A GROUND-BASED SURVEILLANCE CAMPAIGN TO DETECT GPS ARCING – FIRST PRELIMINARY POSITIVE RESULTS

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ABSTRACT

Arc-induced contamination of GPS solar arrays has been proposed as an explanation for the power degradation on GPS satellites in excess of that produced by radiation exposure. In addition, GPS arcs have been proposed as one source of spurious signals in the Los Alamos National Laboratory's radiofrequency detectors on GPS satellites. If these hypotheses are correct, it may be possible to detect such arcs from the ground using large radio and optical telescopes. Correlation of these signals with each other and/or the event times in the nuclear detonation detectors would cement both hypotheses.

We present here the first preliminary positive results of a coordinated campaign of large radio and optical telescope observations on tracked GPS satellites. The observations were carried out in October, 2015 with the Arecibo 305 meter and the Long Wavelength Array radiotelescopes and in November, 2015 with the Long Wavelength Array and the 3.5 meter optical telescope at Kirtland Air Force Base's Starfire Optical Range. Correlations will be made between each telescope's output and the measured times and/or rates of undispersed events in the LANL radiofrequency detectors on the GPS satellites being tracked. Also, correlations of the event rates with predictions based on the space environment from AE9/AP9/SPM will be made. Results of these correlations will be presented for the data analyzed so far. Implications of these measurements for the arc strengths and contamination of GPS spacecraft arcing will be discussed, as will implications for arc rates and effects on other satellites.

1. INTRODUCTION

Ferguson et al ([1], 2016) made a case for the excess power degradation (beyond that due to radiation) on GPS satellites being the result of arcs on the solar arrays contaminating the coverglasses. The Los Alamos National Laboratory (LANL) radiofrequency detectors on-board GPS satellites have seen many transient (undispersed) events that are correlated with the space environment [1].

Attempts were made in 2014 to detect these arcs using a ground-based radio array (the Long Wavelength Array, LWA1) and an optical telescope (at the Magdalena Ridge Observatory, MRO) near Socorro, New Mexico. Although these attempts were unsuccessful, observational difficulties made another attempt seem worthwhile. Consequently, in addition to LWA1, coordinated observations were made of several GPS satellites with a 3.5 m optical telescope at the Kirtland Air Force Base Starfire Optical Range and the Arecibo 305 m radiotelescope at Arecibo, Puerto Rico. The Arecibo-LWA1 observations were done in October, 2015, and the Starfire-LWA1 observations in November. In addition, LANL on-board event times and rates were obtained [2]. While analysis continues, we present here a first look at some of the data.

2. PRELIMINARY OCTOBER LANL RESULTS

Undispersed event times from LANL detectors on one GPS satellite and rates from another on October 17-23, 2015 were obtained by one of us (LANL's David Suszcynsky).

The strategy followed in analysing the event times here is the same as that in [1]. Absolute event times in GPST (GPS Time = UT+17 seconds) were binned by hour to obtain hourly rates. Because the exact times and numerical rates are classified, no numbers are given here. Fig. 1 shows the average normalized rates versus GPST for the 6 dates. Also shown are the 10 keV electron fluxes from the AE9/AP9/SPM model, with a moving average to simulate charge conduction through the solar array coverglasses (see [1] for details).

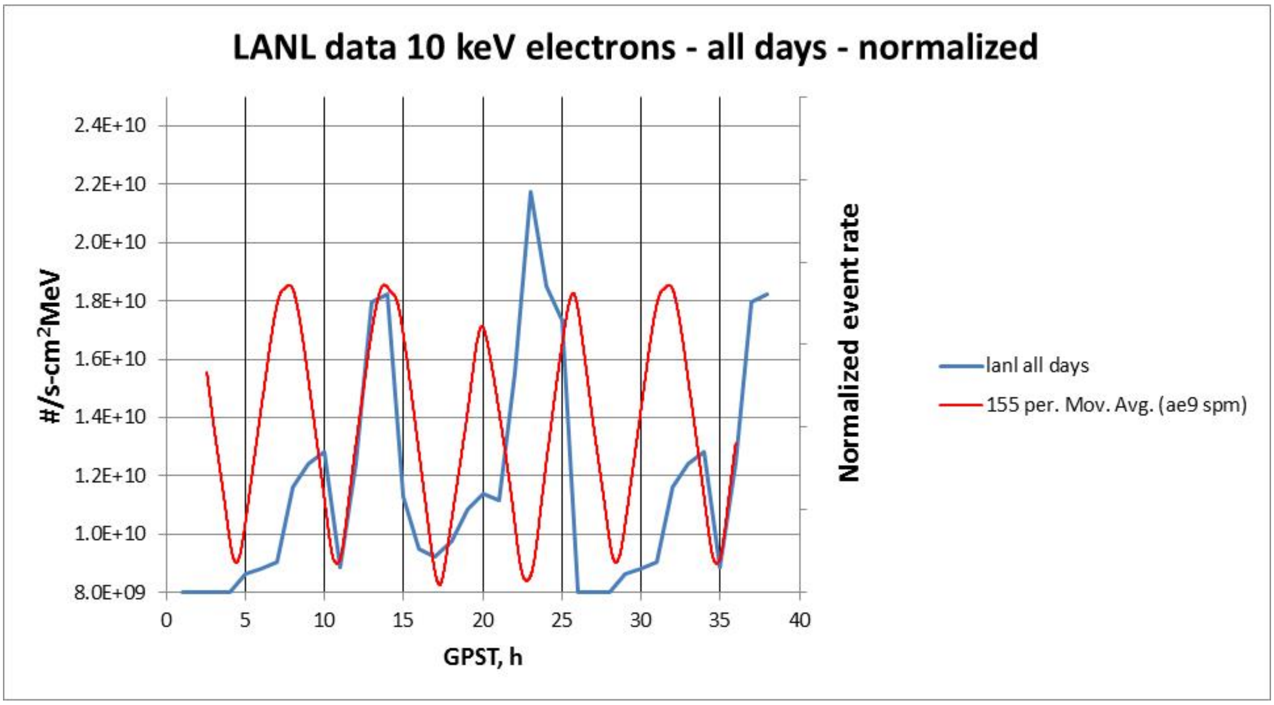

Figure 1. Average LANL data and 155 period moving average of the 10 keV electron flux from the AE9/AP9/SPM model. Although all electrons of energy > 9 keV contribute to charging [2], only the 10 keV fluxes are shown here, as the > 10 keV fluxes show the same phasing.

As was seen before in the 2014 data for a different satellite, the LANL events show a four-peaked structure, and the AE9/A9/SPM fluxes mimic well the times of the four peaks and valleys, except that peak 1 comes late and peak 4 comes early. Deviations from a perfect fit may be caused by local time flux variations not accounted for by the model. All days showed essentially the same time and flux behaviour. As explained in [1], this strong daily time variation would not be produced by electron fluxes (energy > 200 keV) appropriate for deep dielectric charging. Fluxes at energies > 30 keV also don't show the deep minima seen in the data.

It should be noted here that the conduction time found for these dates (155 min) is similar to that (160 min) found in [1], and the bulk resistivity implied is similar to that of coverglasses found in [1]. Thus, surface charging of coverglasses is implicated.

3. PRELIMINARY OCTOBER ARECIBO RESULTS

From UT October 19-22, 2015, radio observations were made of GPS satellites with the Gordon 305 m radiotelescope at the National Astronomy and Ionosphere Center in Arecibo, Puerto Rico. Because the field of view of the telescope is limited to about 20 degrees from the zenith, only one GPS satellite was well placed on the observing dates. On UT 10/21/2015 simultaneous observations of this satellite were also made with the LWA1 array near Socorro, New Mexico. The observations are still being reduced, but there were some intriguing positive aspects to the Arecibo observations. We restrict ourselves here to the Arecibo observations obtained from 01:38 to 01:54 UT on 10/22/2015.

Two radio beams were obtained, one (on-source) centered at 327 MHz and the other (off-source) centered at 432 MHz. The on-source beam was obtained by the dome receiver, and the off-source was obtained by the carriage house receiver pointed opposite 8.8 degrees from the zenith. Tracking of the GPS satellite was done with an accurate ephemeris, and pointing was updated every second and checked on one day by tracking with a receiver tuned to the GPS broadcast frequency. The 327 MHz data were mixed to baseband and recorded using a 53.3 MHz bandwidth 128 channel mock spectrometer, and a spectrum was obtained every 9.6 microseconds. Later, spectrometer channels that had narrowband noise were subtracted, and the remaining spectrum channels were added to give total power. The bandwidth of the 432 MHz off-source receiver was 2 MHz and total power was recorded every 10 microseconds.

In the data described here, numerous strong spikes of one time resolution interval width were seen at the same times (to within 0.1 second) in both the on-source and off-source receivers. These spikes dominated the total power, so their removal was necessary to look for our "true" signal. While the nature of the spikes is not known, they could easily have been produced by lightning or arcing power lines. The spikes were removed by averaging over any data point more than 3 times the average of adjacent points. When these points were removed, it was clear from visual inspection of one minute of data that many of the on-source data points were far above the system noise level and had roughly the same peak power. Histograms of the total power in both beams are seen in Figs. 2 and 3.

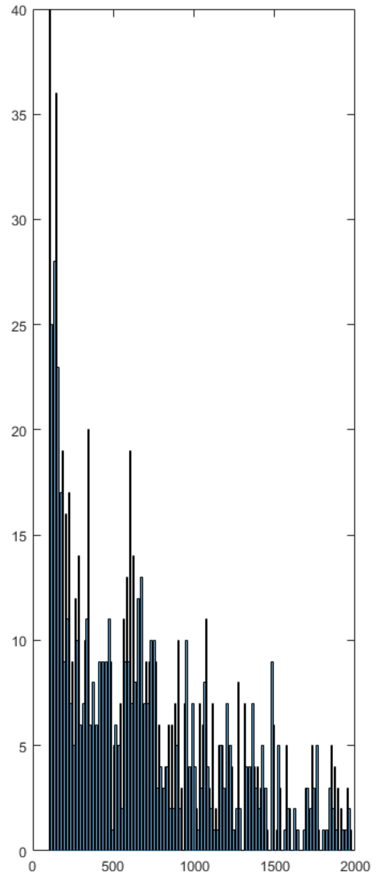

Figure 2. On-source (327 MHz) histogram of total power, arbitrary units. One minute of data ($6x10^6$ points). There is a statistically significant peak at about 650.

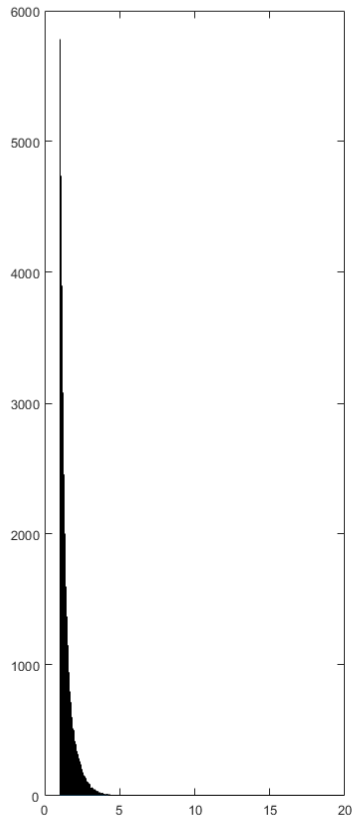

Figure 3. Off-source (430 MHz) histogram of total power, arbitrary units. One minute of data ($6x10^6$ points). There are no statistically significant peaks beyond the base offset. We believe this to be noise.

One way of determining the time width of features is to autocorrelate the data. Then, breakpoints in the autocorrelation function signify feature widths. Autocorrelation functions of the first minute of data are shown in Figs. 4 and 5 for the on- and off-source data streams. The on-source data shows a breakpoint at about 15 lags (144 microseconds), indicating a significant total power feature about 140 microseconds wide. While this is wider than the expected radio arc signal, it corresponds roughly to the time the arc plasma would radiate while crossing a 1.5 meter solar array, assuming a plasma expansion of about 1 cm per microsecond [3].

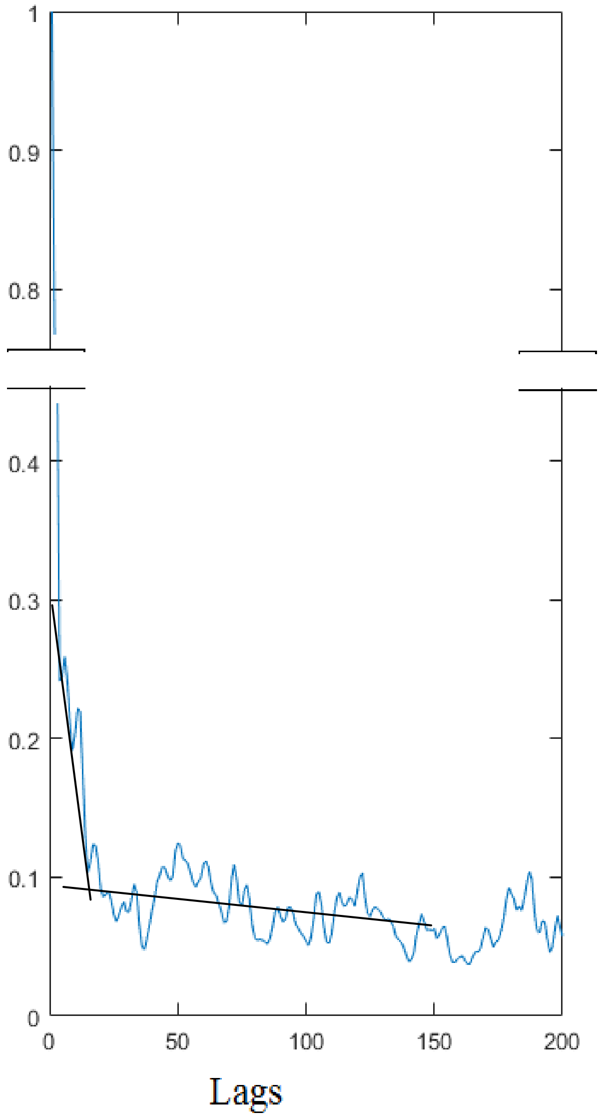

Figure 4. On-source autocorrelation function of total power, first minute of data (6x10^6 points). Breakpoint at about 15 lags (144 microseconds).

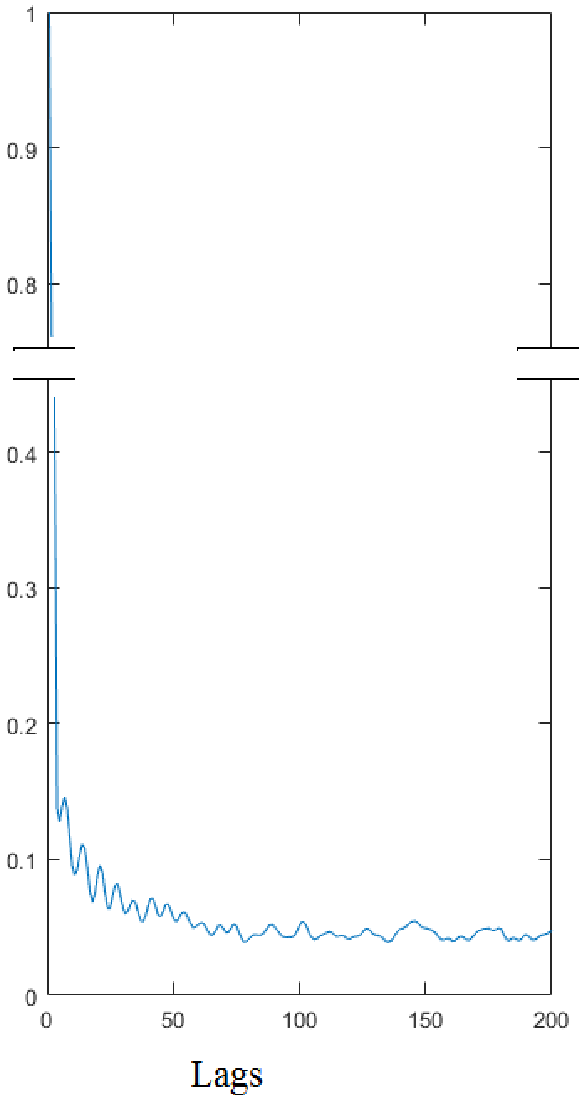

Figure 5. Off-source autocorrelation function of total power, first minute of data (6x10^6 points). No evident breakpoint. Characteristic of noise.

Finally, in Fig. 6 is the on-source time series from which Figs. 2 and 4 were made.

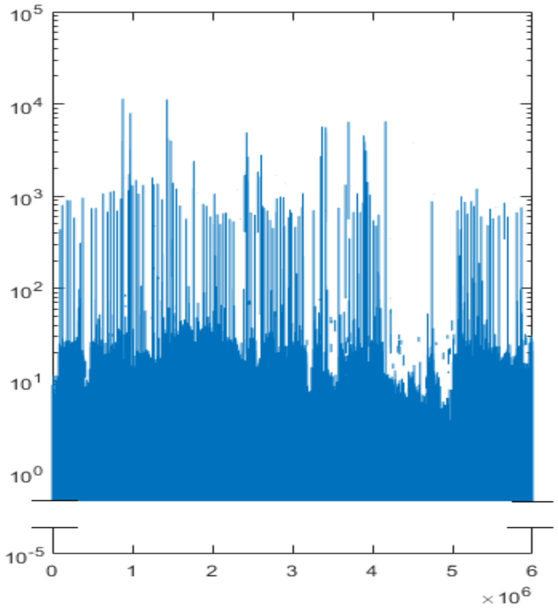

Figure 6. On-source total power time series, first minute of data (6x10^6 points), logarithmic. Note the many peaks between 300 and 1000 which are reflected in Fig. 2.

Fig. 7 shows one of the largest on-source total power peaks in the 15 minute observation interval. It doesn't appear in the off-source data. It has a width comparable with the Fig. 4 autocorrelation (about 15 total points), and came at UT 01:42:00.88. Taking this peak flux to be 25000 counts, and the rms noise to be about 10 counts, for this pulse our signal to noise is about 2500! Taking the SEFD (system equivalent flux density) of the 300 m dish 327 MHz system to be 12 Jy/Tsys (Janskys per system temperature), and an effective bandwidth of 12 MHz (after throwing out the shoulders and bad noise channels), we find the peak flux of this pulse to be about 3000 Jy. Following the discussion in [1], this compares with an expected flux at Earth from a large GPS arc (if all the energy were in a 100 MHz bandwidth) of 50,000 Janskys. This suggests that the radiative efficiency of the GPS arcs in the radio band is something like 6%, amazingly similar to the estimate made in [4] of the radiative efficiency of a plasma.

The 650 count bump in the histogram of peak power (Fig. 2) translates into a 78 Jy flux, and very small arcs, indeed. Plus, the rate of such small events in the Arecibo data is very much greater than the peak LANL event rate, so it is unlikely that they correspond to contaminating arcs on the satellite. The fact that they are all about the same peak strength may be a clue to their nature. If, for instance, they are just blowoffs, discharging the satellite capacitance to space, they would be about uniform in strength, but much smaller than arcs that discharge the large differential capacitances on the spacecraft. Alternatively, they could be switching transients in the power system that are radiated by the solar arrays. Their detection attests to the sensitivity of the Arecibo 305 m dish, the largest radiotelescope in the world.

There are very many other large peaks with widths of about 4-5 samples (40-50 microseconds). Unfortunately, the exact LANL event times are unavailable for the GPS source observed at Arecibo on our observation dates. In Figure 8 is a plot of the AE9/AP9/SPM predictions (similar to Fig. 1) for the time around the observation time above. Here it can be seen that our data taking took place near the maximum expected event arc rate.

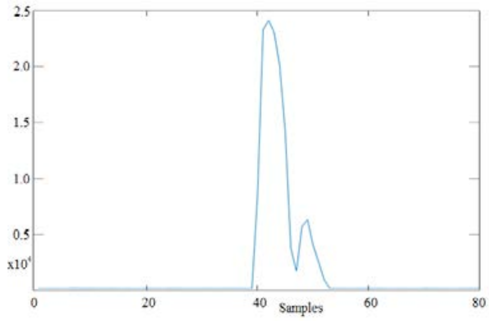

Figure 7. A very large on-source total power spike with width comparable to that in the autocorrelation function.

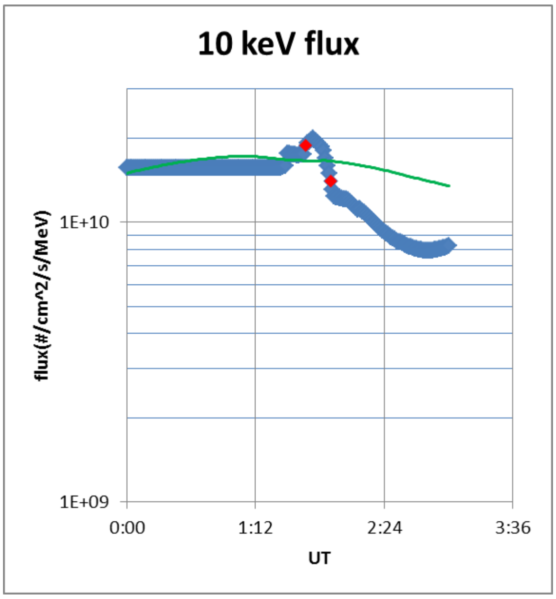

Figure 8. AE9/AP9/SPM model values of 10 keV electron flux for times around our observations. Blue is the electron flux and green is the 160 minute running mean fluence, a proxy for surface voltage and event rate. Red points delineate our data taking interval.

4. CONCLUSIONS

A coordinated surveillance campaign between ground-based radio and optical telescopes and the LANL detectors on GPS satellites has been undertaken, to try to confirm that undispersed LANL events are arcing on the solar arrays, and to confirm that this arcing could be producing the contamination necessary to degrade GPS power. Daily variations in the undispersed LANL event rates seem to follow the variations in the 10 keV electron flux, if allowance is made for conduction time through solar cell coverglasses.

The first preliminary radio data obtained by the Arecibo 305 m radiotelescope show significant differences between the on-source and off-source beam signals, consistent with broad-band GPS pulsed emission of about 140 microsecond width. Rates of these pulses are consistent with LANL undispersed event rates for the GPS satellite in question. However, strict correspondence with the LANL events has not been established. Further analysis of the LANL, Arecibo and LWA1 data obtained in October of 2015, as well as the LANL, LWA1 and Starfire Optical Range data obtained in November of 2015 continues.

If the GPS arcing-power degradation hypothesis is confirmed, the results have important implications for arc rates on other satellites. The arc rates are higher than even the most pessimistic previous calculations would imply. Despite publications to the contrary, [5] for example, arc rates in severe space environments must be in the tens of thousands per year. For this to be so and to not have been noticed attests to the success of satellite power system designers in filtering arc spikes out of the power stream. It also clearly shows that finding and correcting the causes of problems is preferable to covering up (filtering in this case) the problem and living with it.

Confirmation of the arcing contamination of solar arrays as the source of the anomalous GPS power degradation will allow arc mitigation techniques to be implemented. See [6] for one approach. NASA-STD-4005 [7] gives fourteen different ways to mitigate arcing. A reduction of GPS solar array size by 20% or an increase in End-Of-Life power by 25% may result from arc mitigation.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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