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Scientific/Technical/Management Section

1. Science Objectives and Expected Significance of the Proposed Work

A primary goal in NASA's LWS Program is to extend first-principles-based models for the coupled Sun-Earth environment systems. Such models can be used as tools for science investigations, as prototypes for prediction and specification capabilities, and as frameworks for linking disparate data sets at vantage points throughout the domain.

Objectives. This proposed work, called *RADIation environment using ARMAS data in the NAIRAS model (RADIAN),* will expand a physics-based modeling capability of the NASA Langley Research Center (LaRC) *Nowcast of Atmospheric Ionizing Radiation for Aviation Safety* (NAIRAS) system to expand science investigations, prediction and specification capabilities, and link diverse data sets. Specifically, we will use the *Automated Radiation Measurements for Aerospace Safety* (ARMAS) data streams in a Kalman filter data assimilation technique to link the ARMAS data with NAIRAS. This system, with additional future data streams, will be able to specify the weather of the global radiation dose rate environment from the surface of the Earth through Low Earth Orbit (LEO) for recent, current epoch, and a few hours forecast. This task exactly addresses a primary goal and measure of success of the *3.1.2 Characterization of the Earth's Radiation Environment* FST for "demonstrating the temporal, spatial, and magnitude variability in the radiation environment, from tropospheric altitudes to the radiation belts, using observations and existing models reported with appropriate metrics of uncertainty."

Significance. The RADIAN system will enable future science-based, applied engineering operational applications that will especially help manage radiation exposure risks for aircrew, high-altitude pilots, frequent flyers, first trimester fetuses, and commercial space travelers, i.e., high-profile "at-risk demographics."

2. Technical Approach and Methodology

Technical Approach – Environment Background

The at-risk demographics face radiation hazards originating from Galactic Cosmic Rays (GCRs), Solar Energetic Protons (SEPs), and possibly Van Allen radiation belt trapped particle energetic electrons particularly when traveling at and above commercial aviation altitudes greater than 8 km (Figure 1). In general, GCRs originate from outside the solar system, SEPs originate directly from flaring events on the Sun or from acceleration shocks in the solar wind, and energetic electrons from the outer Van Allen radiation belt. Below the top of the atmosphere (~100 km), these primary particles interact with neutral species (predominantly N_2 and O_2) to create secondary and tertiary particles and photons, such as n, p, e, α, π, μ, and γ-rays. The primary particle fluxes decrease with decreasing altitude due to absorption by atmospheric molecules while the secondary and tertiary radiation component, i.e., lower energy cascading particles and photons created by those impacts, increases. These competing processes (decreasing primaries and increasing secondaries/tertiaries with lower altitudes) produce a maximum ionization rate that occurs

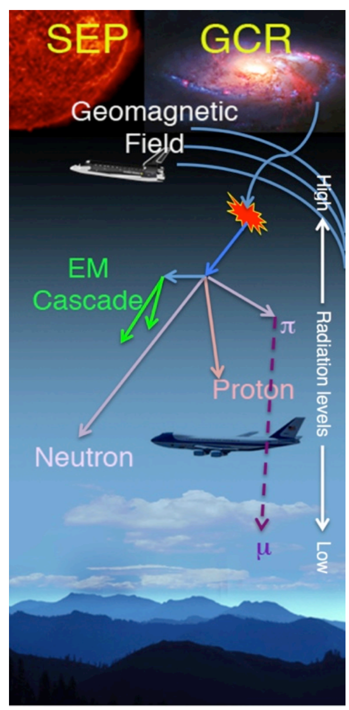

Fig. 1. Radiation environment at aviation altitudes.

between 20 and 25 km (65,000 – 82,000 ft.) called the Pfotzer maximum. Below this altitude, down to the Earth's surface, the dose rate then decreases from particle or photon absorption in an increasingly thick atmosphere. The broad spectrum of secondary radiation consists of particles and photons with varying energies that can radiate in all directions but are generally directed Earthwards. Particles, particularly dominated by protons and neutrons, impact the atmosphere mostly above commercial aviation altitudes, and create a spray of additional energy-degraded particles that collide with the aircraft hull and interior components, people, or fuel to cause a further alteration of the radiation spectrum. This complex radiation spectrum has components shown to cause an increased cancer risk [Grajewski *et al.,* 2011] and our results will eventually be used in applications for informing pilots and air traffic control of radiation hazards to mitigate exposures for at-risk demographics.

Technical approach – state-of-the-art physics-based modeling system (NAIRAS)

Models. There are numerous modeling systems using data that could be considered for RADIAN, e.g., LUIN [O'Brien *et al.,* 1996], CARI6PM [Friedberg *et al.,* 1999; Friedberg and Copeland, 2003; Friedberg and Copeland, 2011], FLUKA [Zuccon *et al.,* 2001], QARM [Lei *et al.,* 2006], AIR [Johnston, 2008], PARMA [Sato *et al.,* 2008], AVIDOS [Latocha *et al*., 2009; Latocha *et al*., 2014], NAIRAS [Mertens *et al.,* 2013], PANDOCA [Matthiä *et al.,* 2014], and KREAM [Hwang *et al.,* 2014]. Recent work by Joyce *et al.* [2014] utilized CRaTER measurements [Spence *et al.,* 2010; Schwadron *et al.,* 2012] in deep space to estimate dose rates through the Earth's atmosphere at a range of different altitudes down to aviation heights.

NAIRAS. However, we believe the existing state-of-the-art radiation environment model is the NASA LaRC NAIRAS system that produces data-driven, physics-based climatology of time-averaged global radiation conditions [Mertens *et al.,* 2013]. First, it covers the entire domain of interest using *physics-based modeling*. It predicts dosimetric quantities from the surface of the Earth, through the atmosphere, and into LEO from both GCRs and SEPs. It includes the response of the geomagnetic field to interplanetary dynamical processes and subsequent influences on atmospheric dose. It uses coupled physics-based models to transport cosmic radiation through three distinct domains: the heliosphere, Earth's magnetosphere, and neutral atmosphere. Second, the physics-based models are driven by *real-time measurements* to specify boundary conditions on the cosmic and solar radiation at the interfaces between the distinct domains or to characterize domain internal properties through which radiation propagates. Third, NAIRAS is at *Technology Readiness Level (TRL) 8*, i.e., fully integrated with operational hardware and software systems, most user documentation is completed, all functionality has been tested in operational scenarios and verification and validation are being completed. Fourth, it is formulated so that physical processes

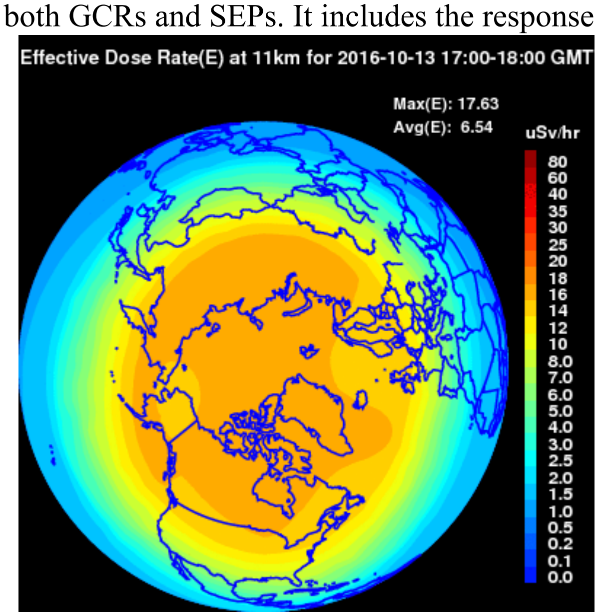

Fig. 2. NAIRAS effective dose output at 11 km for October 13, 2016 (17–18 UT).

can be transparently improved through *modular code updates* as the science improves. Fifth, NAIRAS output can be readily *integrated with independent data streams* to improve the current epoch and near-term forecast radiation weather. Sixth, there is a rather large and *competent community* (NASA centers, research universities, and space weather industry) that collaborates to improve NAIRAS. Seventh, it has been proven to *represent very well radiation climatology* on short time scales. These features lead to high confidence that NAIRAS will continue to evolve and form the basis for a national U.S. capability to manage radiation risks to aviation. As other models evolve, we can imagine that ensemble modeling will also contribute a risk management pathway but we do not address that capability here.

Status. Global NAIRAS data shown in figure 2 have been reported hourly since 2011 (http://sol.spacenvironment.net/~nairas/index.html) as a result of the 2008–2011 NASA DECISION-funded project enabling NAIRAS development. NAIRAS runs hourly at LaRC and the NAIRAS team member Space Environment Technologies (SET) hosts the public website for its data access. SET also provides ingest data to NAIRAS of neutron monitoring and GOES proton data for use in modeling the GCR/SEP differential number flux spectrum, geomagnetic and Dst indices for driving the geomagnetic cutoff rigidity, and NCEP 3-hour reanalysis meteorological atmospheric densities for specifying impact target molecule concentrations used in HZETRN, a core model of NAIRAS. SET's Radiation Alert and Prediction System (RAPS) collects, organizes, and distributes the raw input data to LaRC for NAIRAS use and also operates at TRL 8. For these reasons, we have selected NAIRAS to be the physics-based modeling system of RADIAN.

Technical approach – state-of-the-art real-time data system (ARMAS)

Measurements. Until recently, in situ instruments returned after flight for analysis were the main method for obtaining dose rates at aviation altitudes. These provided a wealth of data related to the aviation radiation environment and made important contributions to model validations of the radiation field at altitude, especially for human tissue damage. A large number of measurements were made using Tissue Equivalent Proportional Counters (TEPCs) under GCR background conditions for post-flight analysis though not during major space weather SEP events [Dyer *et al.,* 1990; Beck *et al.,* 1999; Kyllönen *et al.,* 2001; Getley *et al.,* 2005; Beck *et al.,* 2005; Latocha *et al.,* 2007; Meier *et al.,* 2009; Beck *et al.,* 2009; Dyer *et al.,* 2009; Hands and Dyer, 2009; Getley *et al.,* 2010; Gersey *et al.,* 2012; and Tobiska *et al.,* 2014a, 2014b, 2015, 2016]. Some of the measurements have included neutron flux and dose equivalent measurements with solid-state detectors [Dyer *et al.,* 2009; Hands and Dyer, 2009; Ploc *et al.,* 2013; and Lee *et al.,* 2015].

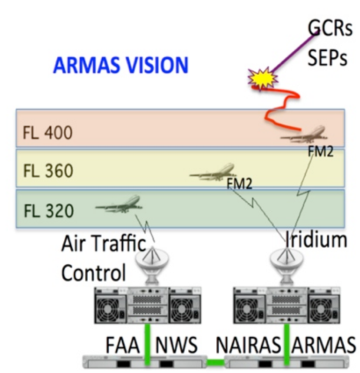

Fig. 3. The ARMAS program vision for dose rate reporting.

ARMAS. However, only one of these systems provides a real-time data retrieval capability from an aircraft that could be useful for real-time monitoring. The ARMAS program [Tobiska *et al.,* 2016] was started in 2011 and is designed to monitor and report the real-time atmospheric radiation environment, providing a flow of actionable information serving two needs of commercial aviation (figure 3). These needs include *i)* knowledge of the state of long-term background radiation from GCR sources that impact crew monthly, annual, and career statistical dose limits and *ii)* identification of short-term hazards from space weather events that could lead to increased deterministic risk for radiation illness. Since 2013 the program has successfully deployed a fleet of six instruments (flight modules – FMs) measuring the ambient radiation environment Total Ionizing Dose (TID) and deriving an ambient dose equivalent rate for tissue at commercial aircraft altitudes. ARMAS transmits real-time TID to the ground, processes it immediately, and then distributes quality, tissue-relevant ambient dose equivalent rates with 5-minute latency.

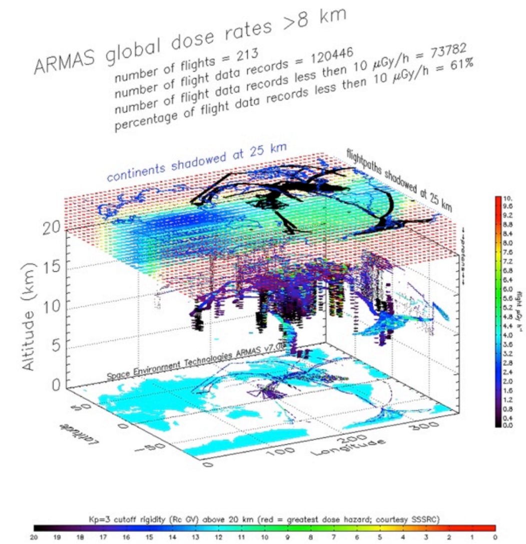

Fig. 4. Global ARMAS measurements of dose rates, 2013–2016.

Status. The program has completed 213 flights up to 17.3 km (56,700 ft.) as shown in figures 4 and 5. ARMAS evolved through NASA Small Business Innovation Research (SBIR) contracts in Phases I, II, IIE, and III to achieve several important TRL milestones: *i)* **TRL 5:** created a global physics-based radiation climatology real-time data stream (RAPS) as input into NAIRAS prototype operations (2010), performed in situ dose rate measurements on commercial aircraft (2011), and calibrated TID measurements with tissue-relevant data using national beam line facilities (2013); *ii)* **TRL 6:** retrieved the first autonomous, real-time measurements from commercial altitudes with 15-minute latency using FM1 (2013); *iii)* **TRL 7:** demonstrated system-level processing in a relevant operational environment with three ARMAS units (FM1, FM2A, FM2B) while simultaneously operating in northern and southern hemispheres (2015) and obtained global dose rate data records from 213 flights (2016); and *iv)* **TRL 8:** released automated real-time ARMAS weather and NAIRAS climatology ambient dose rate equivalent comparison with a 5-minute latency (http://sol.spacenvironment.net/~ARMAS/index.html) from locations around the

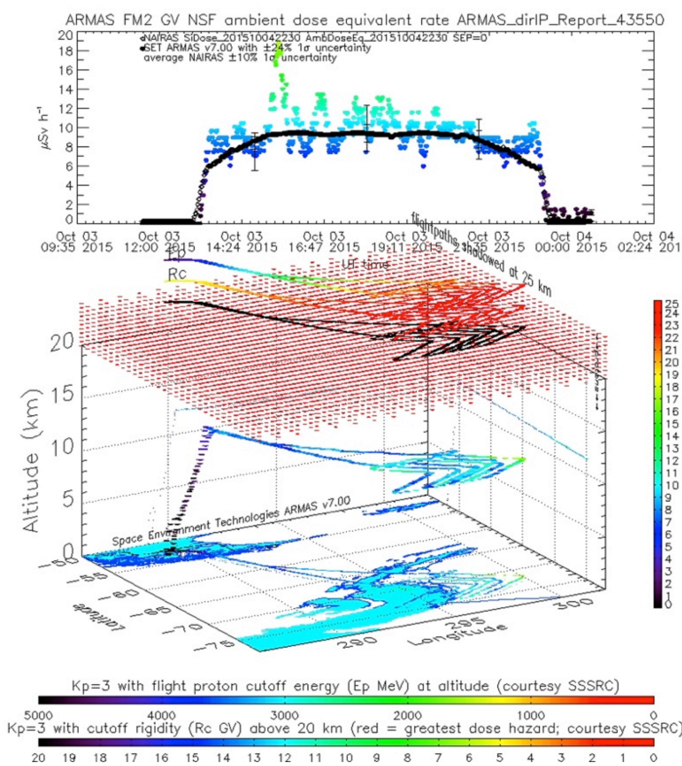

Fig. 5. October 3–4, 2015 ARMAS FM2 NSF/NCAR GV measurements at high magnetic latitudes (colored dots) and compared with NAIRAS (black squares).

Earth (2016) as well as completed validation and verification of dose rates with other instruments and NAIRAS [Tobiska *et al.,* 2016] using FM1, FM2A, FM2B, FM3, FM5A, and FM5B.

ARMAS uses a Commercial-Off-The-Shelf (COTS) TID micro dosimeter, a microprocessor, and a variety of real-time data collection methods (Iridium transceivers, Bluetooth, RS232, Ethernet, or micro SD logger) to report the flight dose rate from aircraft. This TRL 8 system has been flying on aircraft for nearly four years and regularly participates in annual campaigns using the NASA Armstrong Flight Research Center (AFRC) DC-8, B-747, ER-2, the NOAA and NSF/NCAR G-IV and G-V Gulfstreams, and commercial Boeing 737, 747, 757, and 777 as well as Airbus 319 and 320 jets. Besides regular flights of the existing FMs, FM4 and FM7 are contracted to fly on stratospheric balloons in 2017 while multiple FM6s are being prepared for business jet use. For these reasons, ARMAS will be the RADIAN data stream.

Methodology – radiation weather via Kalman filter data assimilation

Community experience. Space weather community resources and knowledge have matured and we can now consider producing more realistic global and regional radiation weather using a Kalman filter data assimilation methodology [Kalman, 1960]. For example, ARMAS has already obtained real-time radiation measurements and, along with NAIRAS, has evolved to TRL 8. We note that meteorologists, oceanographers, and space physicists use data assimilation models, which provide more accurate specifications and forecasts for an environment compared to global physics-based models alone [Schunk *et al.,* 2014]. During the past two decades they been used for space weather investigations as more global measurements have become available. We look to the analogy of tropospheric weather models that need time-resolved temperature, pressure, humidity, and species' concentrations across global locations to make accurate weather predicts. Similarly, for specifying radiation weather, models need data at recent epochs and global locations. Data for assimilation with NAIRAS will consist mostly of TID, either as an absorbed dose or the derived ambient dose equivalent although other measurements such as spectral energies for SEP events could be included when available. While data assimilation models can produce better specifications and forecasts than global physics-based models, there may be mixed results due to the use of different data types, measurement quantities, assimilation techniques, and background physics-based models. Thus, we will begin the process of understanding how best to use data assimilation for producing improved global weather dose rates starting with TID.

Objectives. Because radiation observations in the atmosphere are very sparse (figure 4), assimilation can fill gaps with model output while maintaining consistency between model dynamics and observations when specifying the current state of the environment. We start with two well-qualified components that are already producing a dose rate end product, i.e., the NAIRAS physics-based global model and the ARMAS flight track data stream. *We will combine NAIRAS model output with ARMAS observations at a given time interval and location to refine a current epoch specification and near-term forecast capability. We will quantify error statistics for both as well as use test cases to evaluate the efficiency of the code and real data to understand the technique's robustness. We will use metrics to quantify how progress is being made.* Although NAIRAS and ARMAS both independently exist, their combination into this new data assimilation system (RADIAN) must be considered at TRL 5 where we will start by testing the technology elements (NAIRAS and ARMAS) in an integrated representative environment (RADIAN) using reasonably realistic supporting elements (existing operational infrastructures) and conforming to target environment interfaces (end user dose rate products).

Our **First Phase** will be to evaluate the use of the ensemble Kalman filter (EnKF) technique [Evensen, 1994] similar to the Godinez and Koller [2012] radiation belt application method and will move the project to TRL 6.

Our **Second Phase** will be to refine the EnKF technique for NAIRAS-ARMAS. The discussion below identifies a number of steps that are needed to adaptively refine this technique for sparse, highly variable data in a global context. We will complete this Phase at TRL 7.

Our **Third Phase** will be to evaluate the EnKF technique using metrics developed for similar space weather phenomena such as SEPs and geomagnetic storms; we will end at TRL 8.

Use-case considerations. We are particularly interested in using the Ensemble Kalman Filter (EnKF) assimilation method [Evensen, 1994], which Godinez and Koller [2012] identified as robust and efficient when used with sparse measurements of the radiation belt environment. Theirs is a similar use-case to ours for producing dose rates in an atmosphere that contains non-linear dynamics. A feature of the EnKF method is that it can account for NAIRAS model uncertainty using an adaptive inflation algorithm [Koller *et al.,* 2007] applied to the localized model forecast covariance matrix. NAIRAS model uncertainties include, for example, parameterized approximations of physical processes, incomplete physics, noisy data streams that drive the models, inaccurate boundary conditions that couple multiple models, and numerical discretizations. In the application to atmosphere dose rate data assimilation, these errors in NAIRAS could potentially be larger than errors in the initial conditions. We get a hint of this possibility, for example, by comparing the higher ARMAS dose rates between 15–16 UT in Figure 5 (colored dots) with NAIRAS (black dots). Here, the ARMAS dose rates, with 24% uncertainty, are about 5σ larger than the 14-15 UT data; NAIRAS climatological output has approximately 10% uncertainty. This case poses a challenge for understanding data and model uncertainties. If the NAIRAS forecast covariance matrix is underestimating this time frame it would lead to filter divergence where observations would be completely ignored in the assimilation. We want to adequately include NAIRAS uncertainty in the assimilation of unusual, calibrated data and, therefore, we will explore multiplicatively inflating the forecast error covariance matrix. This requires changing it by a scalar inflation factor to increase the model uncertainty. Godinez and Koller [2012] present a statistically relevant adaptive technique to compute the inflation factor and we will evaluate their methodology in our First Phase.

Inflation factor. The adaptive inflation technique depends on ARMAS temporal and spatial observations of either the measured absorbed dose rate for silicon or the derived ambient dose equivalent rate for tissue. The phase space dose rate (PSD) observations can easily have physical variability of a factor of two or even larger during enhanced radiation conditions along a flight track. Globally, across multiple altitudes, magnetic latitudes linked to cutoff rigidities, and during severe radiation events, it is possible that variability can be a couple orders of magnitude. Because the variations in observations can so large we will consider using more than one inflation factor for the NAIRAS spatial domain. Using only one value may cause over-inflation of the covariance matrix, leading to unrealistic solution states. A remedy for possible unstable solutions will be to use a localized adaptive inflation technique tailored to small regions such as flight corridors through similar cutoff rigidities and constant altitudes where observational ARMAS data would typically exist. By having inflation factors that can be restricted to certain scenarios, it can make our algorithm more adaptive across a wide variety of conditions and can lead to smaller overall error. We plan to compute the inflation factors adaptively using statistical principles as described in Wang and Bishop [2003] that have also been tested as well as implemented by Godinez and Koller [2012].

EnKF. The EnKF Monte Carlo approximation to Kalman filtering is typically used for non-linear models, i.e., the NAIRAS example, and its results approximate those of a classical Kalman filter. It can propagate the NAIRAS covariance matrix using an ensemble of model integrations, i.e., forecasts in sequential data assimilation to calculate the average forecast and the error covariance matrix. ARMAS observations can then be used to update the ensemble each analysis step so as to evolve the forecast model in the next time step. Using the adaptive inflation technique, a changing forecast error covariance matrix would adjust each forecast step with updated observations and provide a capability for improving the accuracy of the model's forecasts.

Example technique. Following the Godinez and Koller [2012] example, the localized adaptive inflation technique in the EnKF operates in the following manner. Modeled discrete state output variables, x_i, from the NAIRAS model, M, are the absorbed dose rate for silicon and ambient dose equivalent rate for tissue. We make the initial assumption that most of the ionizing radiation is from GCR neutrons as modeled by NAIRAS using neutron monitor and the solar polar field. Much of the GCR particle variability will be due to changing particle fluxes organized by energy per nucleon that are modulated by cutoff rigidity perturbations in a disturbed magnetosphere. NAIRAS uses Dst to model this magnetospheric disturbance and SET already provides recent history, current epoch, and forecast Dst [Tobiska *et al.,* 2013] for USAF Joint Space Operations Center (JSpOC) operations. This TRL 9 Dst output is demonstrated at the website http://sol.spacenvironment.net/~sam_ops/index.html?. GOES particle data is important for SEPs and, while rare, their energy spectra are still not well known nor measured. Should an SEP event occur, we can initially use the worst-case CREME96 [Tylka *et al.,* 1997] spectrum of proton (Z = 1) energies scaled by the GOES HEPAD proton fluxes of a similar energy bin in the range of 10–50 MeV. This ratio could then be used to scale other elements, i.e., Z = 2–92. SET has an existing system for other government projects that operationally provides this spectrum and it can be provided to NAIRAS in a future system-level update. NAIRAS forecasts in our case will initially use the previous NAIRAS one-hour data cube evolved from prior time steps, i.e., persistence, in the analysis with updates from the ARMAS data. We may use at least a three-hour look-back period to start the ensemble process though we will consider longer, adaptive look-back periods during medium (–40 to –100 nT Dst) and large (less than –100 nT Dst) geomagnetic storms. Thus, our team has a path forward for providing near-term NAIRAS forecasts beyond the most recent one-hour epoch and metrics will show the utility, or lack thereof, of forecasts beyond the current epoch.

As a start in the First Phase evaluation process, we note that a given x_i variable advances from time t_k to t_{k+1} using the next set of observations, and is written

$$x_i(t_{k+1}) = M(_{t_k \to t_{k+1}})\big(x(t_k)\big), \quad i = 1, \dots, N \tag{1}$$

The EnKF analysis equation is given by

$$\boldsymbol{x}_i^a = \boldsymbol{x}_i + \boldsymbol{K}(\boldsymbol{y}_i^0 - \boldsymbol{H}\boldsymbol{x}_i) \tag{2}$$

where x^a is the analysis, $\boldsymbol{y}^0$ is the perturbed vector of ARMAS absorbed dose rate in silicon or ambient dose equivalent rate. $\boldsymbol{H}$ is the linear observation operator and if $\boldsymbol{R}$ is the observation covariance matrix and $\boldsymbol{P}$ is the forecast covariance matrix, then the Kalman gain matrix, $\boldsymbol{K}$, is

$$\boldsymbol{K} = \boldsymbol{P}\boldsymbol{H}^T(\boldsymbol{H}\boldsymbol{P}\boldsymbol{H}^T + \boldsymbol{R})^{-1} \quad (3)$$

$$\boldsymbol{P} = \frac{1}{N-1}\sum_{i=1}^{N}(\boldsymbol{x}_i - \overline{\boldsymbol{x}})(\boldsymbol{x}_i - \overline{\boldsymbol{x}})^T \quad (4)$$

where $\overline{\boldsymbol{x}}$ is the average of the forecast ensemble members. Next, $\boldsymbol{y}^0$ is defined as

$$\boldsymbol{y}_{\boldsymbol{i}}^{\boldsymbol{0}} = \boldsymbol{y}^0 + \varepsilon_i, \quad i = 1, \ldots, N \quad (5)$$

with ε_i as a random vector from normal distribution with zero mean and a specified standard deviation σ^0, which is the known observational error of 21% for absorbed dose rates in silicon and 24% for tissue-related ambient dose equivalent rates [Tobiska *et al.,* 2016]. The $\boldsymbol{R}$ observation covariance matrix is constructed from the observation perturbations

$$\boldsymbol{R} = \frac{1}{N-1}\sum_{i=1}^{N}\varepsilon_i\,\varepsilon_i^T \quad (6)$$

Following the calculation of the ensemble state variables x_i at the time of the next set of observation from equation (1) we define a local region of influence in the state-space for each grid point j in the state variable $x_{i,j}$, i.e., the flight path at an altitude along a common cutoff rigidity, and do the following:

(i) define the local observation operator H_j,
(ii) identify which observations fall within the local region of influence (similar cutoff rigidity) to determine y_j,
(iii) define the local forecast covariance matrix P_j and local observation covariance matrix R_j,
(iv) compute the local innovation vector $z_{i,j}$,
(v) compute a local inflation factor α_j, and
(vi) for each ensemble member i, inflate the ensemble at grid point j to obtain $\tilde{x}_{i,j}$.

The local innovation vector $z_{i,j}$, the local inflation factor α_j, and the new state vector $\tilde{x}_{i,j}$ are

$$\boldsymbol{z}_{i,j} = \boldsymbol{y}_j^0 - \boldsymbol{H}_j\boldsymbol{x}_{i,j} \quad (7)$$

$$\alpha_j = \frac{\overline{\boldsymbol{z}_j^T\boldsymbol{z}_j}}{Tr(\boldsymbol{H}_j\boldsymbol{P}_j\boldsymbol{H}_j^T)} - \frac{Tr(\boldsymbol{R}_j)}{Tr(\boldsymbol{H}_j\boldsymbol{P}_j\boldsymbol{H}_j^T)} \quad (8)$$

$$\tilde{x}_{i,j} = \overline{x}_j + \sqrt{\alpha_j}(x_{i,j} - \overline{x}_j) \quad (9)$$

We next compute the analysis with the inflated ensemble members, $\tilde{x}_i$. For step (iii) above, the local covariance matrix P_j can either be computed using the local state vectors $x_{i,j}$ or extracted from the global covariance matrix **P**. This cycle will be repeated each time there are observations available in that localized region.

For our application, the observations and state vector are expressed in the same physical variables (absorbed dose rate in silicon or ambient dose equivalent rate), where the observations are interpolated to model grid locations of 1°×1°×1 km. The observation operator H is a matrix with 0 or 1 entries, indicating where observations are not or are available for the state vector.

We note that the ensemble members can also include the drivers to the NAIRAS model. Since, the radiation environment between the troposphere and outer magnetosphere can change dynamically from GCR and SEP flux, we know solar wind high-speed streams, coronal mass ejections (CMEs), and southward interplanetary magnetic field (IMF) states affects this environment. The GCR background varies with a long-term trend and is modulated by the IMF varying with the approximate eleven-year solar cycle or CME-induced Forbush decreases. The highly time variable SEP environment can have order of magnitude changes occurring in tens of minutes. The combined effects of these phenomena on the Earth's Magnetosphere–Ionosphere–Thermosphere (M-I-T) system create the weather of the radiation environment. We consider that the dose rate, $\dot{D}$, is functionally

$$\dot{D} = \frac{dD(f_1,f_2,f_3,f_4,f_5)}{dt} + \varepsilon \qquad (10)$$

where the driving functions are $f_1 = f_{Rc}$, $f_2 = f_{GCR}$, $f_3 = f_{SEP}$, $f_4 = f_{EE}$, and $f_5 = f_{TGF}$ while ε is the combined uncertainty from all terms. We assume the following: Rc is correlated with the ring current disturbance storm time index Dst; the GCRs are correlated with the sunspot number (SSN), the state of the solar polar magnetic field, solar modulation parameter Φ and Forbush decrease from magnetic clouds; the SEPs are correlated with the existence of located flare, CME, or IMF acceleration shock events that create larger GOES proton fluxes ϕ; the outer radiation belt Energetic Electron (EE) precipitation into the mesosphere, possibly from EMIC waves, is correlated with Dst; and terrestrial gamma-ray flashes are correlated with lightning in the presence of large storms or hurricanes. These relationships provide a wealth of ensemble members that can be used in equations (1)–(9) to help create analyses and forecast solutions. Thus, we anticipate from this EnKF methodology that it is possible to use first principles-based models like NAIRAS, combined with new data streams like ARMAS, to achieve substantial progress toward future near-term predictability of the radiation environment.

Methodology – metrics

The NASA Goddard Space Flight Center (GSFC) Community Coordinated Modeling Center (CCMC) has the vision and capability for independently comparing and validating NAIRAS modeled results, ARMAS measurements, and their integration through data assimilation. For a given flight path and a defined duration of measurements, these types of model and data comparison can be performed. We will establish metrics for: *i)* Root-Mean-Square (RMS) difference; *ii)* Prediction Efficiency; *iii)* the ratio of the maximum change in dose rate magnitudes and ratio of the maximum magnitudes; and *iv)* the ratio of the event sum for a defined duration, i.e., total accumulated dose. The calculations of these metrics are described in equations (11)–(15).

i) Root-Mean-Square (RMS) difference. One of the most meaningful and widely used ways to evaluate model performance is to calculate root-mean-square difference between model estimates and observations defined as

$$RMS = \sqrt{\frac{\Sigma(x_{obs}-x_{mod})^2}{N}} \qquad (11)$$

where x_{obs} and x_{mod} are observed and modeled values, respectively. RMS difference has the same unit as observed and modeled values, x_{obs} and x_{mod}. Perfect model predictions have RMS differences of 0. Therefore, the closer the RMS error is to 0, the more accurate the model is.

ii) Prediction Efficiency. Prediction efficiency, one of the skill scores compared against the mean of observations, is also commonly used to describe performance of models:

$$PE = 1 - \frac{RMS_{mod}}{RMS_{ref}} \qquad (12a)$$

$$= 1 - \sqrt{\frac{\Sigma(x_{obs}-x_{mod})^2/N}{\Sigma(x_{obs}-\langle x_{obs}\rangle)^2/N}} \qquad (12b)$$

where x_{obs} and x_{mod} are again observed and modeled values, and $<x_{obs}>$ is the mean value of the observed measurements. In this proposed work, the mean value of the observations $<x_{obs}>$ will be considered from ARMAS measurements. The prediction efficiency ranges from negative infinity to 1. A prediction efficiency of 1 implies a perfect model performance, while a prediction efficiency of 0 means that the model performance is as accurate as the mean of the observed data. A negative value indicates that the observed mean is a better predictor than the model.

iii) Ratio of the maximum change in dose rate magnitudes and ratio of the maximum magnitudes. The root mean square error and prediction efficiency measure how well time series observed data and modeled values are correlated with each other. Metrics based on this ratio will be used to quantify the RADIAN model capacity for producing peak values or short-term variations during certain time periods, even though the performance of NAIRAS may be poorer in terms of the RMS error and/or prediction efficiency. Two types of ratios will be selected – the ratio of the maximum change (maximum minus minimum values; max - min) and the ratio of the maximum (max) values of models to those of observations during a defined time interval:

$$ratio(max - min) = \frac{(x_{mod})max - (x_{mod})min}{(x_{obs})max - (x_{obs})min} \quad , \quad (13)$$

$$ratio(max) = \frac{(x_{mod})max}{(x_{obs})max} \quad (14)$$

where $(x_{obs})_{max}$ and $(x_{mod})_{max}$ are the maximum values of the observed and modeled signals during a defined time window. Perfect models have a ratio of 1. The ratio of max-min and the ratio of max larger than 1 overestimate maximum variations and maximum values. Note that the two ratios depend on the length of time window.

iv) Ratio of the event sum for a defined duration (total accumulated dose). This ratio is given by

$$ratio(sum) = \frac{\sum x_{mod}}{\sum x_{obs}} \quad (15)$$

for the x_{mod} modeled and x_{obs} observed signal values during a defined time window. We will evaluate RADIAN with the results from all four metrics.

3. Perceived Impact of the Proposed Work

Societal impact. The societal impact of this proposed work is far-reaching. We believe this is the first time that a team attempts data assimilation for providing more accurate global atmospheric radiation specification and prediction capabilities. We aim to provide the weather of the radiation environment as compared with the current climatology. This capability is required as a foundation for developing and validating operational radiation monitoring and forecasting as defined by The White House-directed Space Weather Strategy and Action Plan (SWAP) [National Science and Technology Council, 2015] and Executive Order Coordinating Efforts to Prepare the Nation for Space Weather Events [Executive Order 13744, 2016]. SWAP seeks to (i) define the requirements for real-time monitoring of the charged particle radiation environment to protect the health and safety of crew and passengers during space weather events; (ii) define the scope and requirements for a real-time reporting system that conveys situational awareness of the radiation environment to orbital, suborbital, and commercial aviation users during space weather events; and (iii) develop or improve models for the real-time assessment of radiation levels at commercial flight altitudes. RADIAN directly supports the measurement (monitoring), reporting (situation awareness), and modeling (specification and forecasting) thrusts of the SWAP and Executive Order (EO) 13744 initiatives.

Goals and Measures of Success: RADIAN leverages the NAIRAS modeling and ARMAS data stream successes to create more accurate atmospheric radiation data assimilated weather, both current and predicted. It will compare existing data and model outputs for the global radiation environment in the troposphere but can be extended into LEO as more data become available in those regions during a coming era of commercial space travel. This effort represents continued innovative expansion in our discipline area and it encourages the development of more calibrated data sources to understand the dynamic variation of this radiation environment in near real-time. RADIAN will demonstrate the temporal, spatial, and magnitude variability in the radiation environment at tropospheric altitudes, reported with appropriate metrics of uncertainty. In doing so, it will fulfill a critical measure of success for this FST by using observations and existing models.

4. Relevance the Proposed Work to NASA programs

SET, LaRC, and CCMC have joined in this study to promote the innovative development of a calibrated data source integrated into a physics-based model for understanding the dynamic variation of the radiation environment from the recent past into the near future. RADIAN is a successor project evolving from previously successful NASA (non-LWS TR&T) awards including the DECISION NAIRAS project, SBIR ARMAS program, and CIF ARMAS enhancements. RADIAN, ARMAS, and NAIRAS are unique in that NASA Earth Sciences and Heliophysics programs have both found benefit from this work. In addition, the success in our precursor projects is one reason that radiation environment specification and prediction at aviation altitudes has been called out in SWAP and EO 13744 as well as in the U.S. Senate and House bills now working their way through Congress. NASA seeks to understand the science of, and provide societal benefits from, atmospheric radiation research and RADIAN directly advances that goal.

5. Proposed Contributions to the Focused Science Team (FST) Effort

Relevance. RADIAN specifically addresses the Focused Topic 3.1.2 *Characterization of the Earth's Radiation Environment* as it brings together NAIRAS and CCMC modelers with ARMAS observers to make significant progress towards validating existing modeling systems and building a robust radiation weather prediction capability. This work will allow user communities, including Government agencies, international partners, and commercial airlines, to understand the accuracy and uncertainty of existing models/data and to develop future decision aid tools.

Contributions. The contributions from the proposed work to the FST effort will be *i)* validating the existing NAIRAS understanding of the physical mechanisms creating the atmospheric radiation environment, in particular the GCR and SEP sources; *ii)* elucidating areas of mismatch between NAIRAS climatology and ARMAS weather to explore possible new radiation sources such as tertiary particles/photons from outer radiation belt energetic electron precipitation and terrestrial gamma-ray flashes; *iii)* identifying the localized and temporal scales of influence for characterizing atmospheric radiation from the adaptive inflation factor solutions; *iv)* resolving uncertain radiation processes by using RaD-X campaign and ground laboratory beam-line calibration results to improve our characterizations; *v)* providing a platform for improving predictions through forecast SEP and M-I-T coupling; and *vi)* enabling LWS TR&T to programmatically advance by providing cutting edge science, i.e., understanding the dynamic variation of the radiation environment that has a direct societal benefit in the form of future decision aid tools.

We will make metrics results of our RADIAN system evaluation available to other FST members, to the scientific community at-large, and to users. In particular, we propose that the PI of RADIAN also be the FST Leader since this activity will incorporate many of the capabilities by other FST members. We publish regularly (see our team's publications lists in the short biographies below) in order to make our results available to the scientific community and our team members participate widely in scientific conferences such as AGU, AMS, and SWW. SET, in particular, has very close ties to user groups that operate in at least three domains (commercial aviation altitudes, high altitude aircraft, and stratospheric balloons). We solicit needs and requirements from that community who are also our customers, e.g., the S. Korean commercial airline industry, the NASA airborne sciences program, and the World View commercial balloon flight program. Our predictive capability from the EnKF technique will provide unique advantages to specific user communities, especially the International Civil Aviation Organization (ICAO) who is developing standards and recommended practices for aviation radiation. ICAO will be able to advise their member states on radiation exposure management strategies such as moving the flight corridor to lower altitudes or using more equatorward flight paths based on our radiation weather specification capabilities that could provide critical threshold inofrmation.

Milestones. Milestones for determining successful progress in RADIAN include: *i)* evaluating the ensemble Kalman filter (EnKF) technique; *ii)* refining the EnKF technique for NAIRAS-ARMAS; and *iii)* evaluating the success of the EnKF technique using metrics.

Metrics. Metrics for determining the successful progress and outcome of the proposed work include quantifying the RADIAN results compared with test case NAIRAS and ARMAS data via four methods. These are: *i)* Root-Mean-Square (RMS) difference; *ii)* Prediction Efficiency; *iii)* the ratio of the maximum change in dose rate magnitudes and ratio of the maximum magnitudes; and *iv)* the ratio of the event sum for a defined duration, i.e., total accumulated dose.

6. General Plan of Work

The RADIAN plan of work includes key milestones, the management structure, and the expected contribution to our proposed effort by each person.

Key Milestones

The key milestones are three Phases envisioned for this project. In the First Phase we will evaluate the EnKF technique and move the project to TRL 6. This effort will take approximately 1½ years and requires: *i)* purchasing the *Advanced Math and Statistics for IDL* licensed code; *ii)* formulating the ensemble members; *iii)* constructing the localized adaptive inflation technique; *iv)* identifying the forecast period; *v)* verifying the functionality of the operators and covariance matrices; *vi)* validating the local innovation vector; and *vii)* establishing the framework for data output, including both data records and graphical representations. We will work with Co-I Mertens to create EnKF parameters consistent with the physical representations contained within NAIRAS. We will work with Co-I Zheng to construct a metrics framework.

In the Second Phase we will refine the EnKF technique for NAIRAS-ARMAS and move the project to TRL 7. This effort will take approximately 1½ years and requires: *i)* identifying ARMAS and NAIRAS test cases for quiet and disturbed radiation conditions; *ii)* collecting independent data sets for comparative purposes; *iii)* assembling and running the RADIAN system code from end-to-end; *iv)* fine-tuning the localized adaptive inflation factors by temporal and spatial scales; *v)* verifying system level linkages between EnKF code, data retrievals, and output methods; and *vi)* ensuring a robust metrics assessment as an-ongoing part of the RADIAN system. We will work with Co-I Mertens to validate NAIRAS interfaces and model vs. data results. We will work with Co-I Zheng to verify the proper functioning of metrics algorithms.

In the Third Phase we will evaluate the success of the EnKF technique using metrics and move the system-level project to TRL 8. This effort will take approximately 1 year and requires: *i)* identifying valid test cases for the metrics; *ii)* performing metrics on test cases; *iii)* refining the RADIAN system parameters to improve the metrics; *iv)* ensuring robust data–model interfaces; and *v)* publishing and presenting RADIAN results. We will work with Co-I Mertens to update any NAIRAS issues found during the metrics runs and ensure robust model–data interfaces. We will work with Co-I Zheng to provide her with the required cases for the metrics runs and help her evaluate the results.

Table 1. Key Milestones (notional dates)

Milestone	Date	Milestone Tasks
1	2017/07 –2018/12	Kickoff meeting, First Phase EnKF code build and implementation
2	2019/01 –2020/06	Second Phase EnKF code refinement
3	2020/07 –2021/06	Third Phase EnKF code testing and evaluation

Management Structure

SET is the prime on this grant under the direction of the PI Tobiska who will perform most of his work at SET. Co-I Mertens of LaRC will perform most of his work at LaRC. Co-I Zheng of CCMC will perform most of her work at GSFC. Either subcontracts to the NASA LaRC and NASA GSFC Co-Is from SET, or NASA HQ line item set asides to the Centers will be used for funding the Co-Is.

Personnel Contributions

The PI Tobiska will work with SET staff to perform the bulk of EnKF code build and implementation, refinement, testing and evaluation. Each of the Co-Is will work with his or her staff to verify NAIRAS PSD modeling, comparisons with ARMAS observations, and builds/runs for metrics evaluation.

7. Data Sharing Plan

RADIAN data sharing will continue in line with past data-sharing practices of our team members such as making our data available, in real-time, on public URLs. Examples are:

NAIRAS: http://sol.spacenvironment.net/~nairas/index.html
ARMAS: http://sol.spacenvironment.net/~ARMAS/index.html

RADIAN will have its own website but will link to both NAIRAS and ARMAS sites. SET also shares its flight data with colleagues in scientific campaigns such as the Earth Science Division ATom campaign via the ICARTT database for the recent (2016) observing season. We also make regular presentations at scientific meetings and conferences as well as publish our results in peer-review journals such as *Space Weather Journal*.

8. FST Team Leader Plan

Goal. The *Characterization of the Earth's Radiation Environment* FST has an opportunity to empower collaborations between multiple models and datasets so that the dynamic variability of the radiation environment from the surface to near-Earth space can be understood, more accurately specified at the current epoch, and predicted with less uncertainty in the near future. The societal benefits from these collaborations will accrue to the commercial aviation and commercial space travel industries so that humans as well as avionics can work safely and more efficiently between the atmosphere and near-Earth space. A goal is to build a longer-term collaborative framework that will help focus the awarded FST PI teams in their collaborative efforts as well as reach out to external research groups for participation in cutting-edge research.

Collaborations. It is anticipated that awarded FST PI teams in this topic area will find benefit in sharing their research experience and findings with other LWS TR&T funded teams. The use of multiple collaborative tools, including WebEx and/or Skype, Google Docs and/or DropBox, and 1–2 day meetings of opportunity at AGU, AMS, and/or SWW will be tools of our collaborations. We would welcome collaborations with external expert teams that are also performing research in similar areas. We will provide summary reports of our work at annual community scientific meetings and will encourage regular publication of our individual team research efforts as well as our collaborative FST studies in peer review scientific journals.

Experience. The PI for RADIAN, W.K. Tobiska, is proposed as the FST Team Leader. He has extensive experience leading broad teams to successful research conclusions. Examples include: *i)* the AFRL SBIR Anemomilos Dst team (5 institutions) that created operational Dst values (recent history, current epoch, and forecast) for the USAF Space Command; *ii)* the NASA SBIR ARMAS team (13 institutions) that created real-time, calibrated dose measurements on aircraft; and *iii)* the NASA LWS Institute SAFESKY team (21 institutions) that is creating an international path forward for managing aviation exposure risks.

Management. Dr. Tobiska will manage the *Characterization of the Earth's Radiation Environment* FST in addition to his duties as PI of the RADIAN project, if awarded. He will hold a kickoff telecon meeting between the awarded PIs and their Co-Is within 2 months of contract start for the teams. The aim is to hold face-to-face meetings of the entire FST annually if at all possible. Dr. Tobiska will provide quarterly reports to the NASA Heliophysics LWS TR&T program for this FST as well as a final summary.

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Biographical Sketches

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2001 – present, President and Chief Scientist, Space Environment Technologies
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Selected Relevant Publications:

Tobiska, W.K., D. Bouwer, D. Smart, M. Shea, J. Bailey, L. Didkovsky, K. Judge, H. Garrett, W. Atwell, B. Gersey, R. Wilkins, D. Rice, R. Schunk, D. Bell, C. Mertens, X. Xu, M. Wiltberger, S. Wiley, E. Teets, B. Jones, S. Hong, and K. Yoon (2016), Global Real-time Dose Measurements Using the Automated Radiation Measurements for Aerospace Safety (ARMAS) system, *Space Weather,* **14**, doi:10.1002/2016SW001419.

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Dr. Tobiska is the President and Chief Scientist of Space Environment Technologies (SET), Director of the Utah State University Space Weather Center (SWC), and President of Q-up, LLC. His early research of solar XUV to FUV irradiances led to the creation of the internationally distributed Solar Irradiance Platform (SIP) modeling system. He invented the world’s first operational computer code for solar irradiance forecasting while serving as a senior scientist at Northrop Grumman/Logicon. At SET, he extended this expertise into the development of operational space weather systems that now produce solar irradiances, geomagnetic indices, and ground-to-space radiation environment dose rates. At SWC, he has led the effort to produce and disseminate information layers in operational HF communications and GPS accuracies for use by broader technological systems. At Q-up, he organized the activity to commercialize ionospheric communications and navigation products. His career spans work at the NOAA Space Environment Laboratory, UC Berkeley Space Sciences Laboratory, Jet Propulsion Laboratory, Northrop Grumman, SET, SWC, and Q-up. He has been a USAF and a NASA Principal Investigator (PI) in the LWS, SOHO, JSDAP, and UARS programs, a Co-Investigator (Co-I) on the NASA SDO, TIMED, Galileo, and ESA component of the International Space Station (ISS) SOL-ACES instruments. He has been the COSPAR C1 Sub-Commission (Thermosphere & Ionosphere) Chair, the COSPAR International Reference Atmosphere (CIRA) Task Force Chair, and was a Session Organizer for 2002, 2004, 2006, 2008, 2010, 2012, and 2014 COSPAR scientific sessions. He serves as lead U.S. delegate to the International Standards Organization (ISO for the space environment and developed the ISO solar irradiance as well as Earth atmosphere density standards. He is the AIAA Atmospheric and Space Environment Technical Committee (ASETC) Committee on Standards (CoS) chair. He has been an active participant on the American Meteorological Society (AMS) annual Space Weather Symposium organizing committee, the Research-to-Operations Working Group for the National Research Council Decadal Survey, the NASA Heliophysics Division Science Advisory Committee, and the NASA Living With a Star Steering Committee. Dr. Tobiska is an Associate Fellow of the American Institute of Aeronautics and Astronautics and a member of American Geophysical Union, Committee On Space Research, AMS, and ISO TC20/SC14 U.S. Technical Advisory Group. He is a founding member, and Executive Committee member, of the American Commercial Space Weather Association (ACSWA). He has authored/co-authored over 165 peer-review scientific papers as well as 10 books and major technical publications.

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2015 –	Senior Research Physicist, Space Radiation Group, NASA LaRC
2004 – 2015	Senior Research Scientist, Chemistry and Dynamics Branch, NASA LaRC
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Recent NASA projects:

2016 –	Space Radiation Risk, SEP Modeling & Dosimetry, Lead, HEOMD
2014 – 2016	Advanced Exploration Systems RadWorks, Space Env. Lead, HEOMD
2013 – 2016	Radiation Dosimetry Experiment (RaD-X) Flight Mission, PI, SMD
2010 – 2012	IR Interferometry Auroral Ionosphere-Thermosphere Energetics, PI, SMD
2008 – 2011	NAIRAS Model Development, PI, SMD
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2005 – 2008	Ionospheric Response to Geomagnetic Storms, PI, SMD

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Research Associate, USRA/GSFC, September 2001 – July 2003

Dr. Zheng's research experiences include ring current/radiation belt modeling, subauroral electric fields, ionospheric outflow, magnetosphere-ionosphere coupling, magnetospheric physics in general, and space weather physics and modeling. Dr. Zheng has authored/co-authored over 45 peer reviewed journal publications and many other technical documents.

Dr. Zheng is a point of contact for all radiation (and impacts) related models and their implementation at CCMC. She was a PI of a NASA IRAD project that coupled models/observations of radiation storms to an engineering model to examine the impacts on spacecraft and its electronics.

Selected Relevant Publications:

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