EOVSA
Owens Valley Solar Array

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Space Weather Impacts of Solar Radio Bursts

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Solar Radio Burst (SRB) Benchmarks

- **Motivation**
  - Four examples
  - Global-scale effects with no warning
  - Spotty historical record
  - Unknown emission mechanism
- **Benchmarks Challenge**
  - Phase 1 Benchmarks
  - Improving knowledge of emission mechanism
  - Improving monitoring
  - Phase 2 Next Steps

Example 1—The May 1967 Great Storm and the Cold War

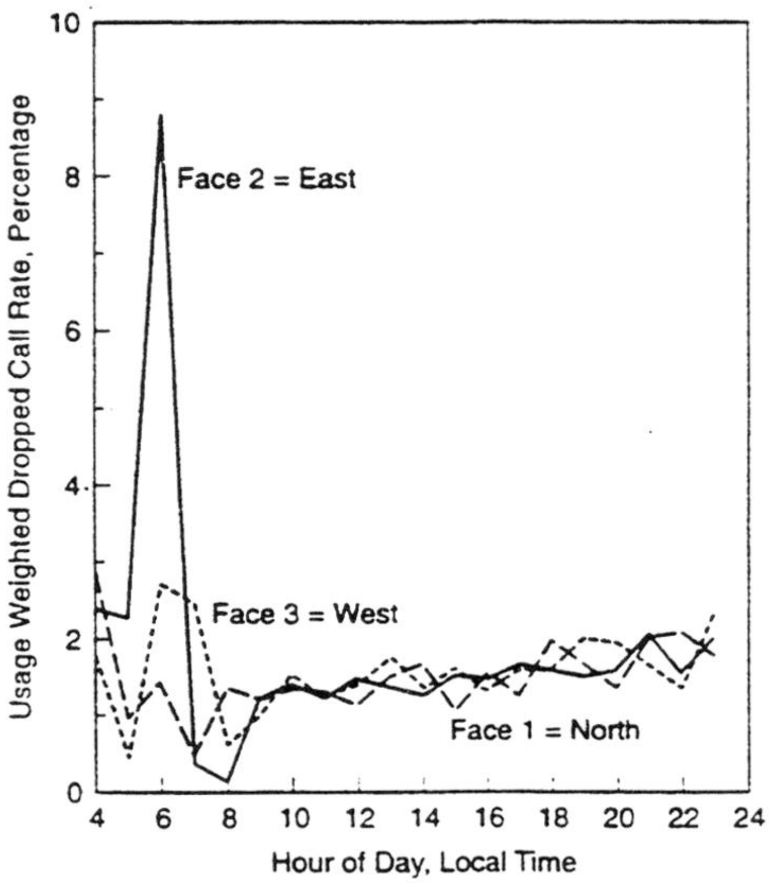
Reported by Knipp et al. (2016) Space Weather Journal

- Direct interference of 1967 May 23 SRB on U. S. Department of Defense (DOD) Ballistic Missile Early Warning System (BMEWS) radars—interpreted as jamming.
  - Affected all three newly constructed radars simultaneously (Alaska, Greenland, England).
  - Thule, Greenland was particularly well aligned with the Sun.
- Response of the Strategic Air Command (SAC) and North American Air Defense Command (NORAD) to the disturbance.
  - Knipp et al. (2016): "Cold War military commanders viewed full scale jamming of surveillance radars as a potential act of war."
  - Citrone (1995): Air Weather Service "notified NORAD in real time of the event and [its potential] impacts," but "outside agencies made uninformed decisions without considering the drastic impacts the event imparted to NORAD's early warning system."
  - Knipp et al. (2016): "during the politically tense days of late May 1967 a full out aircraft launch by western forces could have been very provocative and, just as importantly, difficult to recall in the greatly challenged HF-UHF radio environment."

Example 2—Reported Impact on a Cellular Telephone System

Reported by Lanzerotti et al. (1999)

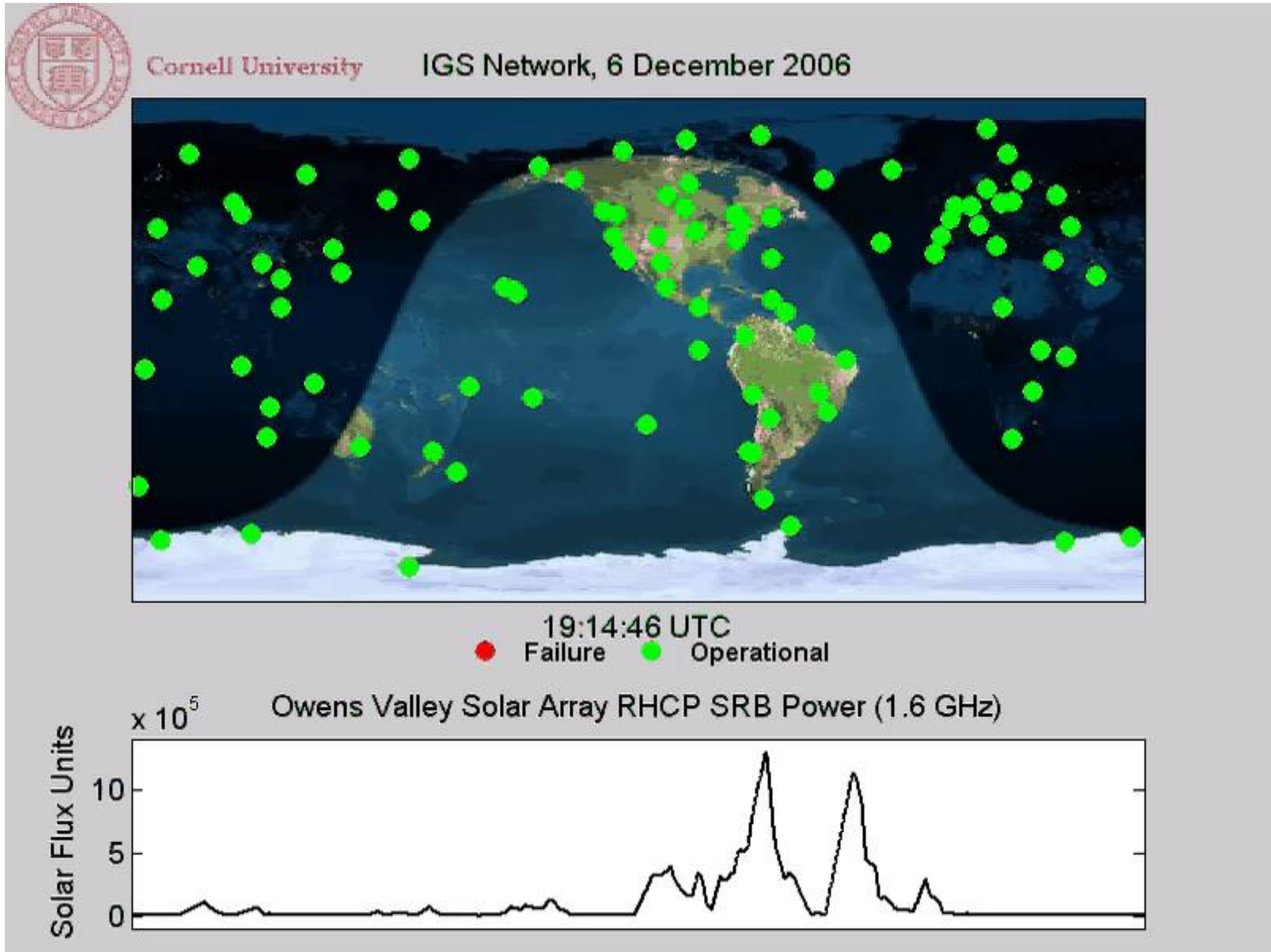
- Cellular telephone companies are highly guarded about performance data to protect their commercial interests.
- Only published report of a direct impact on a cellular telephone system that can be plausibly associated with a solar flare is that of Lanzerotti et al. (1999).
- That paper reports an incident where an east-facing antenna of a cellular base station experienced an enhanced number of dropped calls relative to antennas facing other directions, at a time when the Sun was flaring near local sunrise.
- Attempts have been made to extend the study of this phenomenon by seeking additional data from cell-phone companies, but to date these have been unsuccessful.



Example 3—World-Wide Failure of the Global Positioning System

Reported by Cerruti et al. (2008)

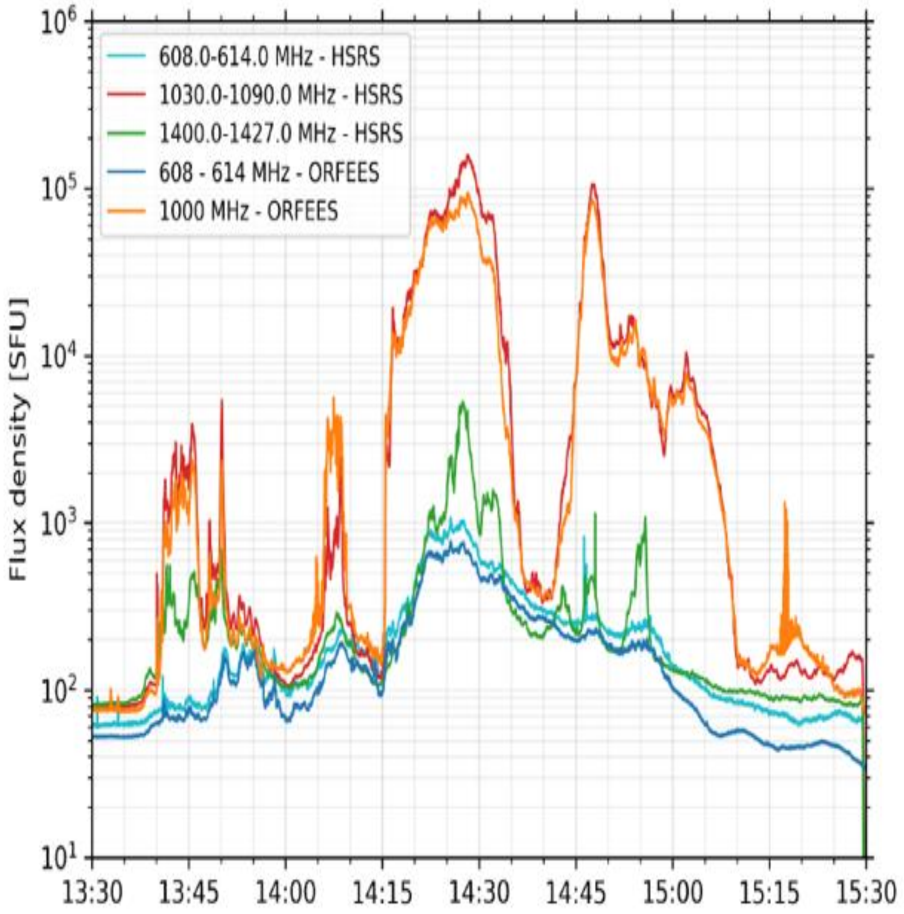
- An SRB on 2006 December 06 (near solar minimum) reached > 1 million sfu.
- Observed in great detail with the Owens Valley Solar Array and a new testbed instrument, it was seen to be:
  - Strong at all GPS frequencies
  - Polarized in the same sense as GPS (RCP)
- The outage was instantaneous and simultaneous over the entire network of IGS and CORS receiver networks, and lasted more than 10 minutes.



Example 4—Regional Effects on Air Traffic Control Radar

Reported by Marqué et al. (2018)

- SRB on 2015 November 04 strongly affected secondary air traffic control radar in Sweden, operating at 1030 and 1090 MHz, and caused milder effects elsewhere in Europe.
- Secondary radar could not display proper information, and caused authorities to reduce air traffic for safety reasons.
- This was a small (M3.7) flare, with modest flux density at typically monitored frequencies, but was two orders of magnitude stronger (> 10^5 sfu) at a relatively narrow band around 1000 MHz.



Lessons Learned

- SRBs affect many different navigation and communication systems.
- The disturbances occur without warning, simultaneously over a large region (over the entire sunlit hemisphere in the case of GPS).
- Events producing high radio noise levels can be modest in other non-radio classifications.
- High radio flux density occurs in relatively narrow frequency ranges, so monitoring a few widely spaced frequencies is not sufficient. Their polarization is not currently monitored, yet that can be essential to gauge effects on some systems such as GPS.
- Comparison of well-calibrated radio measurements with reports from radio monitoring systems shows large discrepancies, so that we do not have good statistics of the occurrence rate of extreme events.

Solar Radio Emission Constraints

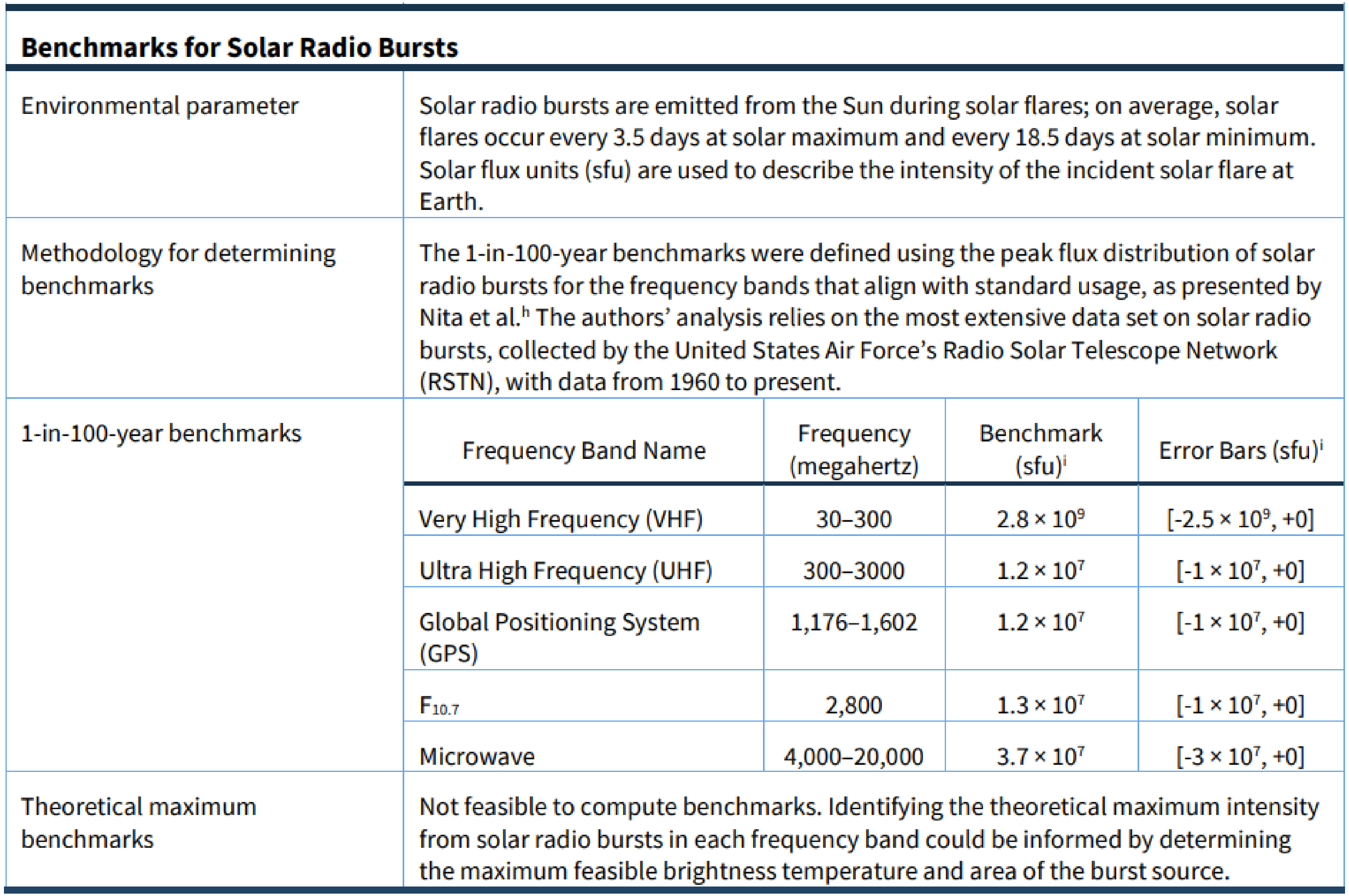
- Space Weather benchmarks call for determining the 100-yr maximum flux density level, as well as a theoretical maximum.
- The flux density is governed by the product of brightness temperature, T_b, and source area solid angle Ω.

$$S_\nu = \frac{2k\nu^2}{c^2}\int_\Omega T_\mathrm{b}\,d\Omega \approx 12\; T_7\; \nu_{\mathrm{GHz}}^2\; L_8^2\ \mathrm{sfu},$$

- To achieve extreme flux densities, both must be large. Normal incoherent processes can have a large area, but only a limited brightness temperature ($\sim 10^{10}$ K).
- Coherent processes, however, can be orders of magnitude brighter, so that even relatively small source areas can produce extreme events.
- We currently do not understand these emission mechanisms, nor what triggers them.

Phase 1 Benchmarks

- 100-yr benchmark of 12 million sfu arrived at by extrapolating event size distributions based on the historical record.
- No theoretical maximum!
- Problems:
  - Historical record is not complete, especially for large events.
  - Extreme events are NOT the same as "normal" events.



<table>
<tr><th colspan="5">Benchmarks for Solar Radio Bursts</th></tr>
<tr><td>Environmental parameter</td><td colspan="4">Solar radio bursts are emitted from the Sun during solar flares; on average, solar flares occur every 3.5 days at solar maximum and every 18.5 days at solar minimum. Solar flux units (sfu) are used to describe the intensity of the incident solar flare at Earth.</td></tr>
<tr><td>Methodology for determining benchmarks</td><td colspan="4">The 1-in-100-year benchmarks were defined using the peak flux distribution of solar radio bursts for the frequency bands that align with standard usage, as presented by Nita et al.[h] The authors' analysis relies on the most extensive data set on solar radio bursts, collected by the United States Air Force's Radio Solar Telescope Network (RSTN), with data from 1960 to present.</td></tr>
<tr><td rowspan="6">1-in-100-year benchmarks</td><td>Frequency Band Name</td><td>Frequency (megahertz)</td><td>Benchmark (sfu)[i]</td><td>Error Bars (sfu)[i]</td></tr>
<tr><td>Very High Frequency (VHF)</td><td>30–300</td><td>2.8×10^9</td><td>$[-2.5 \times 10^9, +0]$</td></tr>
<tr><td>Ultra High Frequency (UHF)</td><td>300–3000</td><td>1.2×10^7</td><td>$[-1 \times 10^7, +0]$</td></tr>
<tr><td>Global Positioning System (GPS)</td><td>1,176–1,602</td><td>1.2×10^7</td><td>$[-1 \times 10^7, +0]$</td></tr>
<tr><td>$F_{10.7}$</td><td>2,800</td><td>1.3×10^7</td><td>$[-1 \times 10^7, +0]$</td></tr>
<tr><td>Microwave</td><td>4,000–20,000</td><td>3.7×10^7</td><td>$[-3 \times 10^7, +0]$</td></tr>
<tr><td>Theoretical maximum benchmarks</td><td colspan="4">Not feasible to compute benchmarks. Identifying the theoretical maximum intensity from solar radio bursts in each frequency band could be informed by determining the maximum feasible brightness temperature and area of the burst source.</td></tr>
</table>

Phase 2 "Next Steps" Activities

- We want to hear of new research since the Phase 1 benchmarks were released that bears on our ability to improve these numbers.
- Our focus will be on what research and new resources are needed to make progress.
- Some obvious candidates:
  - Basic research combining spatial, spectral, and temporal resolutions sufficient to better understand coherent emission mechanisms, especially what governs their brightness and source area.
  - An improved, world-wide monitoring system with much higher frequency resolution, circular polarization measurement capability, and saturation-free flux density measurement.
- We invite Space Weather Workshop attendees and others to provide information and opinions on the above.

Panel Members and Upcoming Meeting

- Dale Gary (New Jersey Institute of Technology)
- Tim Bastian (National Radio Astronomy Observatory)
- Gregory Fleishman (New Jersey Institute of Technology)
- Jasmine Magdalenic (Royal Observatory of Belgium)
- Jade Morton (University of Colorado)
- Angelos Vourlidas (Johns Hopkin University, APL)
- Stephen White (Air Force Research Lab)

Initial Community Input Workshop:

April 23, 2019 at Sheraton Denver West, Lakewood Colorado.

The End