URSI GASS 2023, Sapporo, Japan, 19 – 26 August 2023

Quantifying the Effects of Electron Shot Noise on a Current Biased Antenna

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Abstract

The Parker Solar Probe (PSP) Fields Experiment (FIELDS) Science Operations Team uses FIELDS Radio Frequency Spectrometer (RFS) data and Quasi-Thermal Noise Spectroscopy (QTN) to determine the temperature and density of electrons in the heliosphere. The FIELDS antennas operate with an applied bias current which causes electron shot-noise in RFS data. The presence of high-amplitude shot-noise makes QTN analysis more difficult by obscuring the plasma line and plasma frequency peak. Despite its applied bias current, PSP is one of the first spacecraft to successfully conduct QTN on a current-biased antenna. The effects of the FIELDS antenna bias on the shot-noise spectrum can be quantified by comparing data taken during bias sweep calibration activities. Observing the effects of the applied bias current on the electron shot-noise spectrum can improve determination of electron parameters from QTN and expand contemporary QTN models to account for operating with a bias current.

Key Points:

- PSP is one of the first spacecraft to successfully conduct QTN on a current biased antenna.
- The effect of the bias current on the shot-noise spectrum is observed and quantified by comparing FIELDS RFS data taken during calibration activities in which the applied bias is rapidly varied.
- Quantifying the effects of the bias current on the shot-noise spectrum can improve determination of electron parameters from QTN and expand contemporary QTN techniques.

1 Introduction

NASA's Parker Solar Probe (PSP), launched in 2018, is a heliophysics mission studying the Sun's atmosphere. PSP became the first spacecraft to gather in-situ data of the inner heliosphere when it entered the solar corona in April of 2021. In its current orbit, PSP perihelion is 0.06 au, and its final perihelion distance will be approximately 0.045 au from the center of the Sun—well within the orbit of Mercury and more than seven times closer than any previous spacecraft.

The Fields Experiment (FIELDS) is an instrument suite designed to take direct measurements of electric and magnetic fields and waves. The spacecraft makes electric field measurements as both a current-biased resistively-coupled double-probe instrument *and* as a capacitively-coupled radio and plasma wave instrument [Bale et al., 2016].

The FIELDS Radio Frequency Spectrometer (RFS) is a two-channel digital receiver and spectrometer [Pulupa et al., 2017]. It operates primarily in cross-dipole mode, with one channel making a dipole measurement between the opposing V1 and V2 antennas, and the other channel using the V3 and V4 antennas. The RFS produced data between 10 kHz-19.2 MHz in two frequency bands: the high frequency receiver (HFR) and low frequency receiver (LFR). This project utilizes LFR data, with a maximum frequency of 1.6 MHz.

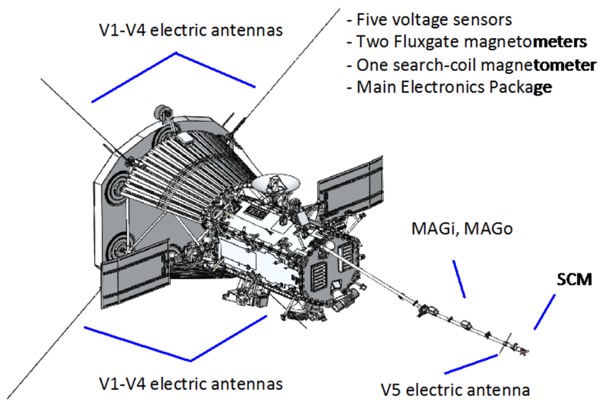

Figure 1. PSP FIELDS instrument suite diagram

2 Biased Antennas

A negative bias current is applied to the PSP V1-V4 electric field sensors to bring the antenna potential close to that of the ambient plasma environment. The applied bias current varies slowly with solar distance and makes the voltage sensors more sensitive to DC and low-frequency electric fields [Diaz-Aguado et al. 2021]. Without this bias current, PSP's electric field sensors would charge to a positive potential with respect to the surrounding plasma.

Electron shot noise is observed when electrons impact onto or depart from a spacecraft antenna. The high frequency signature of these electrons impacting the spacecraft antenna changes the amplitude and spectral shape of shot-noise in RFS data. On an unbiased antenna, the electron shot noise spectrum consists of plasma electrons which impact the antenna. On a biased antenna, the electrons from the bias current increase the amplitude of the short noise spectrum.

3 Quasi-Thermal Noise Spectroscopy

Quasi-Thermal Noise Spectroscopy (QTN) is a highly accurate technique for determining electron temperature and density in space plasmas by examining in-situ measurements of electric field fluctuations produced by thermal oscillations of plasma particles [Meyer-Vernet et al., 2017]. PSP QTN measurements are used to calibrate other plasma instruments on the spacecraft because their density estimate is unaffected by spacecraft potential [Moncuquet et al., 2020].

The electron QTN contribution to the LFR spectrum occurs in the same frequency range as the short noise spectrum. Optimal conditions for QTN therefore occur when bias current is minimized. [Martinovic et al., 2022] used RFS data recorded during short intervals of zero bias current to accurately determine electron parameters from PSP. During the majority of the time when a bias current is applied [Moncuquet et al., 2020] has successfully used a simplified QTN model to determine electron parameters. Figures 2 and 3 show a sample of data taken during solar encounter 12, illustrating QTN spectra close to the Sun.

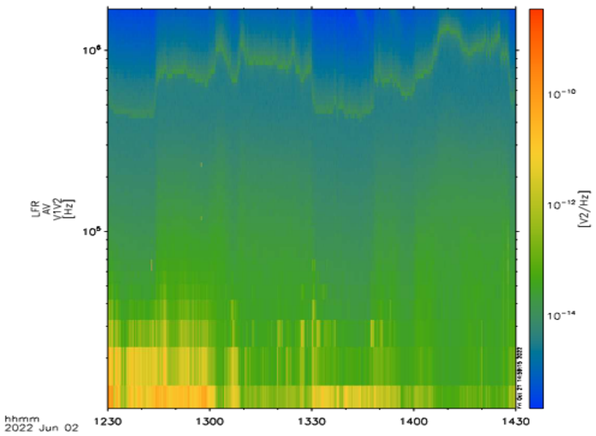

Figure 2. Spectrogram of in-situ data taken during solar encounter 12. The electron plasma line is the feature varying from 430 kHz to 1.3 MHz. Variation of the plasma frequency corresponds to *in situ* electron density variations.

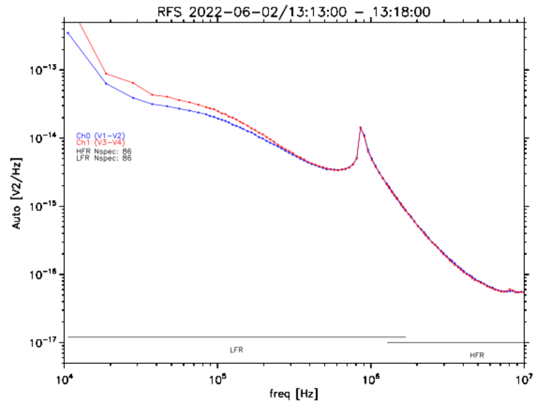

Figure 3. Spectral cut of a 5 minute interval from the spectrogram in Figure 2, with clearly defined plasma frequency peak at ~840 kHz.

4 Bias Sweep

The applied current bias is rapidly varied during periodic calibration activities known as bias sweeps [Diaz-Aguado et al., 2021]. Figure 4 shows a time series of one such bias sweep in which the applied current begins at nominal bias, is rapidly switched to negative saturation, increases the applied voltage in a series of steps until positive saturation is reached, and then stays briefly at zero bias, the ideal operating conditions for QTN.

When the antenna is in negative saturation, a negative bias current drives the antennas to a large negative potential relative to the spacecraft ground. This is indicated in Figure 4 by the time period when the measured antenna voltage approaches -100 V. Positive saturation describes the analogous situation for a positive bias current.

In Figure 5 the average zero-bias plasma line is subtracted from every other spectral cut in the time series in order to isolate the contribution of shot-noise to the measured spectrum.

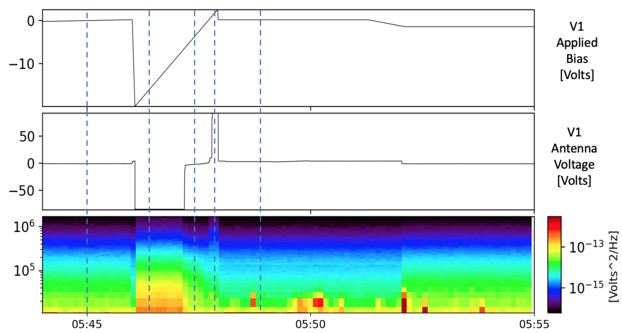

Figure 4. Spectrogram from encounter 7 (Jan 14 2021, solar distance 0.19 AU). The plasma line is clearly visible during zero bias. Dashed lines indicate timestamps of Figure 5 spectral cuts.

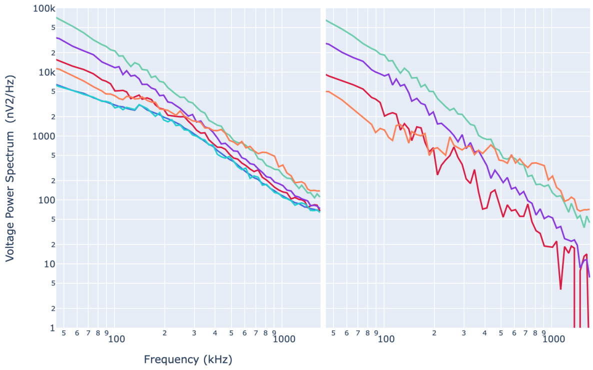

Figure 5. (Left) Spectral cuts showing LFR data from 5 distinct times during the bias sweep intervals, as indicated in Figure 4. (-12 μA (red), -147 μA (green), -26 μA (purple), 14 μA (orange), 2 μA (cyan)). (Right) Spectral cuts with zero-bias line subtracted, isolating the contribution of the applied bias current to the measured spectrum.

An alternative way to observe shot-noise affecting the spectral data is to plot the changes in voltage power spectrum as a function of the applied antenna current, as shown in Figure 6.

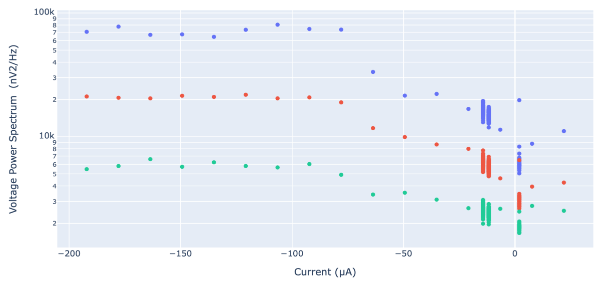

Figure 6. Horizontal spectral cuts taken at 50 kHz (blue), 100 kHz (orange), and 200 kHz (green). The shot noise amplitude is at a minimum for values of bias current near zero.

5 Conclusions and Future Work

The changes in current balance due to biasing changes the amplitude and spectral shape of shot noise, which has been quantified at distances close to the sun (20 solar radii or less). To complete the model of changes in the shot-noise spectrum, we plan to compare QTN data from hundreds of other bias sweeps conducted on PSP at various solar distances. In the future, we also plan to compare the high-frequency results with low-frequency bias sweep measurements.

Acknowledgements

The author would like to thank the ongoing support and collaboration of Aerospace Engineer Tim Quinn.

Parker Solar Probe was designed, built, and is now operated by the Johns Hopkins Applied Physics Laboratory as part of NASA's Living with a Star (LWS) program (contract NNN06AA01C). Support from the LWS management and technical team has played a critical role in the success of the Parker Solar Probe mission.

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