The Atmospheric Ionizing Radiation Environment (AIRE) Institute

Eric Benton[1], Kyle Copeland[2,1], and Brad “Buddy” Gersey[3,1]

[1]Oklahoma State University, Department of Physics, Stillwater, OK USA

[2]U.S. Federal Aviation Administration, Civil Aerospace Medical Institute, Oklahoma City, OK USA

[3]Founders Classical Academy, Flower Mound, TX USA

The Atmospheric Ionizing Radiation Environment (AIRE) Institute

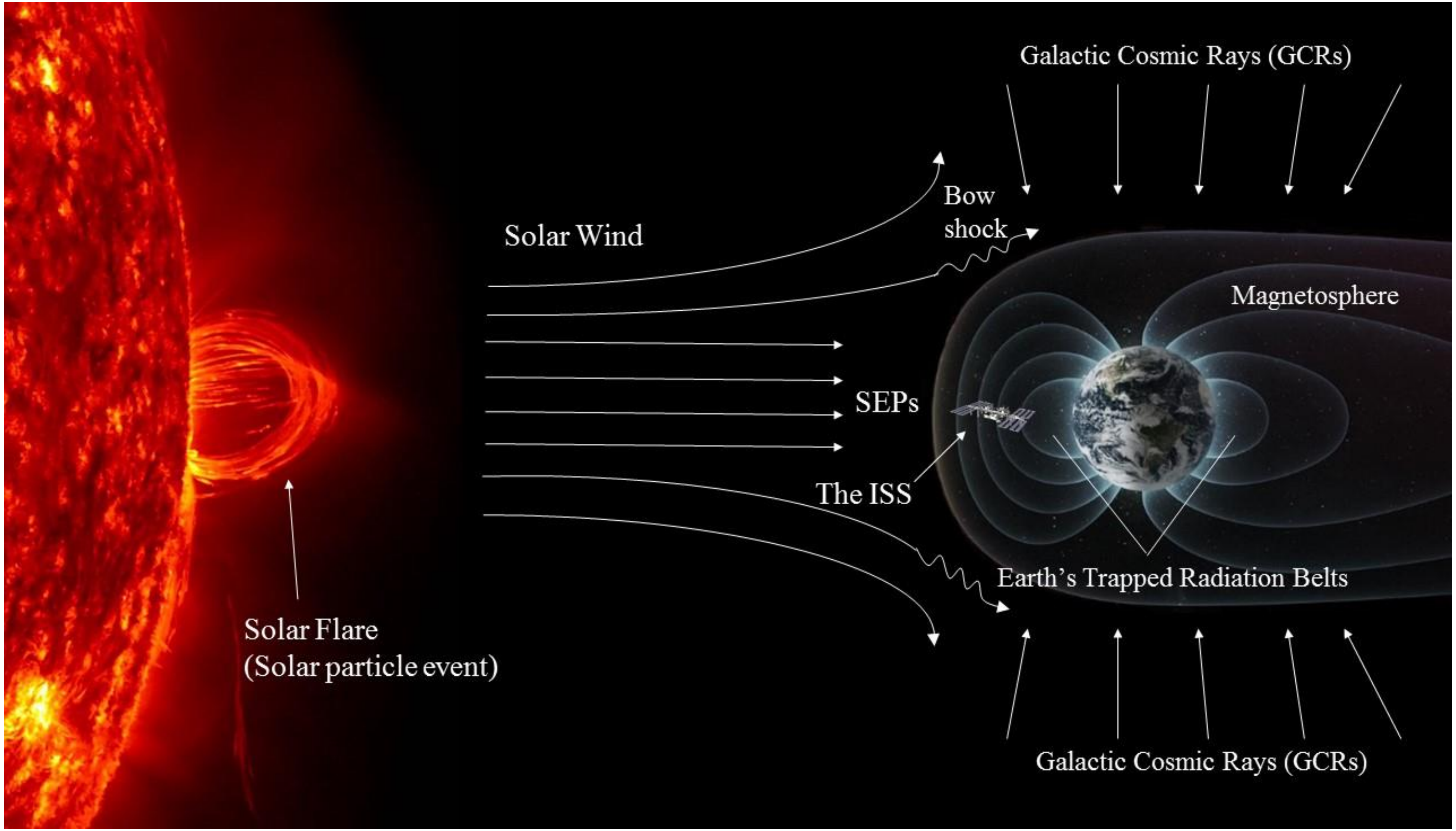
Mission Statement: The Atmospheric Ionizing Radiation Environment (AIRE) Institute's mission is to promote research and education on the Steady State Atmospheric Ionizing Radiation Environment (SSAIRE), its effects on life, on our technological infrastructure and on the environment.

The Atmospheric Ionizing Radiation Environment (AIRE) Institute

- Established at Oklahoma State University in 2021.
- Only group in the USA dedicated to studying the Steady State Atmospheric Ionizing Radiation Environment (SSAIRE).
    - US is behind many other countries (especially in Europe) in this area.
- Different focus from traditional Cosmic Ray research:
    - emphasis is on lower energy SSAIRE, not on higher energy Extensive Air Showers,
    - includes geomagnetic effects, Solar Particle Events (SPE), space weather effects (e.g. Forbush decreases, geomagnetic storms, diurnal effects), Terrestrial Gamma Flashes (TGF) and related thunderstorm phenomena.
- The AIRE Institute is not advocating more regulation (e.g. radiation exposure limits for air crew).
- The AIRE Institute is advocating the need for expanded research into SSAIRE phenomena.

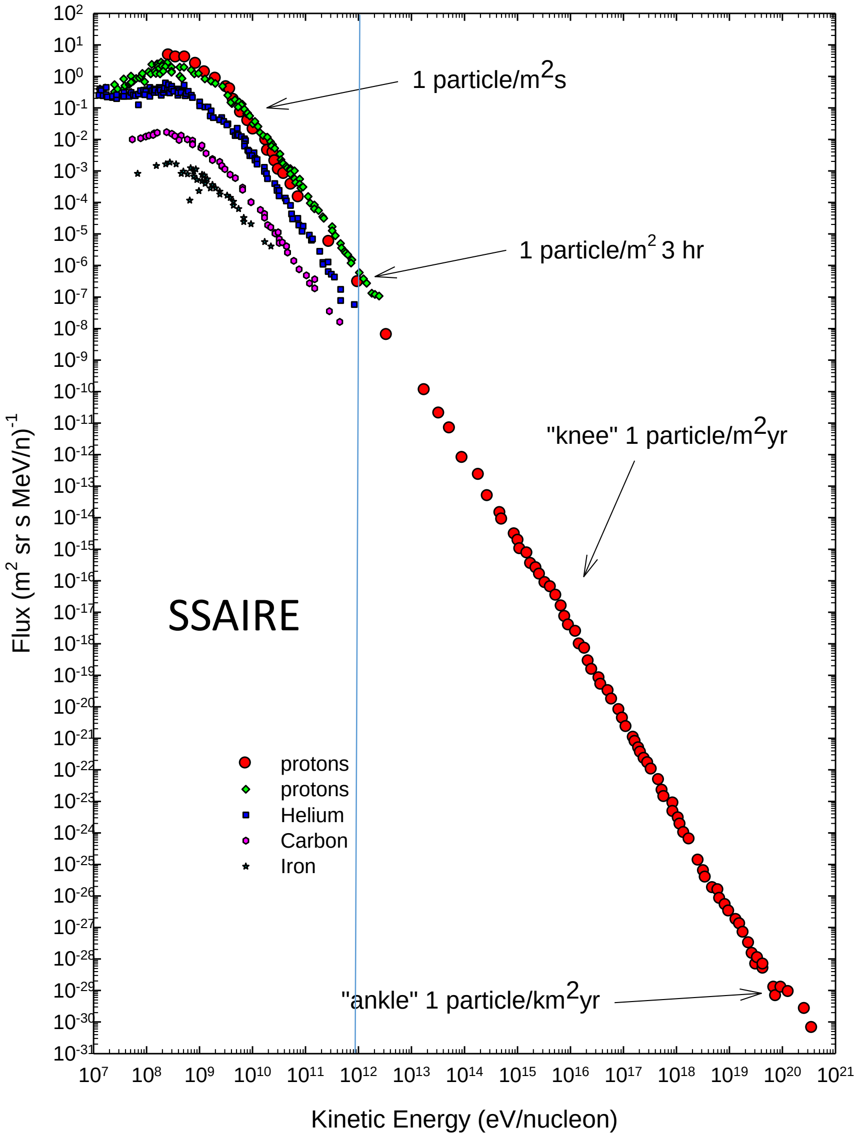
The Steady State Atmospheric Ionizing Radiation Environment (SSAIRE)

- The Steady State Atmospheric Ionizing Radiation Environment or SSAIRE is the name we have given to the ever-present radiation field that permeates our atmosphere.
- The SSAIRE is extremely complex and varies "gradually" as functions of:
  - Altitude
  - Geographic Coordinates (geomagnetic location)
  - Time
- The SSAIRE can be thought of as the "average" radiation field at a given location and time.
- Most of the time the SSAIRE is produced by Galactic Cosmic Rays (GCR) with kinetic energy ≤1 TeV, GCR of higher energy being too rare to make a significant contribution to the average.



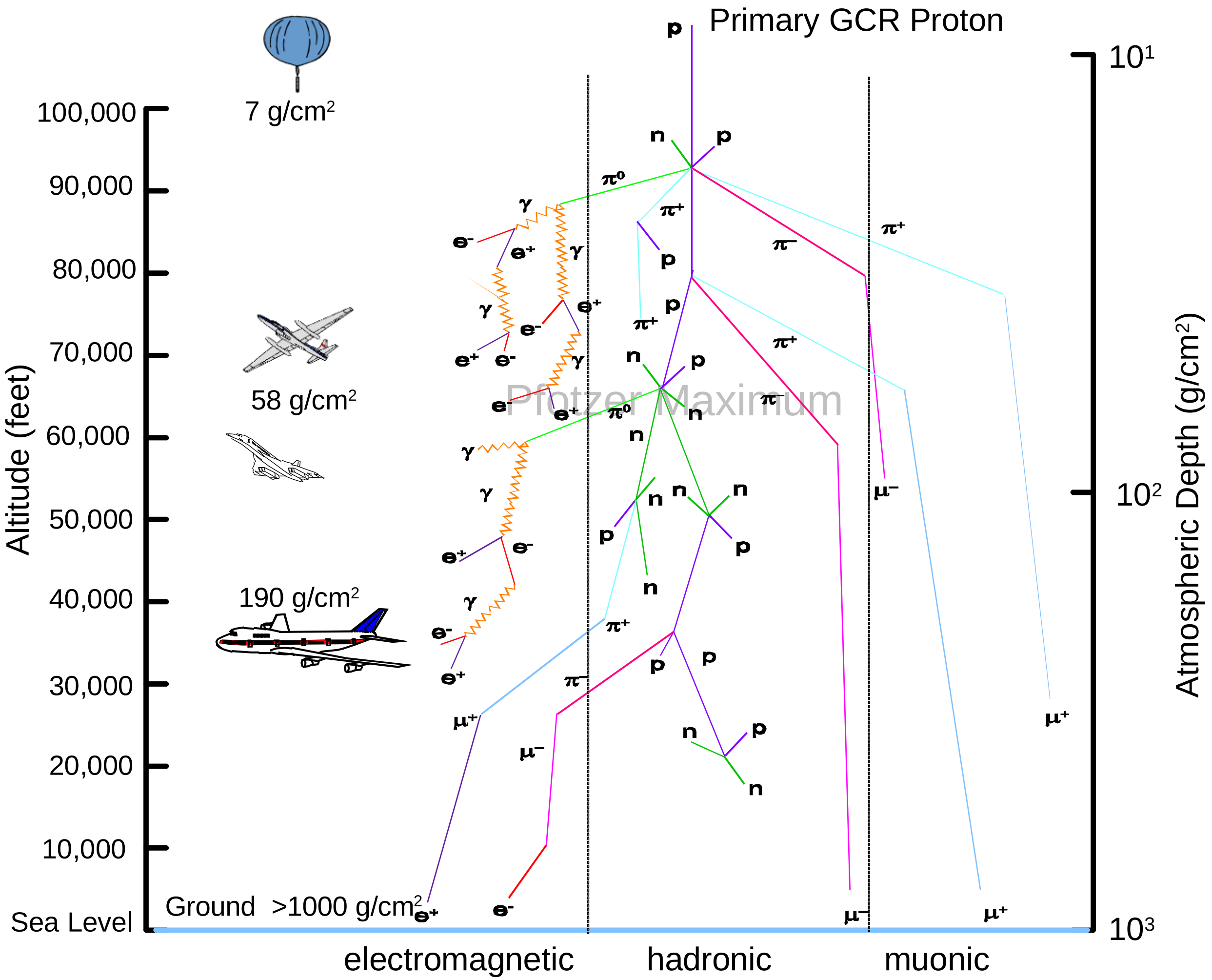
The three major sources of ionizing radiation present in near-Earth space: 1) galactic cosmic rays, 2) solar particle events, and 3) Earth's trapped radiation belts (nowhere near to scale).

GCR Energy Spectra

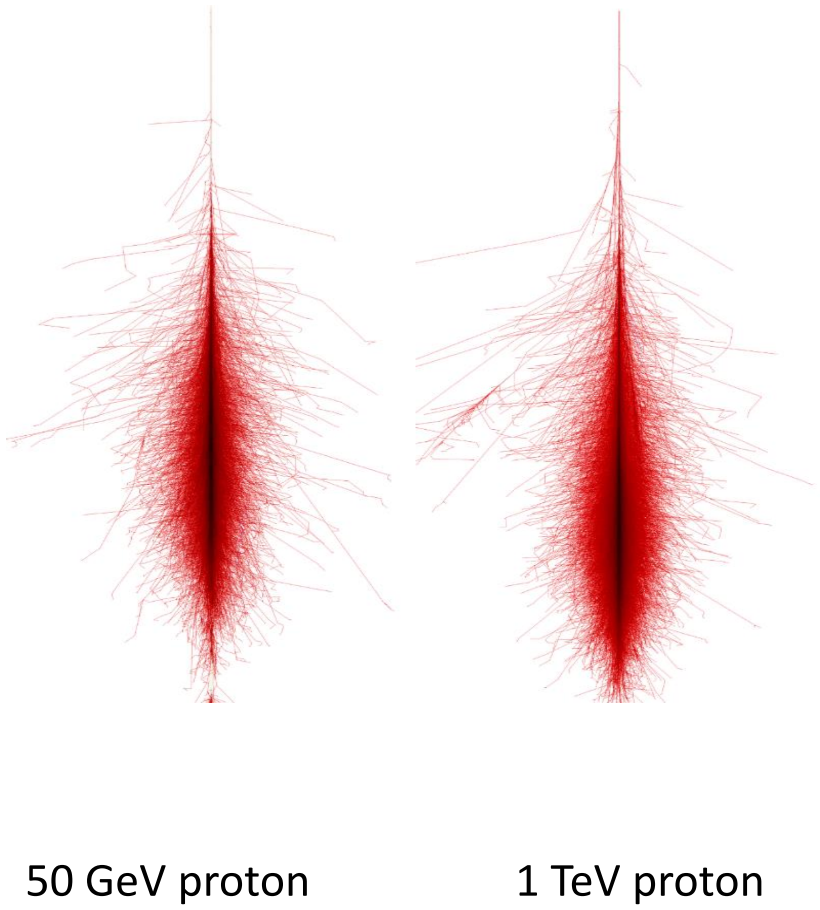


adapted from [Simpson, 1983]

Cosmic Ray Air Showers



A diagram of a cosmic ray air shower illustrating the hadronic, electromagnetic and muonic cascades.



CORSIKA MC code simulations of proton-initiated air showers [CORSIKA website].

$$p + A \rightarrow N_n n + N_p p + N_{\pi^\pm} \pi^\pm + N_{\pi^0} \pi^0 + N_{K^\pm} K^\pm + N_{K^0} K^0 + N_\gamma \gamma$$

where A represents a target nucleus in the air (usually N or O) and N is the number of secondary particles of each subscripted species.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu,$$

and

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu,$$

where μ+ and μ- are positively and negatively charge muons, respectively and ν_μ and are the μ neutrino and μ anti-neutrino, respectively.

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu,$$

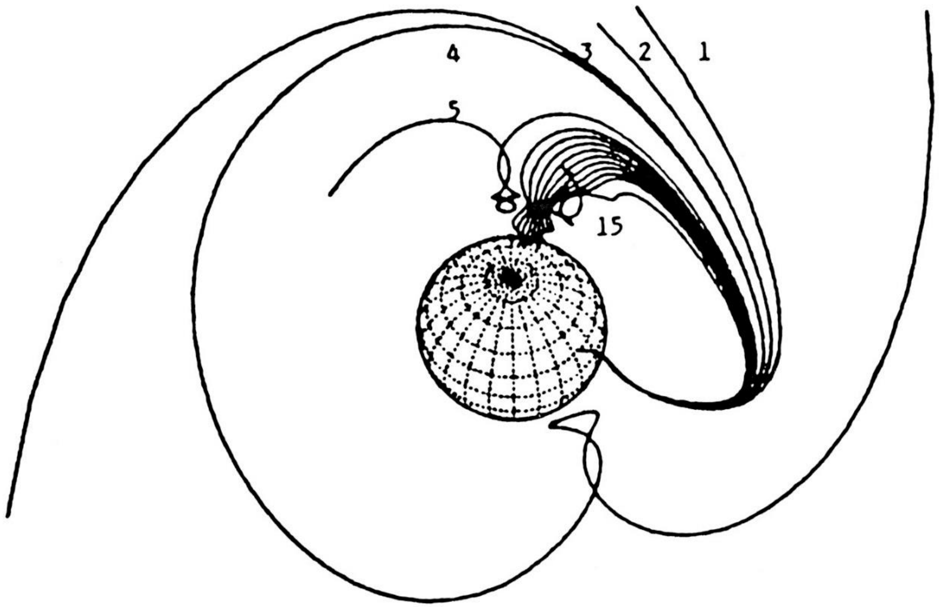
and

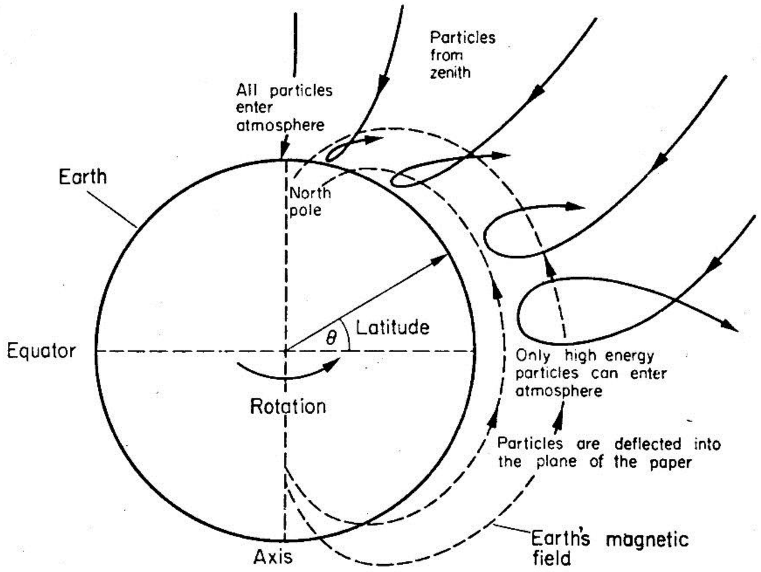
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu,$$

where ν_e and $\bar{\nu}_e$ are the electron neutrino and antineutrino, respectively.

$$\pi^0 \rightarrow 2\gamma$$

Effect of Geomagnetic Field on Incident GCR



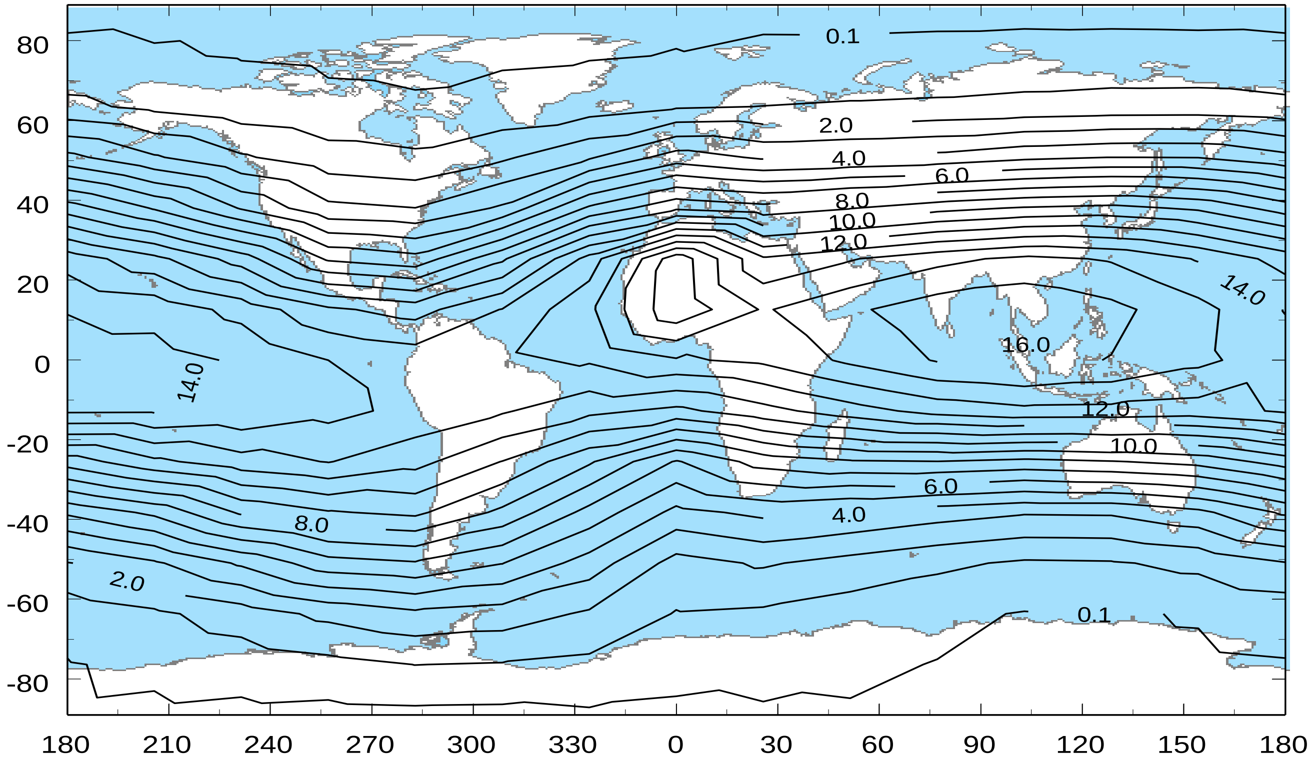


Computer simulations of cosmic ray trajectories interacting with the geomagnetic field prior to penetrating the top of the atmosphere [Shea & Smart].

GCR of a given energy can reach the top of the atmosphere above the poles, but will be deflected away at lower geomagnetic latitudes [Littlefield & Thorley, 2014].

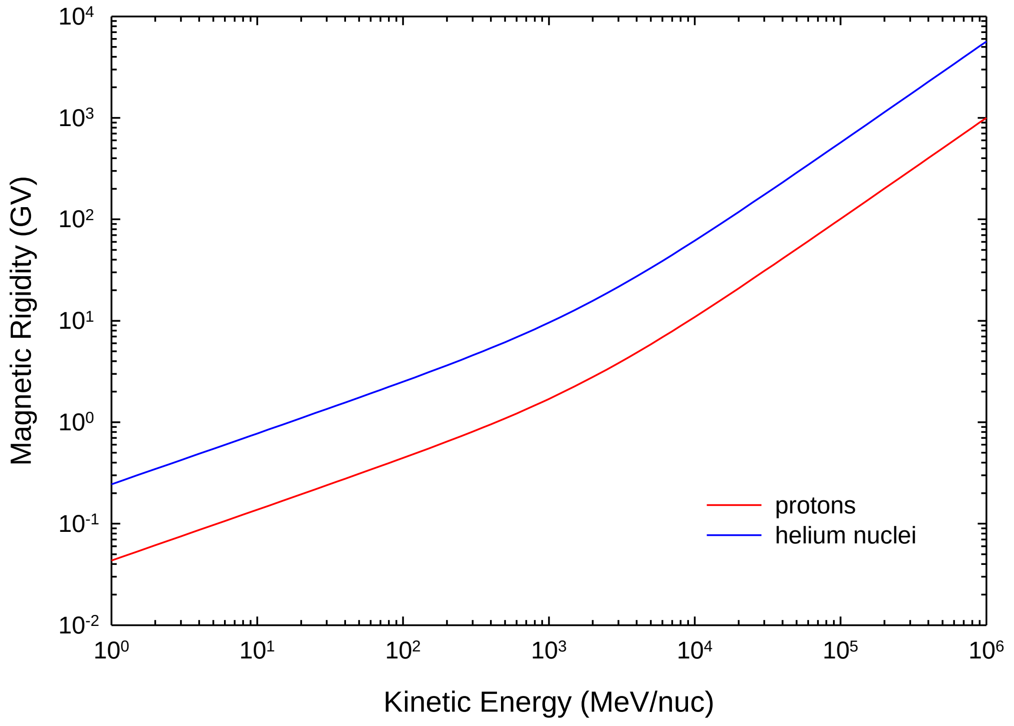
Magnetic Rigidity and Geomagnetic Cutoff Rigidity

$$R = \frac{pc}{Ze} \text{ (GV)}$$

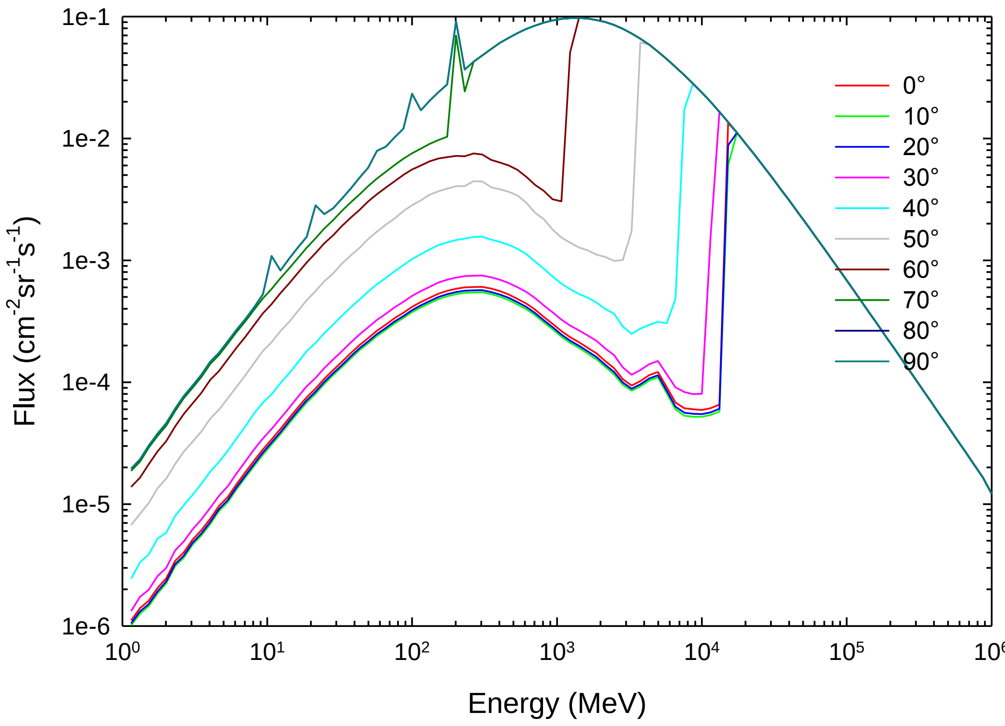


Vertical geomagnetic cut-off rigidity (in GV) as a function of geographic location at 20 km altitude for solar minimum, adapted from [Shea and Smart].

Magnetic Rigidity and Geomagnetic Cutoff Rigidity

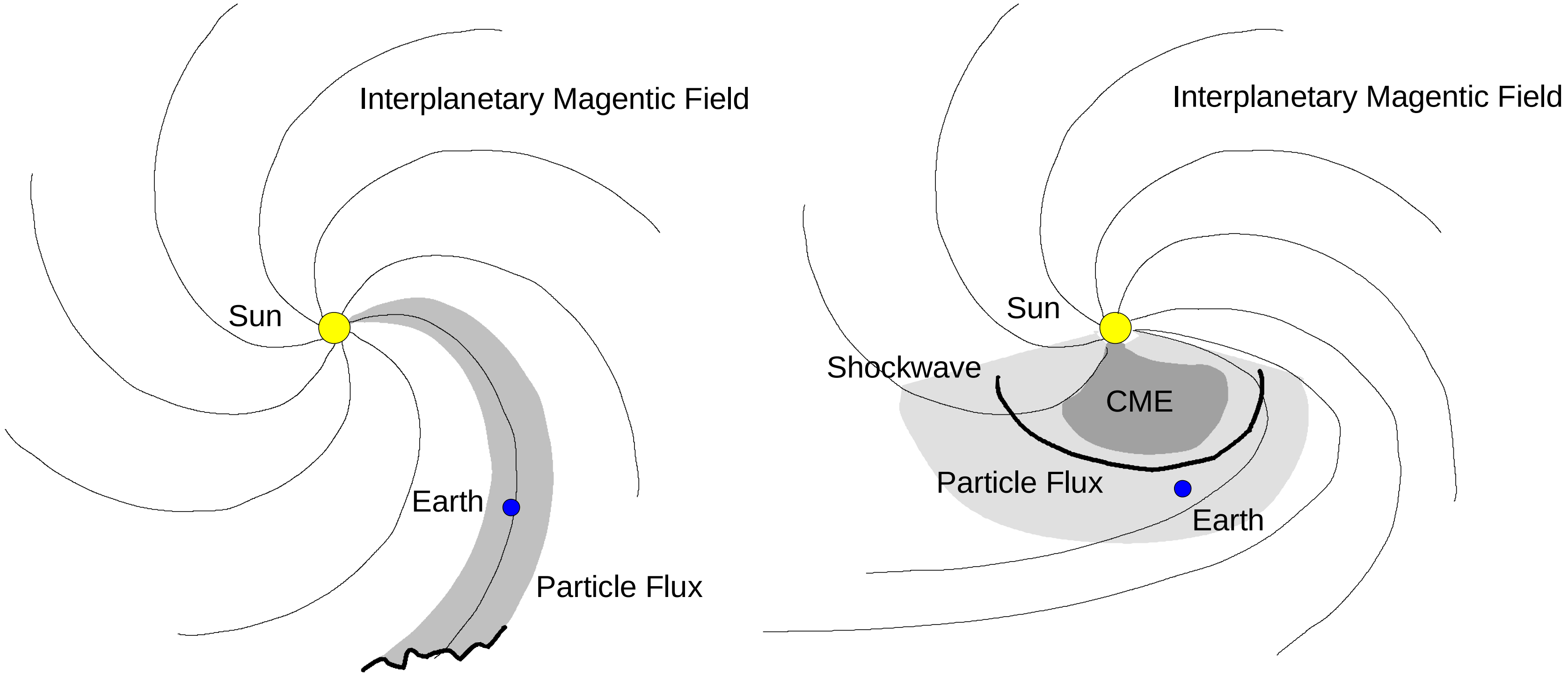


Magnetic Rigidity as a function of cosmic ray kinetic energy for protons and helium nuclei.



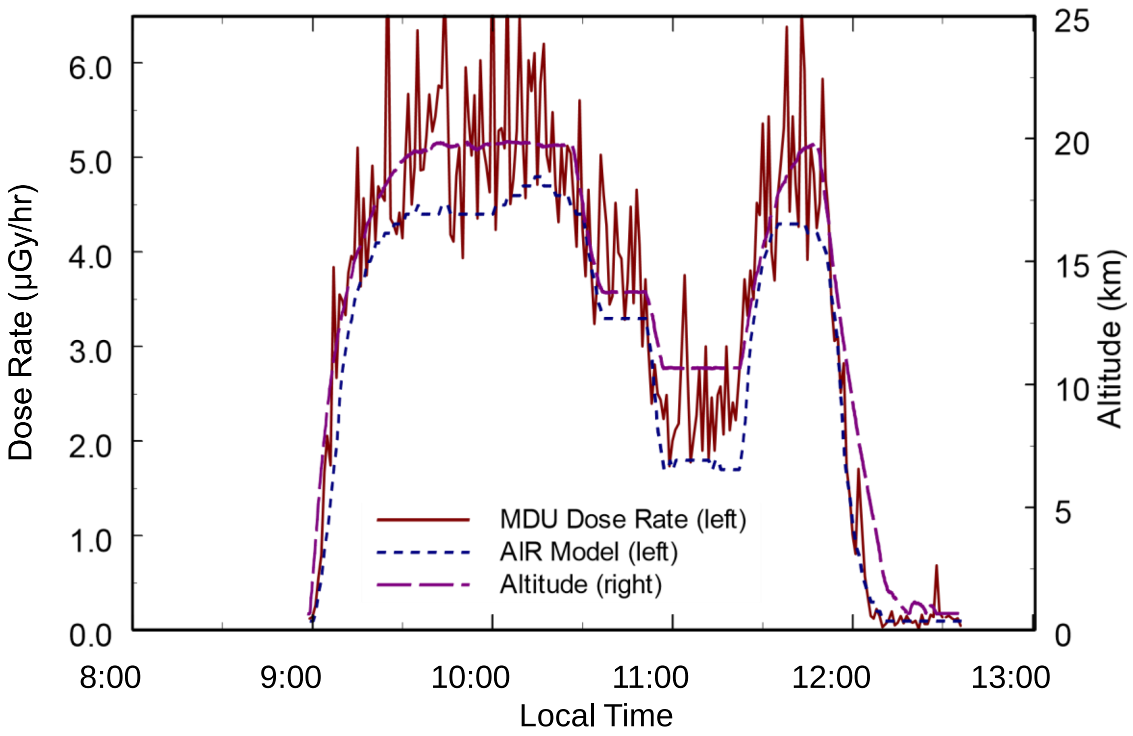
AIREC model calculation of the primary and secondary proton energy spectrum during solar maximum at 90 km altitude, 0° longitude and at 10° increments of latitude from the equator to the North pole.

Two Types of Solar Particle Event (SPE)



The two types of SPE: An SPE associated with an Impulsive Solar Flare, dominated by energetic electrons (left), and an SPE associated with a Coronal Mass Ejection, dominated by energetic protons (right), not to scale.

Representative Atmospheric Dosimetry Measurement



Absorbed dose rate as measured by a Liulin-4 Si spectrometer and altitude as functions of time for a high altitude NASA ER-2 flight over central California. Also shown is dose rate as a function of time as calculated using a NASA computer model. The individual peaks illustrate the variation due to individual air showers.

Open Questions Regarding the SSAIRE

- Health effects on air crew and passengers,
- Effects in electronics/avionics,
- Particle fluxes and multiplicities as function of primary particle type and energy,
- Average height and altitude spread of primary particle first interaction,
- Lateral, as well as vertical structure of air showers, degree of shower overlap as functions of time, angle, altitude, geographic location, weather conditions, etc.,
- Empirical data with which to validate both dosimetric and physics models,
- Temporal variation on various different time scales,
- Effect of ion concentration in the atmosphere (effects on weather and climate),
- Role of major SPEs in modifying SSAIRE,
- "New" phenomena associated with thunderstorms (e.g. Terrestrial Ground Enhancements (TGE) and Terrestrial Gamma Flashes (TGF)),

- SSAIRE consists of a superposition of particle air showers at various stages of development:
    - Most of (nearly all) the time the SSAIRE is the result of GCR,
    - (Very) rarely the SSAIRE will contain particles resulting from SPE,
    - Only handful of SPEs measured at aviation altitudes (NPI, Concorde),
    - Other atmospheric radiation phenomena, e.g. those associated with thunderstorms.
- In general, very few ionizing radiation measurements have been made in the atmosphere (especially when compared to similar measurements made in LEO).
    - Most measurements made at commercial aviation altitudes (e.g. ongoing NPI measurement program).
    - Few measurements on high altitude aircraft (NASA ER-2, WB-57) and on high altitude balloons.
    - No measurements between ~35 and ~300 km.

- Numerous models for estimating air crew and passenger radiation exposure during flight, but few models (AIREC, PARMA) for estimating basic physics quantities (e.g. particle fluxes and energy spectra).
- Multiple reasons for lack of radiation measurements in the atmosphere:
  - lack of low-cost, easy to install/operate instrumentation that can be widely deployed on multiple platforms,
  - lack of cooperation with airlines (especially in USA),
  - little scientific interest, but hopefully changing with growing awareness of the importance of Space Weather.
- In October 2020 *Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act* signed into law, promoting cooperation in Space Weather between US Federal Government (NOAA, NASA, FAA, DOD, etc.), academia and industry.

AIRE Institute Research Goals

- Further our understanding of SSAIRE through a combination of measurements and models.
- Develop, characterize and fabricate a suite of low-cost, easy-to-use instruments that can be widely deployed on a range of airborne, space-borne, and ground-based platforms, and make these instruments available to the aviation and space weather communities.
- Further develop the AIREC computer model to better our theoretical understanding of the temporal and spatial structure of the SSAIRE, both from GCR and SPE.
- Investigate other sources of ionizing radiation in the atmosphere, e.g. those associated with thunderstorms.
- Work with Space Weather community to implement Research to Operations (R2O) monitoring and modeling capabilities in the atmosphere.

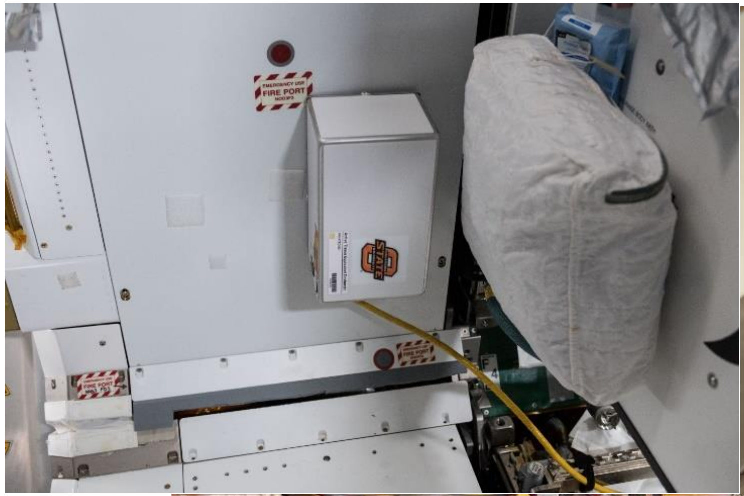
Airborne, Space-borne and Ground-based Platforms

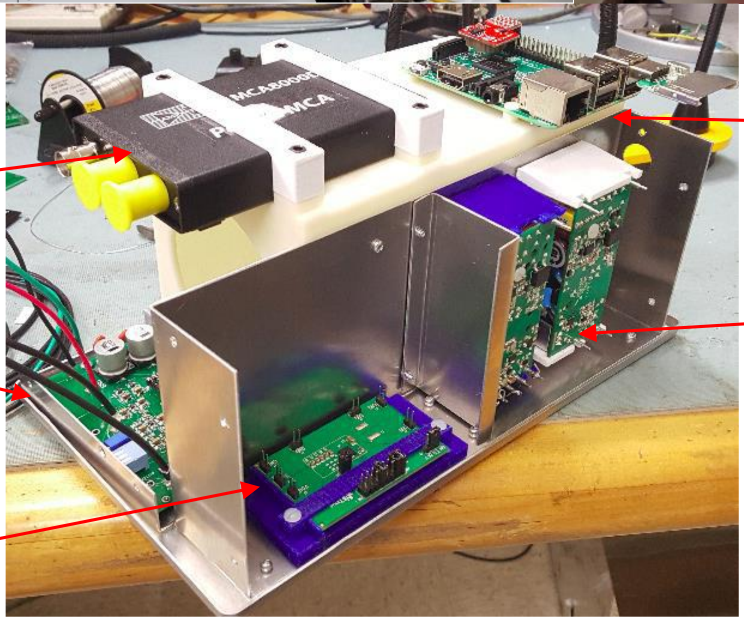
- Commercial, business and military aircraft,
- High altitude research aircraft (NASA WB-57 and ER-2),
- High altitude UAVs (Swift Aerospace HALE, RQ-4 Globalhawk),
- High altitude research balloons (NASA polar balloon missions, Raven Aerospace),
- Suborbital spacecraft, including space tourism (Blue Origin New Shepard, Virgin Galactic),
- Ground-based cosmic ray monitors (neutron and muon),
- Near space amateur balloons and rockets,
- Low Earth Orbit (ISS, SpaceX, cubesats),
- Individual pilots, flight attendants, passengers.

AIRE Institute Educational Goals

- Develop educational website and materials for the aviation community (pilots, flight attendants, passengers, airlines, military, etc.).
- Write a review paper on the SSAIRE for the scientific community.
- Develop educational materials for K-12 and undergraduate university students, including student projects/kits:
  - Cosmic Ray muon counters,
  - Electric Field Mill kits,
  - VLF radio receivers (Whistlers),
  - Exercises for analyzing satellite (e.g. GOES) data available on the internet.
- Continue mentoring/supervising undergraduate and graduate students at OSU.

2018 Active Tissue Equivalent Dosimeter ISS Experiment





AmpTek Pocket MCA-8000D

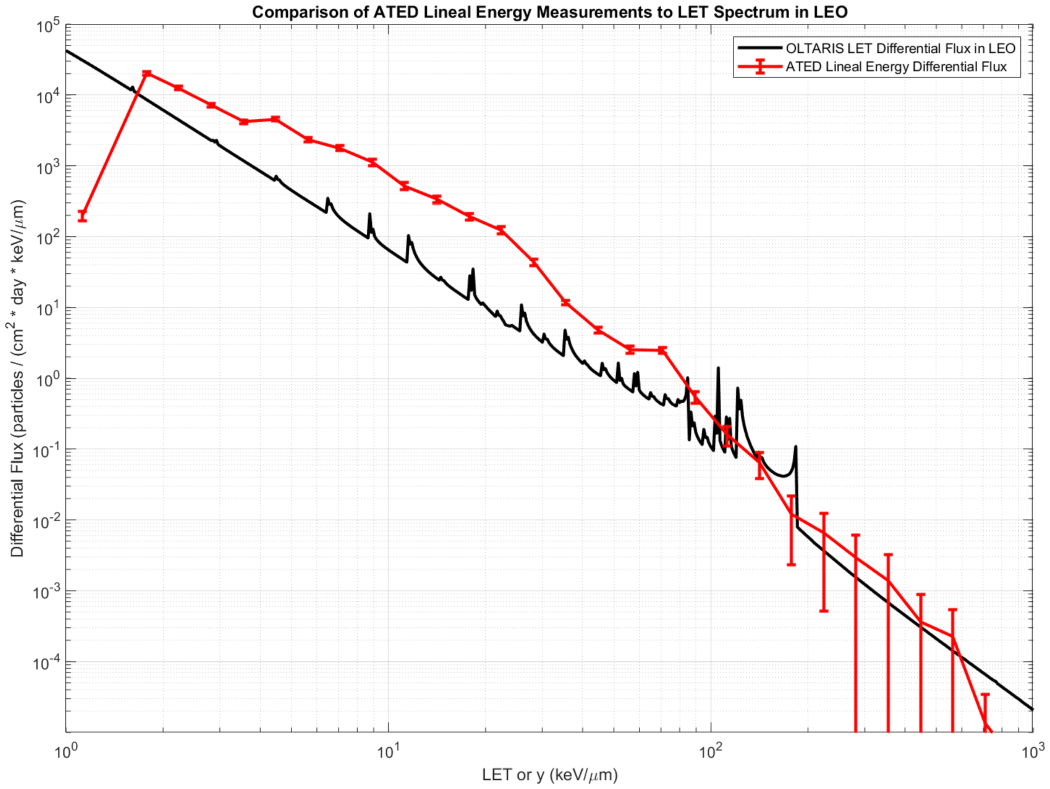
Gaussian Shaping Amplifier

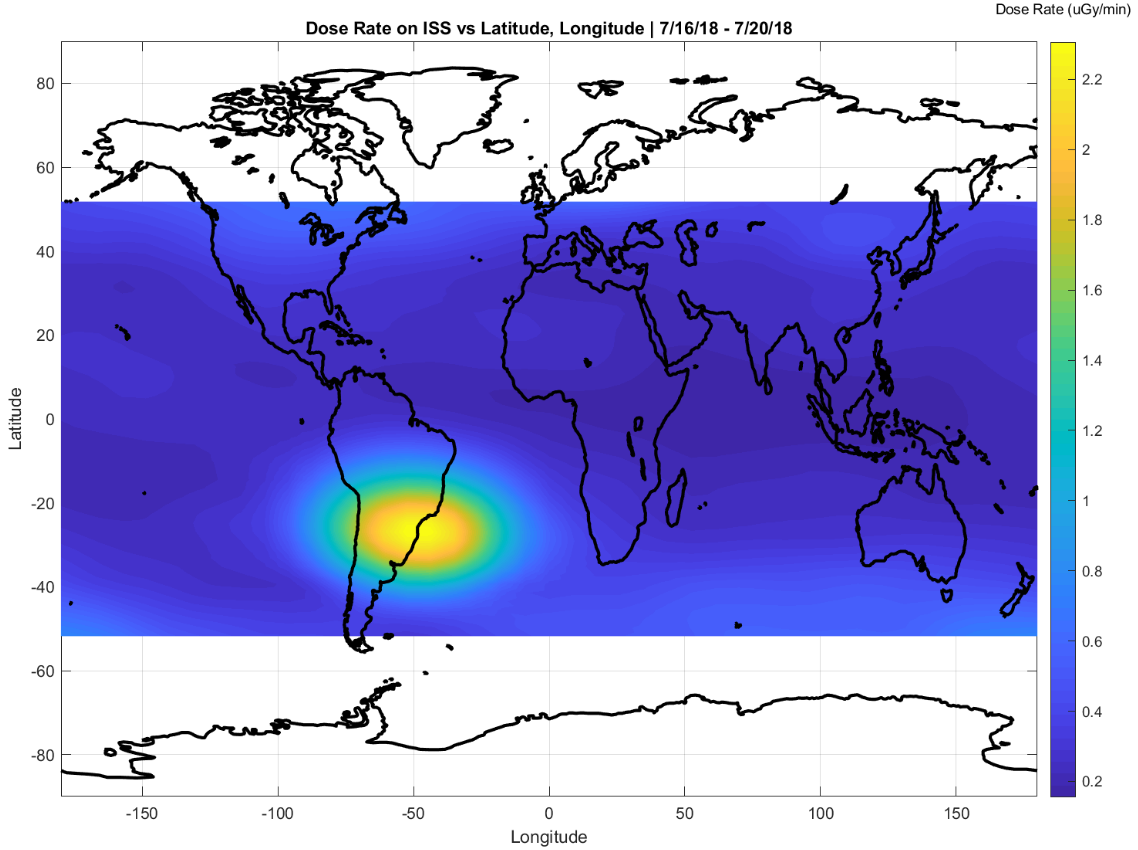
High Voltage

CPU (Raspberry Pi)

AC to DC converters

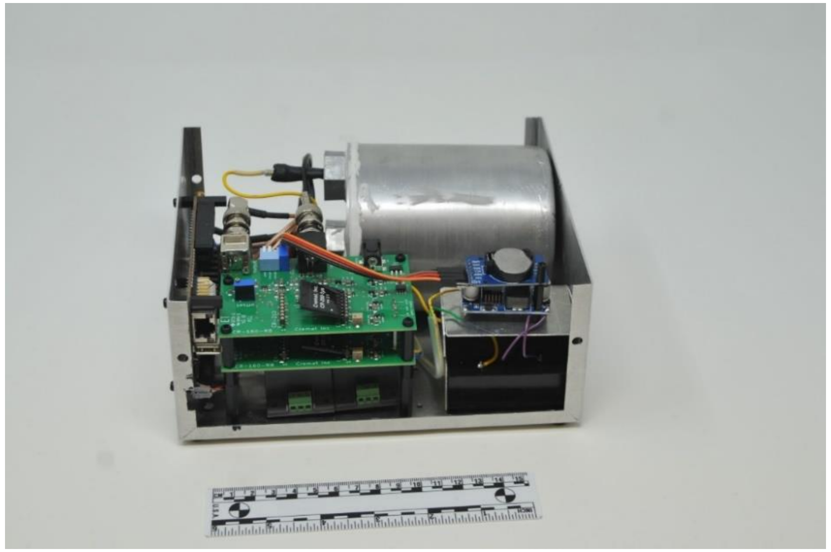
Results from the 2018 Active Tissue Equivalent Dosimeter ISS Experiment

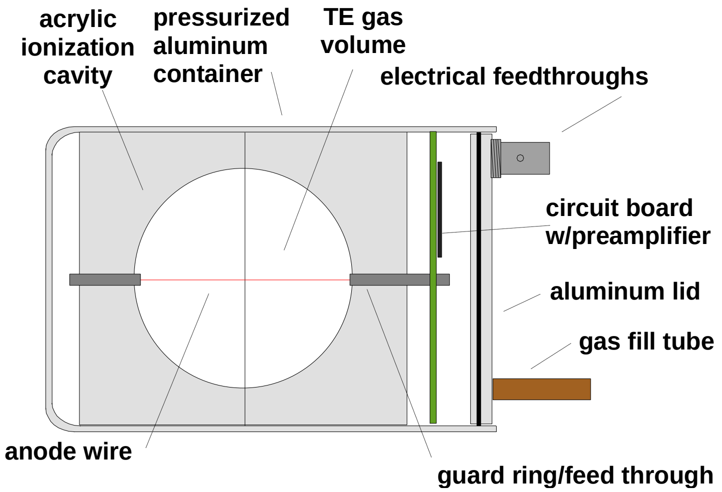




Hayes et al., 2022

Atmospheric ionizing radiation Tissue Equivalent Dosimeter (AirTED) Tissue Equivalent Proportional Counter on NASA WB-57

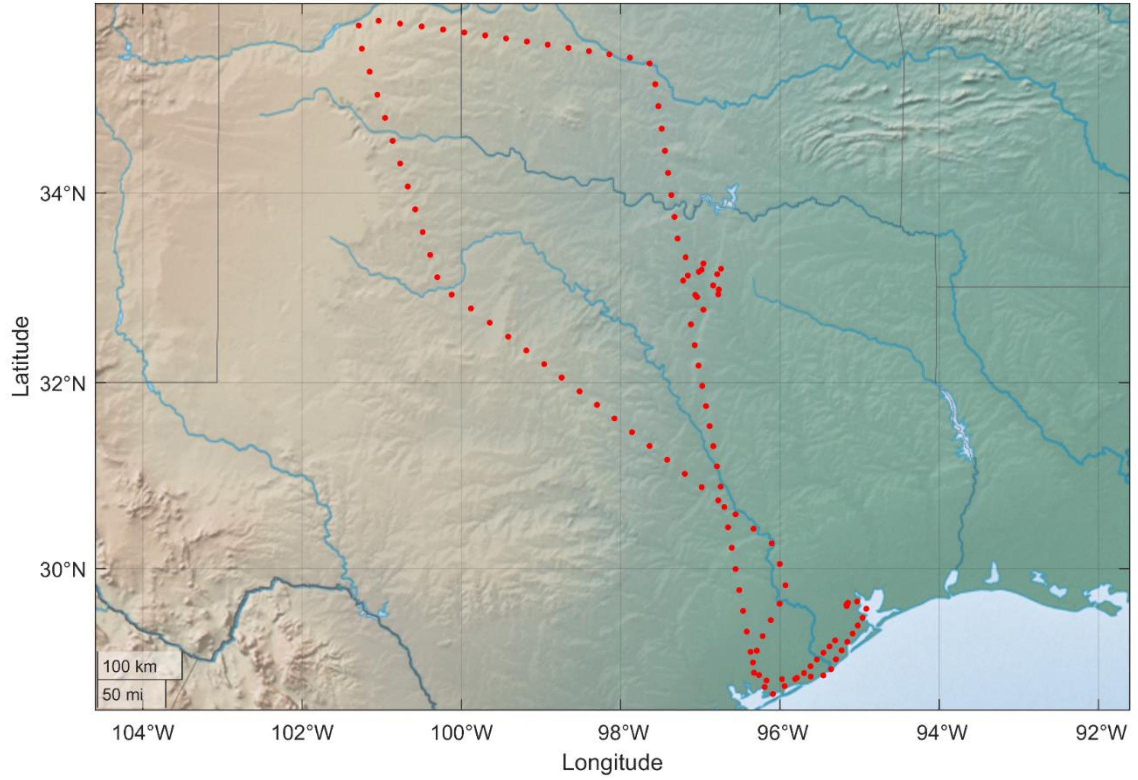


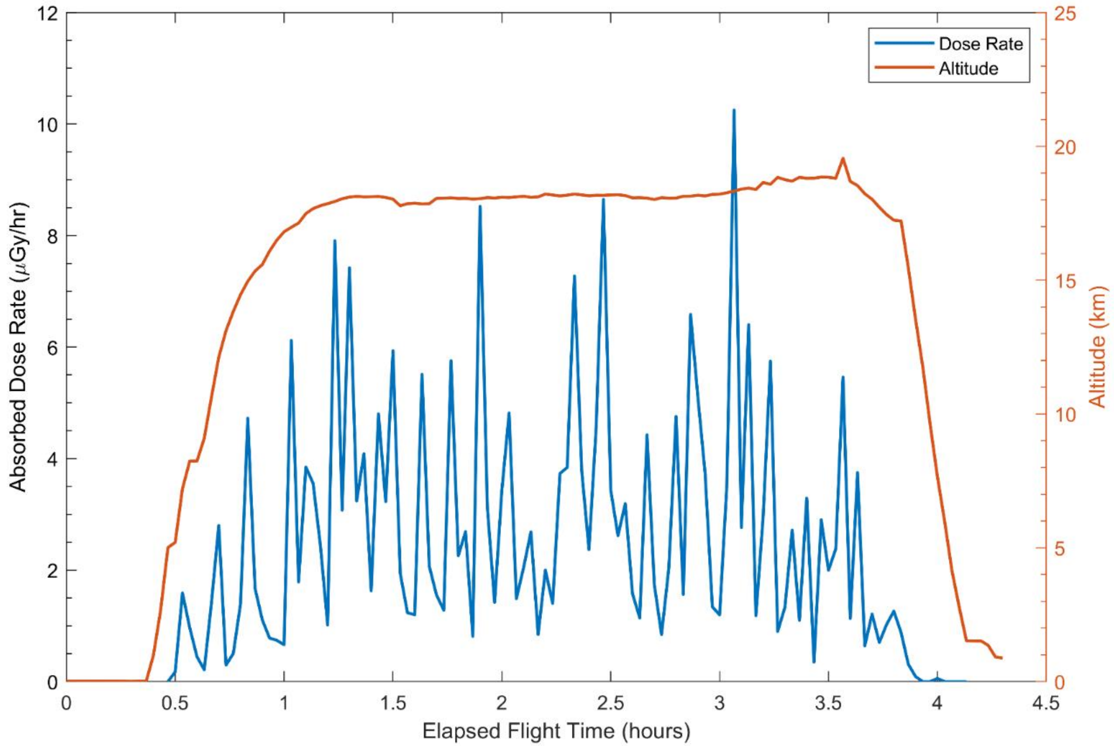


Credit: NASA

Credit: NASA

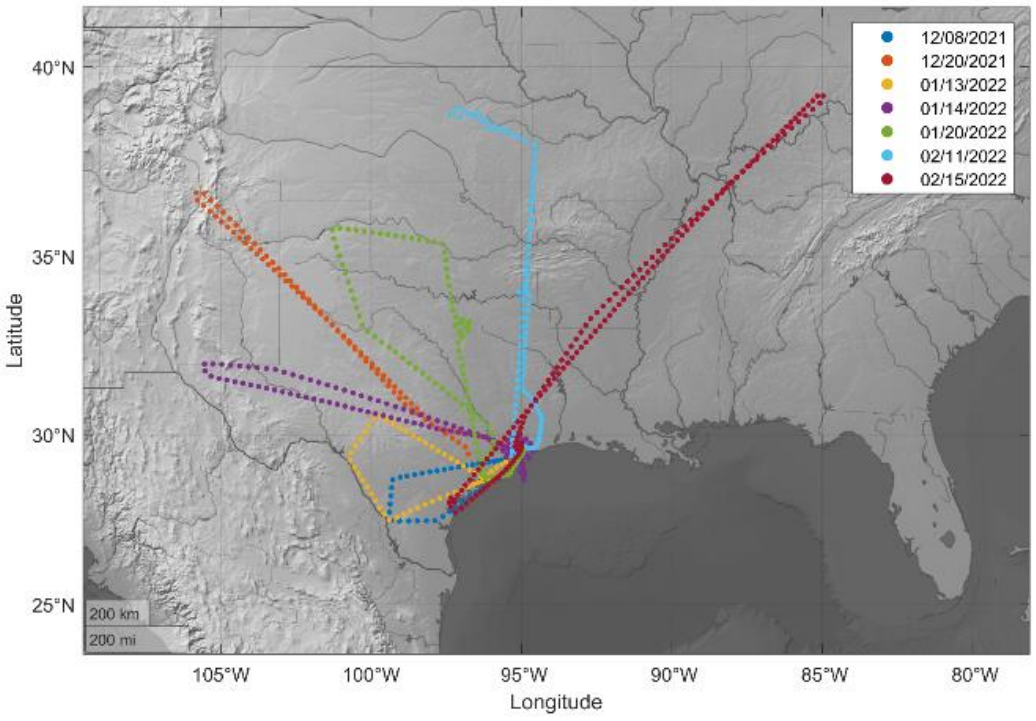
AirTED Flight on NASA WB-57, 20 January 2022

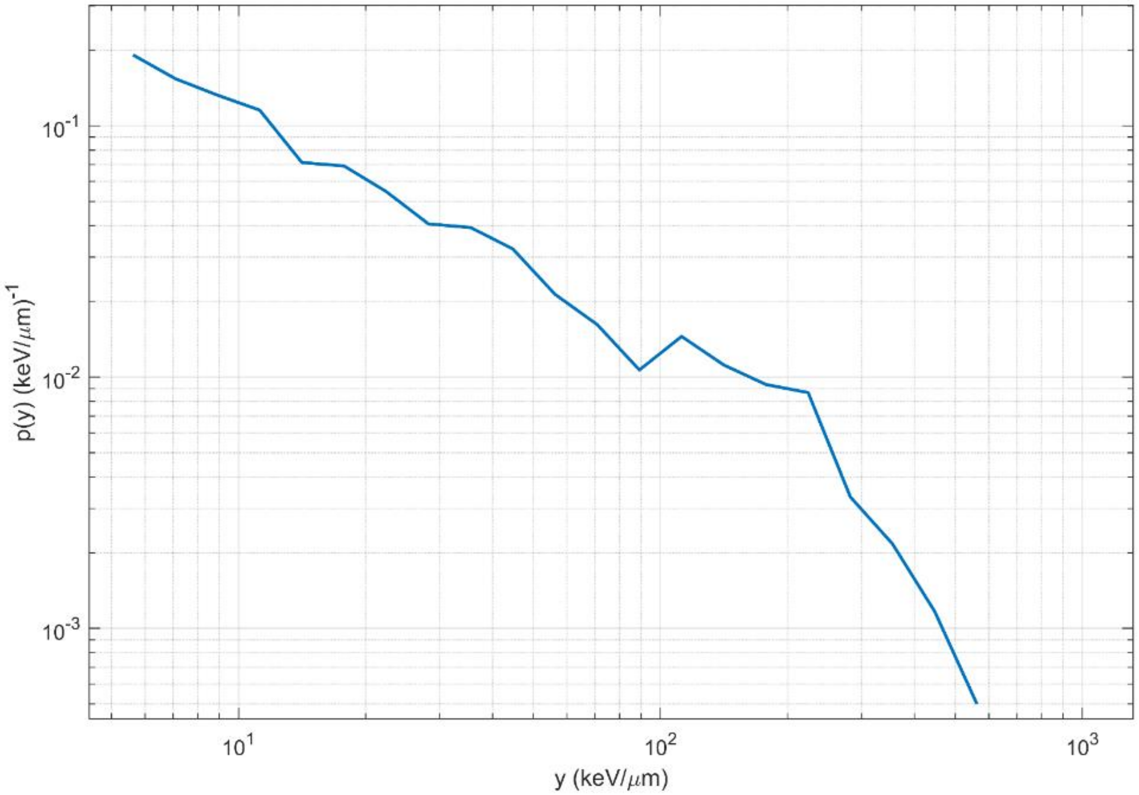




AirTED TEPC

Combined Lineal Energy Spectrum from seven WB-57 Flights





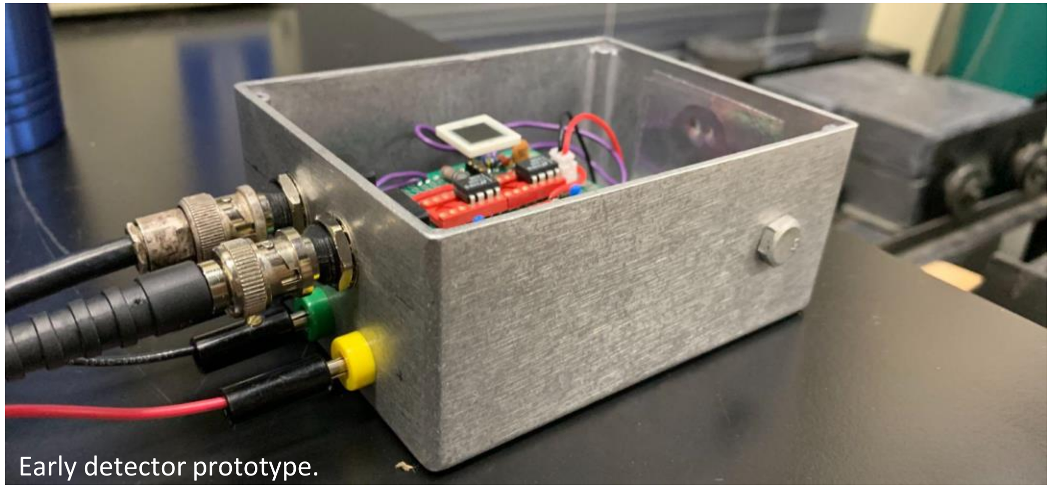
AirTED Measurements and CARI-7A modeled absorbed dose and average dose rates for seven WB-57 flights

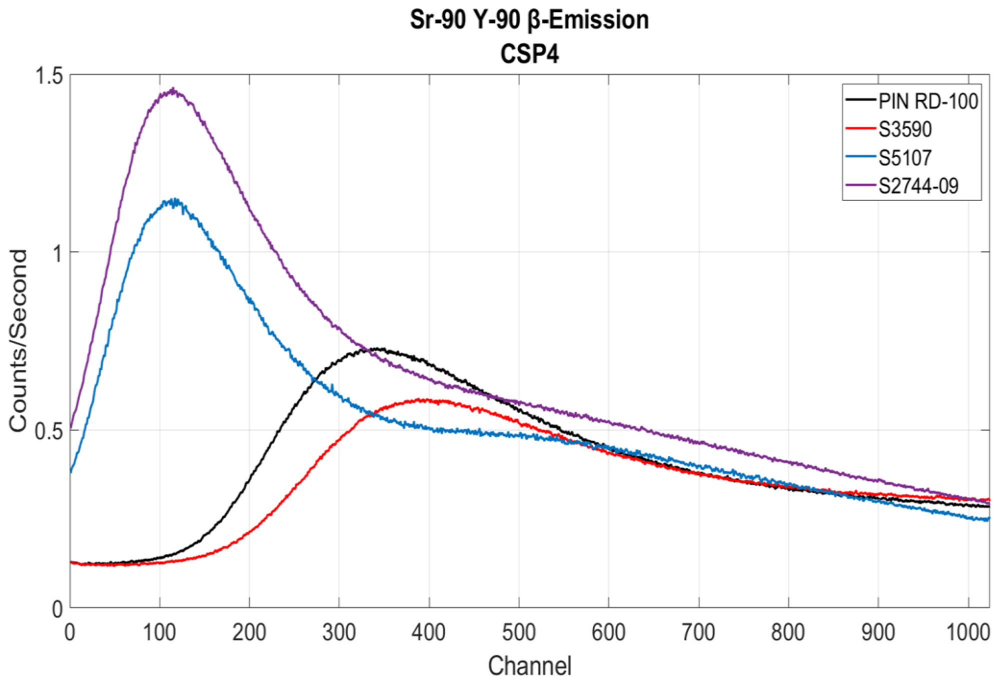
Flight Date	12/8/ 2021	12/20/ 2021	1/13/ 2022	1/14/ 2022	1/20/ 2022	2/11/ 2022	2/15/ 2022
Flight Duration (hrs)	1.36	3.76	1.96	3.33	4.30	3.43	4.89
Measured Absorbed Dose (μGy)	2.1	10.8	3.4	8.4	9.7	7.1	12.8
Average Measured Absorbed Dose Rate (μGy/hr)	1.5	2.9	1.7	2.5	2.3	2.1	2.6
Modeled Absorbed Dose (μGy)	3.8	14.1	5.9	12.1	14.3	11.7	18.2
Average Modeled Absorbed Dose Rate (μGy/hr)	2.8	3.7	3.0	3.7	3.3	3.4	3.7
Percent Difference	46	23	43	30	30	40	30

CARI-7A absorbed dose estimates are consistently higher than AirTED measurements, probably due to lack of sensitivity of AirTED to low LET radiation.

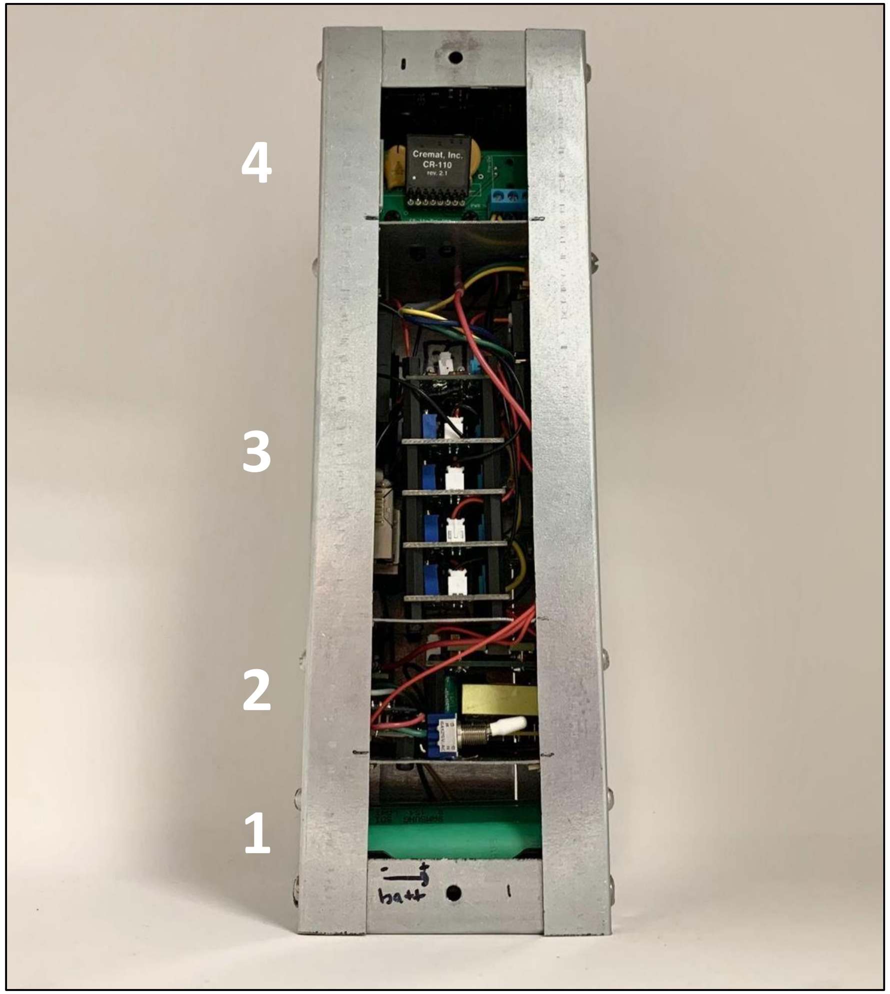
Atmospheric ionizing radiation Silicon Dosimeter (AirSiD)

- Similar to Liulin and AirDos,
- Sensitivity to low LET radiation including electromagnetic cascade component (electrons/positrons, x/γ) and relativistic electrons,
- Based on OSI Optoelectronics RD-100 Si PIN Photodiode,
- New charge-sensitive preamplifier and pulse-shaping amplifier circuit designs developed by OSU physics undergraduate students.

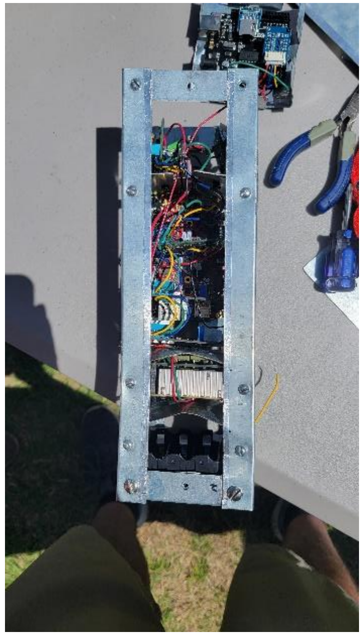

Early detector prototype.



AirSiD Rocket "Test" Flight

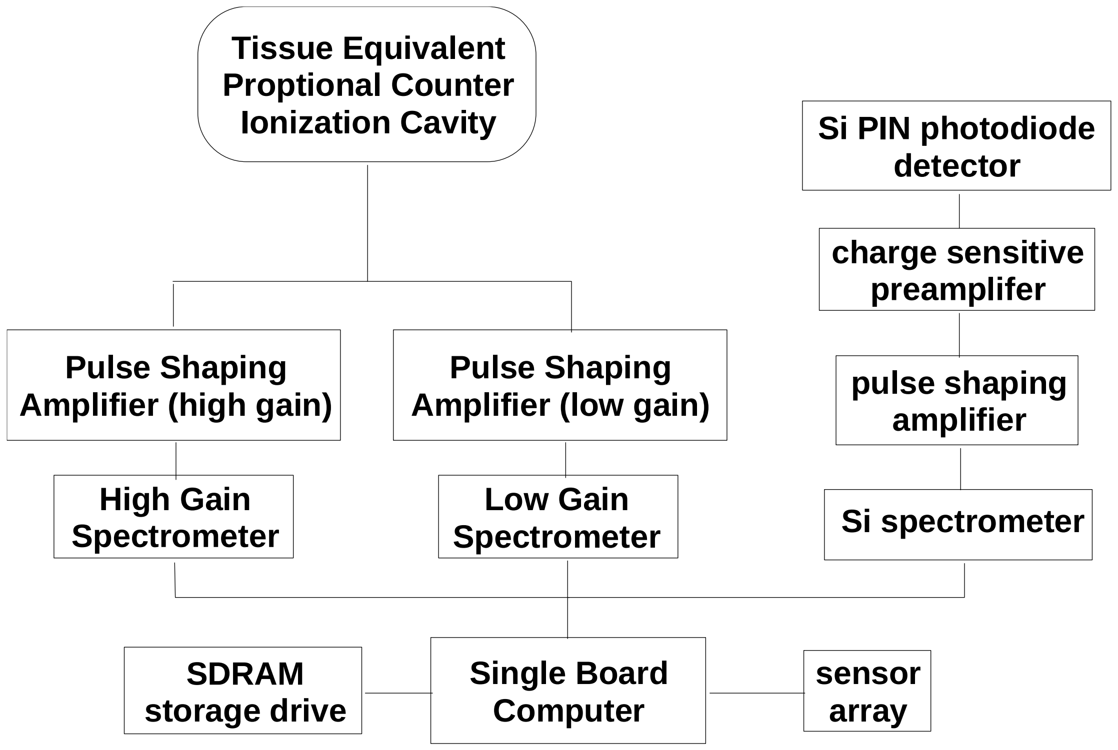


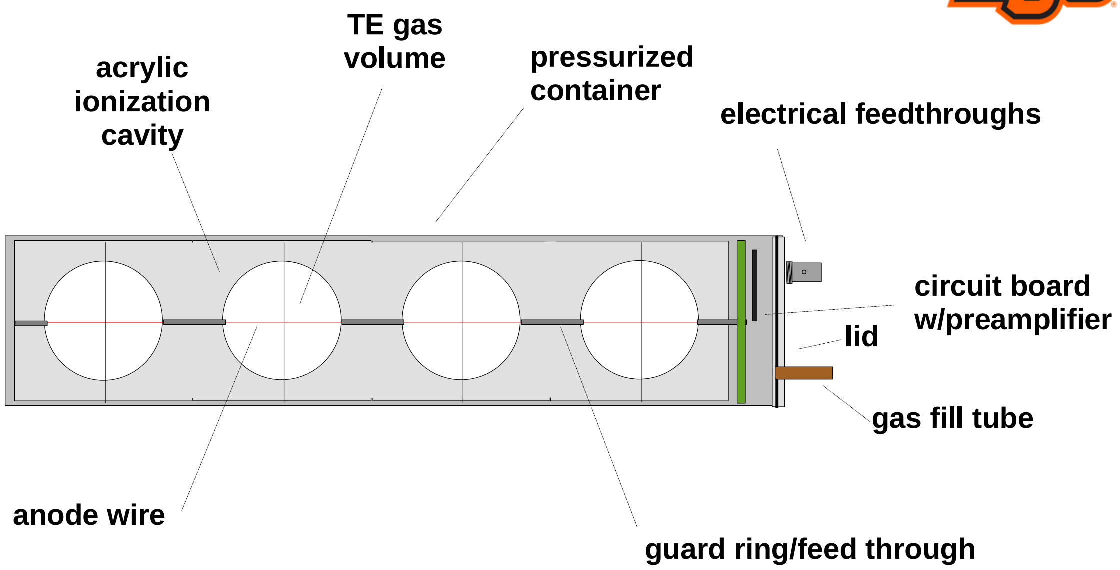
Launch configuration (29.5 x 9.5 x 9.5 cm). From bottom to top, (1) power, (2) high-voltage reverse bias, (3) data acquisition and SA, and (4) detector/amplifier assemblies can be noted.

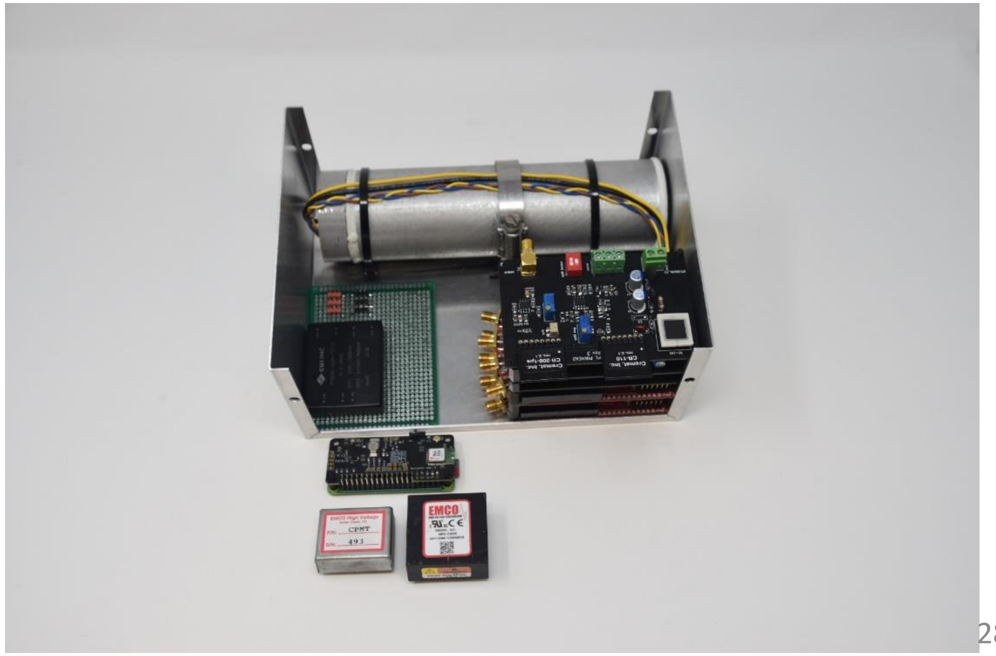


Result: 0.0 +/- noise μGy

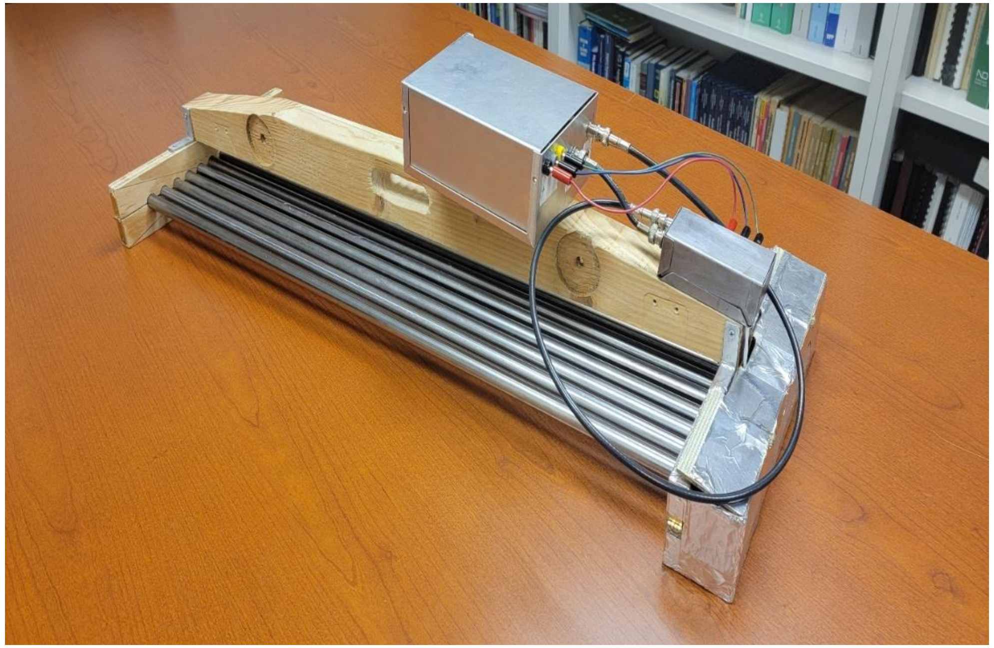
New AirTED/SiD or eATED or ? Prototype

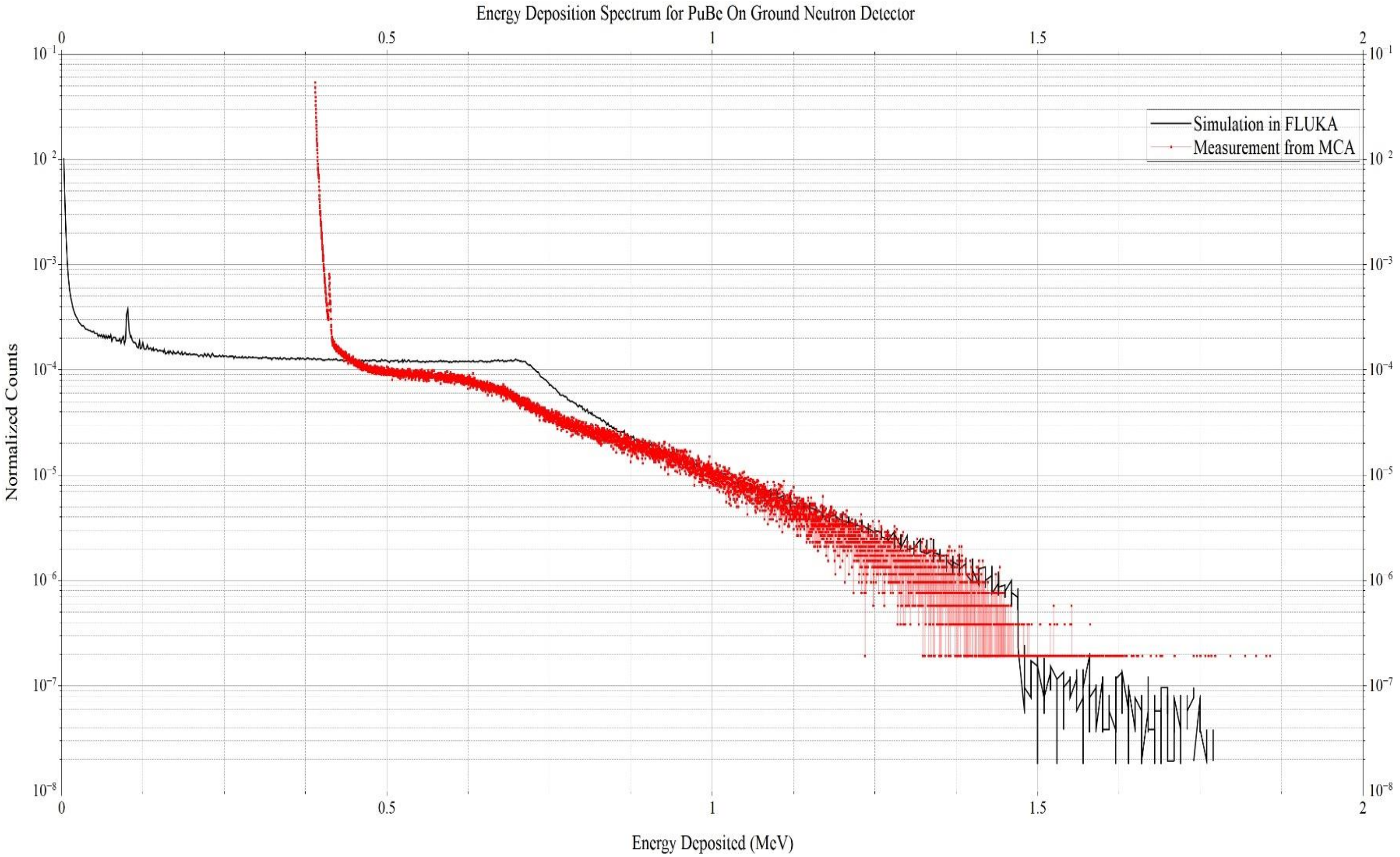






Prototype of Cosmic Ray Ground Monitor





- Currently developing neutron monitor
- Will soon add Muon monitor and x-ray monitor
- application to Space Weather (deploy in worldwide array)
- application to Soil Moisture monitoring for agricultural applications

Prototype of the AIRE Institute ground neutron monitor. Measured energy deposition spectrum from a PuBe source, together with a FLUKA MC calculation for the prototype geometry.

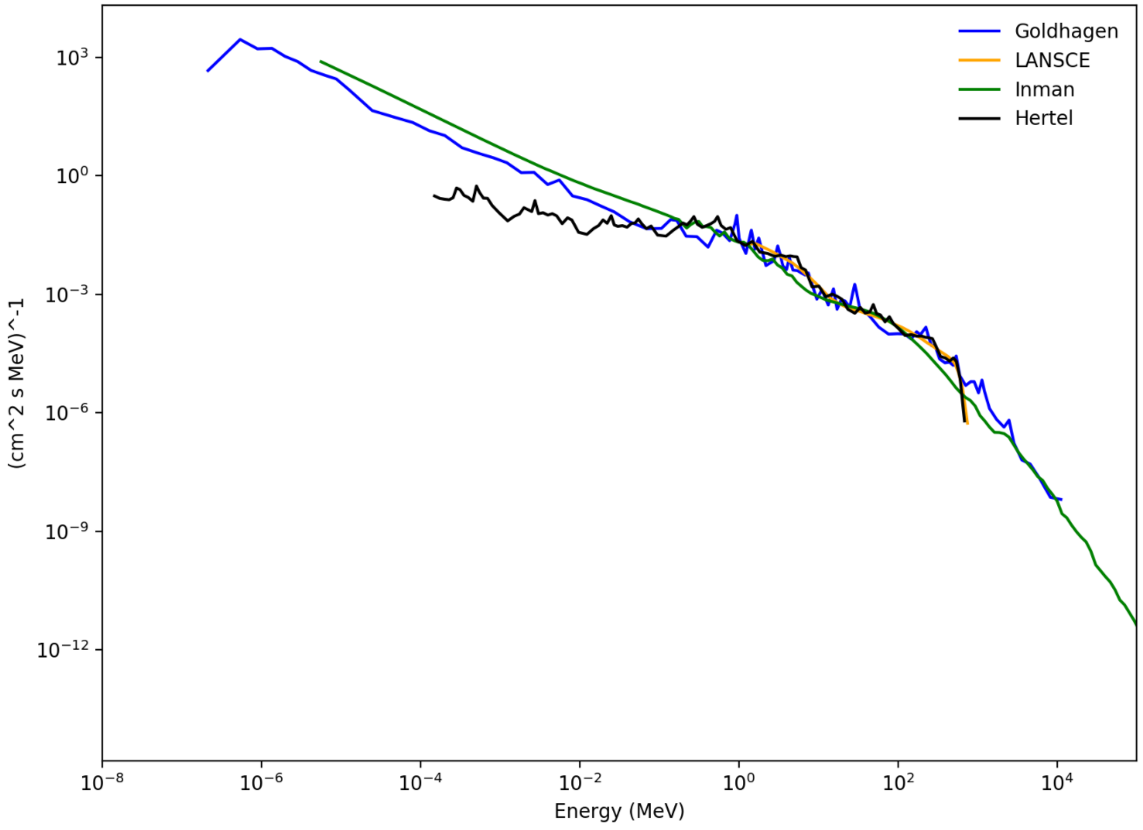
AlmarAIR Personal Aviation Dosimeter

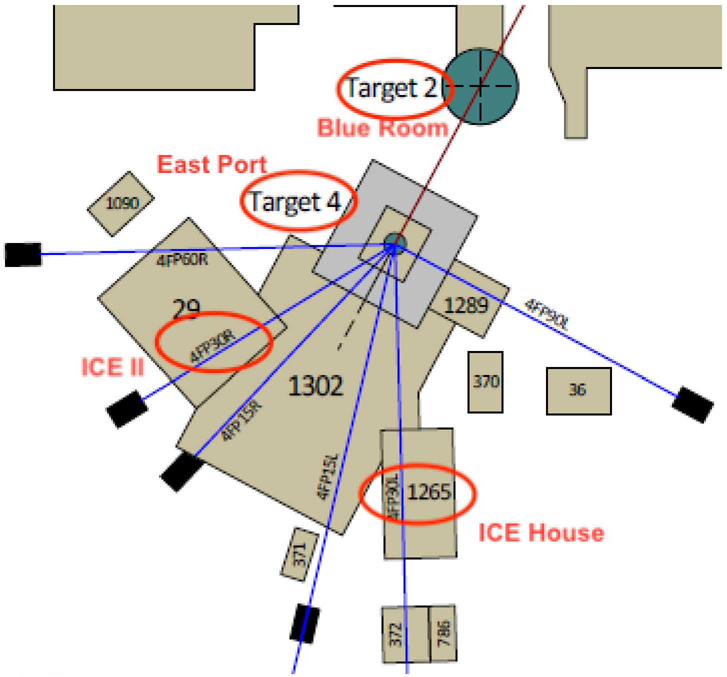
- Based on Almar personal dosimeter developed and manufactured by Herado in Athens, Greece.
- Collaboration between Herado and AIRE Institute.
- Each dosimeter contains 1 to 4 Si MOSFET radiation detectors.
- AlmarAIR will have one bare detector, one covered with a polyethylene radiator and one covered with a ^{6}Li radiator.
- 7.5 x 5.5 x 0.6 cm^3 , 25 g,
- Battery Powered,
- Paperwhite Display,
- WiFi and USB connectivity.

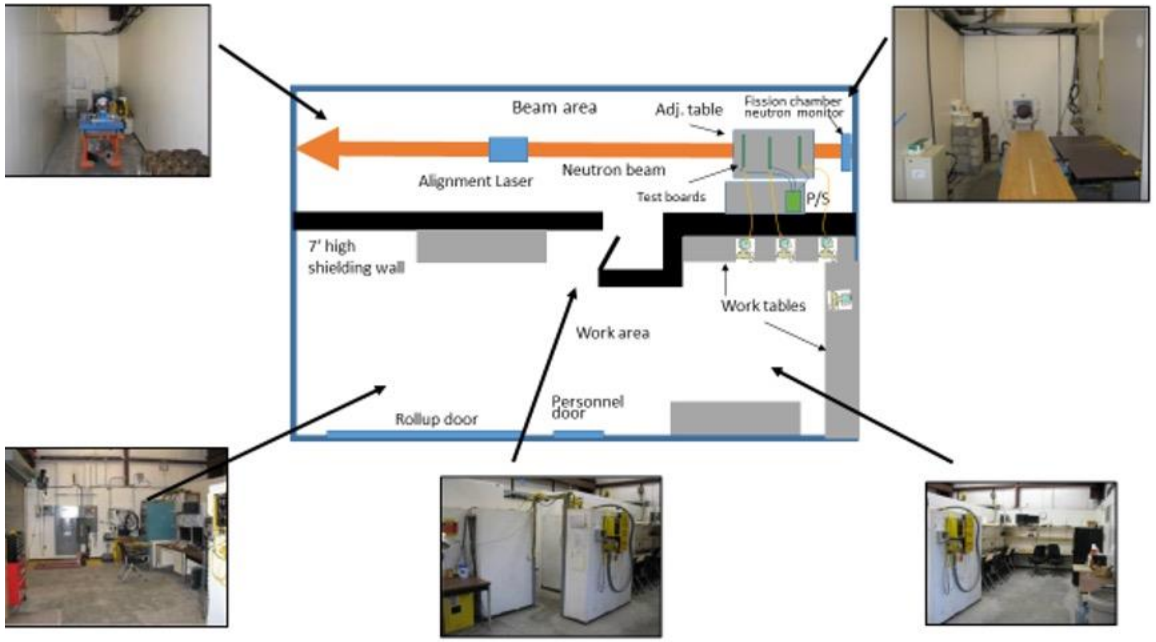
HERADO
Tomorrow's Technology for Today

Los Alamos Neutron Science Center (LANSCE) ICE House Flight Path 30L

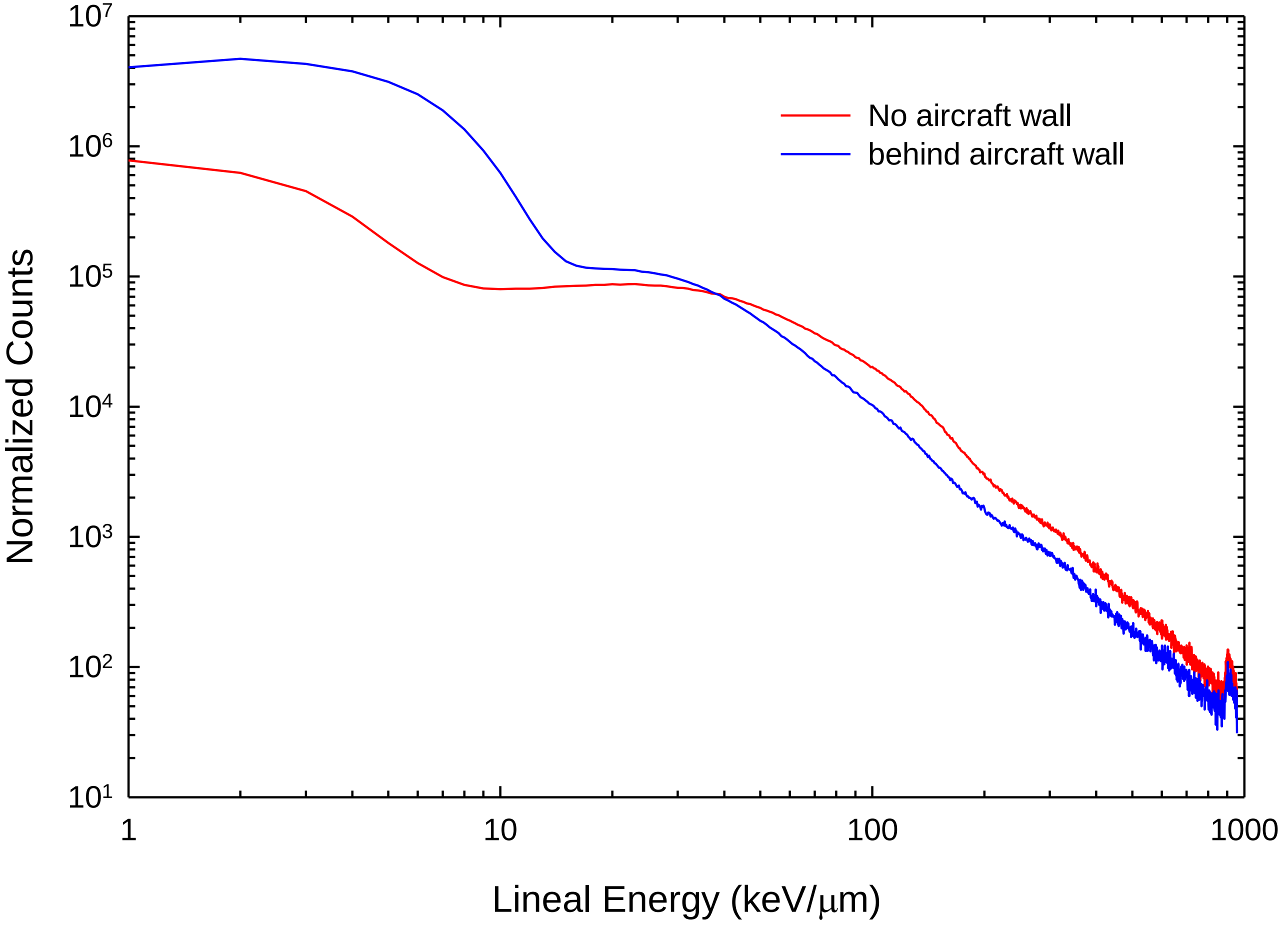
- similar neutron energy spectrum ≤800 MeV.
- 10^6x higher flux than actual environment.







AirTED Prototype in LANSCE 30L Beam

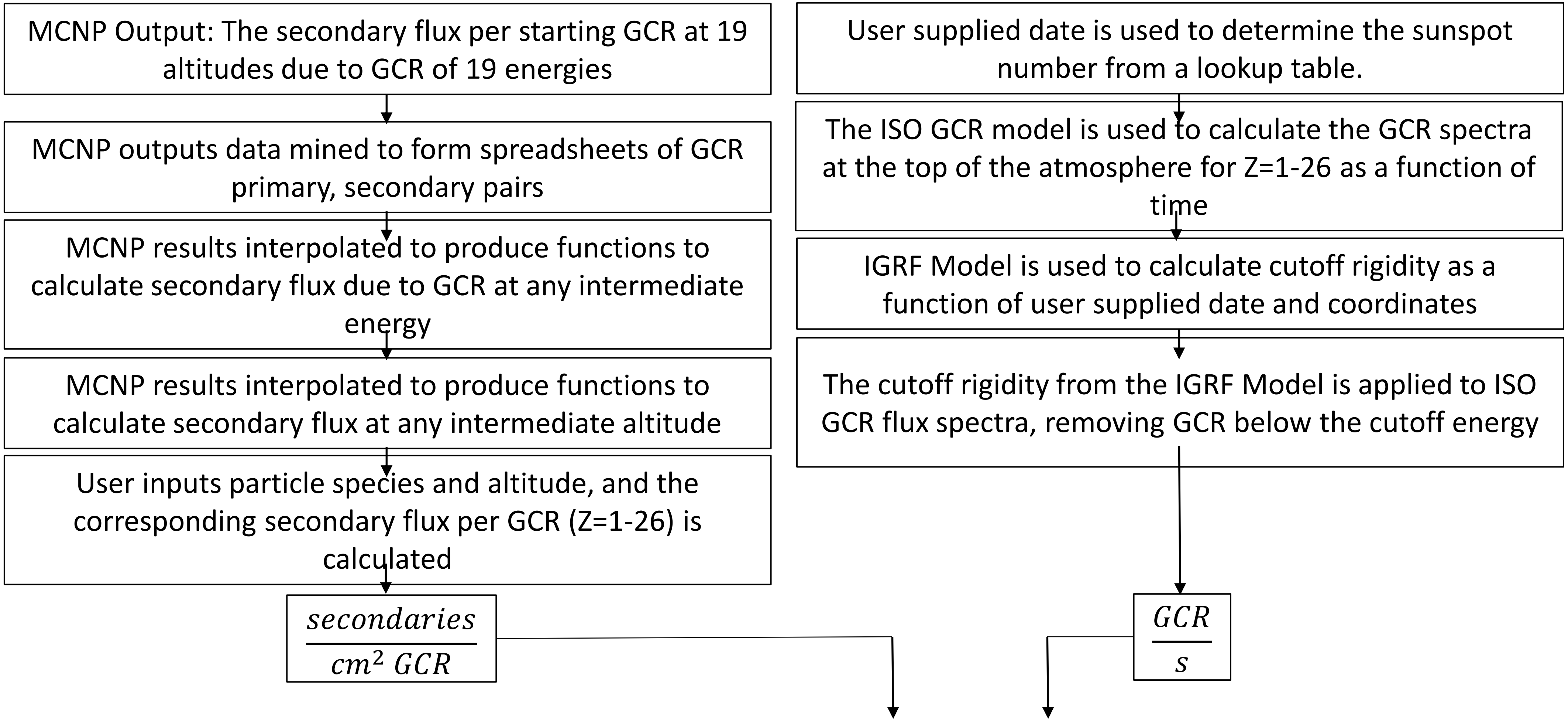


November 2021 experiment

Atmospheric Ionizing Radiation Environment Code (AIREC)

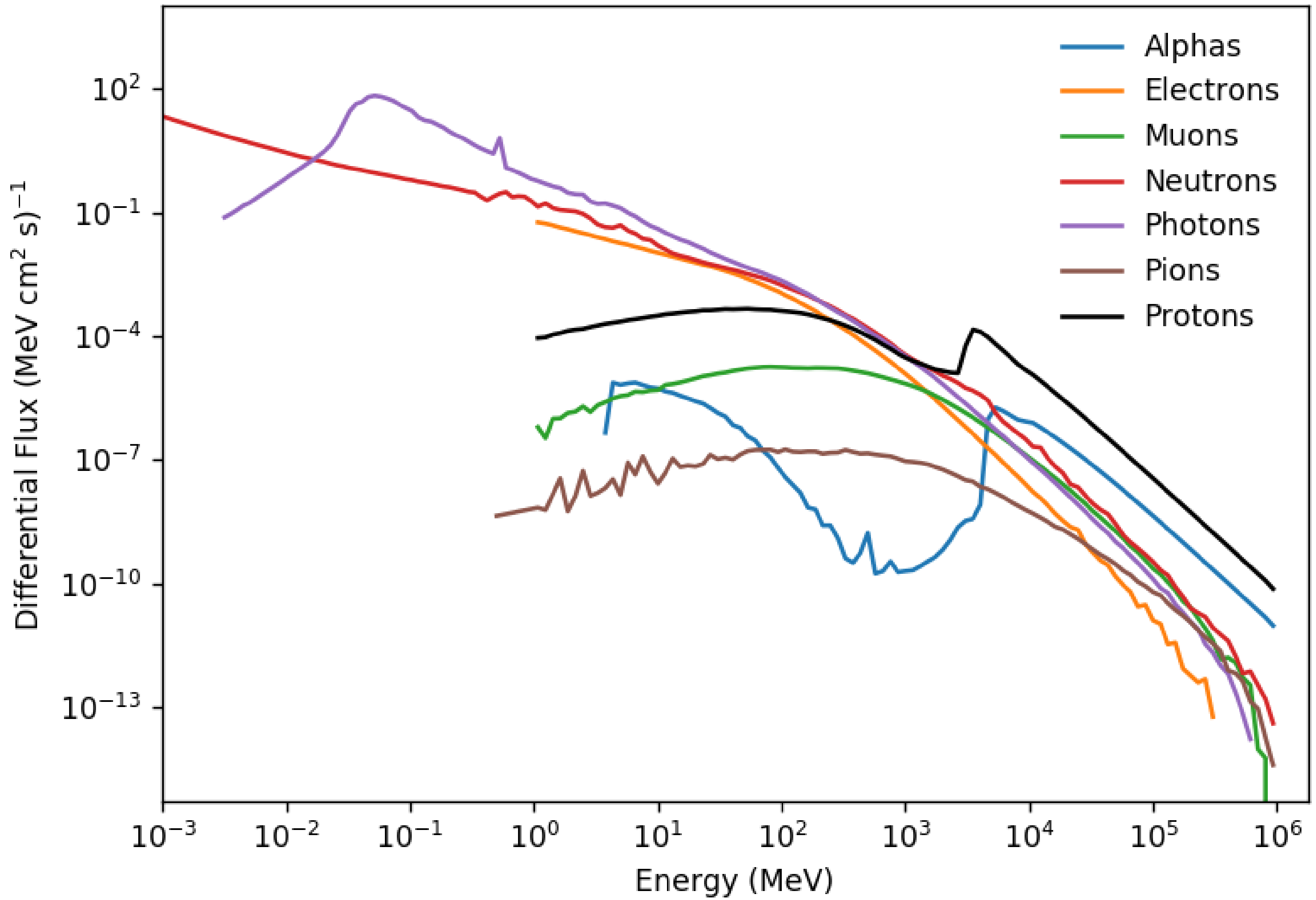
- Based on same MCNPX GCR simulations used in development of the CARI-7 model.
- Instead of Effective Dose, Ambient Dose Equivalent or Absorbed Dose, estimates primary and secondary particle flux and energy spectra as functions of altitude, geographic location and time.
- Altitudes from sea level to 100 km.
- Primary particles of Z = 1 to 26, energies from 1 MeV to 1 TeV.
- Secondary particles including photons, protons, neutrons, ±electrons, ±muons, protons, ±pions, deuterons, tritons, helions, and alpha particles.
- Estimated 2 million CPU core hours needed to simulate GCR showers for this project.

Flowchart illustrating operation of the AIREC code to determine GCR secondary particle energy spectra in the atmosphere as functions of altitude, time and geographic (geomagnetic) location.

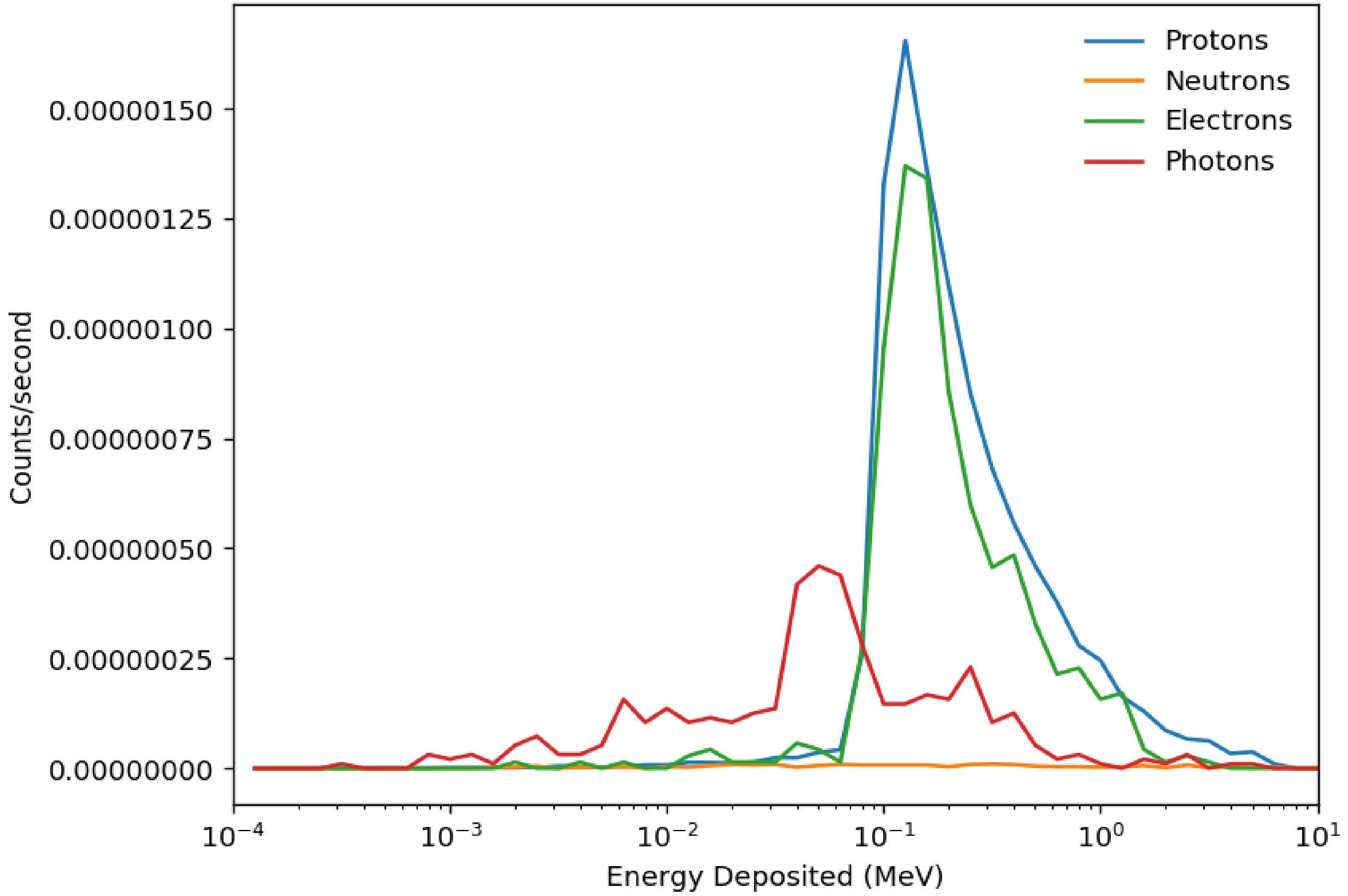


$$\Phi = \sum_{GCR\ Species} \left(\sum_{GCR\ Energy} \left(\frac{secondaries}{cm^2\ GCR} \times \frac{GCR}{s} \right) \right)$$

GCR secondary particle energy spectra produced by AIREC for use in modeling the 2005 DSTB high altitude balloon flight.



Latitude: 34.47° North
Longitude: 255.75° East
Altitude: 36.576 km
Date: November 2005
Multiple Secondary Particles



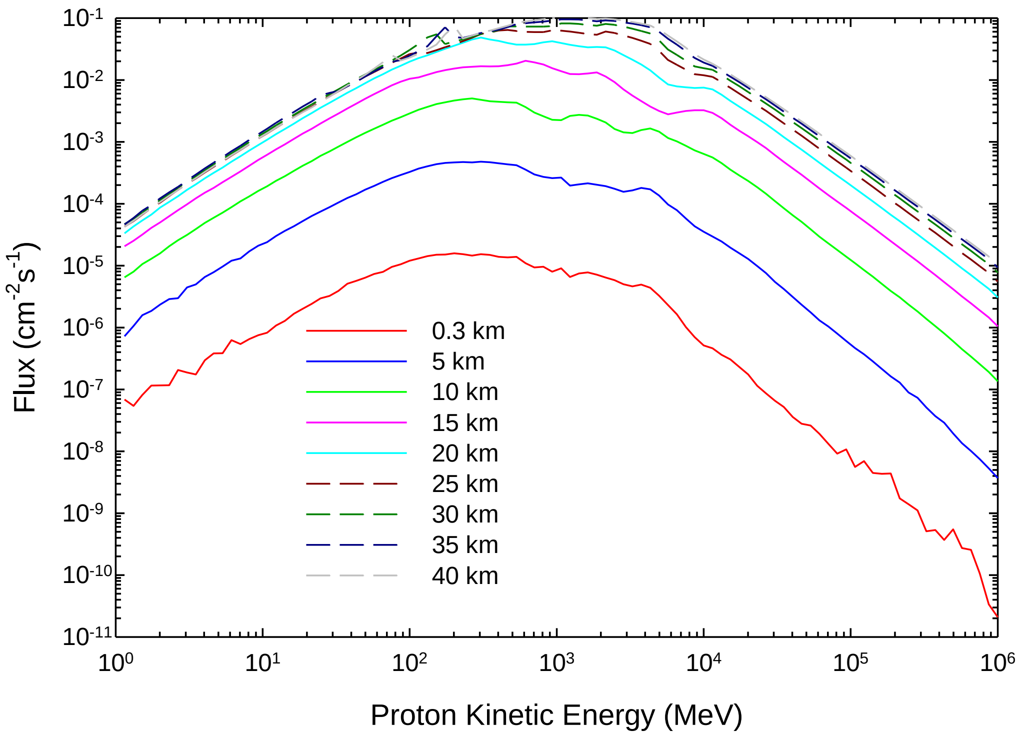
Data Type	Dose Rate (μGy/hr)
Experiment	2.28 ± 0.78
Simulation	2.06 ± 0.50

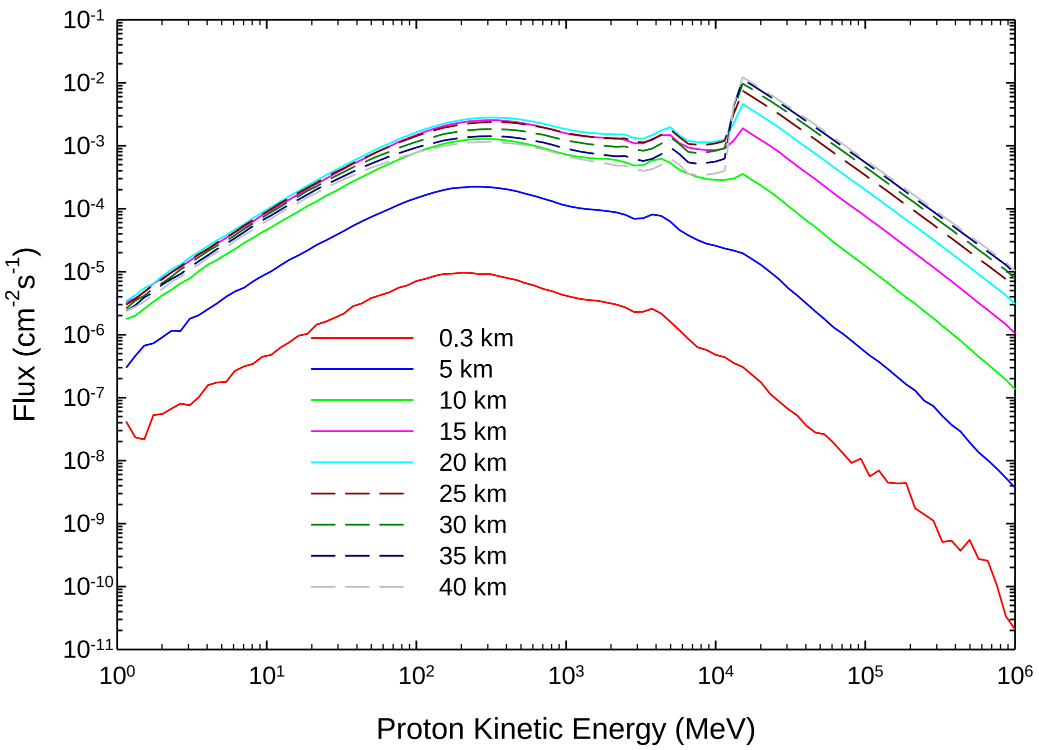
Particle Species	Percentage of Total
Neutrons	1.54%
Protons	52.13%
Electrons	31.29%
Negative Muons	0.53%
Positive Muons	0.69%
Photons	9.13%
Positive Pions	0.01%
Negative Pions	0.01%
Deuterons	1.44%
Tritons	0.13%
Helions	0.09%
Alphas	3.01%

Results of simulation of Liulin-4 silicon detector on DSTB. Left shows the simulated energy deposition spectra in the Liulin-4. Comparison of measured and absorbed dose rates are at upper right, while percent contributions of relevant particle species are shown in the lower right.

OTHER USES OF AIREC

AIREC estimates of the proton energy spectra above the north pole (left) and equator (right) for the same date.



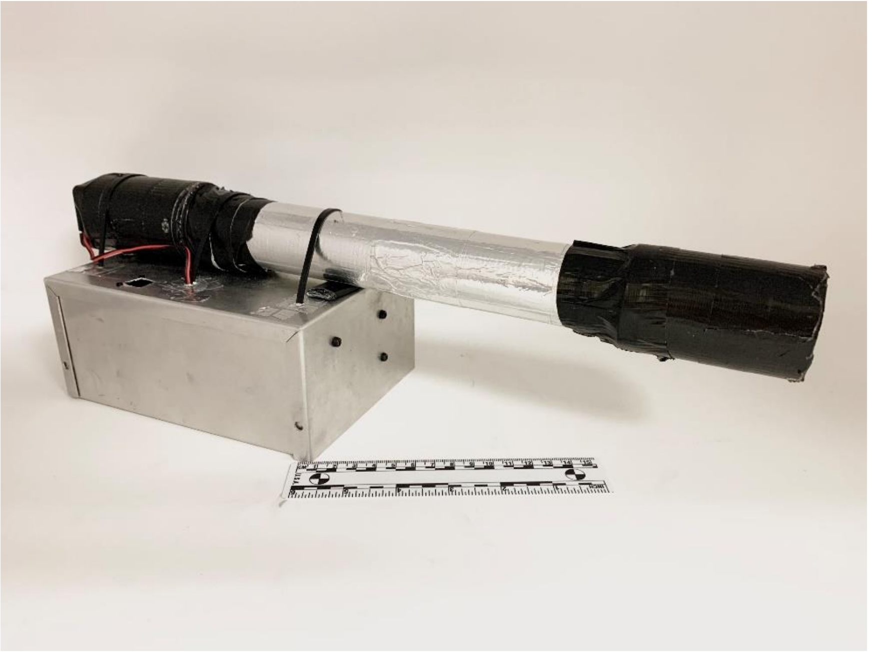


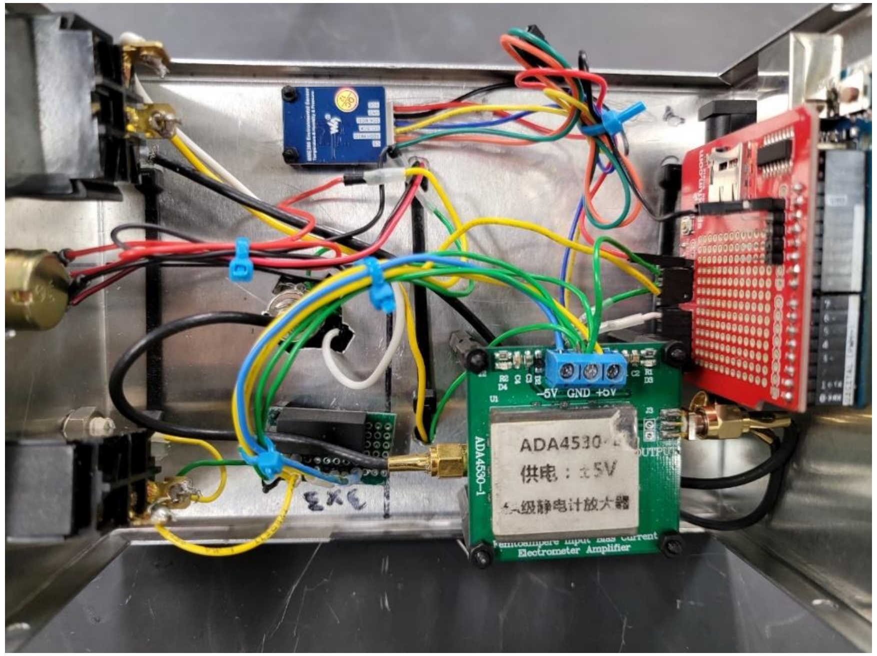
The effect of the rigidity cutoff is seen at ~10^4 MeV. Similar investigations can be carried out for other particle species including neutron, photons, electron/positrons, and muons.

OSU EVB RPL

Student Project: Gerdien Tube

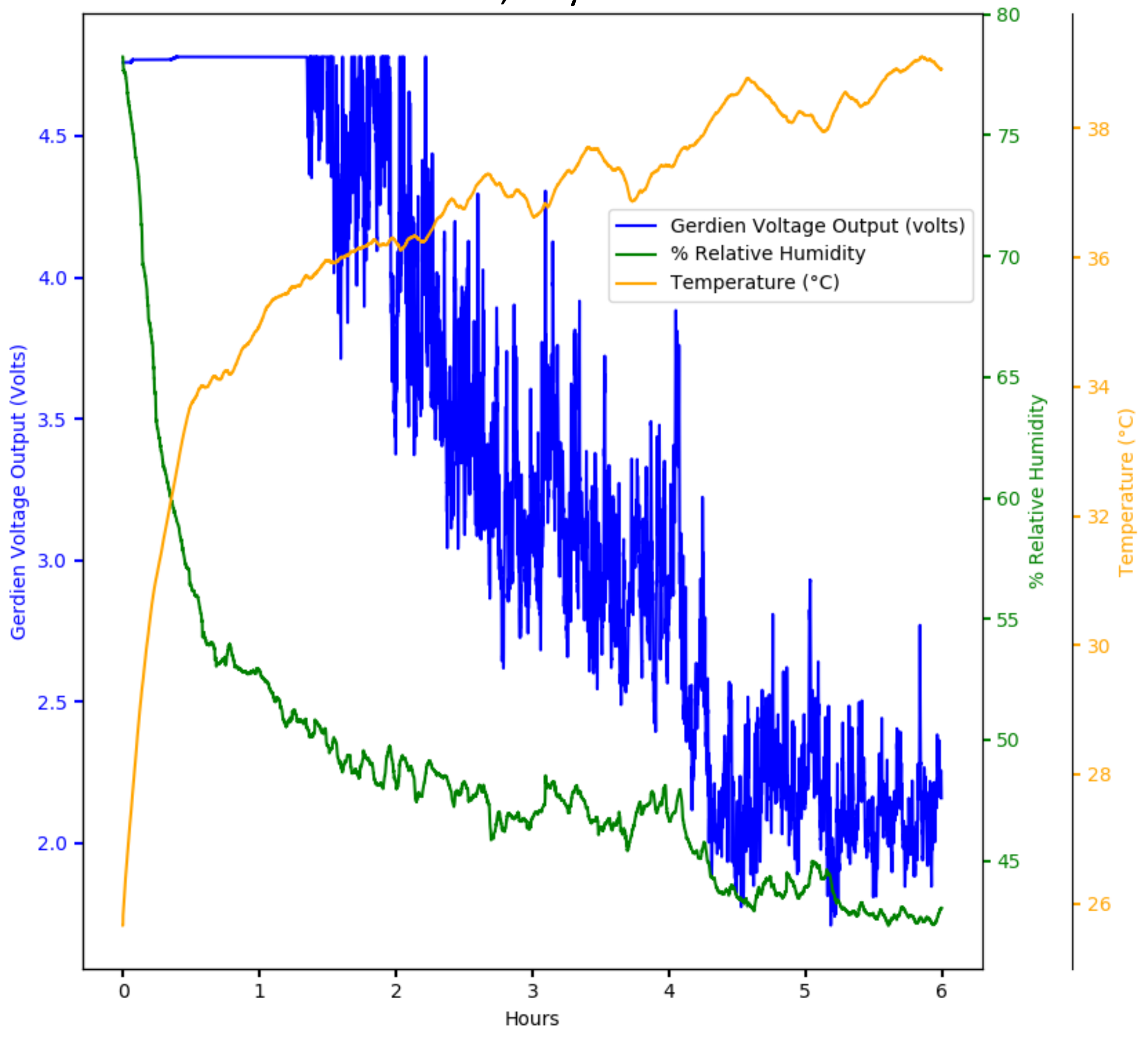
- A Gerdien tube is a type of detector primarily used to measure ion concentrations in air
- A Gerdien tube is made from two coaxial electrodes and ventilated with a fan.
- The electrodes are held at a potential difference to create an electric field in the tube.
- As ions are drawn into the tube they are forced onto the electrodes.
- Voltage output of the tube, temperature, atmospheric pressure, and relative humidity were all recorded during each trial
- All data is timestamped and saved to an SD memory card by an Arduino Uno microcontroller



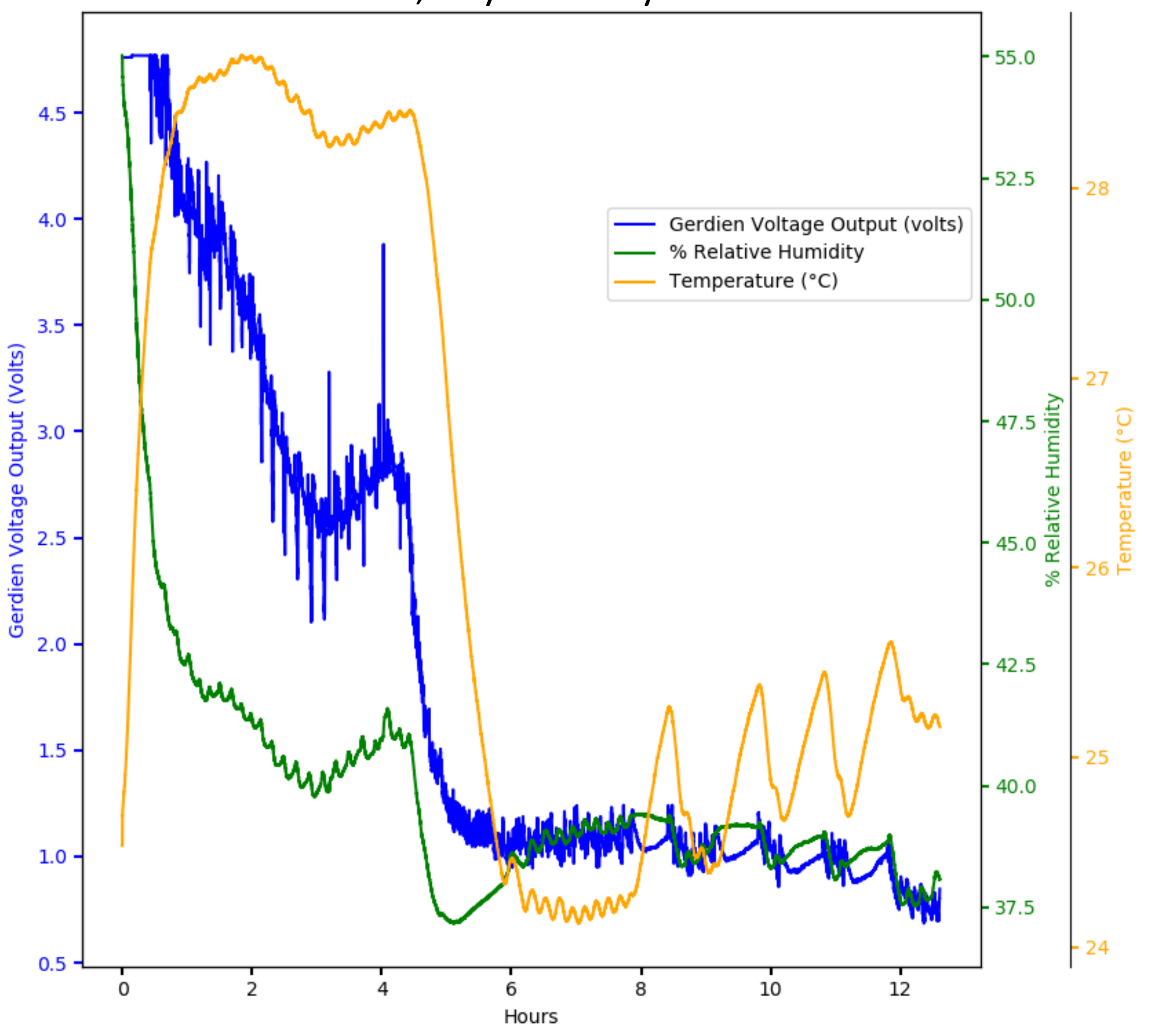


Gerdien Tube Results

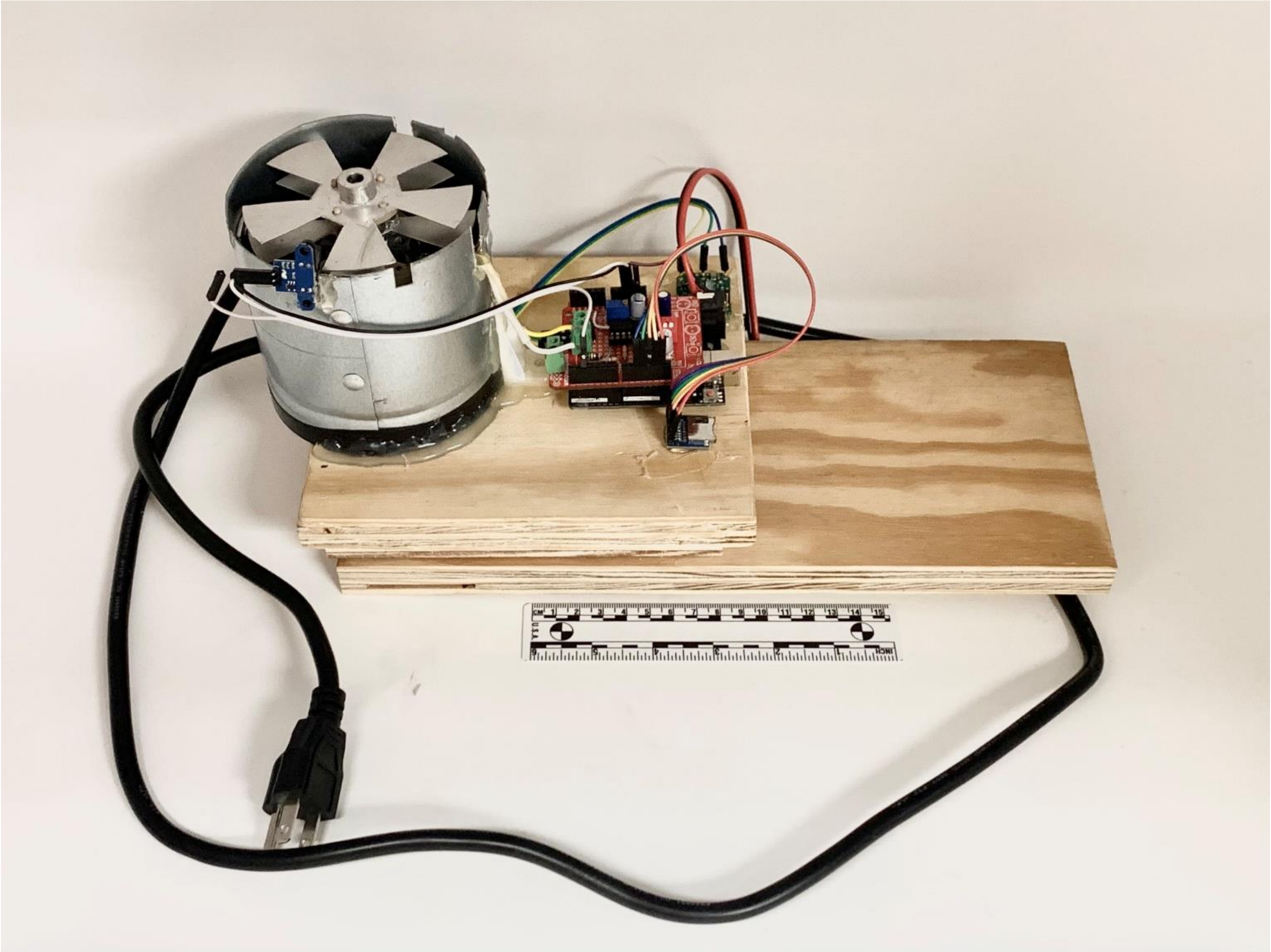
Gerdien Voltage Output, % Relative Humidity, and Temperature
Outdoors, July 16th 2021



Gerdien Voltage Output, % Relative Humidity, and Temperature
Indoors, July 7th – July 8th 2021



Student Project: Electric Field Mill



Conclusions: AIRE Institute Current Projects

- NASA WB-57 ongoing flights:
  - deploys to Korea for summer 2022 campaign,
  - later will add AirSiD (and other detectors) to existing AirTED.
- Ground-based Cosmic Ray monitors (neutron, muon, x-ray).
- Herado AlmarAir personal aviation dosimeter.
- AirTED/AirSiD experiment on Blue Origin New Shepard suborbital flight:
  - 3rd Quarter 2023,
  - dosimetry for space tourism.
- eATED experiment on ISS:
  - 6 months duration,
  - launch of SpaceX-28 in June 2023,
  - implement lessons learned from 2018 ISS experiment.

AIRE Institute Personnel

- Eric Benton (director), Oklahoma State University, Dept. of Physics
- Kyle Copeland, U.S. FAA, Civil Aerospace Medical Institute
- Brad “Buddy” Gersey, Founders Classical Academy

AIRE Institute Students

- Tristen Lee, OSU Physics Ph.D. student
- Mingzheng (Martin) Yang, OSU Physics Ph.D. student
- Conner Heffernan, OSU Physics Ph.D. student
- Garrett Thornton, OSU Physics undergraduate student

AIRE Institute Former Students

- Paul Inman, OSU Physics Ph.D. student (graduated 2021)
- Ryan Boyce, OSU Physics undergraduate student (graduated 2022)

AIRE Institute US Collaborators

- Stephen Wender, Los Alamos Neutron Science Center, DOE LANL
- Jack Miller, Lawrence Berkeley National Laboratory and NASA ARC
- Bryan Hayes, Space Radiation Analysis Group, NASA JSC (OSU graduate)
- Chris Mertens, NASA LaRC

AIRE Institute International Collaborators

- Marianthi Fragkopoulou, Herado, Greece
- Matthias Meier, DLR Germany
- Alex Hands, U of Surrey, UK
- Ondrej Ploc et al., NPI Czech Academy of Science, Czech Republic

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