GPS for Authentication: Is the Juice Worth the Squeeze?

Adam Baker

GPS for Authentication: Is the Juice Worth the Squeeze?

GIAC (GSEC) Gold Certification

Author: Adam Baker, adambakersf@gmail.com

Advisor: Domenica Crognale

Accepted: 19 April 2021

Abstract

For decades, location has been used as a validating factor in authentication. However, this has almost exclusively reflected IP address-based geolocation, a far less precise data point than a GPS coordinate. This paper will compare the precision of IP address location data to that of GPS coordinates, to determine if the increased available precision of GPS coordinates provides sufficient enhancement in value to justify expanding the use of GPS coordinates for authentication.

The author expresses appreciation to Dr. Dennis Eggett of the Brigham Young University Statistics Consulting Center for his assistance.

1. Introduction

In 2019, the author attended several presentations hosted by Infragard, an information security organization. One of the presenters represented a well-known Identity as a Service (IDAAS) provider who outlined his firm's cutting-edge process for calculating authentication confidence based on factors determined about the requesting end-user. That confidence level, in turn, would determine the number of additional factors the requestor would be required to submit to achieve successful authentication. One of the prominent authentication factors listed was "geolocation." In a conversation with the author after the presentation, the presenter described the IDAAS' method for determining geolocation as "IP address", and that the highest resolution of that factor was usually a "time zone, city or zip code" (N. Fisher, personal communication, March 7, 2019).

This firm is hardly alone in using a user's IP address as the basis for geolocation in network-based transactions, nor is it a new phenomenon. As early as 2001, passive geolocation of Internet hosts via their IP address attributes has been a topic of research and the focus of major investment and effort (Padmanabhan & Subramanian, 2001). Because a large number of IP addresses are purchased by Internet Service Providers (ISPs), and many of those were allocated dynamically via DHCP, early methods of IP-based geolocation involved simply resolving the IP address with the region associated with the ISP's business operations. In cases involving local ISPs, this would allow the interrogator to know the city or region of the requestor based on that of the ISP's operation. However, because many ISPs had widely dispersed customers, this method was viewed as unreliable. In the intervening decades, several methods to gain a host's location via IP address and refine the resolution of that factor have been discussed, attempted, or fully put into mainstream production (Taylor et al, 2012).

Location data for connected users is big business, estimated at $21,000,000,000 for the advertising sector alone in 2018 (Lindsey, n.d.). However, even with such importance and investment, current geolocation methods are still of relatively low precision, especially for authentication purposes where precision is crucial. For example, MaxMind, a prominent IP geolocation database service, boasts an accuracy of "82%

Adam Baker, adambakersf@gmail.com

within 25 miles, for IPs located within the US" (Eriksson et al, n.d.). However, for a typical ISP, that address could refer to any one of thousands of customers with a dynamically-issued IP address within those 25 miles.

Alternately, Global Positioning System (GPS) technology's availability has steadily risen with the proliferation of mobile devices and the miniaturization of GPS receiver chips. With its triangulation capability via a constellation of satellites, GPS coordinate-based geolocation is more precise, on average, than IP address-based geolocation (Katz-Basset et al, 2006). But exactly how much more precise is it? And would that additional precision be enough for those in the industry who depend on precise geolocation for secure and reliable operations, such as authentication providers, to advocate more forcefully for its adoption by device manufacturers and device users? This research will quantify the added value of GPS resolution for geolocation. It will provide needed context for decision-makers to consider whether GPS' additional precision is worth overcoming the technical challenges and privacy concerns associated with this active geolocational technology.

2. IP Address as a Geospatial Factor

The Internet Protocol version 4 has been the primary workhorse of communications over the public Internet since its inception. According to Canon (2010):

> "IPv4 was the first stable version of the Internet Protocol (previous versions were developmental)". In 1980, The Department of Defense announced that the ARPANet would migrate to IPv4 on January 1, 1983. In 1985, when the National Science Foundation initiated the NSFNET, NSF staff concluded that the use of the Internet Protocol was essential to the success of the NSFNet and adopted it. In the early 1990s, NSF decided both to allow public traffic on the NSFNet and to privatize the network, establishing the foundation of the current public Internet."

In turn, the Internet's unexpected explosion of websites and traffic in the late 1990s fueled the desire of communications, marketing, and other industry representatives to know, to one degree or another, where their end customers were. Methods were

Adam Baker, adambakersf@gmail.com

suggested, and patents and products soon followed (Parekh et al, 2000). While many of these methods varied in their approaches toward making a geographic location more precise, almost all had IP address-based geolocation at their core.

2.1 A Brief History of IP Address-based Geolocation

In a patent application filed in 2000, employees of Digital Envoy described "Systems and methods for determining collecting and using geographic locations of internet users" (Parekh et al., 2000). As the first patent filed for a method to locate internet users, it set the foundation all others that would follow, and it relied on IP address-based geolocation:

> "A method of determining a geographic location of an Internet user involves determining if the host is on-line, determining ownership of the host name, and then determining the route taken in delivering packets to the user. Based on the detected route, the method proceeds with determining the geographic route based on the host locations and then assigning a confidence level to the assigned location. A system collects the geographic information and allows web sites or other entities to request the geographic location of their visitors. The database of geographic locations may be stored in a central location or, alternatively, may be at least partially located at the web site. With this information, web sites can target content, advertising, or route traffic depending upon the geographic locations of their visitors. Through web site requests for geographic information, a central database tracks an Internet user's traffic on the Internet whereby a profile can be generated. In addition to this profile, the central database can store visitor's preferences as to what content should be delivered to an IP address, the available interface, and the network speed associated with that IP address." (Parekh et al.)

The breadth of the patent's description of how geolocational data would be obtained, and tied to a user via IP address in a database, still reflects the basic way these operations are performed two decades later.

Adam Baker, adambakersf@gmail.com

Many attempts have been made to improve the precision of IP address-based geolocation. In 2006, Katz-Basset et al. compared the two popular methods at that time for deriving geolocation from network traffic, GeoPing and Constraint-Based Geolocation (CBG), with a new method they proposed: Topology-Based Geolocation (TBG). GeoPing geolocated a host by "mapping it to the most representative landmark and using the landmark as the estimate for the location of the host" (Katz-Basset et al). CBG, on the other hand, used a technique of measuring delays between known landmarks, then comparing the target host's delays within overlapping circles representing the landmarks' geospatial relationships to each other.

Because both GeoPing and CBG use packet delay to estimate distance, they were constrained by the fact that Internet traffic often took an irregular path between the host and server. As a new method, TBG increased accuracy by using traceroute to map the network topology between server and host, then added that knowledge to measured end-to-end delays and assessed per-hop latency. Katz-Basset et al. (ibid) asserted that these additional measures would dramatically increase the accuracy and reliability of IP-based geolocation solutions.

In their work "Review of Different IP Geolocational Methods and Concepts," Bendale & Kumar (2014) compared different IP geolocation technologies, and their varied algorithmic instantiations, by average accuracy (Table 1):

Table 1

IP Geolocational Methods and their Average Accuracies

Class	Algorithm	Average accuracy (km)
Delay-based	GeoPing [19]	150 km (25th percentile); 109 km (median) [30]
	CBG [12]	78-182
	Statistical [31]	92
	Learning-based [9]	407-449 (113 km less than CBG [12] on their data)
Topology-aware	TBG [14]	194
	Octant [30]	35-40 (median)
Other	Geo Track [19]	156 km (median) [30]

Source: Bendale & Kumar (2014)

Adam Baker, adambakersf@gmail.com

They assessed that the Octant variation of the topology-aware class of IP geolocational technologies was the most accurate, at a 35-40km median accuracy (Table 1). Even in 2014, this figure is strikingly similar to the claimed accuracy several years later of the MaxMind geolocation database: “80% accurate to within 25 miles (40km), at least in the United States” (Ericksson et al, ibid). Viewed in this light, it appears that IP-based geolocational techniques' accuracy and precision improvements have largely plateaued at a scale that leaves much to be desired for authentication and potentially other security-related applications.

2.2 Human Errors in IP-based Geolocation

Beyond algorithmic or technique-based accuracy limitations, outright IP geolocation mistakes have ranged from mildly comical to downright dangerous. Many of these errors stem from the human factor in the IP-based geolocation process, as people are ultimately required to make judgment calls when determining how, or where, to represent conceptual geographic locations. For example, where is the "center" of a geographic region? A city? A state?

This very question has caused considerable heartache for individuals at different points around the world. For example, starting in 2013, "John" and "Ann" (pseudonyms) of Praetoria, South Africa, began receiving threatening visitors, claiming they were thieves who had stolen digital property, or kidnappers who had taken a loved one, or even murderers (Hill, 2019). Law enforcement representatives from several jurisdictions, complete with search warrants, showed up at all hours of day or night, demanding to search their home and land. This continued until at least 2019. Why? In 2013, the MaxMind database began reflecting the "center" of Praetoria as a coordinate that, on the ground, fell within their house (Hill, 2019). This meant that when a device's IP address (such as a stolen laptop, tablet, or a kidnapped child's cell phone) was geolocated to Praetoria, it would automatically show as precisely at John and Ann's home. Although MaxMind publishes an accuracy "radius" (the assessed precision or degree of error for a given geolocation) for the coordinates in its database, not all mapping websites that use

Adam Baker, adambakersf@gmail.com

MaxMind's database likewise reflect that accuracy radius, and not all users realize or understand its implications (Hill, ibid).

However, the fault didn't truly lie with MaxMind, as it had received the coordinate for Praetoria from the National Geospatial-Intelligence Agency (NGA), the US intelligence agency tasked with delivering "world-class geospatial intelligence that provides a decisive advantage to policymakers, warfighters, intelligence professionals and first responders" (Hill, ibid). In response to a question on the issue from Hill, NGA's spokesperson Erica Fouche responded that "Our Political Geographers use medium-scale maps to place a feature's coordinates as close to the center of a populated place as possible. In this case, John lives near the capital. There was absolutely no intent to place the coordinates on his residence" (Hill, 2019).

John's situation was no isolated incident, as similar issues have arisen in Kansas, Georgia, and other locales, all derived from human cartographers who decided where arbitrary geographic points should be represented in a digital database. But that is a potentially major issue with any geolocational method: the more human judgment is used at lower resolution (to Fouche's point, at "medium-scale"), the greater the margin for error. It is critical to obtain accuracy and precision in as many links of the geolocational chain as possible, something current IP-address based geolocation techniques do not allow.

3. GPS as a Geospatial Factor

GPS technology and its applications have become so unobtrusively ubiquitous in the modern era that it is becoming difficult to remember a time when they were not available. From planning a cross-country road trip's route in seconds, to conducting complicated surveying operations in a fraction of the time of manual methods, to aiding nuclear submarines and commercial airlines in open-ocean navigation with unparalleled precision, GPS has achieved perhaps the most telling mark of a successful technology: it is so reliable and pervasive that users have largely taken it for granted (Cooper, 2019).

Adam Baker, adambakersf@gmail.com

3.1 A brief history of GPS

Although a global satellite-based system for precise navigation and chronometry seems a very modern development, its roots go back almost two decades before the first satellite was launched. At the heart of each GPS satellite is an atomic clock, the groundwork for which was laid via research conducted at Columbia University by I.I. Rabi between 1938-1940 (Taubes, 1997). Accurate to a billionth of a second, the atomic clock was first envisioned as a sufficiently precise way to measure Einstein's theory of gravity by its related effects on time (Taubes, ibid). By 1954, the first portable self-contained atomic clock had been developed (Taubes, ibid). Less than three years later, the Soviet Union launched Sputnik 1, the first manmade satellite (Taubes, ibid). Scientists at Johns Hopkins Applied Physics Laboratory (APL) observed Sputnik and discovered they could calculate the satellite's precise position in the sky by starting from their own known position and measuring the Doppler effect on Sputnik's emanated radio signal (Guier, 1998). Visionary insights from another APL scientist reasoned that the reverse was also true: "…by measuring a radio signal from a satellite whose position is known", an object on Earth could calculate its own position (Stanford University News Service, 1996).

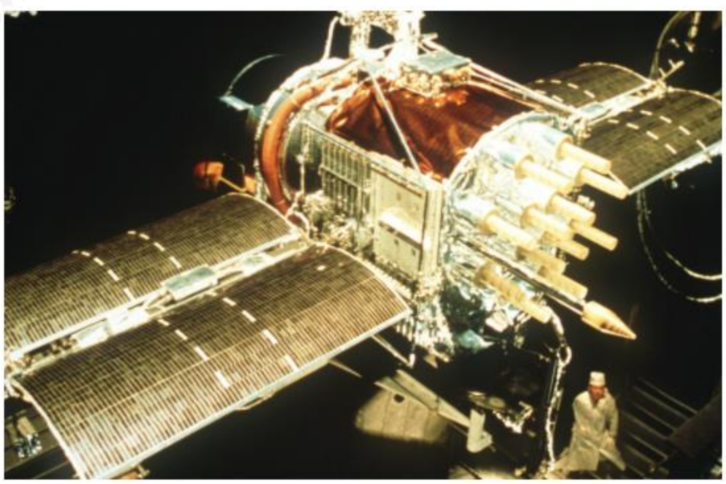
While the US military had long sought a way for its nuclear submarines to accurately calculate their positions in the open ocean and saw the promise of satellite-based navigation as the most reliable way to accomplish it, the civilian team credited with the creation of the modern GPS satellite system had both military and civilian uses in mind (Cooper, ibid). Brad Parkinson, leader of the Stanford engineering team who pitched the US Department of Defense on funding the satellite network, testified as such before Congress three years before a satellite was ever launched: "From day one, I said, there will be a civil navigation capability. Part of the signal would be free and open. Testifying before congress in 1975, from the get-go, I said that GPS was a dual-purpose system-civil and military" (Cooper, ibid).

The concept of the system was deceptively simple— multiple satellites would each continuously broadcast a radio signal containing the precise time, the satellite's location, and its status, to Earth. A passive GPS receiver would pick up the signal, measure the difference in time between the signal's transmission and receipt, and use that data to geometrically calculate the distance from itself to the satellite along the line of the signal (using the equation "distance = rate x time"). Once this had been done with at least four separate satellite signals, the GPS receiver could assess its position by intersecting those lines (US Space Force, n.d.).

To enable this, Parkinson conceived a system of 24 satellites minimum, divided into six separate orbital planes of at least four satellites each, at an altitude of ~20,200km (United States Space Force, 2021). This would ensure that almost every point on the ground would have at least four satellites visible at all times to provide triangulation and precise geolocation. Navstar 1 (see Figure 1), the first GPS satellite, was launched in February 1978, and after many additional launches, the system was considered fully operational in 1995 (Stanford University News Service, ibid). In June 2011, the Air Force added three additional satellites to provide better global coverage (United States Space Force, 2021). This brings the current GPS constellation total to 31 satellites, counting an additional four satellites orbiting in reserve (United States Space Force, 2021). Today, the US Space Force manages the GPS system and continues to update and replace satellites as needed to maintain and increase capability well into the future (United States Space Force, 2021).

Figure 1

NAVSTAR 1 Satellite



Source: US National Archives

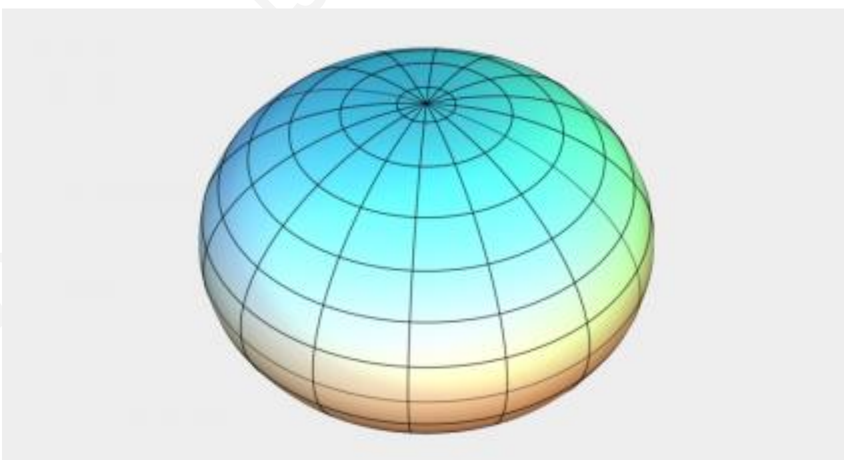
Adam Baker, adambakersf@gmail.com

3.2 Different Levels of GPS Precision

Much to the chagrin of naysayers, the Earth is not flat. Over the centuries, cartographers, navigators, and explorers have continually refined their ability to represent the orb that is our planet, in a way that allowed for precise geolocation and navigation. Today, the US GPS system uses the World Geodetic System 1984 geodetic model (WGS84) to represent locations in a mappable way (GISGeography, n.d.). WGS84 includes a wire-frame reference overlay (Image 2) for the globe that allows for latitude and longitude measurements from given constant locations (for example, 0° longitude passes through the Royal Observatory in Greenwich, England). These latitude and longitude measurements, for GPS, are represented in decimal degrees (GISGeography, ibid).

Figure 2

WGS84 Wireframe Reference Grid



Source: GISGeography

In decimal degrees, the number of decimals indicates the given coordinate's level of precision. Each full degree represents roughly 111km if measured at the equator. The earth is not perfectly spherical but is an oblate spheroid (much like a boiled egg, pressed at the top and bottom to bulge out the middle). Because the earth's shape is not perfect, to maintain consistency of measurement, as the lines of longitude begin to converge toward

Adam Baker, adambakersf@gmail.com

the poles, each "box" made by intersecting lines of latitude and longitude gets progressively smaller. The smaller the box, the higher the degree of precision possible by the measurement system (GISGeography, ibid).

As previously mentioned, the higher the number of decimals in a given coordinate, the more precise it is. The table below shows the level of precision indicated by each decimal level (Table 2):

Table 2

Decimal Degrees Precision Scale

decimal places	decimal degrees	DMS	Object that can be *unambiguously* recognized at this scale	N/S or E/W at equator	E/W at 23N/S	E/W at 45N/S	E/W at 67N/S
0	1.0	1° 00′ 0″	country or large region	111.32 km	102.47 km	78.71 km	43.496 km
1	0.1	0° 06′ 0″	large city or district	11.132 km	10.247 km	7.871 km	4.3496 km
2	0.01	0° 00′ 36″	town or village	1.1132 km	1.0247 km	787.1 m	434.96 m
3	0.001	0° 00′ 3.6″	neighborhood, street	111.32 m	102.47 m	78.71 m	43.496 m
4	0.0001	0° 00′ 0.36″	individual street, large buildings	11.132 m	10.247 m	7.871 m	4.3496 m
5	0.00001	0° 00′ 0.036″	individual trees, houses	1.1132 m	1.0247 m	787.1 mm	434.96 mm
6	0.000001	0° 00′ 0.0036″	individual humans	111.32 mm	102.47 mm	78.71 mm	43.496 mm
7	0.0000001	0° 00′ 0.00036″	practical limit of commercial surveying	11.132 mm	10.247 mm	7.871 mm	4.3496 mm
8	0.00000001	0° 00′ 0.000036″	specialized surveying (e.g. tectonic plate mapping)	1.1132 mm	1.0247 mm	787.1 µm	434.96 µm

Source: Quadrant.io

It is important to note that precision is not accuracy: "Accuracy refers to how close a measurement is to the true or accepted value. Precision refers to how close measurements of the same item are to each other" (University of Hawaii, n.d.). In geospatial terms, accuracy is plotting a point on a map, or on a GPS receiver, in the location that correctly depicts where the object truly is on the ground. Geospatial precision, then, refers to the resolution or "size" of the space wherein the object was determined to be accurately geolocated. In the case of IP-based geolocation, it would be accurate to say that a person is in a city if they are truly in that city. This would constitute accurate, city-level precision. But it would be much more precise, and potentially much more useful for authentication purposes, to be able to say a person is in a particular neighborhood, or a particular house, or attempting to make a purchase in a particular store.

Adam Baker, adambakersf@gmail.com

This dichotomy is concisely demonstrated by the previously referenced MaxMind geospatial database claim of "82% accurate within 25 miles" (Ericksson et al). The 82% figure is the accuracy; "within 25 miles" is the precision. Thus, while accuracy in results still essential, maintaining an equivalent level of accuracy but increasing precision could correspond to an increase in the confidence and utility of the result.

3.3 GPS-based Authentication for Mobile Banking

One of the few sectors where GPS-based geolocation has already been applied by some entities is in mobile banking and financial transactions (Shumsky, 2020). One of the first blog articles on using GPS-based geolocation for authentication was written in 2010 and was aimed at the banking industry (Kitten, 2010). In that article, author Tracy Kitten posited that GPS could be used to verify a customer's location during a transaction (Kitten, ibid). At the time, she also warned that one obstacle to widespread adoption of the technology was depending on the cell carrier to send location information, due to the disparate nature of US cell carrier technologies and their latencies (Kitten, ibid). However, in the intervening decade, the explosion of mobile devices and subsequent development of faster mobile communication technologies like 4G and 5G (Palandrani & Little, 2020) has largely removed the latency issue as an obstacle to widespread GPS use for authentication.

4. Gathering, Measuring and Analyzing Real-world GPS Coordinate Precision with a Low-Cost GPS Unit

Creating a real basis of comparison between GPS and IP-based geolocation precision presents several challenges . As exhibited previously, much research has already been performed to evaluate the precision levels of various IP-based geolocation techniques. However, when dealing with GPS coordinates, the available research was gathered under ideal conditions using relatively expensive products with potentially higher-cost GPS receivers, such as those used in smartphones (US Space Force, n.d.). This is problematic because if authentication providers and others with security interest ultimately decide to comprehensively include GPS coordinates into their authentication schemes, it may require hardware manufacturers to incorporate GPS technology where it is not currently employed, such as in laptop or desktop computers, IoT devices, security cameras, and so on. The additional cost of incorporating GPS technology would become a limiting factor if only expensive GPS receivers were considered. However, a lack of data on the accuracy and precision of low-cost GPS receivers made comparing them using existing datasets impossible. What little data was discovered had been gathered from a single location, and was not robust enough for the purposes of this comparison (Spiess, 2015)

4.1 Low-cost GPS for Testing: the ublox Neo 6M

To counter the lack of precision data on inexpensive GPS unit performance, the author purchased several units of a popular low-cost GPS receiver: the Neo 6M, manufactured by u-blox. This GPS unit is familiar to the hobbyist community and is used in a wide variety of commercial and do-it-yourself devices, such as drones. At the time of this publication, the Neo 6M was available with an external antenna for as little as $2.48US, in a single-unit volume, from several popular international electronics websites. While a newer version, the Neo M8N, is now available, limited amateur testing found little difference between the precision of the two devices, certainly not enough to justify the current increase in cost for the NeoM8N ($6.30US) (Spiess, ibid).

4.2 The GPS Testing Platforms

Two primary Neo 6M testing platform variants were created. The first was simply a Neo 6M GPS module, wired to an FTDI serial-to-USB converter (with an additional USB-to-USB C adapter), connected to a Dell Precision 5550 laptop computer. One of the advantages of using the u-blox Neo 6M was that the manufacturer also provides a testing and evaluation application called u-center (https://www.u-blox.com/en/product/u-center). This application is described by u-blox as follows: "The u-center GNSS [Global Navigation Satellite System] evaluation software for automotive, mobile terminal and infrastructure applications provides a powerful tool for evaluation, performance analysis

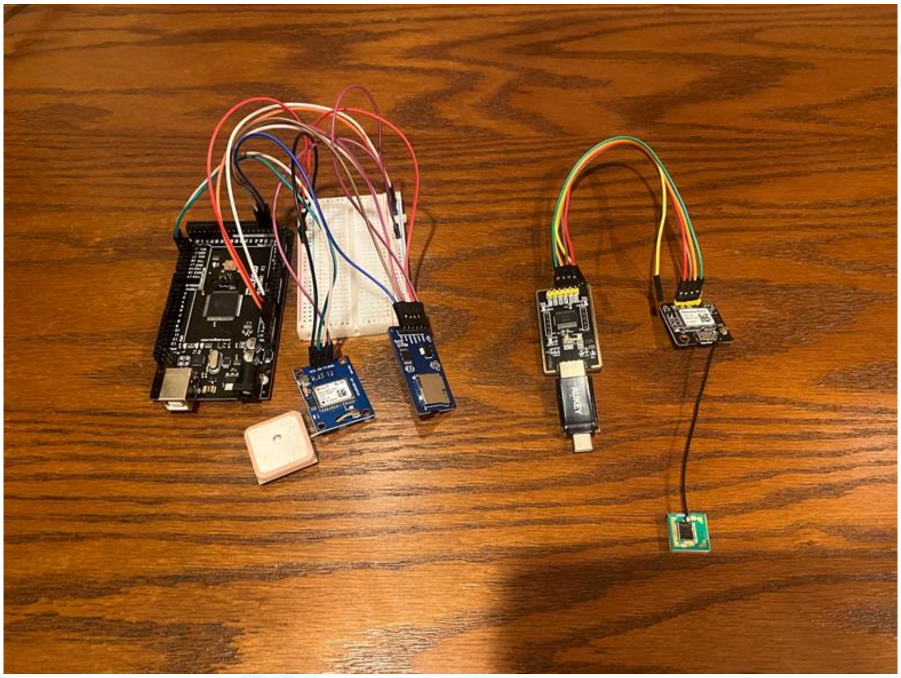
Adam Baker, adambakersf@gmail.com

and configuration of u-blox GNSS receivers. Its unique flexibility makes the u-center GNSS evaluation software an invaluable tool for evaluation, analysis and configuration of u-blox GNSS receivers" (u-blox, n.d.). U-center includes a "map deviation" feature ideal for calculating variance in GPS coordinate precision. Through u-center, the Neo 6M can be used to calculate coordinates, record those coordinates, and plot them in the "map deviation" view to represent deviations as distance between coordinates collected.

The drawback to u-center is that it saves its recorded GPS coordinates in a proprietary format. In case of any requirement during the research to validate the data reported through u-center, and enable a more complete analysis of the GPS coordinates using non-proprietary tools if necessary, a second low-cost GPS testing platform was created as a backup, using an Arduino as the base processing platform. Arduino is an open-source electronics platform that enables the creator to use the Arduino as a bridge between a sensor or sensors as inputs, and an actuator (an output device). In this case, the author's specific testing platform consisted of a Neo 6M wired to an Arduino Mega 2560. A micro-SD card adapter was also connected to the Arduino Mega. Arduino programming language-based code (based on C++) was modified and loaded onto the Arduino Mega, so GPS coordinates received from the Neo 6M module would be written to a file on the SD card.

Image 3

The Author's GPS Testing Platforms



Arduino Mega-based GPS recording system (left) and GPS-to-USB system (right)

4.3 Establishing the Analytical Methodology for Comparison

To determine the best approach for establishing a consistent basis to compare the precision of IP-based geolocation with that of GPS coordinate-based geolocation, the author met with Dr. Dennis Eggett from the Statistics Consulting Center at Brigham Young University. After considering various statistical methods, Dr. Eggett recommended a purely geometric approach: comparing the difference in spatial area between typical IP geolocation precision and GPS coordinate precision. Previous research has assessed the best IP geolocation precision, with the 25-mile (40km) radius figure (while in the United States) appearing in multiple published works. As the data gathered by the author would also be in the United States, 40km would be used to represent IP-based geolocation precision for spatial area calculation and comparison. The subsequent research challenge would be to gather GPS data from a variety of site types using the Neo6M, derive the geolocation precision from the data, and calculate the spatial area constituted by the geolocation precision figure. The final analysis would entail comparing the difference in spatial area between the given IP-based geolocational precision figure of 40km, and that of the low-cost GPS geolocational figure assessed by the author.

4.4 Gathering the Data

To calculate realistic GPS coordinate precision across a variety of locations, the author chose several types of sites for data collection: urban, rural, office, retail and residential. Both GPS testing platforms were used to gather data at the same time, in the same locations. Where possible, indoor and outdoor locations were both tested. At least 5 minutes of data were gathered from a static position at each site, at the rate of one coordinate set per second. Data from sites 1, 2, and 3 were gathered twice, as after gathering the first series, the author found online suggestions that a first "burn-in" period for the Neo 6M was recommended to achieve optimal precision. As GPS receivers require a view of the satellites in the sky, weather conditions and other potentially influential environmental factors are noted in the results, to allow for analysis of any possible effects on the GPS receiver. Coordinate deviation/precision results were rounded to the nearest meter.

Site 1 is a retail shopping center (the "mall"). The Neo 6M was tested in the parking lot of the mall (Figure 3) and inside near the mall's center (Figure 4). The indoor site tested had large skylights approximately 10m on either side and small narrow skylights above. However, the depth of all skylights (estimated to be at least 1m) allowed for only a narrow section of the sky to be seen from the Neo 6M's location. The weather was mostly sunny with a few high clouds.

Adam Baker, adambakersf@gmail.com

Figure 3

Site 1 Outdoor Deviation (rings every 1.25m)

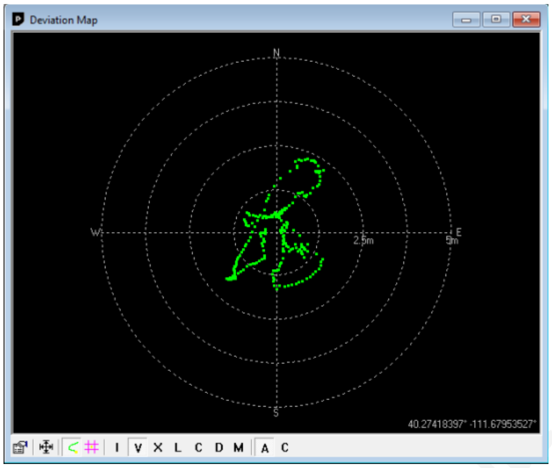
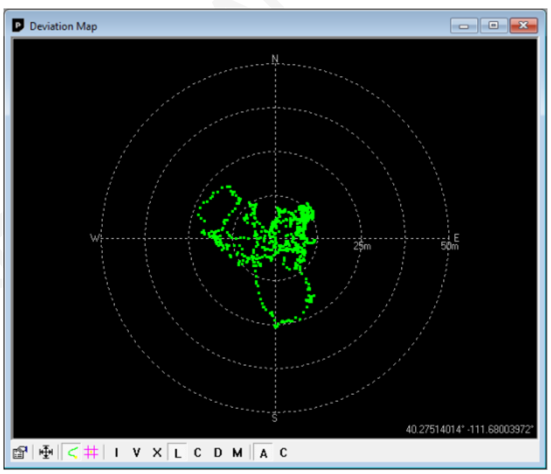


Figure 4

Site 1 Indoor Deviation (rings every 12.5m)

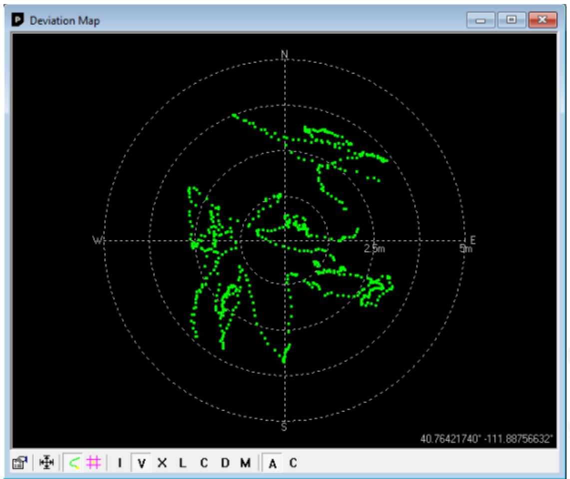


Site 2 is a parking garage in the middle of an urban center, surrounded by taller office buildings to the north, west, and south (Figure 5). The Neo 6M was tested on the roof of the parking garage approximately 5 floors above the ground. This site was chosen because of the logistical difficulty of attempting to gather data, outside a vehicle, while parked on the street. The weather was partly cloudy.

Adam Baker, adambakersf@gmail.com

Figure 5

Site 2 Deviation (rings every 1.25m)

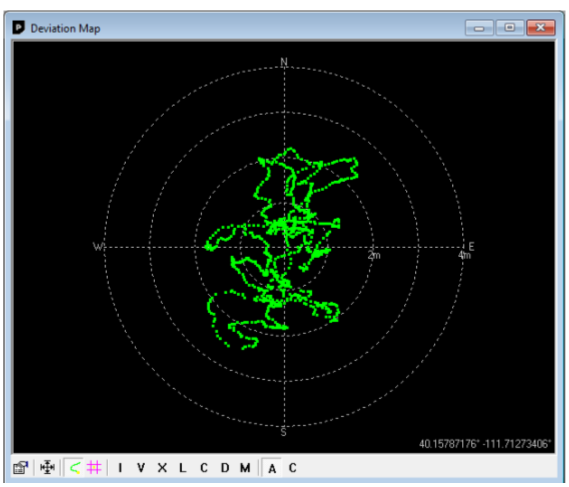


Site 3: Site 3 is inside a 3-story office building near a university in a moderately-sized city (100,000-200,000 population). GPS data collection was attempted, but the GPS was ultimately unable to achieve a position fix. This is most likely due to an insufficient view of the sky from the indoor location.

Site 4: Site 4 is a rural area consisting of farmland and infrequent homes (Figure 6). Data was collected on the side of a road, in mostly sunny weather.

Figure 6

Site 4 Deviation (rings every 1m)

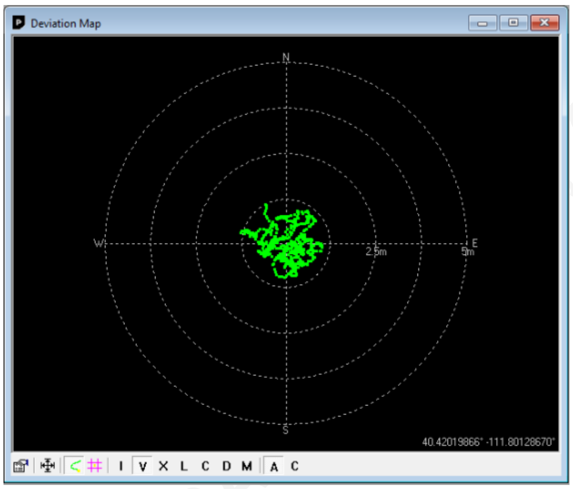


Adam Baker, adambakersf@gmail.com

Site 5: Site 5 is a residential neighborhood (Figure 7). GPS data was collected in a church parking lot in this area. This data was gathered at night, under mostly cloudy skies.

Figure 7

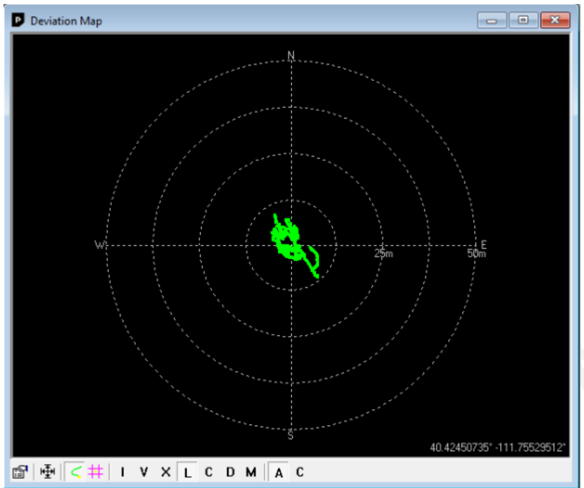
Site 5 Deviation (rings every 1.25m)



Additional testing was done to determine GPS reception and deviation under other less-than-ideal conditions. A subterranean room with a south-facing window (from the northern hemisphere) and a small view of the sky was also tested (Figure 8). The weather conditions were sunny.

Figure 8

Subterranean Room Deviation (rings every 12.5m)

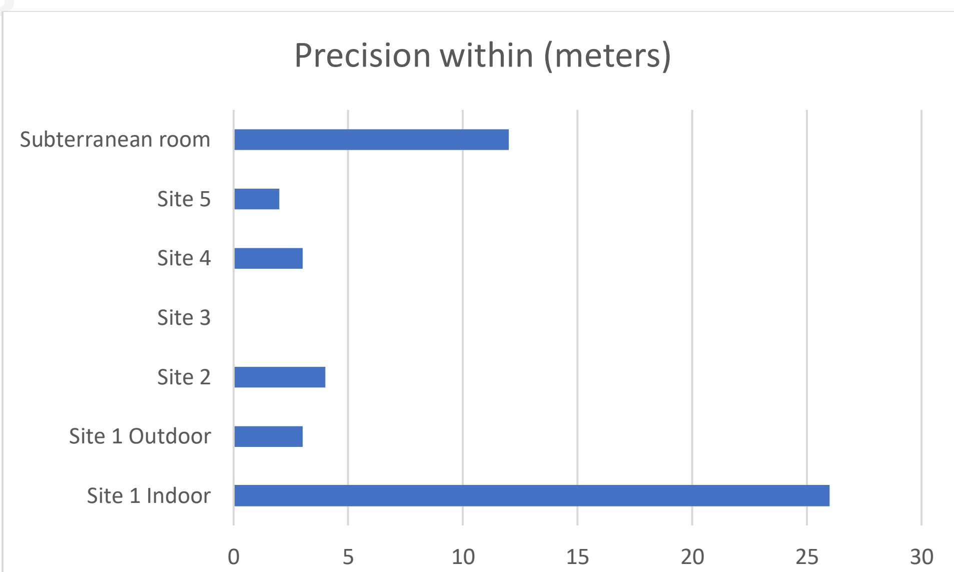


4.5 Analyzing the Gathered GPS Data

Statistical analysis showed precise X and Y-axis deviation measurements within 1 meter of the graphically represented points on the u-center deviation maps. Results were as follows (Table 2):

Table 2

Precision of Collected Low-Cost GPS Coordinates, in Meters



Adam Baker, adambakersf@gmail.com

Overall, the low-cost Neo 6M showed an impressive performance. All outdoor sites had GPS coordinates gathered with precision measured at less than 5 meters. Worst-case data gathered for the Neo 6M, the indoor commercial center, showed precision within a 26-meter radius.

4.6 Comparing Geometric Precision Difference Between IP-based Geolocation and GPS-based Geolocation

Using the oft-cited 25mi radius (40km) for best IP-based geolocation precision, the total area is calculated as follows (rounded to the nearest square meter), using the equation for the area of a circle (area = π (radius)^2).

IP-based location precision total area = π (40 x 1000meters)^2 = 5,024,000,000meters^2

GPS-based location precision total area= π (26)^2 = 2123meters^2

The difference between the two areas is then calculated as follows:

5,024,000,000meters^2 / 2123meters^2 = 2,370,000

This comparison demonstrates that inexpensive GPS-based geolocation is, at its lowest precision, *2.37 million times* more precise than IP-based geolocation at its best. Under the same analytical rubric, the average GPS coordinate gathered was at less than 5 meters of geospatial resolution. At 5 meters geolocation precision, GPS-based geocoordinates are *64 million times* more precise than the most precise IP address-based coordinates.

5. Foreseeable Challenges and Potential Solutions

There are several challenges to the broad implementation of a GPS-based geolocation scheme for authentication. The primary challenge is what to do when a GPS geocoordinate is not available, due to the receiver's inability to achieve a satellite fix (the indoor problem). Achieving geolocational resolution in an area of high human congestion and vertical population density (such as a high-rise apartment complex)

Adam Baker, adambakersf@gmail.com

should also be addressed. Finally, legitimate concerns about data privacy involving a user's location must be solved.

5.1 Using GPS Coordinates while Indoors

Even with the impressive performance of a low-cost GPS receiver like the Neo 6M in the subterranean test site, there will be times when a GPS receiver is unable to view enough of the sky to achieve a satellite fix, such as in Site 3 test. The first possible solution is the use of an indoor GPS repeater, a technology under evaluation and industry use since at least 2013 (Ozsoy, n.d.). The GPS repeater uses an antenna external to the facility to relay signals from the satellites above to any GPS receivers within the building. As GPS technology becomes even more ubiquitous indoors, and its value realized for indoor activities, indoor GPS repeaters could become more widely used and may serve to bring indoor GPS availability closer to outdoor GPS performance.

The second solution to the problem of lack of GPS signal in some situations is for authentication providers to fall back to using an IP-based geolocation value in that case, with additional verification required due to the lower-resolution value. Some authentication schemes are already tiered, in that logic is present in their processes to require additional criteria for validation when submitted values don't match what is expected, or when higher-resolution values are needed (Fisher, personal communication, ibid). Logic could be designed to take advantage of the higher resolution and confidence of a GPS-based geolocation value when it is available, but fall back to IP-based geolocation when GPS is not available.

5.2 Addressing Highly-congested Vertical Areas

The problem of population-dense vertical areas (apartment buildings, office towers, etc.) is an interesting one from a geospatial perspective. A building with a relatively small footprint on the ground, but which rises many stories into the air, would have an inordinate number of people in the same relatively small geospatial boundaries.

Without the ability to discriminate between floors, all users in the building would have the same geospatial coordinate value.

Fortunately, a second criterion exists that helps to increase the resolution of these results: altitude. Combining precise altitude with GPS geocoordinates could help identify not only what building a user is in, but what floor they are on. A GPS-based altitude alone has been measured as accurate within 10-25m, which might pose a challenge to deriving precise values for a person's location in some environments (Graham, 2011). However, the advent of low-cost, high-precision tiny electronic barometer chips, such as the Bosch BME280, may change that equation. The BME280 boasts an altitude accuracy of 1m, and at the time of this publication was available for $0.74US for a single unit from a well-known electronics website (aliexpress.com).

5.3 Addressing privacy concerns

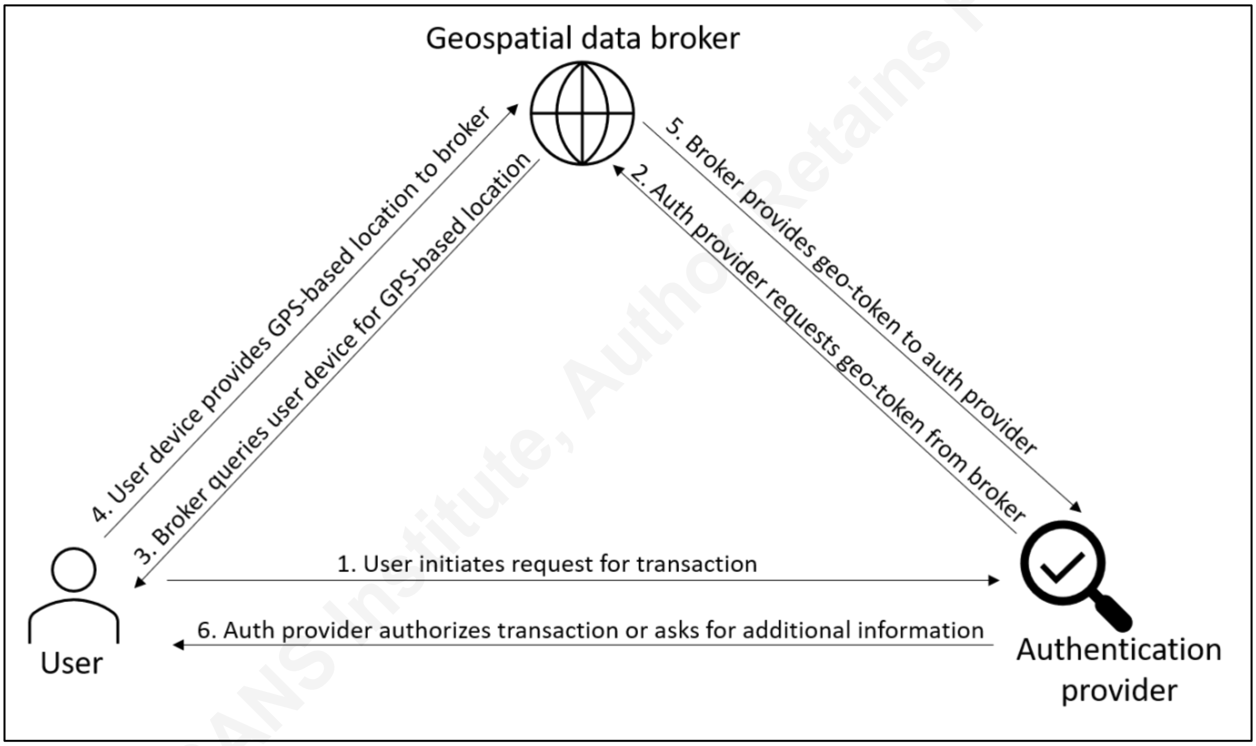
Some customers are understandably concerned about companies or other entities knowing their precise location. As a parallel matter, reluctance to engage further in an area where privacy concerns already exist may create hesitancy on the part of authentication providers who would have to seek permission to use a customer's precise location.

First, authentication providers and other interested parties have not yet truly marketed the benefits to the customer of using precise geolocation. The ability to potentially curb local identity theft-related crimes is real and compelling. For example, credit card skimming, where a malicious actor physically installs cameras or card-reading equipment over legitimate facilities such as ATMs and fuel pumps, and then captures the card and PIN details for later illicit use at another local merchant, could be greatly curbed by using precise GPS-based geolocational verification when transactions are attempted. Banks are being encouraged to tout their use of GPS technology to deter theft and fraud (Progin, 2017). It is easy to envision a similar widespread advertising campaign from authentication providers and other interested parties, quickly illustrating the problems resulting from low-resolution geolocation, and how using precise geolocation can save customers time, money, and potential stress.

If, after authentication providers have fully marketed its benefits, some customers are still reluctant to allow authentication providers direct access to their location data, it may create a space for a "geospatial data broker" or “geo-broker.” Such a firm could hold a strict agreement with the customer not to provide their data to any other entity not explicitly authorized by the customer. A geo-broker could then act as a trusted intermediary between customers and authentication providers or other firms seeking to capture value from precise geolocational data. For example, as an end-user initiates a transaction requiring authentication, the geo-broker could receive a request for location validation from the authentication provider (a service already in use by, and known to, the end-user), then query the user's device for its GPS-based geolocation and match it with the customer's historical patterns. The geo-broker could then pass a geolocational confidence token or "geo-token" to the authentication provider that indicates whether the user's current geolocation matches the expected location, but does not indicate the location itself. If the customer's location is out-of-pattern, the geo-token would indicate that, and the authentication provider could then ask for additional verification details from the end-user (Figure 9).

Figure 9

Proposed Geospatial Data Broker-based Geo-token Authentication Process c



6. Conclusion

While IP address-based geolocation has effectively served many purposes in past decades, GPS-based geolocation technology outshines it wherever it is available. GPS technology is proliferating, becoming more accurate and precise, as well as smaller and less expensive. As shown by this research, GPS-based geolocations are at least 2.37 million times more precise that IP-based geolocations, and under many operating conditions are at least 64 million times more precise. The authentication service industry must decide what it is willing to do to take advantage of GPS' higher level of precision.

Adam Baker, adambakersf@gmail.com

References

Bendale, J., & Kumar, J. (2014). "Review of Different IP Geolocation Models and Concepts". *International Journal of Computer Science and Information Technologies*, Vol. 5 (1) , 2014, 436-440. http://ijcsit.com/docs/Volume%205/vol5issue01/ijcsit2014050192.pdf

Buyukkokten, O., Cho, J., Garcia-Molina, H., Gravano, L., Shivakumar, N. Exploiting Geographical Location Information of Web Pages. Department of Computer Science, Stanford University, Stanford, CA. https://oak.cs.ucla.edu/~cho/papers/cho-geog.pdf

Cannon, R. (2010, December). Potential impacts on communications from IPv4 exhaustion & IPv6 transition. FCC staff working paper 3, Federal Communications Commission. http://www.fcc.gov/working-papers/potential-impacts-communications-ipv4-exhaustion-ipv6-transition

Cooper, Martin. (2019, Summer). GPS: The Roots of its Making and History. *ITNOW*, Vol 61, Issue 2, 20-21. https://web.b.ebscohost.com/ehost/pdfviewer/pdfviewer?vid=3&sid=950b0b21-7c61-414b-872d-ac284b6f4a34%40pdc-v-sessmgr03

Eriksson, B., Barford, P., Sommers, J., Nowak, R. [n.d.]. A Learning-Based Approach for IP Geolocation. University of Wisconsin-Madison, Colgate University. https://nowak.ece.wisc.edu/geoloc1.pdf

Estes, B. (2016, September 26). Geolocation-The Risk and Benefits of a Trending Technology. *ISACA Journal.* https://www.isaca.org/resources/isaca-journal/issues/2016/volume-5/geolocationthe-risk-and-benefits-of-a-trending-technology

GISGeography. (2021, January 3). World Geodetic System (WGS84). https://gisgeography.com/wgs84-world-geodetic-

Adam Baker, adambakersf@gmail.com

system/#:~:text=The%20Global%20Positioning%20System%20uses,mass%20as%20the%20coordinate%20origin

Graham, M. (2009, May). Gps Versus Barometric Altitude: The Definitive Answer. *Cross Country Magazine*. https://xcmag.com/news/gps-versus-barometric-altitude-the-definitive-answer/

Guier, W., & Weiffenbach, G. (1998). Genesis of Satellite Navigation. *Johns Hopkins APL Techical Digest*, Volume 19, Number 1. https://www.jhuapl.edu/content/techdigest/pdf/v19-n01/19-01-guier.pdf

Hill, Kashmir. (2019, Jan 9) How Cartographers for the U.S. Military Inadvertently Created a House of Horrors in South Africa. Gizmodo.com.. https://gizmodo.com/how-cartographers-for-the-u-s-military-inadvertently-c-1830758394

Katz-Basset, E., John, J., Krishamurthy, A., Wetherall, D., Anderson, T., Chawathe, Y. (2006, Oct) Towards IP geolocation using delay and topology measurements. *IMC '06*: Proceedings of the 6th ACM SIGCOMM conference on Internet measurement, 71–84. https://doi.org/10.1145/1177080.1177090

Lindsey, N. The Big Business of Location Data. *CPO Magazine* [online publication]. https://www.cpomagazine.com/data-privacy/the-big-business-of-location-data/

Muir, J. A., & Van Oorschot, P. C. (2009, December). Internet Geolocation: Evasion and Counterevasion. *ACM Computing Surveys*. Vol. 42, Issue 1, 4-4:23. http://web.a.ebscohost.com/ehost/pdfviewer/pdfviewer?vid=0&sid=90c5407b-b0b3-42df-b882-d4d86319c568%40sessionmgr4006

National Geospatial-Intelligence Agency. (n.d.) GPS and Earth Orientation Products. https://www.nga.mil/resources/1597166223496_GPS_and_Earth_Orientation_Products.html

Ozsoy, K., Bozkurt, A., & Tekin, I. (n.d.). Indoor Positioning Based on Global Positioning System Signals. Sabanci University. http://research.sabanciuniv.edu/27141/1/gpsmotl.pdf

Padmanabhan, W. & Subramanian, L (2001). An investigation of geographic mapping techniques for Internet hosts. ACM SIGCOMM, 173-185. https://homes.cs.washington.edu/~arvind/cs425/doc/geomap.pdf

Palandrani, P & Little, A (2020, February 10). A Decade of Change: How Tech Evolved in the 2010s and What's In Store for the 2020s. Globalxetfs.com. https://www.globalxetfs.com/a-decade-of-change-how-tech-evolved-in-the-2010s-and-whats-in-store-for-the-2020s/

Parekh, S., Friedman, R., Tibrewala, N., Lutch, B. "Systems and methods for determining collecting and using geographic locations of internet users". US patent 6 757 740 B1. Filed March 3, 2000.

Progin, A. (2017, June 11). Location-based service a plus for banks. Bankingexchange.com. Retrieved from https://www.bankingexchange.com/technology-channel/item/7153-location-based-service-a-plus-for-banks

Ray, B. (2020, February 11) Wi-Fi Indoor Positioning Systems: The Good, The Bad and the Alternatives. Link-labs.com. https://www.link-labs.com/blog/wifi-indoor-positioning-systems-pros-cons

Shumsky, P. (2020, February 18). Advanced Mobile Banking Security w/GPS. Finextra.com [blog post]. https://www.finextra.com/blogposting/18464/advancing-mobile-banking-security-with-gps

Spiess, A. (2015, September 09). Comparison of precision between Neo-M8N and Neo-6M Modules [video]. Youtube.com. https://www.youtube.com/watch?v=FmdG66kTfsI

Stanford University News Service (1995, June 13). A brief history of satellite navigation [News release]. Retrieved from https://news.stanford.edu/pr/95/950613Arc5183.html.

Taubes, G. (1997, April). The Global Positioning System: The Role of Atomic Clocks. *Beyond Discovery, The Magazine of the National Academy of Sciences*. http://www.nasonline.org/publications/beyond-discovery/the-global-positioning-system.pdf

Taylor, J., Devlin, J., Curran, K. (2012, August). Bringing location to IP address with IP Geolocation. *The Journal of Emerging Technologies in Web Intelligence*, Vol. 4, No. 3. https://www.researchgate.net/publication/273901627_Bringing_location_to_IP_Addresses_withIP_Geolocation

u-blox. u-center product description. (n.d.) https://www.u-blox.com/en/product/u-center

United States Space Force. (2021). Space Segment. https://www.gps.gov/systems/gps/space/

United States Space Force. (n.d.). How GPS Works. https://www.gps.gov/multimedia/poster/poster-web.pdf

United States Space Force. (n.d.). GPS Accuracy. https://www.gps.gov/systems/gps/performance/accuracy/

University of Hawai'i, Curriculum Research & Development Group (CRDG), College of Education. Practices of Science: Precision vs Accuracy. (n.d.). *Exploring our Fluid Earth*. https://manoa.hawaii.edu/exploringourfluidearth/physical/world-ocean/map-distortion/practices-science-precision-vs-accuracy

Whiting, T. (2020, April 27). GPS celebrates 25th year of operation. [News release]. United States Space Force. Retrieved from https://www.spaceforce.mil/News/Article/2166101/gps-celebrates-25th-year-of-operation/

Adam Baker, adambakersf@gmail.com