Radiation Belt Space Weather at NASA: From Basic Research to Operations

Community-Wide Infrastructure to Understand, Predict, and Protect Nation's Assets from Hazards of Near-Earth Particle Radiation

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Summary:
Ambient and increased levels of relativistic electrons and highly penetrating ion radiation can cause substantial economic impact by damaging and destroying orbiting spacecraft and are hazardous for astronauts in space. Protecting the nation's infrastructure from adverse particle radiation effects requires a community-wide systems solution employing a large-spacecraft constellation, capable ground-based operations, and comprehensive data-driven modeling infrastructure.

White Paper:
From planetary exploration and the lunar gateway missions on long transit orbits to the International Space Station, MEO constellations and LEO-GEO transit orbits, an ever increasing number of our nation's space assets dwell in the heart of Earth's radiation belts filled with relativistic electrons and penetrating ions (Figure 1b). Particle radiation in the belts can damage and destroy spacecraft and is hazardous for astronauts health. The recent Van Allen Probes NASA LWS mission revealed many aspects of radiation belt dynamics that had been previously unanticipated or not fully appreciated, and that present a formidable challenge for developing solutions for the mitigation of their hazardous effects on the nation's infrastructure. As was revealed by the Probes, during geomagnetic storms radiation intensities can rise to hazardous levels, significantly exceeding their pre-storm values, and on timescales of minutes or less (Figure 1a). We also learned that rapid enhancements can be produced by highly localized injections or highly nonlinear local acceleration mechanisms with an equatorial footprint comparable to an Earth radius. New particle energization mechanisms discovered by the Probes occur in different locations around Earth, interact with charged particles over different temporal and spatial scales, and thus sculpt a complex spatiotemporal variability in radiation belt intensities.

Radiation intensities can increase by orders of magnitude inward of GEO orbit (Figure 1c). Hence, while GEO spacecraft provide invaluable monitoring of the belts' outer boundary, they do not provide insight into most dangerous radiation enhancements in the heart of the belts. With the de-orbiting of the Van Allen Probes in 2019, the nation no longer has the means to capture the entire span of particle radiation intensities between GEO and LEO. We are now blind to most dangerous manifestations of near-Earth particle radiation. Another critical gap in our knowledge is in the material science, i.e., how charged particles of different energies and

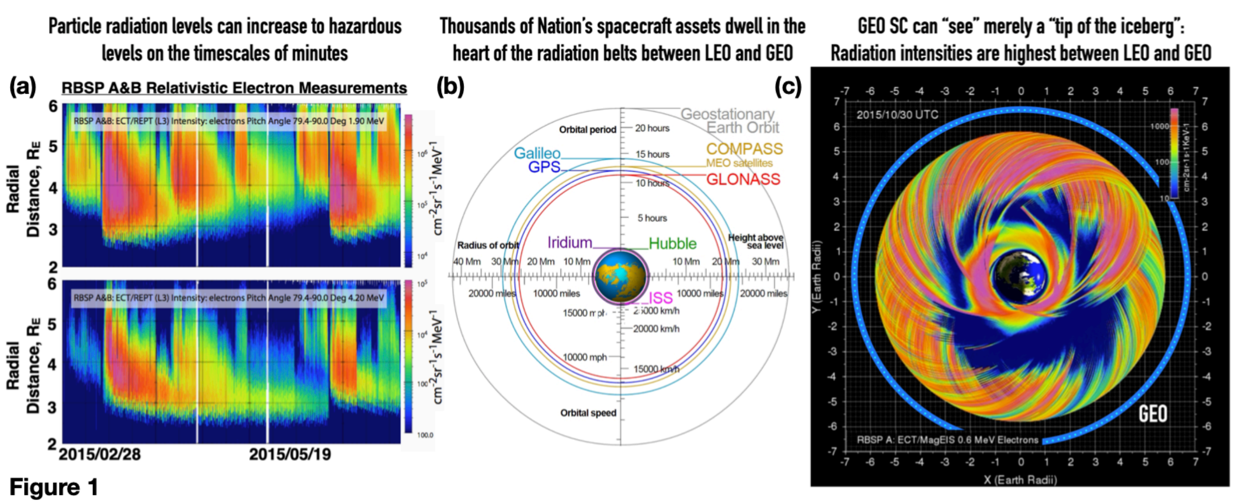


Figure 1

species interact with the materials and electronic components used in spacecraft manufacturing. In order to protect our nation’s infrastructure and Human Exploration program from adverse effects of particle radiation, the observational gap between LEO and GEO must be filled with comprehensive observatories and supported by capable ground-based operations with advanced data-driven modeling capabilities for advanced and accurate operational forecasting, nowcasting, triage, and forensics efforts. Key objectives for such infrastructure are:

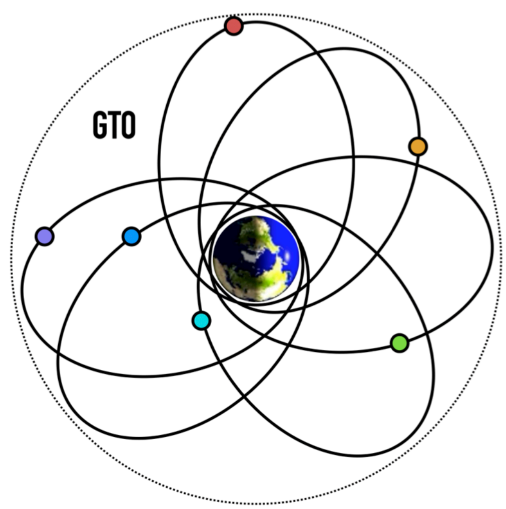
1. Disentangle spatial and temporal variability of radiation belt intensities with multi-point simultaneous measurements around Earth
2. Simultaneous measurements of the entire energy and pitch-angle distributions of both electrons and ions along with the electromagnetic fields/waves that sculpt their intensities
3. Capture the entire extent of the radiation belts between LEO & GEO with a minute “exposure”
4. “Big-data” capabilities to process operational/scientific data from the required large constellation of simultaneous in situ measurements
5. Detailed specification of adverse radiation effects on different materials used in spacecraft manufacturing

The above objectives can be realized only by a large constellation of radiation belt probes with a comprehensive ground-based data and modeling infrastructure. To fully capture particle distributions in the radiation belts, probes’ orbits must be in the equatorial plain, where radiation intensities are the highest. This requires GTO orbits with apogees near GEO and low-altitude perigees below LEO (Figure 2). In order to capture global variability of particle intensities on the timescales of under 10 minutes a GTO constellation must contain >20 probes. To resolve the azimuthal variability of radiation belt intensities and simultaneously sample all mechanisms that sculpt their variability, the probes’ lines of apsides must be distributed around Earth.

A large number of the nation’s space assets, including critical navigational infrastructure, such as GPS, dwell on off-equatorial MEO orbits that cannot be directly sampled by GTO probes. Therefore a number of probes will need to be launched into highly-inclined MEO orbits. These off-equatorial probes would not only measure radiation levels at the exact location of key MEO assets, but would also sample key physical mechanisms that affect radiation belt intensities at higher latitudes. Moreover, off-equatorial MEO probes can carry additional instrumentations such as auroral and ENA imagers that will provide global contextual measurements of auroral activity, cold plasma density, and the ring current, which are key for providing a systems understanding of ~~the~~ radiation belt fundamentals and dynamics.

To comprehensively understand the near-Earth radiation environment and hence make a quantum leap in our ability to protect society from Space Weather effects requires a strong international coalition of Universities, National Labs, and the Commercial Sector. To be fully implemented within the next two decades the infrastructure development plan for the radiation belts can be streamlined and leveraged by the following key components[1]:

- Rapid development/scalability: The concept can be ready for deployment within one-two years. Individual measurement capabilities are deployed separately



Target Capabilities

Energetic electrons: ~keV-10 MeV (e.g., SS telescopes, MagSpec, APD)
Ions: keV-100s keV (e.g., puck)
Plasma: ~eV-10s eV (e.g., Faraday cup, ESA)
Magnetometer: DC-10 Hz (fluxgate, scalar)
Plasma waves: kHz-100 kHz (search coil)
Material science: surface/internal charging (dosimeters)

Figure 2

[1] See WP ‘Solving the Space Weather Problem’ by Vourlidas et al. for more details

based on available resources and launch opportunities. Leverages existing LEO and GEO assets (e.g., GOES, REACH), but fills the gap in between.

- Community-wide participation: No requirement for the payloads to be identical. Contributions of a "standard" payload from multiple contributors supported by multiple programs (e.g, NASA-funded MoO, HFORT/HTIDES, international partners). Supplemented by stand-alone hosted payloads.
- Collaboration with commercial sector: The concept leverages long-term collaboration with the commercial sector (e.g., Millennium) towards geosynchronous launches.
- Simple, streamlined bus design and operations: 8-16 U mass-produced (by one or more manufacturers) busses with common instrument interface. A single maneuver to transfer SC onto highly elliptical (GTO) naturally decaying (to satisfy 25 yr req) orbit.
- Collaboration with SC operators and manufacturers: Establish close collaboration with SC operators for developing data products and metrics of success. Work with the manufacturing community to developing a "material science" payload that quantify charging effects on different materials used in SC design. Platform can also be used as a test-bed for new technologies.
- Big-data component: SOC and operational/scientific data products from a large constellation of simultaneous in situ measurements will require state-of-the art algorithms of machine learning and data-mining.
- Strong modeling component: Global operational products for forecasting and nowcasting radiation intensities by leveraging data-augmented physics-based and data-driven models.