ASSESSMENT OF SEP IMPACT FOR HUMAN EXPLORATION

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PURPOSE

WHAT IS THE PURPOSE HERE?

1. Why do we need data streams?
   → Historical answer: We need eyes on the scene because adverse Space Weather impacts the crew, primarily Solar Energetic Proton (SEP) events.
      → This answer is not good enough.
   → **Real-time data streams are needed to drive forecasting and maintain situational awareness which, coupled with sheltering-in-place, will minimize dose to the human-vehicle system while optimizing and protecting the operational mission timeline.**
   → But, should be driven by quantified impact and how the data will be used.
   → Storm shelter requirements with IPs being developed for Exo-LEO missions. Will protect against 'worst-case' SEPs once on-board instrumentation alerts crew to SEP arrival. Data streams and forecasting will direct storm shelter use and protect critical elements of mission timeline.
2. What follows is a quantified impact assessment.

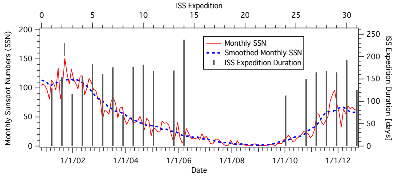
TECHNICAL STRATEGY

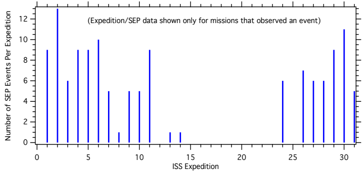
HOW CAN WE ASSESS IMPACT?

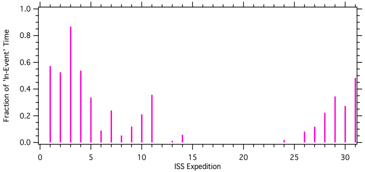
- Largest impact is 'free-space', not on ISS, i.e. missions outside of LEO.
- Have a wealth of instrument data of radiation dose on ISS, some of this pertains to space weather effects (SEPs).
  - But, times of adverse space weather impact on ISS is limited to short time frames (upper latitude passes) and thus relatively low cumulative dose.
- We have 'free-space' particle fluxes in real-time.
- We have 'free-space' particle fluxes over ISS Expedition time frames.
  - Using these fluxes to model the dose effectively moves ISS to free-space.
- Model SEP dose on ISS and thinner shielded vehicle models using measured free-space flux and compare with measured ISS SEP dose.
  - **Will yield a quantified impact of cumulative SEP dose for exo-LEO missions relative to missions that have been conducted in LEO under established processes for radiation mission operations.**

SEP CHARACTERISTICS DURING EXPEDITION TIME FRAME

- → Number of SEPs per expedition ranges from zero (solar minimum), to 13 for Expedition 2 (near solar maximum for cycle 23). (Total of 133 events.)
- → The 'in-event' time defined as the fraction of cumulative time SEP > 10 MeV fluence was above background levels to the total expedition time.
- → The highest in-event time was 87% - Expedition 3 (mid-2001 to 2002, solar max for cycle 23).
- → Operational impacts increase with increasing in-event time. (Discussed further in following charts.)

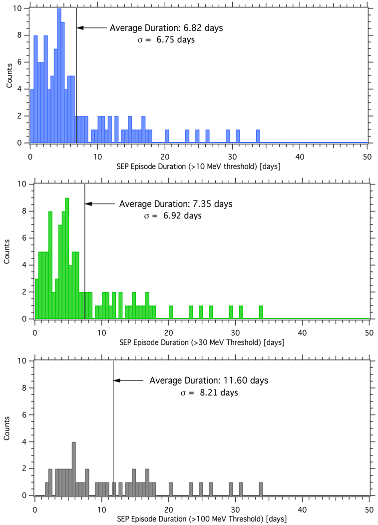






SEP DURATIONS AS A FUNCTION OF ENERGY THRESHOLD

- → To assist in understanding SEP dose relative to 30-day thresholds one can look at duration.
- → Well-known that time profile varies with proton energy.
- → Calculate event duration only for events that have non-zero fluence at a given energy above a threshold value.
- → Going to higher threshold corresponds to filtering out less energetic (and often less intense) events.
  - → As a result the average duration increases.
- → All long-duration events are typically also energetic events.



COMPARISON WITH 30-DAY LIMIT

- Two over-arching risk-mitigation perspectives for Ops: (1) ALARA (2) NCRP 30-Day limits (distinct for skin, eye and BFO).
- Calculations here are point doses. Although they don't take into account body self-shielding explicitly, self-shielding represents only about 5 g/cm^2 of additional shielding thickness.
  - Small contribution for thickly-shielded vehicles (ISS, DSH, SM).
  - Larger effect for thinly-shielded vehicles (CEV). However, 70$\%$ of CEV vehicle thickness is greater than 5 g/cm^2.
  - To compare directly to ISS instrument response, self-shielding is not included.
- To assess a mission greater than 30 days in duration and compare to 30-day limit we have to assess the contribution from individual SEP events.
  - All SEP events over ISS Expedition time frame (2000-2012) are $\lesssim 30$ days.

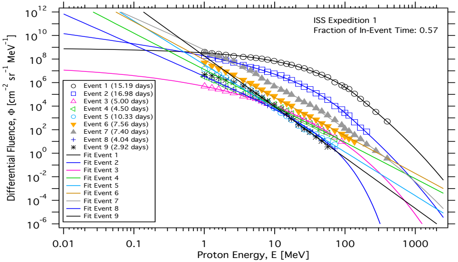
RESULTS

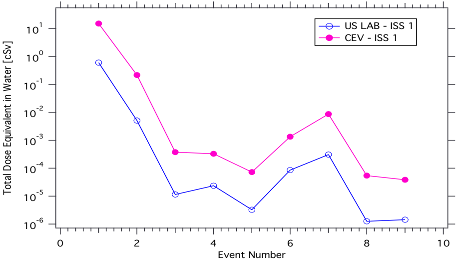
INDIVIDUAL EVENT DOSE: EXPEDITION 1

→ Large dispersion in event dose.

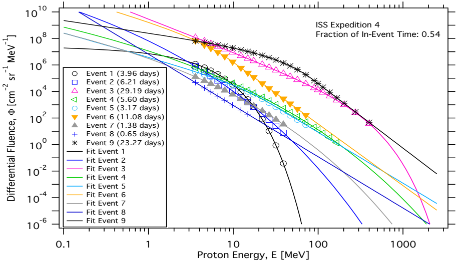
→ Ratio of CEV to USLAB dose relatively constant.

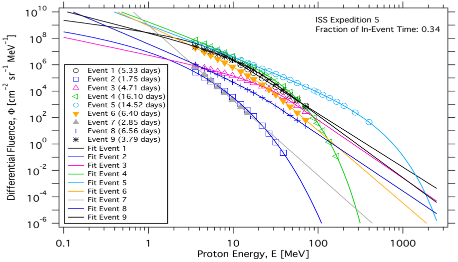
→ Largest doses correspond to large-fluence events with durations on the order of weeks to one month.

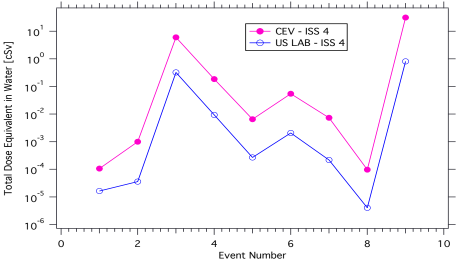


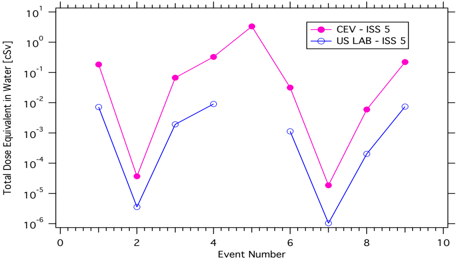


INDIVIDUAL EVENT DOSE: EXPEDITIONS 4 AND 5

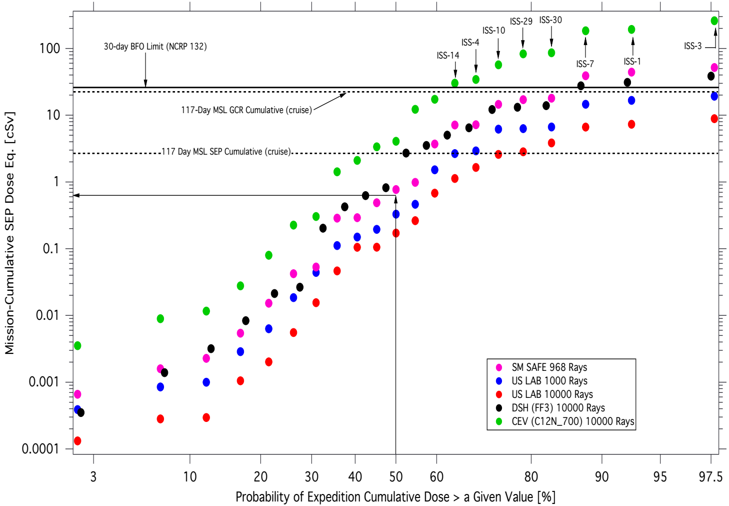








DOSE EQUIVALENT FOR ISS EXPEDITIONS



COMPARISON WITH TEPC MEASUREMENTS ON ISS IN LEO

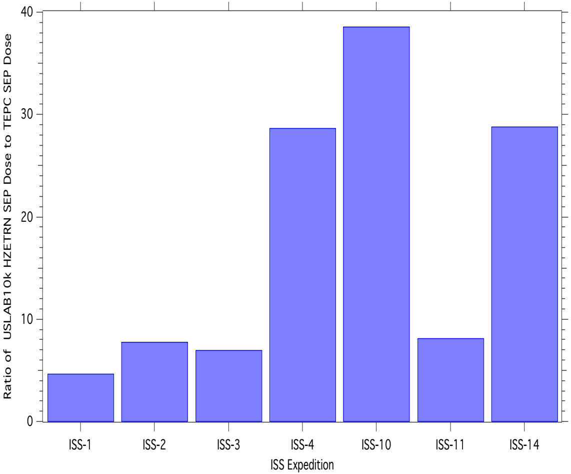
→ Use ISS measurements in LEO (via TEPC instrument) to compare to 'free-space' modeling with US LAB.

→ Yields an estimate of SEP event instrument response for scenarios such as transit to Mars.

→ Expeditions 4, 10 and 11 have the highest estimated ratios of free-space to LEO TEPC response.

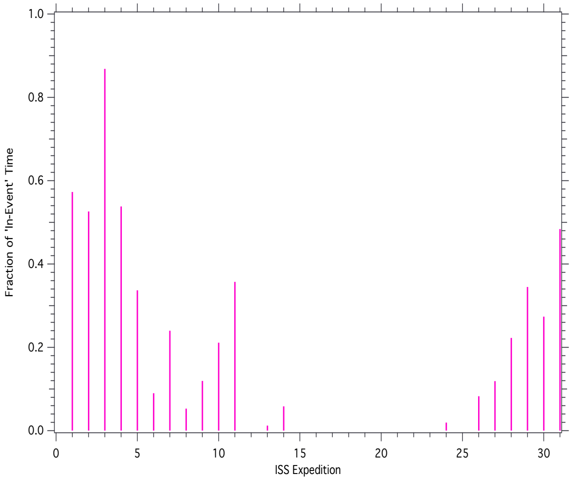
→ Ratio is relative and depends on how well ISS was 'phased' with high latitude regions.

  → Represents a lower bound. Could be much larger response with thinly-shielded vehicle.



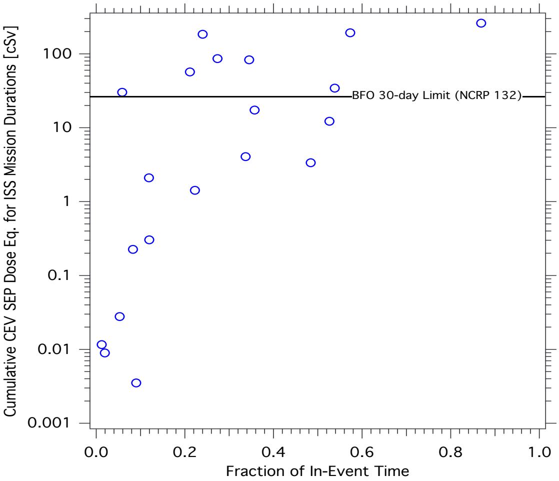
OPERATIONAL TIMELINE IMPACTS

- → In-event time corresponds to time that SEP impact is part of operational decision tree.
- → 18% on average with a standard deviation of 22%.
- → However, there were 5 Expeditions where more than half of the mission time was impacted by having to react in real-time to SEP events.
- → This is particularly disrupting to operational activities that are time critical.



OPERATIONAL TIMELINE IMPACTS: PART 2

- → For lower doses (<10 cSv) cumulative dose equivalent increases with in-event time.
- → Largest cumulative dose equivalent calculated correspondeds to almost a 116-day mission where the proton flux was elevated almost more than 80% of the mission - large operational impact.
- → Without a storm shelter and operational strategies for using it (data streams and subsequent forecasting capability) may be challenging to maintain ALARA and 30-day limit over a wide range of in-event times (10% to $> 80\%$).
- → Now couple this with how dose trend correlates with mean-event time (next slide).

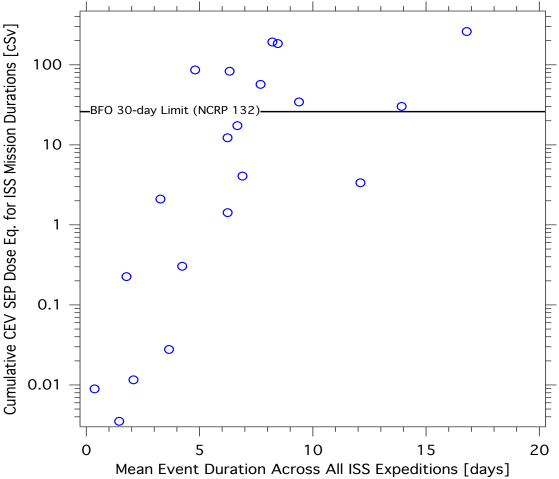


OPERATIONAL TIMELINE IMPACTS: PART 3

→ Mean event time is average event duration over a single Expedition.

→ Expeditions with large doses correspond to mean event durations ranging from roughly 1 to 3 weeks.

→ Take home here is that although the largest doses over an expedition correspond to time windows on the order of 30-days, **the multitude of periods of elevated flux over any given Expedition, without the capability to forecast duration, peak flux, etc, can lead to 'reacting' to these conditions over a relatively large fraction of the entire mission duration.**



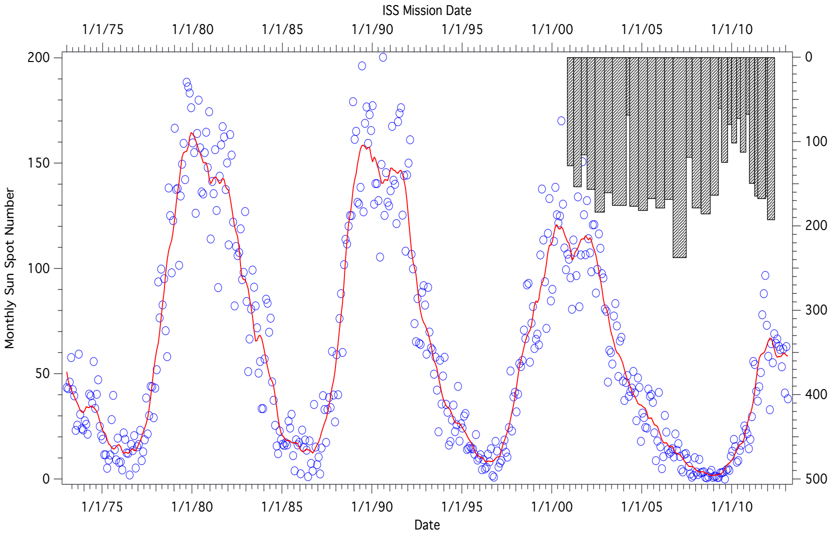
CONCLUSION

CONCLUSIONS

- → Appears that single large episodes dominate the expedition dose and each falls within a 30-day window.
- → Fraction of mission time responding to elevated flux over the course of any single expedition can be quite large (see as high as 87%). Forecasting capability needed.
- → SEP dose equivalent results indicate ISS instrument response would be a minimum of a factor of 40 times greater if ISS was located in free-space than in LEO.
- → All results indicate SEP events can have a large impact on operations for missions beyond LEO. Real-time data relevant to forecasting model input is needed to mitigate operational impacts and optimize storm shelter use to minimize exposure and increase number of mission-safe days.
- → Moreover, we can't focus just on the human but rather the human-vehicle system. Forecasting capability is needed for informing flight control teams when to power down critical systems.
- → Forecasting SEP onset, peak flux and time profile on a 24-hour to 72-hour window needed to mitigate operational impacts.

BACKUP

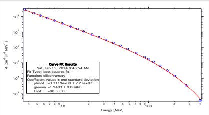
EXPEDITION TIMING WITH SOLAR CYCLE



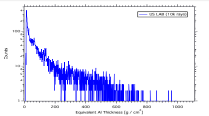
ASSESSMENT STRATEGY

Numerically fit spectra for each ISS Expedition from 1 through 32

SEP Spectrum



Vehicle Shielding Distribution



5 Different vehicle shielding distributions that differ by at least an order of magnitude in mean thickness

Radiation Transport

HZETRN 2010

Simulate ISS TEPC active volume to compare LEO to 'Free-Space'

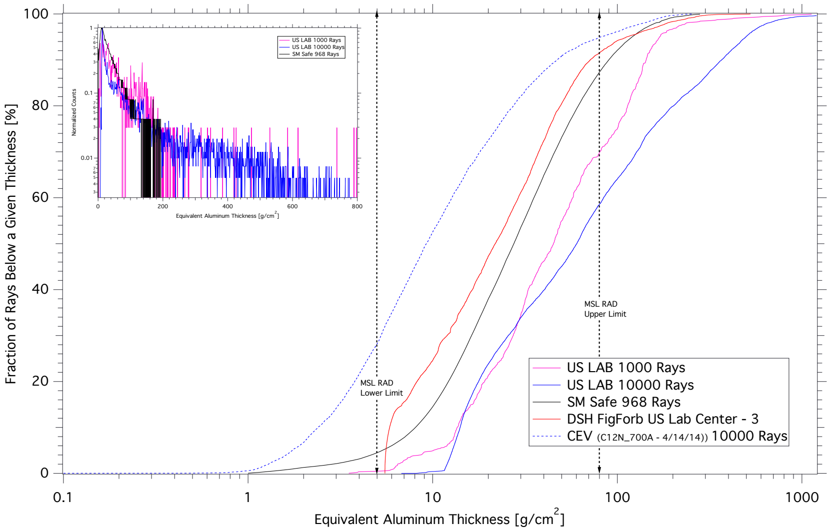
Output

- Dose
- Dose Equivalent
- Compare calculated values to measured values in LEO (TEPC)

Iterate for all permutations of input spectrum and shielding distributions

- Each run for a single input spectrum and shield distribution is roughly 200 minutes of computation time.
- 20 input spectra and 5 shielding distributions
- Must run each twice to get both dose and dose equivalent
- 200 total runs: 4000 minutes of computation time (27.8 days)

VEHICLE SHIELDING DISTRIBUTIONS



CUMULATIVE DIFFERENTIAL FLUENCE INPUT SPECTRA

- → Cumulative differential fluence spectra fit with various functional forms.
  - → Power-law
  - → Weibull
  - → Ellison-Ramaty
  - → Band
- → Choose function that yields the lowest χ^2.