SPACE WEATHER SUPPORT TO NASA OPERATIONS

REQUIREMENTS

STATE OF THE ART

TRENDS

NEEDS AND CONSTRAINTS

ARCHITECTURES

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September 2008

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Overview

- This report is the third in a series designed to examine space weather support to NASA operations
- The focus of this increment is on trends in space weather monitoring, forecasting, and research
  - Previous reports looked at NASA's space weather requirements and how they are met today
  - Subsequent reports will look at architectures that may be implemented to meet future NASA space weather operational support
- The following topics are covered:
  - Background and context
  - Challenges to meeting future space weather support
  - How these challenges are being addressed
  - Reasonable expectations over the next decade

NASA Radiation Study Team, 2006

- In 2006 a study team was assembled to review NASA radiation requirements, impacts, and activities
  - The team was comprised of representatives from the Mission Directorates, Office of the Chief Health and Medical Officer, Office of the Chief Engineer, Office of Safety and Mission Assurance, and the Office of Program Analysis and Evaluation
  - Additional experts with specific domain expertise were consulted as needed
- The team identified the following five broad issue themes that the Agency should address to enhance the effectiveness of its radiation-related activities
  - Knowledge of the Radiation Environment
  - Radiation Standards
  - Radiation Testing Strategies
  - Developing Strategic and Mission Requirements
  - Radiation Health and Safety Compliance

Radiation Study Team Findings

Radiation impacts much of NASA's mission content including:

- Objectives for Earth and space missions
- Electronics and materials development and their safe performance
- Transportation storage and handling of nuclear materials
- Design of space transportation, life support, and robotic systems concepts of operations
- Mission designs
- Nuclear power and propulsion and power systems

Radiation Study Team Recommendations

"The most salient overarching issue identified regarding the Agency's radiation-related efforts is the need to ensure appropriate communication, coordination, and exchange of information between the various diverse and distributed radiation functions within the Agency. All of the subsequent issue themes identified are an outgrowth of this situation. It is recommended that an Agencywide Radiation Advisory Group, reporting to an appropriate NASA senior official, be formed to coordinate radiation-related activities and to facilitate communication and information exchange."

- The current study is an initial response by the Office of the Chief Engineer to provide an overview of space weather and radiation issues affecting NASA operations to enable better NASA-wide communication and coordination

Space Weather

"Space Weather" refers to conditions of the space environment and includes short term fluctuations (meteorology) as well as long term averages and extremes (climatology)

- The space environment extends from the Sun through the heliosphere and includes the magnetospheres and ionospheres of planets and moons of the solar system
- The space environment is characterized by solar electromagnetic flux, magnetic fields, charged and neutral components of the solar wind, and energetic particles superimposed on the solar wind from solar and galactic sources
- The space environment changes over time scales ranging from seconds to millennium, but the most common time scales of interest to operations range from minutes to hours or days; for mission planning and design the relevant time scales range from days to years or decades

“Space Weather” vs. “Radiation”

- There is a potential for confusion between the terms “space weather” and “radiation” in a study of operational requirements
- Space weather is the broader term and encompasses a wide range of phenomenology with operational impact (e.g., electronic upsets, spacecraft charging, orbit decay, material degradation, and crew health risks)
- A **significant subset of space weather impact** is related to the **radiation**, or energetic particle, environment, including electrons, protons, neutrons, and charged ions with energies from KeV to GeV
- The radiation environment inside a spacecraft or habitat is modified by the surroundings (shielding, atmosphere, tissue, etc) and can be enhanced by human-induced radiation sources (power supplies, medical monitoring, invasive radioisotopic tracers)

Space Weather Risk Mitigation is a Multidiscipline Challenge

- **Effective space weather risk mitigation requires coordinated integration of multiple skills and expertise**
  - Understanding of the physics of space weather
  - Space environment characterization and forecast
  - Fundamental biological impact of space radiation
  - Space environment effects and analysis on electronics and components
  - Radiation transport through shielding
  - Systems design
  - Operations impact

Space Weather Challenges

- A key objective of NASA's diverse space weather and space radiation effects programs is to support NASA mission operations by providing **timely, accurate, and accessible** information on the space environment and its potential impact
- The challenges that follow are issues that must be addressed in order to meet the objective

Space Weather Challenges to NASA Operational Mission Support

- Ensure the health and performance of crews living and working beyond the protection of the Earth's atmosphere and magnetic field
- Improve our understanding of the consequences of space radiation exposure to astronauts, with emphasis on reducing the uncertainty to 50 percent
- Ensure appropriate observations for space weather forecasts are available to meet NASA-specific requirements for use in the 2015-2020 timeframe
- Predict the onset and evolution of SPEs within the first hours of an event, with emphasis on the ability to forecast 6 to 12 hour "All Clear" periods
- Develop spacecraft subsystems, including life support systems, for optimum mission performance in the space environment
- Provide efficient and effective space weather operational support to robotic missions
- Develop climatological and dynamic models of the space environment for design and operation of optimal space systems
- Minimize time-lag between development of research models of space weather and their application in user-friendly tools for mission operations
- Develop and implement standards and guidelines for space system radiation hardness and space environment risk mitigation
- Improve Intra- and Inter-agency communication and cooperation in space weather related activities

Human Radiation Research	Operational Space Weather	Programmatic/Policy

Ensure the health and performance of crews living and working beyond the protection of the Earth's atmosphere and magnetic field

What is Being Done?

- Lunar exploration architectures are being designed to meet PEL
- Mission impact is being assessed
- Operations concept studies are under way

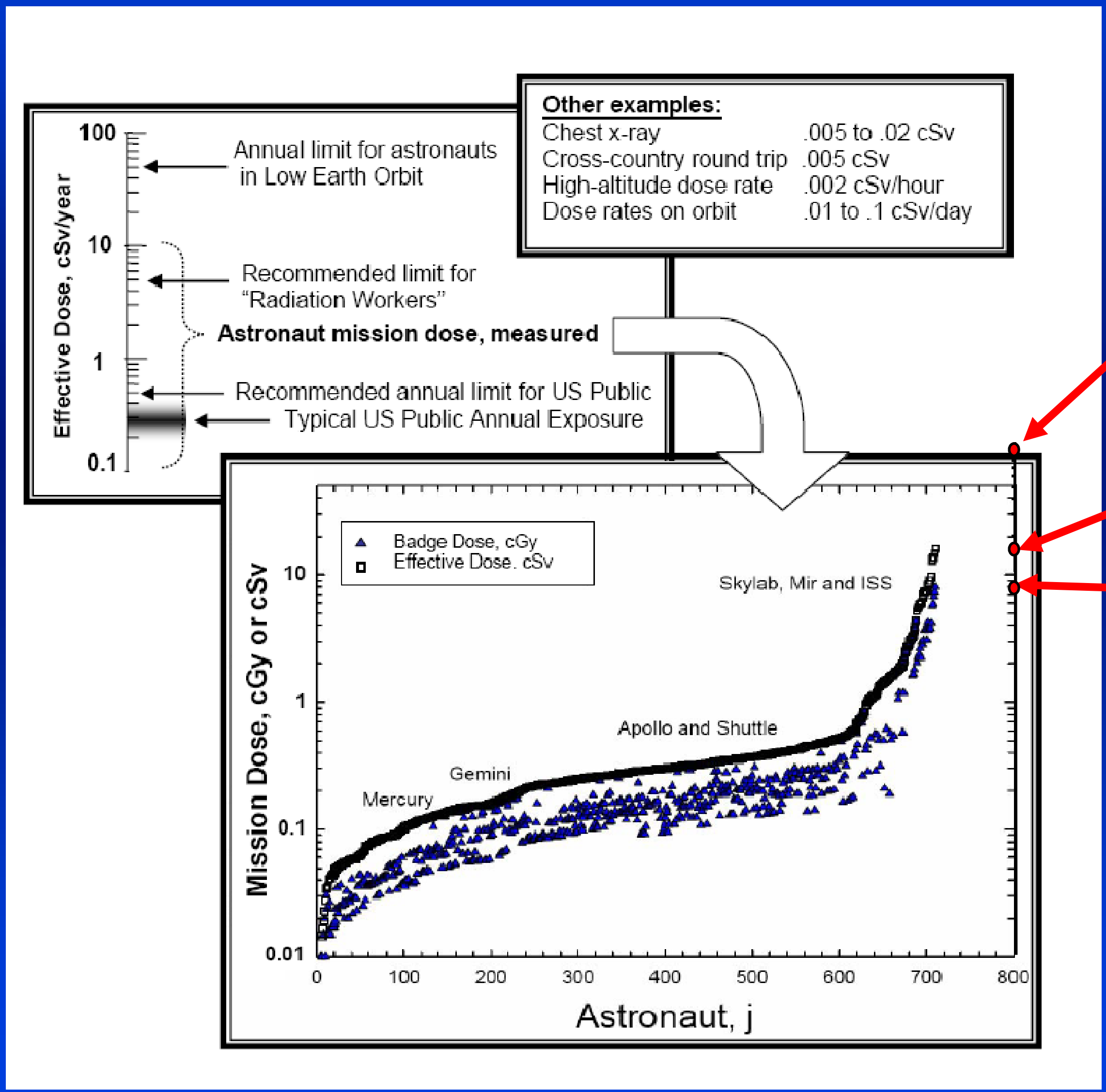
Why is it Important?

- Radiation exposure will be significantly higher than recent experience
  - Factor of two to three higher dose rate
  - Longer average mission duration
- Astronauts on EVA may be exposed to substantial dose/dose rates during solar storms
- Long duration lunar stays (greater than 6 months) may approach or exceed Permissible Exposure Limits (PEL)
- Notional Mars missions exceed current PELs

What Can We Expect?

- Radiation exposure will limit lunar stays to somewhere between 6 months and 1 year
- Surface exploration timelines will be constrained by operations concepts designed to keep exposure "As Low As Reasonably Achievable"

Exposure Experience to Date



Estimated Exposure for Exploration Class Missions[1]

Mars Surface Stay (Solar minimum, 400 days in deep Space, 600 Days on Surface)

6 Month Lunar Mission

3 Month Lunar Mission

[1] Cucinotta, Kim, Ren, NASA/TP-2005-213164

Days in Deep Space to Stay Below Permissible Exposure Limits

Longer duration lunar and Mars missions will require reduction in the present uncertainty of radiological risk predictions, plus possible developments of medical countermeasures

3% REID at 95% Confidence[1]

	Males		Females	
Age	E (cSv)	Days	E (cSv)	Days
30	62	142	47	112
35	72	166	55	132
40	80	186	62	150
45	95	224	75	182
50	115	273	92	224
55	147	340	112	282

[1] Cucinotta, Kim, Ren, NASA/TP-2005-213164

Example age-dependent career effective dose (E) limits for a 1-year mission and calculated days in deep space to stay below 3 percent REID with 95 percent confidence (solar minimum under 10 g/cm^2 Al shielding).

Radiation Impact Is Not Limited To Health

"…astronauts may be unable to accomplish prime mission objectives if they are not permitted to leave the outpost because of a radiation storm" [1]

"It will be the [still tbd] Flight rules and operational procedures that allow (and require) mission control to protect the crew. However, it is not sufficient to create overly conservative procedures. Although there is no loss of life, a mission can still fail because an astronaut sits huddled in a shielded room when it is actually safe for him or her to be drilling for samples outside." [1]

[1] "Managing Space Radiation Risk in the New Era of Space Exploration" NRC report, March 2008

Improve our understanding of the consequences of space radiation exposure to astronauts, with emphasis on reducing the uncertainty to fifty percent

Detail from Cover of NRC Workshop Report, 2006

What is Being Done?

- Permissible Exposure Limits include allowance for uncertainty (95 % confidence that radiation is less than 3 percent risk of exposure induced death)
- Ground-based radiation effects research is underway

Why is it Important?

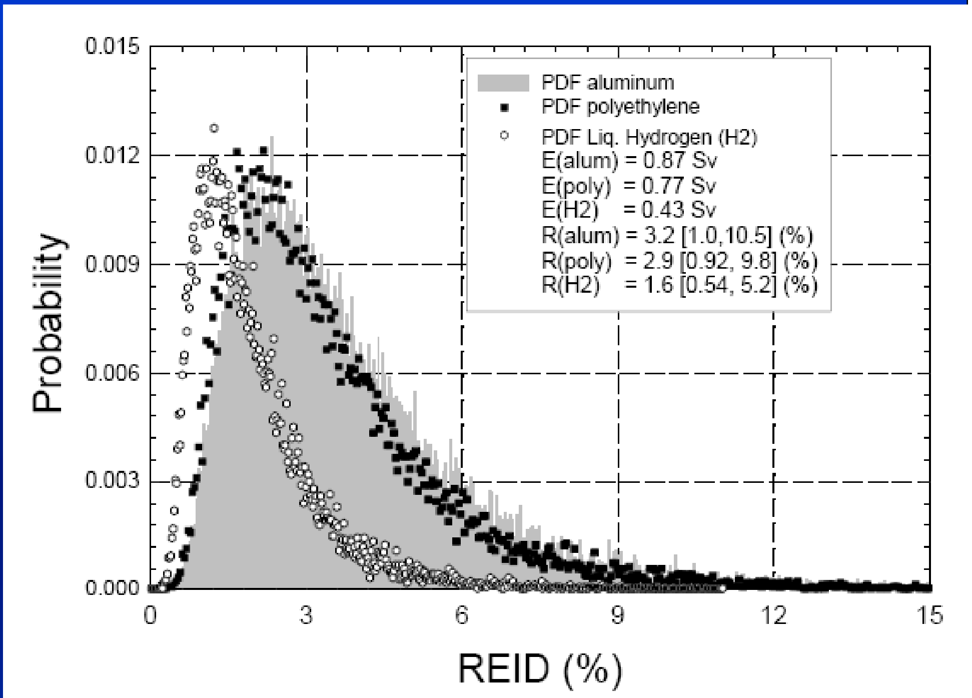
- Lack of knowledge about the biological effects of and responses to space radiation is the single most important factor limiting the prediction of radiation risk associated with human space exploration
- Designing to meet large uncertainty may pose unnecessary mass and performance penalties on exploration architectures
- Non-cancer effects, especially Central Nervous System (CNS) impacts, are potentially severe

What Can We Expect?

- Designs will continue to incorporate uncertainty in limits
- CNS impacts will be better understood over next 5-10 years
- Uncertainty in relationship of cancer to radiation exposure will decrease

Risk Calculation and Uncertainty

- Cancer risks are not measured, but estimated from model calculations that incorporate uncertainties from multiple factors
- Permissible Exposure Limits are set at 95 % confidence interval (CI) for three percent Risk of Exposure Induced Death (over astronaut's lifetime)
- Cancer uncertainty ratio, the ratio of mean risk to upper end of CI risk, has been reduced from ~6 to ~3 since 2000[1]
- Major knowledge gaps in radiation health risks continue in the areas of:
  - Carcinogenesis
  - Neurological damage
  - Degenerative tissue diseases
  - Acute radiation syndromes
  - Immune system responses



Probability Density Functions for 40-year old males on a solar minimum Mars swingby mission behind 20-g/cm^2 shields of aluminum, polyethylene, or liquid hydrogen. Effective doses, point estimates, and 95% CI for REID are shown in insert.
SOURCE: Cucinotta, Kim, Ren, NASA/TP-2005-213164

[1] "Managing Space Radiation Risk in the New Era of Space Exploration" NRC report, March 2008

NASA Space Radiation Health Research

Advisory Organizations (examples)

National Council on Radiation Protection and Countermeasures (NCRP)

National Academies (NAS, IOM, NRC)

Internal and External NASA Advisory and Proposal Peer Review

Funded Research

Human Research Program*

Radiation Health Element

Announcements of Opportunity

- NASA Specialized Centers of Research
- Independent Principal Investigators
- National Space Biomedical Research Institute

NASA Space Radiation Laboratory
(High Energy Heavy Ions and Protons at Brookhaven National Lab)

Loma Linda (High Energy Protons)

Interagency Collaboration

DOE Low Dose Radiation Research Program

National Institutes for Health (NCI, NIAID)

Armed Forces Radiobiology Institute

Brookhaven National Lab (NASA Space Radiation Laboratory)

*HRP is managed within ESMD and monitored by the Advanced Capabilities Division

Validated research findings are incorporated into risk assessment models which are used in operations and form the basis of recommendations to OCHMO for new Permissible Exposure Limits

Ensure appropriate observations for space weather forecasts are available to meet NASA-specific requirements for use in the 2015-2020 timeframe

Why is it Important?

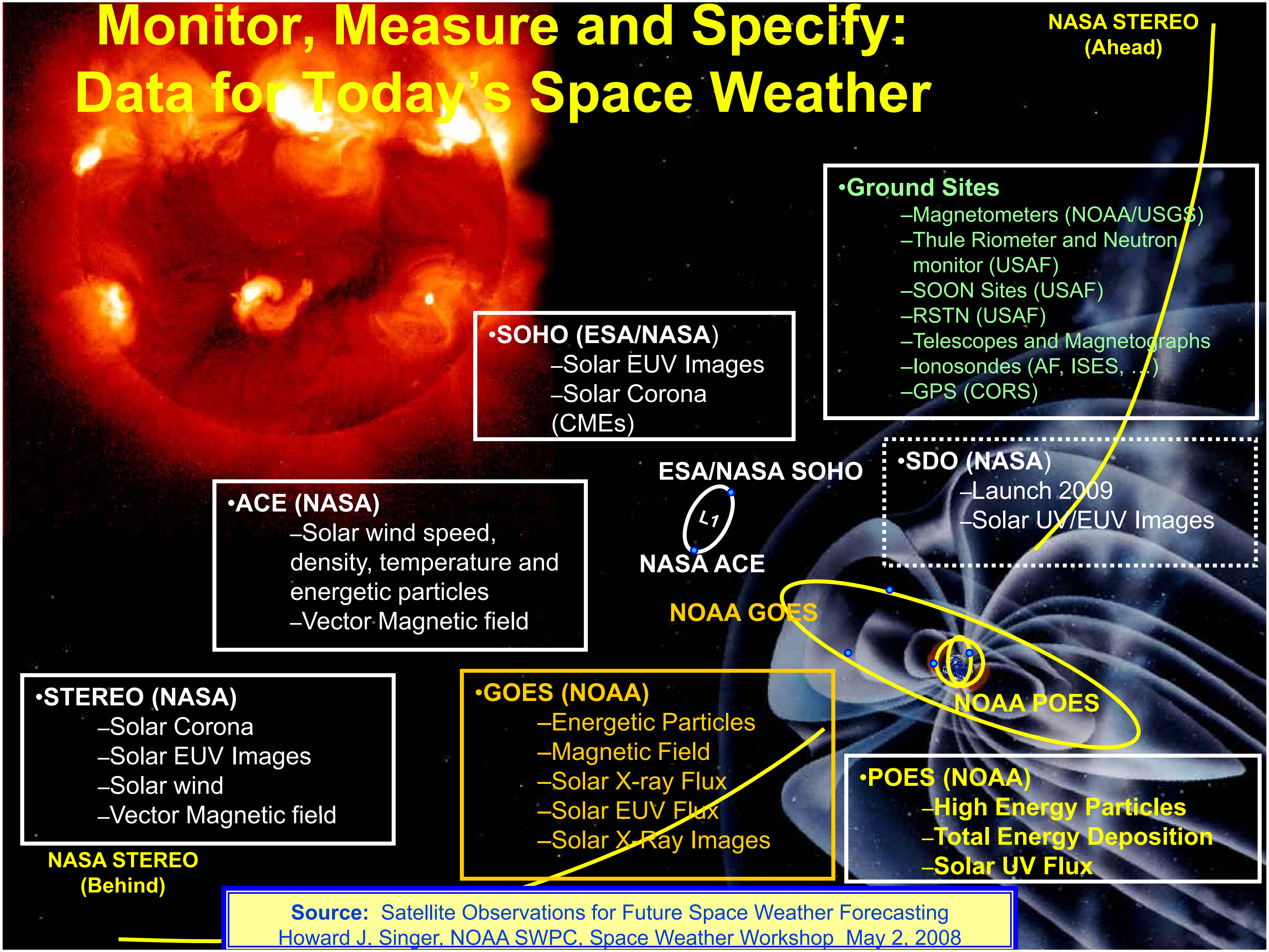
- Space Weather forecasts require reliable and timely solar, solar wind, and energetic particle observations
- NOAA GOES space environment instrument manifest may not meet NASA-specific requirements
- Significant observational data today derives from NASA/ESA Science missions that will not be available in 2015/2020

What is Being Done?

- Operational requirements across NASA are being assessed
- Additional Heliophysics missions are planned for pending solar cycle

What Can We Expect?

- Baseline requirements and options for meeting them will be developed over the next year or two
- Plans to make science mission data available to operations community will continue



Monitor, Measure and Specify:
Data for Today's Space Weather
NASA STEREO
(Ahead)
•Ground Sites
–Magnetometers (NOAA/USGS)
–Thule Riometer and Neutron monitor (USAF)
–SOON Sites (USAF)
–RSTN (USAF)
–Telescopes and Magnetographs
–Ionosondes (AF, ISES, …)
–GPS (CORS)
•SOHO (ESA/NASA)
–Solar EUV Images
–Solar Corona (CMEs)
ESA/NASA SOHO
L1
NASA ACE
•SDO (NASA)
–Launch 2009
–Solar UV/EUV Images
•ACE (NASA)
–Solar wind speed, density, temperature and energetic particles
–Vector Magnetic field
NOAA GOES
NOAA POES
•STEREO (NASA)
–Solar Corona
–Solar EUV Images
–Solar wind
–Vector Magnetic field
•GOES (NOAA)
–Energetic Particles
–Magnetic Field
–Solar X-ray Flux
–Solar EUV Flux
–Solar X-Ray Images
•POES (NOAA)
–High Energy Particles
–Total Energy Deposition
–Solar UV Flux
NASA STEREO
(Behind)
Source: Satellite Observations for Future Space Weather Forecasting
Howard J. Singer, NOAA SWPC, Space Weather Workshop May 2, 2008

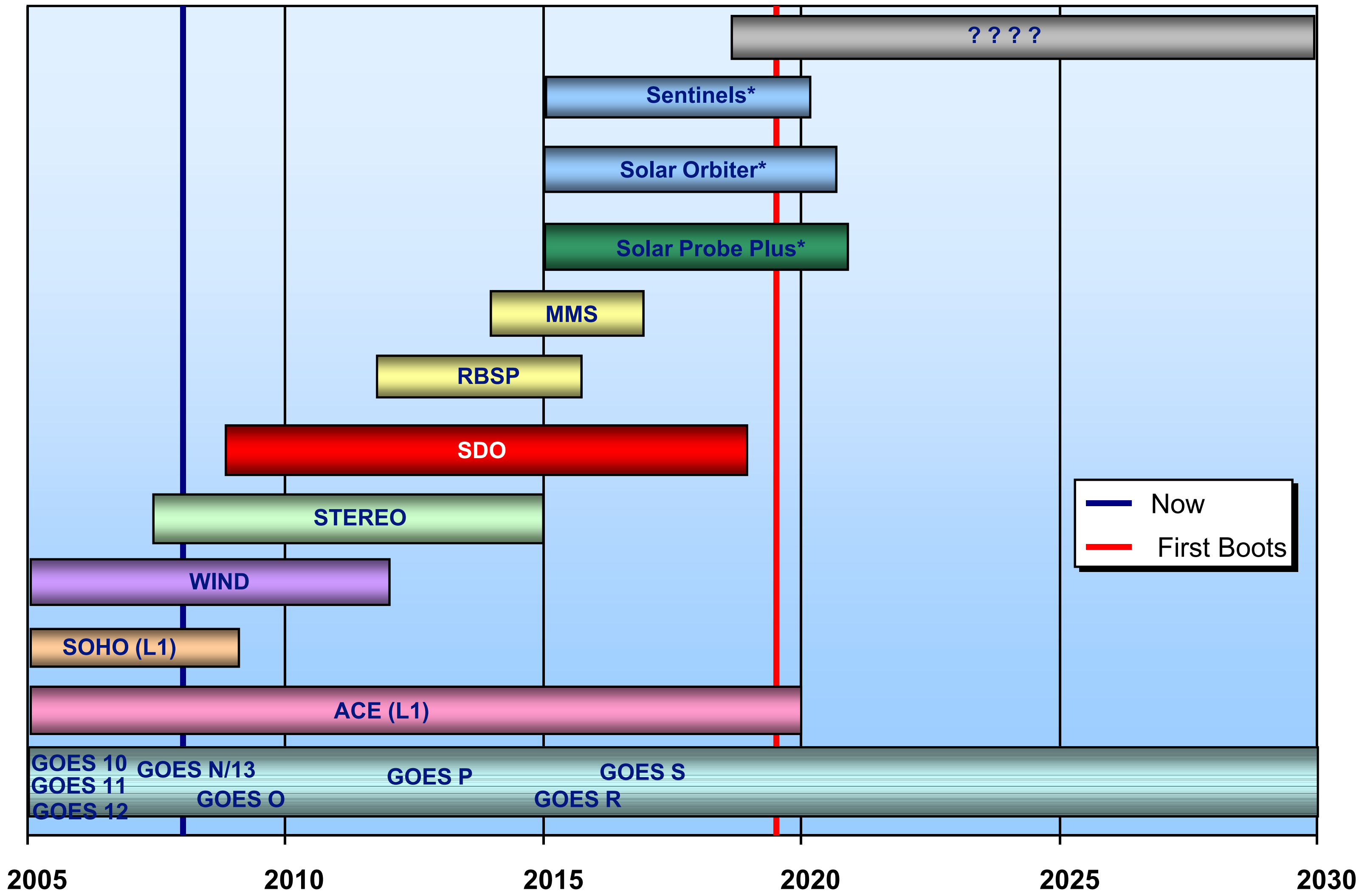
Science Mission Data for Operational Space Weather Support

- In addition to operational satellites, NOAA makes use of data available through NASA science missions
- A subset of science data is transmitted in real time in "Beacon Mode"
  - First instance was from the NASA WIND spacecraft
- Data is delivered through a network of ground sensors, some provided independently of NASA

NEAR REALTIME/BEACON MODE DATA

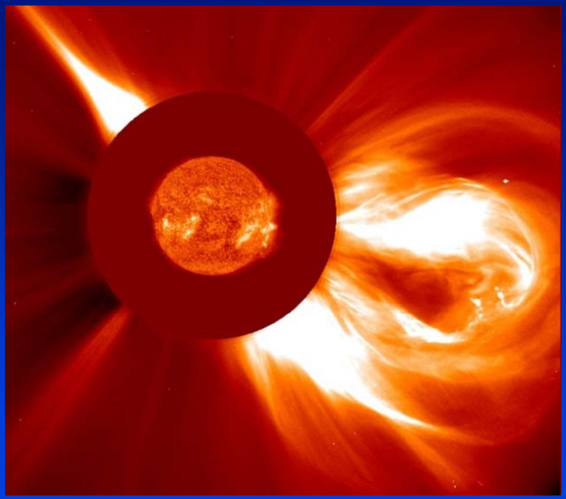
	PRODUCT	DATA DELIVERY
ACE	Solar wind speed, density Magnetic field, energetic particle flux	For about 21 of 24 hours per day, ACE sends data (~464 bps) to NOAA operated ground stations. During the other three hours when NASA is getting high rate data through the Deep Space Network, NOAA gets a copy of the real time data.
SOHO	X-ray, EUV images coronagraph images, energetic particle data	About ~16 hours/day of near real-time coverage (Will drop to 3 downloads of latest images per day after SDO launch)
STEREO	X-ray, EUV images, coronagraph images, energetic particle data	Five hours per day (per spacecraft) The beacon is gathered through DSN as part of the normal daily operations. The remainder of the day is from "partners" who volunteer their antennas. The coverage is good (50%-90% day-to-day).
SDO (Planned)	X-ray, EUV images, Helioseismic data	SDO will have continuous downlink (24x7)

Key Space Weather Mission Timelines



* Sentinel, Solar Orbiter and Solar Probe Plus Not Earlier than 2015

Predict the onset and evolution of SPEs within the first hours of an event, with emphasis on the ability to forecast 6 to 12 hour "All Clear" periods



What is Being Done?

- Significant emphasis placed on understanding fundamental physics of CME and SPE within heliophysics community
- Major research missions underway and planned (e.g., SOHO, Stereo, SDO, HELEX, Solar Probe Plus)
- Focused SPE studies sponsored by NASA LWS, and OCE TEI

Why is it Important?

- Infrequent SPEs increase penetrating radiation flux by orders of magnitude within hours and can last tens of hours to days
- Astronauts on EVA could exceed short-term exposure limits; in extreme cases the total dose could lead to skin rash, nausea, or illness
- Restriction to reasonable shielding can protect astronaut health but could
  - Contribute to astronaut lifetime limits
  - Lead to loss of mission objectives

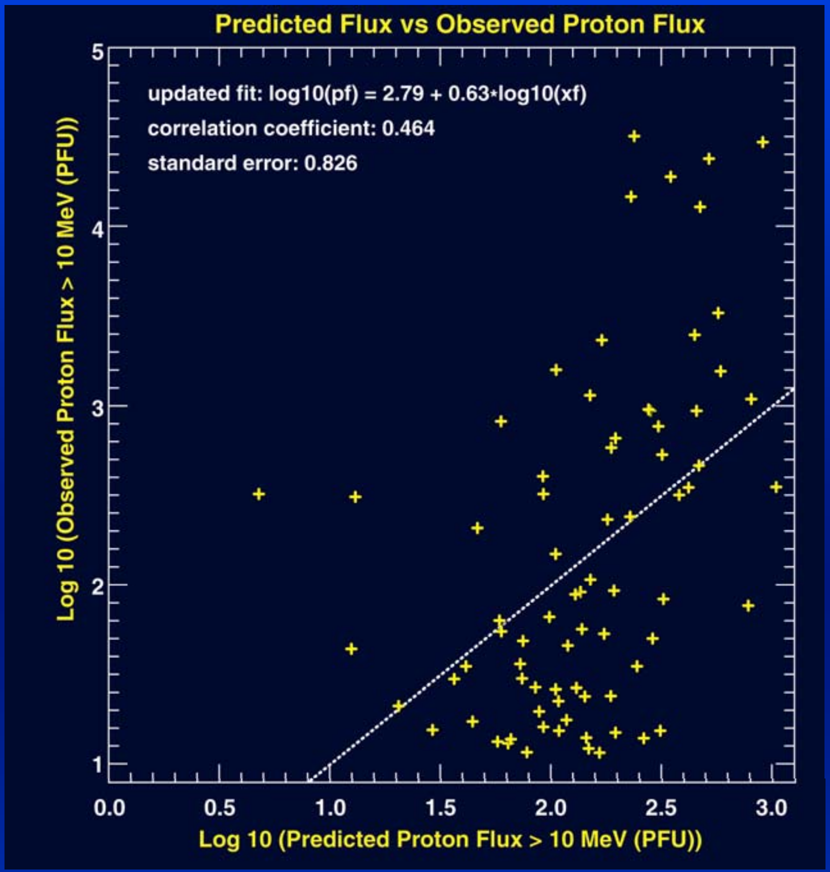
What Can We Expect?

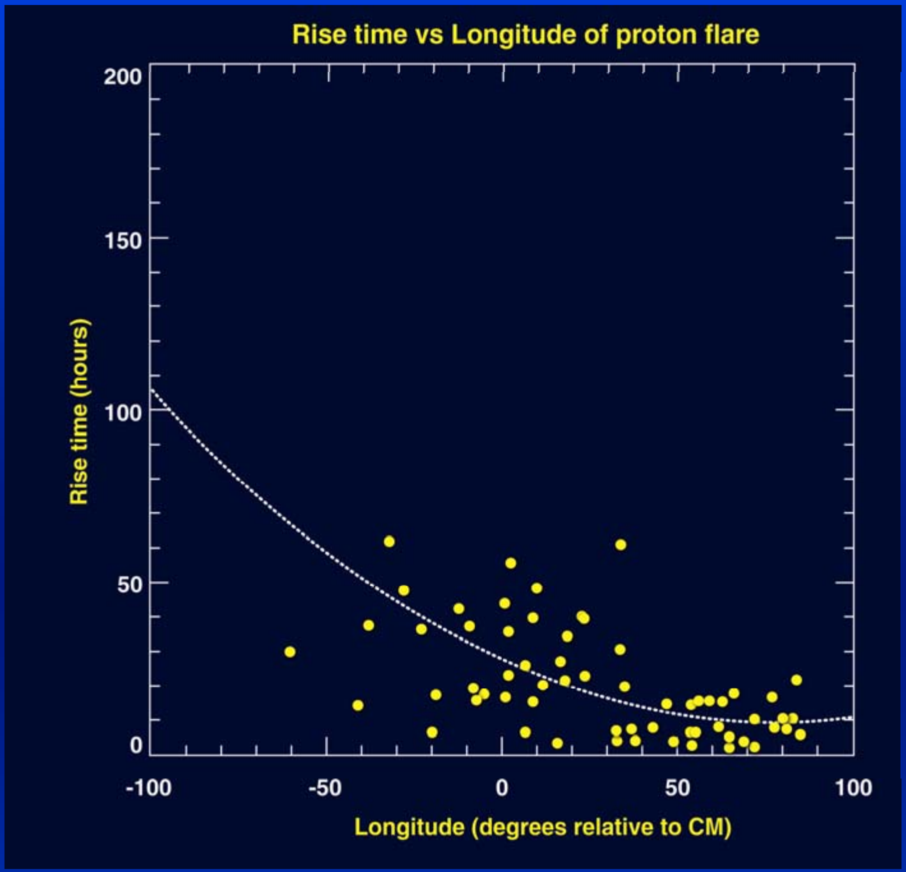
- Better understanding of fundamental SPE physics
- Improved short-term nowcasting after event onset
  - Within first hour of event:
    - Peak flux, time to peak, decay time
- Ability to forecast 6- to 12-hour "All Clear" periods with high skill, with goal to get to 24-48 hour forecast

Operational SPE Forecasting

- NOAA issues 1-3 day empirical forecasts
- NOAA issues alerts and warnings when SPE may be imminent or is underway
- Variety of instruments monitor space environment for onset of SPE
  - GOES detects x-ray precursor, energetic proton flux
  - Active dosimeters on ISS, Shuttle sound alarm after crossing threshold
  - SOHO, STEREO monitor evolving active regions, observe CME eruption, and detect increased energetic proton, electron flux
- Two operational models are in use today
  - PROTONS, by the NOAA Space Weather Prediction Center
  - PPS, by the Air Force Weather Agency
  - Both use solar x-ray and radio wave proxies for their forecasts
  - Both have orders of magnitude uncertainty in intensity forecasts

PROTONS Model Validation Study





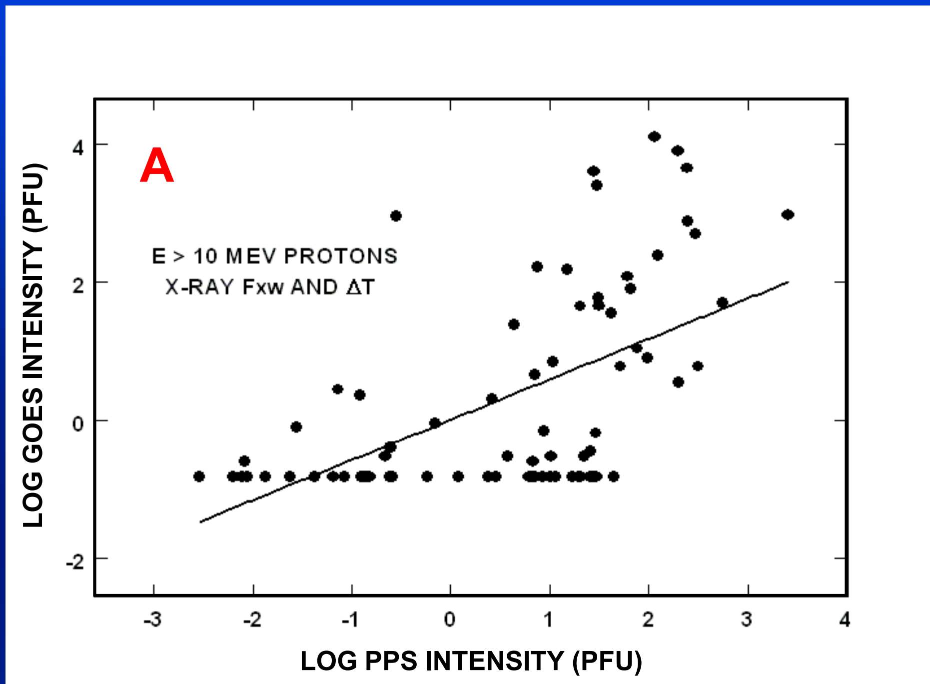
Comparison of PROTONS prediction with NOAA SPE observations for

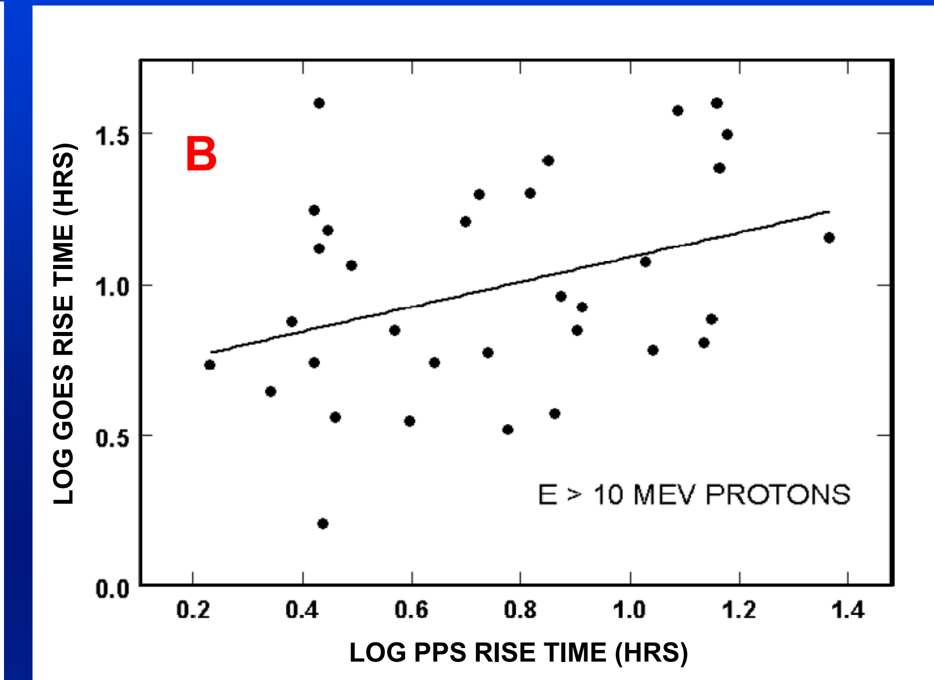
A. Peak intensity

B. SPE rise time

Christopher Balch, NOAA SWPC, *Prediction techniques for Solar Energetic Particles*, Chapman Conference on Solar Energetic Plasmas and Particles, August 2004

PPS Model Validation Study[1]





Comparison of PPS prediction with NOAA SPE observations for
A. Peak intensity
B. SPE rise time

> **"The basic PPS assumption of solar flare sources for the SEP events and the fact that the PPS and PROTONS have endured over three decades as our best SEP prediction tool is testimony to the embarrassingly poor progress made in this crucial area of space weather forecasting."**
> **-S.W. Kahler et al. / Journal of Atmospheric and Solar-Terrestrial Physics 69 (2007) 43–49**

Predicting SPEs Prior To Event Is An Interdisciplinary Challenge

Predict the eruption of a CME

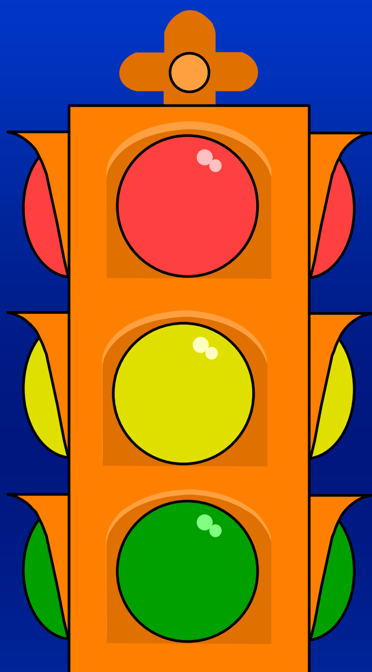
Predict the character of the CME, and ambient corona and solar wind

Predict the efficiency of the CME to accelerate particles

Predict the particle escape from shock and subsequent transport through heliosphere

Short of predicting the SPE, "Nowcasting" seeks to project the evolution of an on-going Proton event as soon as possible after event onset, using as many observables or proxies to the observables as possible. Examples:
Energetic Electron Precursors, PPS 08 (OCE TEI), Artificial Intelligence Techniques

All Clear Forecasts



Red: An SPE is **pending** or **underway**

Yellow: An SPE **may** occur within the next few days

Green: An SPE **will not** occur within the next few days

If it is too difficult to predict an SPE, is it more accessible to identify periods during which a large SPE is highly unlikely?

NASA Heliophysics Research Program

Advisory Organizations (examples)

National Academies (NAS, NRC)

Internal NASA Advisory, eg. - TR&T Steering Committee (TSC)

External experts for Proposal Peer Review:

Funded Research*

Flight Missions
- Underway
- In Development

Research and Analysis
- Heliophysics Theory
- Strategic Research & Technology
- Targeted Research And Technology

Data and Computing
- NSSDC
- AISRP
- GI P
- SDAC
- VxO
- CCMC

Validated research findings are incorporated into improved understanding and models of Space Weather processes

Interagency Collaboration

National Space Weather Program (NASA, NOAA, DoD, NSF)

National Science Foundation

DoD (AFRL, NRL, AFWA)

NOAA Space Weather Prediction Center

International Living With a Star

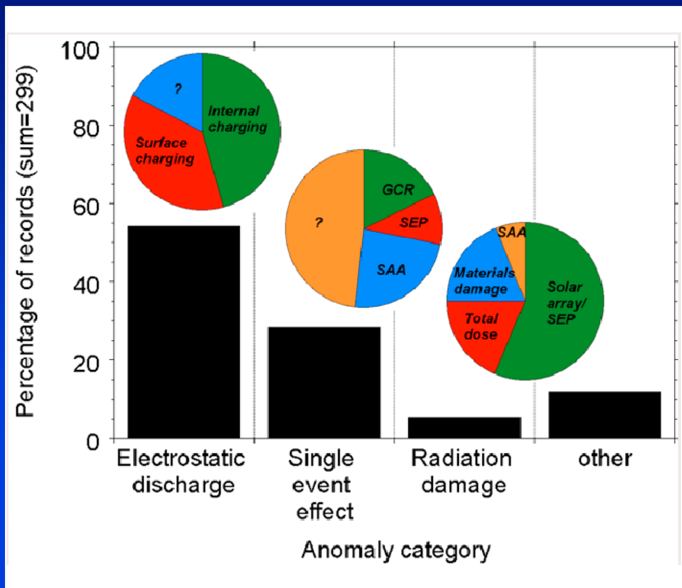
*Heliophysics Research is managed within SMD and monitored by the Heliophysics Division

NSSDC: National Space Science Data Center
AISRP: Applied Information Systems Research
GIP: Guest Investigator Program
SDAC: Solar Data Analysis Center
VxO: Virtual Observatory
CCMC: Community Coordinated Modeling Center

SPE-specific Research Underway

- NASA Heliophysics Missions with significant SPE or CME component
  - ACE
  - Wind
  - Voyager
  - SOHO (with ESA)
  - Hinode (with Japan)
  - STEREO
  - SDO (2009)
  - HELEX (NET 2015)
  - Solar Probe Plus (NET 2015)
- NASA LWS TR&T Focused Studies
  - 2008: Use Inner Heliospheric Observations to Better Constrain Coronal Mass Ejection (CME) and Solar Energetic Particle (SEP) Event Models
  - 2007: Extreme Space Weather Events in the Solar System
  - 2006: Flares particle acceleration near the Sun and Contribution to large SEP events
  - 2005: Shock acceleration of SEPs by interplanetay CMEs
  - 2004: Solar-energetic particles origin at the sun and inner heliosphere
- Other NASA LWS related efforts
  - 2004 Strategic Capability: Earth – Moon – Mars Radiation Model
  - Series of SPE forecasting workshops
    - “Forecasting All Clear” Workshop in April 2009
- NASA OCE Technical Excellence Initiative
  - MSFC PPS update to PPS08
  - MSFC “All Clear” Forecast Study

Develop spacecraft subsystems, including life support systems, for optimum mission performance in the space environment



What is Being Done?

- Continued efforts to explore failure mechanisms through test to define qualification methods and determine appropriate space performance predictive means
- Limited development of new radiation tolerant electronics

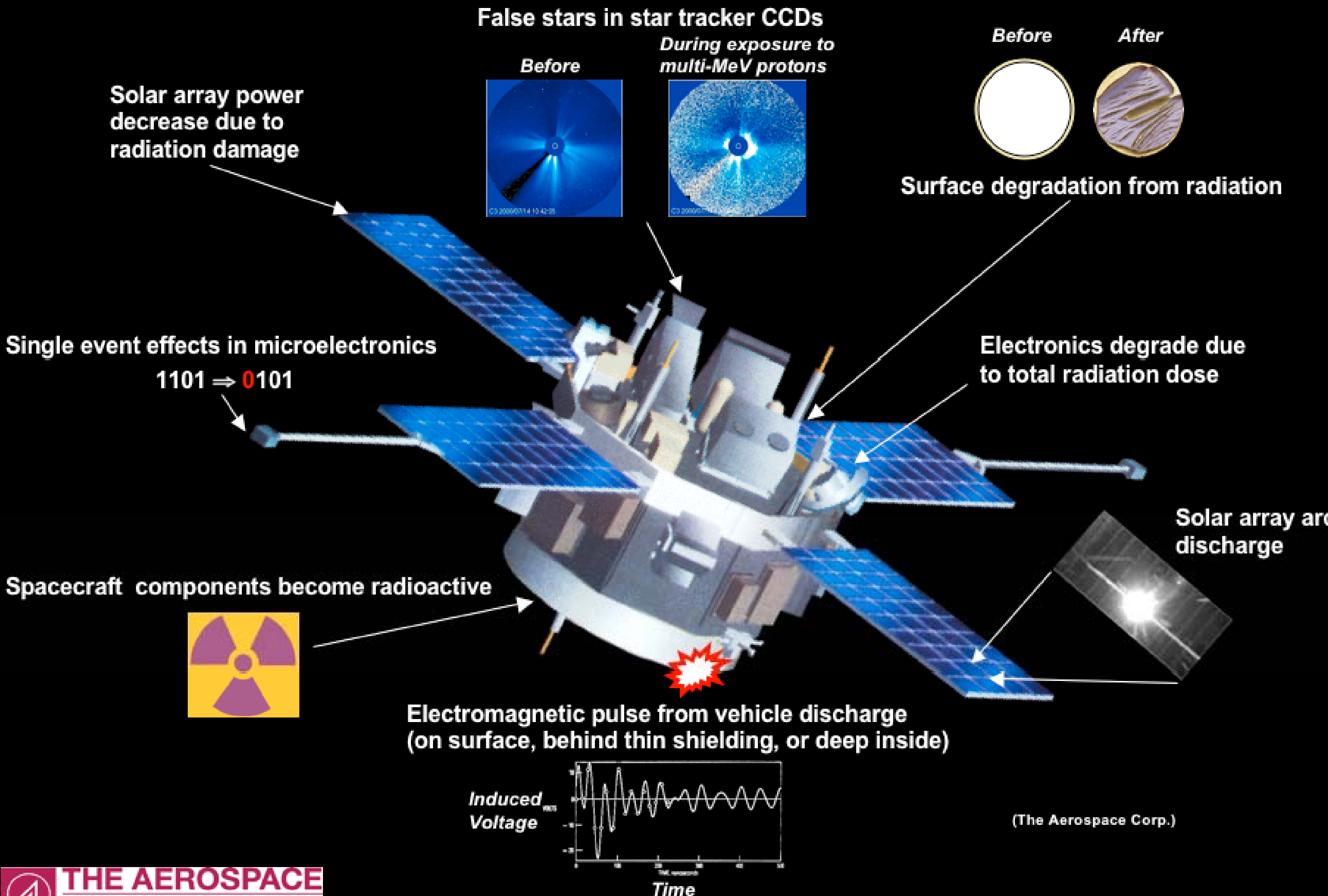
Why is it Important?

- Space systems can degrade or fail from a variety of space environment impacts
- Commercial electronics have become increasingly sensitive to single particle issues (processing, memories) and total cumulative damage failures (power devices, analog)
- Appropriate radiation tolerance leads to successful mission lifetimes and safe operation
- Environment mitigation impacts size, weight, and power (SWaP)

What Can We Expect?

- Improved techniques/materials to survive space environment
- Increased reliance on system level radiation tolerance
- Better tools for physics-based performance analysis

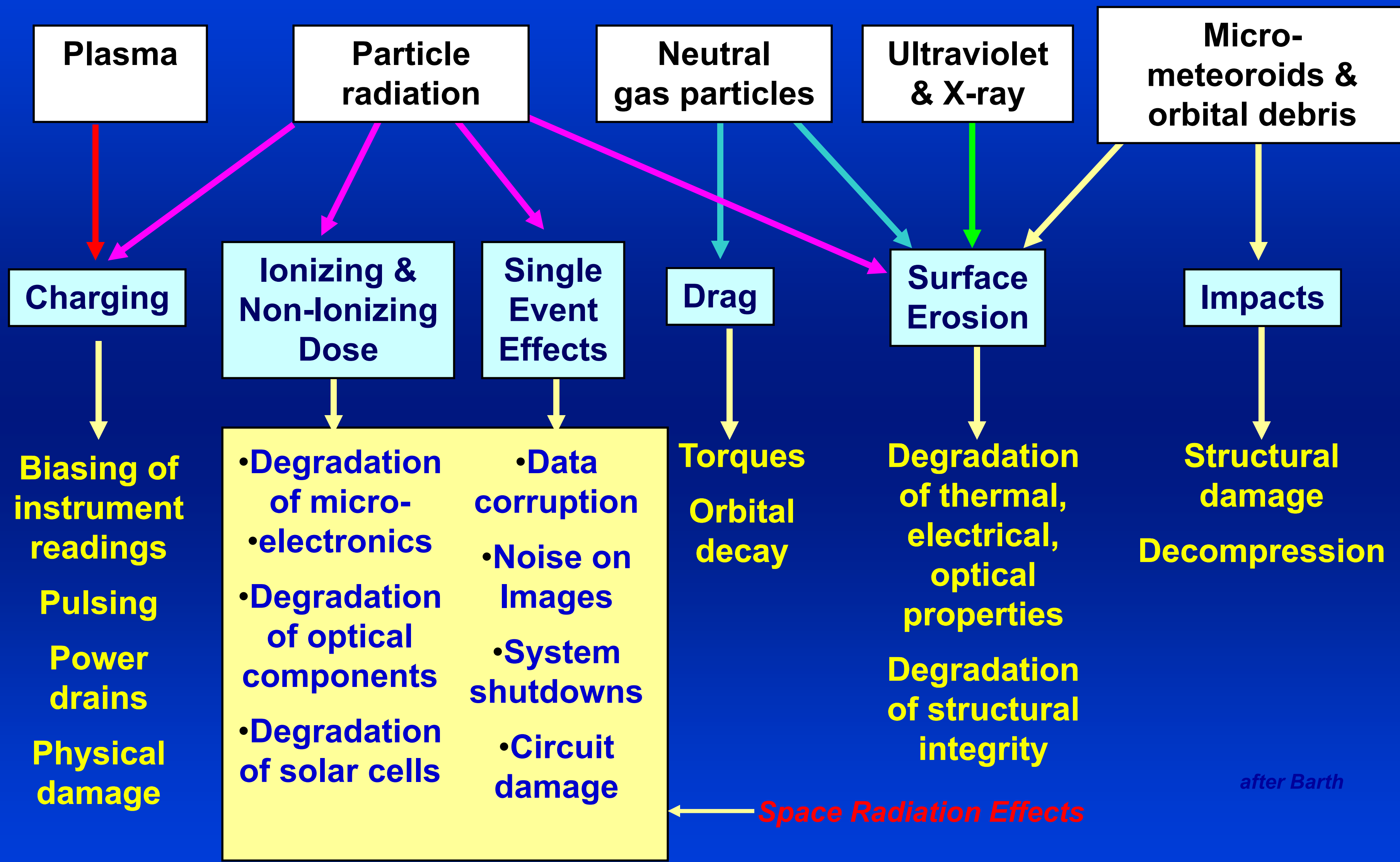
Major space environment hazards



THE AEROSPACE CORPORATION

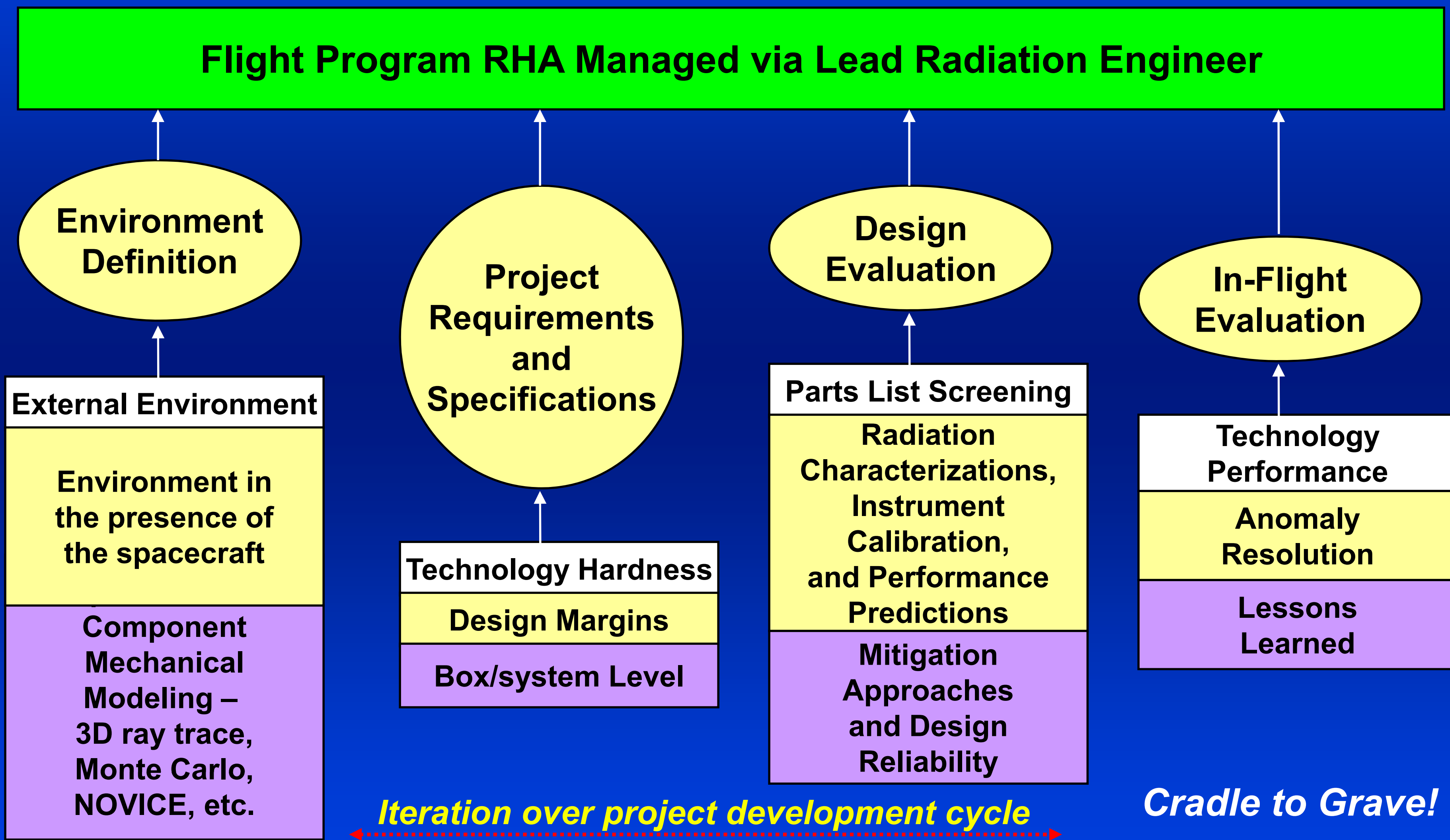
The space environment and its effects on space systems,* J. E. Mazur, J. F. Fennell and P. O'Brien, AAS 08-041

Space Environment Effects



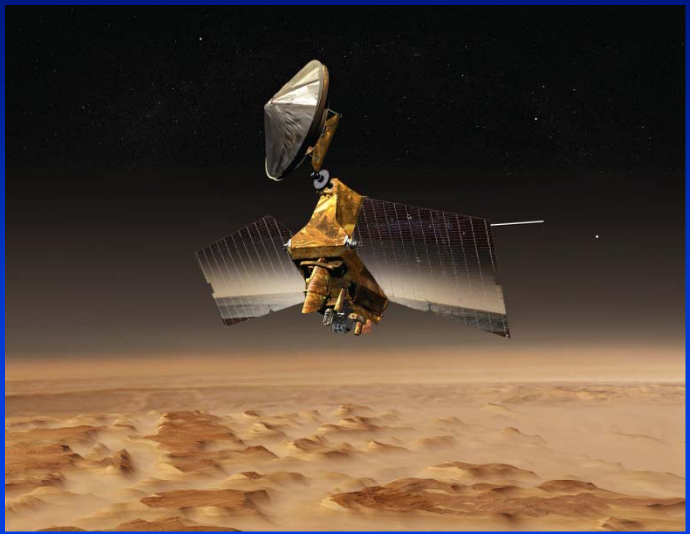
From: Space Radiation Effects on Electronics: *A Primer for Designers and Managers, by Ken LaBel, NASA GSFC*

Flight Program Radiation Hardness Assurance (RHA) Flow



From: Space Radiation Effects on Electronics: *A Primer for Designers and Managers, by Ken LaBel, NASA GSFC*

Provide efficient and effective space weather operational support to robotic missions



What is Being Done?

- Growing mission awareness of value of space weather forecasts
- Increasing mission communication with NOAA SWPC
- NASA OCE Technical Excellence Initiative underway within NASA CCMC to develop tools for operational space weather support

Why is it Important?

- Space weather can impact launch and mission operations, up to and including loss of mission
- Coordinated space weather support can be more efficient and cost effective
- Feedback from missions is absent, including feedback to the designers and to the Heliophysics science community

What Can We Expect?

- Continuous Improvement in coordinating operational space weather support to NASA launch and mission support

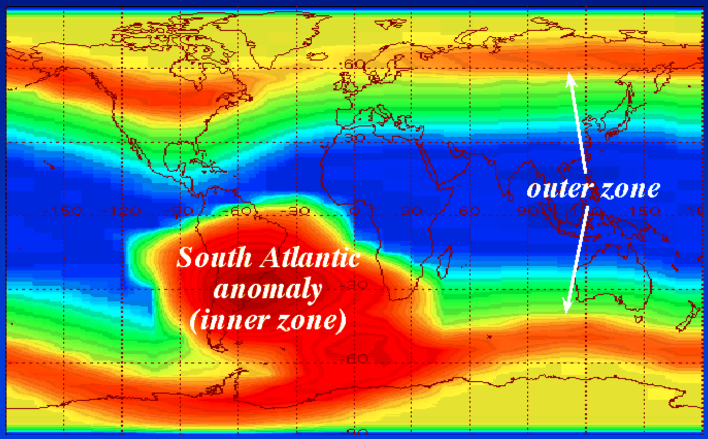
Space Weather Impact on Mission Operations

- Mission operational space weather support is managed by individual projects and hence is extremely ad hoc
- Response to space weather fluctuations range from "ride it out" to "retreat to safe mode"
- Intermediate operational responses include:
  - Restrict mission operations
  - Shut down sensitive subsystems
  - Lower voltages on HV systems
  - Delay routine maintenance or complex procedures
- Space weather situation awareness is also used to support anomaly resolution
- Space weather requirements and specific criteria for launch are established by launch system provider, not NASA

Future Space Weather Support to Mission Operations

- NASA robotic mission operations can benefit from better-coordinated space weather support
- NOAA SWPC will continue to be an important element of robotic mission support
  - Alerts and warnings for near-Earth missions
  - State of the Near-side Sun for Planetary missions
- The NASA SRAG-model may be a starting point for NASA-wide robotic support
  - Diversity of robotic missions and operational environments may limit role to space environment situation awareness and interface to NOAA SWPC
- The NASA Community Coordinated Modeling Center is developing a prototype system for compiling space weather models and data in a user-friendly format (OCE-sponsored Technical Excellence Initiative)

Develop climatological and dynamic models of the space environment for design and operation of optimal space systems



What is Being Done?

- Continued effort underway to better understand the physics of the space environment
- Radiation Belt Storm Probes to be launched in 2011
- Improved dynamic model of the radiation belts, in particular, is being developed (AP(9), AE(9))

Why is it Important?

- Design tolerance to space environment effects starts with the expected operating environment
- Inadequate climatologic models lead to larger safety margins than may be necessary or, worse, to too little margin
- Better dynamic models of the space environment may enable more operational responses to space environment

What Can We Expect?

- Better characterization of the radiation belts, through improved models and from pending missions, especially the Radiation Belt Storm Probe
    - Leads to reduced risk and cost, improved performance and lifetime
- Better understanding of Galactic Cosmic Ray and Solar Particle Event variability

Overview[1]

- Systems design for the space environment benefits not only from on-orbit experience with evolving technology but also from many measurements of the space environment in these orbits
- Even though databases exist, several factors press the need for a better specification and understanding of the space environment
  - Uncommon orbits where few if any space systems have spent time
  - Use of new materials that are directly exposed to the combined particle and photon space environment
  - Need to understand the dynamic response of the environment to space weather storms
- The development of new space environment specifications and models based on modern and more comprehensive data sets requires specialized support because it falls between pure science and focused engineering

1) The space environment and its effects on space systems,* J. E. Mazur, J. F. Fennell and P. O'Brien, AAS 08-041

Why Improved Models Are Needed

- **Existing space environment models are Inadequate**
  - Large uncertainties in some regions
  - Environment definitions do not exist for some energy ranges
  - Models lack functionality for contemporary applications, averages and worst case are insufficient
- **Why is this important?**
  - Required by engineers to build better spacecraft in pre-operation phases
  - Used to support operational planning and on-orbit anomaly investigations
  - Radiation belt models are also used to support human space flight

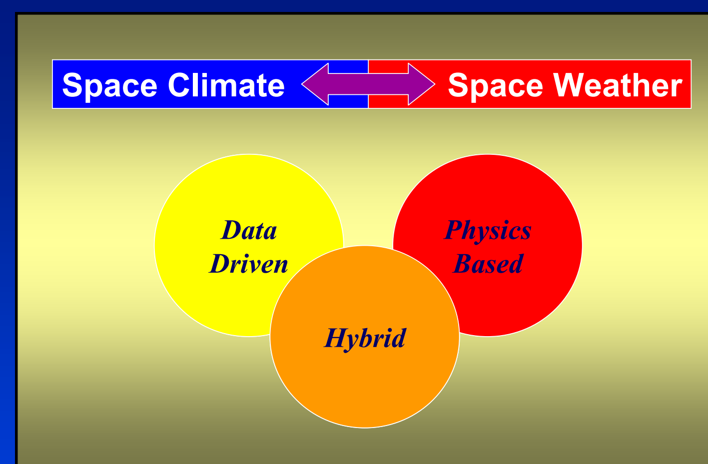
Mission Concept
Mission Planning
Design

→ **Space Climate** — Minimize Risk

Launch
Operations

→ **Space Weather** — Manage Residual Risk

Anomaly Resolution → **Both** + ***in situ* measurements**



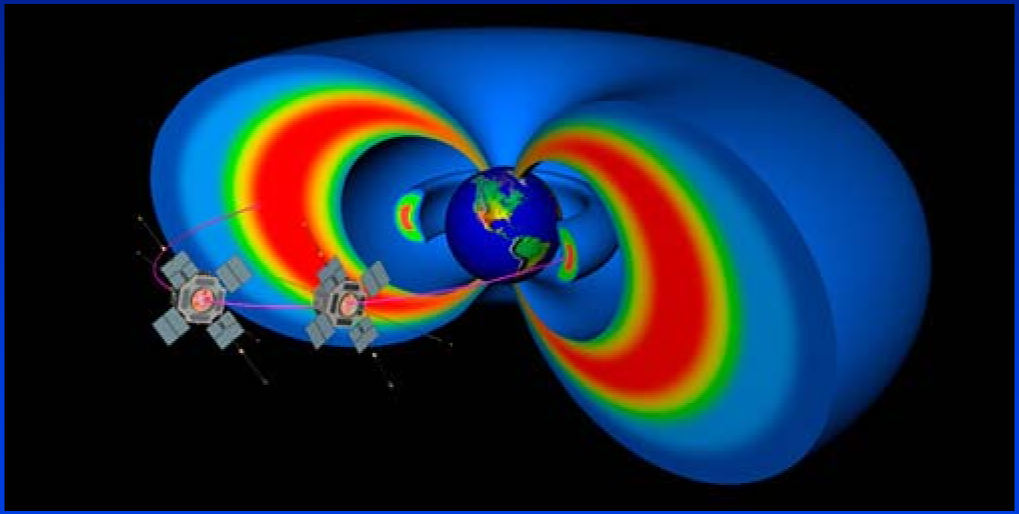
Presentation by J. Barth to Working Group Meeting on New Standard Radiation Belt and Space Plasma Models, Oct 2004

Updated, Dynamic Model of Radiation Belt Underway AP(9) and AE(9)

- The National Reconnaissance Office, NASA, the Air Force Research Laboratory, the Aerospace Corporation, Los Alamos National Laboratory and the Naval Research Laboratory have recently embarked on a project to produce the next generation radiation belt model, AP(E)-9
- This model upgrade will offer significant improvements in terms of the radiation hazards specified, accuracy and uncertainty quantification, spectral and spatial coverage, and time-correlated probability of occurrence statistics.
- Preliminary requirements have been gleaned from participation in DoD sponsored Space Environment Effects Working Group and NASA Living With a Star workshops
- The new model will improve upon the existing AE-8/AP-8 model by including new capabilities and extended energy and species coverage to include:
  - Protons 100 eV – 1 GeV
  - Electrons 100 eV – 10 MeV
  - Ions 1 keV – 200 keV
- A statistical description natural variability of the radiation belts will be included as will indications of uncertainty due to inaccuracy and scarcity of measurements
- An empirical component will provide simple percentage confidence levels for flux levels as functions of energy and location while the “Standard Solar Cycle” component will provide a more detailed description of the temporal correlations via a fly through capability
- Preliminary versions are scheduled to be available by March 2010

Radiation Belt Storm Probe

- The LWS Geospace program will launch two spacecraft, the Radiation Belt Storm Probes, to discover the fundamental physics underlying the source, loss, and transport processes that govern the radiation belts
- Observations from the two spacecraft will enable the development of empirical and physics-based models for the radiation belts
- The empirical models will be used by engineers to design radiation-hardened spacecraft, while the physics-based models will be used by forecasters to predict geomagnetic storms and alert both astronauts and spacecraft operators to potential hazards
- The knowledge gained from the mission will be applicable to particle acceleration processes occurring throughout the plasma universe
- RBSP spacecraft will be launched in 2011

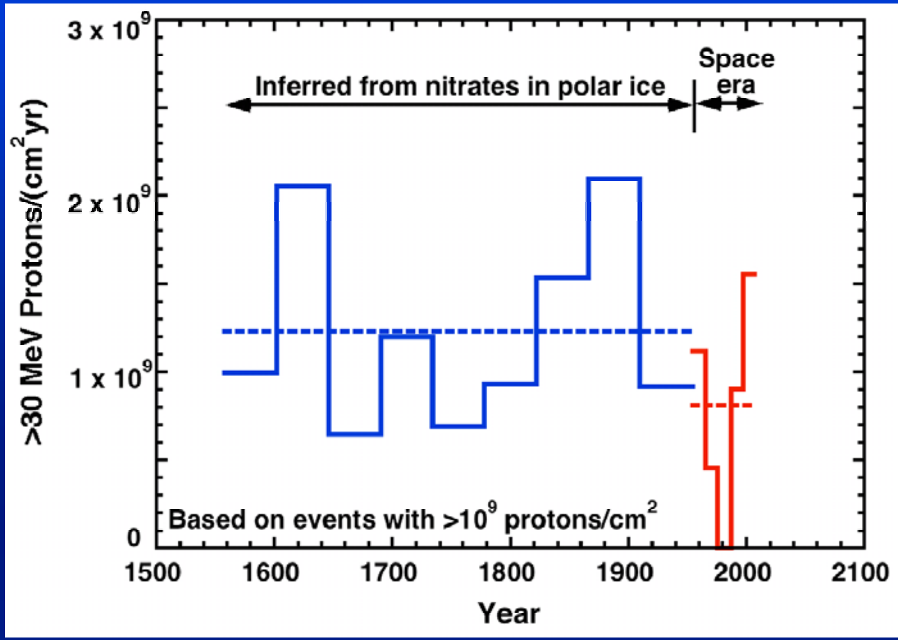


Uncertainties Remain In GCR/SPE Climatology

NRC report "Managing the Space Radiation Risk in the New Era of Space Exploration," March 2008, identified several areas for further work on climatological data of Galactic Cosmic Radiation and Solar Particle Events

- **Finding 2-4 Space Radiation Climate** Ice-core studies indicate that the past ~50 years may have coincided with a comparatively benign space radiation climate, in terms of both GCR modulation levels and the frequency of very large SPE events.
- **Finding 2-5 King spectrum as a design standard**. Although the committee recognizes the advantages of adopting a specific solar proton spectrum as the design standard, NASA's current strategy of evaluating the efficacy of an SPE shielding configuration using only the August 1972 King spectrum is not adequate. Under typical depths of shielding for Exploration vehicles, the level of radiation exposure produced by other large events in the historical record could exceed the exposure of August 1972.
- **Finding 2-6 Spectral data fitting**. There is no theoretical basis for any of the published spectral fits to large SPEs. The extrapolation to energies beyond 100 MeV must therefore be guided by data. Solar proton spectral forms based on data that do not extend to ~500 MeV may very well give misleading results in evaluations of the efficacy of radiation shielding for astronauts.

SPE Ice-core Record



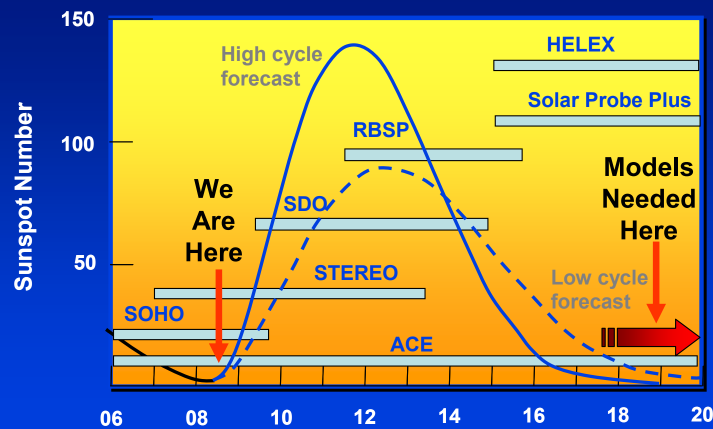
***Radiation risks from large solar energetic particle events*, Mewaldt, et al, Turbulence and Nonlinear Processes in Astrophysical Plasmas, D. Shaikh, ed., AIP Conference Proceedings, (2007)**

- Studies by McCracken, et al, of nitrates in ice cores suggest that the historical rate of significant SPEs may be 6-8 times what has been observed over the last 50 years
- A statistical analysis by Kim, et al, found no significant differences between the recent rates of large SPEs and the historical record (P = 0.12, Fisher's exact test)

McCracken, K.G., G.A.M. Dreschhoff, E.J. Zeller, D.F. Smart, and M.A. Shea. 2001a. Solar cosmic ray events for the period 1561-1994. 1. Identification in polar ice, 1561-1950. Journal of Geophysical Research 106:21585-21598.

Myung-Hee Yoon Kim, M J Hayat, A H Feiveson, F A Cucinotta, Prediction of frequency and exposure level of solar particle events, Health Physics Journal, HPJ-S-08-000862.

Minimize time-lag between development of research models of space weather and their application in user-friendly tools for mission operations



What is Being Done?

- NASA's Living With a Star is a space weather-focused and applications driven research program
- CCMC supports transition of research models to operations
- NOAA SWPC is pursuing a "Development Testbed Center"

Why is it Important?

- Interdisciplinary research is leading to better physics-based, integrated models of the dynamic space environment
- Further, significant progress is expected over the next decade
- Operational forecast tools can benefit from this improved understanding
- The transition requires time, resources, a dedicated effort and a different mind-set
- Better coordination is needed between scientists (push) and users (pull)

What Can We Expect?

- Better communication and cooperation between research and operations to identify needs / models appropriate for transition
- Dedicated resources to support transition effort
- Faster turn-around from research to operations
- Improved space weather operational support

Definition of Terms[1]

For the purposes of this report[1], the following definitions of research, operations, and transitioning activities are adopted:

- **Research activities** — *develop* scientific understanding of important processes and/or *demonstrate* the capabilities of new analysis, modeling techniques, or measurement technologies, typically through acquiring, calibrating, and characterizing a specific set of measurements.
- **Operations activities** — *routinely and reliably generate* specific services and products that meet predefined accuracy, timeliness, and scope/format requirements, as well as *disseminating* or making them available to a variety of users in the public, private, and academic sectors.
- **Transitioning activities, or processes** — *transfer* new or improved scientific knowledge or technologies produced by research to operations. The end-to-end set of processes for transitioning research results into operations is a *transition pathway*.

1) Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations, NRC (2003)

Longstanding Challenge to Space Weather

- "The slow transition of research to operations is a well-documented issue in this field; it has been discussed in numerous recent studies"[1]
  - *Radiation and the International Space Station Recommendations to Reduce Risk.* National Academy Press, Washington, D.C. 2000
  - *The Sun to the Earth and Beyond: A Decadal Research Strategy in Solar and Space Physics.* The National Academies Press, Washington, D.C. 2003
  - *Space Radiation Hazards and the Vision for Space Exploration: Report of a Workshop.* The National Academies Press, Washington, D.C. 2006
  - *Report of the Assessment Committee for the National Space Weather Program*. OFCM (Office of the Federal Coordinator for Meteorological Services and Supporting Research FCM-R24-2006. OFCM, Silver Spring, Md. 2006.

[1] "Managing Space Radiation Risk in the New Era of Space Exploration" NRC report, March 2008

Overview[1]

- Not all NASA research missions are or should be driven by operational needs or requirements — a major and essential part of the NASA mission is to increase fundamental understanding of Earth and the universe, regardless of foreseeable operational opportunities.
- However, many NASA missions have both a fundamental research component and the potential for applications of the science and technology for the benefit of society.
- Ideally, the research-to-operations process related to observational technologies includes
  - (1) the demonstration that useful measurements can be acquired, quantitatively calibrated, and characterized; and
  - (2) the development and implementation of the observing, data processing, modeling, and dissemination systems, allowing the measurements to be routinely obtained and used.

1) Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations, NRC (2003)

Transition Process Involves Both the Research and Operations Communities[1]

- A transition process should be based on a balance between research push and operational pull
- This balance, which will vary from one mission to another, can be achieved through increased dialogue between the two communities and through overlap within their respective missions (i.e., research missions that have an operational component and vice versa)
- The data from research missions should be tested in operational settings and the operational impact assessed
- Conversely, the collection, processing, and archiving of operational data should take into consideration the needs of the research community as well as the operational impact of the data

1) Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations, NRC (2003)

Research Vs. Operational Tools

Research

Focus is on understanding the physics appropriate to the system being modeled

- Validated and verified
  - With compiled data
- High accuracy
- As needed to support retrospective analysis

Little to no requirement for:

- Timeliness
- Consistent continuous coverage

Significant downtime can be scheduled or accommodated

Failure delays science

Operational

Focus is on operational decision support

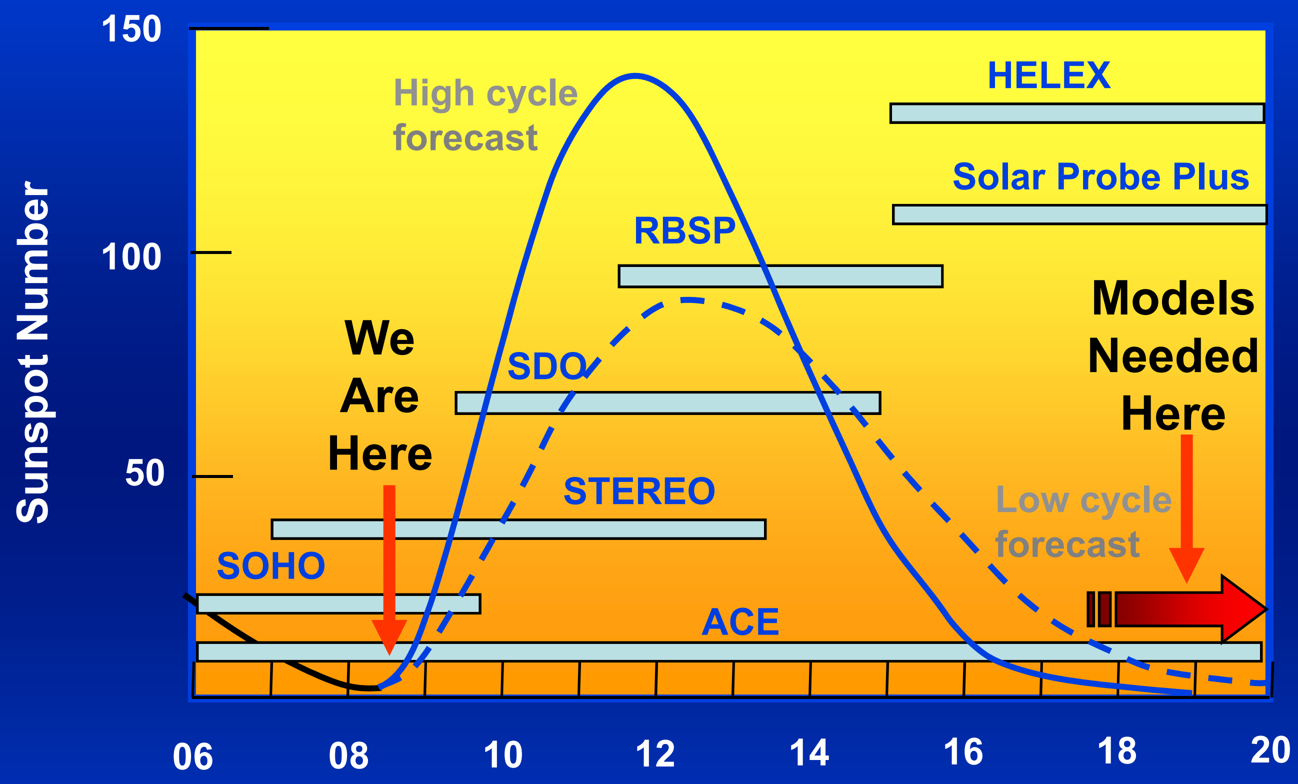
- Validated and verified
  - With available realtime data
  - Responsive to data loss
- To sufficient
  - Accuracy
  - Reliability
  - Availability
- In a usable form
- In a timely fashion

Minimal downtime for maintenance

Failure has significant operational consequences

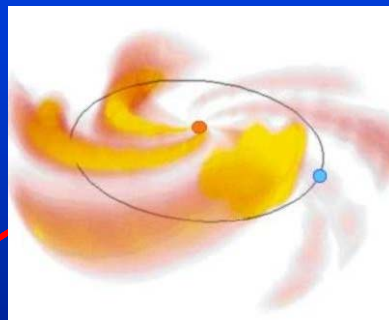
- Research models are fundamentally different from operational tools
- The transition requires time, resources, a dedicated effort and a different mind-set
- Better coordination is needed between scientists (push) and users (pull)

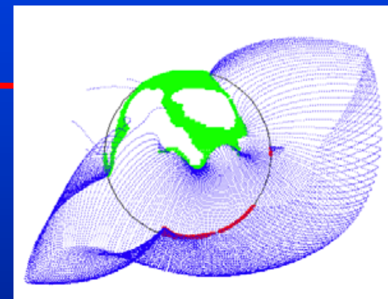
Faster Turn Around Needed From Research To Operations

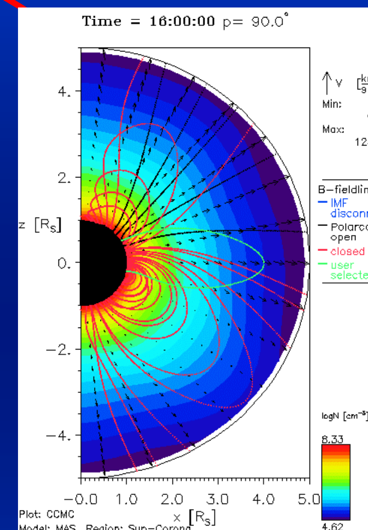


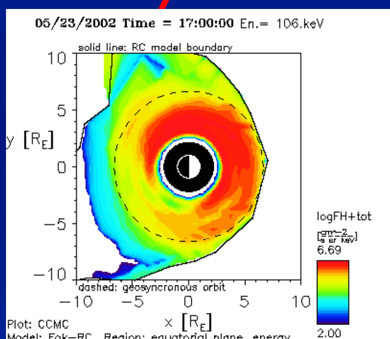
Significant improvements in understanding fundamental space weather physics is expected from the Heliophysics Science program over the next decade, but there will be a limited amount of time to incorporate this new understanding into operational tools.

Community Coordinated Modeling Center

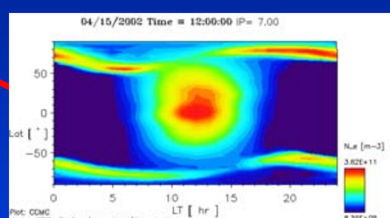


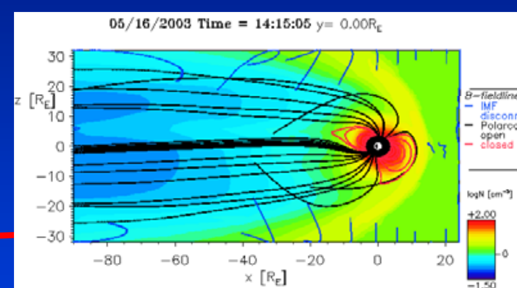






- Facilitate Community Research
  - Execute simulations on request
  - Tailored analysis and visualization
  - Education support
- Support Space Weather Operations
  - Transition of research models to operations
  - Test and evaluate models
  - Real-time execution of SWx models





Air Force/NOAA Operational Product Development Activity

- The Air Force Weather Agency has funded a study, being carried out by the National Center for Atmospheric Research , to develop a concept of operations for a space weather developmental test-bed center (DTC) or rapid proto-typing center that would be shared and supported jointly with NOAA to complete the pipeline:

Research → Community Coordinated Modeling Center → Developmental Testbed → Operations

- NOAA is planning and programming funds in FY2010 to begin funding of the DTC
- NCAR will hold a community workshop in November of this year to solicit input from the entire community on how to best operate such a DTC

Develop and implement standards and guidelines for space system radiation hardness and space environment risk mitigation

What is Being Done?

- Identified as key recommendation by the 2006 NASA Radiation Study Team
- Standards for Human Health were substantially revised (NASA Standard 3001, NASA Space Flight Human System Standards, Vol 1)

Why is it Important?

- Standards form the basis for the Agency's ability to respond to radiation threats to all systems in all design reference missions[1]
- It is from standards that requirements are developed which drive the design of future space architectures[1]
- Many satellite programs are essentially "new starts" that can benefit from consistent guidelines based on past experience

[1] *NASA Radiation Study Team, 2006*

What Can We Expect?

- Better guidance to new programs
- Improved spacecraft reliability
- Lower costs through shared resources
- More rigorous collection of Lessons-learned across missions

Standards Overview[1]

- Currently, there are many standards in place that, while possibly sufficient for Low Earth Orbit (LEO), may not meet the needs of new missions, environments, electronics, and materials
  - Further, since many of those missions, environments, electronics, and materials are not yet well defined, the unknowns force high margins that are kept at multiple levels, resulting in inconsistent methodologies
- Critical to the standards development process will be a methodology for close collaboration between all parties
  - Architectures that meet standards for radiation tolerance performance must also meet standards for mechanical and structural properties, physical properties, optical and thermal properties, electrical properties, and human properties
  - Only through a formal process, which results in an iterative review of all standards and how they relate to one another, can this collaboration be assured

[1]NASA Radiation Study Team, 2006

Radiation Study Team Findings on Standards

- ***Radiation Hardness Assurance Standards***
  - Standards for radiation hardness of space systems are not adequate. There are multiple standards for testing of electronics and for material properties, but no single standard or group of standards encompasses all issues and many of them are outdated. New standards are needed in some areas (e.g., electrostatic discharge or microprocessor testing) while updates are needed in others (e.g., radiation-induced conductivity of materials or lifetime exposure degradation of electronics). Data for many modern materials and circuits that take into account new mission scenarios are either inadequate or do not exist.
- ***Spacecraft Charging Standards***
  - Spacecraft charging guidelines are not consistent with modern electronics. Guidelines associated with issues such as surface/volume resistivity, buried charge, breakdown strength, triboelectric charging, and photoemission are either not current or do not exist.

Radiation Study Team Recommendations on Standards

4.2.1 Clearly identify philosophical approaches to engineering designs

Identify and agree upon which philosophical approaches to standards development exist and which approaches apply to which system.

4.2.2 Conduct a standards gap analysis

Conduct a gap analysis to identify standards in need of update or initial development.

4.2.3 Establish a radiation standards coordination group

This group could develop a process for a collaborative approach to standards development and revision that encompasses all systems.

Improve Intra- and Inter-agency communication and cooperation in space weather related activities

What is Being Done?

- Significant coordination and shared programs between NASA, NOAA, NSF, and DoD
- NASA participates in National Space Weather Program
- NASA's SRAG has close working relationship with NOAA SWPC

Why is it Important?

- Space Weather is an inherently multi-discipline and interagency activity
- Significant skills and infrastructure exists within NOAA, NSF, and DoD
- Within NASA, multiple programs make overlapping contributions, demands (SMD, ESMD, MOD)
- Communication needed to ensure effective use of resources and coordination of programs

What Can We Expect?

- Continued strong interagency cooperation
- "One-NASA" contribution to national dialogue on space weather needs
- Coordinated programs across NASA

Previous Calls For Interagency Cooperation
(Examples, Many More Exist)

Decadal research strategy in solar and space physics (NRC, 2003, pp. 19-20):

The principal agencies involved in solar and space physics research NASA, NSF, NOAA, and DOD should devise and implement a management process that will ensure a high level of coordination in the field and that will disseminate the results of such a coordinated effort including data, research opportunities, and related matters widely and frequently to the research community. For space-weather applications, increased attention should be devoted to coordinated NASA, NOAA, NSF and DOD research findings, models, and instrumentation so that new developments can quickly be incorporated in the operational and applications programs of NOAA and DOD.

Radiation shielding study (NRC, March 2008, pp. 89-90):

The nation's space weather enterprise should integrate its scientific expertise with operational capability through coordinated efforts on the part of NASA, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Department of Defense (DOD). Where multiple end users benefit, NOAA is appropriate as the lead organization in charge of operational forecasts. However, for NASA-unique lunar support requirements, NASA's Exploration Systems Mission Directorate should take a leadership role in defining and providing resources.

Examples of Interagency Space Weather Coordination

- National Space Weather Program, Office of the Federal Coordinator for Meterological Supporting Research,
  - Co-chairs (Committee on Space Weather)
    - Heliophysics Division, NASA Headquarters
    - Upper Atmospheric Research Program, NSF
    - USAF/XOWX, DOD
    - NOAA, Space Weather Prediction Center
- NASA, NOAA, NSF, and DoD have participated in shared funding across
  - Programs
  - Research
  - Workshops
- NOAA SWPC and NASA SRAG have established a close operational working relationship

Placeholder Exists in Constellation Architecture Requirements Document for Interface with NOAA

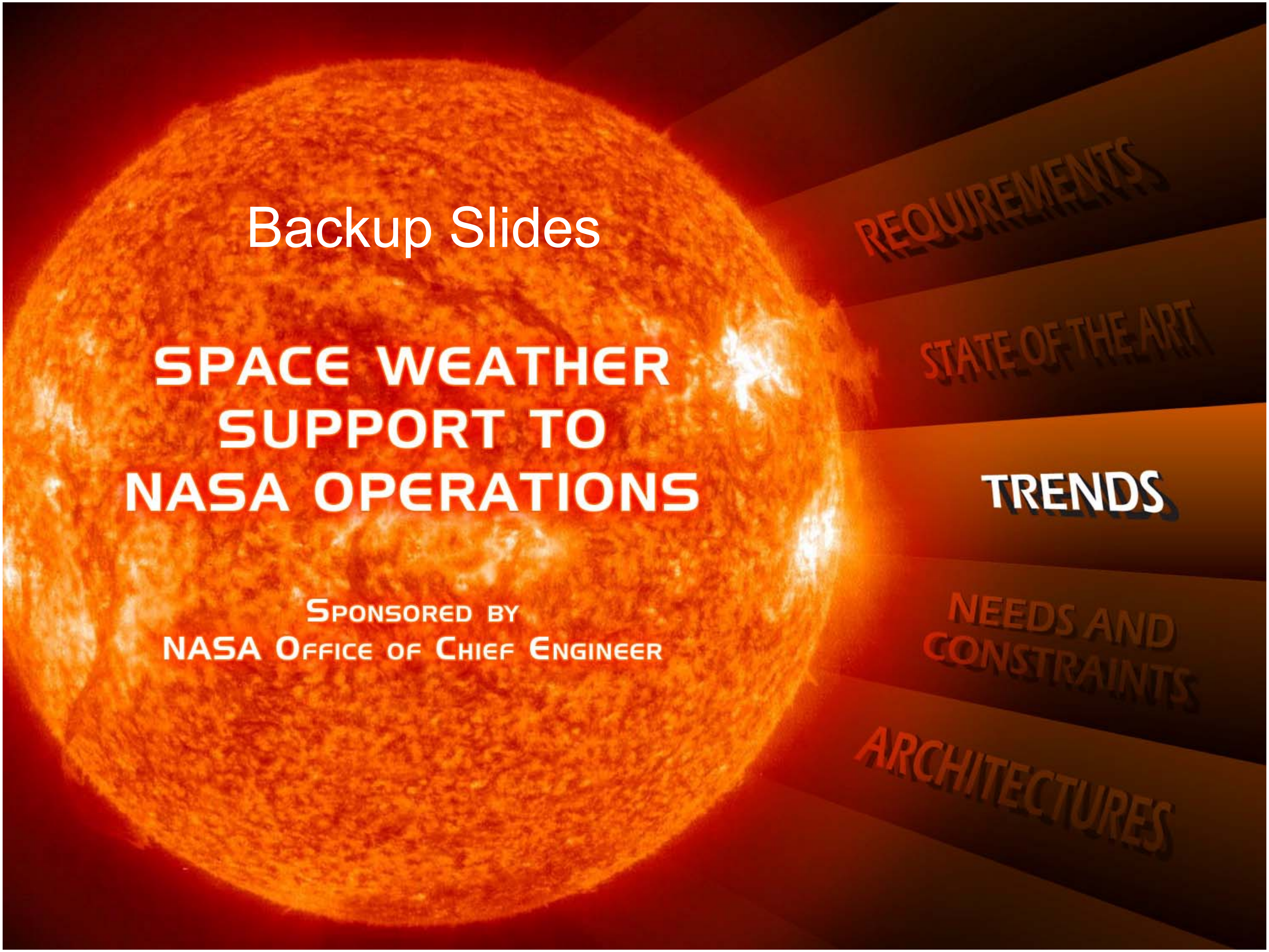
- **4.7.6.2.6 MS Architecture Definition**

- **[CA5125V-PO] Space weather services for all mission phases for all flight systems shall be verified by inspection. The inspection shall consist of a review of documentation provided by MS [*Mission Systems*] showing closure of MOU (TBD-001-409) with National Oceanic and Atmospheric Administration (NOAA) providing space weather services and the MS facility and facility systems used to generate the weather services are built and certified. The verification shall be considered successful when the inspection shows closure that there is an agreement with Constellation Program and NOAA on the fulfillment of the MOU and that all of the MS facility and facility systems are ready to support space weather services operations during all mission phases for all flight systems.**

- **Resolution Plan:**
  - **Update TBD once MOU between MS (or Headquarters/CxP) and NOAA is baselined for space weather services provision to MS.**

Improving Intra-Agency Coordination

- **NASA Radiation Study Team, 2006, concluded:**
  - The most salient overarching issue identified regarding the Agency's radiation-related efforts is the need to ensure appropriate communication, coordination, and exchange of information between the various diverse and distributed radiation functions within the Agency
- **Communication and coordination is improving**
  - Office of Chief Engineer has identified space weather and radiation effects as a "Cross Cutting Initiative" impacting multiple NASA directorates
  - An Inter-directorate team is being established with representatives from SMD, ESMD, SOMD, OCE, OCHMO to develop a roadmap to ensure appropriate viability, availability, and implementation of space weather assets for Exploration missions
    - Kick-off meeting in October 2008
    - Facilitating POC: Steve Guetersloh, Space Radiation Analysis Group/JSC


Backup Slides
SPACE WEATHER
SUPPORT TO
NASA OPERATIONS
SPONSORED BY
NASA OFFICE OF CHIEF ENGINEER
REQUIREMENTS
STATE OF THE ART
TRENDS
NEEDS AND
CONSTRAINTS
ARCHITECTURES

Objectives vs. Challenges

- In seeking feedback to draft versions of this report, a consistent theme was "are these goals, objectives, or challenges?"
  - This report is organized around a central objective, followed by ten challenges to meet that objective (Slide 9)
  - This approach was chosen to be consistent with the interpretation that space radiation risks are (a significant) part of the impacts of exposure to the space environment (Slide 7)
  - An alternative (potentially viable) organization is shown on the following slide, which separates
    - Goals in "Managing Radiation Risks"
    - Challenges to "Space Weather"
    - Cross-cutting "Programmatic/Policy" issues (to which one could add "ensure adequate and stable program funding")
  - A concern is that to follow this alternative path would lead to continued segmentation of space weather (impacts to electronics, forecasting vs research, policy vs science, etc.) which would be detrimental to the goal of enhanced communication and coordination across the various communities

Alternative Presentation Of Goals/Objectives/Challenges

Overall goals in managing SPACE RADIATION risks are:

1. **Ensure the health and performance of crews living and working beyond the protection of the Earth's atmosphere and magnetic field.**
2. **Improve our understanding of the impact of space radiation exposure on astronauts, with emphasis on reducing the uncertainty to fifty percent.**

The objective of a comprehensive list of SPACE WEATHER challenges is to support NASA mission operations by providing information on the space radiation environment that is timely, accurate, and accessible.

SPACE WEATHER specific challenges are:

a. **Ensure appropriate observations for space weather forecasts are available to meet NASA-specific requirements for use in the 2015-2020 timeframe.**
b. **Predict the onset and evolution of SPEs within the first hours of an event, with emphasis on the ability to forecast 6 to 12 hour "All Clear" periods.**
c. **Provide efficient and effective space weather operational support to robotic missions.**
d. **Develop space system electronics, including life support systems, for optimum mission performance.**
e. **Develop climatological and dynamic models of the space environment for design and operation of optimal space systems.**
f. **Minimize time-lag between development of research models of space weather and their application in user-friendly tools for mission operations.**

Cross-cutting PROGRAMMATIC/POLICY issues include:

1. **Develop and implement standards and guidelines for space system radiation hardness and spacecraft charging.**
2. **Improve Intra-and Inter-agency communication and cooperation in space weather related activities**
3. ***Ensure Adequate and Stable funding to meet program objectives (added to list)***