The Electrojet Zeeman Imaging Explorer (EZIE) mission and the Microwave Electrojet Magnetogram (MEM) radiometer instrument

Sidharth Misra, Sharmila Padmanabhan, Pekka Kangaslahti, Oliver Montes, Javier Bosch-Lluis, Richard Cofield, Isaac Ramos
Jet Propulsion Laboratory, California Institute of Technology
sidharth.misra@jpl.nasa.gov; 1-818-354-1256

Jeng-Hwa Yee
Johns Hopkins University Applied Physics Laboratory

ABSTRACT

The Electrojet Zeeman Imaging Explorer (EZIE) mission is a multi-satellite 6U CubeSat mission designed to temporally and spatially sample the Earth's current induced magnetic field. The EZIE mission will help discern amongst competing theories of the spatial structures of Auroral Electro Jets (AEJ). The EZIE mission uses a unique payload design relative to traditional magnetometers; a 118.75 GHz mm-wave polarimetric radiometric system with a digital spectrometer backend, called the Microwave Electrojet Magnetogram (MEM) system. MEM measures the Zeeman split in frequency of the Oxygen absorption line that is directly proportional to the strength of the magnetic field of the observation. The polarimetric nature of MEM helps inform about the direction of the magnetic field. The MEM system consists multiple-beams in a push-broom configuration to detect magnetic fields at a approximate altitude of 80km.

INTRODUCTION

The Electrojet Zeeman Imaging Explorer (EZIE) mission is a multi-satellite mission designed to remotely sense Earth's current induced magnetic field vector. The EZIE mission directly addresses the NASA Heliophysics goal of "discerning the physical mechanisms behind ionospheric electrojets that are a consequence of the dynamic solar wind."

EZIE mission will fly three 6U CubeSats in a string-of-pearl sun-synchronous configuration. Each CubeSat will have four beams capable of imaging the AEJ cross-track at different spatial sampling frequencies and incidence angles. EZIE will thus be able to produce a complete spatial and temporal map of the current induced magnetic field vector B.

Each EZIE spacecraft is capable of measuring current induced magnetic fields by using the Zeeman effect phenomenon observed at the 118GHz oxygen line. Depending on the strength of the incoming magnetic field, as well as the relative orientation of the observing instrument and the direction of the magnetic field, the 118 GHz oxygen line splits in frequency into two different lines. The spectral distance between the two peaks is directly proportional to the strength of the magnetic field, as observed at 90km altitude.

Each spacecraft consists of the Microwave Electrojet Magnetogram (MEM) payload. The MEM payload consists of four 118GHz mm-wave radiometers with a digital backend spectrometer. The four RF receivers are oriented in different directions to achieve cross-track sampling. MEM measures both horizontal and vertical polarizations of the incoming signal. The digital backend ingests the two polarizations and digitally computes all four polarization states of the incoming signal (H,V,3rd,4th). The digital backend also computes the spectra of the signal, allowing the ability to measure spectral distances of the Zeeman split. Thus MEM is able to measure residual current-induced magnetic fields in addition to the geomagnetic background fields. The MEM instrument has unique calibration requirements as the shape of the spectra is critical compared to the absolute brightness temperature of the spectra. MEM and EZIE do special maneuvers before and after science looks to ensure spectral flatness.

The next section presents the EZIE mission concept led by APL, followed by a discussion of the MEM payload instrument developed by JPL-CalTech.

EZIE MISSION

The auroral electrojet forms a global current system in regions spanning the high-latitude ionosphere to several thousands of km deep into the Earth's magnetosphere. The currents represent a key interaction observation between the Earth's upper atmosphere and surrounding space. The structure of the AEJ holds the key to understanding the manner in which energy is transported and how interactions occur between the solar-wind / magnetosphere and ionosphere / thermosphere. These interactions are relevant to any celestial body with a magnetosphere within streaming plasma. There are several competing theories regarding the temporal and spatial structure of AEJs [1-3].

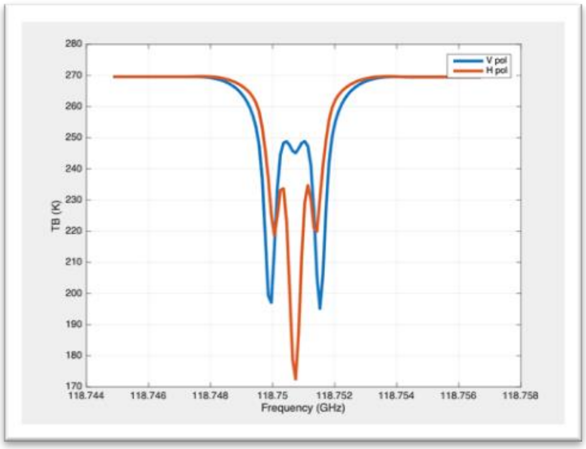

Figure 1: Simulated brightness temperature spectra for V pol (blue) and H-pol (red)

The EZIE mission will fly 3 6U CubeSats, each with a payload that has four push-broom beams. The 3 CubeSats in a pearl of strings configuration will help with the temporal sampling of the AEJ. The four beams will help with the spatial sampling of the AEJ. EZIE will produce a complete map of the Earth's magnetic field. This in turn is related to the current distribution that will help distinguish between several hypothesized physical mechanisms that describe the magnetosphere-ionosphere systems.

Figure 1 shows simulated brightness temperatures as received by the payload due to a current induced magnetic field from the AEJ. The distance of the peaks away from the center frequency are directly proportional to the magnetic field strength of the B field component. As the separation of the peaks increases in frequency the component B field magnetic strength also increases. EZIE uses this Zeeman effect principle to backout information of the B field [4-5]. The difference in shape between the H-pol and the V-pol represents the difference in the contribution from different components of the B-field vector and relative orientation of the observation angle. The relative shapes between all four Stokes brightness temperature gives information about the direction of the B field.

MEM PAYLOAD

Figure 2 shows the overview of the MEM instrument. Each payload instrument consists of four radiometric front-ends. Four feed horns are fed through four different reflectors. The reflectors are pointed at four unique angles to spatially sample the AEJ field across a wide swath. The feed horns are narrow band feeds optimized to 118.75GHz input. The signal from the feed is split via an Ortho mode Transducer before being amplified and down converted to an IF signal fed into the digital backend system. The digital backend system, receives polarimetric H and V pol inputs from all four receivers at once, digitizes them and computes an output spectra that is used to measure the Zeeman split of the signal.

Figure 3 shows the current payload set up that will be fit within 2U of a 6U CubeSat. The MEM payload is built of two heritage CubeSat missions, TEMPEST-D for the front end RF system, and CubeRRT for the digital spectrometer system [6-7].

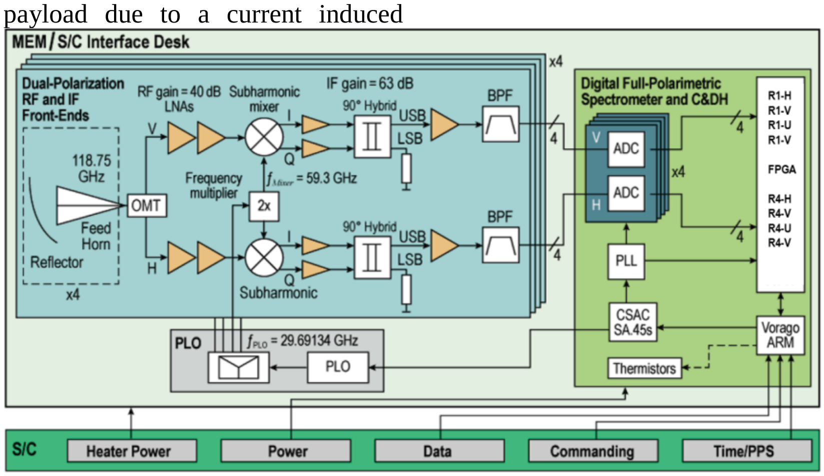

Figure 2: Block-diagram of the MEM payload instrument

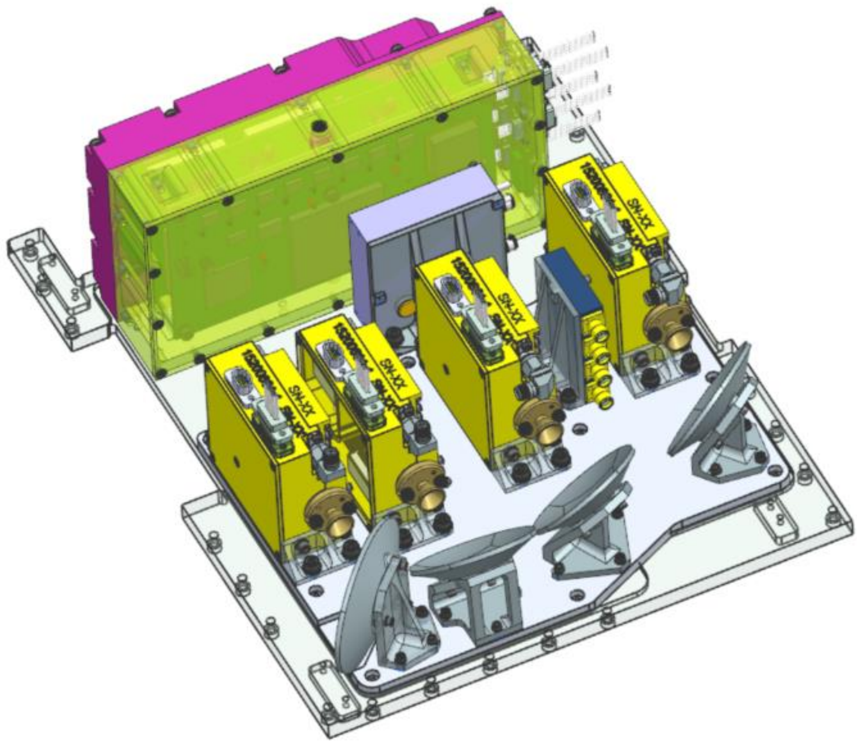

Figure 3:CAD of the MEM payload instrument to be fit within a 2U system

MEM RF, IF, and Antenna System

Due to the narrow bandwidth (50MHz) on an RF signal of 118GHz, a simple pottorn horn optic was used for the feed horn design. The beam patterns with reflector form a half-power beamwidth of less than 4 degrees as required for the EZIE mission for adequate spatial resolution of the B fields. Figure 4 shows the Mueller matrix antenna pattern across all four Stokes (V,H,3rd,4th). The co-pol and cross-pol numbers are important for EZIE as a cross pol mixing potentially results in an magnetic field direction offset.

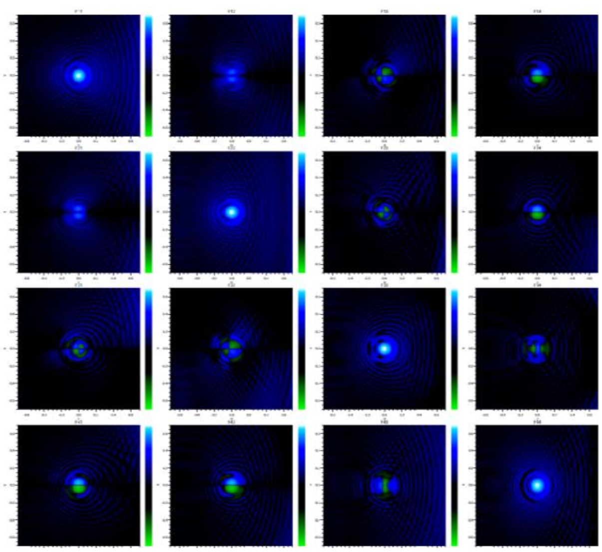

Figure 4: Mueller matrix of the MEM antenna. The 4x4 matrix represents the co- and cross-pol antenna patters across all fourth Stokes parameters. The diagonal elements represent the co-pol. The color-scale has been normalized to 1 (white) and -1 (green).

The RF system (Figure 5) following the feed horn goes into an OMT to split the signal into horizontal and vertical polarization. Following a series of LNAs and attenuators the signal goes through a sub-harmonic mixer that ingests a 29.6GHz LO input through a frequency doubler. The IQ output of the subharmonic mixer is combined to reject one of the sidebands and fed to the digital backend through an anti-aliasing filter.

End-to-end testing of a benchtop system indicates good sideband rejection, low noise front-end, no system oscillations. The receiver noise temperature as measured at ambient temperatures is around 440K to 490K.

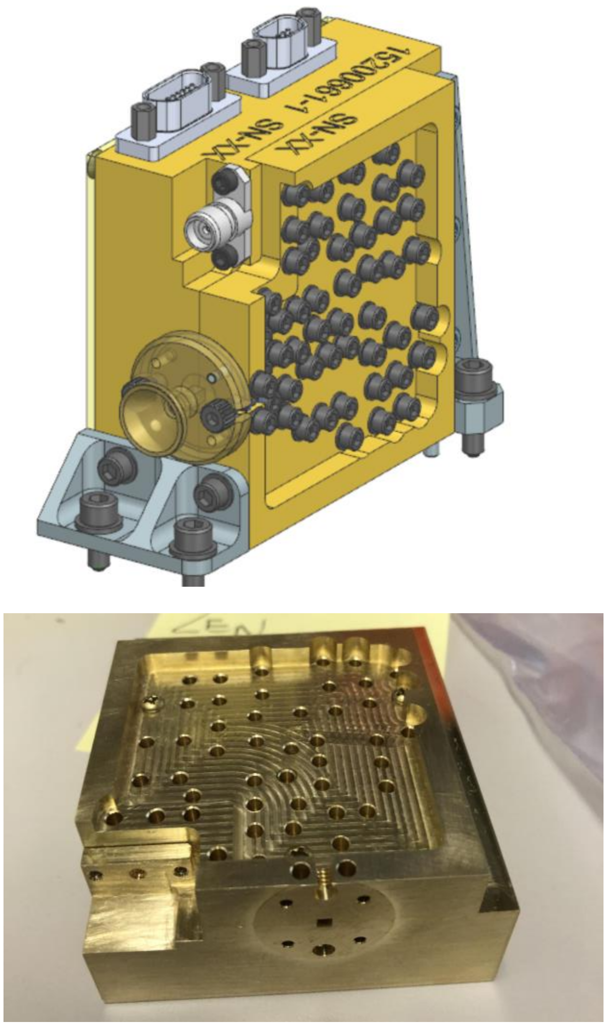

Figure 5: The RF/IF module.

MEM Digital Backend

The MEM digital backend contains a poser distribution unit, a DC-DC convertor, as well as the main board for signal processing as well as command and data handling. The digital backend uses a space qualified Xilinx Kintex Ultrascale fed through 8 ADCs sampling dual polarized IF signals from four receivers. All the command and data handling occurs through and external space qualified processor.

The signal processing system consists of a 1024 channel poly-phase filter bank (PFB) for each polarization. The output of the PFB for H-pol and V-pol is fed into a single complex multiplier. The output of the multiplier produces 3rd and 4th Stokes signals. All Stokes power measurements are then made within the DSP via accumulation. EZIE science only requires less than 12MHz of signal bandwidth, resulting in a selection of relevant frequencies to downlink for science.

Frequency stability is a key for the EZIE mission since the science measurement is dependent on the output spectra of the signal. The digital backend and the LO are fed through an ultra-stable atomic clock reference to ensure minimum frequency drift.

MEM Radiometric Calibration

For EZIE and MEM, absolute brightness temperature calibration is secondary, compared to the shape of the spectrum. The spectrum and the separation of frequency peaks requires any instrument associated spectral shape be calibrated out. Thus, MEM does not carry any internal calibration system. Instead the EZIE mission performs periodic cold-sky looks. The cosmic microwave background is extremely stable and flat at 118.75GHz. These cold-sky looks are performed around every science measurement of the AEJ. The cold-sky looks enable flattening of the spectra before science measurements and also anchor the calibration to a stable source.

MEM also uses a parametric model of the receiver temperature with respect to physical temperature to calibrate out any gain and offsets within the system. Such a calibration was verified on the TEMPEST-D [8] CubeSats with respect to internal calibration points. The absolute brightness temperature is anchored by model brightness temperature of the atmosphere.

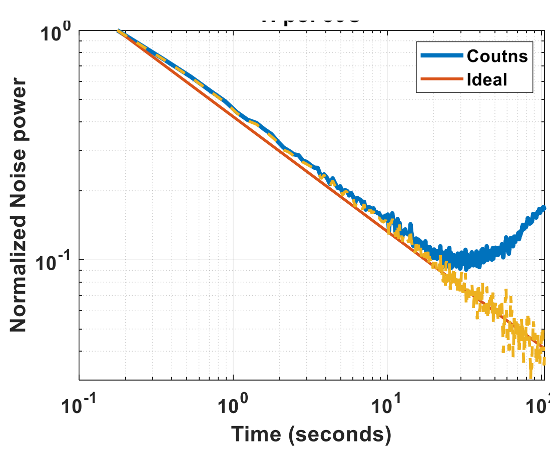

Figure 6: Normalized Alan-deviation curve. Blue represents uncalibrated noise performance with respect to time, red represents an ideal curve, and yellow represents the spectral ratio calibration. .

MEM is also unique in calibrating out 1/f noise (gain variations) of the system. The spectra of interest is calibrated by taking its ratio with a spectral point away from the 118.75GHz line. This allows any common mode gain variations to cancel out, giving an extremely stable radiometer instrument. Figure 6 shows the Alan-standard deviation curve of the benchtop radiometer, comparing uncalibrated spectra with a ratio calibrated spectra. The results clearly indicate a very stable system with minimal 1/f variations. The figure shows noise decreasing with time (yellow) without any uptick in noise performance (blue at ~30sec) indicating a majority of the contribution is from white noise vs 1/f noise.

Acknowledgments

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