

iMESA-R: AN INTEGRATED, MINIATURIZED, ELECTROSTATIC ANALYZER- REFLIGHT

Dr. Parris C. Neal

Space Physics and Atmospheric Research Center, Department of Physics, USAF Academy, CO,
parris.neal@usafa.edu

C1C Nikolas D. Taormina

Department of Electrical & Computer Engineering, USAF Academy, CO, C15Nikolas.Taormina@usafa.edu

C1C Alex R. Strom

Department of Electrical & Computer Engineering, USAF Academy, CO, C15Alex.Strom@usafa.edu

NOMENCLATURE

iMESA-R= Integrated Miniaturized Electrostatic Analyzer-Reflight

LEO = low earth orbit

SWAP = size, weight and power

GPIM = green propellant infusion mission

OTB =orbital test bed

SPI = serial peripheral interface

USART = universal synchronous/asynchronous receiver/transmitter

hmF2= altitude of the peak density in the ionosphere F2

ABSTRACT

This paper discusses the purpose and design of the Integrated Miniaturized Electrostatic Analyzer (iMESA) instrument being constructed at the United States Air Force Academy as a Senior Cadet Capstone Design project. The instrument uses a new laminated electrode design which provides a high-pass energy filter (similar to a retarding potential analyzer) for ions or electrons. By varying the voltage across the electrodes, the energy distribution of the charged particles up to 95eV, typically ions, in Low Earth Orbit (LEO) can be obtained. From the data we derive the plasma density, temperature, and spacecraft charging. These measurements can then be assimilated into ionospheric models, improving both the “nowcast” and forecast of the ionosphere. The design is simple, reliable, and has a low size, weight and power (SWAP) requirement from the host spacecraft.

The instrument is a multi-disciplinary cadet project including cadets from the departments of Physics and Electrical and Computer Engineering. The current design includes an improved electrostatic analyzer design, as well as a dosimeter providing total dose and dose rate. An earlier design is presently flying on STPSat-3. We are currently building four of these newer flight instruments which together will enable a low cost “space weather constellation.” The constellation will be hosted on the Department of Defense Space Test Program (DoD STP) Green Propellant Infusion Mission (GPIM), the Orbital Test Bed (OTB), STPSat-4, and STPSat-5. Due to the small size (~10cm x 10cm x 5cm), light weight (<1kg), and low power (~2.5W) this instrument lends itself to implementation on almost any platform from large satellite to small “cube sat” size buses. This small SWAP instrument allows a dramatic increase the number of “*in-situ*” measurements of the low-Earth orbit environment, thus increasing the accuracy of space environment models.

I. INTRODUCTION

iMESA-R provides a low cost, size, weight, and power device that will gather ionospheric plasma data in order to help better predict space weather. The low Earth orbit environment is dominated by the ionosphere, plasma

made of neutral atoms and molecules, positively charged ions and negatively charged electrons created by solar photoionization of the residual neutral atmosphere. Plasma instabilities, typically Rayleigh-Taylor instabilities, cause irregularities or depletions in the plasma density¹. The non-uniform distribution of electron density causes a non-uniform index of refraction in the ionosphere. Variations in the index of refraction create phase and amplitude scintillation in the radio frequency (RF) signals used for satellite communication and navigation. In extreme cases, this can lead to loss of lock in Global Positioning Satellite (GPS) navigation signals as well as loss of SATCOM. An understanding of the conditions which are conducive to plasma bubble formation is essential to enabling a “now-cast” and “forecast” of the ionosphere.

The iMESA is a design patented by USAFA² and has been flown on three successful missions. Exhibit 1 below shows the iMESA instrument slated for the GPIM mission. The slits that can be seen in Exhibit 1 are the ion entry apertures. The operation of the analyzer is described later in the paper.

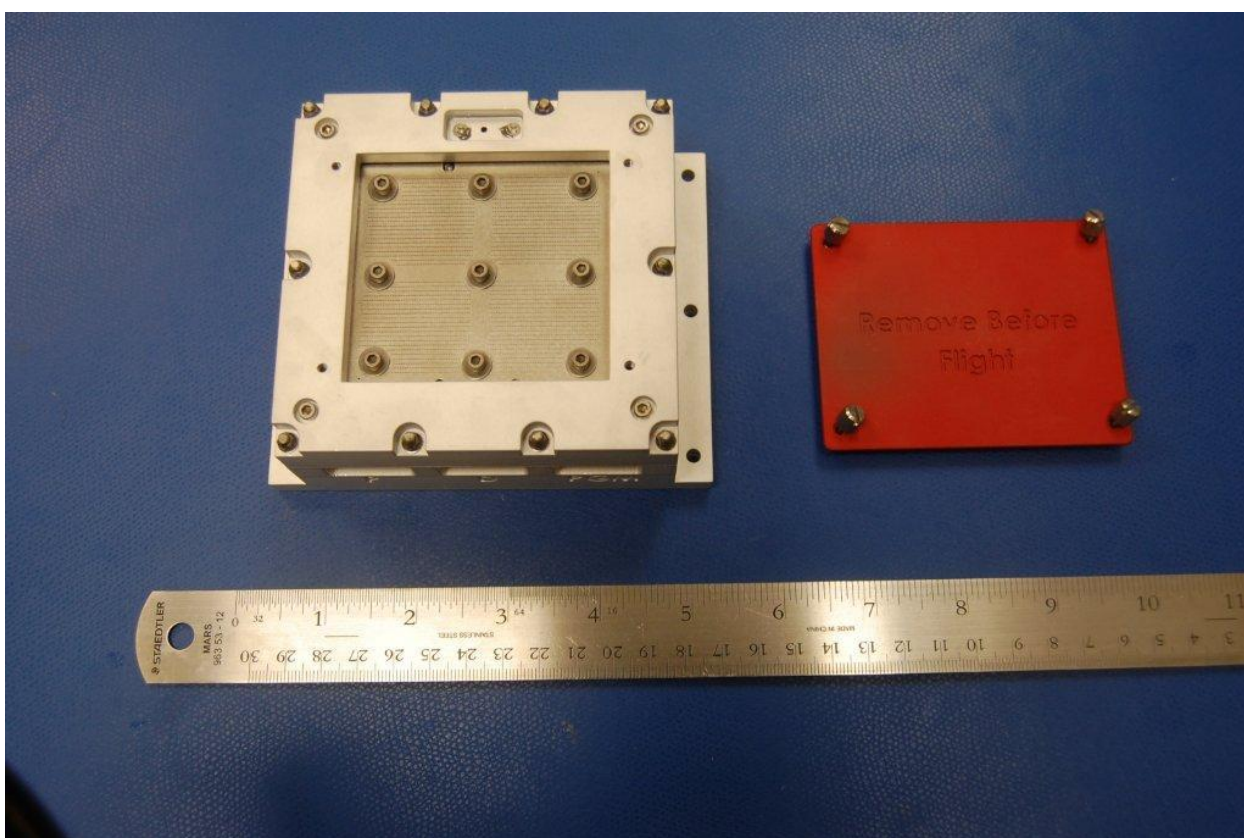


Exhibit 1: Green Propellant Infusion Mission (GPIM) iMESA flight instrument

The iMESA instrument measures the energy spectrum of the low energy plasma in the ionosphere. From this energy spectrum, we can derive the plasma density, temperature and spacecraft charging of the host spacecraft³. Exhibit 2 shows an example from the STPSat-3 mission. The energy time spectrum covers 0-40 eV in energy, and approximately 90 minutes (one full orbit) in time. The color scale is the ion current measured by the instrument, and is proportional to the plasma density. In the example shown in Exhibit 2, the measured current is approximately 4-5 nA. The width of the distribution is proportional to the temperature and the actual energy of the distribution is proportional to the host spacecraft charging.

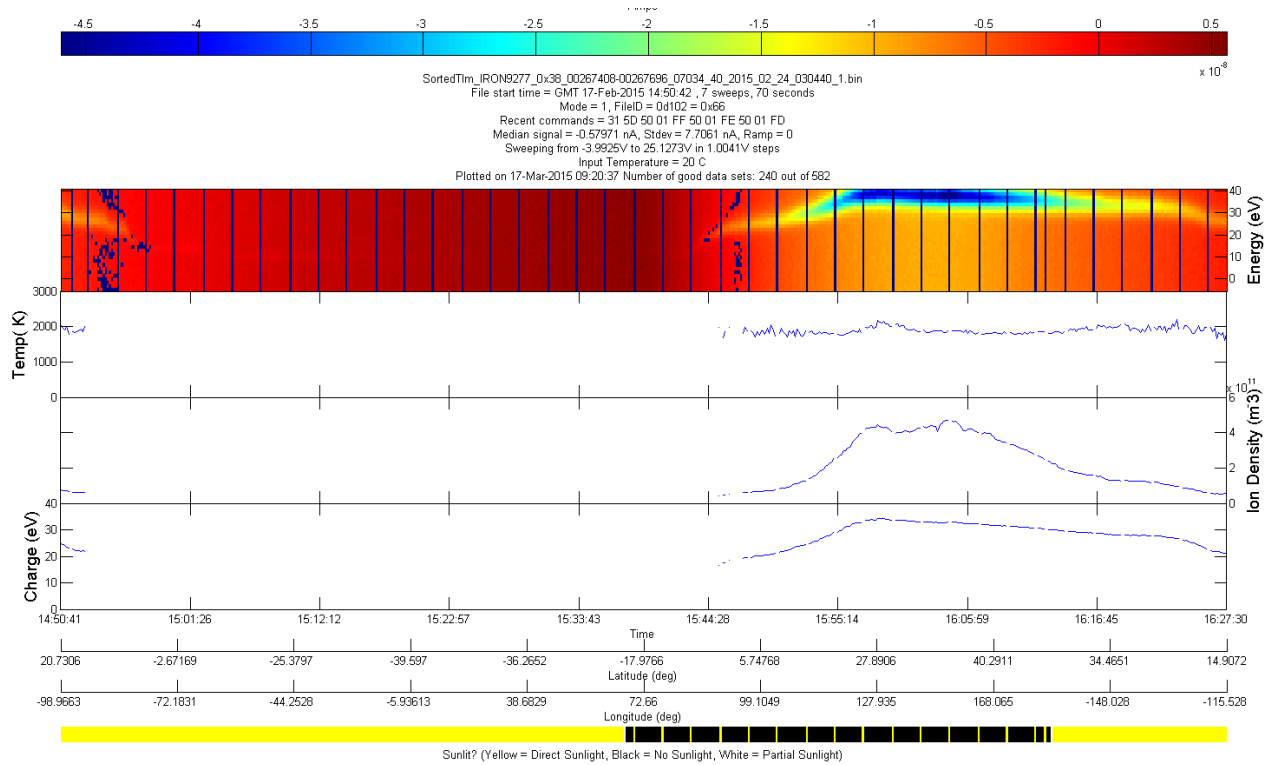


Exhibit 2: STPSat-3 Data. The top graph is the Energy-Time Spectrogram from which the following three data graphs are derived. The plasma temperature is shown first, followed by the ion Density, followed by the magnitude of the spacecraft charging. All the plots are a function of time during a particular orbit along with the position of the satellite.

iMESA is scheduled to be flown on four more Space Test Program satellites over the next two years. Exhibit 3 provides a summary of these flights and Exhibit 4 shows their anticipated ground tracks.

Satellite	Launch Date	Altitude (km)	Inclination (degrees)
GPIM	Mid-2016	650 then 550	24
OTB	Mid-2016	720	24
STPSat-4	Launch Readiness NLT Aug 2017	400	51.6
STPSat-5	Launch date TBD	550	97

Exhibit 3: Anticipated launches of iMESA during the next two years.

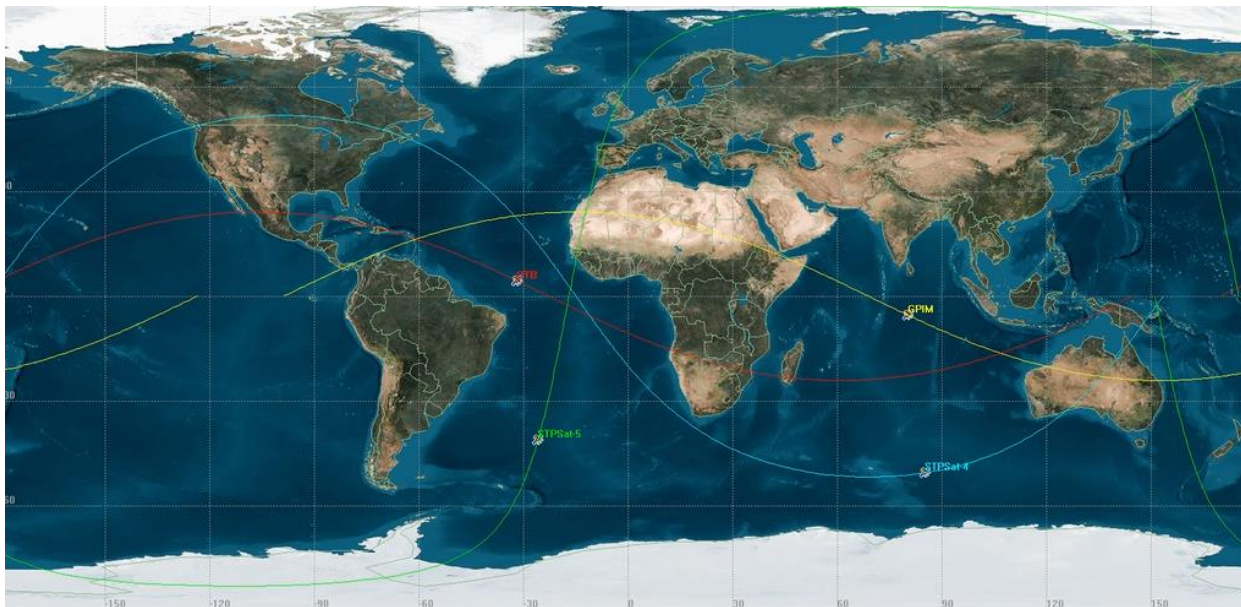


Exhibit 4: Anticipated Ground Tracks of iMESAs flying on GPIM, OTB, STPSat-4, and STPSat-5 Missions

There is a new feature on the most current iMESA. In addition to measuring ion spectra in the ionosphere, each iMESA is equipped with a dosimeter which measures energy absorbed from electrons, protons, and gamma rays with a resolution of $14\mu\text{rads}$ and a range of 40 krads. Measurements from the dosimeters will be used to gather data about the radiation environment in LEO and its effect on spacecraft components⁴.

II. SCIENCE

The purpose of the iMESA is to gather data to improve general space weather forecasting and assist in predicting the formation of plasma bubbles. Space weather forecasting is important because much like regular weather, space weather can have negative effects on a mission, such as communications loss or loss of GPS lock. As of now, information about the ionosphere is mainly gathered from ground stations and GPS data. This data has been ingested into a suite of models called Global Atmospheric Ionosphere Model (GAIM). One of the models in GAIM is a full physics model that can create a very accurate aftercast of ionospheric conditions in regions where actual measurements are not available. For the purposes of this paper, this aftercast model will be considered the “true” atmospheric conditions⁵. As accurate as this model is, it cannot, by nature, be processed fast enough to create a forecast. To create a forecast, a different model is used that can be executed much faster. The inputs to this forecast model come from GPS stations that are all over the world. These stations measure the Total Electron Content (TEC) between the stations and the satellites. From these measurements, total number of electrons may be derived through the ionosphere. This creates boundary conditions from which a space weather forecast may be derived using the GAIM forecast model.

The accuracy of this model compared to the truth is a function of the amount of *in-situ* measurements used. GPS-TEC data and the few *in-situ* ionosphere measuring instruments limit the predictive power of the forecasting model. In order to increase the accuracy, more data about the ionosphere is needed. The iMESA was created to increase the amount of *in-situ* measurements while being a low cost SWAP instrument. To show how iMESA data could improve the current forecasting model, a simulation at USAFA was conducted using a 10 satellite “string of pearls” constellation of iMESAs⁵. In Exhibit 5 below, the left-most panel (a) shows a visual comparison of ion density predicted by the forecasting model with only GPS-TEC inputs versus aftercast truth. The differences in

prediction versus truth are color scaled with green being zero error and red and blue being the larger deviations. The next two panels show the same forecasting model with both GPS-TEC data and measurement data take by the iMESAs in the string of pearls constellation. The middle (b) has the constellation flying at 500km and the right (c) has them at 350km. Each panel shows a longitudinal slice of the earth at 161.25 degrees along with latitudes from -60 to 60 degrees and altitudes up to 600 km. Panels (b) and (c) show that the predicted forecast augmented by iMESA *in-situ* data is closer to “truth” than with GPS-TEC data only.

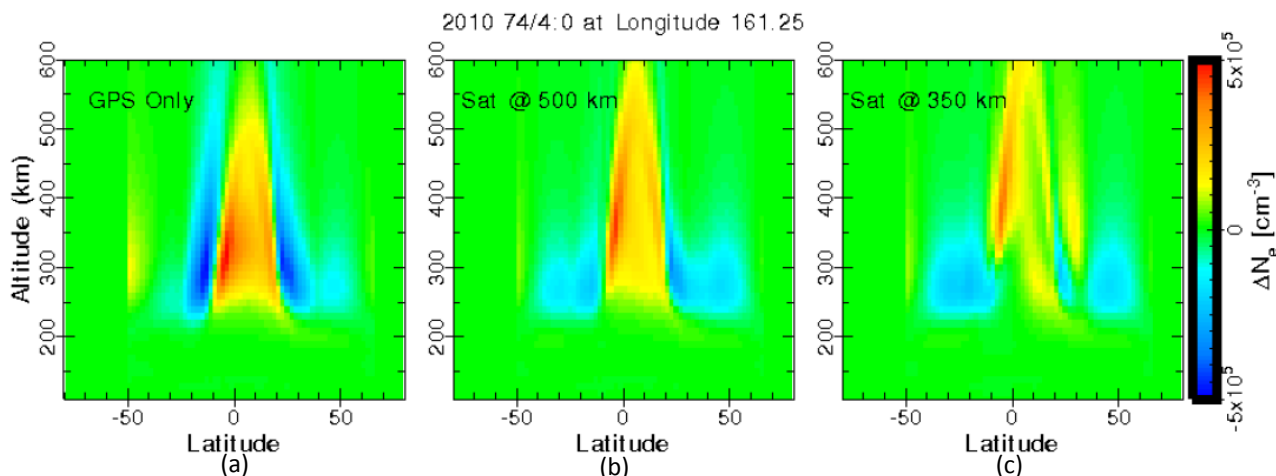


Exhibit 5: All frames show difference between the GAIM full physics aftercast model and a GAIM forecast model. Frame (a) refers to differences between full physics model and the forecast model using only GPS-TEC data, the green area shows zero difference between the models. Frame (b) refers to the difference between the full physics model and the forecast model using GPS-TEC data along with data from 10 simulated iMESA satellites in a “string of pearls” constellation at 500 km altitude, noting that there is more agreement between the two models indicated by the zero difference green area. Frame (c) refers to the difference between the full physics model and the forecast model using GPS-TEC data along with data from 10 simulated iMESA satellites in a “string of pearls” constellation at 350 km altitude, noting that there is again more agreement between the two models indicated by the zero difference green area⁵.

As shown by Exhibit 5 placing iMESAs into orbit increases accuracy of the forecast model compared to *a priori* truth. It should also be noted that although the iMESAs gather information at certain orbits, the data they gather improves knowledge at many different altitudes. The question then becomes “how many iMESAs would be needed” to improve forecasting for the entire globe. The answer depends on what metric one intends on calculating. The simulation shown in Exhibit 5 used ion density as the calculated parameter. However, if a different metric was chosen, the simulation could once again be used to find the point of diminishing returns in regards to the number of iMESAs needed in orbit to improve the forecast to a desired fidelity.

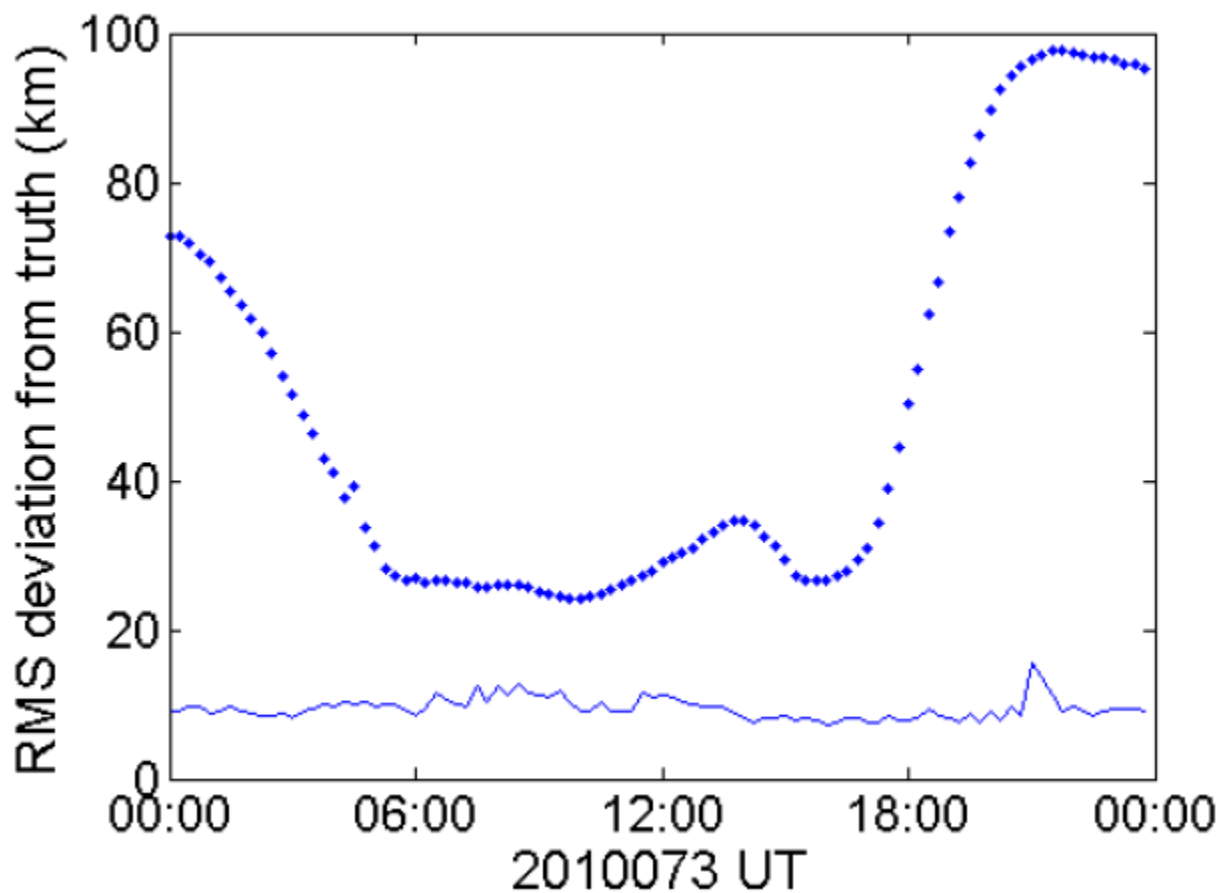


Exhibit 6: Plot of the Root Mean Square (RMS) deviation of hmF2 (the height of the F2 ionospheric peak) of the GAIM forecast model compared to the GAIM aftercast model, summed globally over the model grid. The data is shown over the course of an arbitrarily chosen day (2010 day 073). The upper dotted line shows the forecast model when only GPS-TEC data is ingested, compared to *a priori* truth. The lower solid line shows the (quantifiably improved) forecast model when both GPS-TEC data and simulated *in-situ* iMESA-R data is ingested, compared to *a priori* truth⁵. The simulated *in-situ* iMESA data comes from a Walker Constellation of 25 iMESA satellites.

Another such simulation is shown in Exhibit 6⁵. In this test, the globally summed Root Mean Square (RMS) hmF2 altitude was predicted with the GAIM forecasting model for an entire day. The dotted line represents the globally summed RMS differences in forecast hmF2 altitude with only GPS-TEC data versus the GAIM full physics model aftercast truth. The same simulation was run again except with measurements from a constellation of 25 iMESAs in a Walker configuration in addition to the GPS-TEC data. The difference between this forecast and the aftercast truth are shown by the solid blue line. Adding iMESA data in this context could improve global RMS hmF2 predictions from 80 to 20 km as shown in Exhibit 6. Although the ideal number of iMESAs needed in orbit are different based on the metric being predicted, the bottom line is that the more devices taking *in-situ* measurements, the more accurate the forecast model becomes. The improvements in predicting the density and temperature of the ionosphere could help prevent communication loss with satellites or GPS lock loss during critical times.

III. THE INSTRUMENT

The iMESA is made up of two printed circuit boards, the head and the brains board, and a series of metal plates. These boards are encased in an aluminum frame to protect them. The instrument is 118.75 mm x 101.60 mm x 34.42 mm and can be either barnacle or flush mounted with a simple change of assembly configuration and no hardware changes. Exhibit 7 is an exploded view of the iMESA assembly. The iMESA collects positive ions on an anode plate at the head board of the instrument. The energy selected ions are read as a current on the head board. The amplifier chain on the head board amplifies this current from a range of -14 to 36 nanoamps and conditions the signal to be digitized then passes it to the brains board. The microcontroller then stores the data on an SD card for later download to the satellite and then to the ground.

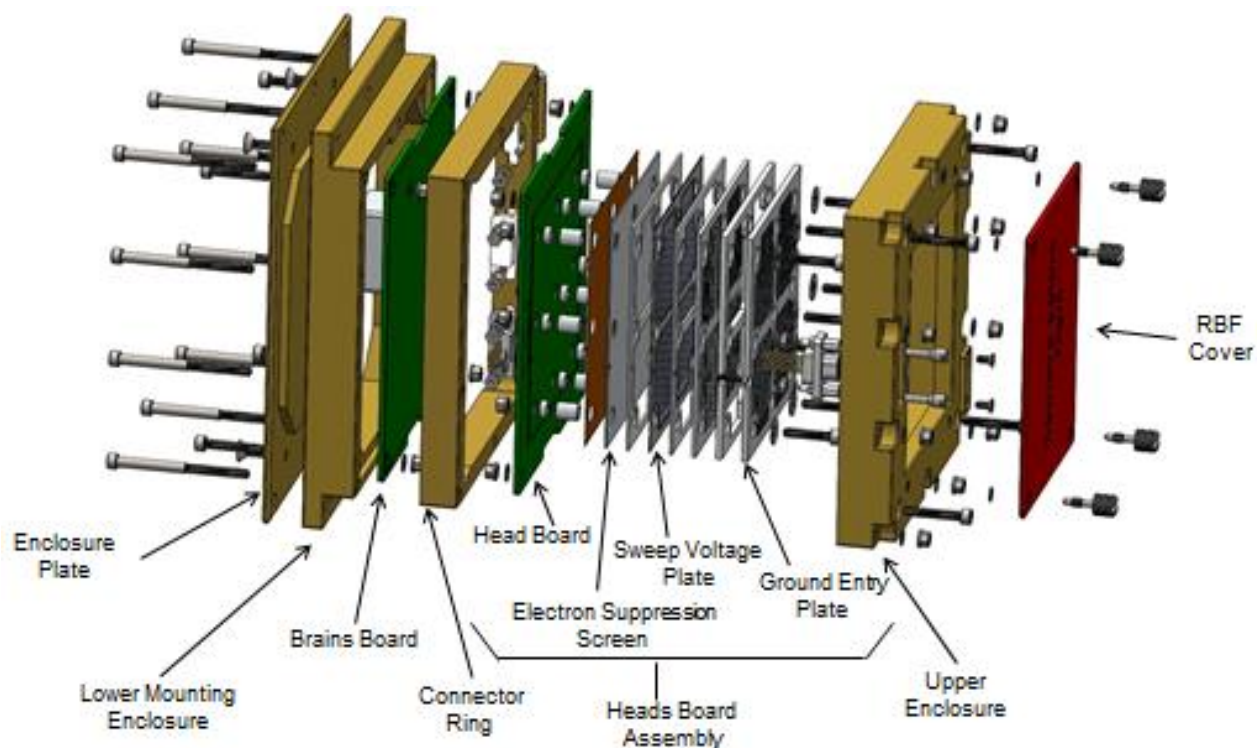


Exhibit 7: iMESA Exploded View. The exploded view of the instrument shows how the iMESA is assembled. The chassis of iMESA consists of four aluminum sections that are “sandwiched” together with the printed circuit boards held in between. The left most PCB is the “brains” board containing the digital control circuitry along with the spacecraft communication circuits and the power supply system. The brains board is mounted onto the lower mounting enclosure. There is an “auto-aligning” inter-board connector between the brains PCB and the second PCB, the “head” board. The head board contains the main analog conditioning circuits used to convert the collected ion current into the representative voltage signal that is digitized on the brains board. Additionally, mounted on the right hand side of the head board is the analyzer “plate stack.” The “plate stack” consists of, from left to right: (1) the anode, (2) electron suppression screen, (3) sweep voltage plate, and (4) chassis potential entry plate with Teflon insulating layers between each one. The sweep voltage plate and the entry plate have co-aligned slits whereby the ambient plasma is allowed to enter the instrument. This head stack is then attached to the head board with an array of nine bolts. The completed head board is then mounted to the aluminum upper enclosure.

The iMESA “head stack,” referring to Exhibit 7, consists of four conducting layers separated by Teflon insulating layers. The first conducting layer is the anode plate that collects the incoming ions as a current, the next is an electron suppression screen (needed mainly for ground based vacuum chamber calibration), followed by the slitted voltage sweep plate, and lastly the chassis potential entry plate. The slits on the entry plate and the voltage sweep plate are co-aligned. A single slit pair is shown in Exhibit 8. As the simulation⁶ in Exhibit 8 shows, a swept voltage is placed on the right-hand plate and the electric field created between the entry plate and voltage sweep plate only allows ions with a certain energy or higher to actually arrive at the anode plate to be collected as “signal.” All ions with energies below the cutoff energy (voltage) value are repelled and not measured.

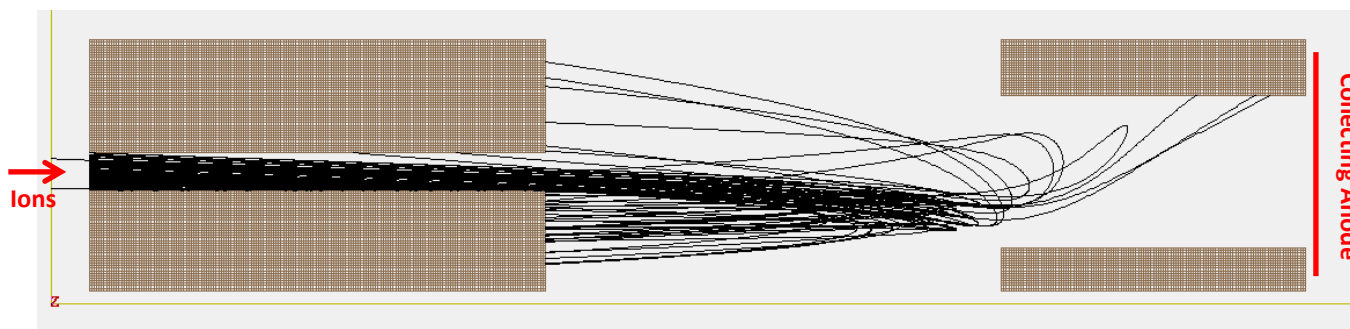


Exhibit 8: Above is the cross sectional area of one of the slit pairs that make up the high pass energy filter analyzer. The slit on the left wherein ions enter is 0.006 inches tall and 0.0775 inches long. Additionally, the width of slit on the instrument is 0.018 inches wide. The plates on the right are charged by the instrument sweep voltage, thus setting the cutoff energy of the high pass energy filter. The black lines are the path the ions take. If the ions have a sufficiently high energy they can pass all the way through the filter and be detected as signal current. If the ion energy is below the selected energy threshold they are rejected. These ion trajectories were simulated with SIMION 3D⁶.

The instrument is a high pass energy filter. The cutoff energy of this filter is set by the voltage placed on the sweep plate. The relationship between the applied voltage and the cutoff energy of this filter is referred to as the plate factor. This instrument has a plate factor of “1”. This means the allowed incoming energy cutoff is equal to the applied sweep voltage. The entry plate and voltage sweep plate slits are lined up in such way that each ion must pass through a retarding potential in order to make it to the current collecting anode. This creates a path for the particles to follow such that only ions with sufficient energy or higher make it through the electric field plate analyzer. Exhibit 8 above shows the path of ions in the head stack assembly. This is called a selective analyzer; the voltage and thus the strength of the field can be adjusted such that the cutoff of the high pass energy filter can be adjusted. The current measured at different cutoff energies can then be used to derive ion density and temperature along with spacecraft charging.

IV. ONBOARD ELECTRONICS

The core of this instrument is a set of printed circuit boards that creates the voltage sweep for the energy selective electric field, measures ion current signal, takes dosimeter readings, monitors the head and brains board temperature, and stores data. The head board is primarily analog circuitry and the brains board is mostly digital circuitry. The brains board regulates the power coming from the satellite, generates and monitors the sweep, and digitizes all science and house-keeping data including; the ion current signal, dosimeter data, and board temperatures.

The iMESA is powered from unregulated spacecraft power and can accept an input voltage range of 18 to 36 Volts. Internal to iMESA other voltages (+96, ± 24 , ± 5 and +3.3 volts) are produced for the onboard electronics. Without the dosimeter active, the iMESA consumes 2.1 watts of spacecraft power. When the dosimeter is turned on the iMESA will draw about 2.5 watts. The dosimeter can be turned on or off in flight by ground command. The power system on board is an improvement over previous iMESAs in terms of bus noise. This device uses an internal 12V mezzanine voltage bus with only a single power supply facing the spacecraft power bus. Past iMESAs have used up to three spacecraft facing power supplies. Although the old design was more power efficient, this single power supply approach will reduce noise sent back to the satellite. This design will also allow the iMESA to be reconfigured for different spacecraft power system voltages by merely changing the single input power supply. All the internal power supplies sourced from the 12V bus with the exception of the digital logic supply (3.3V) isolate digital ground and analog ground. The +3.3V logic power supply is a 3-terminal regulator making the 12V mezzanine bus ground return the iMESA's internal digital ground. The other voltage supplies mentioned earlier all operate off of the 12V mezzanine bus but are isolated supplies. The combined output grounds of these other supplies are connected together and constitute iMESAs internal analog ground system. The iMESA maintains separate digital, analog, and chassis grounds. However, the three grounds are eventually all connected together at a single star ground point as to reduce noise and eliminate signal ground loops. It is important that the instrument be connected to chassis ground because the plasma measurements are made with respect to the entire spacecraft chassis frame.

The brains board also generates the signal needed for the energy selection voltage sweep. The iMESA can create a 10, 30, or 100V sweep centered on any chosen voltage in the range of -10V to +90V. This means that the user can "focus" on any desired ion energy range of interest. The iMESA "analyzer stack" consists of the sweep plates, anode, and Printed Circuit boards. This "stack" has a plate factor of "1" as mentioned earlier. This means that the imposed sweep voltage magnitude is the magnitude of the high pass ion energy cutoff. Because of the characteristics of the device, any ion energy signal that gets passed into the iMESA will be broadened. The broadening is proportional to how sharply the energy cutoff occurs. This is often referred to as the "instrument function." By simulation, and confirmed experimentally, the ratio of this widening versus the actual energy (i.e. $\Delta E/E$) has been determined to be about 1%. This means that the energy resolution when measuring a 100eV energy plasma is about 1eV. The sweep starts when the microcontroller sends a signal to the DAC over the Serial Peripheral Interface. The DAC has four outputs. Any sweep command will direct two output two signals at a time to be generated. One output is selected from among the first three channels and the other from the fourth channel (see Exhibit9). The first three channels each correspond to an available sweep range (10V, or 30V, or 100V). The first channel is used for a 10V sweep, the second channel for a 30V sweep, and the third channel for a 100V sweep. The fourth channel is variable and used to set the offset of the sweep or the starting voltage for the sweeps. This allows the sweep voltage ranges to be centered about any value in the energy range (-10 to +90V). The sweep is monitored by another circuit that scales the sweep output voltage for digitization and inclusion with the data stream. This monitored signal will identify the magnitude of the sweep voltage present on the energy selection plates. Exhibit 9 shows the circuitry involved in making the sweep work.

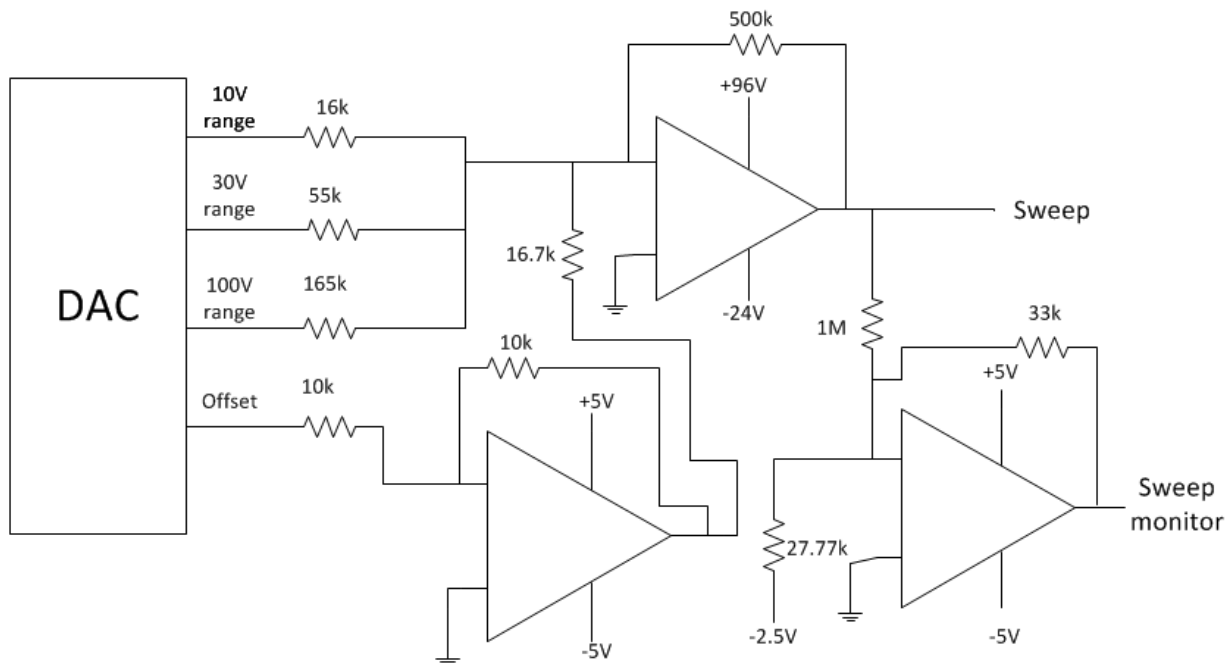


Exhibit 9: The sweep is initiated by the microcontroller which selects the DAC outputs. Two DAC signals are generated at any given time; one value for a chosen sweep range and a second on the offset output. One of the 10V, 30V, or 100V ranges is asserted. The offset output is ground commanded thus choosing the desired sweep starting value. The sweep monitor circuit scales and offsets the actual sweep voltage for digitization and inclusion in the data stream identifying the sweep voltage value at any time. The sweep monitor value is digitized by the microcontroller system along with the other system data values.

In addition to the sweep voltage, the microcontroller communicates on SPI with the sweep voltage DAC, the ADC, and the SD card. The DAC creates the sweep as explained in Exhibit 9. The ADC digitizes signals from the head board ion signal, the head board and brains board temperature readings, the sweep monitor signal, and the four channels of dosimeter data. The microcontroller stores all of the data on the SD card. The communication between the satellite and the iMESA is also handled by the microcontroller; however, it is done through the USART. This is done because the microcontroller can only talk to one peripheral at a time through SPI, thus is busy executing commands and storing data. The USART, therefore, provides another microcontroller communication channel allowing the satellite to talk to the iMESA at any time independent of the SPI bus. The ATMEGA128L has two USART ports. Exhibit 10 below shows the relationship between the microcontroller and its peripherals.

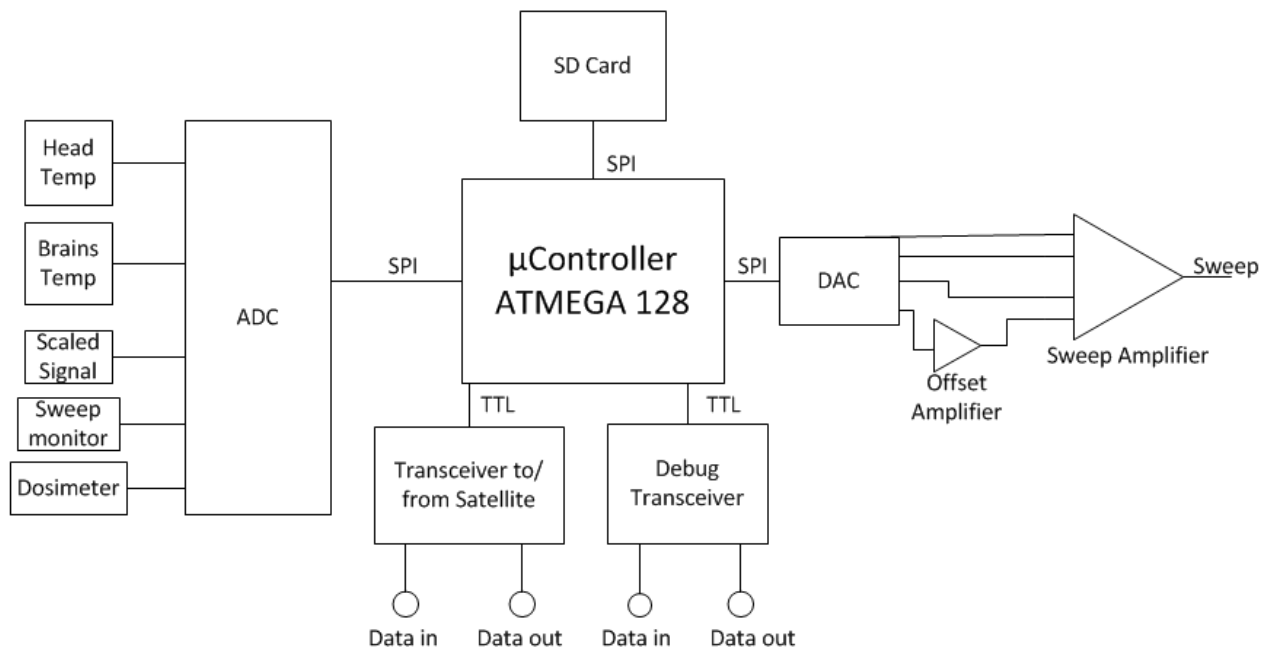


Exhibit 10: Peripheral interface. The microcontroller communicates with the ADC, the sweep DAC, and the SD card all over the Serial Peripheral Interface bus (SPI bus). Because the microcontroller needs to respond to spacecraft commands asynchronously, transmissions to and from the satellite are done over a USART port.

The head board is the mechanical mount for the head stack and routes the voltages to the sweep plates. Another function it executes is the ion signal processing. When the ions reach the anode, they are collected as a current which is sent into an amplification chain. The first trans-impedance stage amplifies the current by a factor of 10^7 ohms. After that, the signal is processed by a programmable gain voltage amplifier. This stage has switchable gains of 1, 2, 5, or 10. The gain can be selected by ground command. The increase of gain can be used to examine very small signals with more fidelity. The final block in this chain scales and offsets the signal so that it is acceptable for ADC input. When the programmable gain amplifier has unity gain the LSB of the ADC is equivalent to about 90 pico-amps of current, ignoring noise. Exhibit 11 below shows the amplification chain.

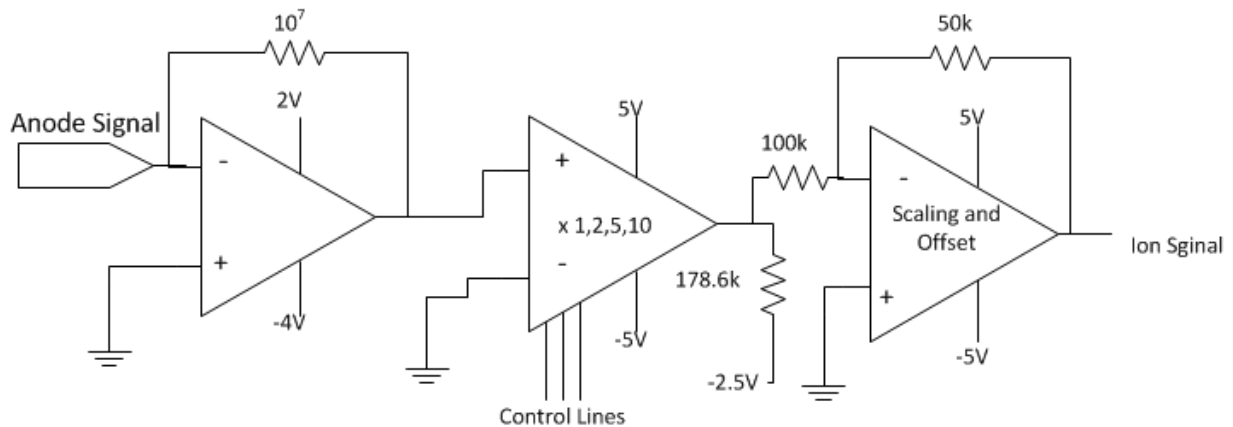


Exhibit 11: 3 Stage amplifier chain. Ions are collected by the anode and fed into the chain from the left. The first stage is a trans-impedance amplifier with a gain of 10^7 ohms. The second stage is a switchable gain instrumentation stage which allows small signals to be read more accurately. The ground command selectable gains of this stage are 1, 2, 5, or 10. The third stage scales and offsets the signal so it can be processed by the ADC.

VI. CODE AND DATA PROTOCOLS

The ATMEGA 128 microcontroller being used is programmed in the C language. The basic structure of the code is to first initialize all peripherals, such as the DAC, ADC, SD card, and the USART communications ports. After initialization the code runs in an endless “while true loop” until a flag is set to either conduct a sweep or process a command. The way these flags are set is through an interrupt structure. To elaborate, while the code is spinning in the while loop if any bytes are received over the USART communication line the code will jump to an interrupt service routine. In this routine one byte of a command is “read-in” and stored in a buffer. There is one interrupt for every byte received. If this buffer reaches the length of a valid command, the command flag is set. The code then returns to the exact place in the while loop that it left off. The while loop always examines the flag’s status and if a flag has been set the loop jumps to the appropriate subroutine. This could be anything from taking a sweep to sending data back to satellite. There are many different presets for things such as sweeps, dosimeter data, and temperature.

A Python script ground station was created to communicate with iMESA over the USART communication port simulating the spacecraft. The script can be told to send to the iMESA a specific command byte stream. It then sends a command packet of bytes, one byte at a time, to the instrument. The script then waits for an acknowledgement packet and a data packet if necessary, based on the command originally sent to the instrument and the instrument’s response. The present version of the script can handle communications on two different communication ports.

The iMESA has two USART communication ports and one JTAG programming port. One of the USART ports is for ground based debugging and the other is used for satellite communication with the instrument. The satellite communication port is divided into command A and data A signals. On the command A side; command packets from the ground and autonomous status of health requests from the satellite are accepted. On the data A side; the instrument’s outputs are data packets, acknowledgement packets, and status of health replies. The instrument requires timekeeping from the satellite as a data field in the state of health request. Both command A and data A ports operate at 115200 baud. Once commanded, the instrument begins generating voltage sweeps at

approximately a 1 Hz rate, all the while collecting the digitized ion signals, internal temperature, and dosimeter data. All this data is stored internally in the SD card until a ground command is received to download stored data to the spacecraft. All of iMESA's various modes of operation along with data download processes are ground command driven. All onboard USART interfaces are 1 start bit, 8 data bits, 1 stop bit without parity or flow control.

VI. CONCLUSION

Forecasting space weather is important because mission failure due to space environmental hazards is a real concern. Space weather can cause loss of GPS lock and communication issues. Space weather models can be significantly improved by obtaining more *in-situ* measurements. The iMESA is a low cost, low SWAP electrostatic analyzer to accomplish this task. The simple rugged construction, low parts count, and high quality *in-situ* measurement capability make iMESA an excellent candidate instrument for LEO plasma data collection. The instrument measures the energy spectrum of the plasma parameters in the ionosphere. It is a high-pass energy filter with an energy resolution ($\Delta E/E$) of 1%. This data can be used to derive the plasma density, temperature and spacecraft charging of the host spacecraft. We have shown that these *in-situ* measurements can significantly enhance the forecast accuracy of existing space weather simulations, thus enhancing space or GPS communications predictions. The instrument can also take dosimeter data of electrons, protons, and gamma rays that can be used to determine the effect of these particles on spacecraft systems. The Air Force Academy is currently building four iMESA instruments which will constitute a space weather constellation. The information from this constellation can be used to supplement existing models of the ionosphere relatively cheaply and improve space weather forecasting.

¹ C. Y. Huang, W. J. Burke, J. S. Machuzak, L. C. Gentile, P.J. Sultan. (2002). Equatorial plasma bubbles observed by DMSP satellites during a full solar cycle: Toward a global climatology. *Journal of Geophysical Research*.

² C. L. Enloe, L. Habash Krause, R. K. Haaland, T. T. Patterson, C. E. Richardson, C. C. Lazidis, R. G. Whiting. (2003). Miniaturized electrostatic analyzer manufactured using photolithographic etching. *Review of Scientific Instruments*, 1193-1195.

³ C. L. Enloe, L. Habash Krause, M. G. Mcharg, O. Nava, Paul B. Shoemaker, Ehren Ehmann, John D. Williams. (n.d.). Characterization of a Plasma Source for Ground-Based Simulation of LEO Plasma Conditions. American Institute of Aeronautics and Astronautics.

⁴ J. E. Mazur, W. R. Crain, M. D. Looper, D. J. Mabry, J. B. Blake, A. W. Case, M. J. Golightly, J. C. Kasper, H. E. Spence. (2011). New measurements of total ionizing dose in the lunar environment. *Space Weather*.

⁵ Richard L. Balthazor, M. G. Mcharg, C. L. Enloe, B. M. Muller, D. J. Barnhart, Z. W. Hoeffner, Robert Brown, Ludger Scherliess, Lance T. Wilhelm (2015). Methodology of evaluating the science benefit of various satellite/sensor constellation orbital parameters to an assimilative data forecast model. *Radio science*. In Press.

⁶ Dahl, D. A., SIMION 3D, Software Package, Ver. 8.0, Idaho National Engineering Laboratory, Idaho Falls, ID.2006.