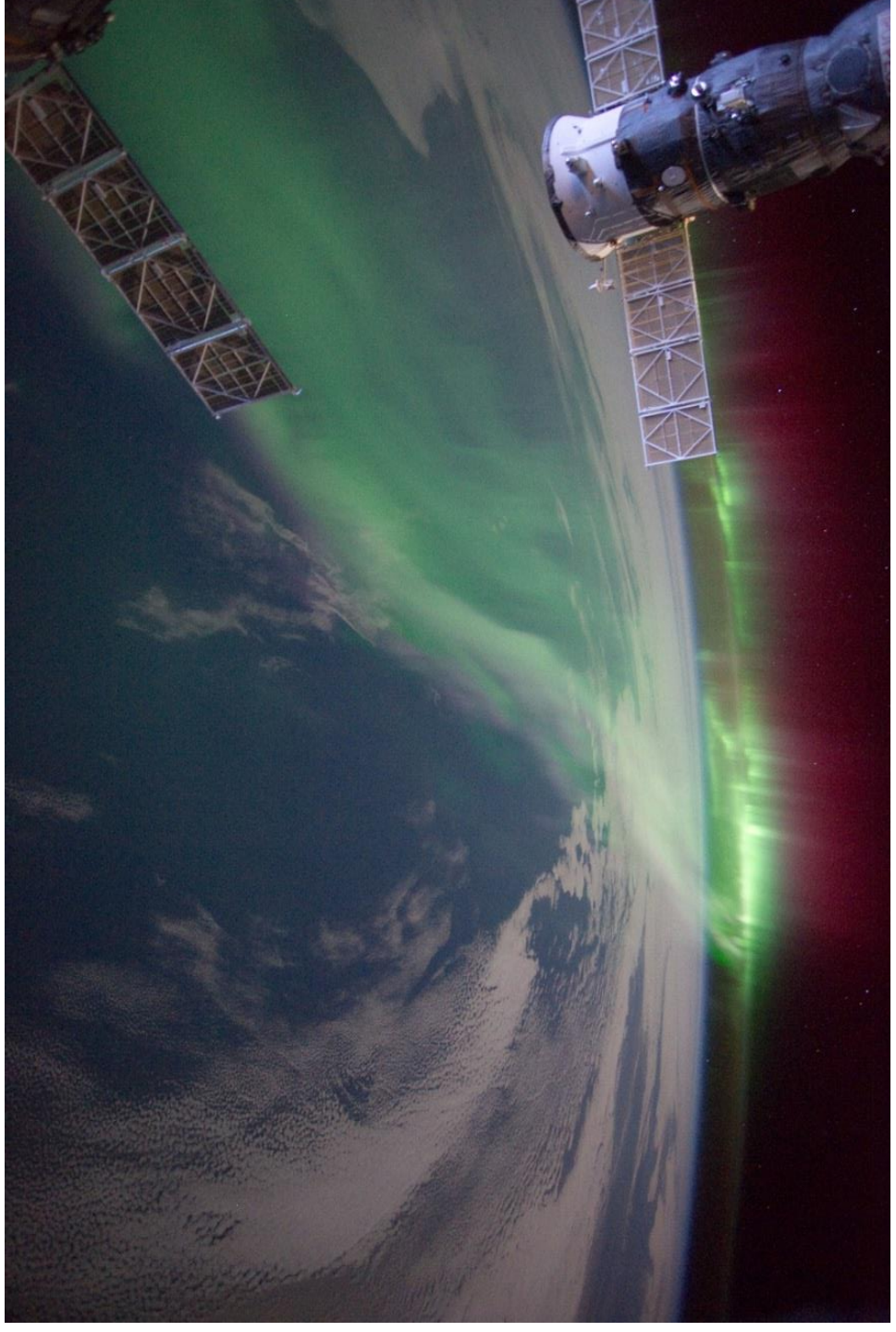


An Assessment of Space Weather Architectures to Support Deep Space Exploration

Joseph I. Minow[1], Linda Neergaard Parker[2], Christopher J. Mertens[1], John R. Allen[3], Dan J. Fry[4], Edward J. Semones[4], Rachel A. Hock[5], Insoo Jun[6], Terry G. Onsager[7], Antti A. Pulkkinen[8], and Chris St. Cyr[8]

[1]NASA Langley Research Center, Hampton, Virginia
[2]Universities Space Research Association, Huntsville, Alabama
[3]NASA Headquarters, Washington, D.C.
[4]NASA Johnson Space Center, Houston, Texas
[5]Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio
[6]The Jet Propulsion Laboratory, Pasadena, California
[7]NOAA Space Weather Prediction Center, Boulder, Colorado
[8]NASA Goddard Space Flight Center, Greenbelt, Maryland

SEE-MAPLD 2021
31 August – 2 September 2021, Virtual

joseph.minow@nasa.gov

Introduction

- NASA's Engineering and Safety Center (NESC) assembled a technical assessment team to evaluate space weather architecture options for use in protecting future human and robotic space systems from the space radiation hazards due to energetic ions in solar particle events (SPE)

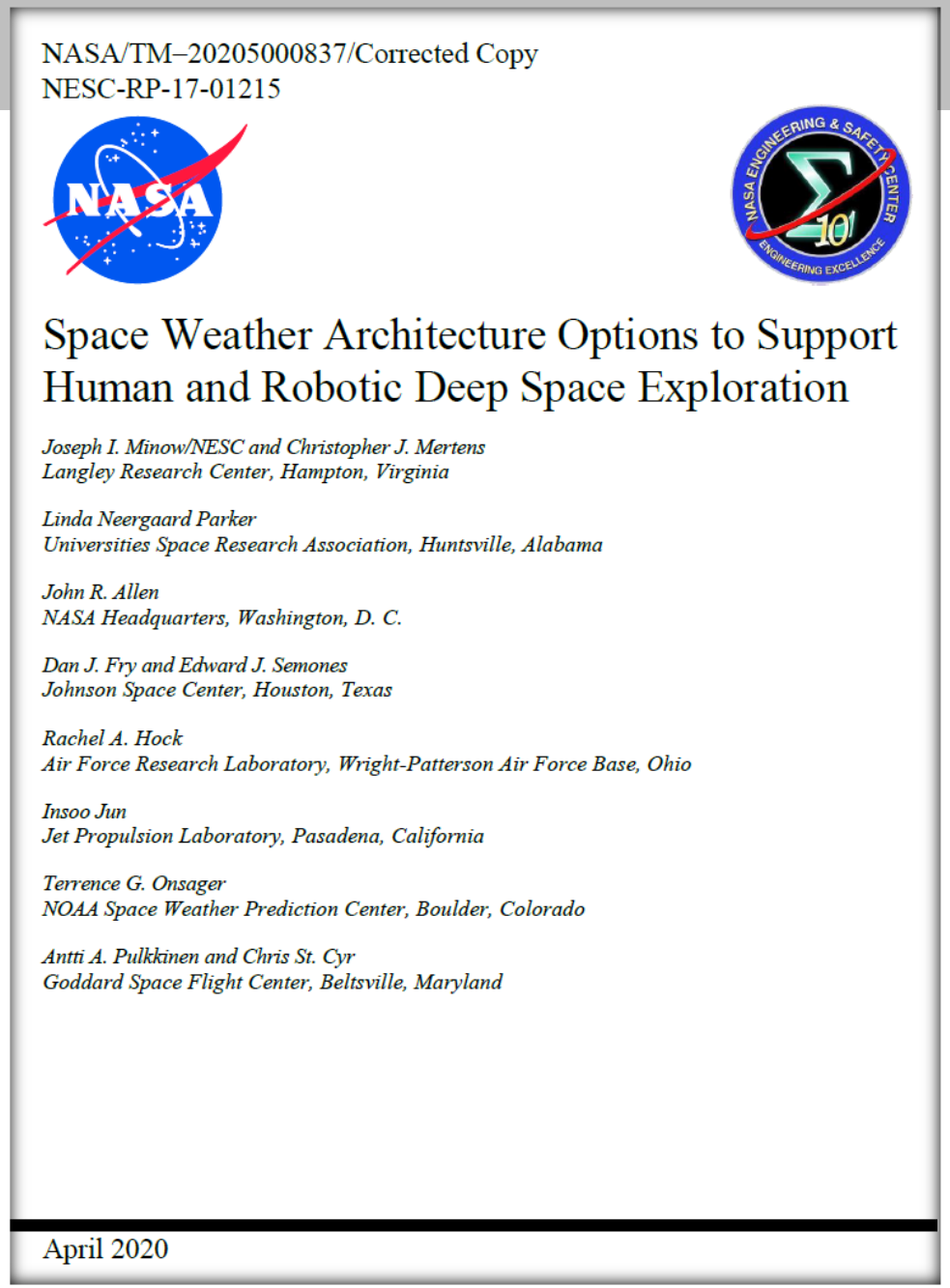
- Stakeholders: HEOMD and SMD senior leadership

- Results from the assessment are published in a NASA Technical Memorandum titled "*Space Weather Architecture Options to Support Human and Robotic Deep Space Exploration*" available at:

  URL: https://ntrs.nasa.gov/citations/20205000837

- The assessment includes a summary of past NASA work in evaluating SPE threats to crew and vehicles, an analysis of the operational response time and the relevant SPE ion energy threshold levels to support space operations, and a set of specific space weather architectures to support missions to the Moon and Mars.

- This presentation is a summary of the study and the contents of the final report.



NASA/TM–20205000837/Corrected Copy
NESC-RP-17-01215

Space Weather Architecture Options to Support Human and Robotic Deep Space Exploration

Joseph I. Minow/NESC and Christopher J. Mertens
Langley Research Center, Hampton, Virginia

Linda Neergaard Parker
Universities Space Research Association, Huntsville, Alabama

John R. Allen
NASA Headquarters, Washington, D. C.

Dan J. Fry and Edward J. Semones
Johnson Space Center, Houston, Texas

Rachel A. Hock
Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio

Insoo Jun
Jet Propulsion Laboratory, Pasadena, California

Terrence G. Onsager
NOAA Space Weather Prediction Center, Boulder, Colorado

Antti A. Pulkkinen and Chris St. Cyr
Goddard Space Flight Center, Beltsville, Maryland

April 2020

Scope of the Study

- The assessment considered near-real-time monitoring assets, space radiation analysis tools, and forecast methods that could support NASA's crewed HEOMD and robotic SMD missions beyond low Earth orbit that meet the following constraints to the greatest extent possible:
  - In-situ radiation and remote solar monitoring hardware planned for deployment on exploration vehicles,
  - Existing space environment sensors from NASA, NOAA, DoD, and other organizations, and
  - A minimal set of new hardware (spacecraft, instruments) only where necessary.
- The assessment goal was to provide NASA with options for a robust and cost-effective space weather situational awareness architecture that could effectively reduce space radiation risks for crewed and robotic operations in the inner heliosphere in orbits about Earth, cislunar space, and Mars.
- Space environment models were reviewed and used as key drivers for instrument selection, but validation and performance metrics for each were not assessed. This was considered beyond the scope of the assessment.

Study Elements

Task 1:	Previous Space Weather Studies
Task 2:	Operational Response Time for Space Weather Monitoring
Task 3:	Relevant Forecasting Tools
Task 4:	SPE Threshold Levels for Exploration Missions
Task 5:	Space Weather Architectures

Task 1: Previous Space Weather Studies

- Reviewed prior/current work on space weather architectures to understand any possible gaps in knowledge in fulfilling the requirements.

- Considered hardware requirements, habitat designs including storm shelters for manned missions; and space weather monitoring assets for future missions using information from NASA, NOAA, and DoD.

- **Summary**
  - At the time of Apollo, GCR and SPE risks were managed with a detailed ground based observational approach
  - No major SPE event occurred during Apollo mission, plan was to continue nominal operations until radiation sensors onboard the Apollo CM confirmed elevated radiation environment
  - Humans have only operated in low Earth orbit since Apollo. risk was mitigated by the protection of Earth's magnetic field
  - Mitigation has also been successful by diligent monitoring of radiation exposure and adherence to standards
  - There has been significant advances in the understanding of the space environment (e.g., SPE, GCR), modeling, forecasting, biological requirements and risks, and affects on avionics since the 1970s

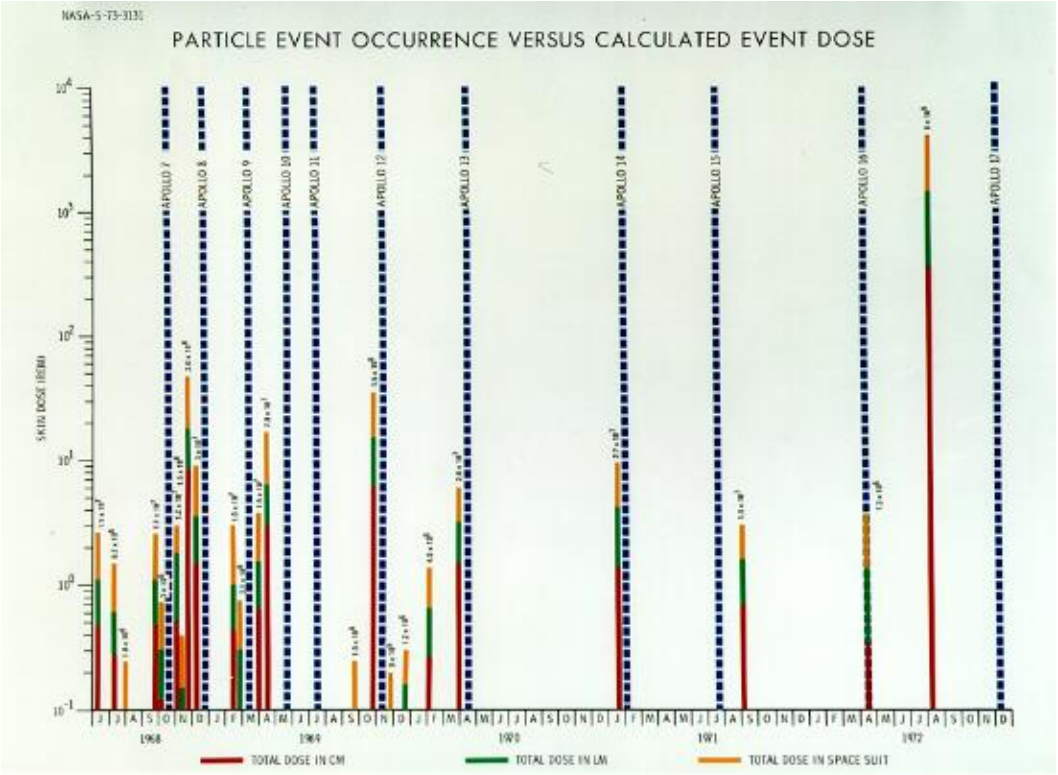


Figure 10. Solar proton events during the Apollo Program.

https://srag.jsc.nasa.gov/publications/tm104782/techmemo.htm

Apollo 1973 SPE Flight Rules

Condition	Mission phase	Rule	Comments
Major solar flare has been predicted.	All	Continue mission.	
Major solar flare has occurred.			
Unconfirmed particle event has occurred.	All	Continue mission.	Report: particles have not been confirmed. No mission impact is indicated.
Confirmed particle event and SPAN or real-time analyses indicate the MOD will be exceeded during the mission.	Prelaunch	Hold until data analysis indicates that the MOD will not be exceeded.	
	Earth parking	Continue mission. If data analysis indicates that the MOD will be exceeded by a significant amount before mission completion, translunar injection is no-go.	Translunar injection is no-go only if firm computation before go/no-go indicates more than the MOD.
	All other phases	Continue mission. Consideration will be given to early (or extended) transearth injection and inhibiting crew transfer to the lunar module.	
Confirmed particle event and spacecraft telemetry or personal radiation dosimeter read-out projections indicate the MOD will be exceeded during the mission.	Translunar coast	Continue mission. Consideration should be given to entering in next best preferred target point if the total dose can be reduced significantly without increasing total risk to the crew.	Crew should begin personal dosimeter and radiation survey meter read-outs. A projection of greater than the MOD is not required for crew read-outs.
	Lunar orbit	Continue mission. Consider extending lunar orbit stay time if the total dose to the crew would be reduced significantly by lunar shielding.	Hatch-down attitude may be used to reduce the total dose. If a particle event is confirmed, the crew will transfer from the lunar module to the command and service module.
	Lunar stay	Consider reducing the lunar stay time or extravehicular activities if the total dose to the crew can be reduced significantly without increasing the total risk to the crew.	Comparison of command and service module and lunar surface personal radiation dosimeters is advised.
	All other phases	Continue mission.	

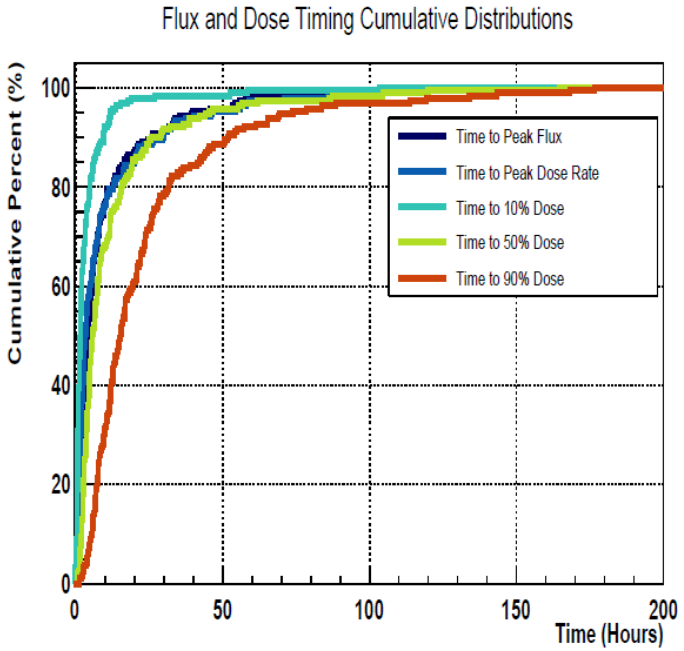
English et al., Apollo Experience Report—Protection against Radiation, NASA Technical Note D-7080, 1973.

Task 2: Operational Response for SPE Monitoring

- Calculate statistics for critical SPE timing parameters using ESA's Solar Energetic Particle Environment Modeling (SEPEM) Reference Data Set Version 2.0 (RSDv2.0) data set:
  - 41 years (1974 – 2015) IMP-8, GOES 5 MeV to 289 MeV protons
  - Generate data set of SPE events with background-subtracted flux
  - Compute dose rates inside shielded spacecraft (using a proxy 10 g/cm^2 aluminum spherical shield) using the HZETRN radiation transport code
  - Identified SEP events that cause an increase in dose above background behind shielding
  - Calculated critical timing parameters for these dose-significant events
- Summary:
  - 192 SPE events in 41 years resulted in an increase in dose above background behind shielding (10 g/cm^2 aluminum sphere)
  - 19 (10%) of the events were multiple SPE events in quick succession, leading to elevated fluxes for up to 13 days
  - Once an SEP event begins, probabilistic values for duration, time to peak flux and dose rate, time to 10%, 50%, and 90% dose can be inferred from this study
  - If the time parameters and value of the peak flux can be predicted, it is possible to estimate:
    - The total dose
    - Determine whether 10%, 50%, or 90% dose has likely been reached
  - **Dose mitigation actions will be most effective if they occur within the first 2 hours of an SPE, which will likely reduce at least 50% of the SPE dose**

SPE Event Parameters

- Event date
- Onset time
- Event end time
- Duration
- Inter-event time
- Peak 66-95 MeV flux
- >66 MeV fluence
- >95 MeV fluence
- Fluence spectrum
- Peak dose rate
- Total dose
- Time to peak flux
- Time to peak dose rate
- Time to 10% dose
- Time to 50% dose
- Time to 90% dose

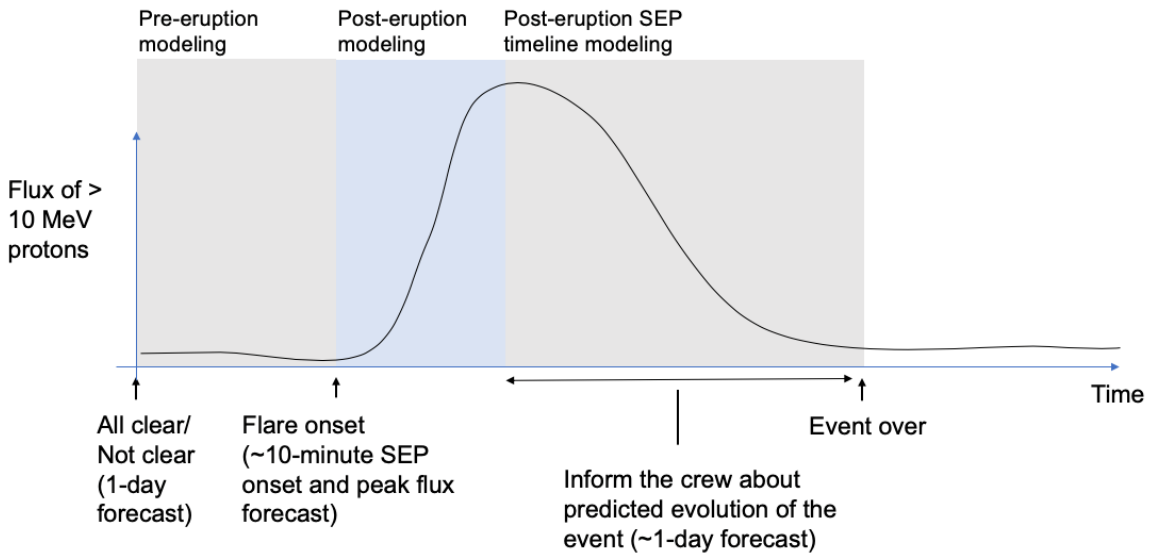


Task 3: Relevant Forecasting Tools

- What types of space weather models are needed and available to support the future human space exploration operations?
  - Models selected based on their ability to provide useful predictions for SPE proton flux through some phase of operations timeline

- Develop model catalog with information on:
  - Prioritized modeling needs
  - Model input and output, input are the observational needs that drive the architecture design
  - Model maturity

Operations Timeline

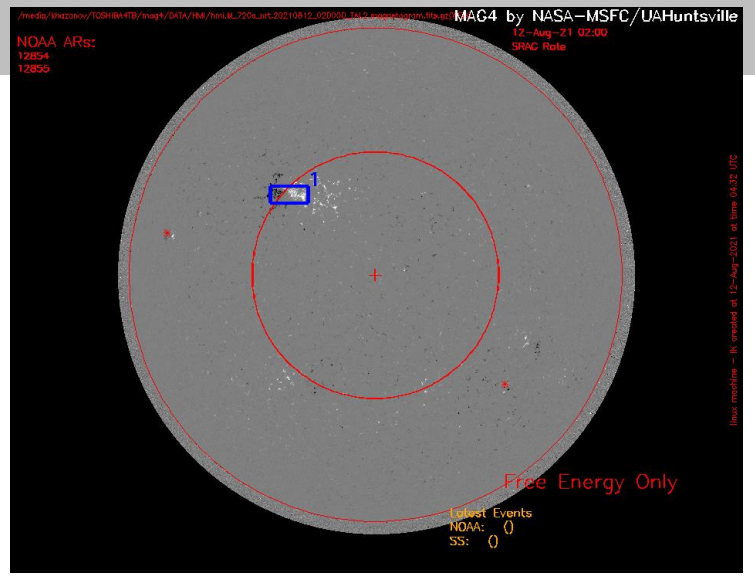


- Catalog of prioritized space environment models with observational requirements provide potential space weather nowcasting and forecasting tools:
  - Probabilistic pre-eruption flare/SPE/CME prediction modeling
  - Empirical post-eruption modeling
  - Post-eruption time profile models
  - Solar wind and CME transport models
  - Space environment effects models

Task 4: Relevant Forecasting Tools

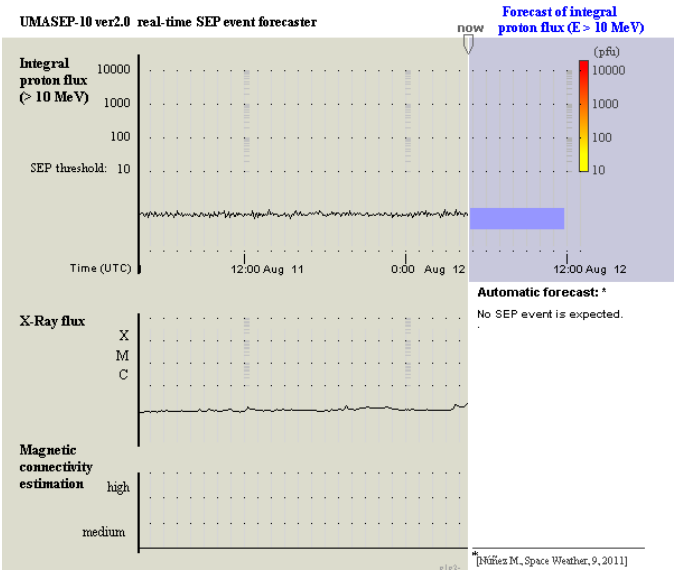
- Pre-eruption
  - Use: all clear forecast and probability of flare, SPE, CME
  - Models: ASAP, ASSA, MAG4, SWPC/SpaceWOC (human generated)
- Post-eruption
  - Use: assessment of SPE parameters
  - Models: AER SEP, AF-DEPT, COMESEP, ESPERTA, FORSPEF, Proton Events, PPS, REleASE, SEPMOD, SEPsFLAREs, SOLPENCO, SPARX, SPRINTS, St Cyr model, SWPC, SWPC Protons, UMASEP
- Post-eruption time profile
  - Use: assessment of the SPE time profile
  - Models: AF-DEPT, PATH, PREDICCS, UMASEP
- Solar wind/CME transport
  - Use: situational awareness/SEP timeline
  - Models: SWMF corona/solar wind, LFM heliosphere, SWA-Enlil/Cone, CORHEL
- Space environment impact models
  - Use: tools that support space system design and real-time nowcast of radiation exposure effects
  - Models: CRÈME-MC, FLUKA, Geant4, HZETRN, NOVICE, Shieldose

MAG4 12 Aug 2021



https://www.uah.edu/cspar/research/mag4-page/

UMASEP 13 Aug 2021

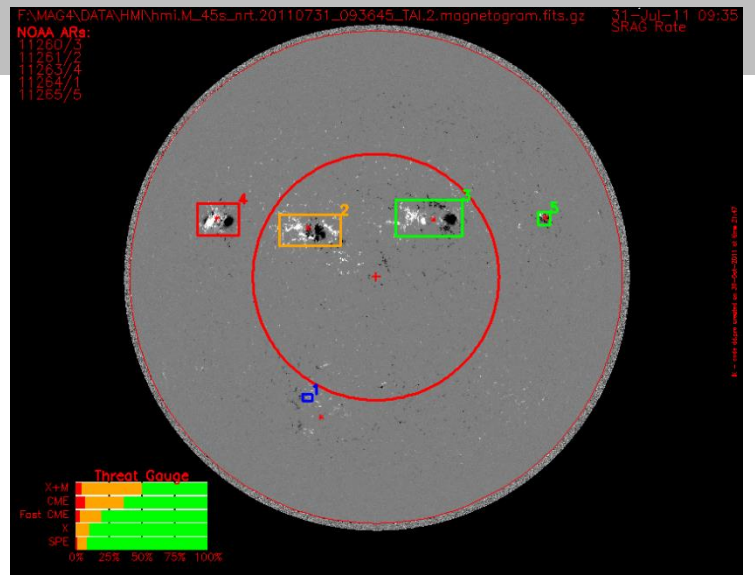


http://spaceweather.uma.es/forecastpanel.htm

Task 4: Relevant Forecasting Tools

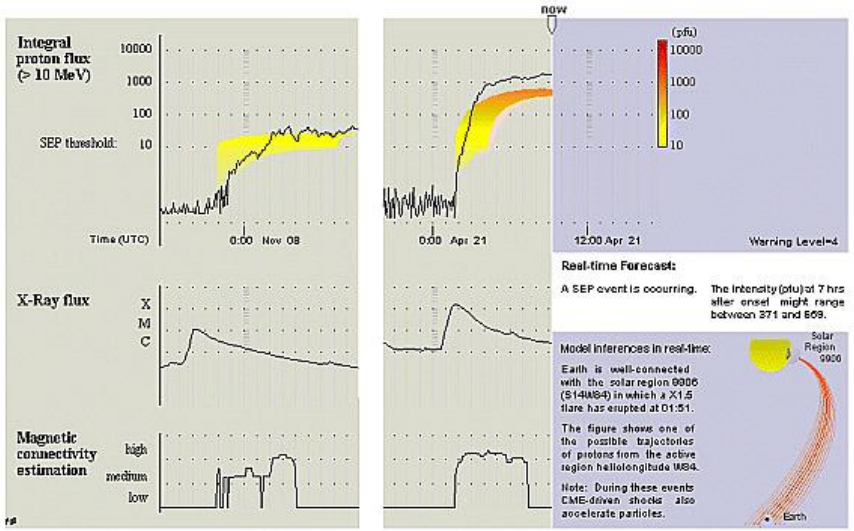
- Pre-eruption
  - Use: all clear forecast and probability of flare, SPE, CME
  - Models: ASAP, ASSA, MAG4, SWPC/SpaceWOC (human generated)
- Post-eruption
  - Use: assessment of SPE parameters
  - Models: AER SEP, AF-DEPT, COMESEP, ESPERTA, FORSPEF, Proton Events, PPS, REleASE, SEPMOD, SEPsFLAREs, SOLPENCO, SPARX, SPRINTS, St Cyr model, SWPC, SWPC Protons, UMASEP
- Post-eruption time profile
  - Use: assessment of the SPE time profile
  - Models: AF-DEPT, PATH, PREDICCS, UMASEP
- Solar wind/CME transport
  - Use: situational awareness/SEP timeline
  - Models: SWMF corona/solar wind, LFM heliosphere, SWA-Enlil/Cone, CORHEL
- Space environment impact models
  - Use: tools that support space system design and real-time nowcast of radiation exposure effects
  - Models: CRÈME-MC, FLUKA, Geant4, HZETRN, NOVICE, Shieldose

MAG4 31 Jul 2011



https://www.uah.edu/cspar/research/mag4-page/

UMASEP 8 Nov 1987, 21 Apr 2002



Nunez, Space Weather, 2011

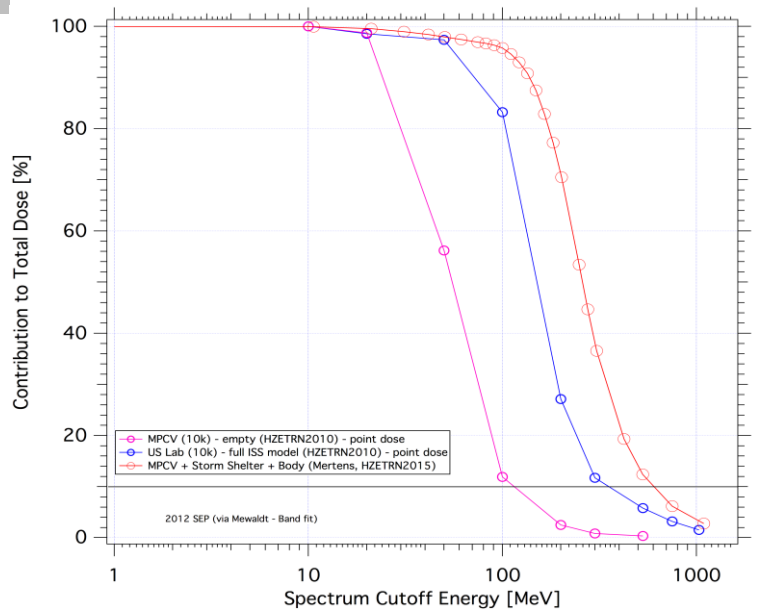
Task 5: SPE Threshold Levels for Exploration Missions

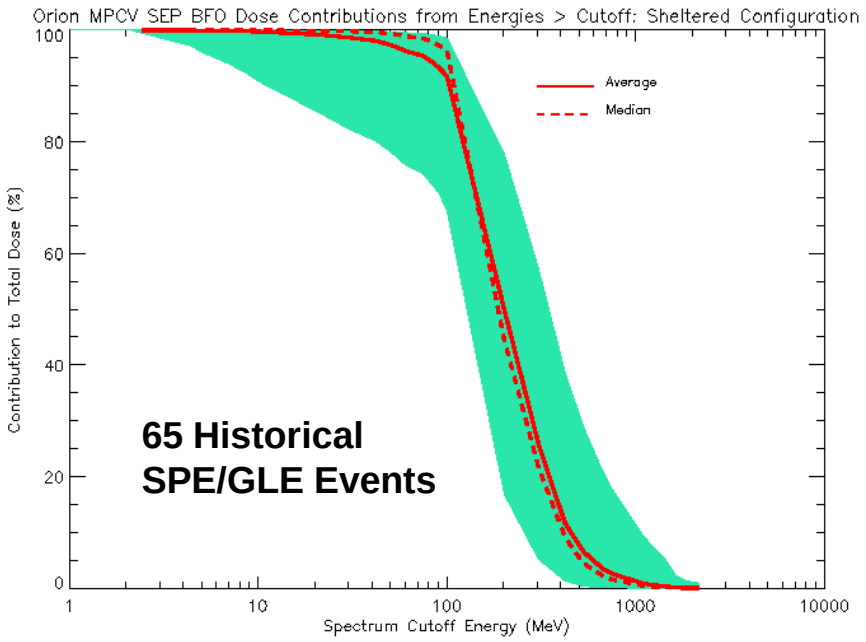
- Identify the dominant proton energy range relevant to crew radiation risk that needs to be measured to have sufficient knowledge of the environment to protect crew health and safety
  - Lower and upper energy threshold
  - Risk metric: dose to blood-forming organs (BFO)

- Methodology
  - Set of 65 historical SPE/GLE events
  - Vehicle models – focus on MPCV (Orion), including storm shelter and body self shielding
  - Compare with point dose in MPCV alone to assess expectations of instrument response
  - Determine BFO dose as a function of different proton energy bins

- Results
  - Protons with energies ≤1 GeV need to be incorporated to include more variance among ensemble of relatively hard spectra
  - Generally, only protons of energy >30 MeV can penetrate the pressure vessel
  - Flux increases at lower energies have served as a signature for adverse space weather conditions
  - Real-time information on proton flux at energies as low as 10 MeV are valuable for EVA operations

Proton Energy Contribution as Function of Threshold Energy, May 2012 SPE Event





Space Weather Architectures

Moon (and Sun-Earth Line at ~1 AU)

- No new types of instruments are required beyond currently available space weather monitoring assets and planned in-situ energetic particle monitors on crewed spacecraft
  - Continued work in maturing predictive SPE modeling and prediction making use of the measurements will be essential
- Assumes current space weather assets are available during lunar missions, but some (e.g., ACE, SOHO, STEREO, SDO) have exceeded their design life
  - NASA and other Federal Agency support for replacement assets is essential
- Architectures:
  - **Baseline:** currently available assets to obtain measurements of photospheric magnetic field maps, energetic ions and electrons, soft x-ray flux with flare location detection
  - **Enhanced:** Baseline measurements plus white-light coronal emissions, and in-situ magnetic field and solar wind plasma
  - **Comprehensive:** Enhanced measurements plus space-based solar rate (e.g., Type II, III) measurements

Con-ops Component	Modeling Objectives	Modeling Requirement	Measurement Requirement	Instruments Required	Mission Requirements	Existing Assets, Assumed Available for Lunar 2024
Mission planning and situational awareness (launch, EVAs)	Pre-eruption modeling	24-hour/ 6-hour lead-time forecast of solar eruptions (flare, SEP, CME) Probability of >10 MeV p+ NOT exceeding 10-100 pfu or >100 MeV, not exceeding 1 pfu in next 24 or 6 hours	Photospheric magnetic field LOS or vector)	Photospheric magnetograph	Carry out all measurements along Sun-crewed vehicle line (Sun-Earth line for lunar missions), or close to line 100% instrument and modeling duty cycle for soft X-rays 24/7 observational and modeling data feeds	GONG (operational), SDO/HMI R
			Solar continuum/ white-light	Continuum/ white-light solar imager		SOON (operational), SDO/HMI R
			Solar soft X-ray	Soft X-ray spectrograph		GOES O
Deploy and enter storm shelter or return to lander	Post-eruption modeling	SEP onset time prediction	Solar soft X-ray	Soft X-ray spectrograph		GOES O
		SEP peak flux prediction	Flare location	EUV imager/ H-alpha imager/ X-ray imager		GOES O SDO/AIA R
			Energetic protons	Energetic charged particle detector		GOES O
			CME parameters	Coronagraph		SOHO/LASCO R Stereo/COR R
		Probability of >10 MeV p+ exceeding 10-100 pfu or >100 MeV p+ exceeding 1 pfu	(Interplanetary) Energetic electrons	Energetic charged particle detector		SOHO/COSTEP R ACE/EPAM R
			Solar radio bursts (Type II & III)	Solar radio telescope		Ground-based Radio Solar Telescope Network O
			CME parameters	Coronagraph		SOHO/LASCO R Stereo/COR R

R: research O: operational

Space Weather Architectures

Moon (and Sun-Earth Line at ~1 AU)

- No new types of instruments are required beyond currently available space weather monitoring assets and planned in-situ energetic particle monitors on crewed spacecraft
  - Continued work in maturing predictive SPE modeling and prediction making use of the measurements will be essential

- Assumes current space weather assets are available during lunar missions, but some (e.g., ACE, SOHO, STEREO, SDO) have exceeded their design life
  - NASA and other Federal Agency support for replacement assets is essential

- Architectures:
  - **Baseline:** currently available assets to obtain measurements of photospheric magnetic field maps, energetic ions and electrons, soft x-ray flux with flare location detection
  - **Enhanced:** Baseline measurements plus white-light coronal emissions, and in-situ magnetic field and solar wind plasma
  - **Comprehensive:** Enhanced measurements plus space-based solar rate (e.g., Type II, III) measurements

Con-ops Component	Modeling Objectives	Modeling Requirement	Measurement Requirement	Instruments Required	Mission Requirements	Existing Assets, Assumed Available for Lunar 2024
Inform crew about expected evolution and end of SEP event	SEP Time profile/ duration; post-threshold SEP event model/ determine CME arrival	Flux as function or estimate of time below threshold) for >10 MeV p+	Energetic protons	Energetic charged particle detector		GOES O ACE R
			CME parameters	Coronagraph		SOHO/LASCO R Stereo/COR R
Nowcasting	NA	NA	Flux at >10 MeV p+, >30 (or >50) MeV p+, >100 MeV p+	Energetic charged particle detector		GOES O ACE R

R: research O: operational

Space Weather Architecture: Mars

Baseline:

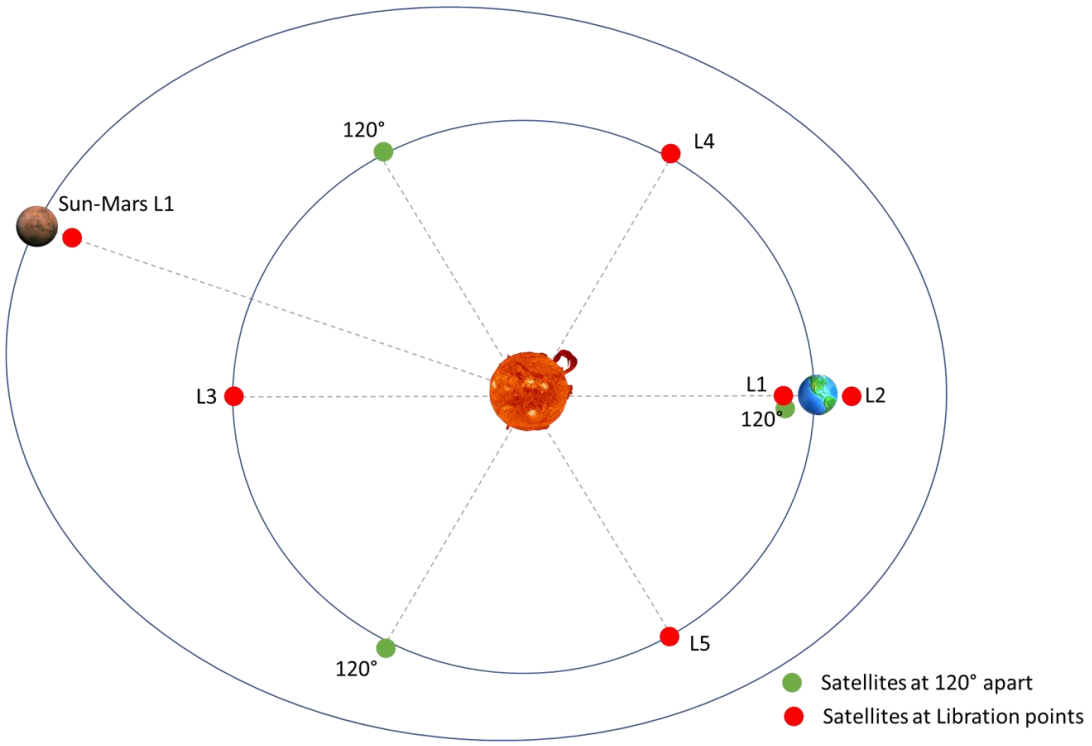
- Sustained Sun-Earth line baseline instruments plus suite of instruments on the Mars vehicle:
  - Solar photospheric magnetic field maps
  - Solar soft X-ray fluxes and flare location
  - Energetic ion and electron spectra and fluxes

Enhanced:

- Sustained Sun-Earth line baseline instruments plus an improved suite of instruments on the crewed Mars vehicle:
  - White-light coronal imaging
  - In-situ magnetic field
  - Solar wind plasma properties
  - Space-based radio measurements

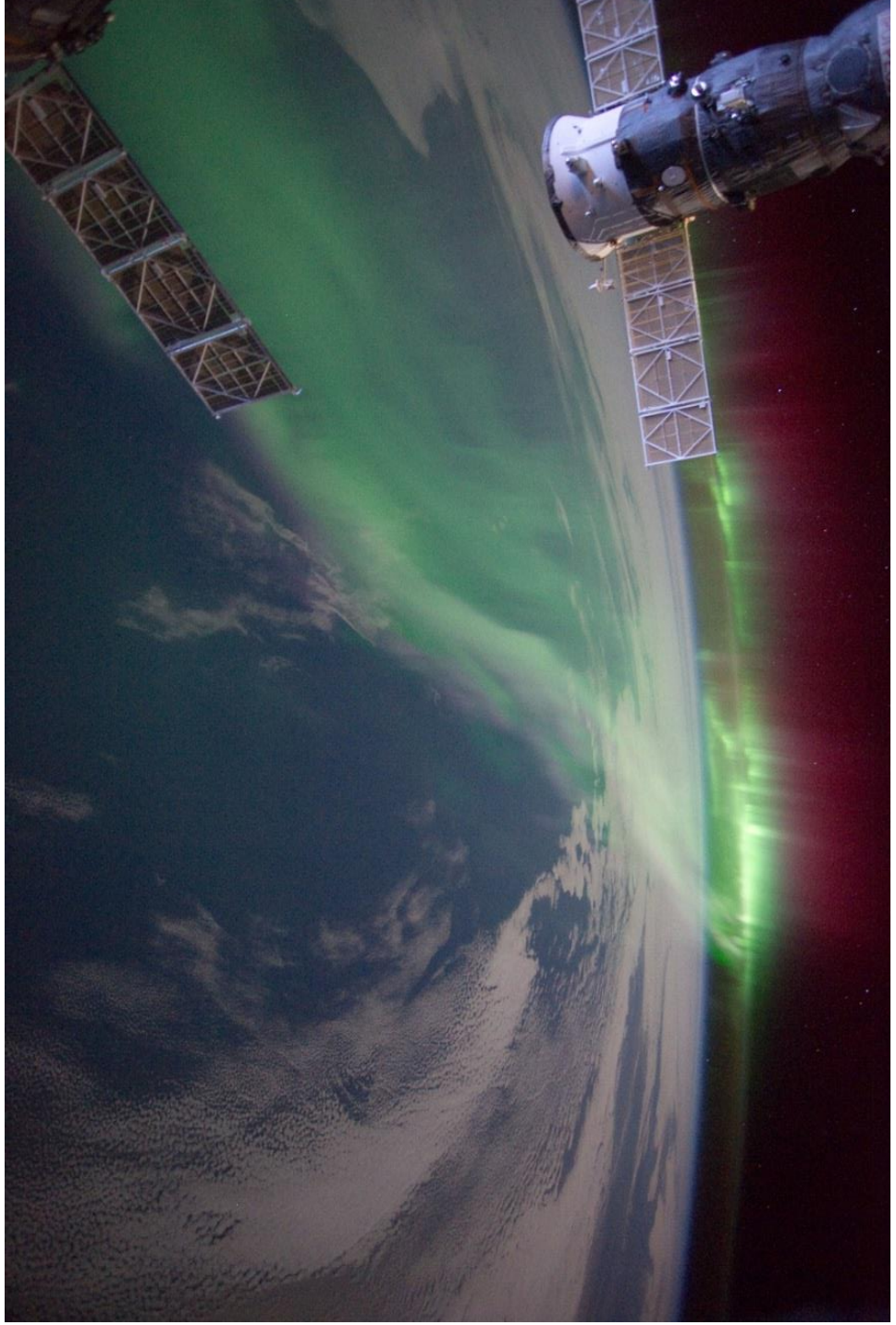
Comprehensive:

- Sustained Sun-Earth line baseline instruments and new constellation of three space weather spacecraft in solar orbit at 1 AU and 120° apart. Each spacecraft carry a suite of remote sensing and in situ instruments including:
  - Solar EUV imager
  - Heliospheric imager
  - EUV/FUV solar spectral irradiance
  - Intravehicle dosimeter



Space Weather Architecture Summary

HEO Mission Target	Classification	Description
Moon	Lunar 2024	No additional hardware required over the existing NOAA & USAF assets. However, lunar platform should be used as a proving ground for future Mars missions (see Bridging Missions)
Mars	Baseline	Sustained Sun-Earth line assets. Crewed vehicle flying with Mars baseline instrumentation.
	Enhanced	Sustained Sun-Earth line instrumentation. Crewed vehicle flying with Mars enhanced instrumentation.
	Comprehensive	3 spacecraft 120° apart @ 1 AU; all spacecraft have the same remote sensing and *in situ* instrumentation.
Bridging Missions	ISS Platform	Proving ground for the Lunar/Mars mission. Instrument priorities: magnetograph, coronagraph.
	Gateway Phase I	Energetic charged particle sensors.
	Gateway Phase II	Develop a Mars vehicle instrument package using lessons learned from the ISS proving ground and Phase I.
	Mars	Instrumentation flying as a hosted payload on robotic Mars science missions.



Report is available to the public from the NASA Technical Report Server:

URL: https://ntrs.nasa.gov/citations/20205000837.

Questions?