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LDRD PROJECT NUMBER: 238118
LDRD PROJECT TITLE: Simultaneous Celestial Navigation
PROJECT TEAM MEMBERS: Jose Rodriguez (Project Investigator/Lead), Daniel Bender (Researcher), Matt Stefanick (Researcher), David Turner (Researcher), Anna Broome (Researcher)

ABSTRACT:

GPS technology is widely used for navigation across various applications. However, GPS signals can be contested or denied, necessitating alternative positioning methods for high-consequence systems.

This project explores a non-RF-based approach to estimate geolocation using stellar and celestial measurements, combined with data from inclinometers and a real-time clock.

The initial iteration of this method, developed in FY20/21, achieved an estimated location accuracy within approximately 3 kilometers of the true location with a 3-sigma bound of about 8 kilometers. The next iteration aims to enhance this technology further, targeting an estimation accuracy within 100 meters of the true location, representing a 30-fold improvement over the initial method.

INTRODUCTION AND EXECUTIVE SUMMARY OF RESULTS:

A non-RF-based method for producing geolocation using commercial-off-the-shelf hardware was developed in FY20/21. This method utilizes stellar measurements in combination with data from an inclinometer and a clock. It is portable and applicable to systems equipped with a camera, clock, and inclinometer. For instance, the research team successfully applied this method using an Android smartphone, which contains the necessary instruments. The algorithm for estimating geolocation was executed on the smartphone's processor, achieving an accuracy of approximately 15 kilometers from the true location.

The accuracy of this method is closely tied to the angular precision of each instrument, with the inclinometer being the dominant factor. While the method has been demonstrated only at static locations, it has the potential for application on moving platforms. The best geolocation estimate achieved on the FY20/21 hardware was within 3 kilometers of the true location, with a 3-sigma bound of about 8 kilometers. This all-optical method does not rely on RF signals, making it a desirable alternative to GPS.

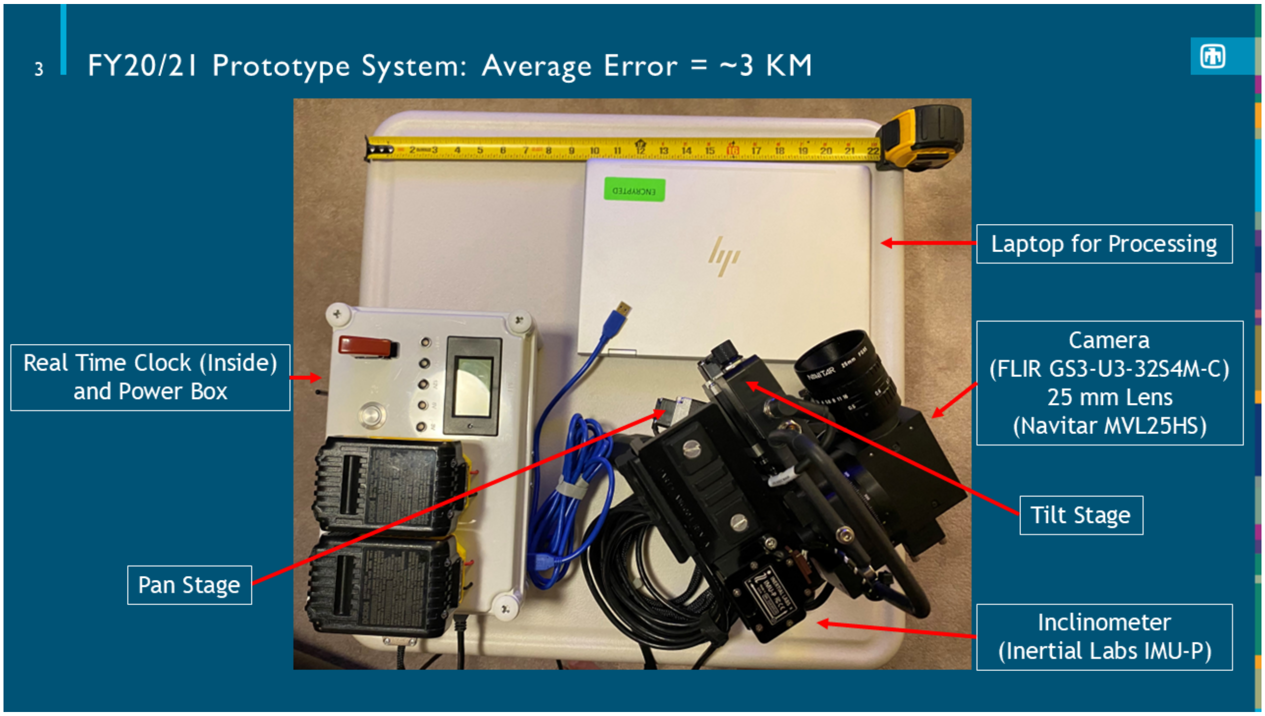

Figure 1: FY20/21 Rig

The next iteration aims to improve this method further, targeting an estimation accuracy within 100 meters of the true location, representing a 30-fold enhancement over the initial iteration.

One limitation of the method is the accuracy of the inclinometer. The initial iteration used an inclinometer with an accuracy of 0.05 degrees, which corresponds to the approximate 3 kilometers of geolocation accuracy. Simulations indicate that using an inclinometer with an accuracy of 0.0014 degrees could achieve a geolocation accuracy within 100 meters.

Another limitation is the minimum wait time of 30 seconds required to ensure a unique estimated geolocation. The research team proposed a two-camera system to reduce this wait time to a few seconds by providing two views of the sky from the same location. However, practical challenges arose when attempting to align the cameras with an angular separation greater than a few degrees. Consequently, both cameras were aligned in the same direction, roughly parallel to the inclinometer's yaw axis, minimizing modeling errors.

Additionally, the method currently operates only at night, as the initial camera can only capture stars at night. The team considered using Visible/SWIR InGaAs cameras that can potentially operate during both day and night. However, logistical issues delayed the integration of these cameras, leading to a focus on nighttime operations.

The research team constructed two rigs, referred to as the VectorNav Rig and the Wyler Rig. Each rig utilized two visible cameras with 25 mm and 100 mm lenses. The VectorNav Rig employed a VectorNav VN-110 IMU as its inclinometer, providing pitch and roll measurements accurate to within 0.05 degrees. Its purpose was to replicate the initial iteration of the method and explore algorithm improvements to enhance accuracy beyond the initial 3 kilometers.

The Wyler Rig utilized a combination of Wyler Inclinometers, providing pitch and roll measurements accurate to 0.00045 and 0.00016 degrees, respectively. This rig aimed to demonstrate the feasibility of achieving 100 meters of geolocation accuracy.

Both rigs were outfitted with Raspberry Pi 5 single-board computers to execute the algorithm on relatively inexpensive processing power, showcasing the simplicity of the method's algorithm and its small processing footprint. Each Raspberry Pi 5 was equipped with an I2C Real-Time Clock, ensuring time accuracy within 1 second.

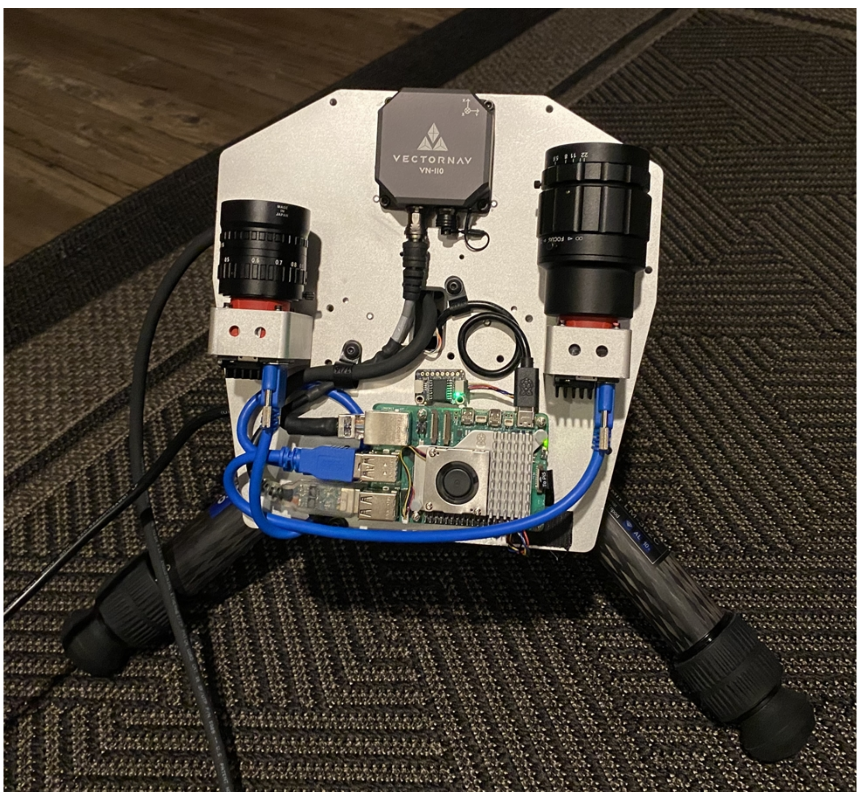

Figure 2: VectorNav Rig, 25 mm Lens Camera on left, 100 mm Lens Camera on right, Raspberry Pi 5 below each Camera

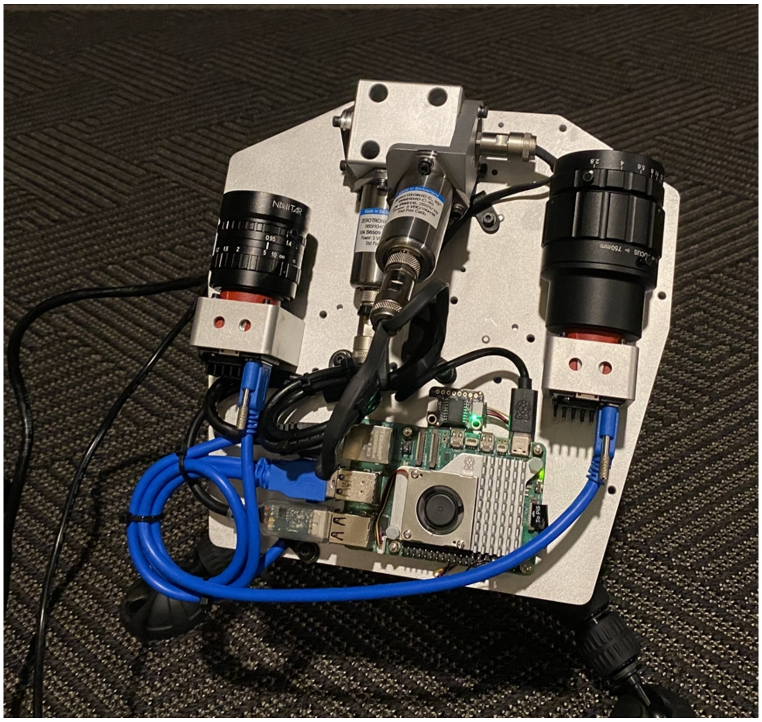

Figure 3: Wyler Rig, 3 Wyler Inclinometers were used to measure Pitch and Roll Angles

The research team successfully reduced the number of star measurements to a single camera image, rather than requiring a series of stellar images. This simplification maintained accurate geolocation while significantly decreasing the number of measurements needed. Initially, the algorithm ran on a laptop with sufficient processing power, generating a geolocation solution in approximately 30 seconds. The next iteration transitioned processing to a Raspberry Pi 5, which, while less powerful than a laptop, was able to produce a geolocation estimate within 10s of seconds due to the reduced number of measurements. Future work aims to achieve a geolocation estimate within a maximum time of about 5-10 seconds.

Table 1 presents the final results for each rig, comparing the performance of using one camera versus two cameras for geolocation estimation. The Wyler Rig demonstrated the best performance, achieving an estimated geolocation of 0.64 kilometers with a 3-sigma bound of 1.64 kilometers when utilizing both cameras. This table serves as a guide for designing future systems that require a non-RF-based geolocation solution.

VectorNav Rig			Wyler Rig	
25 mm Lens Camera	25 mm Lens Camera with 100 mm Lens Camera		25 mm Lens Camera	25 mm Lens Camera with 100 mm Lens Camera
Accuracy = 1.29 KM	Accuracy = 0.91 KM		Accuracy = 0.78 KM	Accuracy = 0.64 KM
3-Sigma Bound = 2.18 KM	3-Sigma Bound = 1.78 KM		3-Sigma Bound = 1.73 KM	3-Sigma Bound = 1.64 KM
~2x improvement in Accuracy and ~4x improvement in 3-Sigma Bound	~3x improvement in Accuracy and ~4x improvement in 3-Sigma Bound		~4x improvement in Accuracy and ~5x improvement in 3-Sigma Bound	~5x improvement in Accuracy and ~5x improvement in 3-Sigma Bound

Table 1: Single Image Performance

An additional application involved using each rig to capture a series of stellar images to produce a geolocation estimate. This approach was initially implemented with the first rig in FY20/21. However, it has the drawback of requiring an extended wait time to ensure effective convergence of the solution. While this application was not explored in depth, it presents an opportunity for future research. The expectation is that the geolocation would converge to the accuracies demonstrated in Table 1 or better, potentially reducing the 3-sigma bound.

Unfortunately, the intended goal of achieving 100 meters of accuracy was not realized. The data obtained is limited due to the resources and scope of the project. Additional time is needed to further develop the Wyler Rig and investigate the discrepancies between the simulated results and the predicted accuracy of the Wyler Rig. However, both rigs demonstrate improvement over the FY20/21 Rig, marking a positive step forward. These results can inform the design of future systems that may accommodate these accuracy levels. Nonetheless, achieving 100 meters of accuracy remains the primary goal for any future work.

DETAILED DESCRIPTION OF RESEARCH AND DEVELOPMENT AND METHODOLOGY:

The research team began this project by exploring several key areas:

1. **Improving Stellar Measurements from Star Images**: To reduce errors in stellar measurements, the team implemented a distortion correction for each camera. This correction minimizes the positional error between the detected location of each star and its predicted position in the Camera Coordinate System. Additionally, the team stored the RMS Error and the number of star matches to filter out star images with high error rates and few matches. The initial iteration of the method did not account for distortion correction and relied solely on a series of star images to mitigate errors arising from stellar measurements. To further enhance detection, a coarse star catalog was created, allowing the team to use this preliminary solution to focus on a reduced set of stars in a

fine star catalog. This effectively increased the number of stars detected in any given star image, thereby helping to reduce measurement error.

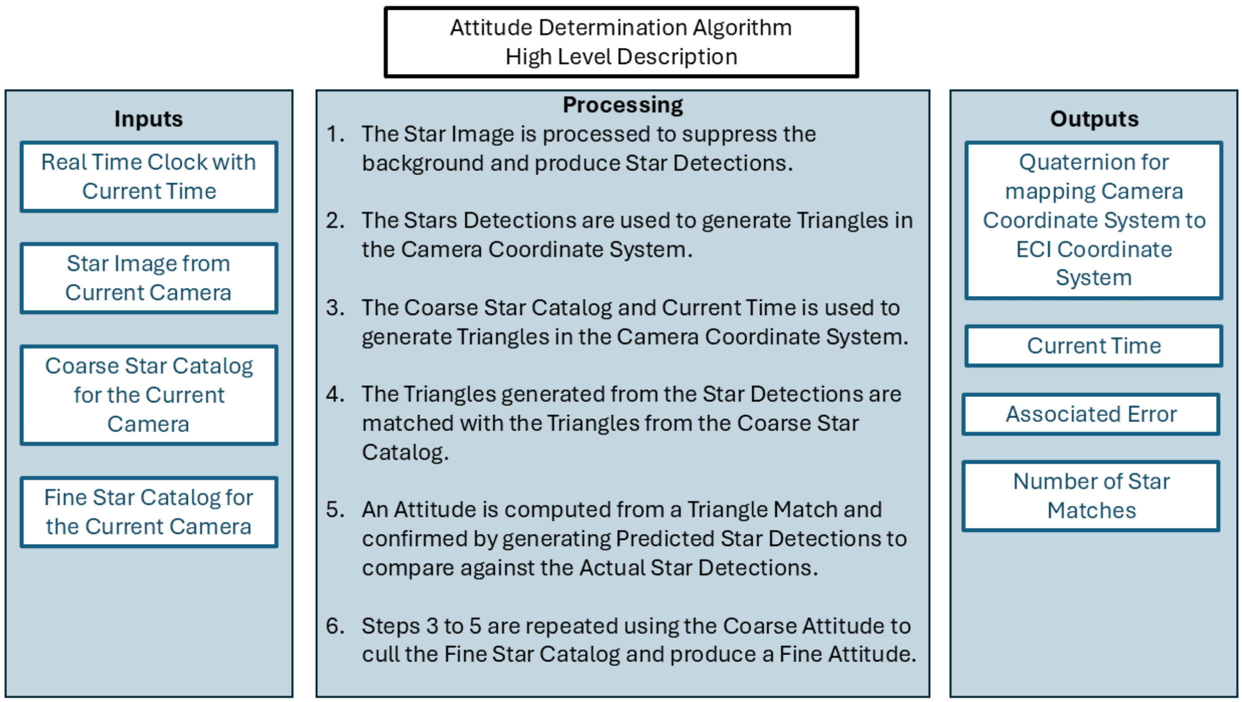

Figure 4: Attitude Determination Algorithm

2. **Enhancing the Location Determination Algorithm**: The team explored a new approach to improve processing efficiency in the location estimation algorithm. The initial method treated each detected star as a single measurement. For a candidate location, each star could be transformed into an elevation measurement, which was then compared to inclinometer measurements to generate an error metric. Ideally, a perfect geolocation solution would yield an average error metric of 0.0 degrees, indicating a perfect match between transformed star measurements and inclinometer data. However, this approach's processing time was directly proportional to the number of star matches. The new method focuses on star measurements only during the generation of the quaternion that describes how the camera axes map to the Earth-Centered Inertial (ECI) Coordinate System. For a candidate location, the camera axes can be transformed from the ECI Coordinate System to the Horizontal Coordinate System, which is then used to generate pitch and roll angles. These angles can be compared to the inclinometer's pitch and roll measurements, significantly reducing processing time by only requiring comparison of the three axes of the camera.

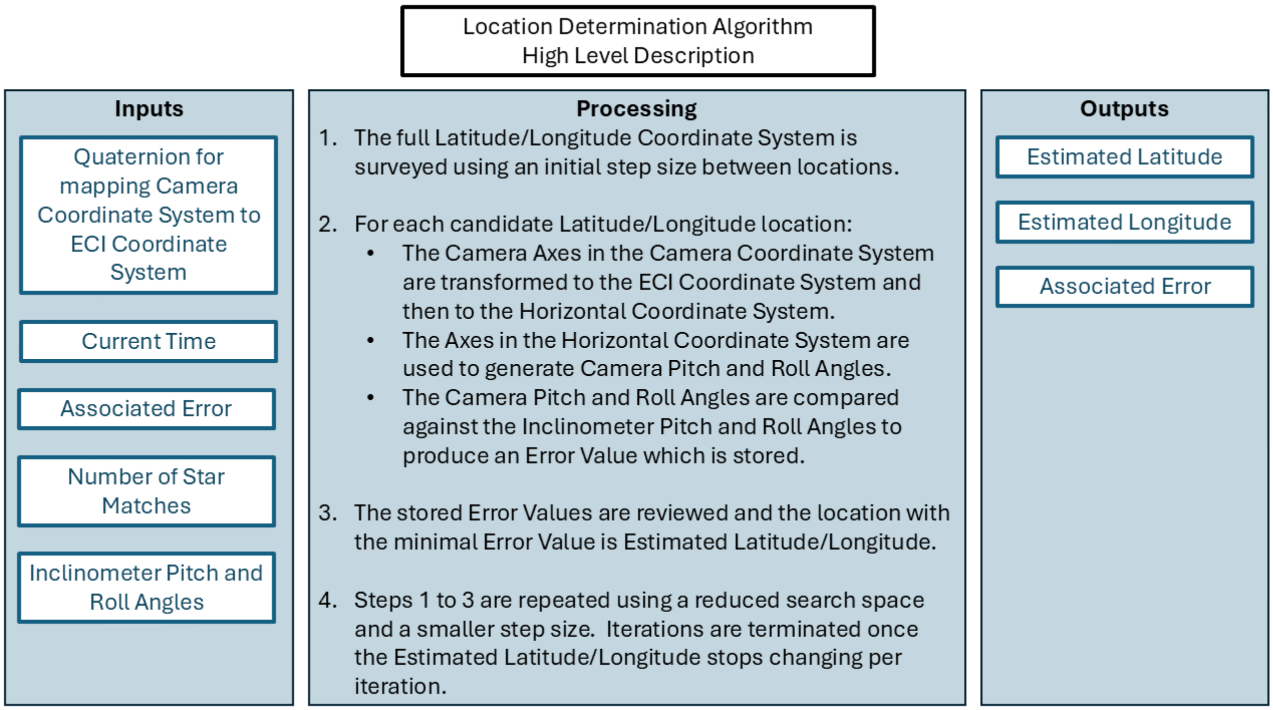

Figure 5: Location Determination Algorithm

3. **Comprehensive Review of Modeling and Calibration for Each Rig**: A thorough review of modeling and calibration was conducted for each rig. As previously mentioned, distortion correction was applied to the star images to minimize measurement error. This correction was generated by using each rig at a known location. Other aspects of modeling and calibration included estimating the focal length and modeling the relationship between the camera and the inclinometer. The estimated or actual focal length is important, as the nominal focal length provided by the manufacturer can vary slightly from lens to lens. Accurate modeling of the camera's relationship to the inclinometer is essential for the location estimation algorithm to generate an error metric for a candidate location when comparing the three camera axes to the inclinometer's pitch and roll angles.

4. **Utilizing SolidWorks for Mechanical Research and Development**: Each component of the VectorNav and Wyler rigs was designed and analyzed using SolidWorks to facilitate the creation of a versatile R&D plate that could be configured as either a VectorNav Rig or a Wyler Rig. This design process allowed the exploration of various geometries for camera placement and inclinometer placement, optimizing the setup for accurate measurements. Additionally, the R&D efforts ensured that each component could be

securely installed and maintained its position over time. It is crucial that once components are installed, they do not shift relative to one another, as this rigidity is essential for the ongoing applicability of the modeling and calibration processes. Any movement of a component would compromise the validity of the modeling and calibration, potentially leading to inaccurate geolocation estimates.

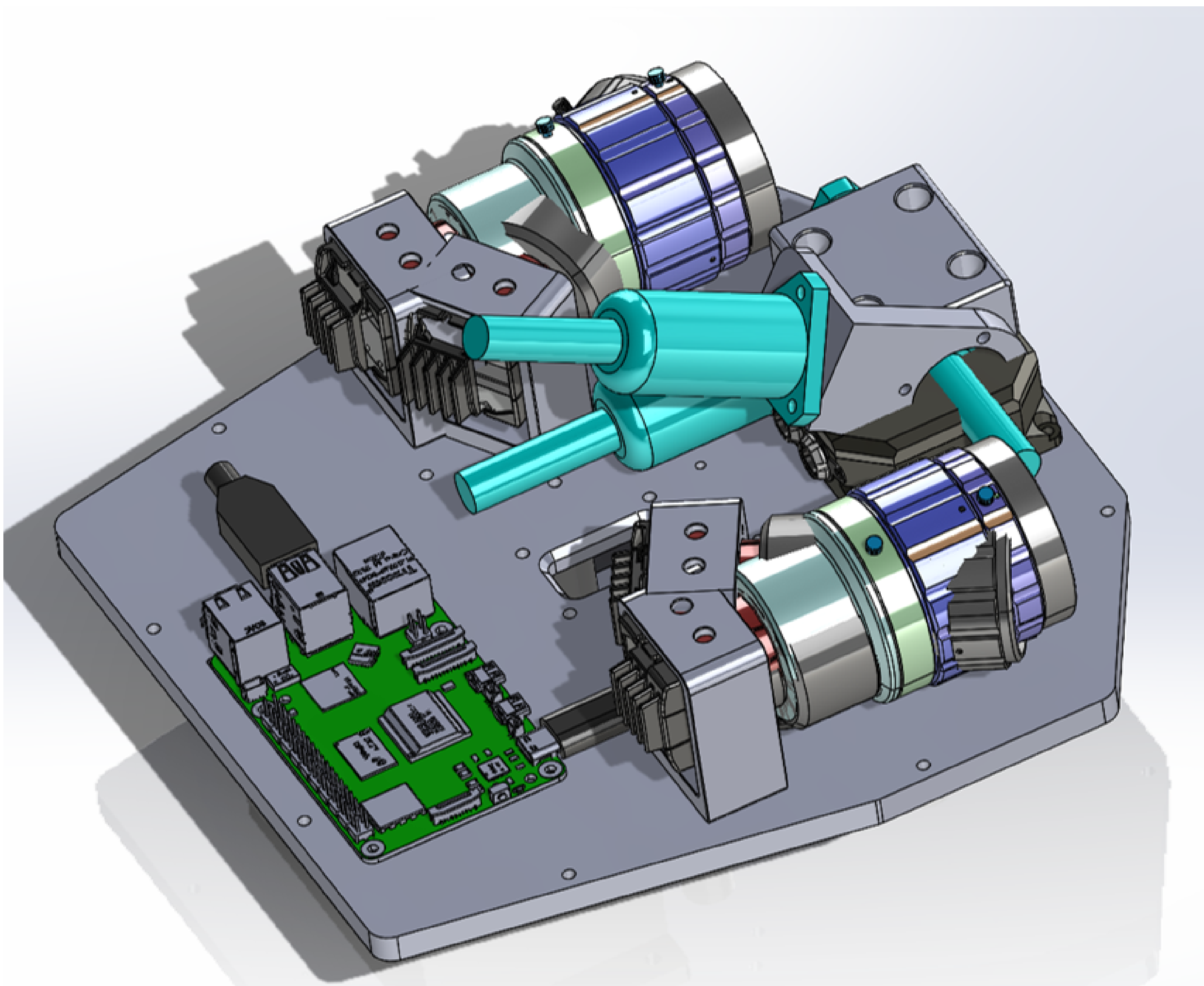

Figure 6: SolidWorks view of R&D Plate

5. **Creation of a Wyler Inclinometer Mount**: The VectorNav Rig employs a VN-110 Inertial Measurement Unit (IMU) to produce the pitch and roll angles necessary for location estimation. The company has developed a well-defined integrated solution for customers requiring an IMU, which the research team effectively leveraged for

measuring pitch and roll angles. In contrast, the Wyler inclinometers do not function as traditional IMUs. The team chose these inclinometers due to their high accuracy, which is essential for minimizing geolocation errors. Wyler has established a strong reputation for providing quality hardware, although in this case, it is offered as a non-integrated solution. To ensure the production of highly accurate pitch and roll angles, the research team designed and built a Wyler Inclinometer Mount. This mount incorporates two inclinometers for measuring pitch angles and one inclinometer for measuring roll angles. The pitch inclinometers are offset from each other by 45 degrees, allowing a full range of pitch angles from 0 to 90 degrees. The roll inclinometer is limited to a range of ±10 degrees, which is sufficient for the requirements of this project.

RESULTS AND DISCUSSION:

The results of this project are as follows:

1. **Improving Stellar Measurements from Star Images:** The applied distortion correction enabled the 25 mm camera to achieve an accuracy of approximately 1 pixel on average, while the 100 mm camera attained an accuracy of about 0.60 pixels. These values correspond to approximately 0.007774 degrees of accuracy for the 25 mm camera and 0.001184 degrees for the 100 mm camera. Simulations indicate that the inclinometer accuracy needs to be around 0.0014 degrees to achieve 100 meters of accuracy. The results show that only the 100 mm lens meets the accuracy requirements for achieving 100 meters of geolocation accuracy, as the 25 mm lens exceeds the 0.0014-degree threshold and thus cannot resolve stars adequately for this level of precision. As shown in Table 1, the Wyler Rig achieved only 640 meters of accuracy. Further refinement of the Wyler Rig is necessary to address discrepancies between predicted and actual performance.

2. **Enhancing the Location Determination Algorithm:** The location determination algorithm was overhauled to significantly decrease processing time while effectively producing geolocation results using minimal measurements. The inclusion of RMS error associated with stellar measurements and the number of star matches allowed filtering out data with undesirable error levels. This filtering process was based on calibration data, identifying the RMS error and number of star matches that resulted in the least geolocation error. For each rig, the 25 mm lens camera utilized an RMS error threshold of 1.5 pixels (0.012 degrees), while the 100 mm lens camera used a threshold of 1.5 pixels (0.003 degrees). Any star measurements exceeding these thresholds were excluded from location estimation. Additionally, the 25 mm lens camera required a minimum of 60 star matches, while the 100 mm lens camera required at least 70 star matches for valid location estimation.

3. **Comprehensive Review of Modeling and Calibration for Each Rig:** The distortion correction was modeled using a 2D polynomial, comparing predicted star locations in the Camera Coordinate System with detected/matched star locations. This correction allowed accurate positioning of detected stars. The focal length estimation was conducted over a small grid of focal lengths to minimize positional error in star locations. Lastly, the mapping of the camera to the inclinometer was achieved using 321 Euler rotations (yaw-pitch-roll) to align the camera axes with the inclinometer axes. By utilizing a known location, the camera axes were aligned to the inclinometer axes, and the alignment with the least error was selected for mapping.

4. **Utilizing SolidWorks for Mechanical Research and Development:** The application of SolidWorks facilitated the rapid development of each rig. The initial VectorNav Rig separated the 25 mm and 100 mm lenses by 60 degrees to diversify star measurements and leverage the geometry of the known separation. However, this separation complicated the pointing of the cameras; for instance, the 25 mm lens could capture a clear sky while the 100 mm lens might encounter clouds. Additionally, the separation made mapping back to the inclinometers more challenging, as the inclinometers do not provide reliable yaw measurements. By aligning each camera's heading axis with the inclinometer's yaw axis, one degree of freedom (the yaw axis) was eliminated, improving the alignment of the camera axes with the inclinometer axes.

5. **Creation of a Wyler Inclinometer Mount:** The Wyler Inclinometer Mount functioned as intended. However, the Wyler inclinometers occasionally failed to read reliably over the serial port, resulting in dropped angle readings. More software development is needed to address this issue. Additionally, due to time constraints, only one pitch inclinometer was utilized, as further software development was required to manage the transition between the first and second pitch inclinometers.

6. **Additional Results:** Once the modeling and calibration of each rig were completed, location estimation became straightforward. The rig was set up outdoors and aimed at a patch of sky. A star image was collected using the 25 mm lens camera, the current time was recorded, and the pitch and roll angles were stored. The custom software processed the data using the Location Estimation Algorithm to produce an estimated location. This estimated location was then used to bootstrap the Location Estimation Algorithm for the 100 mm lens camera, which was necessary due to the larger star catalog and helped reduce processing time. While data collection was relatively easy, it was time consuming, requiring clear skies for both modeling/calibration and testing. Some cloud cover could be tolerated, but it was generally undesirable, as clouds could skew star detections.

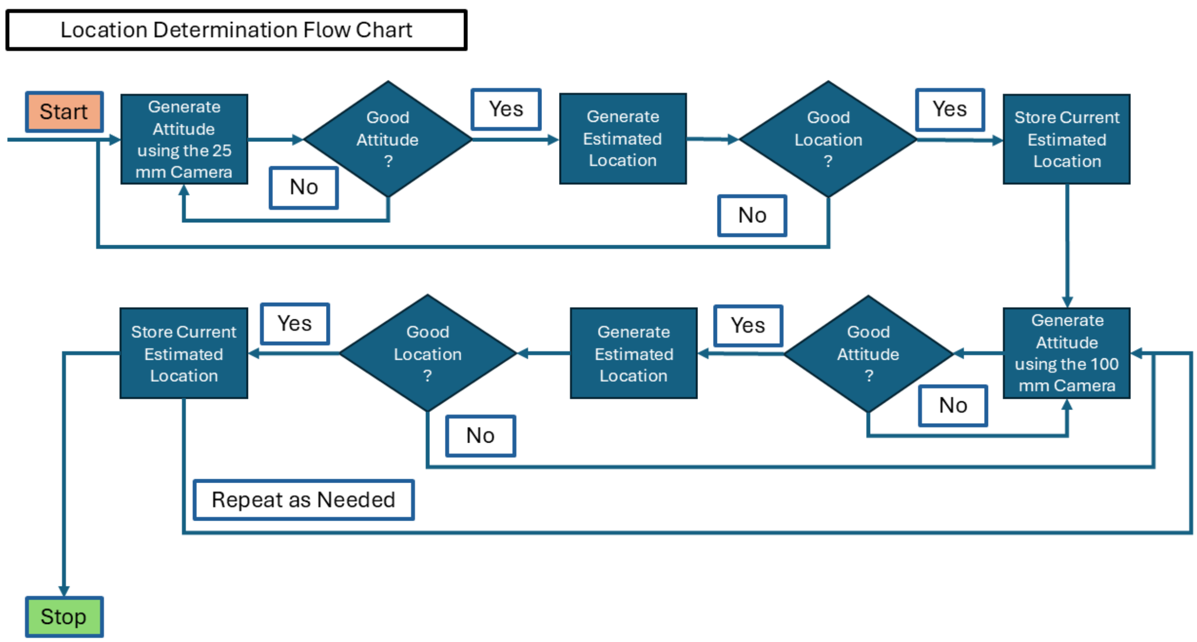

Figure 7: Location Determination Flow Chart

ANTICIPATED OUTCOMES AND IMPACTS:

The following are the anticipated next steps for this project, driven by the limited time and resources available during FY25:

1. **Further Software Development**: With the construction of each rig, additional software development can be undertaken to reduce processing time. The custom software was initially developed for one camera, with the second camera integrated later. Due to time constraints, sufficient software development was focused on ensuring improvements over the FY20/21 Rig. A significant emphasis was placed on enhancing the Location Estimation Algorithm. Additionally, it may be necessary to replace the Raspberry Pi 5 with a more powerful single-board computer to further decrease processing time. The overall goal is to enable quick and reliable estimation of locations.

2. **Verification of the VectorNav VN-110 Against the Wyler Inclinometers**: The VectorNav VN-110 is a tactical-grade IMU that undergoes rigorous quality testing to ensure reliability. It can be used to verify that the pitch and roll angles produced by the Wyler Inclinometer match those generated by the VN-110 in a coarse sense. This

verification will confirm that the Wyler Mount accurately produces the system's pitch and roll angles, rather than unintended measurements.

3. **Integration onto a Moving Platform**: Integrating the VectorNav and Wyler rigs onto a moving platform represents a logical next step and would demonstrate the rigs' capability as subsystems within a larger system. A suitable initial test platform could be a slow-moving vehicle for preliminary surveys. It is essential that the rigs are installed on a stable base to prevent blurring of the star images and ensure reliable star measurements.

4. **Visible/SWIR InGaAs Cameras**: As previously mentioned, Visible/SWIR InGaAs cameras have the potential to detect stars during the daytime. The research team encountered logistical challenges in procuring these cameras; however, limited testing was conducted with one camera during the day. Unfortunately, the team was unable to detect stars using both the 25 mm and 50 mm lenses. Although a blue light filter was employed to enhance detection, it also failed to yield any star detections. The team is currently reviewing configurations to ensure that no errors were carried over from the transition from a visible camera to the Visible/SWIR InGaAs camera. Future work will certainly include research and development with these cameras to determine their capability to detect stars as a function of background sunlight. If stars can be detected during the daytime, this would significantly expand the operational envelope for this method of location estimation from nighttime only to any time of day.

5. **Investigation of Other Inclinometers for 100-Meter Accuracy**: The VectorNav VN-110 IMU was selected for this project due to its comparable accuracy to the IMU used in the FY20/21 Rig, as well as its ease of procurement and integration. The associated costs were reasonable, making it a practical choice to mitigate risk for this project. However, its accuracy is limited to 0.05 degrees, resulting in a maximum geolocation accuracy of approximately 1 kilometer with the VectorNav Rig. In contrast, the Wyler inclinometers were chosen for their accuracy, which is below the 0.0014 degrees required to achieve the predicted 100-meter accuracy. The cost of these inclinometers was also appropriate for the project. However, the research team faced the challenge of integrating each inclinometer to effectively create an ad hoc IMU, which was a notable drawback. Moving forward, further research is needed to identify an IMU that meets the desired high accuracy. Additionally, the research team could leverage any quality testing associated with this potential high-accuracy IMU to ensure reliable measurements. While the costs may be higher, achieving the necessary accuracy for 100 meters of geolocation is likely to justify the investment.

6. **Investigation of Longer Focal Length Lenses**: As previously mentioned, the measured accuracy of the 100 mm lens camera is 0.001184 degrees, which is below the 0.0014

degrees required for achieving 100 meters of geolocation accuracy. However, a longer focal length lens may be necessary to ensure that the accuracy remains below the threshold needed for this level of precision. While longer focal length lenses are generally easier to procure and use, they do add additional weight to the rigs due to the extra glass. Moreover, additional mechanical design considerations will be required to ensure that the lens remains stable and does not shift, which is crucial for maintaining reliable calibration. This investigation represents a logical next step, and experiments could be conducted relatively quickly by leveraging the existing VectorNav and Wyler Rigs.

CONCLUSION:

The VectorNav and Wyler Rigs demonstrate significant improvements over the original FY20/21 Rig. While the ambitious goal of achieving 100 meters of accuracy was not fully realized, it has driven innovation and ingenuity throughout the project. Each rig now serves as a testbed for long-term testing to verify that their accuracy is maintained over time. Additionally, these rigs can help determine the duration for which modeling and calibration remain valid before new adjustments are necessary.

Data collected during the summer in Albuquerque, NM, informed the current configurations; however, using the rigs in fall, winter, or spring conditions may require additional modeling and calibration data specific to a season. Furthermore, more extensive testing in various locations around the world is essential to demonstrate the global applicability of these systems. Ultimately, future systems can leverage these rigs as valuable tools for potential integration into broader applications.

ADDENDUM:

This project encountered several logistical challenges related to hardware procurement. The first issue involved lead times associated with tariffs that a U.S.-based dealer attempted to pass on to Sandia regarding the Wyler inclinometers. This situation effectively delayed the design and fabrication of the Wyler Rig, necessitating a greater focus on the VectorNav Rig. Once the tariff issue was resolved (with the U.S. dealer absorbing the cost), the Wyler Rig could be designed and built, which occurred approximately three months before the project's conclusion.

The next challenge was the lead time for obtaining the Visible/SWIR InGaAs cameras. There was significant back-and-forth communication between the U.S. dealer and Sandia regarding the export of the cameras from Germany, where the manufacturer (Allied Vision) is located. After some miscommunication, the initial order was canceled but later resubmitted. Ultimately, the issues were resolved, and the cameras were delivered, but only about two months before the project's completion. As a result, more emphasis was placed on building the VectorNav and Wyler Rigs, which are designed to operate exclusively at night.