Positioning and Testing of Inertial Measurement Units

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This paper discusses our ongoing research into assessing the accuracy of inertial measurement units (IMU). We used three different IMU's varying in price and performance. The utilization of the different models was explored over the recent August 21st, 2017 total solar eclipse high-altitude ballooning live stream project. The IMU's were used on the ground tracking station for orientation. Understanding the precision and accuracy of different units was paramount to the ground station's functionality. The results of our findings are presented in this paper; distinct configurations, including being near metallic materials and how that affected the inertial measurement unit's performance are discussed.

Nomenclature

ABS	=	acrylonitrile butadiene styrene a common thermoplastic polymer
Arduino Uno	=	microcontroller board based on the ATmega328
BNO055	=	application-specific sensor nodes implementing a 9-axis absolute orientation sensor
CAD	=	computer-aided design
CNC	=	computer numerical control, automated machining of tools by computers
IMU	=	inertial measurement unit
FDM	=	fused deposition modeling 3D printer
GPS	=	global positioning system
Mu-metal	=	nickel-iron soft metal, used in shielding electronics

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RFD900	=	900MHz ISM band radio modem, for long-range serial communication
SLA	=	stereolithography 3D printer
Ubiquiti	=	Wi-Fi modem
XML	=	data package

I. Introduction

A. Project Overview

This research was done as a component of the 2017 total solar eclipse NASA live stream project. The goal was to stream live footage of the eclipse from 60,000 to 80,000 feet to the NASA website. In addition to our team, there were 55 other teams nationwide that used our project as a foundation to live-stream their own eclipse video. A key component of the project was the affordability, this was important in allowing other teams a chance to participate in the project and as such was capped at $4,300 per system. To meet this budget the project configuration consisted of a series of payloads containing a variety of commercially available electronics and camera systems strung underneath latex weather balloons. The video systems consisted of a raspberry pi and, depending on the configuration, one or eight cameras in addition to a power board and batteries. The still image payloads consisted of similar hardware, but with modified firmware. Transmission frequencies to the ground station consisted of a combination of RFD900 for still images and Ubiquiti Wi-Fi 5.8 GHz for video. An overview of the system can be seen in figure 1.

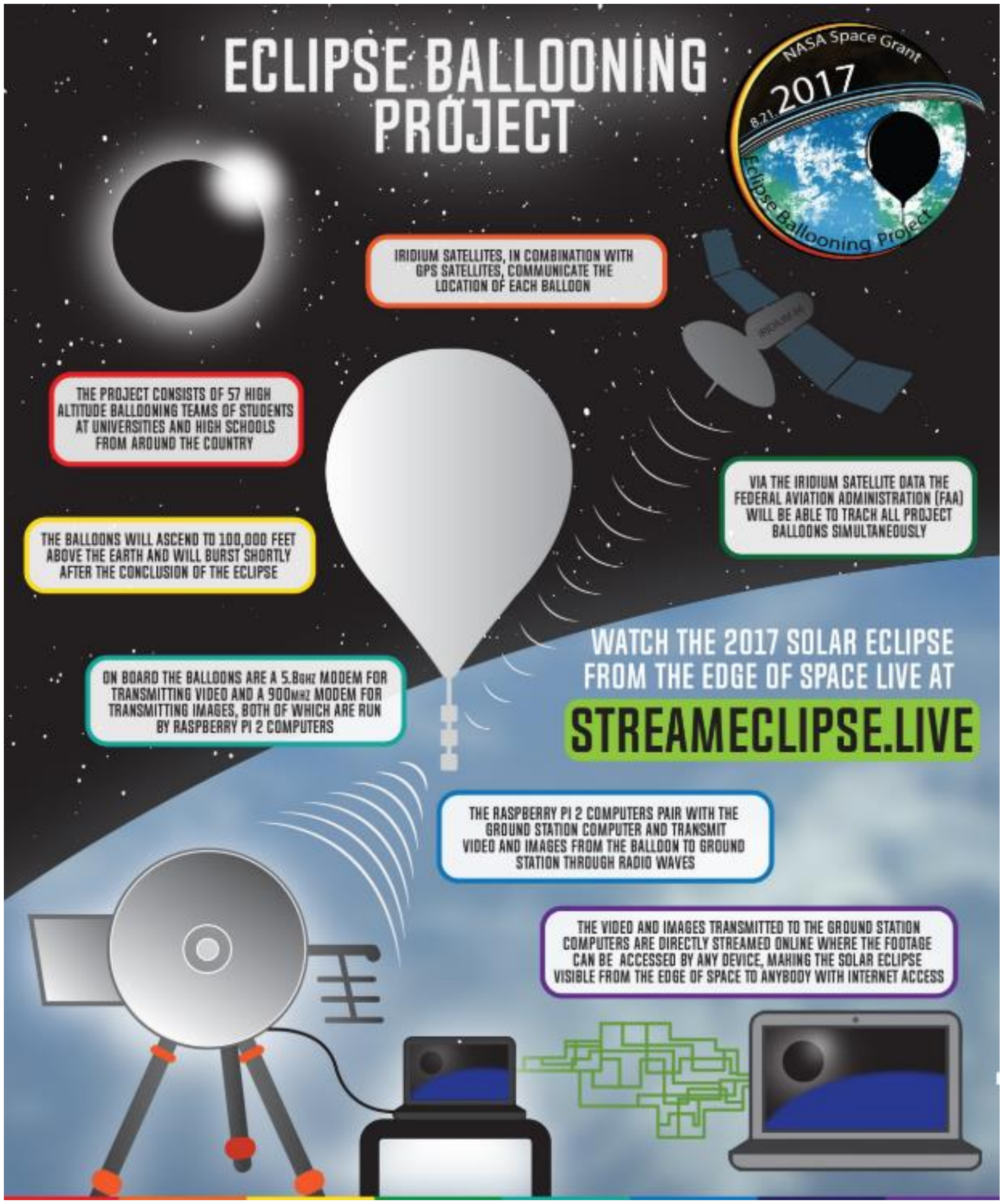

Figure 1: Flow chart of overall project Ref. [1].

In addition to the payload systems, the project included a ground based system that was used to track the balloon in addition to being able to send and receive transmissions. The Ubiquiti Wi-Fi band of the video transmission had a ±2.8° acceptance angle, therefore the pointing accuracy of the ground station needed to meet or exceed the accepted beam angle of the antenna. It can be deduced how important the accuracy of the IMU was for the system.

The ground station consisted of a variety of components, which can be seen below in figure 2. The IMU and GPS systems were used during initial setup to ensure that the absolute position and orientation of the directional antennas could be derived. To do this, the IMU communicated with an Arduino Uno that was equipped with a GPS shield. After a calibration sequence performed during every instance of the system setup, the GPS and IMU would return a combination of Euler vectors and global position. After the data is obtained, it gets passed through to the ground station computer through serial communication. The GPS data is used in conjunction with a lookup table to determine the magnetic declination of the systems location. This data is then used to calculate the absolute magnetic bearing of the ground station system.

Throughout the duration of the flight one of the payloads communicated it's GPS location through the Iridium network. Data received was passed from an XML packet into a database maintained on the Montana State University campus. Once every three seconds the ground station computer would access the database to receive the positional data of the balloon. After receiving the data, the computer used the Haversine function to calculate the bearing and elevation between the ground station position and the position of the balloon.

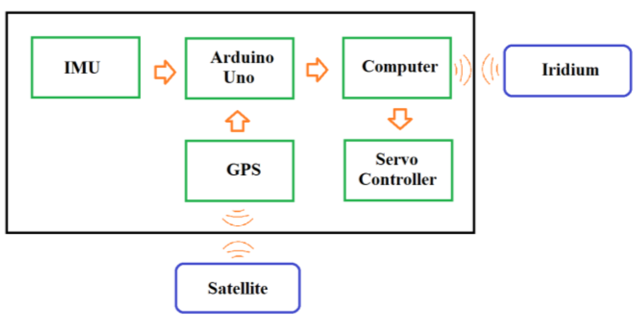

Figure 2: Ground station flow chart.

B. IMU Overview

An inertial measurement unit (IMU) is a system that can measure linear and angular motion through a combination of gyroscopes, accelerometers and magnetometers. A simplified reference can be seen below in figure 3 below. There are two standard configurations to attaching an IMU. The first is, a fixed position (strapdown), the second is being gimbaled. The IMU will report a variety of information including but not limited to; velocity, acceleration, and magnetic fields. These data points can be used to calculate relative or absolute position. Most low cost IMU's are used to give relative position, this is due to the sensitivity restriction of the magnetometers in use. When paired with a GPS, the system can account for declination to find true north in addition to magnetic north. While it's possible to use a microcontroller to calculate the positional data, some of the algorithms can be too intensive, so for the project, the calculations are handled by the ground station computer. There are two main mathematical methods used, the first is quaternions, which prevents gimbal lock, while the second is Euler vectors, which does not. The ground station was designed to be stationary, Euler vectors were used since gimbal lock was not a concern. One of the most recent studies on the functionality of inertial measurement units was done by Frank Van Graas from Ohio University in 2013 Ref. [2].

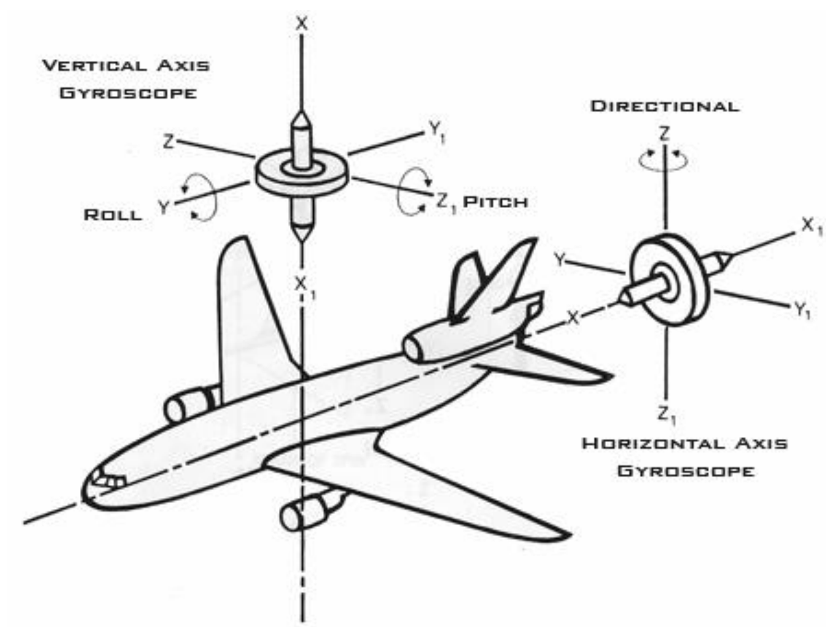

Figure 3: Function of gyroscope Ref. [3].

C. Research in Question

The research done in this paper started when we noted loss of transmission of the payloads at shorter than anticipated distances and that the antenna on the ground station did not appear to be pointing in the correct direction. This was discovered when the values began changing drastically when the IMU was placed further away from the 80/20 bar (6105-T5 aluminum alloy) that it is mounted to and near the servo motors that are on the ground station. The purpose of this research was to find a solution to the interferences and develop a configuration that optimized the performance of the ground station. This was done by experimenting with different IMU models and implementing an assortment of mechanical configurations. The IMUs that were tested include the BNO055 Bosch IMU mounted on an Adafruit breakout board (existing IMU on system), the DC-4E from Sparton Industries, and the VN-100s from Vectornav Technologies. This information would be able to assist similar configurations and problems faced with IMU positioning.

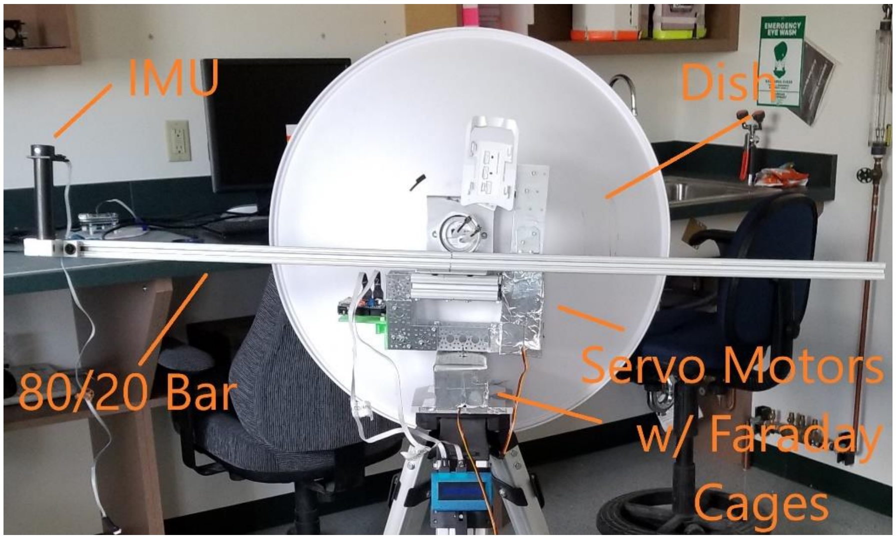

Figure 4: Configuration of IMU on 80/20 bar and servo motors.

II. Materials and Methods

A. IMU models tested

The first potential problem explored was if the bearing from the BNO055 was accurate. The procedure used to test the IMU consisted of mapping out known locations with a GPS receiver. The unit used was a Trimble Geo 7x receiver. The data collected was then processed using a program called Pathfinder Office Through this process we could set up a control area to do testing. Through this test we confirmed the accuracy of the BNO055 to be ±1.5°.

The next test was to see if a more expensive unit with a higher accuracy would increase the performance of the system. The models that were tested alongside the BNO055, was the DC-4EP and the VN-100. Each varying in price and accuracy which can be found in the figure 5 below. This test was using the signal strength of the Ubiquiti modem and a compass bearing as a reference. Through this process we tested all three units and compared the data.

All three IMU's were within 1° of each other, the price of the BNO055 was a fraction of the cost with comparable results. Since, our system had a beam acceptance angle of ±2.8°, we ended up staying with the BNO055 IMU.

Model	Manufacturer	Cost per Unit	Accuracy
BNO055	Adafruit	$35	±1.5°
DC-4EP	Sparton	$700	±.3°
VN-100	Vectornav	$1,000	±.2°

Figure 5: Tested IMU data.

B. Interference from 80/20 bar

The 80/20 bar is comprised of a non-magnetic alloy, it was observed that the IMU reported a bearing that was influenced by being in proximity to the bar. This effect was significant, leading to errors as large as 8°. The 6105-T5 aluminum alloy consists of aluminum, magnesium, and silicon, including trace amounts of iron, manganese, copper, chromium, nickel and zinc Ref. [4]. Normally an IMU is capable of being calibrated around the soft-iron effects presented by these materials. However, the discrepancy was noticed too late in the project for a code fix to be implemented, thus requiring a hardware modification to minimize the discrepancies.

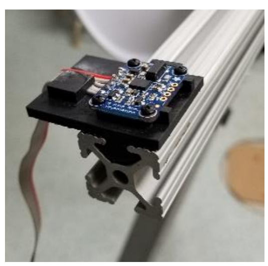

Figure 6: Original IMU bracket.

There were two main brackets that were created to reposition the IMU away from the bar to solve this problem. The original bracket set flat on the 80/20 bar and on the same axis, as seen above in figure 6. Both brackets that were constructed stood 6 inches off the rod, we noticed anything less interference was detected and anything more was excessive. Another design concern was that the IMU needed to be able to be remove from the bar for calibration. The first bracket was created for rigidity and resilience. It was constructed out of a rail-to-tube holder, a 6-inch ABS rod and a CAD mount which was 3D printed on a Formlabs Form 2 SLA 3D printer at 100 micron resolution. The bracket extends out from the ABS rod to remain in the same axis as the 80/20 bar, this can be seen in figure 7 below. During ground station testing we received non-variable readings from the IMU which, in turn gave a good signal to the payloads. Making the first bracket a viable solution.

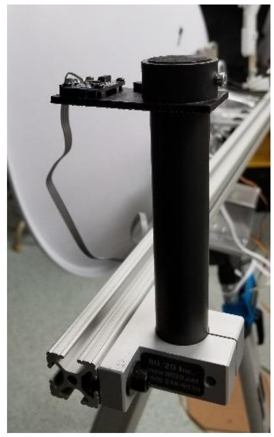

Figure 7: First new IMU bracket.

The second bracket that was constructed consisted of a piece of acrylic sheet which was CNC laser cut and a CAD mount which was printed on a Ultimaker 2+ FDM printer at a 400-micron resolution, this can be viewed below in figure 8.

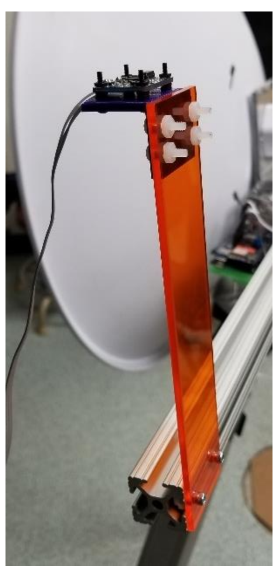

Figure 8: Second new IMU bracket.

The reason for the construction of the second bracket was cost considerations and manufacturing times. The second bracket was 40 times less expensive and could be manufactured 19 times faster using the FDM printer and CNC laser cutter. The complexity of the first IMU mount resulted in inaccuracies when printed on the FDM printed. We were forced to use the SLA printer. In figure 9 below there is a full price and time break down. This was taken into strong consideration with the project nearing its conclusion. The first bracket also required ordering parts which had limited availability. With over 55 teams this would not be a feasible option. The first bracket is the one that we used and the second is the one we shipped out to the other teams, who wanted it.

First IMU Bracket		
Parts	Cost per unit	Time to make
6" ABS Rod	$3.57	1wk shipping
Rail-tube holder	$34.10	1wk shipping
IMU printed mount	$12.00	7 hours
Total	$49.77	1wk, 7hours
Second IMU Bracket		
Parts	Cost per unit	Time to make
Acrylic sheet 3mm	$0.73	2mins
IMU printed mount	$0.50	20mins
Total	$1.23	22mins

Figure 9: Price and Time breakdown of first and second bracket.

C. Interference from Servo Motors

The IMU bracket had the ability to be mounted anywhere on the 80/20 bar. When it was placed closer to the servo motors it began to experience a ±2° variability. In theory, the frequency of the servos was one of the harmonics of the clock on the BNO055, which was causing interference and leading to inaccurate measurements. To counteract this, we designed Faraday cages for both servo motors (tilt and pan). The choice of metallic material was between mu-metal and 1060 aluminum alloy. Mu-metal is slightly better at shielding than aluminum above 1MHz Ref. [5]. We needed shielding below 1MHz since the clock on the BNO055 max frequency was 400kHz, because of this we decided to go with Aluminum. Another consideration was the cost and availability of mu-metal. For the construction of the Faraday cages .025 inch 1060 aluminum alloy was used, below in figure 10 you can see the cages mounted on the system. The cages were grounded to the base plate, while the system was grounded using a copper rod. Aluminum flashing tape was used to cover seems and holes for components.

Figure 10: Faraday cages on tilt and pan servo motors.

III. Conclusion

The purpose of this research was to find the best IMU for our system, solutions to the interference caused by the 80/20 bar and servo motors that would optimize the performance of our ground station. In part II section A, we tested three different IMU units varying in price and performance. After testing them in a controlled area we concluded that the BNO055 was the best unit for our project. In section B, the main goal was to develop a solution to the 80/20 bar interference. In conclusion of this section, raising the IMU away from the metallic material 6 inches decreased variability by 8°. In section C, the main goal was to eliminate the interference caused by the servo motors that was causing a 1-2° variability. The solution was to construct Faraday cages out of 1060 aluminum alloy with a .025 inch thickness. Measuring the differential of the Faraday cage addition to the system was challenging since the BNO055 had a ±1.5° accuracy. Keeping that in mind we decided that it was worth keeping the cages on the system considering they were not affecting it in a negative way.

On the 2017 total solar eclipse many of the 55 teams had success recording the event live. Unfortunately, Montana State University had technical difficulties. The issues that arose on the eclipse day were unrelated to the research in question in this paper. The information in this paper will be beneficial to other teams having similar issues with inertial measurement units. Design information, including part files and drawings are available upon request for the Faraday cages and IMU brackets.

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References

[1] "About the Eclipse Ballooning Project," *Eclipse Ballooning Project* Available: http://eclipse.montana.edu/about/.

[2] Graas, F. V., "Workshop on GNSS Data Application to Low Latitude Ionospheric Research," *International Centre for Theoretical Physics*, Jun. 2013.

[3] *Gyroscopes Theory - DutchOps.com powered* Available: http://www.dutchops.com/Portfolio_Marcel/Articles/Instruments/Gyroscopic_Instruments/Theory_Gyroscopes.htm.

[4] "Technical Data for Aluminum Extrusion," *Technical Data for Aluminum Extrusions - T-Slot Aluminum Details | Faztek* Available: http://www.faztek.net/technical.html.

[5] Loya, S., & H. (2016). Analysis of Shielding Effectiveness in the Electric Field and Magnetic Field and Plane Wave for Infinite Sheet Metals. *International Journal of Electromagnetics and Applications*. doi:10.5923/j.ijea.20160602.02