Celestial Navigation through Zenith Image Analysis

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Abstract

Navigation in the general sense, be it sea, air, or land has grown increasingly dependent on a global positioning system, GPS. However, recent years have begun to show the failings of this system such as weak signals, jamming, refraction off tall buildings, and dead zones. One potential solution to the non-GPS navigation problem is to return to celestial navigation, charting a course by the stars. This paper explores a method of celestial navigation that might be entirely novel: zenith imaging analysis. It is a modern, computer vision approach using Astrometry.net, the open source, online image-analysis tool. This paper details the implementation and theory behind the method. It also includes an analysis of the method's potential as a low-cost, reliable subsystem solution for long-range travel.

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1 Introduction

The global positioning system and its foreign analogues in Galileo and GLONASS have attained complete dominance as the primary navigational tool in most applications. From freighters to drones, most guidance systems rely first and foremost on their GPS modules.

The GPS system itself suffers from a number of increasingly concerning failings, however. GPS uses weak signals and is thus very easy to jam over large areas. These failings have created demand for a cheap and effective alternative to complete reliance on the GPS network. The current alternatives to GPS navigation suffer from various problems including cost, weight, speed, lack of universal applicability, and/or accuracy. Magnetometry, for example, demands prohibitive sums of money and a specialized structure to be effective, but is otherwise very precise and successful. The problems with most methods can be solved with more advanced components and improvements in implementation, but there is a simpler, cheaper and more effective solution available.

One common response to the non-GPS navigation problem is a return to celestial navigation. Travelling with the guidance of the stars is an old technique but it has been vastly improved with modern astronomy and optics. Various implementations of celestial navigation are currently in use by the U.S. military and certain civilian entities [Cregge, 2013]. The goal of this paper is to investigate and develop a new method of celestial navigation that is dependent on a recent advance in the analysis of star photos, specifically Astrometry.net. This method, called *zenith-image analysis*, uses an image of the stars above an observer's head and a precise measurement of time to calculate the observer's latitude and longitude independent of which stars are in the image, meaning it doesn't need a gimbal or the ability to track certain navigational stars like more traditional astronavigation systems do.

This paper will discuss the motivation behind this development along with more information on other non-GPS navigation tools. An in-depth examination of the theoretical foundation of zenith-imaging analysis will be presented along with in-silico and experimental implementations. The value of this method will be analyzed and the value of this work as grounds for future research will be briefly touched on.

2 Problem Statement

The problem that inspired this paper was simple: a drone in the field has lost the ability to effectively use GPS and it needs a new way to get home. The reason it lost GPS is irrelevant, but there are a great many ways this system can fail. GPS is dependent on a very weak signal, meaning that it takes very little power to jam the signal over a wide area. For example, the United States military is developing a system called **NAVWAR** that, among other things, can block GPS signals in a five hundred mile radius [Center, 2001]. To give that figure a slightly greater impact, the entirety of modern France can be contained in one such system easily. A single plane with a one watt jamming device can disconnect devices that have already made contact with a satellite at distances of nearly thirty miles, and potentially affect the ability to connect to a satellite initially over even greater distances [Brewin, 2013]. This military capacity means that GPS cannot be relied upon in warzones or even in areas with mildly frosty relations due to the simplicity and indirect nature of the jamming operation.

What makes this problem worse is that even civilians have formidable jamming capabilities. Jamming devices are currently illegal to sell or use in the United States, but it is not uncommon to find dead zones where jamming devices are in use. Consumer GPS jammers have a much smaller range than their military counterparts, usually ranging between a dozen feet and a mile [Hill, 2017]. Common reasons for finding holes in the GPS network include truckers trying to avoid tracking devices, undercover police officers, and hobbyists trying to avoid GPS-locked aviation guidelines [Hill, 2017]. As a result of these shadows in the network, both drones and planes are required to have some way of avoiding collisions and determining place that does not depend solely on the GPS network.

The proposed method, *astronavigation*, is the analysis of celestial bodies to determine position. A common abstraction in astronavigation is to assume that all stars visible from earth are actually points on a celestial sphere that rotates around an axis shared with the Earth. This abstraction works largely because the stars are far enough away that despite the Earth's motion relative to them, their perceived direction(position in the night sky) does not change noticeably. Given this model, the stars will still rotate over the surface of the Earth. This means that only the poles will have a constant set of stars that can be seen overhead from month to month. However, if you bring a further constraint to the problem then the stars only appear in particular places on the celestial sphere over specific locations on Earth. That constraint is time. If the exact time is known at a specific point of longitude, Greenwich, England for example, then functionally the celestial sphere no longer rotates. The problem of identifying location from the stars becomes one of identifying which stars are above and how they relate to the viewer.

For example, if an observer knows that it is precisely 8:30 pm on April 16$^{\text{th}}$, 1954 in Greenwich, and the observer also identifies Polaris is fifteen degrees, six arc-minutes and forty arc-seconds above the horizon, then the observer's exact latitude and longitude coordinates can be determined.

A final line of thinking on the problem is the question of precision. As might be guessed, astronavigation depends strongly on extremely precise and accurate measurement of a very small point very far away. The previous paragraph mentions arc-minutes, which are roughly one sixtieth of a degree. If a measurement is wrong by one arc-minute, then the resulting estimate of position is wrong by roughly one nautical mile. This means that very small and usually negligible sources of error are magnified by incredible factors in the context of this problem. Factors like the wind tilting an aircraft or a gyroscope drifting half a degree become critical failures in the subsystem.

This magnification also offers a bit of promise for future work. Since a single arcminute can make such a difference in the precision, a small improvement in accuracy through the application of a new statistical modelling system can provide vastly improved viability. This means future work in image refinement or noise reduction could introduce this system to much smaller operations than are currently possible.

Other possibilities for extension include adding sun tracking in order to make the system work during the day and during twilight hours. Current models allow for reasonably accurate prediction of location using only the sun, so it is entire possible to double the effective use cases of this tool.

3 Previous Work

Historically, aviation has depended greatly on the skills of the pilot. This increased distance between pilot and craft had led to new challenges in introducing autonomous drones into civil airspace. While prior FAA regulations required the pilot to simply *see and avoid* other aircraft so as to allow flight without modern instruments, Fully autonomous drones cannot 'see' in any legal sense. Thus, they must *sense and avoid*. The primary focus of drone research is, then, collision avoidance and navigation. The primary navigational method is GPS, due to its exceptional coverage, precision, affordability, low weight, and compact size. However, GPS can frequently be unreliable. In both the civil and military airspace, GPS is often jammed, spoofed, or otherwise tampered with [Hill, 2017] to the point of being an unacceptable point of failure. Despite this problem, GPS does remain the gold standard of navigational aids. Many methods have been proposed, tested, and implemented as solutions to the problem of non-GPS navigation.

The first and most obvious solution is to use exceptionally accurate and precise tools to measure the forces on a craft and use that to calculate the current location using a previous known location. This is known as *dead reckoning*. As the name implies it is usually met with little success. However, some recent papers [Ojeda and Borenstein, 2007] have shown careful use of math and new technology can present decent results even with this method. The dead reckoning system, or inertial navigation system, or *INS*, was deployed on a person's ankle and used to determine their position after a walk. The potential applications of this sort of method to aerial vehicles is more suspect due to the potential for unpredictable wind and other complex forces on the aircraft.

Another approach to this problem is Light Detection and Ranging or **LiDAR**, which originated as a portmanteau of light and **RADAR** (*Radio Detection and Ranging*) but eventually grew into a backronym. More to the point, LiDAR depends on a series of pulsed light emissions being measured at emission and receipt, then using the minute differences to calculate range. That is, LiDAR is a large bundle of laser range-finders being used in conjunction to create a 3D map of an area.

The primary draw of LiDAR is its ability to penetrate thin surfaces, allowing the device to map the areas below thin cover. This is largely used in forestry surveys [Li et al., 2014] due to the exceptional performance with leaves. The system does not offer much promise as a primary drone navigational technique, however, due to the active nature. As an active system, LiDAR sends out pulses which can be easily interfered with or detected. This poses a challenge in hostile environments.

A slightly less popular but nonetheless fascinating method is navigation by infrasound. This is believed to be the navigation method used by homing pigeons [Bauer et al., 1998] and as a result shows great promise as a potential navigational solution usable from almost anywhere on earth. The concern is precision, however. As the cited paper shows, infrasound is difficult to measure precisely and it is further difficult to discern significant infrasound signals from noise. Thus far there has been no significant success using infrasound to navigate, at least none that this team has managed to find.

Another option investigated largely for its unique and fascinating qualities is *Optical flow*. Optical flow is a subset of computer vision where two images are taken at a specific time step apart and then analyzed to determine differences in color, pixel density, and other properties to show change over time. This is used mainly to determine if an object in the image has moved closer to the perspective or further away. What makes optical flow interesting is how easy it is to program autonomous routines using this information. Take for example a region of the image is moving closer at a rate faster than other parts of the image. If the goal is collision avoidance, then simply turn away from that side of the camera. If the goal is pursuit of a target, then turn toward that region to keep it in focus. If the goal is avoiding pursuit, then turn toward the area of motion and drive backward [Timizer, 2001]. It is incredible how simple and diverse the uses of this information is. However, ease of coding is not the highest priority in drone navigation, and as such the other problems with this technique including high computational requirements tend to leave it as a poor choice.

Along the lines of using computer vision is the use of marker recognition for small quadrotor vehicles as described by Blythe et. al. where they used a *3DR IRIS+* quadrotor paired with a Raspberry Pi to recognized black square markers on the floor to help the drone towards its intended location [Jonathan D. Blythe, Krzysztof A. Borowicz, Alyssa Nicole Hollander, 2016]. This paper goes in depth with the hardware and controls of the *3DR IRIS+* and the software of OpenCV for object/marker recognition, but an item of note is that they implemented a method to establish "null" zones so that the drone does not go back to the same marker it was before and continues in the path laid out on the ground before the test began. While this method offers promising results in the vein of quadrotor navigation and guidance, this avenue of quadrotor navigation is out of the scope of this paper and will be left to explore in future work by other scientists.

Another entry in the series of navigational methods chosen for interesting qualities is navigation by signals of opportunity. The method is fundamentally answering the problem of lacking a GPS signal by asking what other signals are available. A signals of opportunity navigation system is composed of a great many receivers for various signals such as radio or television broadcasts, and then using known signal emitters such as towers or stations to triangulate position. This is relatively expensive and bulky [Yan and Fan, 2008], however, and is further limited to urbanized areas that have a sufficiently high density of stray signals. It is thus unfit for use on the oceans, rural areas, or undeveloped countries.

A modern way of tackling the issue of non-GPS navigation would be the use of machine learning or fingerprint navigation. This generally involves two phases of action: Training and Comparison. The training phase generally consists of running the flying instrument through environments akin to the actual area of action the drone will actually be flying through. Fingerprints are the data the drone uses to navigate and over time running many training flights the collection of fingerprints grows and so does the accuracy. These fingerprints can be gathered in a multitude of ways from received signal strength indicators **(RSSI)**, computer vision, and/or magnetometry among other things [Wang et al., 2014] [Tariq et al., 2017]. Once the training phase is complete/sufficient then the comparison or implementation phase begins. This again can be implemented many ways such as a nearest neighbor algorithm to find the truest position based off the current assumed/probable location of the candidate signal. [Wang et al., 2014] explores this nearest neighbor approach under an indoor situation detecting active wifi and cell phone signals. Other strategies of the comparison phase could be the neural network approach. Neural Networks make probabilistic decisions based off of a database of trained data in groups. Similarly the navigator or drone would use its trained data to analyze groups of passively detected points to come to the best made decision. All said, fingerprint navigation implementations offer an interesting way for a drone to travel.

The United States Air Force Institute of Technology in Ohio has preformed a study of how magnetometry can be used to navigate [Canciani and Raquet, 2017]. They used a previously produced magnetic anomaly map of about 35 square kilometers from 2012 to fly a turbine Geo-survey. Then during the test flight the plane was able to simply match the magnetic readings of the map to the ones the plane was passively detecting from the outside. One issue the authors mentioned was that the plane must fly fairly close to the ground for the best accuracy. While the paper did not mention exactly how low, the authors expressed low altitudes are better many times in the text. Another issue is the weather can change magnetic signals picked up by the sensors. This will need to be compensated for either by attaching the required sensors to the flying instrument or by actively sending them up to the flying instrument from the ground, both options of which add to the weight and cost of the overall system. Cost is always a factor in problem solving, the Air Force used what are called "optically pumped scalar magnetometers" which costs in the range of $15,000 to $25,000 putting it far outside the financial range of the average civilian. Cost and low altitude aside the magnetometry method yields excellent results with only 13 meter errors in true location.

An interesting study out of the University of Alabama Huntsville uses the Panoramic annular lens attitude determination system or **PALAD** [Mark A. Stedham, 1995]. Implemented on a high altitude satellite, this system uses a special lens that reflects and refracts light to create an 360 degree photo or panorama of the satellite's surroundings at about 45 degrees in angle height-wise. This system enables the camera (with the lens attached) to see all the way around its current position. The paper uses this panorama to determine the attitude in the satellite by calculating the position of the earth in the photograph. The lens style approach seems promising, assuming the altitude requirement is not too extreme.

Filtering, when used for navigation purposes, removes any unwanted data and provides a better estimation of the user's position. According to [Wang et al., 2014], there are at least three major types of filtering used for navigation: Kalman, Exponential Weighted Moving Average **(EWMA)**, and Linear Weighted Moving Average **(LWMA)**. Kalman filters use matrix multiplication to remove any noise, minor or major, from a data set over time. EWMA serves the same purpose as the Kalman filter, which is to remove unwanted noise, but this method saves some computing time at the cost of some accuracy. If applied in the right context EWMA may out-preform the Kalman filter if the accuracy is lesser needed. Similar to the previous two methods, LWMA again serves to filter out noise from a data set while saving time computation-wise. [Wang et al., 2014] uses LWMA to remove any errors when measuring the wifi signal strengths surrounding the navigating drone, and [Si et al., 2017] uses a form of Kalman filter called "Memory fading unscented Kalman filter" where they put more weight on recent data estimations and less weight on older estimations. A robust filtering system will be explored more in the future work section.

4 Theory and Implementation

The method explored in this paper depends strongly on an understanding of some basic astronomy terms. As such these terms will be defined and explained in one place for ease of reference, while also detailing the basic theoretical framework of the method. To begin, the objective of this paper is to find the latitude and longitude of an observer using an exact time at Greenwich and an image of the stars directly above the observer. The first essential point is the conversion from latitude and longitude to celestial coordinates. This project will use equatorial coordinates: declination and right ascension. The convenient property of equatorial coordinates is that the celestial equator is in the same plane as the terrestrial equator and the celestial poles are similarly shared. Note figure below.

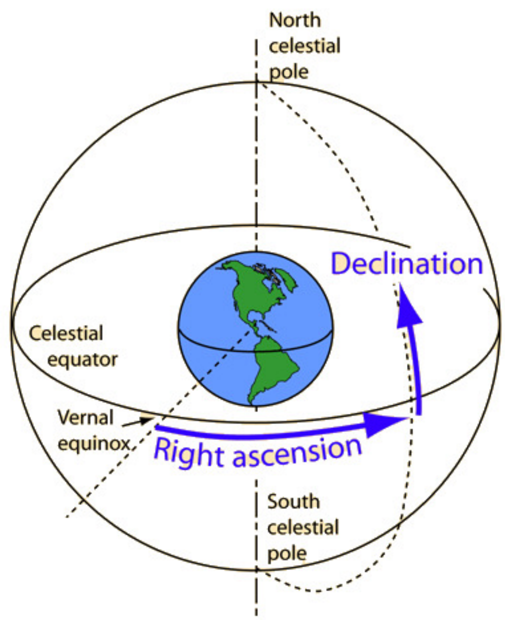


Figure 1: Image demonstrates the relation between declination, right ascension, and the poles and equators. Credit to R. Nave at Georgia State University.

Declination is the angle between the equator and the celestial object, so it corresponds directly with terrestrial latitude. Right ascension, or **RA**, is the angle east from the vernal equinox to the object. The natural next definition is that the vernal equinox is, for these purposes, an arbitrary fixed celestial meridian. Next, Greenwich apparent sidereal time, or **GAST**, is the angle in hours of the vernal equinox with respect to Greenwich.

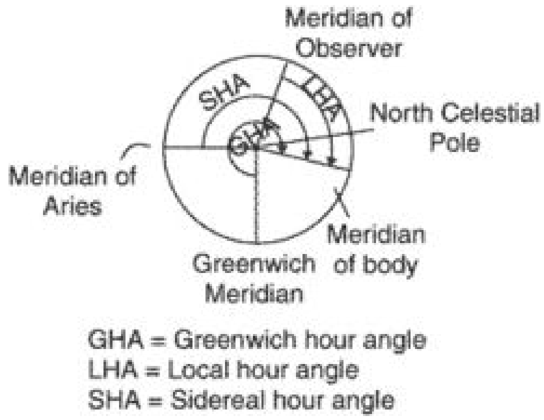


Figure 2: Image demonstrating various astrometric quantities. GHA being a unit conversion of GAST. Note that in the case examined by this paper, the meridian of the body is the meridian of the observer. Also note meridian of Aries is another name for the vernal equinox. Courtesy of An Illustrated Dictionary of Aviation Copyright 2005 by The McGraw-Hill Companies, Inc. All rights reserved.

The last necessary element is the observer's zenith, or the point directly over the observer's head. Longitude can then be defined as the angle between the meridian at the observer's zenith and Greenwich. With this definition it is clear that, with right ascension being the angle between the vernal equinox and the observer, and GAST being the angle between Greenwich and the vernal equinox, the combination of these values is equivalent to longitude. This is the basic theoretical underpinning of zenith-imaging analysis.

The reason this method has not been attempted before is that until recently there was not an easy and accurate way to obtain meta-data about an arbitrary starfield image. That is, the lost-in-space problem had not yet been solved for images in the general case. This problem was solved in 2010 by the team behind Astrometry.net [Dustin Lang et al., 2010], and their program provides accurate meta-data, including the right ascension and declination needed by this project. The fact that the image needs to be centered on zenith is important for this step because Astrometry.net provides only the RA and declination of the center of the image.

At this stage in the process, the method determines latitude simply by outputting the declination given by Astrometry.net, but the longitude calculation requires more steps. Specifically, at this stage the time at Greenwich, more accurately the UTC time, is used to calculate GAST. Due to the precession of the axis of the Earth, the difference between a sidereal day and a solar day, and a number of other factors influencing the movement of the celestial sphere relative to the surface of the Earth, this conversion is rather complicated and requires a number of very small adjustments. For this purpose, an algorithm provided by the United States Naval Observatory will be used [Observatory, 2011]. This algorithm is laid out in detail in an appendix, and it is also implemented in Python in a Github repository under the title LatLongFromDecRA.

Once GAST has been found by this algorithm, the RA of the observer's meridian is added to GAST once converted to degrees and the sum is reduced into the standard longitude units of degrees west or east.

5 Tools

Astrometry.net is one of the central components of the current implementation of zenith-image analysis.

It is useful for any engineer or scientist using this photo analysis library/tool to know about how sky images are processed using the Hierarchical Equal Area isoLatitude Pixelization, or HEALpix, system of analysis of sphere surfaces. The HEALpix system divides the sky into equal area arc-planes depending on the size the user wants. Division of the sphere begins at 12 individual sections then each of of those pieces can be recursive split into 4 equal surface area subsections following the pattern 12,48,198,768... [Górski et al., 2005]. This equal division of spheres is what Astrometry.net can use to analyze and "pattern match" the catalogs of HEALpix sections with the input image asked to be solved.

Astrometry.net uses Bayesian decision making process as they describe in there paper "...if it passes a Bayesian decision theory test against a null hypothesis." The algorithm will only come to a conclusion if it believes the field is highly probable to be the correct math to what is in the input catalog. You can see a reduced complexity version of this by either looking at the full output in the online implementation or setting the verbose flag in the downloaded local version where it begins to give you "log-odds" ratios. It can be observed that these numbers sit in the range of 1 to 20 when the photo's data is being matched with the wrong catalog section or resolution, but suddenly rises up into the 400+ range when it finds a correct match and gives the full successful output. [**?**]

The algorithm provided by the United States Naval Observatory, **USNO**, finds Green apparent sidereal time using current UT1. One of the simplifying assumptions made by this project is that UTC is equal to UT1, which bears an error of roughly one second. That is, it is relatively simple to keep a clock accurate to UTC but quite difficult to maintain a precise estimate of UT1, even though UT! is the accepted astronomical standard for these calculations. On a similar level of error, the algorithm used is accurate to within half of a second until past the year 2100. These values are well within acceptable precision as will be shown in the results section.

The project does make use of Greenwich apparent sidereal time rather than Greenwich mean sidereal time, **GMST**, despite the former being slightly more difficult to calculate. This small difficulty is handled because GAST is marginally more precise for astronomical calculations and loses precision slower.

Stellarium is a night sky simulator used in this project to create a test environment. This software is completely free and is often used for educational purposes, being largely aimed at amateur astronomers and enthusiasts. As a result, the precision of the program does not quite stand up to scientific rigor as can be seen in the results section below. It also lacks strong predictive powers, with the error increasing rapidly as time passes the current date. This might be due to the most recent stellar survey occurring every fifty years, and this program might simply reproduce that most recent interpretation of the stars.

The simulator offers several useful features, most notably it provides the latitude and longitude coordinates of the observer to within several decimal places, along with the current time and a UTC conversion factor accurate to the minute. It also provides various patterns, labels, and artwork to accompany the starfield, but in this application those were unused.

Figure 3: ZWO ASI178MM monochrome 1/1.8” CMOS IMX178, 6.4 Megapixels or 3096 x 2080 pixles, 2.4 um pixel size, 7.4mm x 5mm sensor size, 120 gram weight, 14-bit ADC output, USB 3.0 with a Tamron 16mm C-mount lens, 25.9 x 19.5 Field of View and a 5mm C to CS mount spacer

It is worth noting that lower quality cameras such as the ones included on a common cell phone are not powerful enough because few stars will appear in the photograph and those that do will be so small and spread out that Astrometry.net doesn’t have enough information on surrounding stars to come to a conclusion beyond the threshold of certainty.

Lastly, in order for Astrometry.net to function Flexible Image Transport System, or **FITS**, data files are needed. These files contain the location, RA and DEC, of the stars in the specific HEALpix sectional. The exact FITS file or set of FITS files needed by the target depends on the focal length of the camera you use which in turn gives you the field of view for the image captured. Using the appropriate FITS file(s) for the job will cut down significantly on computation time. For example, a much more telescopic image would benefit in the matching process by using much more focused FITS files that are concentrated around specific smaller HEALpix tiling. The experiment used smaller equipment compared to a telescope with a wider field of view where much broader HEALpix tiles were used.

Astrometry.net provides some tools to build you own FITS files out of many different formats such as comma separated value files, images, or even binary tables; however they also host freely available preformatted FITS files on there website athttp://data.astrometry.net/4100/ for the 2-MASS full sky survey and http://data.astrometry.net/4200/ for Tycho-2.

6 Results

6.1 Experimental

The prototype zenith-image analysis system was developed using a the ASI178MM camera, pictured above, rested in the most level part of a parked motor vehicle aimed straight up at the night sky at time past astronomical twilight to ensure minimum light pollution from the setting sun. This was done using an open source python library produced by Stephen Marple, which can be found at https://github.com/stevemarple/python-zwoasi coupled with the camera's own software development kit, or **SDK**, to access the camera easily and effectively using the scripting language Python. Choosing this language over C++ or C increases readability and development speed at the cost of some computation speed optimizations. After many images were saved to the hard-drive, they were run through a locally downloaded version of Astrometry.net to find the exact location of the photograph on the celestial sphere. The downloadable version of Astrometry.net only functions on Linux distributions and OSX, albeit with some adjustments necessary to function on OSX.

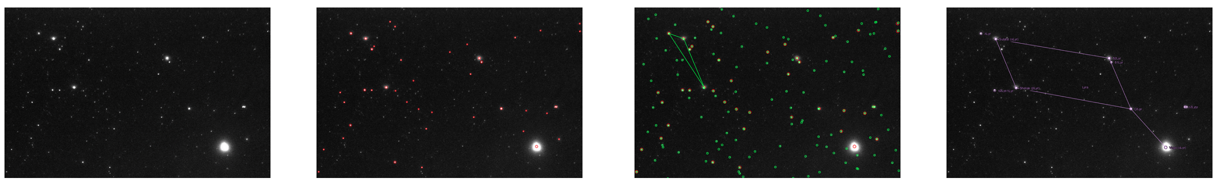
Astrometry.net generates a large set of meta-data about the input photograph along with the FITS files it is using to analyze the photograph. This output includes things such as the width and height of the photograph in degrees, field rotation angle, and, most relevant to this work, right ascension and declination of the center of the image. For example, "Field center: (RA,Dec) = (265.023791, 33.453755) deg." which identifies a quite exact position on the celestial sphere. This provides most of the necessary information to determine latitude and longitude, only needing the GAST from the USNO algorithms described earlier.

The relationship between exposure and gain was a subject of interest. Exposure is simply the time the sensor is allowed to gather photons. On the other hand, gain is used in low light environments to capture a fully colored image. It effectively increases light sensitivity at the cost of higher noise in the image. Noise is the static "dust" that falls over the image naturally. This happens because the image goes from having a thin range of light/color values to having a wide range of values. Image stacking was used to compensate for the increased noise. It is a process where a small group of images is taken, usually from two to sixteen, and aligned on top of each so the key points are found by creating peaks in the sum image, then the mean value of each pixel is used to create the final image. The fully stacked image is thus smoother than any one of the original images. This effect causes starfield images to have more definition around the edges of the stars, the noisy grey-black field of the night sky is faded into one color, and clouds often get darker as they fade together into the background. It is unclear at this moment without a plethora of testing if image stacking reduces the error in the image analysis process. The library used in this study was the GitHub project made by user "maitek", real name Mathias Sundholm, called "image stacking" which uses OpenCV to perform image stacking. The two main OpenCV methods used by the author are Oriented FAST and Rotated BRIEF, or **ORB**, and Enhanced Correlation Coefficient, or **ECC** [Bradski, 2000]. ORB is the faster less accurate method and ECC is the slower more accurate method. In practice for star field image stacking no reason was found to opt into the high accuracy ECC as there seems to be negligible difference between the results of the ORB and ECC method, therefore for the purposes of zenith-image analysis ORB seems preferable.

Significant research was done to find the best camera for this purpose that fit budgetary constraints. For Astrometry.net to read and interpret the photographs, the camera mounted to target needs to be high resolution and have partial telescopic zoom level, which ensures the stars are large enough on screen and in focus of the lens. Astrometry.net ask for a small number of closely clustered stars rather than a large field of dispersed groups. The primary design paper for Astrometry.net states that the system works well on 13 by 9 arcminute images and sub-images down to 8 by 8 arcmin but suffers a serious drop in performance on 7 by 7 arcminute images [Dustin Lang et al., 2010]; however, the results found that a small 16mm lens outputting at about 26 by 17 degrees or 1440 by 1020 arcminute images performed well in testing. A problem arose when testing began with a 170 degree fish-eye lens with a greater number of total stars, but frequently stars would be too small or too distorted by the fisheye lens. An attempt was made to "defish" or stretch the photo into a rectilinear form, however this led to a stretched distortion in the stars toward the outer circle of the photo rendering them inoperable by Astrometry.net.

Overall Astrometry.net reasonably efficient in terms of both memory and processor demand for most scenarios involving long-range navigation. The algorithm from a lost-in-space position can find its position on the celestial sphere in under five minutes. This time can be cut down provided you augment the input photo with supporting known factors. These can include the field of view's height and width, the estimated RA and DEC location of where the target is believed to be, a radius of imprecision, and a given "depth" of stars, meaning only match the n brightest stars where n is some number between 20 to 50. This information would be easily available with a camera controlled by OpenCV and iterated use of zenith-image analysis.

Below is example test case of the Astrometry.net code base evaluating the constellation Lyra:



(a) Raw input (b) Star detection (c) Star classification (d) Star labeling

Figure 4: Example workflow of Astrometry.net on the constellation Lyra

6.2 Simulation

In addition to the tests performed under experimental conditions with the physical model, a series of trials were performed in simulation due to the wider range of test locations available without the potential error introduced by using images from other astronomers that might not be pointed at zenith. A set of starfields were captured in the astronomy simulation program Stellarium under varying conditions. Stellarium provides a great deal of data which allows these tests to be easily reproduced and tightly controlled. The true longitude, latitude, and time of observation were varied between tests and recorded in the first appendix in two seperate charts along with the calculated latitude and longitude. The images were taken precisely centered on the observer's zenith and with a field of view of roughly one degree. The images also ignored atmospheric effects, although these last qualities are impractical to reproduce in a true test environment. One point worth noticing is that certain entries in the table, notably two through five and several entries in the teens, have very similar but not identical UTC times. This is because they were all taken at various positions on the globe while the simulation was paused, meaning they should have identical times. This lack of precision will be discussed later in the paper.

	Mean Value	Absolute Mean Value	Error in Miles
Latitude Error	~ 0	0.0674	4.65
Longitude Error	0.162	0.185	12.8

Figure 6

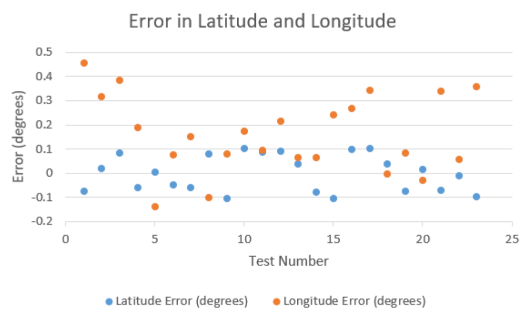


Figure 5

Another talking point in the appendix charts is the very last entry, which shows a date well past the time of this paper's writing. Stellarium is able to predict the stars' positions into the future and this capability was tested with a smaller but still significant data set. Only this entry was kept since, as can be seen, it produces vastly less precise longitude estimates than the entries closer to the time of the simulation. This entry was not used in the analysis in the rest of this section. It is possible that this method deteriorates with time, but due to the extreme improbability of geometry breaking down in a few years, it is instead hypothesized that Stellarium uses relatively imprecise constants to generate future star positions.

Note that in the summary table, the latitude errors average arithmetically to zero. This is a rounding error, but nonetheless the mean should approach zero as the sample size increases since the error is purely random scattering around the true value. The mean longitude error, however, does not approach zero. It instead approaches a value between one fifth and one sixth of a degree, indicating a slight bias eastward in all estimates. The value 0.162 which will be called the 'magic constant' was used in further analysis to see if it could be used to reduce the error in estimates, and it did. Naturally this is subject to overfitting since the constant was calculated from this data, but time constraints prevented the gathering of another data set purely for testing this anomaly. Individual test cases outside the source set were used and they had similar improvements in error.

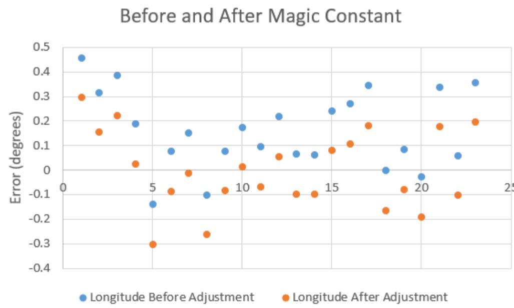


Figure 7

This magic constant represents a failure somewhere in the information pipeline. Simply subtracting the magic constant from all entries results in a decrease in average error of roughly three miles. One of the tools used must have created a bias, but at this time it is uncertain which had this effect.

As mentioned in the tools section, Astrometry.net does not actually behave optimally with such a narrow field of view. This was not discovered until too late in the development process to run another batch of tests, however this might contribute to explaining the degree of error found in the example set.

7 Conclusion

This paper has detailed the theoretical grounds, a potential implementation, and given an idea of the precision of an entirely novel approach to celestial navigation and non-GPS navigation in general: zenith-image analysis. This method is exceptionally cheap to implement and relatively quick to return results, primarily demanding memory to store indices.

The first matter to discuss is the imprecision of this method as shown in the charts above. The mean error in latitude is just under five miles, and the mean error in longitude is between nine and thirteen miles. It is abundantly clear that this is, at the very least, insufficient for being the sole guidance system for a vehicle, however it is a constant level of imprecision and is accurate anywhere on the globe. This means that it is an ideal candidate for pairing with an inertial navigation system for instance, which can boast much higher precision but offers diminishing returns.

The relative precision of latitude and longitude is unsurprising, given the additional complexity of the longitude problem. Historically longitude puzzled navigators for over two millenia longer than latitude, since latitude was solved by at latest six hundred B.C. while longitude took until the fifteen hundreds for a working theoretical solution and another two hundred years for a successful implementation [University, 2007]. Further, longitude has another layer of spinning and variance, where latitude is perpendicular to the plane of rotation, longitude is directly affected. Regardless, the gap can be closed and methods of improving both estimates will be explored in the future work section below.

The eastward bias in the longitude estimates, the magic constant, is still a mystery to this team. Given time to create a suitably large dataset of field tests it would be possible to verify if the bias is a symptom of Stellarium, but it is also probable that the alignment used in the field would be off zenith by a relatively stable amount. This would produce another consistent bias and the two would likely confound any attempt to check if the original bias disappeared. It is possible that this bias is inherent to Astrometry.net. This could be tested by using another meta-data generating program such as SExtractor, but it is unlikely that Astrometry.net is the source of the bias for several reasons. While it does use a heuristic to determine which stars are in the image, it is an impossibility to, through noise, change the relative position of the stars. That is, in order to move the estimated center to the right, the stars themselves would have to be shifted to the left in some sense. This might be possible due to some alignment of satellites and meteor events, but it is incredibly unlikely to be so consistent.

8 Future Work

This paper opens many potential avenues of research. The most immediately promising is improving the precision of this method. As noted in the results section, the Stellarium clock was not accurate to the minute, meaning as much as twelve percent of the error in the longitude estimates might be recovered by using a more accurate measurement. Since the true time and the given time could differ by as much as two minutes, that creates at most two arc-minutes of potential error in the longitude estimate and thus nearly two and a half miles of error. So simply using a more accurate clock to test this method might create much more accurate results.

Another improvement to make is in the accuracy of angle at which the photograph was captured. In the experiment, a level was used to approximate where the flatest position, relative to gravity, was on the surface of the earth. This causes potential error where the camera is off-zenith by tenths or hundredths of a degree and this sight error magnifies to serious proportions when calculating the target's latitude and longitude. It is the team's suggestion this method (taking a photo, processing it by Astronomy.net's programs, and then, based off the center RA and DEC, calculating the latitude and longitude) be tested using a massive scientific observatory where the exact GPS location is known and the telescope is tuned to zenith with an maximum certainty. This extreme measure is simple but eliminates any potential bias in the acquisition of the photograph.

Optical flow could be explored to form an estimate of relative velocity of the target while it's moving. Optical flow as mentioned in the previous work section functions by tracking the change in pixel positions of relative objects. This could be used to track the velocity of the stars as they appear in the zenith-image. Of course, the stars have an apparent natural velocity, that is to say if the observer is not moving the stars appear to naturally rotate around the celestial axis. This rotation around the axis can be mathematically calculated and then the difference from this zero-velocity calculation and the observed optical flow velocity can be used to get information similar to that given by an inertial system. Deserving of a small mention is the fact that the Earth's axis does not stay in place, it goes through a process known as precession where the axis very slowly 'wobbles' in a sinuous path. A similar effect could be possible through long-exposure photographs where it causes what can be called "star trails" forming in the resulting photograph. This line of photographic information could potentially be capitalized on. The full line of information gives the locations of the start, finish, and all other points in between. Again by mathematically calculating the arc based on the normal apparent rotation of the stars above the target and the precession of Earth's axis you can then figure the difference between the normal zero-velocity calculation and the observed star trail which should provide similar information to the method above.

On a similar vein to the potential offered by testing outside Stellarium, it would also offer an answer to the question posed in the simulated results section: Why do predicted starfields perform so poorly? If starfields generated by other software, or simply waiting until 2021 to gather more images, produce results comparable to the data gathered at the time of this research it would put to rest the potential time decay of this method, unlikely though it is.

There is also the question of the error in latitude, though it is the smaller of the two. One possible source of the error is conversion from geometric to geodetic latitude. Given the fundamental premise of this research is rooted in great circles and angle summation, it is clear that this method utilizes geometric latitude while most applications, possibly including Stellarium, use geodetic latitude. Determining and exploring the difference between these systems might further increase the precision.

The magic constant explored in the results section also offers some interest. The exact source of this error isn't yet known. Astrometry.net may have a drift in the right ascension, or Stellarium could provide the necessary bias. In any case, looking into the source of this error would quite likely be fairly simple given more research time but it would also provide very immediate and sizable improvements to the implementation's precision.

This project would benefit greatly from additional live testing under more varied conditions and with greater scrutiny. The conditions that zenith-imaging analysis was tested under were fairly close to ideal and it would be extremely useful to learn how well this method holds up under various test conditions in more challenging environments.

Zenith-image analysis was always intended to be a secondary navigation system. It isn't quite precise enough to be the primary locating tool for flight or most overland travel. Implementing another navigational system, such as more traditional astronavigation, an inertial guidance system, or any of the alternatives mentioned in the previous work section would provide valuable insight into how this system functions and if it is reliable enough to be a major contributor in a true navigation test. Similarly, filtering fits neatly into the comments above about magnification of error. A well-designed filtering system to analyze the previous estimates of position might offer substantial improvements. The tests run in this paper were all 'lost-in-space' calculations, taking the maximum amount of processing time and the minimum of assisting observations. Performing zenith-image analysis in succession and using modern techniques to minimize the noise and collate the data might offer much better precision in field testing.

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9 Appendix A

ID	Local Date	UTC Time	True Longitude	Right Ascension	Calculated Longitude
1	7/10/2018	18:21:13	20.432	223.903	19.973
2	7/10/2018	18:20:57	76.865	280.410	76.547
3	7/10/2018	18:21:17	1.946	206.506	1.560
4	7/10/2018	18:20:18	-70.054	133.456	-70.244
5	7/12/2018	09:08:50	-155.676	271.889	-155.538
6	7/12/2018	09:10:20	46.703	114.051	46.624
7	7/12/2018	09:09:43	169.297	236.573	169.146
8	7/12/2018	17:07:12	148.865	319.791	148.964
9	7/12/2018	09:10:04	103.135	170.482	103.055
10	7/12/2018	09:09:07	-68.108	359.254	-68.285
11	7/12/2018	09:08:47	-101.189	326.142	-101.285
12	7/12/2018	09:09:05	-40.865	26.344	-41.083
13	7/12/2018	09:08:39	-0.973	66.388	-1.039
14	7/12/2018	09:09:51	69.081	136.4430	69.016
15	7/12/2018	21:19:47	-70.054	180.368	-70.297
16	7/13/2018	3:18:42	35.027	15.396	34.756
17	7/14/2018	23:30:48	84.649	9.782	84.302
18	7/16/2018	1:48:02	-29.189	291.680	-29.188
19	7/16/2018	3:52:41	-128.432	223.599	-128.517
20	7/18/2018	11:43:40	167.351	279.532	167.377
21	7/18/2018	12:02:50	112.865	229.484	112.524
22	7/19/2018	15:54:45	-81.730	94.293	-81.790
23	7/19/2018	15:55:51	25.297	201.297	24.938
24	10/27/2021	6:53:45	-41.838	96.670	-42.627

Figure 8

ID	True Latitude	Declination	Calculated Latitude
1	-28.703	-28.629	-28.629
2	18.973	18.952	18.952
3	46.216	46.130	46.130
4	0.008	0.066	0.066
5	62.757	62.752	62.752
6	8.270	8.315	8.315
7	-44.27	-44.214	-44.214
8	-30.649	-30.73	-30.73
9	44.27	44.374	44.374
10	54.000	53.895	53.895
11	-27.730	-27.818	-27.818
12	72.486	72.394	72.394
13	0.486	0.446	0.446
14	0.486	0.564	0.564
15	-46.216	-46.112	-46.112
16	10.216	10.116	10.116
17	-62.757	-62.860	-62.860
18	29.676	29.634	29.634
19	-17.027	16.953	16.953
20	74.432	74.413	74.413
21	9.243	9.310	9.310
22	25.784	25.793	24.793
23	-61.784	-61.687	-61.687
24	78.324	78.338	78.338

Figure 9

Appendix B

The following equations are provided by the United States Naval Observatory [Observatory, 2011] for the purpose of finding Greenwich apparent sidereal time using UTC.

Let JD_0 be the Julian date of the midnight before the date of interest. Let H be the UT hours since that midnight, and let JD = JD_0 + H/24. Subtract 2451545.0 from JD to find D, and similarly JD_0 to find D_0. D is the number of Julian days since January 1st, 2000. Using these values, GMST in hours is

$$GMST = 6.697374558 + 0.06570982441908D_0 + 1.00273790935H + 0.000026T^2$$

Where T is the number of centuries since 2000. This will need to be reduced to modulo 24h. Next find GAST with

$$GAST = GMST + eqeq$$

Where $eqeq = \Delta\Psi cos(\epsilon)$. Here $\Delta\Psi$ is the nutation in longitude, given by

$$\Psi \approx -0.000319sin(\Omega) - 0.000024sin(2L)$$

And Ω is the longitude of the ascending node of the moon,

$$\Omega = 125.04 - 0.052954D$$

With L, the mean longitude of the sun,

$$L = 280.47 + 0.98565D$$

and finally, ϵ is the obliquity.

$$\epsilon = 23.4393 - 0.0000004D$$