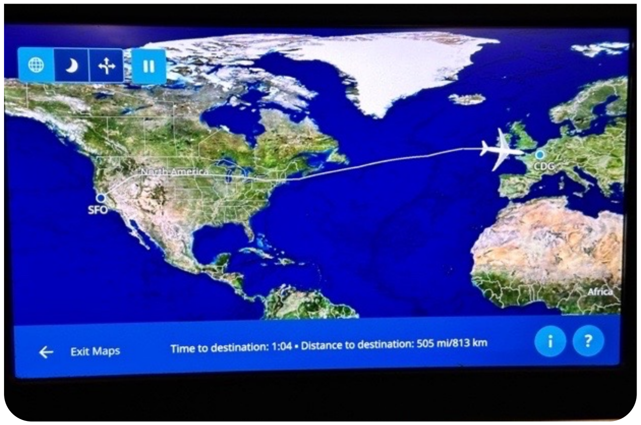
Goal 3: Gannon superstorm trifecta – CMEs, SEPs and Forbush decrease

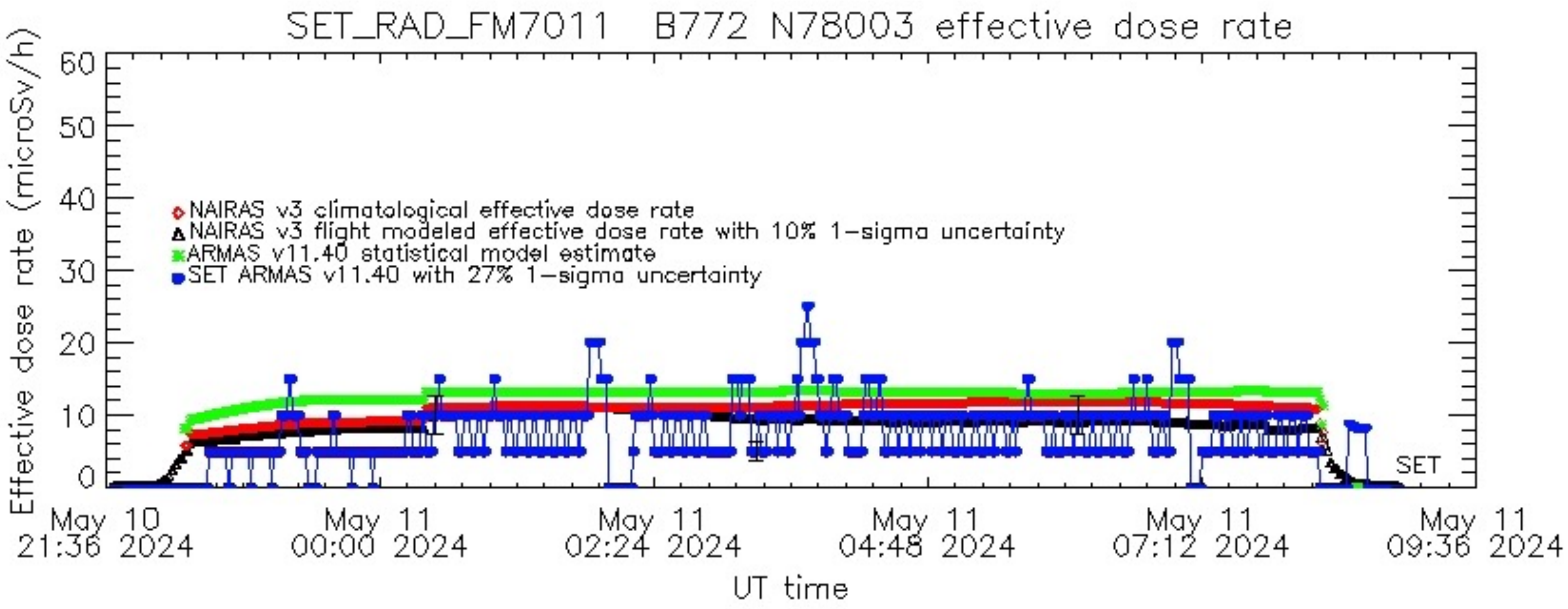


https://spaceweather.knmi.nl

Goal 3: ARMAS measurements during the Gannon extreme storm

- A commercial airline flight between San Francisco and Paris carried the ARMAS FM7 radiation monitor during the extreme geomagnetic storm (Gannon storm) May 10–11, 2024.
- G5 storm, SEP event, and Forbush decrease all contained in data



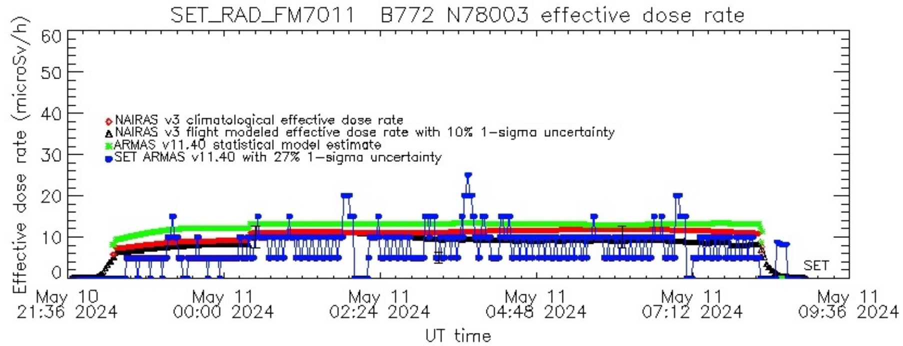


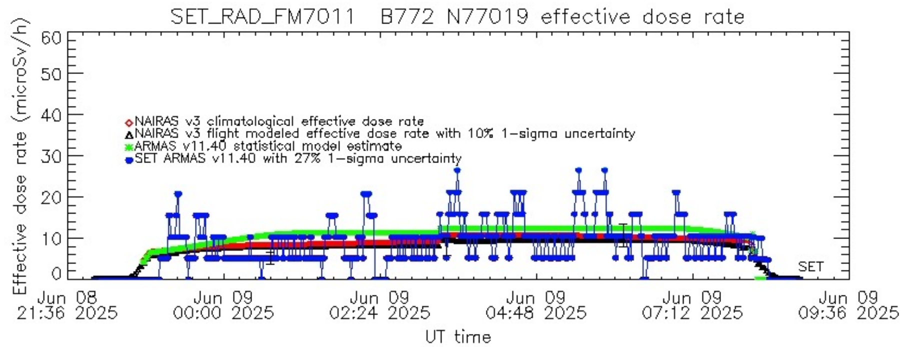
Goal 4: ALARA strategy validation using ARMAS measurements during the Gannon extreme storm and during quiet conditions

- Two commercial airline flights between San Francisco and Paris carried the same ARMAS FM7 radiation monitor, where one flight occurred during the extreme geomagnetic storm (Gannon storm) May 10–11, 2024 and one flight occurred during quiet geomagnetic conditions June 8–9, 2025.

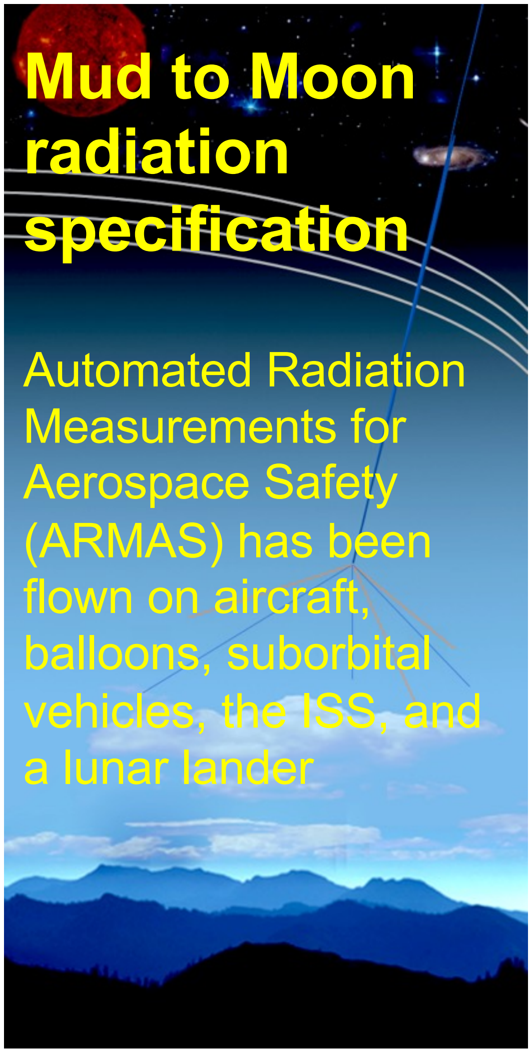
- The flights' results validated the ALARA strategy of using operational decisions during extreme space weather to create shielding by flying lower magnetic latitudes to gain more Earth magnetic field shielding and by flying lower altitudes to use atmosphere depth shielding.

- A third shielding method provided by nature in the G5 storm is a Forbush decrease at the beginning of a storm; it reduced the number of lower energy protons entering the Earth's atmosphere and lowered the "floor" of GCR radiation exposure from cosmic rays.



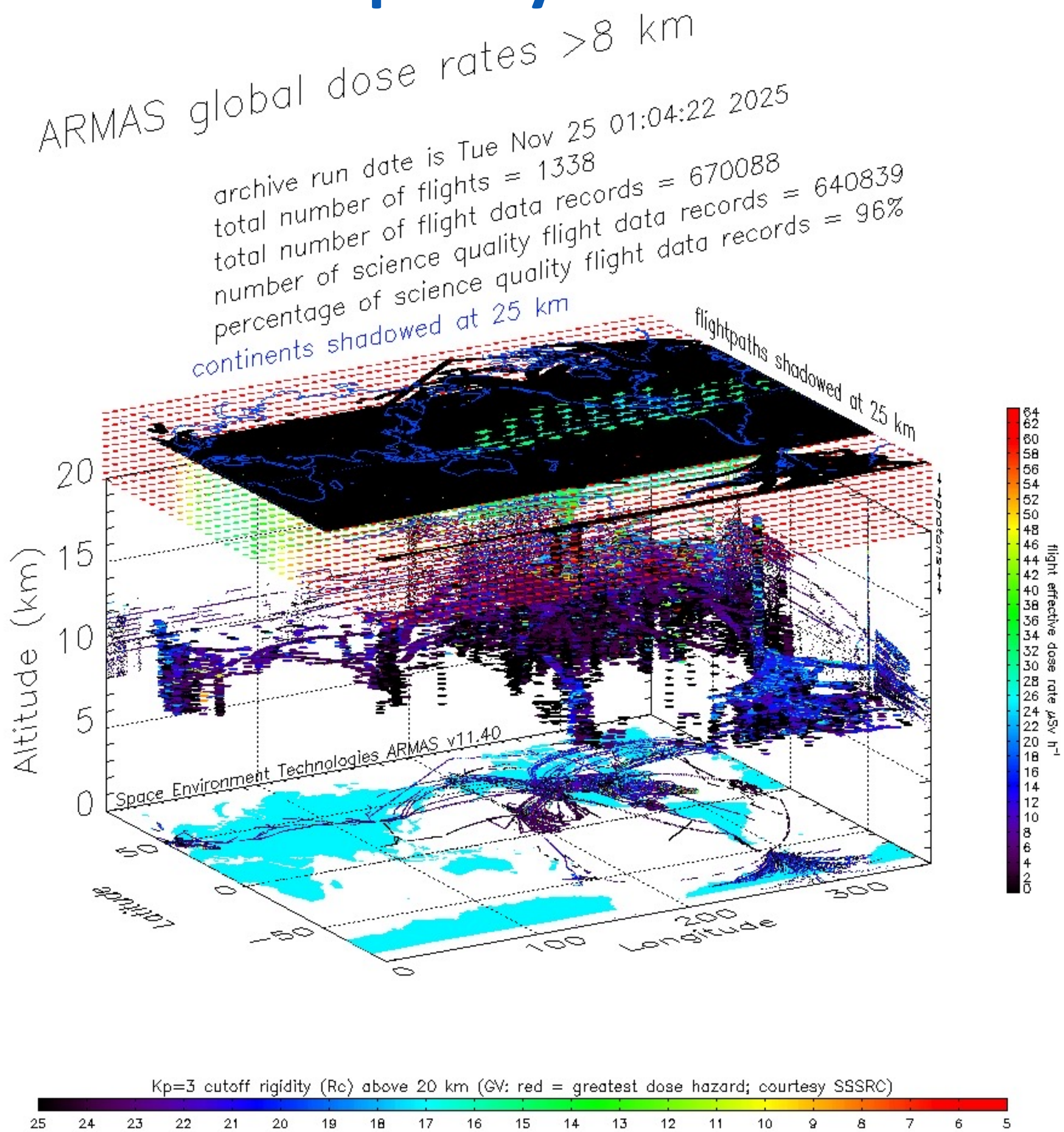


Goal 5: 640,000 ARMAS science quality measurements

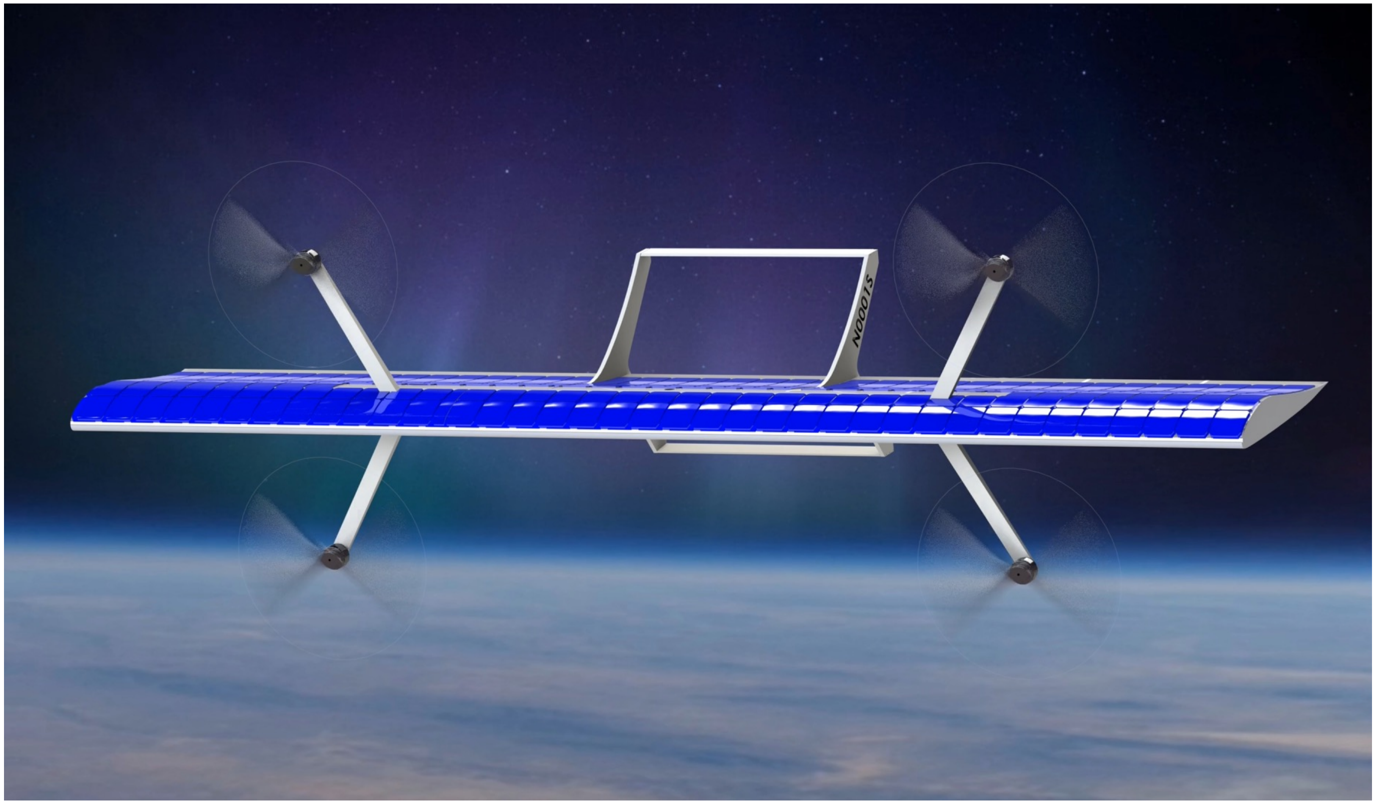


Mud to Moon radiation specification

Automated Radiation Measurements for Aerospace Safety (ARMAS) has been flown on aircraft, balloons, suborbital vehicles, the ISS, and a lunar lander

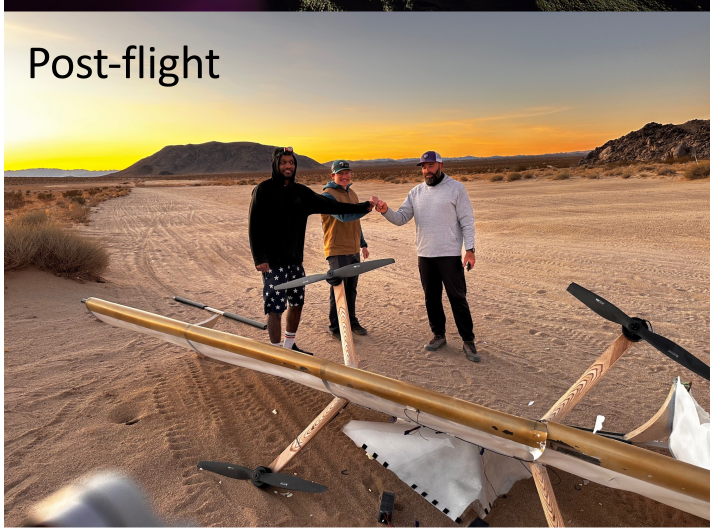


Goal 6: ARGOS 3 flight design for continuous ARMAS measurements



1. 5 m wingspan and 1 m chord length can achieve 20 km altitude
2. 10 kg payload capacity with 5 U volume is the baseline for ARGOS 3
3. Temperature survivability at –70° C for avionics demonstrated with WVE flight
4. 75 m/s (170 mph) cruise velocity can traverse Mojave to Mt. Shasta in 5 hours or 2000 km diameter area in 24 hours

Goal 6: Summary of the ARMAS ARGOS flight on December 18, 2024



Flight details: ARGOS vertical ascent flight to 100 ft in 10–20 mph winds

- ✓ Controlled ascent has been demonstrated in quadcopter mode
- ✓ Payload power/mass budget demonstrated for 10 kg

Successes of the ARMAS flight program 2013 – 2025

1. ARMAS has developed the largest and most complete U.S. database of aerospace global measurements from the surface to LEO (and soon the Moon) with 3.8 million 10-second science quality data records that inform NAIRAS, CARI, and ML models.
2. 2/3 of ARMAS funding came from SBIR NASA and NOAA funding, 1/3 commercial
3. ARMAS provides a solution for the SWAG User Needs Survey (Sep 2024) Findings and Recommendations 3.2:

   "**There is a lack of measurements, reporting, limits, education, and hazard mitigation pathways for radiation exposure across the aviation industry**
   - U.S. and international commercial and corporate aviation lack information required for tracking, reporting, and understanding radiation exposure at aviation altitudes
   - There is an overall lack of understanding of the radiation environment
   - Without proper education and awareness, this can lead to misinformation or incorrect action among crew and the flying public"
4. ARMAS provides a validated, TRL 9 U.S. capability for (i) Air Traffic Management support with real-time streaming radiation weather and (ii) deep space radiation monitoring for human space flight.

ARMAS forecasts

G4 storm September 2015

forecast for altitude level of 19 km, i.e., the operating regime of the ARGOS aircraft