Space Weather Operations and Research Infrastructure: Workshop Part I

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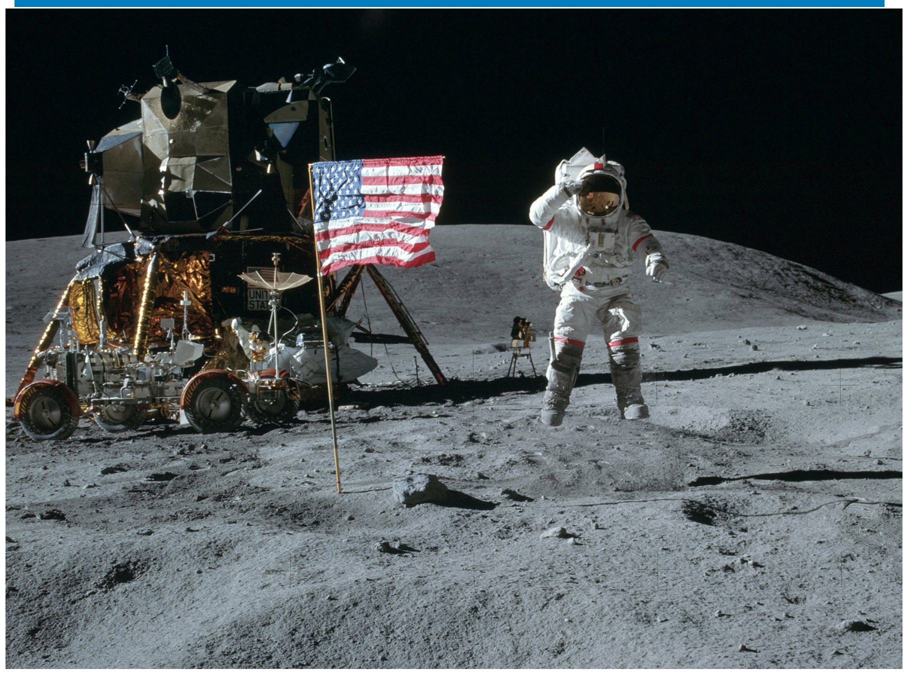
APOLLO ERA



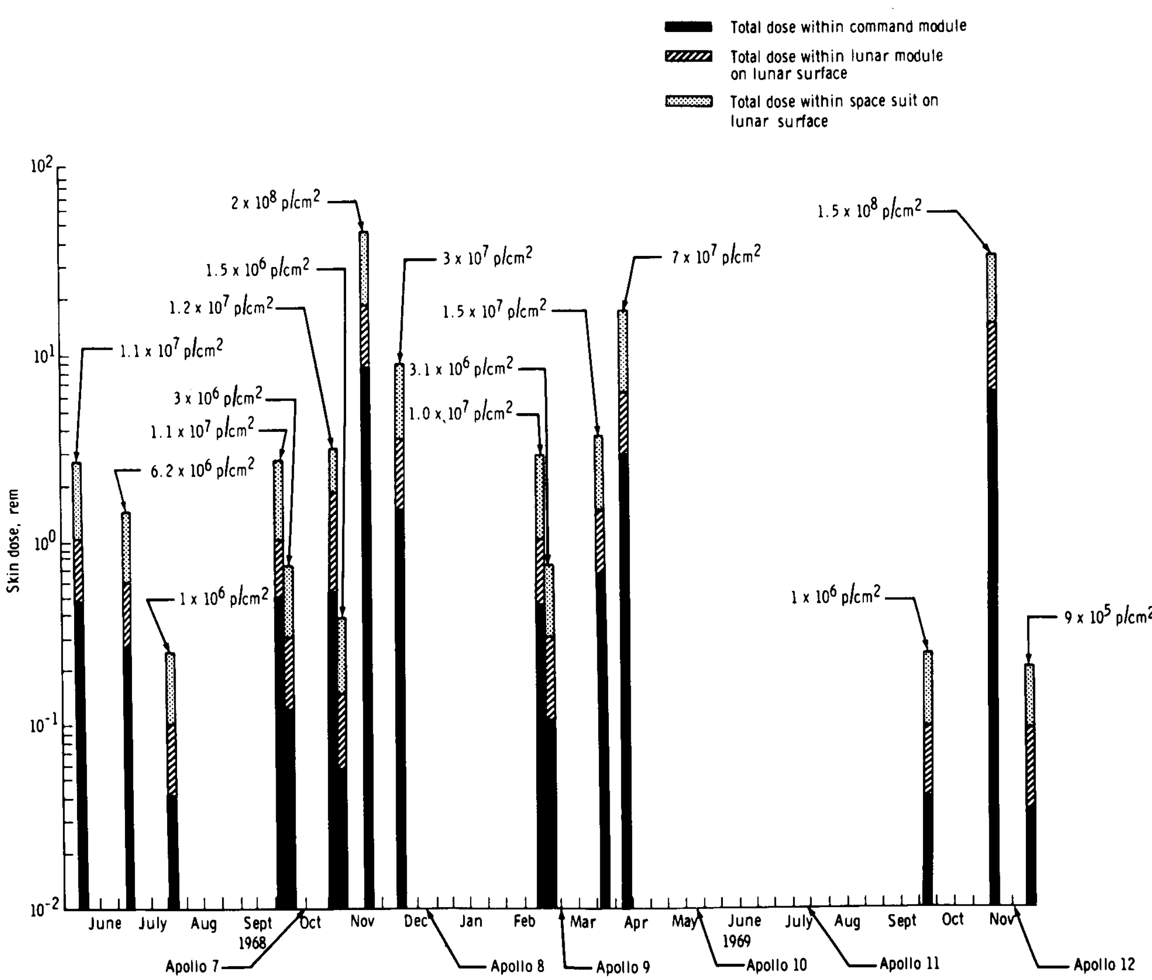


Figure 1. - Radiation-dose estimates for particle events between June 1968 and December 1969.

TABLE II. - SOLAR-FLARE RULES FOR APOLLO MISSIONS

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.	

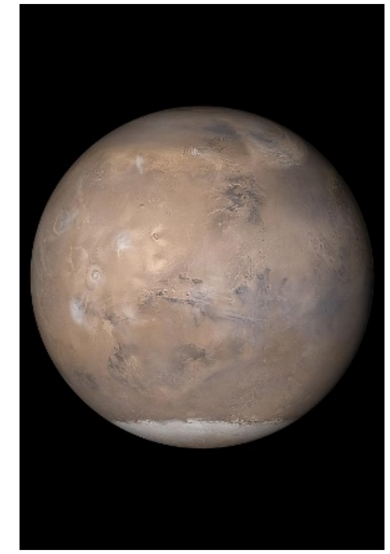
SPACE ENVIRONMENT MISSION RULES

- ACTION WILL BE BASED ON CONFIRMED EVENTS BY MORE THAN ONE DATA SOURCE
- MAXIMUM OPERATIONAL DOSE LIMITS
  - SKIN 400 REM
  - DEPTH 50 REM (5 cm)
- NATURAL RADIATION
- ARTIFICIAL RADIATION

Space Radiation

ISS

- Galactic Cosmic Rays (GCR)
  – Continuous, higher in polar regions
- Trapped Radiation
  – South Atlantic anomaly (SAA)
  – 6-9 times/day
- Solar Particle Events (SPEs)
  – Limited to polar regions
- Neutron, Secondary Radiation
  – Vehicle Shielding



Beyond LEO

- Galactic Cosmic Rays (GCR)
  – Continuous
- Trapped Radiation
  – Transit through Van Allen Belts
- Solar Particle Events (SPEs)
  – Full event
- Neutron, Secondary Radiation
  – Vehicle Shielding, planetary albedo

Astronaut Mission Exposures (i.e. includes vehicle and body self shielding)

- Exposures have been calculated in the blood forming organ (BFO) of a female phantom protected by 20 g/cm^2 of aluminum
  - The BFO sites are distributed throughout the body and therefore provide a reasonable "average" body dose
- For the lunar surface cases, the GCR surface exposure was assumed to be ½ the free space exposure
  - Previous studies have shown this to be a reasonable approximation for dose, for which albedo neutrons have a negligible contribution
  - Consideration of other quantities (e.g. dose equivalent, effective dose, or REID) would increase the contribution of albedo neutrons to no more than ~20% of the total exposure for this shield configuration
- Exposure from 1989 SPE to female BFO for this shield configuration is 98 mGy
  - Assumed to occur during transit for lunar mission scenarios
  - Assumed to occur during transit for Mars 500 day mission
- Comparison against MSLRAD cruise data and ISS data suggests raw model estimates for GCR exposure are ~30% low on average
  - Model generated GCR exposure values have been scaled up by 30% to account for systematic error
  - Attributable to 3D effects, high energy physics, pion contributions, and possible errors in GCR model

Model exposure estimates (mGy)

	Duration	Solar min	Solar max	Solar max + 1989 SPE
Free space	720	370	180	278
	360	185	90	189
	240	123	60	158
	120	62	30	128
	90	46	23	121
	60	31	15	113
	30	15	8	106
Lunar	4 wk. surface	7	4	102
	4 wk. transit + 2 wk. surface	18	9	107
	4 wk. transit + 4 wk. surface	22	11	109

Space Weather Concerns for Human Spaceflight – A Quick Summary

- **X-Ray Flare**
  - **No direct Impact**
  - **Can be associated with SPE/ESPE**
- **Geomagnetic Storm**
  - **Impact crews *only* if there is an increase in solar energetic particles (SEP)**
  - **Can 'compress' Earth's geomagnetic field/ protection**
- **Solar Particle Event (SPE)**
  - **Definition: >10MeV proton flux >10pfu (GOES)**
  - **Minimal impact unless crew is EVA**
  - **Low energy particles do not penetrate vehicle**
- **Energetic Solar Particle Event (ESPE)**
  - **Definition: >100MeV proton flux >1pfu (GOES)**
  - **Concern – SRAG monitors closely and makes recommendations to Flight Control Team (FCT)**
  - **Crew may be asked to avoid lower-shielded areas or shelter in highly-shielded areas of vehicle**

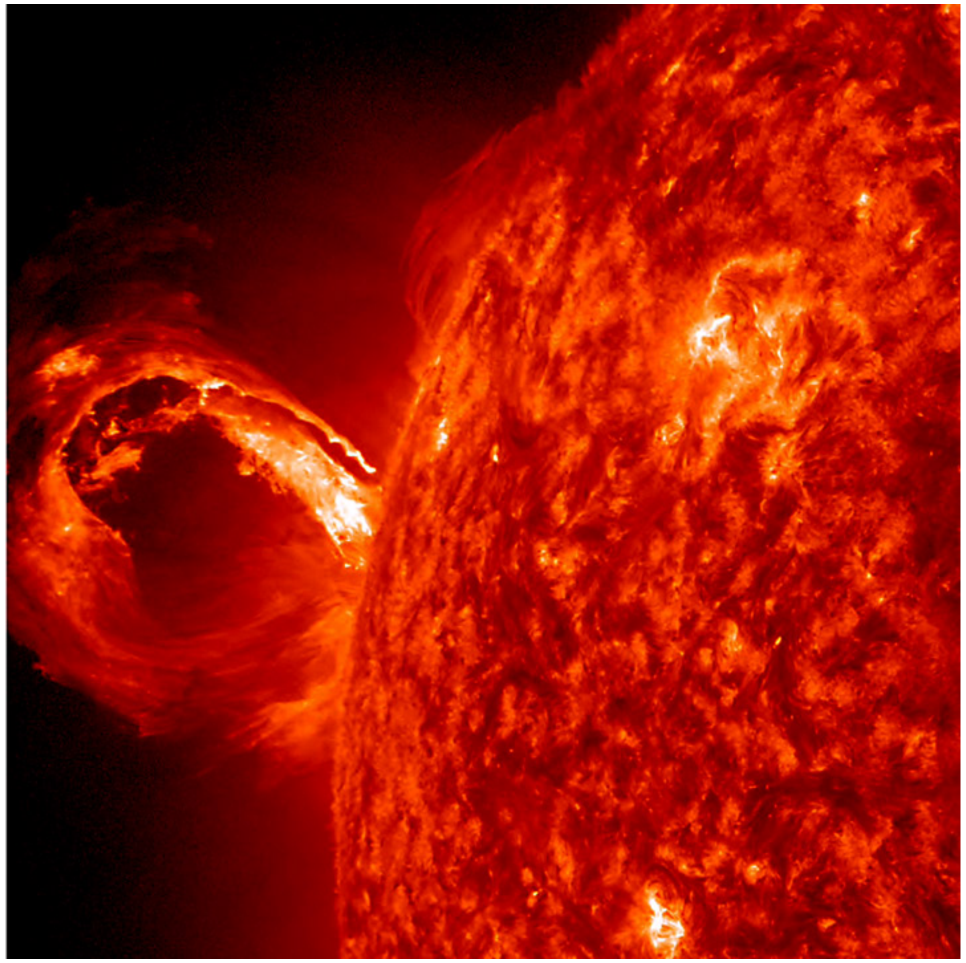


Image of Coronal Mass Ejection (CME) taken by NASA's Solar Dynamics Observatory (SDO) on May 1, 2013.
From: https://sdo.gsfc.nasa.gov

Operations at JSC – Flight Control Team

- **Flight Director responsible for safe mission execution.**
- **CAPCOM communicates with crew.**
- **Flight Surgeon monitors crew health.**
- **Biomedical Engineer (BME) monitors hardware/software related to crew health.**

Operations at JSC – Support Team- SRAG

- Monitors the space radiation environment and warns FCT of solar events.
- Provides FCT with mission dose projections.
- Provides Surgeon with dose projections prior to EVAs.
- Monitors status of SRAG's radiation instruments on the spacecraft.
- Returns to console within 45 minutes during proton events.
  - Shift to 24 hr coverage during Artemis missions
- Supports operations around the clock during proton events.

Current State: ISS SEP Operations

- All SEP forecasting/nowcasting is based on direct SRAG-SWPC interface

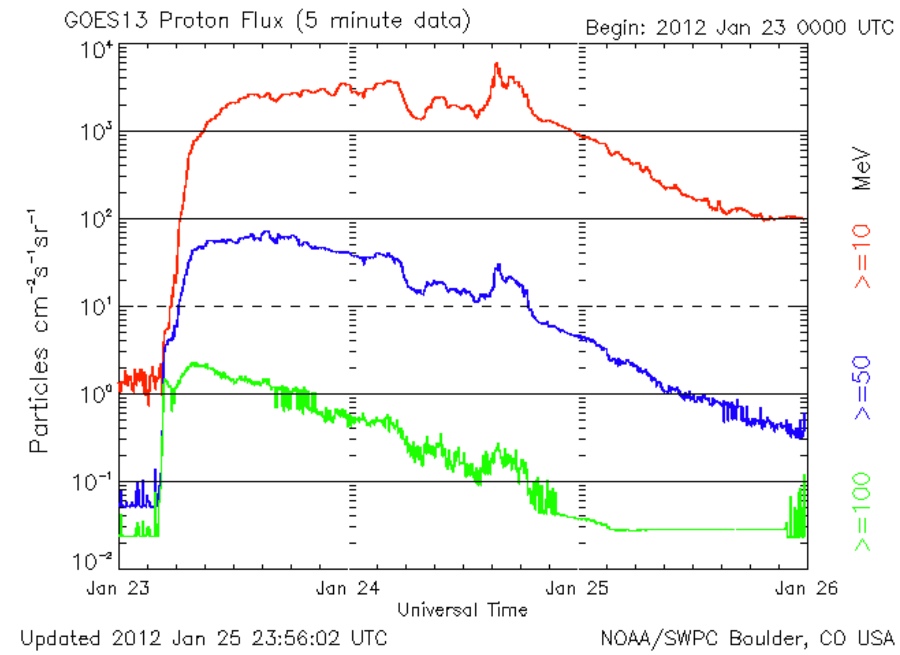
- SRAG flight controller monitors console during space weather contingency operations such as Solar Energetic Particle (SEP) events
  - Alert/Warning messages to management and flight control team
  - Ensure ISS radiation monitoring system availability

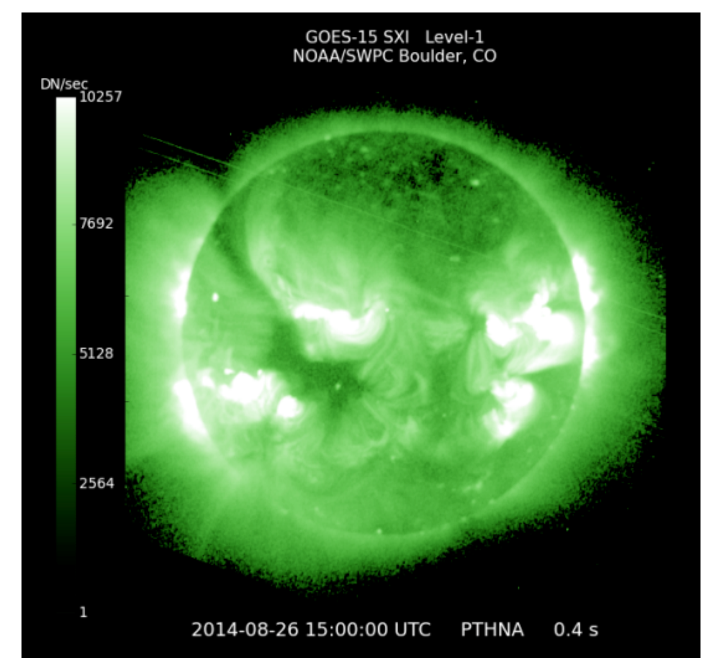
- If SEP dose projection is determined to be negligible, then no action will be taken

- If energetic particle event has increased above threshold or radiation detector alarm activation is confirmed, inform crew to remain in higher shielded areas during intervals of high risk orbital alignments.

- ISS higher shielded locations used to protect crew
  - Service module aft of treadmill (panel 339), Node 2 crew quarters, and U.S. Lab

- This response evolves over several hours with international coordination. Beyond low earth orbit missions will require this process to be much faster. SEPs can reach peak flux levels in < 5 hours.





Timing Results for 10 Large SEP Events in Dose

SEP Event Date	Onset Time	Duration (Days)	Peak Flux (66.13 – 95.64 MeV)	Fluence >66.13 MeV	Fluence >95.64 MeV	Peak Dose Rate (cGy/hr)	Total Dose (cGy)	Time to Peak Flux (66.12 – 95.64 MeV) (hr)	Time to Peak Dose Rate (hr)	Time to 10% Dose (hr)	Time to 50% Dose (hr)	Time to 90% Dose (hr)
1989/10/19	13:05:00	13.96	10.90	3.96e8	1.80e8	1.15	21.84	26.3	26.3	9.8	29.8	134.1
2000/07/14	10:35:00	5.67	10.70	2.79e8	8.66e7	1.19	13.24	5.8	2.6	1.8	7.3	23.8
2000/11/08	23:40:00	5.93	11.10	2.42e8	6.30e7	0.956	10.63	4.0	4.3	2.5	7.5	16.8
1989/09/29	11:50:00	10.45	3.72	1.64e8	7.38e7	0.580	9.17	8.0	8.1	3.6	11.6	28.8
2003/10/28	11:20:00	3.93	6.86	2.05e8	5.66e7	0.480	9.10	12.9	13.1	5.1	14.1	42.3
2001/11/04	16:45:00	5.10	9.83	1.61e8	3.84e7	0.672	6.49	33.6	33.7	4.9	29.2	36.2
2005/01/15	23:55:00	8.28	10.19	1.14e8	4.87e7	2.04	6.37	103.3	103.3	52.3	104.5	113.8
2012/03/07	02:00:00	5.58	1.76	8.19e7	2.62e7	0.187	4.06	13.4	13.4	11.2	25.2	47.2
2001/04/15	14:00:00	5.71	2.47	4.40e7	2.19e7	0.512	2.73	1.7	1.2	0.9	3.7	65.4
1989/08/12	15:25:00	12.92	1.52	5.40e7	1.71e7	0.104	2.36	13.1	85.8	11.8	86.3	119.3

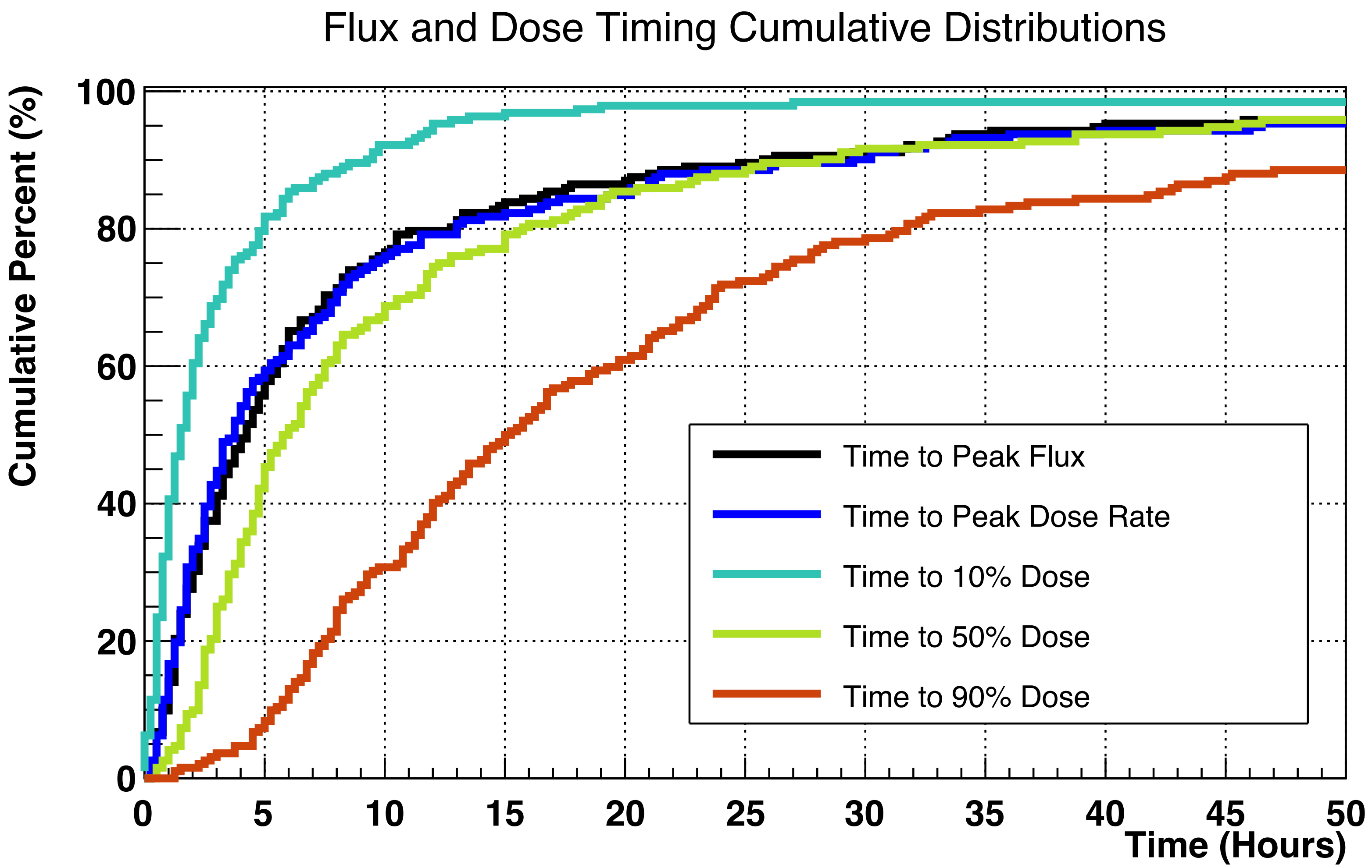
Flux and fluence units are [MeV^{-1} cm^{-2} s^{-1} sr^{-1}] and [cm^{-2}]. Dose calculated for 10 g/cm^2 Al sphere.

Uncertainty in timing is approx. ± 30 min.

1989/10/19, 2005/01/15, 2001/04/015, 1989/08/12 consist of multiple SEP events in quick succession.

Flux-Dose Timing Comparison: Cumulative Distributions

- Time to Peak Flux (**black**) and Time to Peak Dose Rate (**blue**) are very similar
- Events that reach peak flux after 20 hours, also reach 50% dose (**green**) at about the same time



Beyond Low-Earth Orbit Differences: Gateway-Lunar Surface

- Each SEP event will impact Gateway and each Lunar Surface mission
  - Will need more detailed forecasting to discern which ones may be serious with advance warning
  - **NASA will continue to utilize SPWC** for core forecasting for Artemis Program, but additional operational tools will be utilized for fast response to mission control
- Three questions the Console Operator always fields during periods when large active regions are present on sun:
  - Will there be an event (SEP)?

    Need reliable All-Clear for SEP to support Gateway-Lunar Surface mission planning
  - How intense will it be?
  - How long will it last?

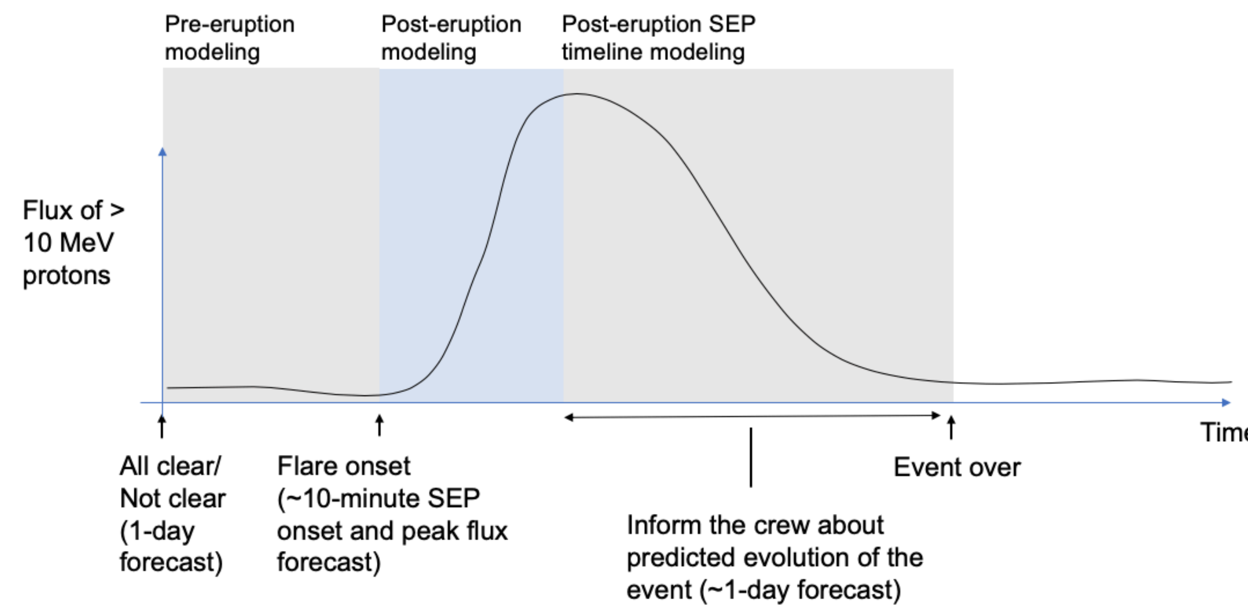
    Need reliable forecasts of SEP event peak flux and temporal evolution to support Gateway-Lunar Surface operations

- To help answer these questions SRAG-CCMC have collaborated on a joint project to assemble suite of models in scoreboard framework that includes (we hope) significant EU/ESA component: **Integrated Solar Energetic Proton Event Alert / Warning System (ISEP)**

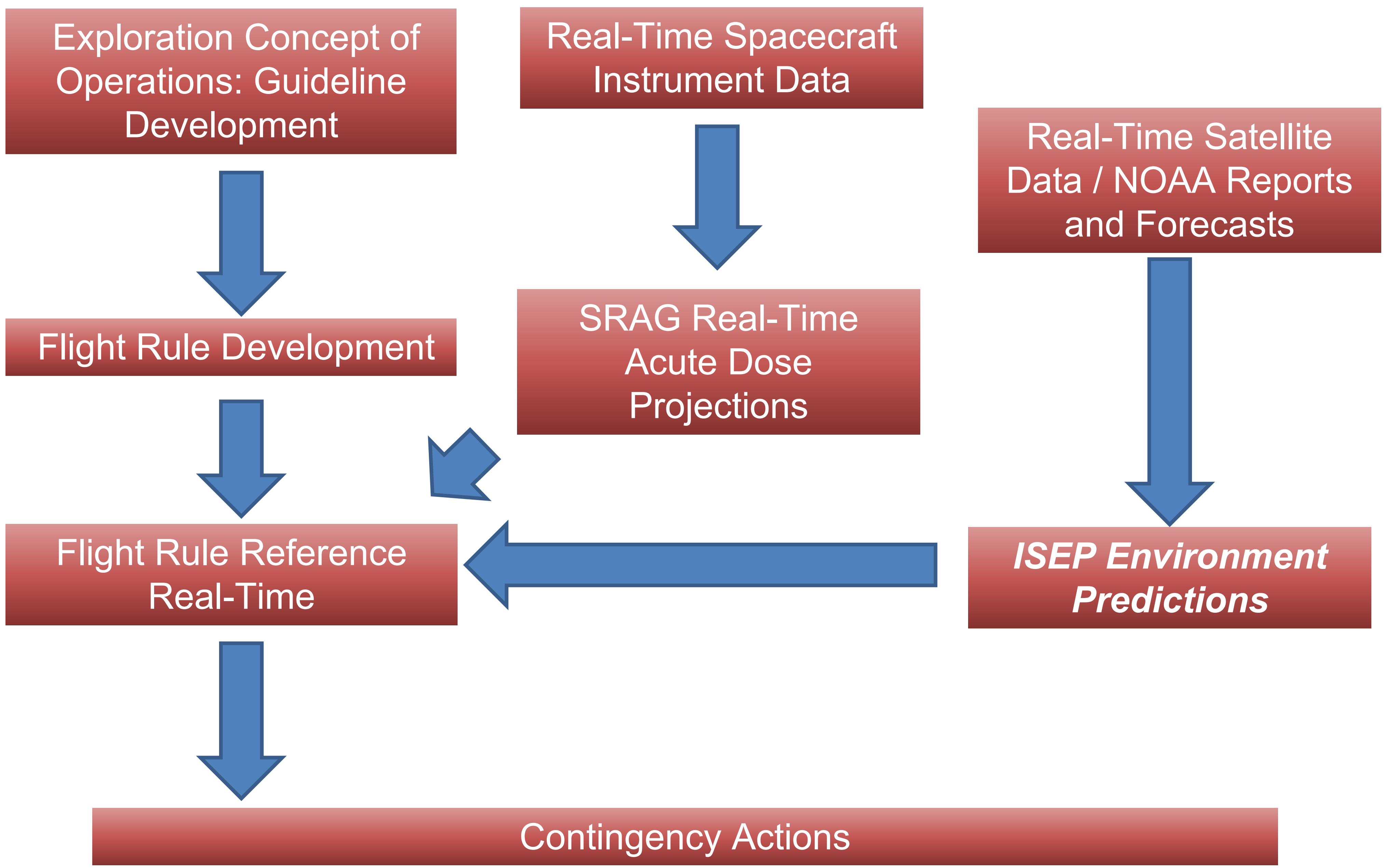
Integrated Solar Energetic Proton Event Alert / Warning System (ISEP)

Transition of Research Model Investments to Operational Tools

- Focus on community-accepted scoreboards at CCMC:
  - Statistical-based models: models identified will be integrated to run as an ensemble.
  - Physics-based models: more complexity over statistical models and less mature but builds on past agency investment in forecasting temporal evolution.
- Leverage current capabilities
  - Current GOES-SMD data streams
  - GSFC/CCMC and JSC/SRAG expertise and functionality to develop ensemble techniques and operational architectures
- Utilize
  - Magnetogram observations via SDO and GONG
  - CME observations via STEREO and SOHO
  - Solar wind observations via DSCOVR
  - SDO AIA observations
  - GOES X-ray/SUVI and particle data



Operational Schema



Space Weather Operations Recommendations

- We need to communicate evolving forecast needs and requirements to forecasting centers (SWPC) and researchers to establish core forecasts beyond LEO
  - Data needed to drive current and future prediction models should have primary and backup support.
- Create international/national SEP forecasting collaborations between/within space agencies
  - Not only at modeler/scientific project level, but at space agency operations/implementation level\Lay the groundwork for Artemis (international human missions) by developing forecast tools now that can be tested during ISS operations and initial Artemis missions, before longer Artemis missions take place
- Build the foundation for human Mars missions by collaborating on space weather architectures that could be possibly flown on manned vehicles to provide input data for forecast models at locations away from Sun-Earth
  - HERMES and ERSA on Gateway - PPE are big step in this direction.