The Probability of False Go/No-Go Determined by GOES Proton Flux: Proposed Launch Constraints for Avoiding Damaging Solar Energetic Particle Events

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Introduction

The space environment is full of harmful radiation and high energy particles that can cause damage to materials and affect computer systems by e.g., single event effects (SEEs), total ionizing dose (TID), etc. There are three main sources of high energy particles:

- Trapped radiation in Earth's Van Allen belts (electrons and protons)
- Solar energetic particles (SEPs) (protons and heavy ions)
- Galactic cosmic rays (GCRs) (protons and heavy ions)

In this study, we focus on the SEPs and their time series (e.g. Figure 2) and energy spectrum to quantify probabilities of launch go/no-go.

The SEPs originate from solar particle events (SPEs) that are associated with a solar flare and/or a coronal mass ejection (CME). These events are difficult to predict. Recent work has been done on these prediction techniques (e.g. for solar flares, Chang Liu et al 2017).

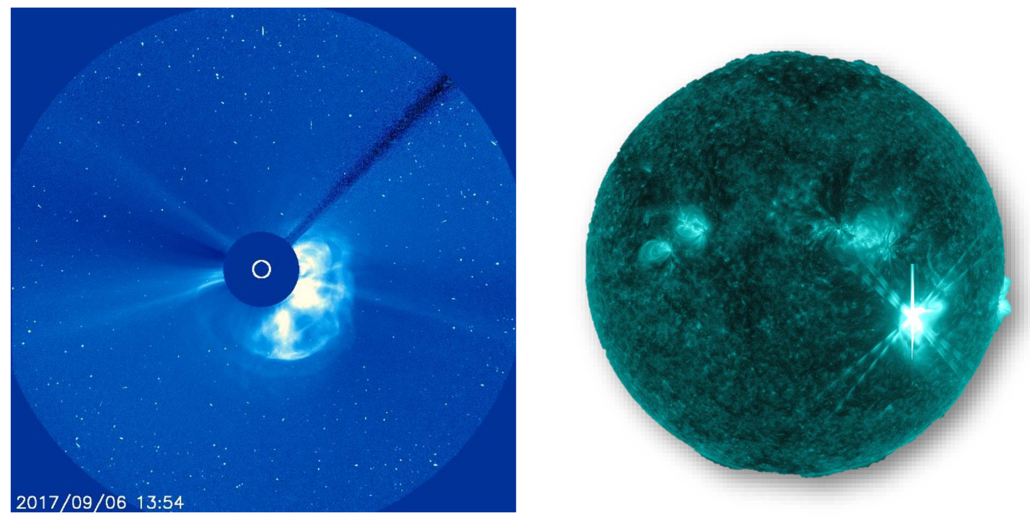

Figure 1: Left, SOHO/LASCO example of CME. Right, SDO/AIA 131Å example of solar flare.

The Geostationary Operational Environmental Satellite (GOES) has been observing SEPs for decades. The > 10 MeV proton flux is shown in Figure 2 since 1986. The SEPs are influenced by the 11-year solar cycle and typically come from active regions on the Sun. These active regions, if strong enough, have associated sunspots that follow the solar cycle (Figure 3). Past solar maximums occurred during 1989, 2001, and 2014.

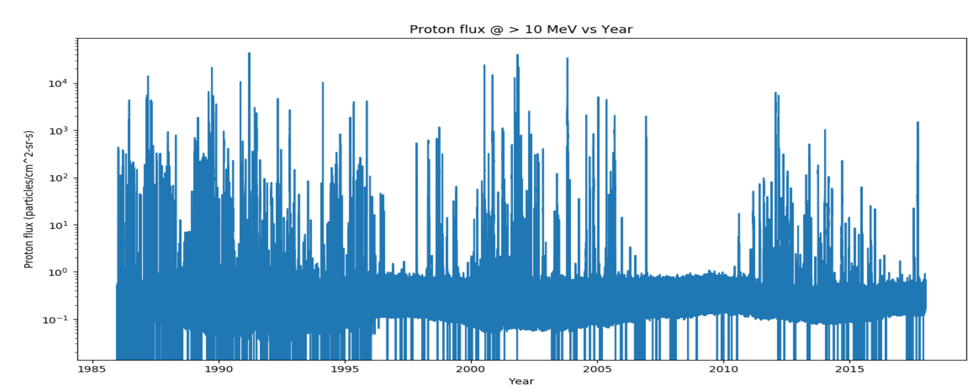

Figure 2: Maximum integral proton flux of available GOES systems in orbit from 1986 to 2017.

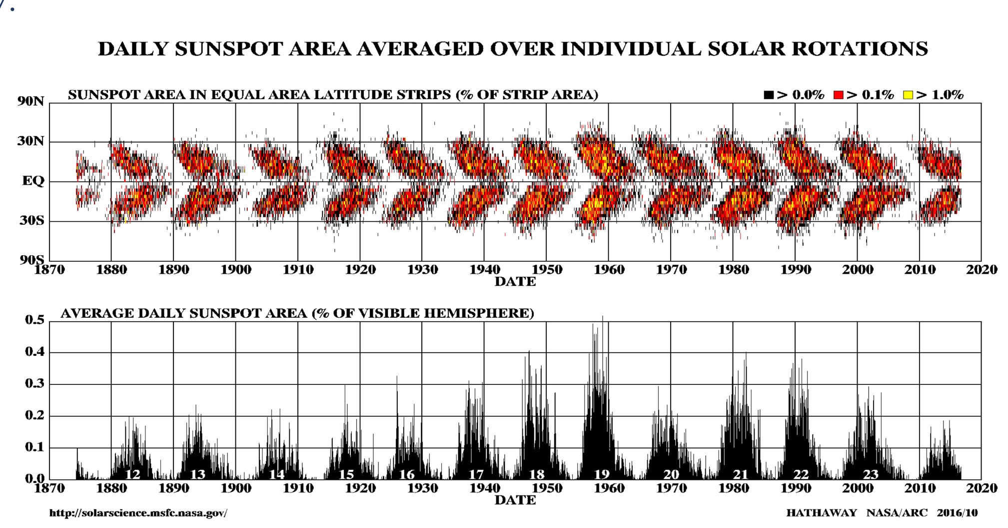

Figure 3: The butterfly diagram of sunspots showing the 11 year average solar cycle from observations from over a century ago.

Most hardware used in space applications are not sensitive to linear energy transfer (LET) values of less than 1 MeV*cm²/mg. Therefore, as shown in Figure 4, important elements that can contribute damage to hardware are helium to iron.

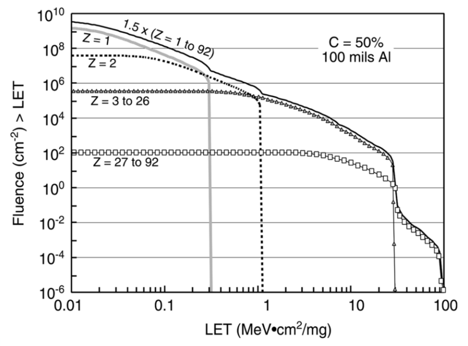

Figure 4: Fluence vs LET through 100 mils of aluminum shielding (Xapsos 2007).

Methodology

To compute the probability of false/true go/no-go, we use the binary classification tests of sensitivity and specificity. In short, we want to answer the following questions:

A. Was the flight constraint violated prior to launch?

B. Was the design environment exceeded during the mission?

We generate a test launch time for each data point in the GOES proton flux dataset, amounting to 3,365,281 separate launch times. For each launch time, we count the number of true positives, false negatives, false positives, and true negatives in order to calculate the probability of false go/no-go launches.

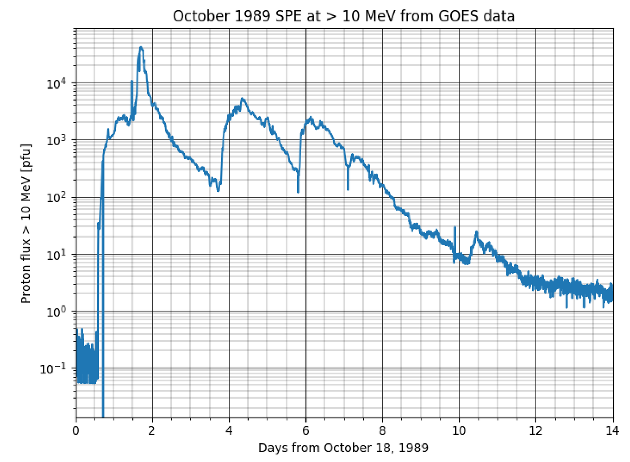

Figure 5: Proton flux at energies > 10 MeV during the infamous October 1989 SPE.

	B	not B
A	True Positive	False Positive
not A	False Negative	True Negative

- **Probability of false Go** = false negative / total cases
- **Probability of false No-Go** = false positive / total cases

Ground Rules and Assumptions

1. The GOES proton fluxes can be used as a proxy for the solar heavy ion fluxes. (There are no live data streams of heavy ion observations, but there is for proton fluxes.)
2. The GOES data from 1986-2017 is representative of the activity of the Sun over the solar cycle.
3. The launch constraint is considered violated if, in the last 15 minutes before launch, the proton flux exceeds the launch constraint at least once.
4. The hardware environment is considered violated if the proton flux exceeds the hardware environment at least once during the mission time.

The GOES/EPS/SEISS proton data and ACE/SIS (Stone et al. 1998) heavy ion data were compared. For each species from the SIS instrument, the fluxes were summed to create an integral flux. Figure 6 shows the qualitative agreement between the proton fluxes and heavy ion fluxes. We found that the > 10 MeV proton fluxes correlated better with the heavy ion fluxes than the > 50 MeV protons did.

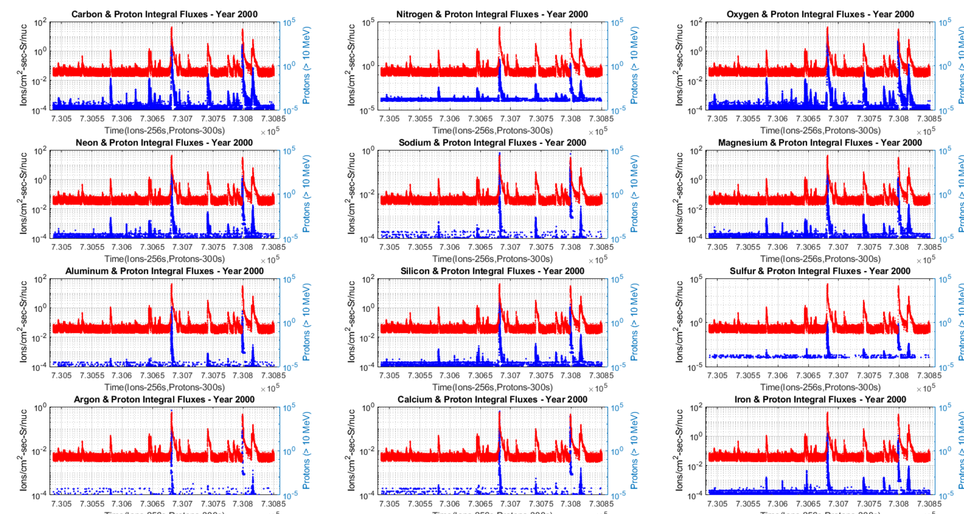

Figure 6: Comparison of GOES proton fluxes with ACE/SIS heavy ion fluxes for species that include carbon, nitrogen, oxygen, neon, sodium, magnesium, aluminum, silicon, sulfur, argon, calcium, and iron (helium and nickel are excluded here).

Results

Using the GOES proton flux database as a function of time and integral energy channel, the four parameters varied in this analysis were:

(note, pfu = particle flux unit = particle/cm²-s-sr)

- **Launch constraint** $\in [10, 1000]$ pfu
- **Hardware design environment** $\in [10, 1000]$ pfu
- **Mission length** $\in [15\ minutes, 1\ day]$
- **Proton integral energy channel** $\in [> 10\ MeV, > 100\ MeV]$

Below we show the parameter search exhibiting the dependencies of the launch constraint, design environment, and integral energy channel on the probabilities of false go/no-go. We chose 8 hours for the mission time in all panels in Figure 7, however we checked the results for the full mission length range defined above. In general, the probability of false go is proportional to the mission time. The probability of false no-go has an inverse power law with respect to mission length.

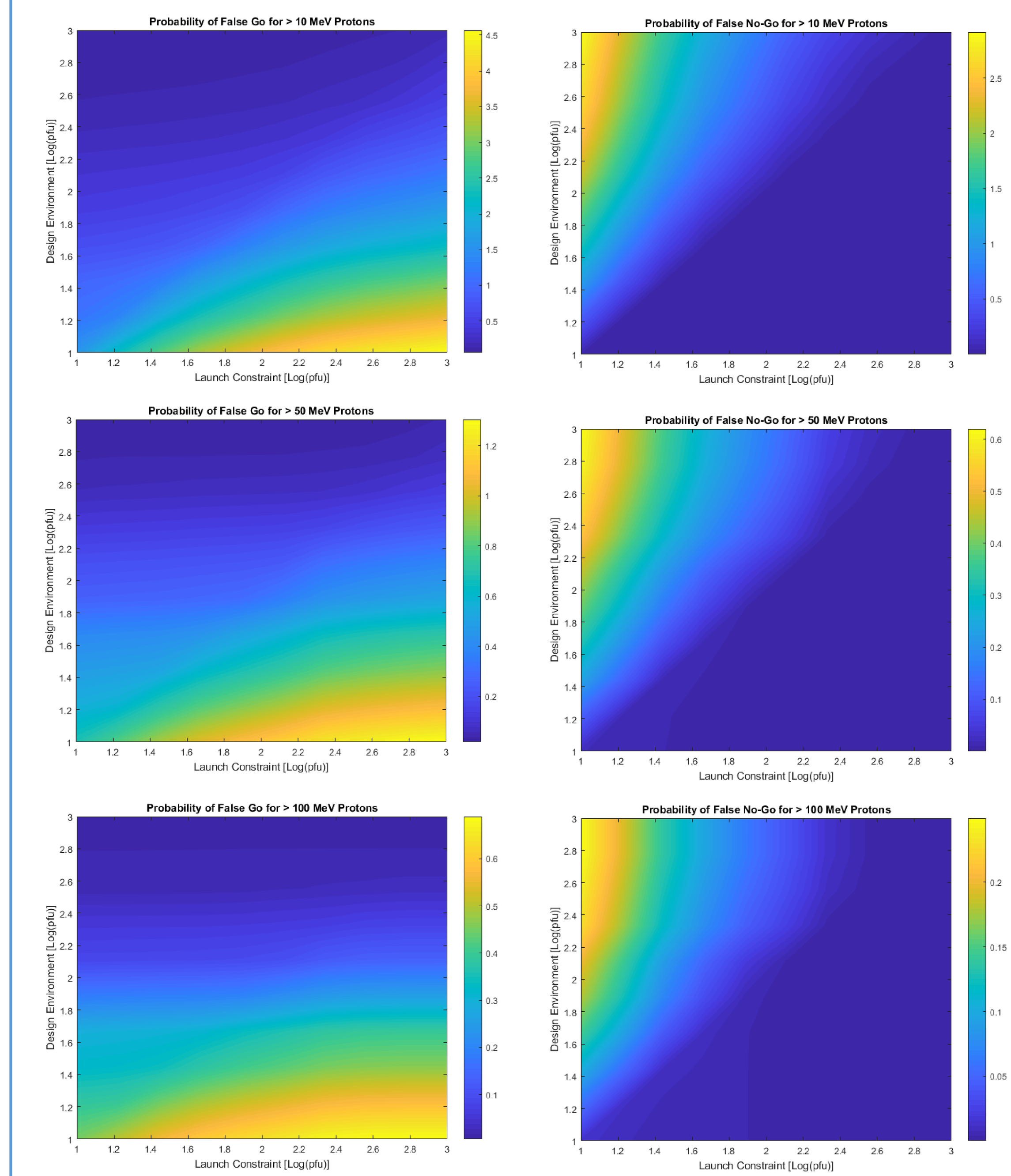

Figure 7: The probability, in percent, of false go/no-go as a function of design environment, launch constraint, and integral energy channel. Left column, probability of false go. Right column, probability of false no-go. First row, > 10 MeV protons. Second row, > 50 MeV protons. Third row, > 100 MeV protons.

There are three ways to try to optimize the probabilities shown above in Figure 6. We could either choose:

- To minimize the false go probabilities only
- To minimize the false no-go probabilities only
- To minimize both

The first two cases are the most straight forward. We would either want to have a greater design environment and lower launch constraint, or to have a lower design environment and high launch constraint, respectively. In the third case, the balance will depend on any modifying factors when bringing the two percentages together. If there is no bias towards minimizing the false go over the false no-go, then we would want to use a launch constraint threshold that follows closely to the design environment threshold.

Conclusions

Space hardware, if not designed properly, can be vulnerable to SPEs, specifically the heavy ion species. Since there are no live data streams of heavy ion fluxes at this time, we need to use a proxy that is live. The GOES proton fluxes are updated every 5 minutes and can be used as an operational method for a launch constraint. We have shown, qualitatively, that the GOES proton integral fluxes correlate with the ACE/SIS heavy ion integral fluxes. Therefore, we infer the assumption that the proton fluxes are a useful proxy for the heavy ion fluxes is valid.

The trends that we found in the parameter analysis were as follows.

<u>The probability of false go</u>:

- Approximately **linearly proportional** to mission length
- For **higher** launch constraint and **lower** design environment, the probability of false go is **higher**
- For **lower** launch constraint and **higher** design environment, the probability of false go is **lower**
- For **increasing** integral energy, there is a **lower** probability of false go overall
- For **increasing** integral energy, there is a **weaker** dependence on the launch constraint

<u>The probability of false no-go:</u>

- Approximately, there is an **inverse power law** with respect to mission length and the dependence becomes **weaker** for **higher** design environments
- For **higher** launch constraint and **lower** design environment, the probability of false no-go is **lower**
- For **lower** launch constraint and **higher** design environment, the probability of false no-go is **higher**
- For **increasing** integral energy, there is a **lower** probability of false go overall

In planning for a launch constraint, many other factors should be considered. Some of these factors may include:

- The cost of scrubbing or delaying a launch due to a violation of a space weather launch constraint
- The affect of launch availability for a given launch constraint on a specific mission
- The risk of encountering an environment that exceeds the design specifications (i.e., what are the impacts on loss of crew and/or loss of mission?)
- The costs for designing hardware to a higher specification level

GOES 16 and 17 both have a heavy ion sensor that can measure ions up to Z = 28 in the energy range 10-100 MeV/nucleon. However, calibration has not been finished yet. These instruments will be vital in defining a better launch constraint for hardware that is susceptible to heavy ion effects in terms of LET and SEEs.

References

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