



Spectral Characteristics of GEO Satellite Arcing – 300 To 350 MHz

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Abstract

In a series of previous papers, the detection of arcing on GPS, Van Allen Probe, and GEO satellites with the Arecibo Observatory Wm. E. Gordon 305 m radiotelescope has been reported and elaborated. In this paper, characteristics of the radiofrequency spectra of two true GEO satellites are reported as they were measured with the Arecibo Mock spectrometer every 9.6 microseconds, and are contrasted with spectra of impulsive RFI (RadioFrequency Interference) events. It is shown that the arc spectra in the 300–350 MHz range are not continuous, but consist of a number of narrow spectral lines. These lines are consistent within the duration of single arcs, but change between arcs, so that when averaged over many arcs, the appearance of a continuous spectrum is approximated. This behavior is replicated in the laboratory within charging-induced vacuum arcing on small solar array samples. In contrast, the spectrum of impulsive RFI (including, but not limited to lightning strokes) is essentially random from one 9.6 microsecond sampling interval to the next. Since the spectrum of a true arc changes little throughout many samples, it cannot be due to the risetime of the arc current, which is much less than one sampling interval. Furthermore, in laboratory experiments done at very high time resolution (< 1 ns), there is little correlation between the arc current spectra and the arcing RFI spectra, indicating that even arc current fluctuations within each arc can have little to do with the UHF spectra observed.

Keywords Satellite arcing · Radio spectra · Satellite surveillance

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1 Introduction

As reported in Ferguson et al. [2, 4], GPS arcing has unambiguously been seen at 327 MHz with the Arecibo 305 m radiotelescope. Similar detection of arcing on GEO satellites has been reported in Plis et al. [5]. Here we report spectral observations of two true (low inclination) GEO satellites with a new 327 MHz feed mounted on the carriage house of the Arecibo telescope. These observations suggest the use of high time resolution 300–350 MHz spectra as satellite design improvement tools and radiofrequency RFI eliminators.

2 The Observations

As mentioned in Plis et al. [5], observations were carried out on UTC (Universal Coordinated Time) date March 24, 2019 at the Arecibo Observatory. A new wide-band (50 MHz) feed designed by J. Breakall of Pennsylvania State University was used with a center frequency of 325 MHz, and a 30 MHz filter was used to help eliminate local interference. The SEFD (System Equivalent Flux Density) of the new feed was about 55 Jy/Tsys. Both linear polarizations were added, and a 128 point spectrum in the frequency range 300–350 MHz (a frequency resolution of 0.4 MHz) was obtained every 9.6 microseconds. 10 min scans were obtained alternately on and off the source by 4 beamwidths (1.33 degrees), to account for the background noise. Two satellites were observed, SES10 and AMC-3. Statistics on the arcs observed may be found in Plis et al. [5].

3 The Analysis

Based on what we thought were good arc vs noise discriminators (peak flux and arc width), several arc candidates were found. Spectra were obtained from the data stored at Arecibo. Analysis was done in Microsoft Excel™ and color plots produced and edited in Microsoft Paint™. Spectra were normalized by total power over the 50 MHz bandwidth at each time interval, and false color plots of the spectra each arc candidate were examined. Surprisingly, three of the arc candidates turned out to have essentially random frequency spectra throughout their duration and two of these are labelled RFI in Fig. 1. Six other arc candidates (4 of SES10 and 2 of AMC-3) had frequency spectra well correlated in time from beginning to end, and based on previous work, two of these are shown also in Fig. 1. Here, the 6-digit number is the UTC time (HRMINSEC) of the event, and frequencies are displayed from left to right, and times within the pulse are displayed from bottom to top. Each color from dark blue to dark red corresponds to a signal twice the previous.

Three things are obvious in Fig. 1. First, the true arc spectra have longer durations (5 samples) as opposed to the RFI (3 samples). Secondly, RFI spectra are more random in frequency and time than true arcs. And third, true arc spectra

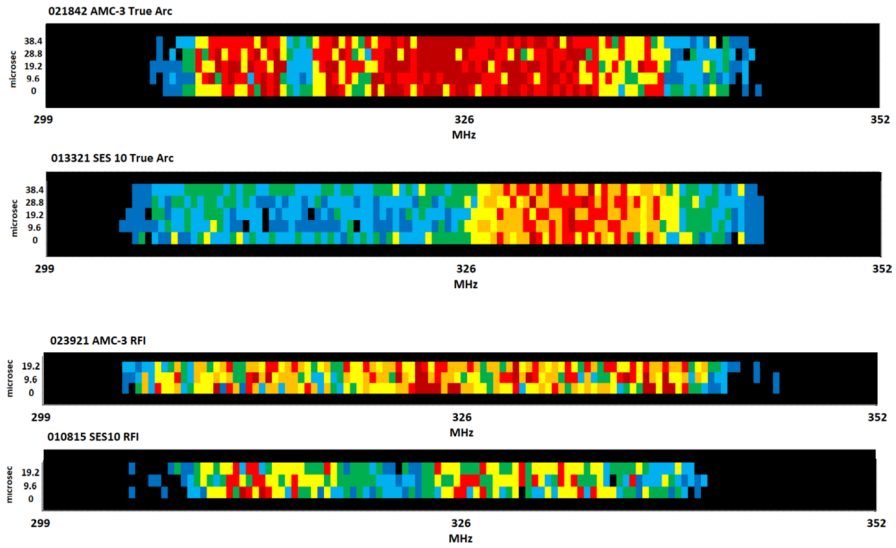


Fig. 1 Spectra of true arcs (top two) and impulsive RFI (bottom two)

have many “lines” that persist throughout the pulse duration. The third point is illustrated in Fig. 2, where we show one spectrum of pulse 021,842, at the time labelled 9.6 microsecond in Fig. 1. The “lines” are the grouped spikes. The noise in this figure can be estimated from the depth of the “valley” at about 315 MHz. Slight saturation of the signal can be seen at about 323–326 MHz.

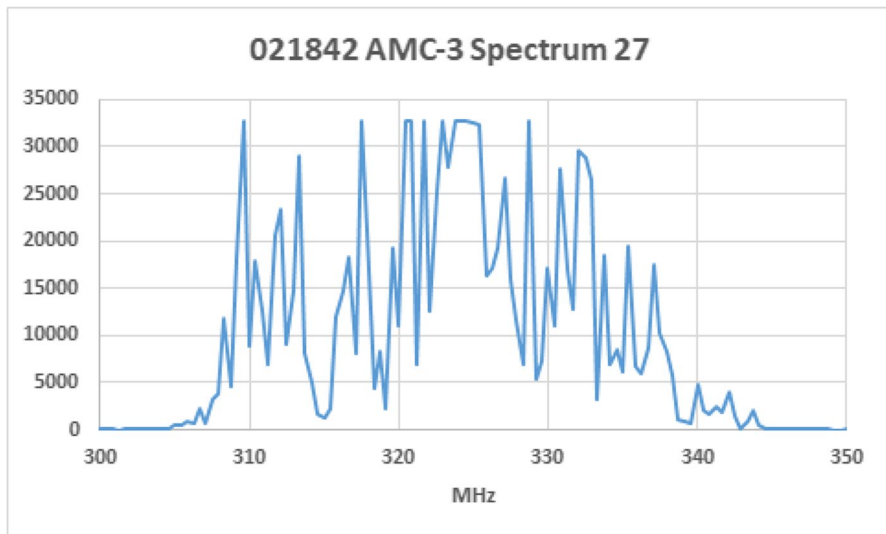


Fig. 2 One 9.6 microsecond spectrum of a true arc from AMC-3

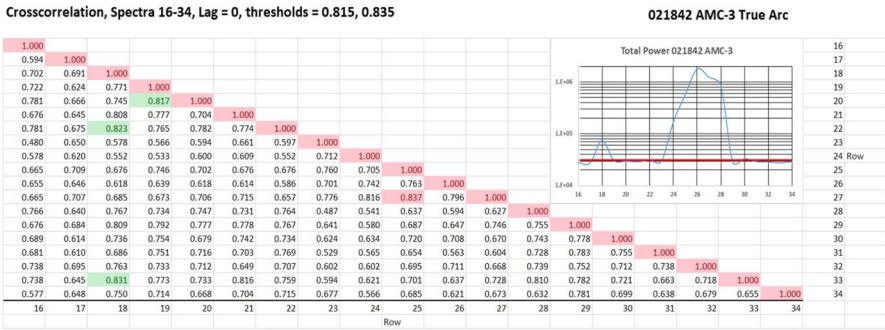


Fig. 3 Cross-correlations of true arc spectra at time intervals (rows) throughout a 182 microsecond interval

One way of quantifying the degree of correlation of the spectra from early to later times is shown in Fig. 3. In the original matrix of frequency versus time, 51 spectra separated by 9.6 microseconds were examined. Here, the correlation of each spectrum 16 through 34 (with zero frequency lag) with every other spectrum is shown. Inset is the total power over the 50 MHz bandwidth for each row, with a logarithmic scale to emphasize the excellent signal to noise, and the baseline power. In green are those linear cross-correlation coefficients greater than a threshold (0.815 in this case) and in pink are those greater than another threshold (0.835). It can be seen that the highest correlations one or two rows from each other occur within the two total power peaks, with the best correlation near the major total power peak. Contrast this behavior with Fig. 4, where an RFI peak is shown. Here the correlations are uniformly lower, and none greater than 0.815 is seen anywhere near adjacent rows.

This is suggestive that a good objective discriminator between true arcs and impulsive RFI might be the cross-correlation of spectra over one or two adjacent time intervals. If the correlations reach a sufficient level, a true arc may be indicated.

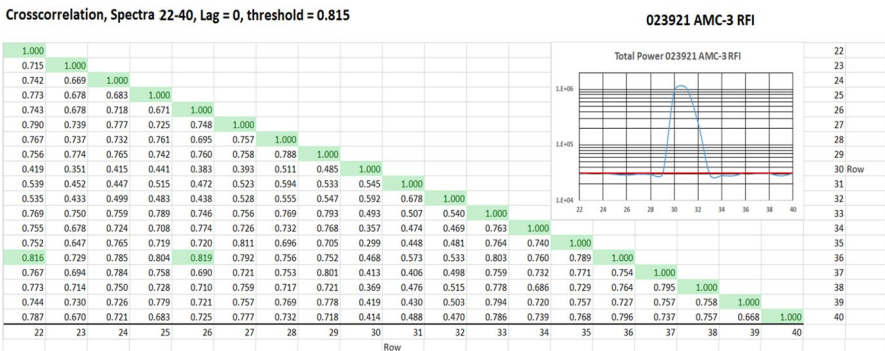


Fig. 4 Cross-correlations of RFI spectra at time intervals (rows) throughout a 182 microsecond interval

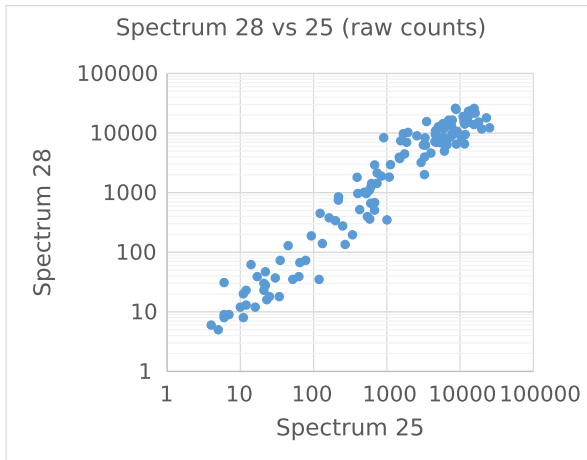


Fig. 5 AMC-3 true arc. Spectrum 28 raw counts versus spectrum 25, almost 30 microseconds earlier

Figure 5 shows the raw spectrum for Row 28 plotted against that of Row 25 for 021,842 AMC-3 (neither is saturated at the peaks) to give a visual indication of how tight the correlation is over 29 microseconds for a true arc.

4 Laboratory Arcing vs True Satellite Arcs

Measurements of arcing on a small (4 cell) string of GPS-like solar cells was undertaken in the Spacecraft Charging and Instrument Calibration Laboratory (SCICL) at Kirtland Air Force Base as part of a NRC Senior Fellowship for one of us (B.V. Vayner). Details of the experimental setup are given in [7]. Experiments were done in an evacuated glass bell jar, and radiated emissions were measured by a broadband Yagi antenna several meters away and an E-field meter located just outside the bell jar. Differential voltages necessary for arcing were produced by irradiating the sample with an electron gun and biasing the cell circuit negative. The time resolution of the measurements was 2 GHz, allowing spectra up to 1000 MHz frequency to be obtained. Spectra obtained were of the arc current (using voltage drop across a small resistor or, interchangeably, a Pearson coil), the RF spectrum of radiated emissions, and the spectrum of the exterior electric field. The oscilloscope was triggered by a small dipole antenna located outside the chamber. Many of the arcs were visible to the eye, and some could be located at the edge of the 4-cell array or at an interior point (probably near cell interconnects). Two different discharging capacitances were used, to give two different arc widths and intensities.

When the experiment was first undertaken, it was expected that the high frequency emissions would have a continuous spectrum, and they would reflect the spectrum of rapid current fluctuations and be coincident with them. None of these suppositions were found to be true. First of all, the high frequency RFI produced by the arcs was found to consist of narrow lines, sometimes in the same frequency

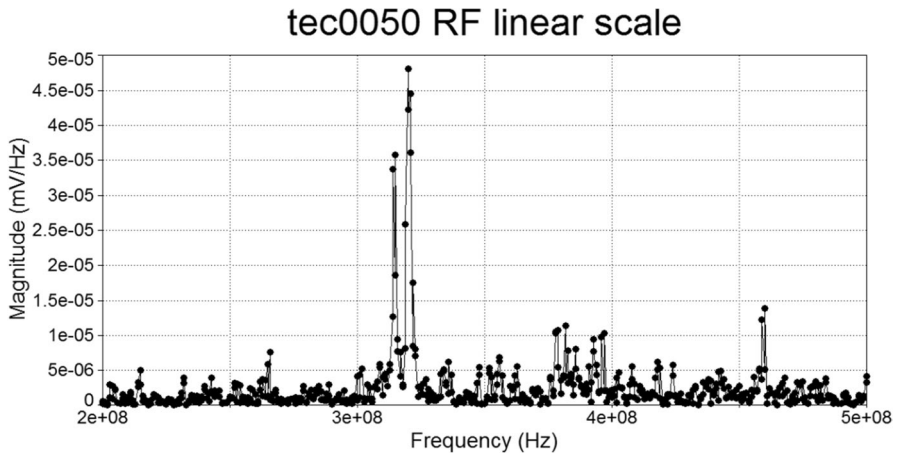


Fig. 6 Laboratory arc spectrum with most of the radiation in the 300–350 MHz range

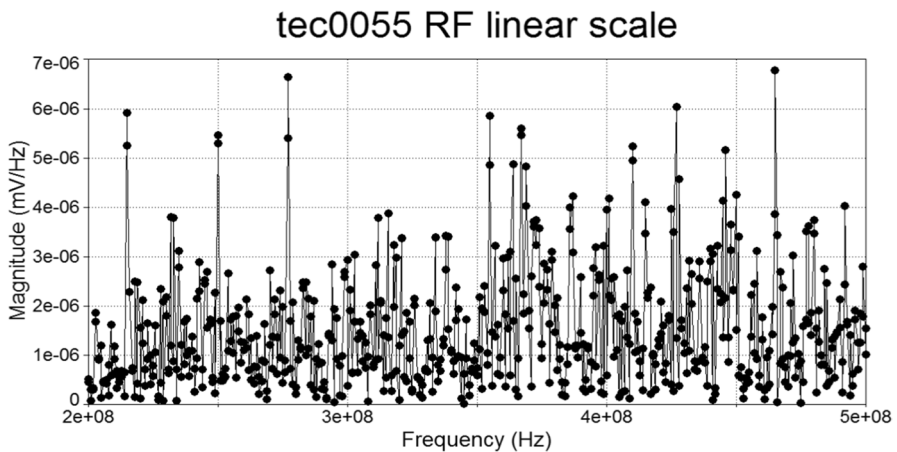


Fig. 7 Laboratory spectrum with much less high frequency emission, and very little in the 300–350 MHz range

range as measured at Arecibo (300–350 MHz) and sometimes not. Two examples are shown in Figs. 6 and 7. The 300–350 MHz spectrum in Fig. 6 is reminiscent of true arc spectra seen at Arecibo. Figure 7, however, shows a spectrum where the lines are much less intense but are spread over a very wide frequency range. Although the lines here look like noise, they are some 20 dBm above the background, and so are real spectral spikes. The tec numbers indicate which arcs are represented, so these very different arc spectra were of arcs at not very different times. In Figs. 8 and 9 are the respective arc currents. Neither arc current spectrum (not shown) shows significant power above 100 MHz. Because of limitations on the number of recorded samples, the last portions of these arcs are not shown.

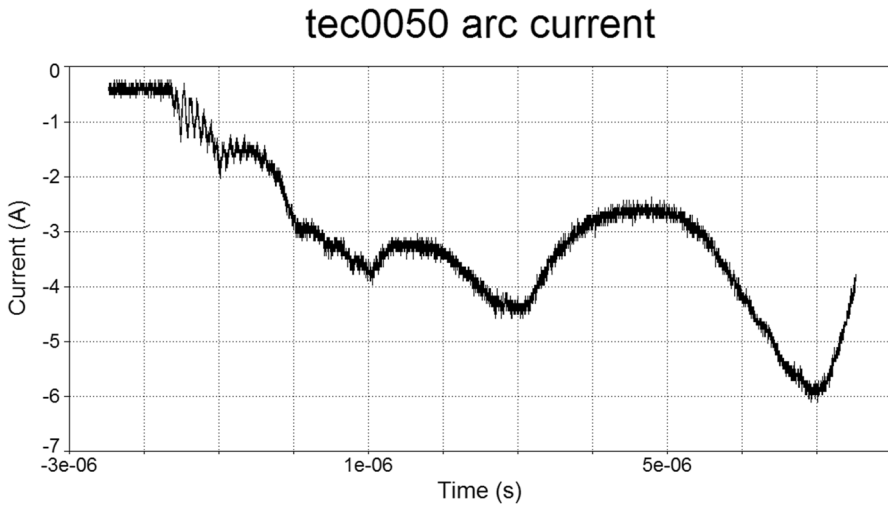


Fig. 8 Arc current for the arc of Fig. 6. The sign is such that high negative values are high arc currents

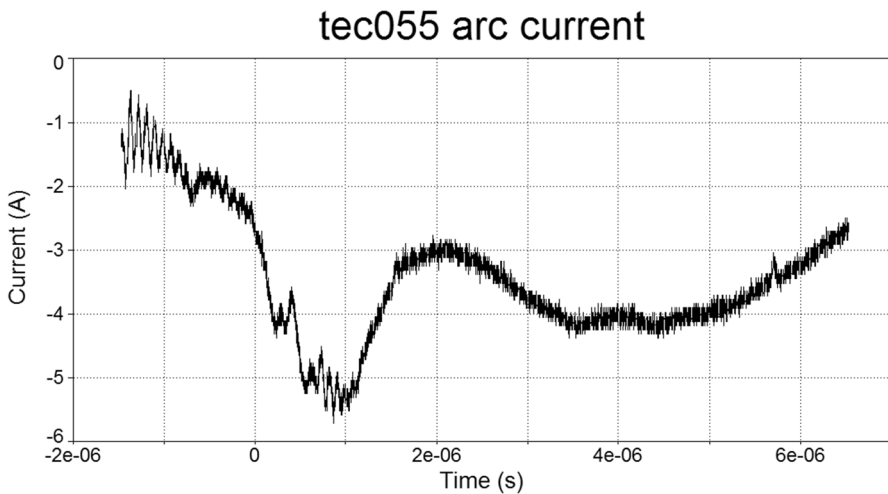


Fig. 9 Arc current for the arc of Fig. 7. The sign is such that high negative values are high arc currents

It must be noted here that the arc current traces are very complex and non-repeating, so the idea of a “standard” arc waveform is incorrect. Usually, the electric field measurements mirrored the arc currents (the exceptions seemed to occur randomly), so electric field meters could be used in orbit as relatively effective arc detectors.

In Fig. 10 is shown an arc current spectrum that exhibited high intensities at 50–300 MHz early in the arc. The corresponding arc current time trace is shown in Fig. 11. Here it can be seen that the arc current fluctuates dramatically early in the arc, but seems to settle down after less than 1 microsecond. It is this time period

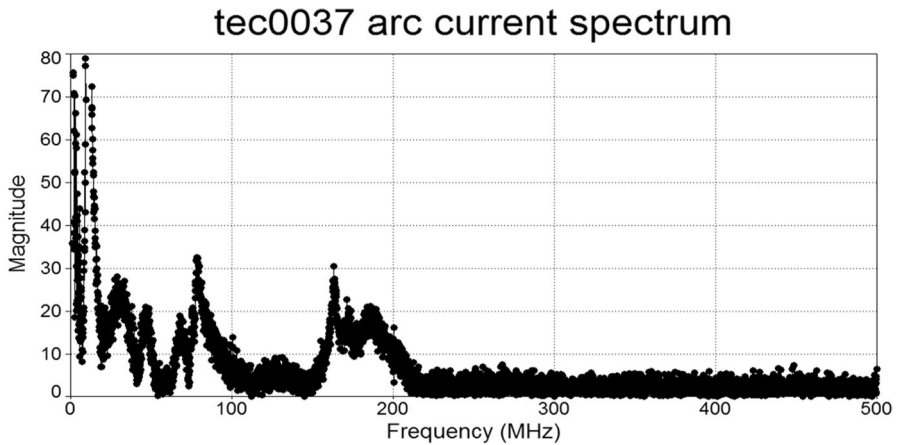


Fig. 10 Arc current spectrum showing significant high frequency power above 100 MHz

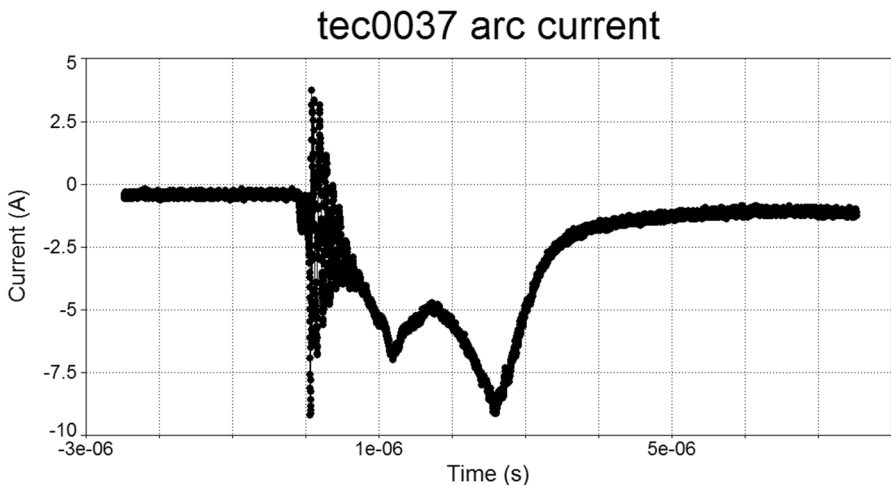


Fig. 11 Arc current trace for the arc of Fig. 10

which we believe have the high frequency components in the arc current spectrum. All of these data were obtained May 10, 2019. On that date, 61 files were obtained using an external capacitor of $C = 10$ nF, beam energy 5 keV, bias -4.4 kV.

Because of the RC time constant of the external circuit, none of these arcs lasted longer than about 10 microseconds, or about 1 sampling interval in the Arecibo data. In Vayner and Ferguson [7], using a 100 nF capacitor instead of 10 nF, arcs of up to 30 microseconds width and 100 A amplitude were obtained. In all of the arcs that occurred in the laboratory there was little or no correlation of the RF spectrum with the arc current spectrum. Thus, the hypothesis that the arc current fluctuations are producing the 300–350 MHz lines seen at Arecibo is not correct. And, in each

arc, the RF spectral line frequencies are different. Since these frequencies are far above the plasma frequency for these arcs, and because for an arc of 50 microsecond width the initial arc plasma would be much more dense and have a higher plasma frequency than the plasma at later times, it is tempting to discount the plasma as the source of radiation. Other published work on vacuum arc spectra [1, 6] use long-timescale arcs and average arc current spectra, and seem to show that on the average, there are arc current fluctuations in the right frequency range, depending on the cathode material, but these are not the narrow RF lines seen here. Although it is certain that the laboratory arcs and the arcs in space have similar RF spectra, the origin of the radiation is still unknown.

5 Arc Spectra and Arc Widths of Different Satellites

Theoretically, the arc current duration of vacuum flashover arcs should depend on the extent of the surface to be discharged and the speed of the ions in the expanding plasma cloud [3]. In Ferguson et al. [2, 4], arc durations of up to 144 microseconds are considered, and in Ferguson et al. [3], it is shown that arc durations (“spike widths”) of up to 134 microseconds are probably real. Assuming that the arc radiates RF throughout the discharge of solar cell coverglasses, the RF duration should then depend on the length or width of the arcing solar array and the plasma ion components from the arc-site. Taking the canonical value of the ion speed to be 10 km/s (1 cm/microsecond), a 50 microsecond arc-width might correspond to a discharged array extent of 50 cm. However, arc-site constituents that are more massive than average will expand slower than this, and make for longer arc durations, whereas those that are lighter will have shorter arc durations. Likewise, satellites with large contiguous solar arrays should have longer arcs than those with small arrays. Thus, arc duration may be different for satellites with different solar array designs and buildup. Following the reasoning in Rosen and Anders [6] and Anders and Oks [1], it is likewise to be expected that the arc spectra of different satellites may differ.

6 Conclusions

Spectra of solar array arcs on GEO satellites have been measured with a new 327 MHz feed on the Arecibo 305 m radio telescope. As opposed to the spectra of impulsive interference pulses, which are essentially random in the range 300–350 MHz, the spectra of true satellite arcs consist of a multitude of narrow RF lines which are highly correlated over at least a 50 microsecond timescale throughout the duration of an arc. These solar array arc spectra have been reproduced in the AFRL Spacecraft Charging and Instrument Calibration Laboratory at Kirtland Air Force Base. The RF spectra bear no relation to the fluctuation spectra of arc currents. However, the arc current spectra are highly correlated with the electric field fluctuations measured nearby the arc-site, enabling high time resolution E-field sensors to be used as arc detectors on future satellites.

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Code Availability Not applicable.

Declarations

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Consent to Participate Not applicable

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Conflicts of Interest/Competing Interests Not applicable

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