Characterizing the global aviation radiation environment

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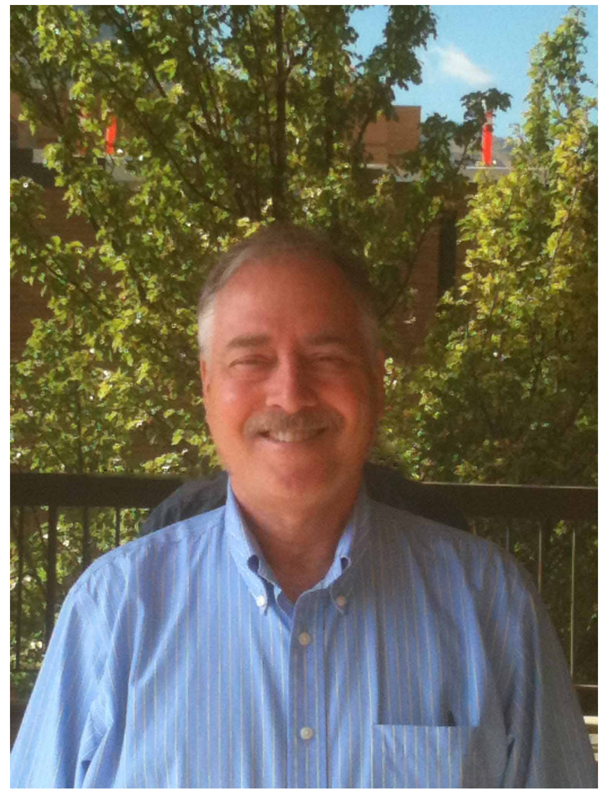
- **President**: Space Environment Technologies
- **Career**: NOAA SEL, UC-Berkeley, JPL, USC, USU, SET, Q-Up
- **PI**: NASA, NOAA, DOE, USAF contracts
- **Lead U.S. delegate:** ISO space environment standardization
- **ACSWA:** Executive Committee member
- **Expertise areas**: solar/ionospheric/atmospheric/ radiation physics and their applications to solving societal challenges



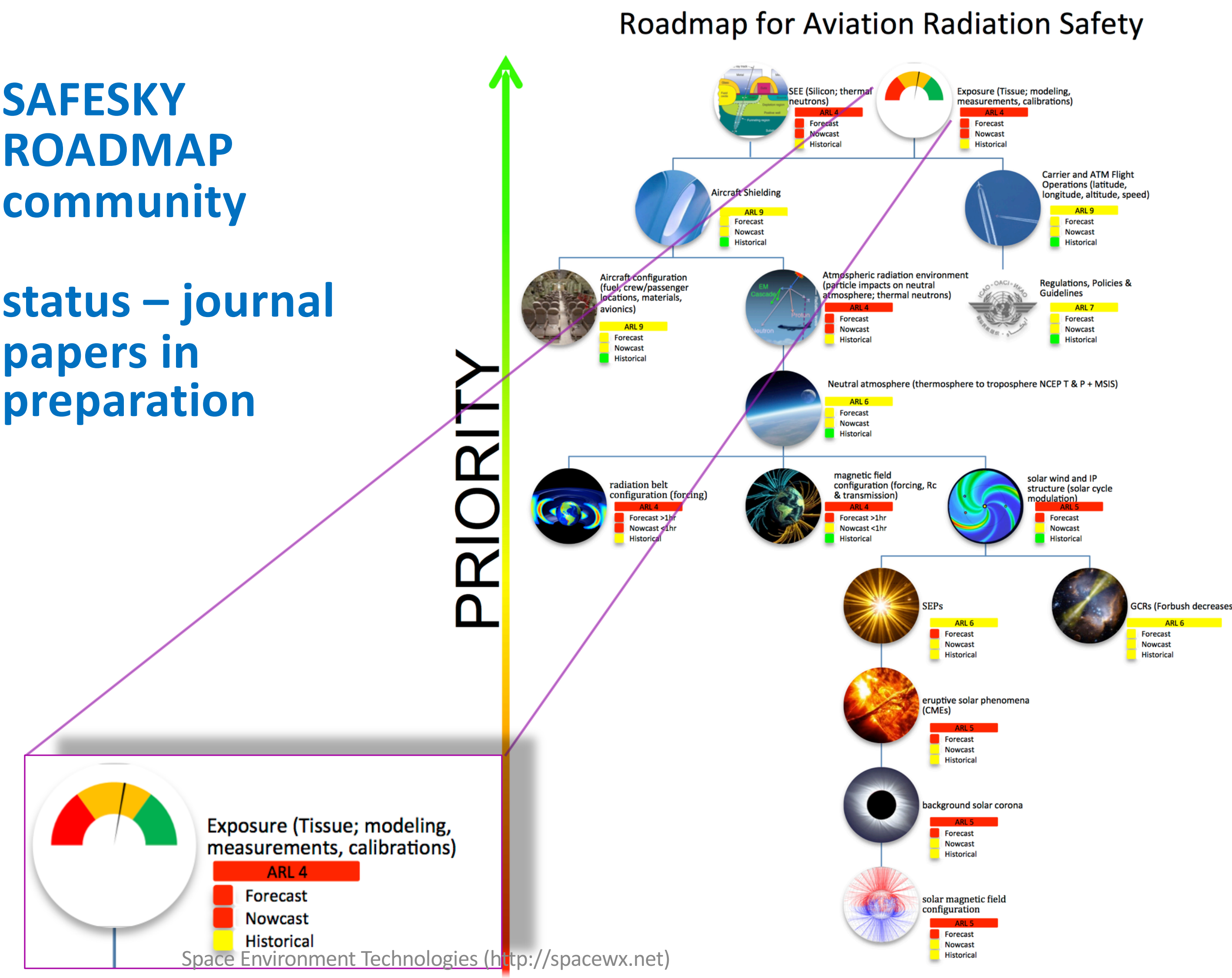
The dynamic radiation environment at aviation altitudes

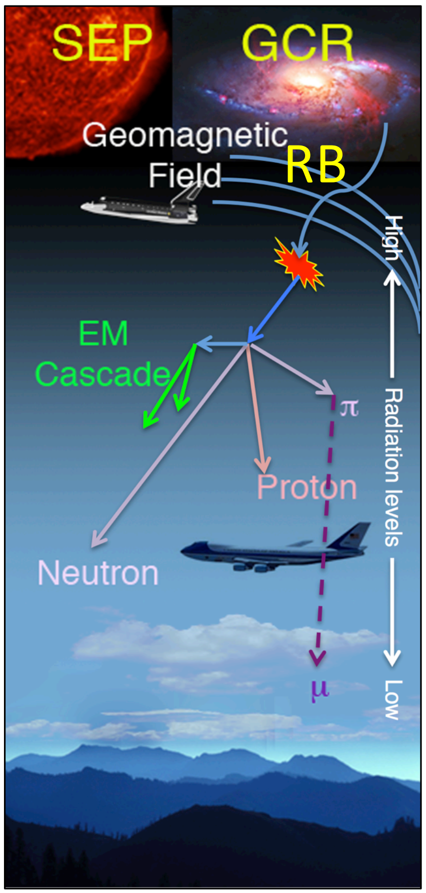
1. Background to radiation environment
2. Instrumentation
3. Calibration of ARMAS with TEPC
4. Measurements and modeling
5. Expanding our scientific understanding
6. Improvements to achieve forecasting accuracy
7. Enterprise collaborations

Background

SAFESKY ROADMAP community

status – journal papers in preparation





<u>Improving our understanding</u>: Space weather creates a dynamic radiation environment at aviation altitudes

3 radiation sources above 8 km

- **Global phenomenon:**
  - ✓ <u>**GCRs**</u> modulated by the state of the heliosphere's magnetic field create a career health issue and source for avionics SEUs (well-known phenomena)
- **High latitude phenomena:**
  - ✓ <u>**SEPs**</u> from solar flare events can affect fleet operations and aircrew/passenger monthly limits (well-known phenomena)
  - ○ <u>**REPs**</u> from Van Allen belt energetic particle precipitation most likely creates a gamma-ray environment affecting career total absorbed dose (current research activity)

Radiation Environment in the Upper Atmosphere

- Galactic cosmic and solar particle radiation interact in the upper atmosphere of the Earth
- The mixed radiation field inside an aircraft contains many radiation components including high-energy neutrons, protons and heavy ions and some gamma rays
- The intensity of the primary and secondary components of this radiation field increase with altitude and latitude
- FAA has estimated aircrew exposures range from 0.2 – 9.1 mSv/yr (compared to 0.5 mSv/yr exposure for average nuclear power plant worker)

Atmospheric Exposure Variables

- **Altitude**: Shielding by air molecules
  - 1030 g/cm2 at sea level
  - 55 g/cm2 at 20 km (66,000 ft)
    - ✓ *Dose Equivalent rate, dH/dt, at 20 km is ~400 x dH/dt at sea level*
- **Latitude**: Shielding by geomagnetic field
  - Bends lower energy particles back into space
  - dH/dt at poles is ~6 x dH/dt at equator (at 20 km altitude)
  - Effect on *dH/dt* increases with altitude

Improving the state-of-art: accelerating progress towards aviation radiation operational nowcasts and forecasts

- **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 v9
  - ✓ ATED
- **MODELS**
  - ✓ NAIRAS v1
  - ✓ CARI-7
  - ✓ AVIDOS
  - ✓ KREAM

2017-2019

Step 3: Monitoring

(a few daily NAT or NoPAC flights; tech demo regional monitoring; initial data assimilation)

Summer 2020

- **DETECTORS**
  - ✓ ARMAS v10
  - ✓ ATED
- **MODELS**
  - ✓ NAIRAS v2
  - ✓ CARI-7

2020-

Step 4: Nowcast & forecast

(100+ daily flights for track truth, continuous balloon loiter or hi-alt/long endurance regional monitoring; operational data assimilation and initiation of ensemble modeling)

Radiation Detection Systems for Use in Aircrew Dosimetry Measurements

- **Automated Radiation Measurements for Aerospace Safety Flight Module (ARMAS FM)** – easy to use in aircraft and measures all ionizing radiation (heavy particles to photons)
- **Tissue Equivalent Proportional Counter (TEPC)** microdosimeter – "gold standard" for human tissue dose against which all detectors are compared
- Both of these detector systems are capable of detecting both the primary and the secondary radiation fields aboard aircraft

The Thermo-Scientific EPD TruDose Electronic Personal Dosimeter System

- Easy to use and operate
- Excellent electronic personal dosimeter for the radiation fields found in a hospital environment
- Only capable of measuring the dose from X-rays, gamma rays and beta particles (all in specific energy ranges)
- Incapable of measuring the dose from the majority of the primary and secondary radiation field found aboard aircraft

Radiation Protection Terminology for Measured Quantities

According to the Environmental Protection Agency (EPA):

- **Exposure (R)** describes the amount of radiation traveling through the air. Many types of radiation monitors measure exposure. The units for exposure are the coulomb/kilogram (C/kg, international unit) and the roentgen (R, U.S. unit).
- **Absorbed dose (D)** describes the amount of radiation absorbed by an object or person. The SI unit for absorbed dose is the Gray (Gy). The U.S. unit for absorbed dose is the Rad. One Gray is equal to 100 Rads.
- **Dose equivalent (H)** describes the amount of radiation absorbed by person, adjusted to account for the type of radiation received and the biological effect of that particular type of radiation. The SI unit used for dose equivalent is a Sievert (Sv). The U.S. unit for dose equivalent is a Rem. One Sievert is equal to 100 Rems.

General Radiation Safety Limits

- **Annual Dose Limits**
  - Whole body 5 rem/yr (5000 mrem/yr)
  - Extremities 50 rem/yr (50000 mrem/yr)
  - Eye 15 rem/yr (15000 mrem/yr)
  - Prenatal 0.5 rem per 9 months

- **GENERAL PUBLIC** 100 mrem per year

Recent cancer risk medical studies findings

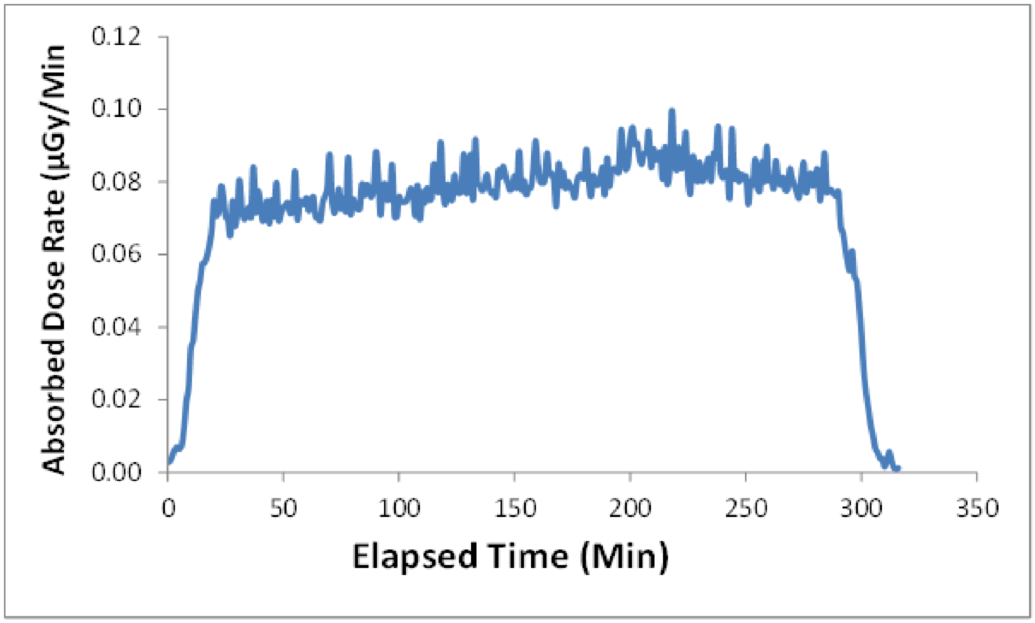
- **Recent publications** (*JAMA Dermatol., 2015*; *Occup. Environ. Med.,* 2003; *Environ. Health,* 2017)**:**

1) Pilots, aircrew experience deep tissue cancers
2) In addition, pilots, aircrew also have 2 times incidence of shallow tissue cancers
3) Occupational exposure may contribute to melanomas (UV-A photons?)
4) Pilot and aircrew lifestyle is **not** a contributing factor for increased risk
5) Shallow tissue cancers (melanoma and basal cell carcinoma) are induced by ionizing radiation
   - These cancers found to increase with occupational exposure criterion for pilots
   - **Melanoma and BCC were common in the trunk region of pilots – this precludes occupational UV-A exposure being responsible since UV-A would not penetrate the clothing and BCCs, melanomas are found in cabin crew members that aren't often near the windows**
   - **Gamma and X-rays are the energy range (0.5–5.0 MeV) that would penetrate clothing and give a dose to the underlying skin**
   - Cosmic rays[1] & solar energetic protons[2] would give mostly deep tissue dose from penetrating secondary neutrons and protons (prostate cancer, lymphoma, etc.)

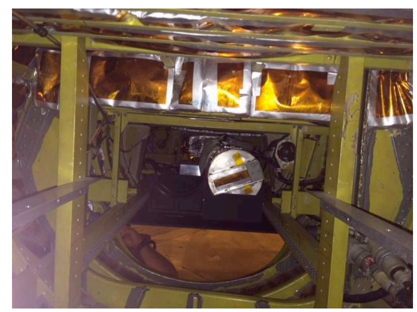
[1]GCRs = Galactic Cosmic Rays; [2]SEPs = solar energetic particles

Instrumentation

Tissue Equivalent Proportional Counter (TEPC) Dose Rate Measurements for ER-2 on 9/9/2015 at AFRC

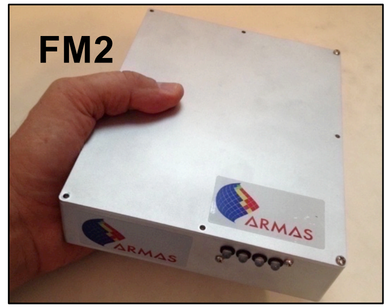


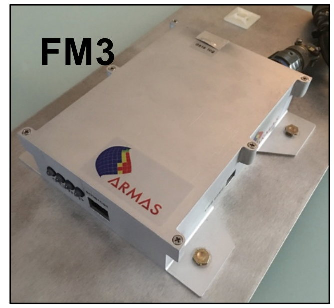
TEPC and ARMAS FM in ER-2 Q-Bay

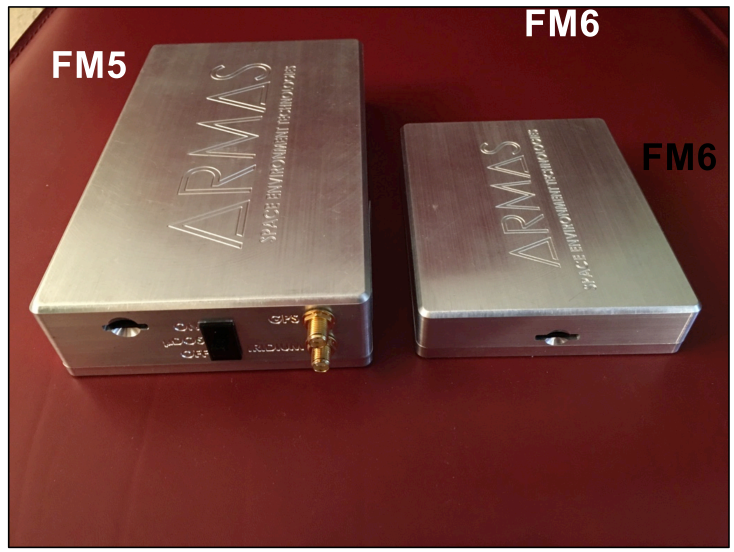


Improving real-time data collection: ARMAS measurements 2013-2020

ARMAS Flight Module 1 (FM1)
on NASA AFRC DC-8







Improving the measurement domains: 750+ ARMAS Flights from 0-106 km in 2013–2020

✓ 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
- ✓ **Commercial**:
  - Boeing 737, 747, 757, and 777
  - Airbus 319 and 320
  - Bombardier Q200
  - CRJ 200, 700; Embraer 175

✓ Balloons

- ✓ **World View Enterprises:** Stratollite (f)

✓ NASA space stations

- ● ISS (Low Earth Orbit)
- ○ Gateway (Lunar Orbit)

✓ Proprietary vehicles

- ✓ **Perlan** Stratospheric glider (e)
- ✓ **Virgin Galactic** SS2 and WK2 (g)
- ✓ **Blue Origin** New Shepard (h)
- ● Cubesat
- ○ Lunar lander

✓ Flown
● In progress
○ Potential


(a)


(b)


(c)


(d)


(e)

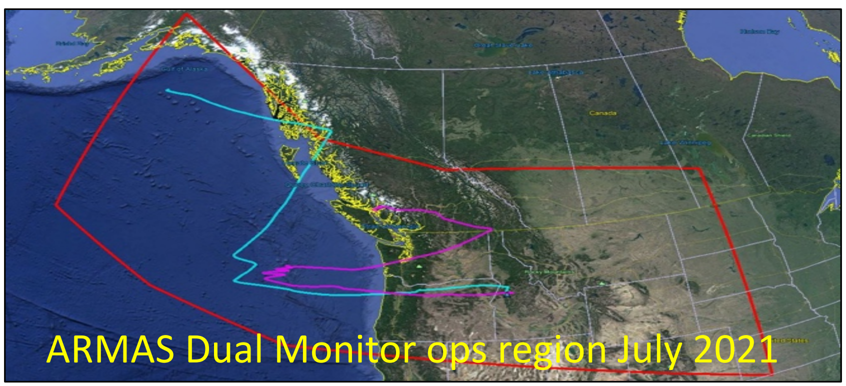
(f)


(g)

(h)

Improving operational monitoring:

ARMAS Dual Monitor to demonstrate operational radiation monitoring over North CONUS with World View Stratollite (July 2021)



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

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

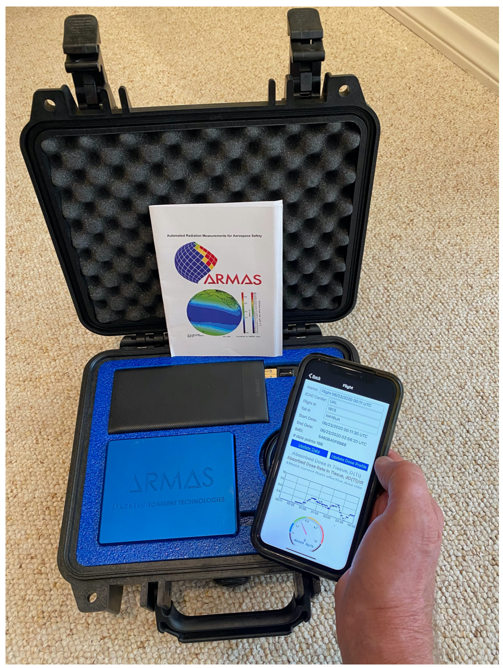
- Current and post-flight dose rate status displayed on app that is paired with FM7
- Dose rate can be transmitted to ground using WiFi

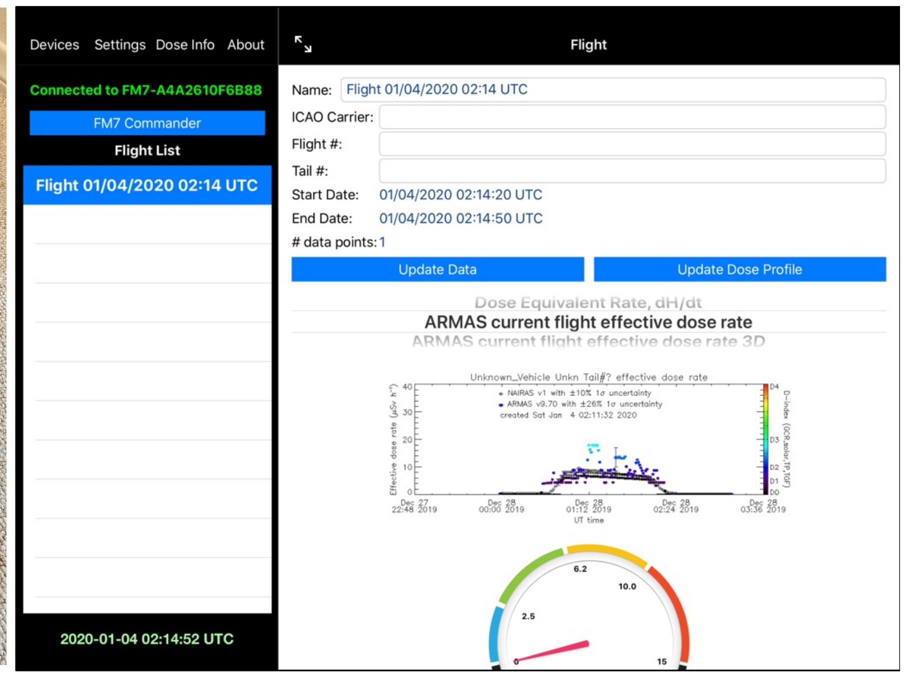
✓ Real-time dose rates: measured absorbed (Si) and derived absorbed (Ti), dose equivalent, ambient dose equivalent, and effective

Availability:

✓ 12 units 2018-2020

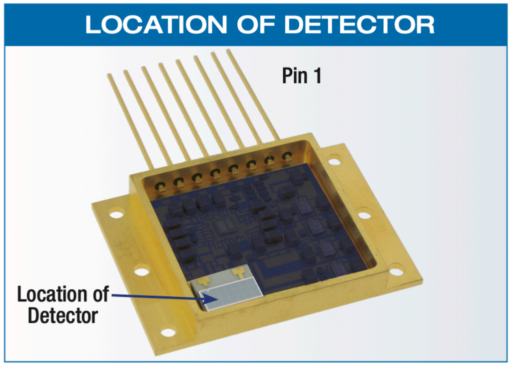
✓ 4th production run Aug 2020

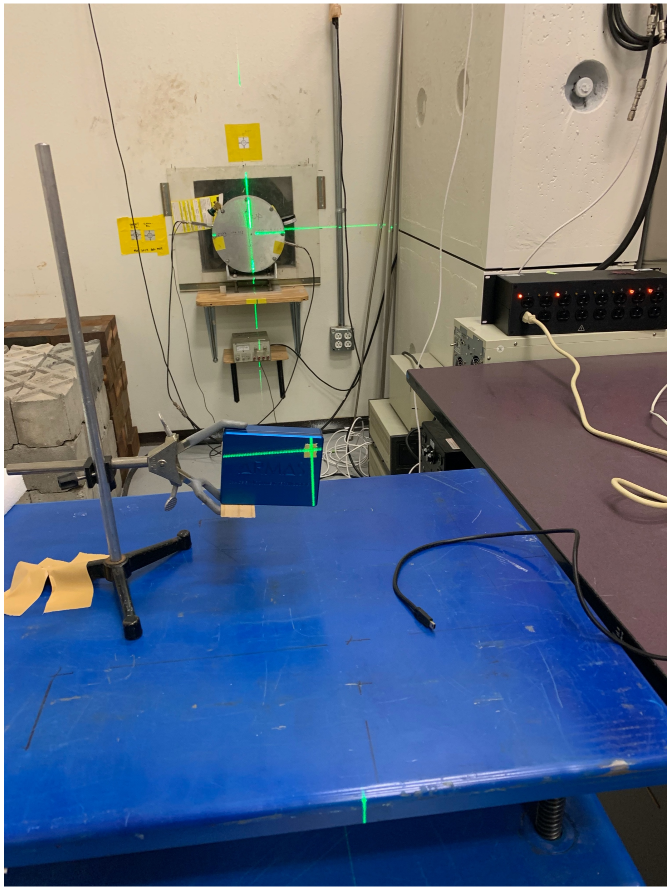




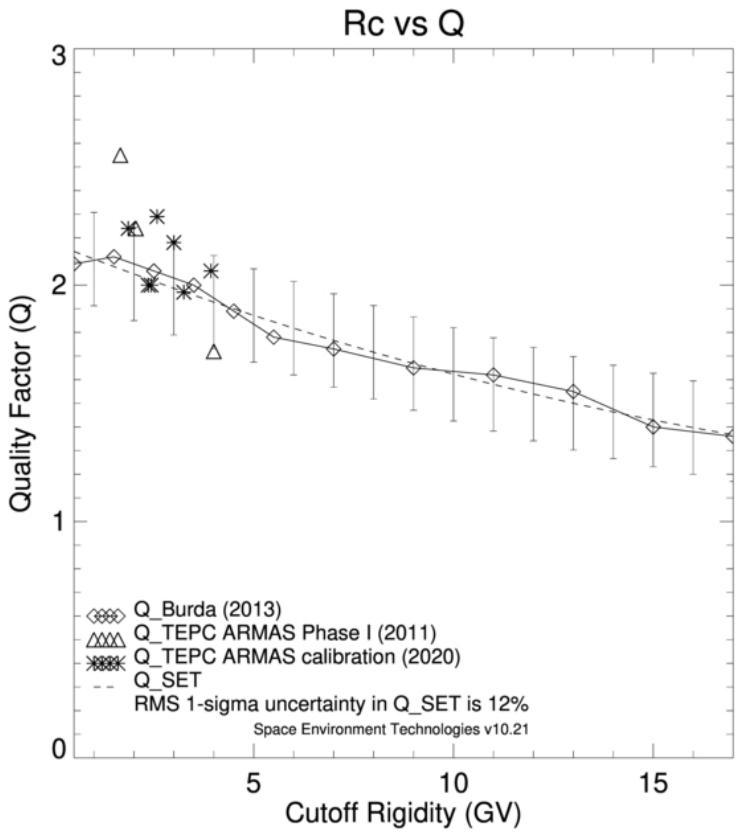
Calibration

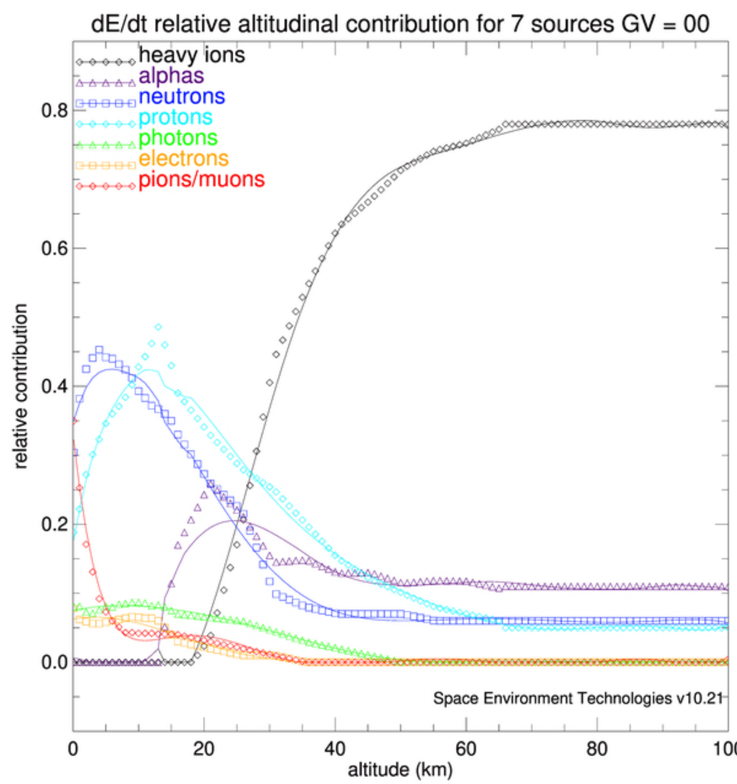
Improving operational data: Calibration of ARMAS dose rate in tissue with the TEPC



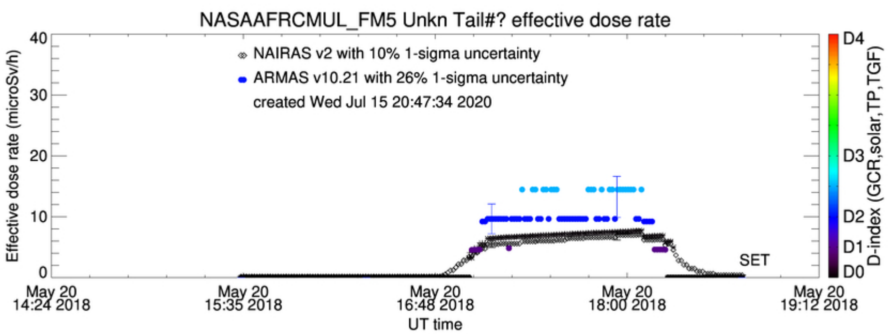


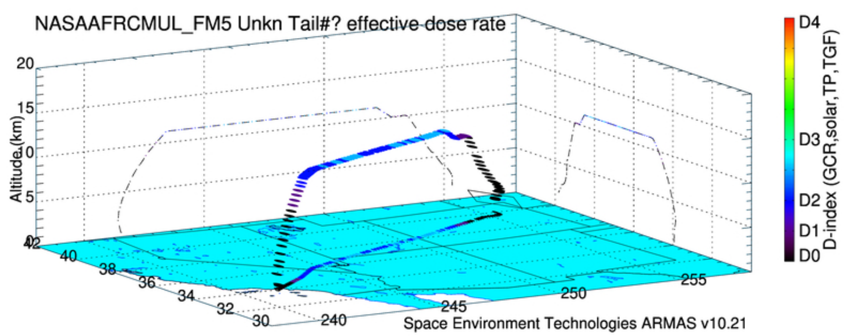
Improving operational data: Calibration of ARMAS Quality factor with the TEPC





Improving operational data: Validation of ARMAS dose rate in tissue with the TEPC





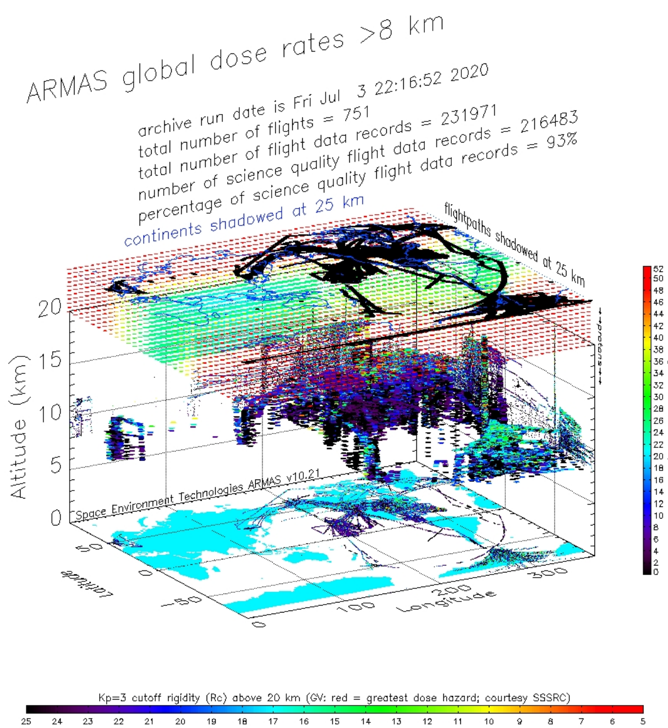
Detector	Date	Flight	Absorbed dose rate dD(Ti)/dt (μGy/h)*	Dose equivalent rate dH/dt (μSv/h)*	Q (unitless)*
TEPC	20 May 2018	LAX – DEN	2.37 ± 0.06	4.69 ± 0.21	1.97 ± 0.04
ARMAS	20 May 2018	LAX – DEN	2.40 ± 0.61	4.73 ± 1.20	1.97 ± 0.03
TEPC	23 May 2018	DEN – LAX	2.51 ± 0.06	5.48 ± 0.25	2.18 ± 0.04
ARMAS	23 May 2018	DEN – LAX	2.39 ± 0.80	4.75 ± 1.59	1.99 ± 0.03
TEPC	27 Mar 2019	LAX – DEN	2.44 ± 0.06	5.59 ± 0.25	2.29 ± 0.05
ARMAS	27 Mar 2019	LAX – DEN	2.40 ± 1.04	4.83 ± 2.09	2.01 ± 0.04
TEPC	06 Apr 2019	DEN – LAX	1.49 ± 0.04	3.34 ± 0.15	2.24 ± 0.04
ARMAS	06 Apr 2019	DEN – LAX	1.24 ± 0.48	2.55 ± 0.98	2.06 ± 0.03
TEPC	14 Jul 2019	LAX – IAD	2.51 ± 0.06	5.56 ± 0.25	2.22 ± 0.04
ARMAS	14 Jul 2019	LAX – IAD	2.48 ± 1.09	5.28 ± 2.32	2.13 ± 0.05
TEPC	19 Jul 2019	IAD – LAX	2.42 ± 0.06	5.30 ± 0.24	2.19 ± 0.04
ARMAS	19 Jul 2019	IAD – LAX	2.48 ± 1.01	5.17 ± 2.10	2.08 ± 0.05
TEPC	09 Sep 2015	Palmdale	4.77 ± 0.21	9.82 ± 0.73	2.06 ± 0.06
ARMAS	09 Sep 2015	Palmdale	4.60 ± 1.02	8.89 ± 1.97	1.93 ± 0.01

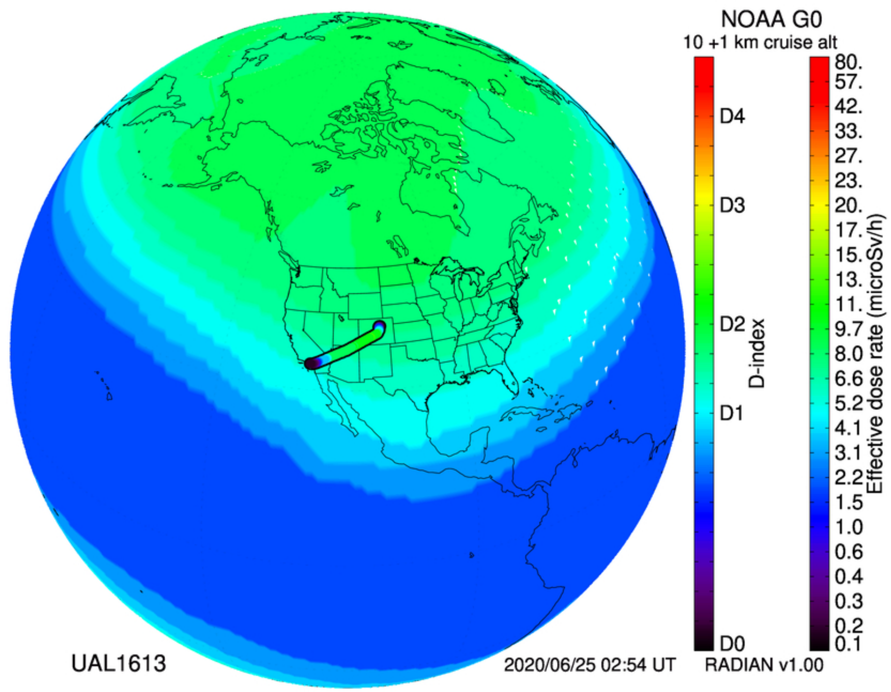
*Average *TEPC* and median *ARMAS* values at cruising altitudes; all flights are commercial except Palmdale ER-2.

Measurements and modeling

Improving global data :
ARMAS v10.21 measurements

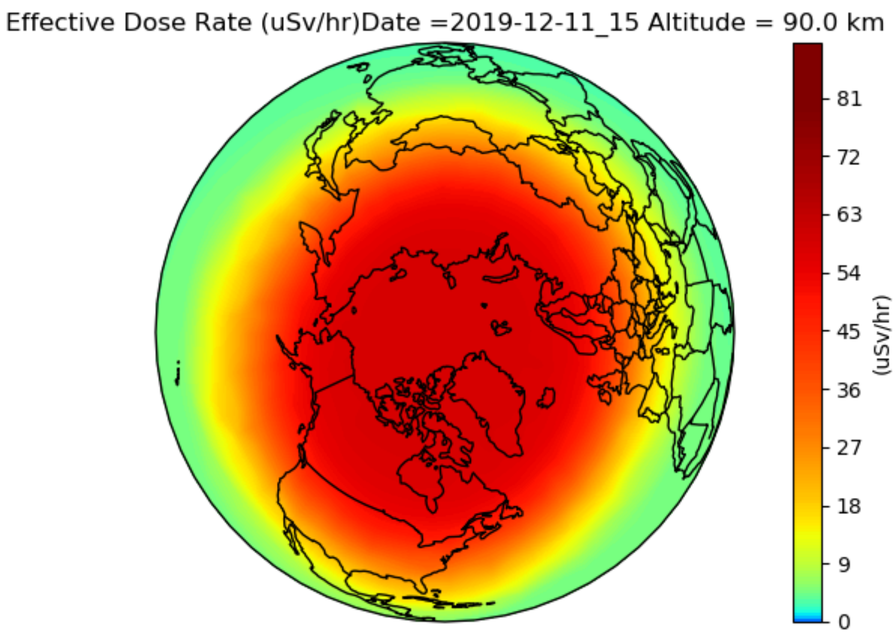
ARMAS global measurements
between 2013-2020



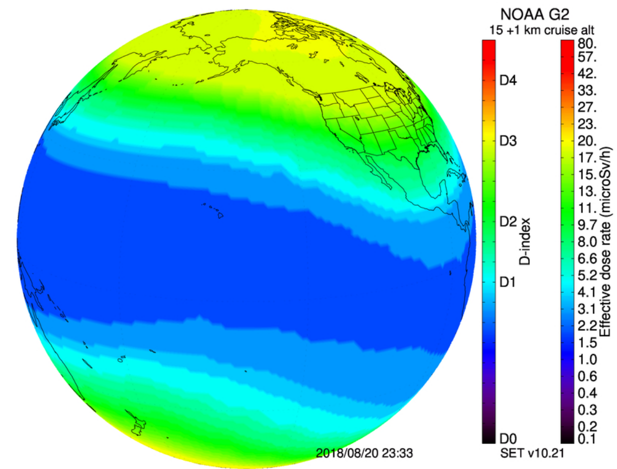


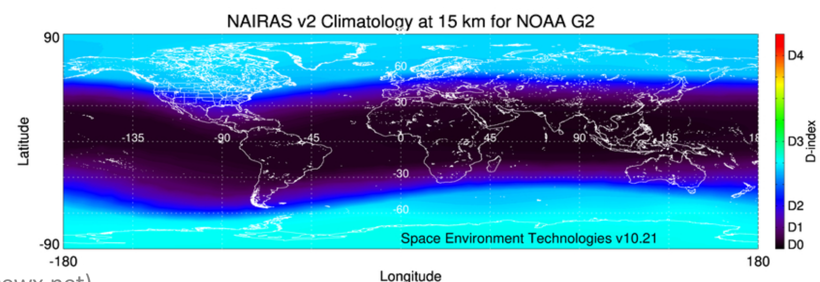
Improving global modeling: NAIRAS

NAIRAS v2 during Blue Origin New Shepard flight



NAIRAS v1 during commercial flight

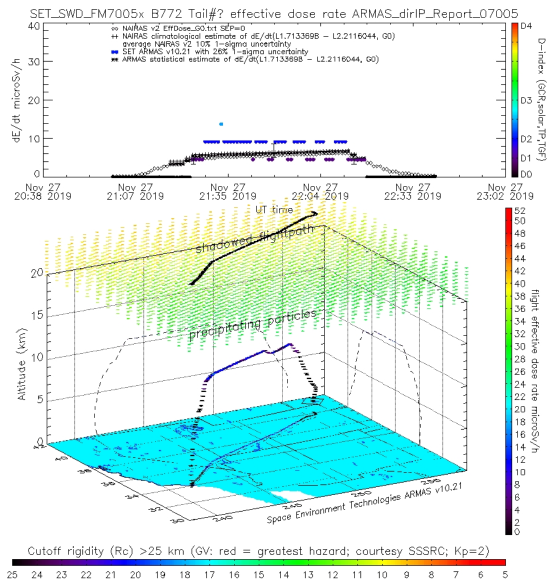




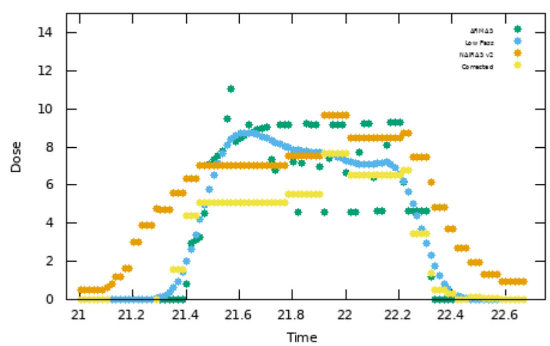
Space Environment Technologies (http://spacewx.net)

Improving radiation weather with RADIAN data assimilation

NAIRAS v1 and ARMAS v10.21



NAIRAS v2 and ARMAS v10.21



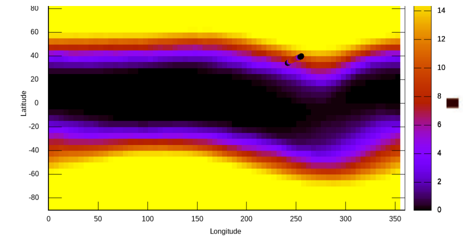
ARMAS v10.21 data is now being assimilated into NAIRAS v2

Height-dependent optimal interpolation solution is used

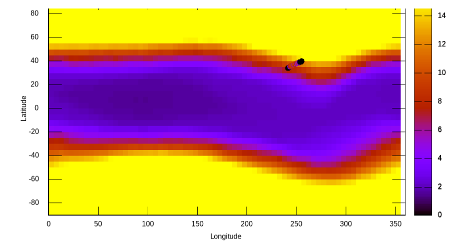
R^2 comparison results:

- ARMAS vs. NAIRAS
  66.9%
- ARMAS vs. corrected NAIRAS
  80.1%
- Low Pass ARMAS vs. NAIRAS
  75.4%
- Low Pass ARMAS vs. corrected NAIRAS
  87.6%

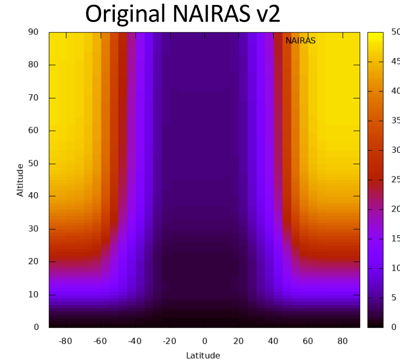
Original NAIRAS v2 plus ARMAS v10.21



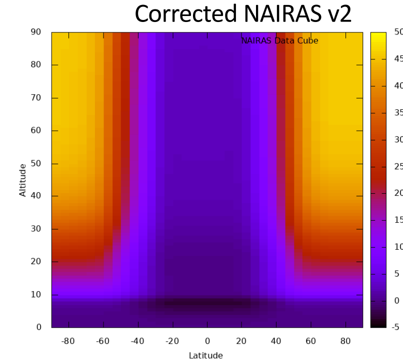
Corrected NAIRAS v2 plus ARMAS v10.21



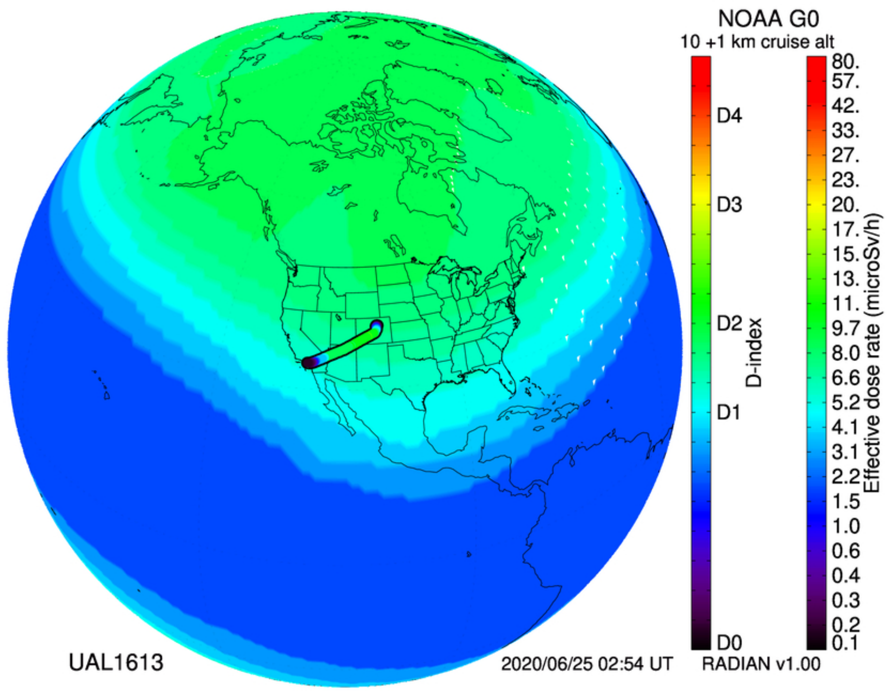
Original NAIRAS v2

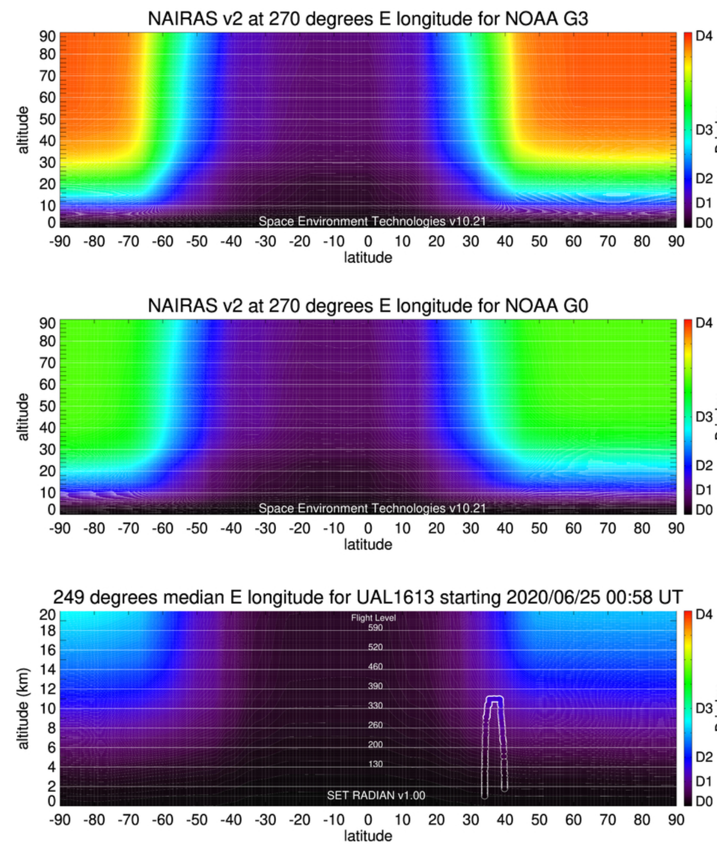


Corrected NAIRAS v2



Improving global weather: RADIAN



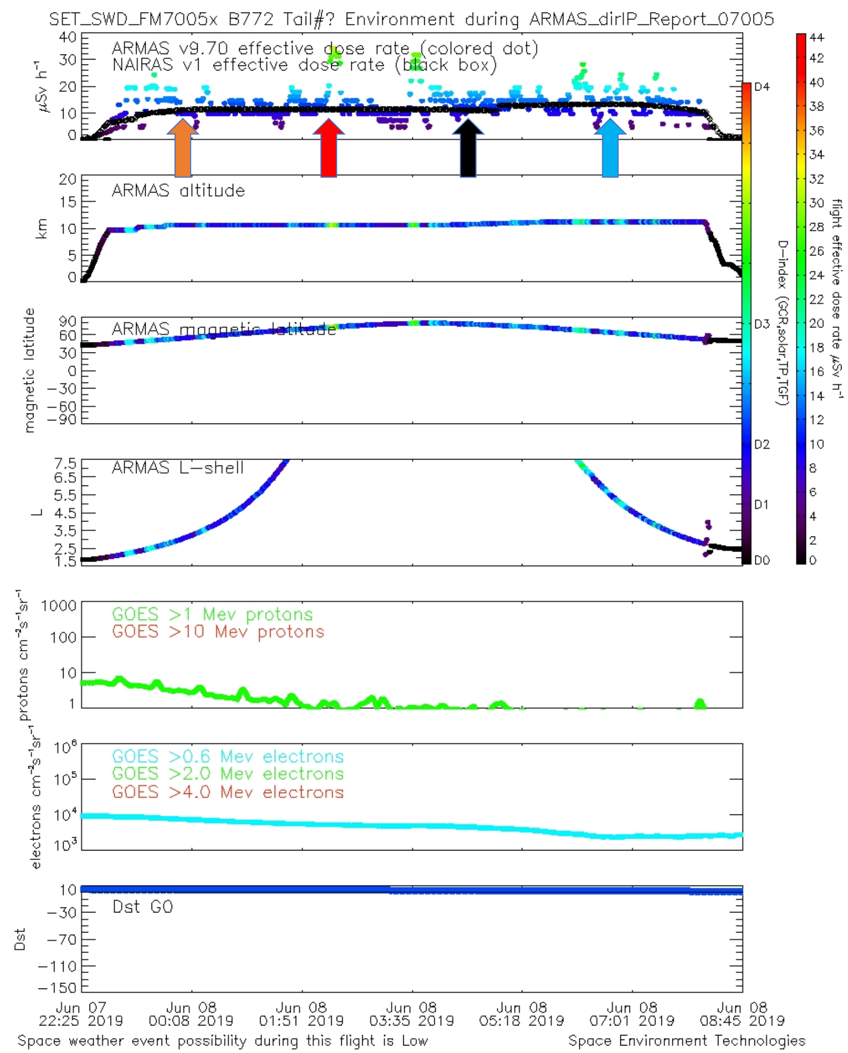


Expanding our scientific understanding

ARMAS

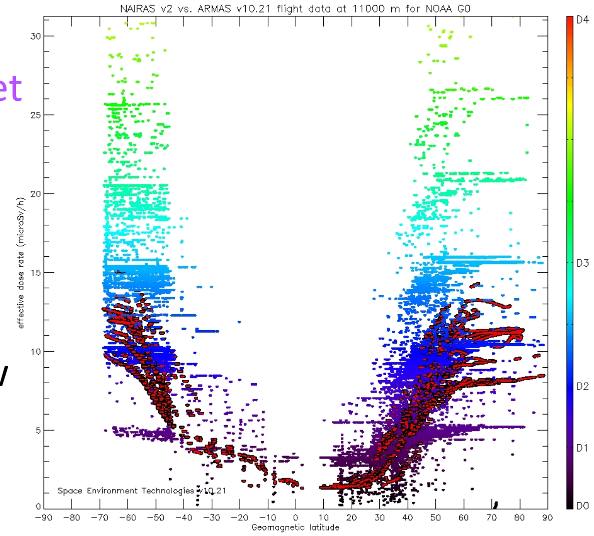
[Improving scientific understanding]: dynamic environment exists even during extremely quiet geomagnetic conditions

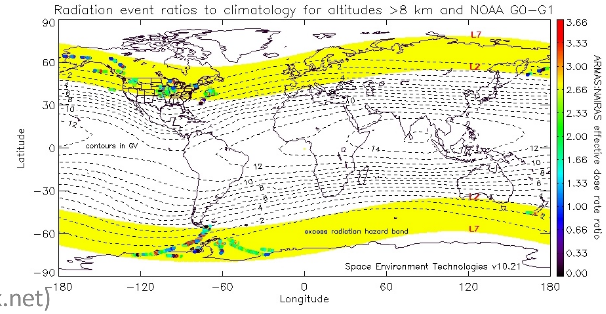
- Strong solar minimum GCR background
- Precipitating higher magnetic latitude particles likely produce more secondary radiation and cause greater accumulated dose compared to GCR background
- Dose rate changes with increasing altitude
- Changes in dose rate with magnetic latitude



Improving scientific understanding:
science questions remain – what is source of excess radiation?

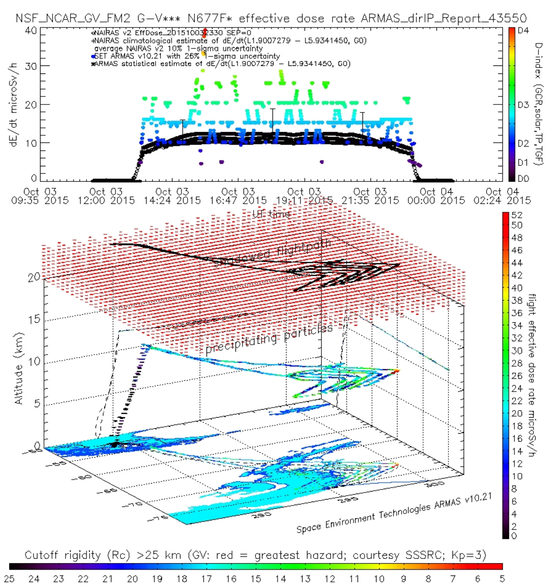
- **Observation**:
  - ARMAS data show large radiation variations even during quiet geomagnetic conditions
- **Hypothesis**:
  - Radiation belt energetic particles at L-shells 2–7 are "leaky" into atmosphere and cause added radiation component
  - Resultant γ-rays cause added tissue exposure hazard for crew
- **Experimentation**:
  - Fly long-duration airborne instruments to monitor a region over the North Pacific and North CONUS air traffic routes (ARMAS Dual Monitor)
  - Physics-based modeling of radiation belt energetic particle precipitation
  - Incorporate measurements into NAIRAS v2 (RADIAN)

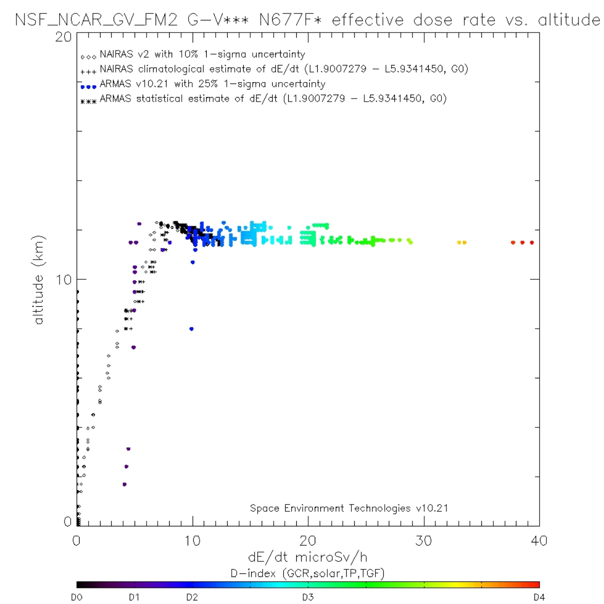


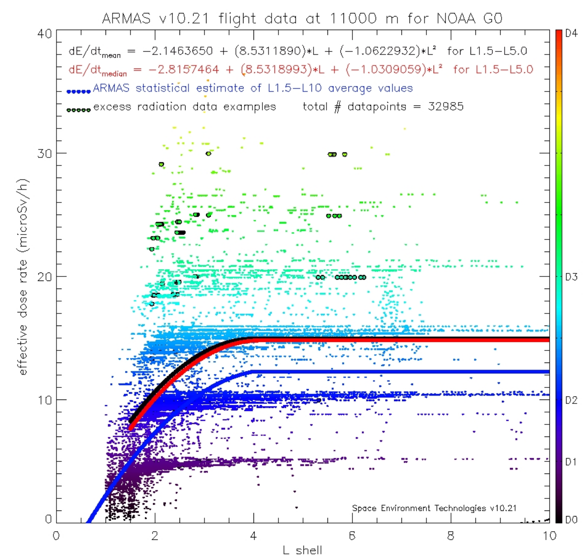


Improving scientific understanding:
Source of excess radiation - observations

- **Observation**:
  - ARMAS data show large radiation variations even during quiet geomagnetic conditions

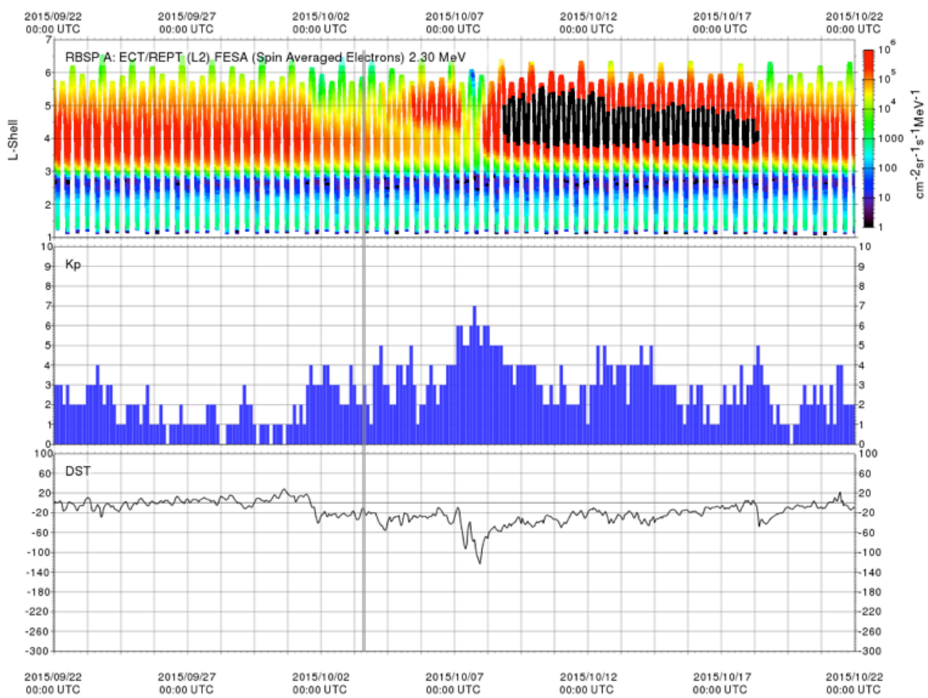


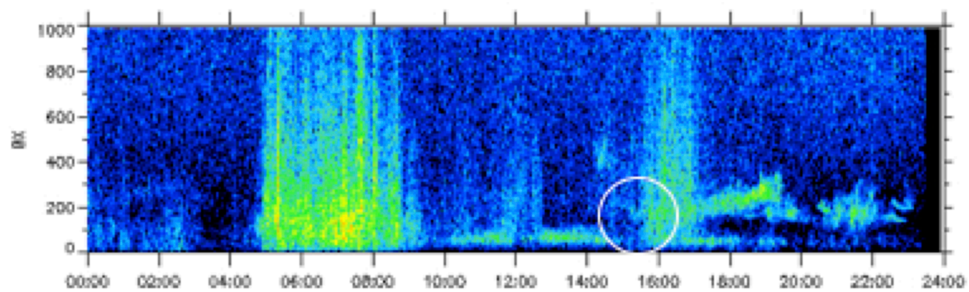




Improving scientific understanding:
Source of excess radiation - hypothesis

- **Hypothesis**:
  - Radiation belt energetic particles at L-shells 2–7 are “leaky” into atmosphere as a result of EMIC waves that cause pitch angle scattering

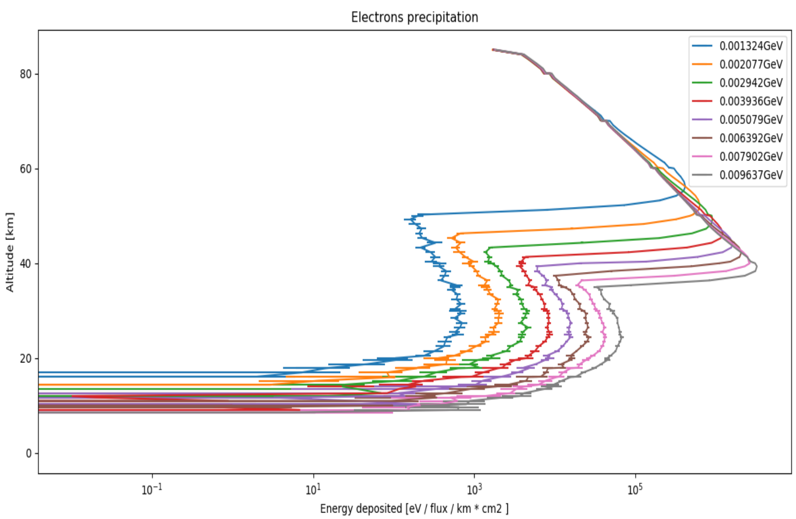




Improving scientific understanding:

Source of excess radiation - hypothesis

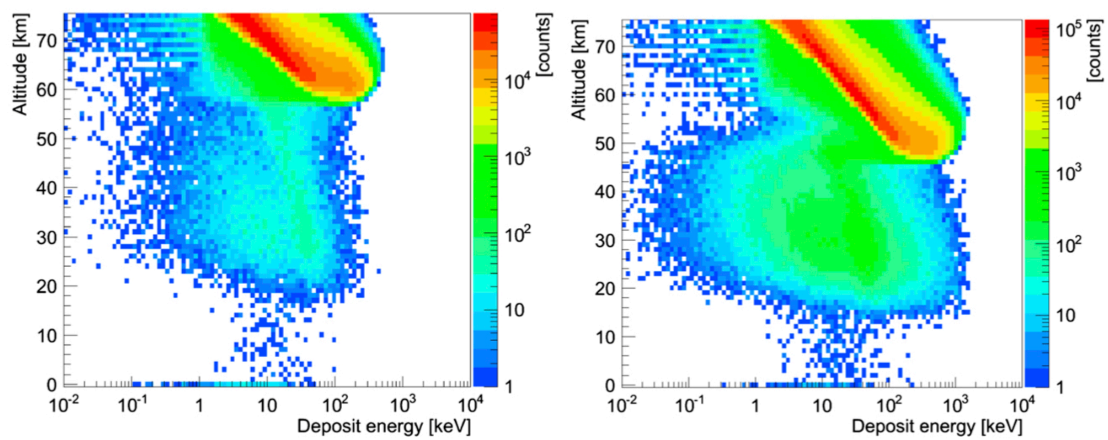
- **Hypothesis**:
  - Electrons precipitation into mesosphere and create resultant Bremsstrahlung γ-rays



Credit: G. Gronoff

0.6 Mev

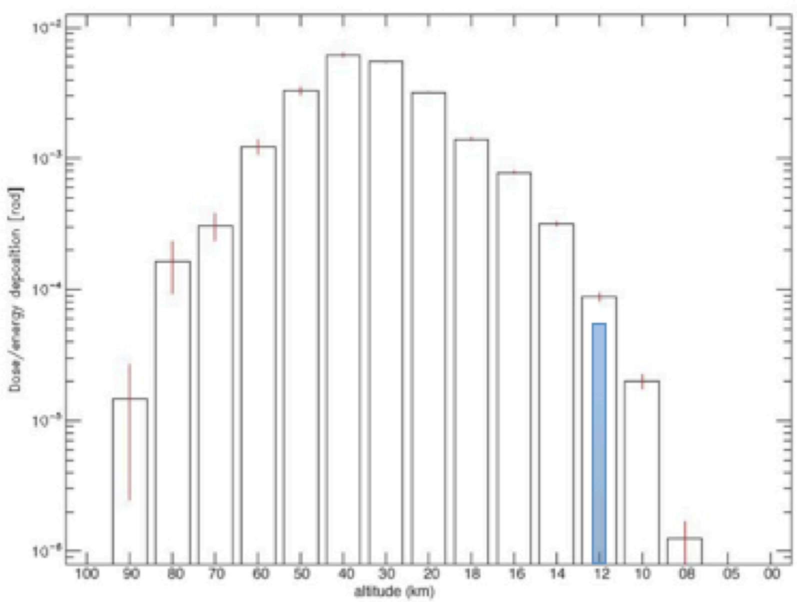
20.0 MeV

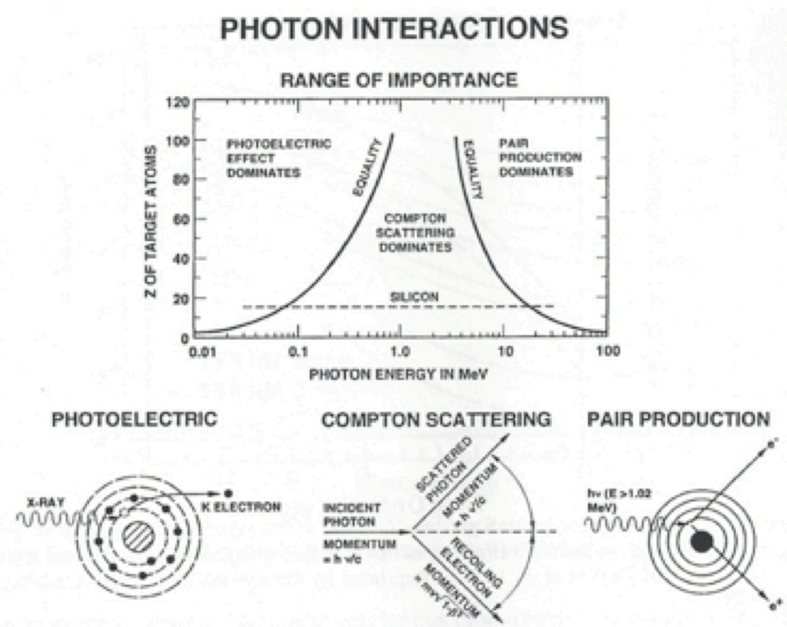


Credit: Tsurutani et al., 2016

Improving scientific understanding:
Source of excess radiation - hypothesis

- **Hypothesis**:
  - γ-rays are at same dose levels as measured by ARMAS detector via Compton scattering in silicon





Improving scientific understanding:
Source of excess radiation - hypothesis

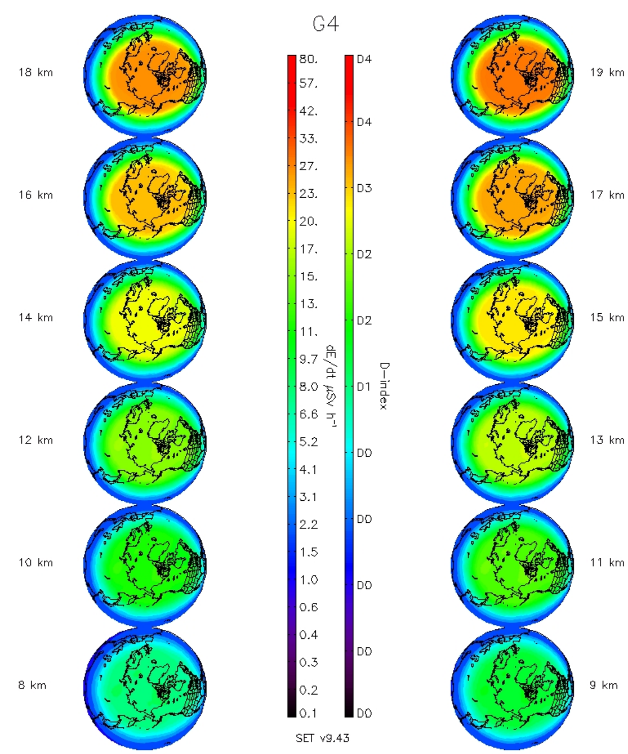
- **Hypothesis**:
  - γ-rays cause added exposure hazard for crew and may be source for shallow tissue cancers
  - Recent cancer risk studies indicate 2X increased incidence of melanoma and other cancers in pilots and aircrew
  - Occupational exposure may contribute to melanomas & basal cell carcinoma
  - Melanoma & basal cell carcinoma induced mostly by photon ionizing radiation
    - **Melanoma and BCC common in the trunk of pilots precluded UV-A source**
    - **GCRs, SEPs not a source since they mostly provide deep tissue dose (and cancers) from penetrating secondary neutrons and protons**
    - **Gamma and X-rays are in the energy range (5.0–0.5 MeV) and can penetrate clothing to give a dose to the underlying skin in the trunk of the body**
    - **Gamma and X-ray source can exist at commercial aircraft altitudes from relativistic electron sources that absorb in the mesosphere and stratosphere to produce hard X-rays and γ-rays**
    - **L-shell band 2–7 appears to be the region of higher exposure risk for shallow skin cancers**
    - **ARMAS technology can locate regions of higher radiation**
    - **Beams can be avoided if locations are known**

Improvements to achieve forecasting accuracy

Improvements to achieve forecasting accuracy

Users: aircrew (quicklook) and flying public

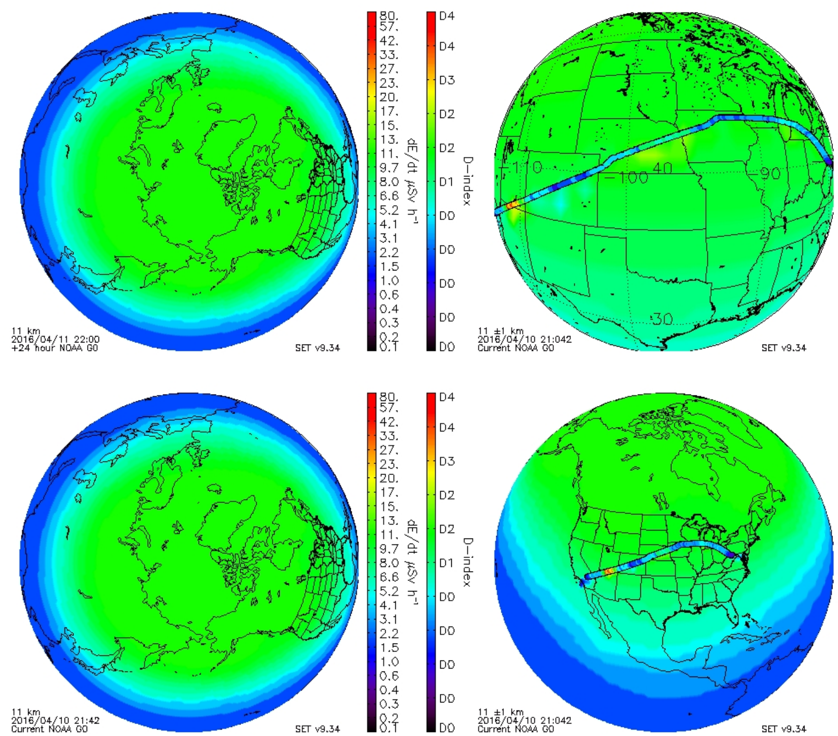
- Climatology forecast
- NAIRAS color-scheme
- D-index and associated effective dose rate scales
- Shows current NOAA G-scale level of activity
- 1-km steps from 8–19 km
- Northern or southern hemisphere view



Future directions for nowcasting and forecasting

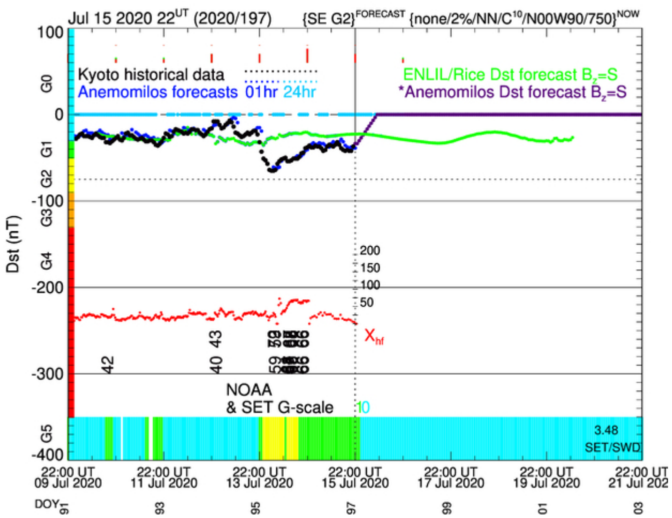
Users: air traffic management, company operations, pilots

- 24-hour forecast (climatology, top left)
- Current epoch (specification, bottom left)
- Flight track (due diligence archive, top right)
- Regional track (situational awareness, bottom right)

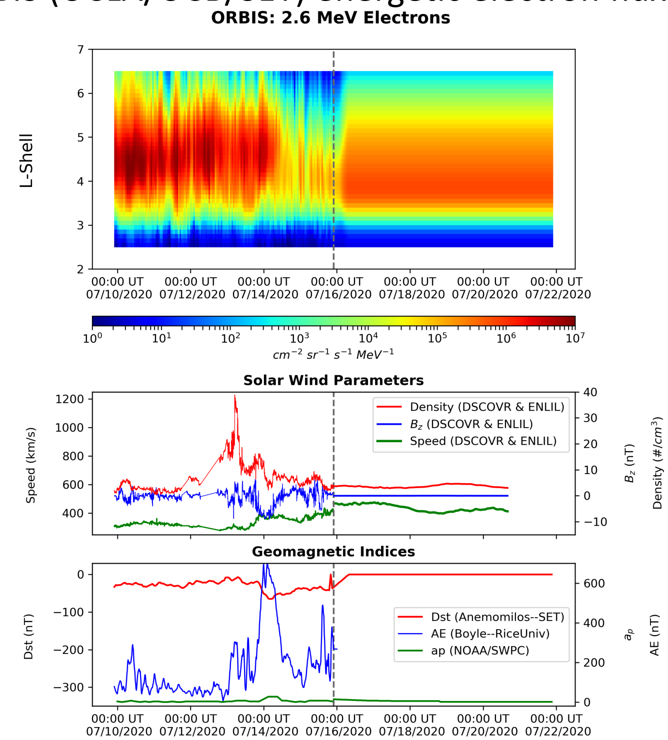


Improving radiation forecasting: ORBIS produces energetic electrons and protons with neural net algorithm driven by Dst

Historical, current, and forecast Dst



ORBIS (UCLA/UCB/SET) energetic electron fluxes



- Historical, current, and forecast Dst is ingested into a neural net algorithm to create the particle fluxes trained on RBSP data
- Particle fluxes will be used as a driver to NAIRAS v2 trapped particle environment along with GCRs, SEPs, and cutoff rigidity

Enterprise collaborations

Improving public access with NASA ARC Interactive Database of Atmospheric Radiation Dose Rate

PI: Irina N. Kitiashvili (NASA/Ames-BAERI), Co-Is: Viacheslav M. Sadykov, Nagi N. Mansour

Project Goal and Objectives

Develop a convenient, user-friendly and reliable infrastructure, that will provide dynamical intuitive access to measurements of the solar radiation flux in the Earth atmosphere at high altitudes, obtained with the Automated Radiation Measurements for Aerospace Safety (ARMAS) device (Tobiska et al., 2015-2018) together with quick analysis and visualization tools based on the HelioPortal Web platform (https://helioportal.nas.nasa.gov/) originally developed as a multi-instrument database of solar flares (Sadykov et al., 2017).

Major Tasks

1. Development of the radiation database design

The web page will be designed for convenient and fast access to the data. It will be expandable to new data, and scalable to large data volumes expected in the future.

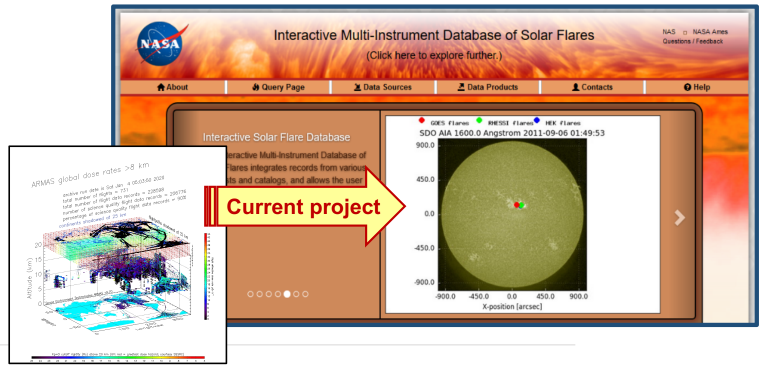
2. Development of the front-end search engine and visualization tools including data processing and classification procedures

The search tool will return the user query results in the form of a table according to specified criteria. It will provide the capability to visualize and download the output data in a variety of formats

3. Integration of the Radiation Database to HelioPortal and public release

NASA HelioPortal

https://helioportal.nas.nasa.gov/



Milestones

September, 2019: Develop the initial design of the radiation database, build the database prototype (completed)

January, 2020: Complete development of the database search and basic data processing codes and tools (Task1).

March, 2020: Develop of visualization and more advanced data processing tools (Task 2).

July, 2020: Complete the database optimization and integration into the HelioPortal, provide link to the solar events database, and public release (Task 3).

Improving Enterprise Partnerships: agency, industry, university collaborations are at the forefront of radiation monitoring progress

NAIRAS has provided a scientific foundation:

- ✓ Agency (NASA LaRC), university (CISM), industry (SET)
- ✓ Provides currently available public service data
- ✓ Provides customer-tailored products and services (multiple routes, altitude plots)
- ✓ Operating NAIRAS v2 backup from SET servers (Q4 2019)

ARMAS has provided real-time measurement access:

- ✓ Industry (SET), agency (NASA HPD, SBIR, FO, LaRC, ARC, AFRC), university (PVAMU, OSU)
- ✓ Fabrication, testing and deployment of ARMAS FM7 (2018–2019)
- ✓ Released ARMAS FM7 app (v1 FM7 data retrieval Q4 2019)
- ✓ Develop ARMAS public app (v2 public use for situational awareness Q1 2020)
- o HelioPortal data access to atmospheric radiation database (Q3 2020)
- o ARMAS Dual Monitor operational technology demo (July 2021)

RADIAN has provided a global radiation weather capability:

- ✓ Industry (SET, SolarMetrics, AER), agency (NASA HPD SBIR, LaRC, GSFC/CCMC, FAA, USAF/AFRL), university (UCLA/UCB, USU), international (KSWC)
- ✓ ORBIS current and forecast radiation belt particle populations for NAIRAS v2
- ✓ Calibrate ARMAS v10 to TEPC and quantify uncertainty (Q2 2020)
- o NSET forecast effective dose rates for high-flyers (2019 – 2024)
- o Develop RADIAN ensemble modeling (2020 – 2022)
    - New operational data sources for assimilation (REACH, FMx on new platforms)
    - Ensemble modeling to characterize uncertainty and improve accuracy (CARI-7, KREAM)

Backup slides

Improving Enterprise activities: NASA's NAIRAS, ARMAS, RADIAN, ORBIS and HelioPortal Programs & USAF NSET Program

NASA Programmatic Goals related to radiation:

- make advances in science, technology, and exploration
- make space missions safer and improve NASA's future capabilities

Enterprise-level Value Proposition:

- astronauts, high-altitude pilots, commercial aviation crew and passengers, and commercial space travelers need real-time radiation weather information
- a per user low-cost capability can be provided with operational radiation environment monitoring that generates data for assimilation into global models and creates air and space traffic management decision-aid tools

NASA-funded programs lay foundation for aerospace radiation monitoring:

1) NAIRAS: NASA LaRC (C. Mertens, PI) global radiation model
2) ARMAS: SET (K. Tobiska, PI) global radiation measurements
3) RADIAN: SET (K. Tobiska, PI) ARMAS data assimilation into NAIRAS
4) ARMAS Dual Monitor: SET (K. Tobiska, PI) 30-d & 65,000 ft. monitoring tech demo
5) ORBIS: UCLA (J. Bortnik, PI) dynamic radiation belt forecasting
6) HelioPortal: NASA/Ames-BAERI (I. Kitiashvili, PI) interactive database of atmospheric radiation

USAF-funded program expands aerospace radiation monitoring:

7) NSET: AER (R. Quinn, PI) atmospheric radiation forecasting for high-flyers

Typical Annual Occupational Doses

Source	Dose (mSv)
Artificial sources	
Nuclear industry	
Uranium mining	4.5
Uranium milling	3.3
Enrichment	0.1
Fuel fabrication	1.0
Nuclear reactors	1.4
Reprocessing	1.5
Medical uses	
Radiology	0.5
Dentistry	0.06
Nuclear medicine	0.8
Radiotherapy	0.6
Industrial sources	
Irradiation	0.1
Radiography	1.6
Isotope production	1.9
Well-logging	0.4
Accelerators	0.8
Luminizing	0.4
Natural sources	
Radon sources	
Coal mines	0.7
Metal mines	2.7
Premises above ground (radon)	4.8
Cosmic sources	
Civil aircrew	3.0

Data for 1990–1994 Source: UNSCEAR Report 2000, Vol. 1, Annex E, Tables 12, 16, 22 and 43

Doses on flights

Cities	Effective Dose (µSv)
Vancouver ➤ Honolulu	14.2
Frankfurt ➤ Dakar	16.0
Madrid ➤ Johannesburg	17.7
Madrid ➤ Santiago de Chile	27.5
Copenhagen ➤ Bangkok	30.2
Montreal ➤ London	47.8
Helsinki ➤ New York (JFK)	49.7
Frankfurt ➤ Fairbanks, Alaska	50.8
London ➤ Tokyo	67.0
Paris ➤ San Francisco	84.9

Source: Exposure of Aircraft Crew to Cosmic Radiation, a report of the EURADOS Working Group 5 to the Group of Experts established under Article 31 of the Euratom Treaty. European Commission

http://www.iaea.org/Publications/Booklets/RadPeopleEnv/pdf/chapter_9.pdf

Measurements – ground-based: creating portions of the mixed radiation field aboard aircraft

- Los Alamos Neutron Science Center (LANSCE)
  - 1–800 MeV neutrons
- Loma Linda University Medical Center (LLUMC)
  - 200 MeV protons
- Lawrence Livermore National Laboratory (LLNL)
  - 1.17 & 1.33 MeV gamma-rays
- Brookhaven NASA Space Radiation Laboratory (NSRL)
  - 1 GeV Fe^{+}