VALIDATION TESTING AND GROUND SUPPORT EQUIPMENT DEVELOPMENT OF THE GRIDS INSTRUMENT FOR THE PETITSAT SATELLITE

Jonathan Green

Virginia Polytechnic and State University

Advisor: Gregory D. Earle

Abstract

The following report discusses a testing methodology, ground support equipment development, and evaluation of a CubeSat space science instrument named GRIDS. The GRIDS instrument will be the primary scientific instrument aboard the NASA petitSat mission, set to be launched in 2020. The mission intends to investigate mechanisms, prominently MSTIDS, causing plasma irregularities in the Ionosphere. The mission will both develop a greater understanding behind the physical link between the mechanism and irregularities and quantify the mechanisms affect.

The report addresses methods of ground support equipment development (LabView) and manners to validate developed systems (Machine Vision), in order to develop an effective, automated, and streamlined test environment for purposes of validating a CubeSat plasma-based instrument. The following methods used can also be equipped for testing of other CubeSat instrumentation, allowing for future inexpensive satellite missions promoting space science.

I. Research Objective

The following research report discusses the evaluation, validation testing, and ground support equipment (GSE) development for a unique space science instrument named GRIDS (Gridded Ion Distribution Spectrometer), shown in Figure 1. The GRIDS instrument combines two conventional sensors, an Ion Drift Meter (IDM) and Retarding Potential Analyzer (RPA), into a single sensor head for purposes of size and mass reduction. The coupled IDM and RPA instrument will measure overall plasma density, ion temperature, relative composition of H^+ and O^+, and the three-dimensional ion velocity vector components aboard the petitSat (Plasma Enhancements in The Ionosphere-Thermosphere Satellite), set to be launched in 2020 [1].

The petitSat mission, with the GRIDS instrument as the primary space science instrument, aims to: (1) *observe drift density and O+/H+ signatures of plasma enhancements as a function of magnetic latitude and* (2) *determine the relative contribution of Medium-Scale Traveling ionospheric Disturbances (MSTIDS) to the generation of plasma enhancements in the ionosphere* [1]

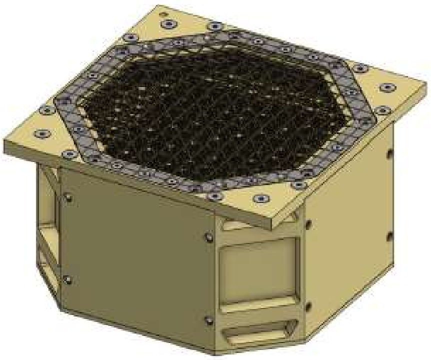


Figure 1: GRIDS Instrument

To ensure the successful completion of the scientific goals and objectives for the petitSat mission, this report particularly addresses the IDM sensor and its corresponding testing methodology, GSE development, and evaluation.

The report discusses the following topics to achieve the objectives of the GRIDS-IDM instrument testing:

1. Establish test objectives and procedures for functionality validation testing of the GRIDS-IDM Instrument.
2. Develop a LabView interface for automating test procedures and facilitating data collection of GSE.
3. Implement machine vision tools to validate GSE and characterize GSE error.
4. Space-simulation vacuum chamber testing and evaluation.

The main objectives of the GRIDS-IDM instrument testing are to:

1. Validate functionality in a space-simulation vacuum chamber
2. Demonstrate sensitivity of GRIDS-IDM instrument to angle of arrival of the ion beam relative to the instrument aperture [2].

II. Background and Motivation

The Ionosphere is the outer most region in the Earth's atmosphere, ranging from 75 to 1000 kilometers above sea level, and therefore is subjected to the most intense radiation originating from the Sun and other cosmic bodies. Ambient atoms in this region are stripped of an electron and are effectively 'ionized', hence the regions name [3]. This ionized region of plasma has refractive characteristics that enables a critical technology: radio propagation, which has wide ranging applications in global communication, navigation, surveillance, and over-the-horizon (or beyond-the-horizon) radar [4] However, the ions in this region that enable radio technology can also lead to distortions of radio signals. Irregular density regions of plasma including depletions (bubbles), enhancements (blobs), and scintillations have been found to cause distortion in radio propagation [1]. Therefore, it is imperative that the mechanisms behind the irregularities be comprehensively studied and understood.

There has been relative debate on the source of these plasma irregularities, however one mechanism has been identified as a potential source: Medium-Scale Traveling Ionosphere Disturbances (MSTIDs). MSTIDs are quasi-period perturbations within the F-layer of the ionosphere, and hypothetically produce an uplift of O^+ plasma that result in regions of density irregularities [1]. Therefore, in order to validate and quantify the effect of the following mechanism, physical measurements of the uplift and the corresponding velocity vector need to be measured to correlate MSTIDs and irregular plasma regions.

In order to accomplish these goals, the petitSat mission intends to collect in-situ data of plasma enhancements and pair it with remote data on MSTIDs occurrences (collected from ground-based sensors). In-situ data on plasma enhancements will be accomplished with a 6u CubeSat, equipped a unique space-science instrument: GRIDS, that intends to measure the overall plasma density, O^+ and H^+ component density, and the plasma drift velocity vectors [1]. The GRIDS instrument combines two instruments: (1) a Retarding Potential Analyzer, that measures plasma density, temperature, and the orbital velocity vector, and (2) an Ion Drift Meter, that measures the relative arrival angle. The two instruments in unison allows for a complete thermal profile and a three-dimensional velocity vector of the ions. Finally, by pairing O^+ ion data from the GRIDS instrument with remote MSTIDs data, the physical link between regions of plasma irregularities and MSTIDs can be validated and the mechanisms affect can be quantified.

This research report addresses the functional validation testing of the GRIDS instrument, in particular, the IDM portion of the GRIDS sensor head, in order to verify the instruments ability to measure varied angular entries of ions. Therefore, validating the basis of the GRIDS instrument and allowing for successful data encapsulation for the petitSat mission.

III. Instrument Description: Ion Drift Meter

The GRIDS instrument can be separated into two fundamentally and functionally distinct elements: (1) the grid stack and (2) the collector segments. The grid stack consists of a series of biased grids that intend to discriminate ion entry into the sensor. During the IDM operation of the GRIDS instrument, the inner grids are grounded while the outermost grid is biased to a static +5-volts to discriminate from light-ion entry into the sensor aperture.

The collector segments are a segmented array of four conductive surfaces. Ion atoms that travel through the aperture and past the grid stack collide with the surface and transfer charges. The internal circuitry of the GRIDS instrument measures the charge as a current for each the four individual collectors [5] .

To determine the arrival angle, the internal GRIDS electronics adds the currents in collector pairs, for a total of four pairings, that represent the top, bottom, left and right of the overall collector area. Figure 2 represents the segmented collector layout and the pairing of the collectors to provide the intermediate current measurements.

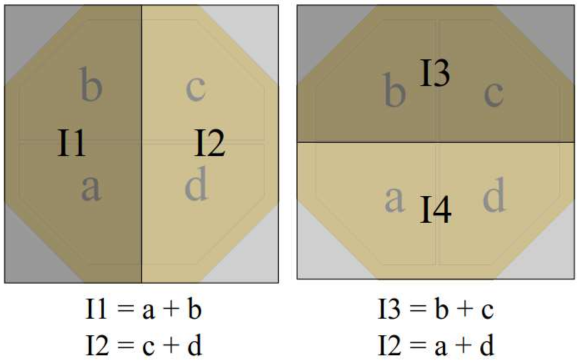


Figure 2: Segment Collector Pairs

The opposing pairs (I1-I2, I3-I4) allow for determination of the ratio of current between the two halves of the collector area for further calculation on the entry angles: alpha and beta. Additionally, with knowledge of the GRIDS instrument's dimensions, the equations for the two arrival angles (alpha, beta) become simple trigonometric equations, listed below. Equation (1) represents calculation of the alpha angle; Equation (2) represents the calculation of the beta angle.

$$\tan(-\alpha) = \frac{W}{2D}\frac{1-\frac{I_1}{I_2}}{1+\frac{I_1}{I_2}} \qquad (1)$$

$$\tan(\beta) = \frac{W}{2D}\frac{1-\frac{I_3}{I_4}}{1+\frac{I_3}{I_4}} \qquad (2)$$

Where W represents the width of the GRIDS aperture; D represents the depth from aperture to collector segments within the GRIDS enclosure; I represents the collector pairs visualized in Figure 2.

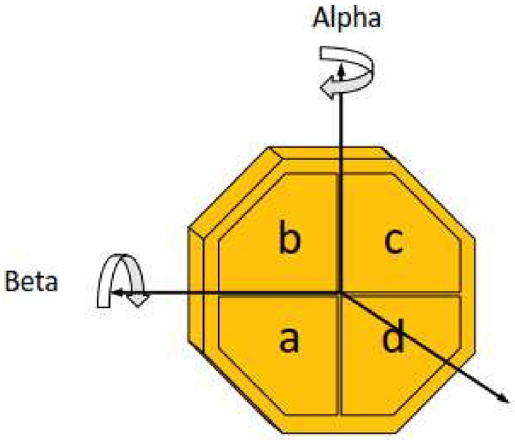
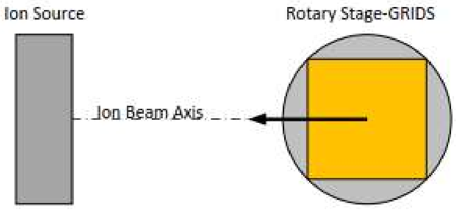


Figure 3: Alpha/Beta IDM Angles

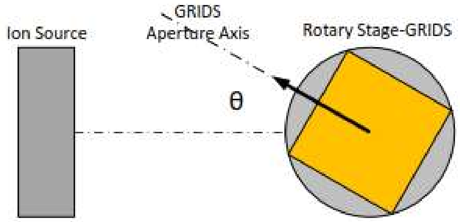
The two calculated angles will correspond to the two arrival angles in the zenith-nadir and orbit normal direction. When the arrival angles are combined with the RAM velocity vector, a three-dimensional velocity vector of ion drift is the result.

IV. Test Objectives and Procedures: IDM Functionality Test

To ensure the functionality of the GRIDS-IDM instrument, the instrument needs to be tested within the space-simulation vacuum chamber equipped with a hot-filament ion source. The chamber would reproduce the low-pressure environment experienced in orbit, while the ion source would simulate plasma with a localized beam of ions. In order to reproduce the varied angular entry of the upward ion drift, a motorized rotary table was implemented to rotate the GRIDS instrument about the ion beam axis.



(a) GRIDS in initial position



(b) GRIDS in at varied arrival angle θ

Figure 4: GRIDS-Rotary Table Test Implementation

To test the additional arrival angle of the GRIDS instrument, the instrument was simply rotated 90° to test the alternative collector pairs.

Due to the high variation of the density and asymmetry of the ion beam, testing was limited to strictly a functionality test in a space simulation environment. Calibration and space flight qualification of the instrument would be accomplished in an iterative round of testing; with the aid of a high precision current source to stimulate the collector plates independently. Moreover, the excessive heat radiating from the filaments within the ion source, testing needed to be limited to around ~3 minutes to prevent potential damage to the filaments and deformation of ion source components.

The itemized list below represents the testing procedure for the GRIDS-IDM functionality test.

GRIDS-IDM Test Procedures:

1. Align the GRIDS instrument aperture to be directly perpendicular to the ion source aperture. Zero the motor controller.
2. Clockwise (CW) angular sweep from -5° to +5° at 0.5° increments. Angular index incremented for either:
    a. Interrupt signaling successful packet read from GRIDS-IDM instrument.
    b. 8-second timer expiring. Ensures set testing intervals to mitigate potential thermal issues with hot filament ion source.
3. Counterclockwise (CCW) angular sweep from +5° to -5° at 0.5° increments.
4. Repeat CW and CCW sweeps for >3 iterations.
    a. Ensures iterative trials at similar ion source conditions (temperature, current);
5. Rotate GRIDS instrument 90° to test beta angle.
6. Repeat Steps 2-4

V. GSE Development: Rotary Stage LabView Interface

A LabView graphical user interface (GUI) was developed to allow for complete automation of GRIDS-IDM testing and to easily facilitate motor controller data collection.


VISA In: COM17
Filename notes:
GRIDS Packets Per Step: 1
Angular Position: 0
Step Time: 0
Save State Time: 0
Step Index: 0
# of Steps: 0
Driver Response:
Target: 0
ASCII Command:
Time Step (s): 4

Figure 5: Rotary Stage GUI

The GUI communicates over RS-485 to a single axis stepper motor controller (NSC-A1) that drives a motorized rotary stage (RM3-100V).

The GUI contains custom functions to run the CW and CCW sweeps for customizable test parameters (angle range, angle step size, number of IDM packets received, step timeout timer, and rotary stage speeds). Moreover, the GUI possessed both interrupt capabilities mentioned in Section IV, by implementing a global interrupt that is triggered with every retrieval of a full IDM data packet; and setting an additional timer where its timeout triggers the next angle index.

In order to reliably and consistently retrieve angle data during a test run, the interface employs a state machine where the idle state consistently queries the angle for the NSC-A1 controller, displays the angle on the interface for monitoring purposes, and saves the data and timestamp to an excel file. Allowing for angle data recording and monitoring at a cadence of 100 milliseconds.

Extra functionality is included to externally control the rotary stage with both ASCII commands and user commands and buttons. In total the GUI possess five modes of operation: (1) Free Move, (2) Query, (3) CW, (4) CCW, and (5) Zero.

VI. GSE Validation: Rotary Stage Error Characterization

Before testing of the GRIDS-IDM instrument, the GSE, including the motor controller, motorized rotary stage, and LabView GUI were validated and characterized with the use of a machine vision tool. The tool, developed and published as GitHub repository and modified by Space@VT engineer: Brett Poche, implemented a python script that tracked a laser pointer in a standard video file, and returned the pixel location of the pointer and the corresponding time stamp [6]. With the addition of a frame of reference and the distance from the laser origin to frame of reference, the measured angle becomes a simple trigonometric equation, shown below in equation (3).

$$\theta = \tan^{-1}\frac{\frac{\Delta pixel}{Pi}}{D} \qquad (3)$$

Where θ represents the measured angle of the rotary stage; Δpixel represents the change in pixel location from a predefined datum; Pi represents the pixels per inch; and D represents the distance from the laser pointer aperture to the defined frame of reference.

The GSE was evaluated as a fully integrated system. Ensuring that the full and assembled experimental set up had been tested and validated.

The validation objectives were to ensure that GSE angular error, or difference from the motor controller to the measured angle (from the machine vision tool), did not exceed 0.1˚ for any angular value over the interval range for IDM testing (-5˚ to +5˚). Moreover, in order to assess the GRIDS instrument angle measurements, the error of the experiment set up must be characterized and quantified for later use in uncertainty.

The following figure, Figure 6, is a plot of the angle error as a function of GUI commanded angle.

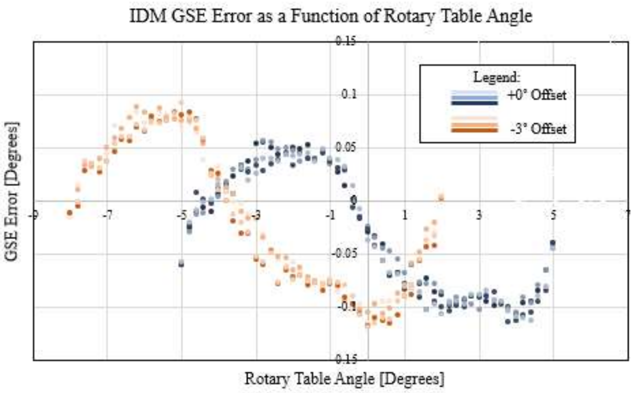


Figure 6: GSE Error vs. Rotary Stage Angle

The blue scatter plot represents three iterations of angled sweeps from -5˚ to +5˚ at 0.2˚ intervals. The darker points represent the first sweep, and the points lighten in color for each iterative sweep. The angular error, or difference of motor control angle and machine vision calculated angle, can be seen to follow a sinusoidal trend. This indicates that there is inherent error within the setup of the laser tracker, possibly due to misalignment of the laser pointer and rotary table. However, to ensure the error is product of the set-up, and not the GSE, an additional sweep was tested but with a -3˚ offset.

The orange scatter plot represents three iterations of angled sweeps from -8˚ to +8˚ at 0.2˚ intervals. Once again, the darker points represent the first sweep; the color gradually lightens for each iterative sweep. The sinusoidal pattern is seen once again, therefore concluding that the error pattern is not a function of the GSE or the commanded rotary table angle. Rather, the error exists in the experimental set up.

Despite the sinusoidal pattern of error, the magnitude of error mainly varied within +0.05˚ and -0.1˚. Therefore, validating the GSE with consideration to the previously mentioned validation standard.

VII. Test Results and Analysis: IDM Functionality Test

Following successful validation of the IDM GSE, both the alpha and beta arrival angle measurements of the GRIDS-IDM instrument were tested and measured against the motor controller.

Alpha Angle:

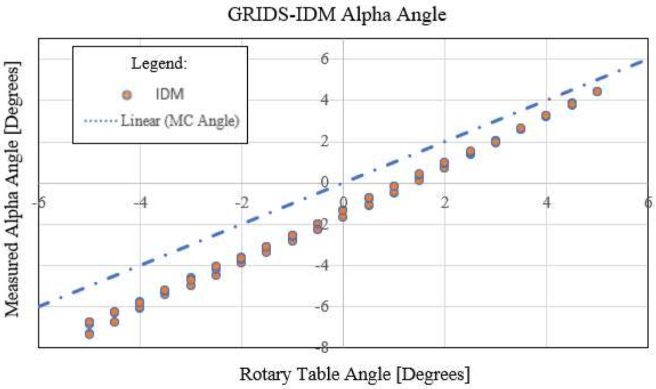


Figure 7: IDM Alpha Angle vs. Rotary Stage Angle

The blue dashed line represents the ideal linear trend for the IDM alpha angle calculation. For instance, a rotary stage angle of 2˚ would correspond to an IDM alpha angle calculation of 2˚. The orange points represent the calculated alpha angle for the GRIDS-IDM Instrument. The average error, difference of controller and IDM angle measurements, was found to be 1.42˚.

Beta Angle:

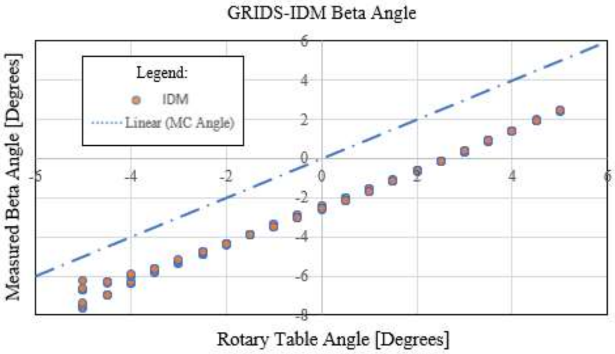


Figure 8: IDM Beta Angle vs. Rotary Stage Angle

Once more, blue dashed line represents the ideal linear trend for the IDM beta angle calculation. The orange points represent the calculated beta angle for the GRIDS-IDM Instrument. The average error for the beta angle was somewhat greater than the alpha angle calculations and was found to be 2.43˚.

Analysis:

Although the IDM calculations for both the alpha and beta angles varied to the true angle value by noticeable differences: 1.43˚, and 2.43˚ respectively. This error can be contributed to imperfections of the GRIDS GSE equipment and experimental setup. There are two associated causes: (1) misalignment of the ion source to the direct center of the GRIDS aperture. And (2) a time variant ion beam that varies with both density and uniformity over time [7].

However, despite the error offset due to experimental setup, the testing had achieved the two proposed objectives by demonstrating a linear response in the IDM arrival angle calculations as a function of rotary stage angle; and by demonstrating this relationship within a space-simulation vacuum chamber.

VIII. Conclusion

Large satellite missions, using similar instruments, have contributed greatly to our understanding of the space environment in LEO altitudes. By validating and calibrating a CubeSat sized version of the GRIDS instrument, the work described above will enable the next generation of small satellite measurements and thereby continue to improve our understanding of the near Earth orbital environment.

X. References

[1] Klenzing, J., Clagett, C., Davidson, R., Earle, G., Jones, S., Martinis, C., Paschalidis, N. and Pfaff, R. (2016). *Plasma Enhancements in The Ionosphere-Thermosphere Sattelite (petitSat)*. pp.1-20.

[2] Earle, G. D, et al, GRIDS Prototype Vacuum Testing Report Virginia Tech Team (2019)

[3] The Earth's Ionosphere. (n.d.). Retrieved: http://solarcenter.stanford.edu/SID/activities/ionosphere.html

[4] McNamara, L. (1994). *Radio amateurs guide to the ionosphere*. Malabar, Fla.: Krieger Pub.

[5] Davidson, R. L, et al, petitSat Mission Gridded Retarding Ion Drift Sensor Interface Control Document (2019).

[6] Montgomery, B, et al, python laser tracker. Retrieved: github.com/bradmontgomery/python-laser-tracker

[7] Robertson, E., G. Earle, and J. Green, A configurable ion source for validating spaceflight based thermal plasma measurement systems, *Rev. Sci. Instrum*., under review for publication in 2019.