# UNDERSTANDING GPS NAVIGATION IN CONTESTED ENVIRONMENTS

**Ted Driver***

The United States' Global Positioning System (GPS) has been around for more than 25 years, and with great accuracy available to the public since May of 2000. GPS heralded an era where no one could get lost anymore - we can all know our location on the ground, in the air or in space to the meter level, with a small device. GPS is a unique technology that is very accurate, but also susceptible to interference. In this paper, I will outline how GPS works to set a common level of understanding, including the height systems used, then I will describe how GPS can be affected by both physical and radio constraints. I will also describe how we can mitigate these effects, in part, by using additional Global Navigation Satellite Systems (GNSSs) like GLONASS and Galileo. Finally, alternative location determination technologies are covered. By combining these technologies, I argue that we need to strive for a single, accurate position determination solution that will allow the Uncrewed Aerial System (UAS) market to grow.

## INTRODUCTION

The Global Positioning System (GPS) has allowed precise location determination to become ubiquitous. Designed in the 1970's by the Air Force and civilians [Parkinson, Spilker, 1996, Vol. I, Ch.1], and reaching its initial operating capability in 1995, this radio-navigation system provided a way for the US military to ascertain their location quickly and accurately anywhere in the world. GPS could be used by both military and civilian users, but the military had much more accuracy than civilians initially. In the original system, measures were built in that degraded the signals. This degradation, called Selective Availability (SA), modified the navigation signals so that civilians could not determine their position any more accurately than 100 meters or so. In May of 2000, President Clinton signed a policy order[†] which allowed the military to turn off SA and the US vowed to never turn it on again. One of the reasons behind this move, is that SA could easily be defeated by differential position determination, known as DGPS [Parkinson, Spilker 1996, Vol II, Ch.1; Kaplan, Hegarty, 2006, Ch.8].

Once civilians had similar accuracies as the military, the commercial market for location determination took hold and eventually led to GPS receivers on a chip. Prior to this innovation, GPS receivers were separate devices that required a significant amount of time to generate their first position estimate (Time to First Fix: TTFF). As smart phones were invented, location technologies were also upgraded so that precise location determination could be inserted into any hand-held device. There is a rich history of location determination for those interested in pursuing the topic.

* Head of Analytics, OneSky Systems Inc., 7150 Campus Drive Suite 260, Colorado Springs CO 80920.

† https://www.gps.gov/systems/gps/modernization/sa/

See the references for more information [Parkinson, Spilker 1996, Vol I, Ch.1; Misra, Enge, 2006, Ch.1].

GPS is not without its challenges, however. Extremely low signal strength and few satellites lead to easy obstruction by physical and electronic means. GPS works well in open areas and through weather, but when employed in cities or in radio crowded environments, it can fail. Understanding these failures and how to deal with them is the focus of this paper. Let us start by understanding how your position error is generated.

## UNDERSTANDING YOUR POSITION ERROR

In a very general sense, any true position is a combination of a measured position and an error in that measurement. For GPS, your position is measured by trilateration using the known locations of at least four GPS satellites. Once you have your measured location, you need to know how accurate the measurement is. Error analysis shows [Parkinson, Spilker 1996, Vol I, Ch.11, eq.13b] that your position measurement error is defined as

$$\Delta\vec{r} = (\boldsymbol{G}^T\boldsymbol{G})^{-1}\boldsymbol{G}^T \cdot \Delta\vec{\rho}_c \quad (1)$$

Where

$$\boldsymbol{G} \equiv \begin{bmatrix} \hat{L}_{1x} & \hat{L}_{1y} & \hat{L}_{1z} & 1 \\ \hat{L}_{2x} & \hat{L}_{2y} & \hat{L}_{2z} & 1 \\ \cdots & \cdots & \cdots & \cdots \\ \hat{L}_{jx} & \hat{L}_{jy} & \hat{L}_{jz} & 1 \end{bmatrix} \quad (2)$$

**G** is a geometry matrix, composed of coordinates of the unit vectors to each satellite, from your approximate receiver position. The number 1 is used in the last column to represent time in the calculations. $\Delta\vec{\rho}_c$ is a vector of range errors which occur between your receiver and each GPS satellite. These consist of terms from errors in each satellite's ephemeris and clock estimates as well as from errors in atmospheric propagation modeling and multi-path. The error in your position estimate then is represented as $\Delta\vec{r}$, which includes the spatial corrections to add to your current position, as well as a temporal term that is added to your receiver's clock to correct it. The ability to solve for a clock correction here allows GPS receivers to use inexpensive time keeping devices, instead of highly accurate atomic clocks. The trade-off is that you need at least four satellites in view, instead of three, to calculate your position.

In equation (1), the position error can be thought of as the product of two separate quantities:

$$\mathbf{H} = (\boldsymbol{G}^T\boldsymbol{G})^{-1} \quad (3)$$

And

$$\vec{\mathrm{U}} = \boldsymbol{G}^T \cdot \Delta\vec{\rho}_c \quad (4)$$

So that

$$\Delta\vec{r} = \mathbf{H} \cdot \vec{\mathrm{U}} \quad (5)$$

Here, the **H** matrix is a pseudoinverse of the geometry matrix and it represents the Dilution of Precision (DOP) of the position error. It is completely determined by the number of and the positions of the satellites with respect to the GPS receiver. $\vec{U}$ is the user range error (URE), a vector of errors in the range determination along the line of sight vector from the receiver to each satellite. These two quantities are the basis for all discussions of GPS accuracy.

*User Range Errors*. The effect these two values have on your position estimate is not equal – the URE is relatively small compared to the possible magnitude of H. URE values are limited to atmospheric effects, and the orbital and clock modeling capabilities of the GPS Master Control Station. There is not much you can do to affect the URE value in a standalone GPS system. Real-time Kinematic (RTK) systems can affect your URE, by using carrier wave position determination. Very rarely, a clock onboard a GNSS satellite may malfunction, causing the URE for that satellite to increase greatly. These are extremely rare events and modern software can usually remove that satellite from you position solution.

To review the components of the typical user range error, a GPS error budget is used. This is one I routinely follow, and other error budgets also exist.

| **Error Source** | **Typical Error magnitude** | **Notes** |
|---|---|---|
| Satellite ephemeris and clock prediction errors | 0.2 – 5.0 meters, varies by satellite, clock type, and time | Satellite orbital positions and clock states are predicted days in advance and sent to users when needed. Prediction errors grow over time. The best orbital predictions are available at Zero Age of Data (ZAOD). These are controlled by the GPS Control Segment. |
| Atmospheric mis-modeling | Ionospheric mis-modeling for single-frequency users: 4 meter and up.<br>Tropospheric mis-modeling for thick atmosphere, and close to the horizon: 0.7 meters and up. | Dual frequency users can usually remove ionospheric errors. Note that scintillation, when occurring, can cause fades and dropouts as well. |
| Multi-path errors | 0 – 1.5 meters typically | In areas with signal reflection issues. |
| Receiver errors | 0.8 meters | Receiver thermal noise, and other cabling related issues |
| Total, root mean square error | 6 – 9 meters and up. | |

**Table 1. Typical GPS Error Budget for User Range Errors**

*Dilution of Precision*. The **H** matrix is always a 4x4 matrix, generated by taking the pseudoinverse of a Nx4 geometry matrix. The value N here is the number of satellites you use to make a distance measurement from. The more satellites you have, the smaller the magnitude of **H**. A value of importance to the Unmanned Aircraft Systems (UAS) community is the horizontal DOP (HDOP) value. HDOP is calculated by taking the first two diagonal elements of the **H** matrix, in root-sum-square fashion:

$$HDOP = \sqrt{H_{11}^2 + H_{22}^2} \tag{6}$$

A high value for HDOP translates directly into a large horizontal position error from equation (5). Low values of HDOP likewise lower your horizontal position error. Other figures of merit exist for your vertical accuracy and total position accuracy as well; VDOP and PDOP, respectively. Those values are determined in a similar manner as HDOP, using different portions of the **H** Matrix [Parkinson, Spilker 1996, Vol I, Ch.11, Sec.III]. Figure 1 shows that the more satellites you can access, the lower your DOP value will be.

This shows that access to more satellites provides better accuracy for your position determination. Where the value of HDOP decreases below 1, this helps your position accuracy by decreasing the value of the product in equation (5).

So, what might keep you from being able to make a distance determination to a navigation satellite? Anything that reduces the number of satellites used in equation (5), will generally cause you position determination error to increase. Let us call the ability to use a satellite in a navigation solution *visibility* and discuss what might hinder your visibility when using satellites for navigation. Note that changing the orientation of the satellites in space would also affect the magnitude of **H**. This is not seen in practice, as the GPS satellites do not vary greatly in their orbital positions. However, this same math is applicable to any beacon-type of navigation system though, and the positions of beacons would affect DOP values.

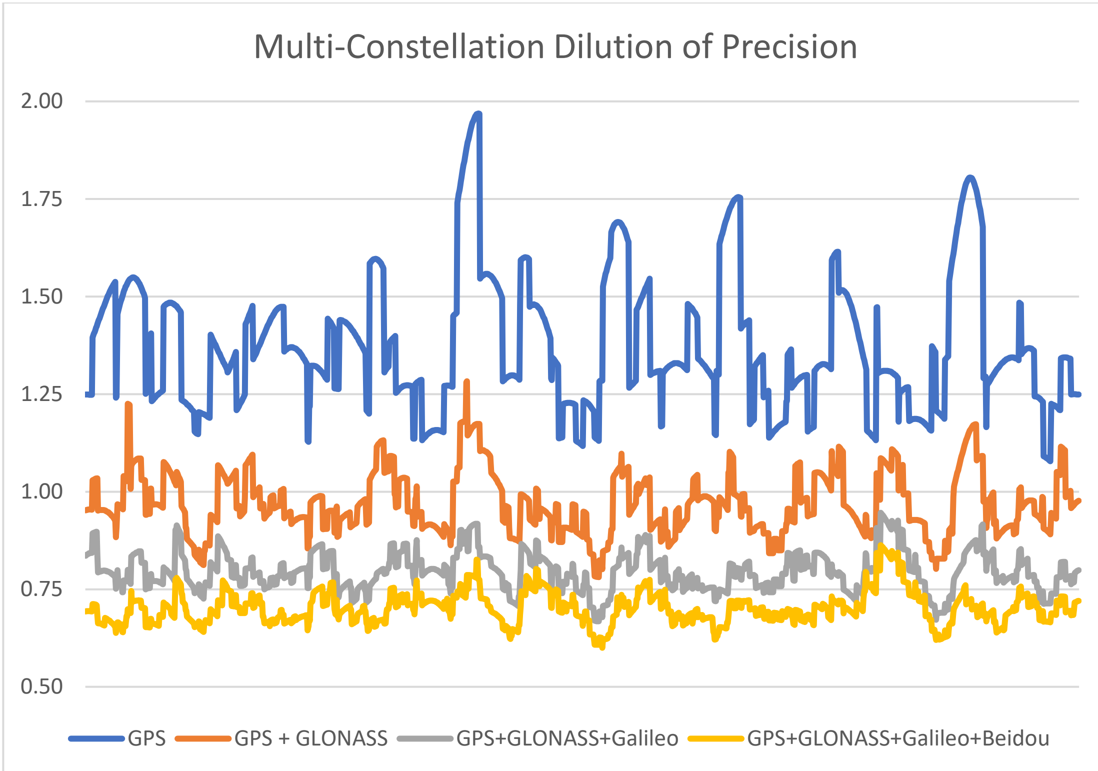


**Figure 2. Multi-Constellation Dilution of Precision**

## VISIBILITY

We must have at least four satellites to which we have measured the distance from a receiver (actually, the phase center of the antenna for the receiver) before we can determine its position. For a satellite to be visible, we must not only consider physical barriers to the signal, but also barriers due to radio frequency interference, antenna gain and receiver processing problems. Of these impediments, physical and radio frequency barriers are the primary focus of this paper.

If line-of-sight visibility is met between the receiver and the satellite, the receiver's antenna gain must also be large enough to produce a signal that can be processed by the receiver. Commercial grade GPS antennas are typically dipoles, that provide a constant gain across the sky. This is helpful for receiving satellite signals from any direction, but it can also allow unwanted signals.

Receiver processing problems stem from the need to acquire and maintain lock with multiple stages in the receiver processing hardware. Receiver hardware must first search for the GPS signal amongst the RF background noise because GPS satellite signal power resides below the noise floor. Once found, receiver hardware then searches for the pseudorandom noise (PRN) code and makes a distance measurement to the satellite based on this code [Parkinson, Spilker 1996, Vol I, Ch.7, Ch.8]. Issues such as multi-path [Parkinson, Spilker 1996, Vol I, Ch.14] affect the distance measurement process in this stage.

### Physical Visibility

To start, let's look at physical barriers to satellite visibility. Obviously, satellites must be above the horizon to be used. When GPS was first built and GPS receivers had only 4 channels (the minimum needed), the ideal satellite geometry was determined to be 3 satellites spaced equidistantly close to the horizon and 1 satellite at zenith, forming a tetrahedron. It turns out that maximizing the volume of this tetrahedron minimizes DOP (for the case of 4 satellites) [Parkinson, Spilker 1996, Vol I, Ch.5 Sec.IV]. At the horizon, satellites encounter different issues than those at mid or higher elevation angles. Satellites near the horizon are much further from the receiver than those higher in the sky and the satellite's navigation signal must travel through more atmosphere than higher satellites. The first problem is partially solved by the GPS designer's; they modified the satellite's transmission antenna gain pattern to allow for more gain near the limb of the Earth, and less near the center. This gives a near constant received power to receivers anywhere on Earth. The second problem concerns technicalities with modeling the delay of the GPS signal through a thick troposphere [Parkinson, Spilker 1996, Vol I, Ch.13]. To counter these induced errors and to avoid lower local terrain, many receivers use a constant mask angle; an angle below which no satellite will be considered in the position solution. The mask angle is typically between 5 and 15 degrees from the horizon and is equivalent for all azimuths.

Terrain that sits above the mask angle is also a barrier. Both natural and artificial terrain will block signals. Artificial terrain includes buildings, towers and other objects that will block line-of-sight visibility between a receiver and a satellite. To understand when terrain may obscure your signals, you will need a terrain database, and you will need to know the terrain dataset's reference frame. Datasets for natural terrain exist and can be queried for heights at specific locations. Datasets for urban terrain can be created from GIS data and used in a similar manner. Understanding when these obscurations will affect your satellite visibility requires complex analytics involving the determination of satellite orbits, precise time and coordinate systems and defining when line-of-sight vectors pierce terrain from receiver locations on the Earth.

Equally important to accounting for terrain, is understanding the terrain's reference frame. A GPS receiver determines its position in three dimensions, producing a latitude, longitude, and altitude. The receiver's altitude is defined in the system that all of GPS uses: World Geodetic System 1984 (WGS-84). A height expressed in WGS-84 can be converted to heights in other systems that may make more sense for the mission. When flying for example, heights Above Ground Level (AGL) may make the most sense. In other cases, you may be dealing with heights above Mean Sea Level (MSL). All of these systems are related and values in one system can be converted to values in another. For example, here is an example of terrain height values from our OneSky SDSP height service[*]:


```json
{
    "TerrainHeightFromWgs84": 4283.1394147693254,
    "MeanSeaLevelHeightFromWgs84": -16.108077610647548,
    "TerrainHeightFromMeanSeaLevel": 4299.2474923799728
}
```


**Figure 2 – Terrain height Example**

[*] https://saas.onesky.xyz/SDSP/Documentation/Terrain

The values in this sample can be understood from this figure:

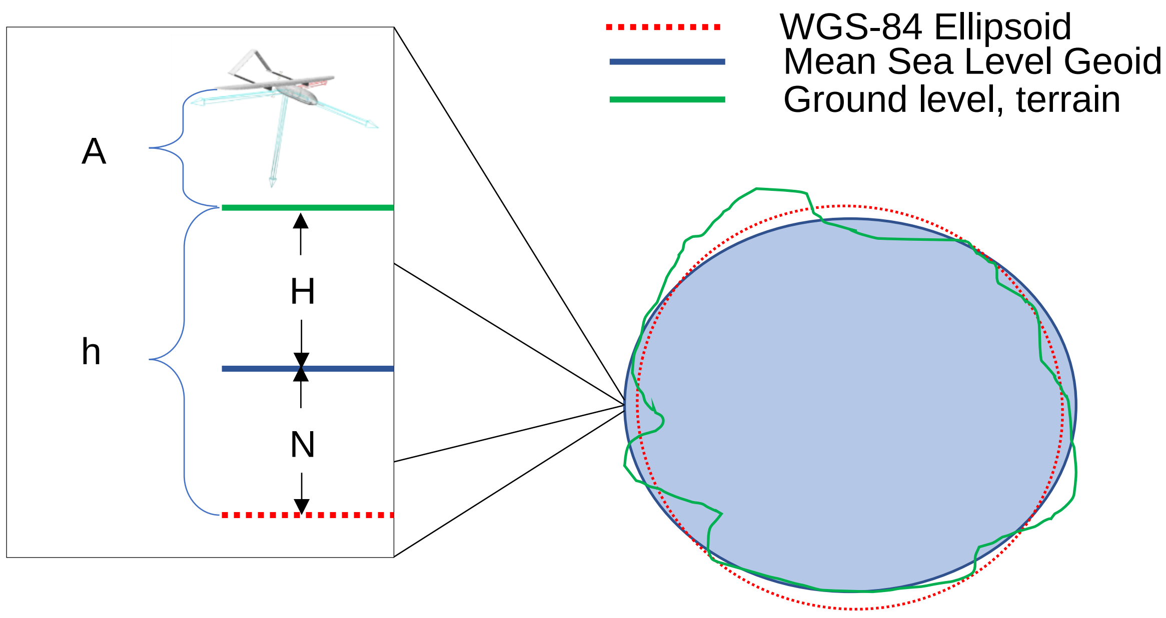


**Figure 3 – Terrain Height Definitions**

From Figure (3), it can be seen that

$$h = H + N \tag{7}$$

The green layer in the figure represents ground level. The values H and N may both be negative, depending on the terrain height with respect to the MSL geoid or WGS-84 ellipsoid heights. These definitions represent standard variables for geoid measurement [Kaplan, Hegarty, 2006, Sec.2.2.4; Misra, Enge, 2006, Sec.4.1.2]

In the example from Figure (2), TerrainHeightFromWgs84 is equivalent to h in Figure (3), MeanSeaLevelHeightFromWgs84 is equivalent to N and TerrainHeightFromMeanSeaLevel is equivalent to H.

The terrain at this location is roughly 4283.14 meters from the WGS-84 geoid. This is the value GPS would report. The Mean Sea Level geoid is roughly 16.1 meters below the WGS-84 geoid at this location. The last entry shows that the height at this location (near the top of Pike's Peak) is 4299.25 meters above sea level; derived by subtracting the second value from the first. If you were flying at 250 feet AGL at this location, your GPS would report an approximate altitude of

$$4283.14\, meters_{WGS-84} + \frac{250\, feet_{AGL}}{3.28084\, feet/meter} = 4359.34\, meters_{WGS-84} \tag{8}$$

Your height above MSL then is:

$$4359.34\, meters_{WGS-84} - (-16.108) = 4375.45\, meters_{MSL} \tag{9}$$

So, the values 250 feet, 4359.34 meters and 4375.45 meters all represent the same altitude at that location – just with respect to different reference frames. The lesson here is that when we begin to enter heights into UAS Traffic Management (UTM) systems or other flight systems, we must understand to which frame the values are referenced. Entering data without considering the data's frame of reference will produce errors, which may lead to hazardous events.

During the NASA TCL 4* trials in Corpus Christi in the summer of 2019, OneSky saw evidence of this misunderstanding. In Corpus Christi, the difference between GPS altitudes in the WGS-84 reference frame and altitudes in the Mean Sea Level frame is -27.3 meters. This means that if altitudes from GPS receivers onboard drones on the ground were interpreted to be referenced to MSL, they would show up 27.3 meters above ground level on systems using the WGS-84 reference – which is what we saw in the OneSky UTM system for a few vehicles. Figure 4 shows an example of the UAV paths being offset from the ground by this amount.

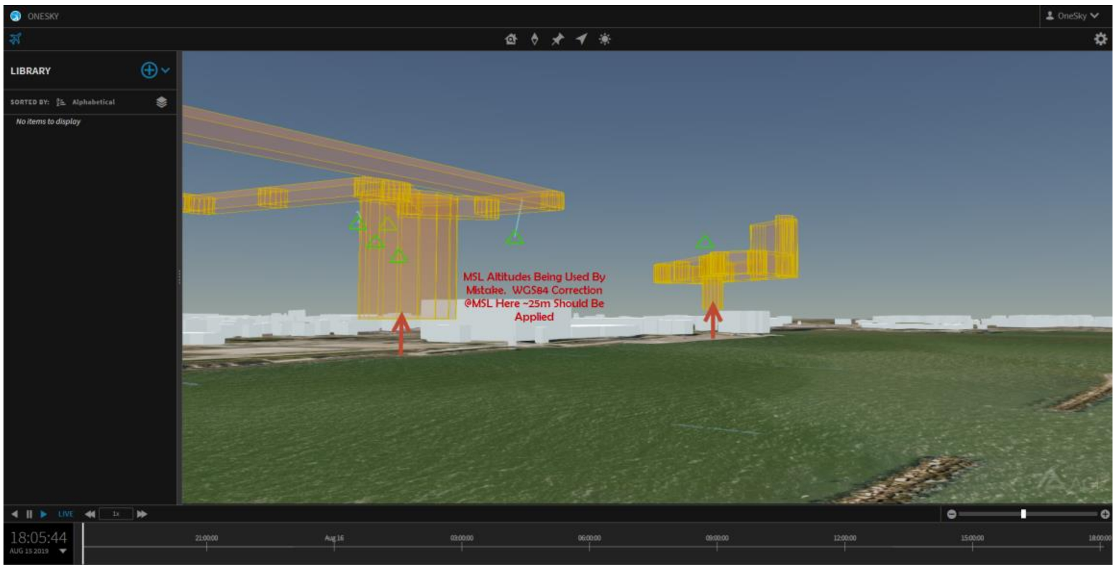


**Figure 4 – Misunderstood Terrain Reference Example**

### Radio Visibility

Here, radio visibility means that a signal from a satellite can reach the receiver with enough power to be tracked. This means that we can acquire the signal and then maintain track of the signal once acquired. There are pertinent technical details that drive this process, and they are covered in depth in the references [Parkinson, Spilker 1996, Vol I, Ch.7-8; Kaplan, Hegarty, 2006, Ch.4-5; Misra, Enge 2006, Ch.11-12]. For our discussion, I'll look at the artifacts that will reduce our Carrier to Noise value below 35 dB-Hz; a reasonable value used to acquire a GPS satellite.

GPS navigation signal power on the Earth is below the noise floor. At moderate latitudes, the received signal power is approximately -154.5 dBW, and the noise floor is -140 dBW/MHz [Misra, Enge 2006, Tables 10.2 and 10.13]. This fact is the Achille's heel in the radio navigation scheme because it allows for easy disruption. Of course, it is illegal to broadcast in the Aeronautical Radio Navigation Service (ARNS) frequency bands, but it does happen, intentionally and unintentionally.

Navigation satellites are spread throughout the sky, so disrupting signals in one direction may not affect signals in another direction, unless the disruption source is close or powerful. Because the signal from navigation satellites is so weak, a jamming signal with only one watt of power can increase the jamming to signal ratio high enough where a receiver within 30 miles will lose lock.

* https://utm.arc.nasa.gov/utm2019.shtml

Depending on the gain pattern of that jammer, that 30 miles could be directed horizontally, vertically or a both[*].

Geometry plays a role and must be understood to know how your signal may be disrupted. The position, orientation and antenna gain patterns of GPS jammers as a function of time must be known to fully model a radio environment. Figure 5 shows a route taken by an aircraft, that has two GPS jammers nearby. The Jammers are directional, with their gain patterns displayed in a colored wireframe depicting their antenna's gain value. The route is colored with the Jamming to Signal ratio (J/S) value. Green indicates a low J/S, and black indicates a high J/S value. Here, it is clearly seen that even with static jammers, the effect on an aircraft route varies as the route geometry and GPS satellite positions vary.

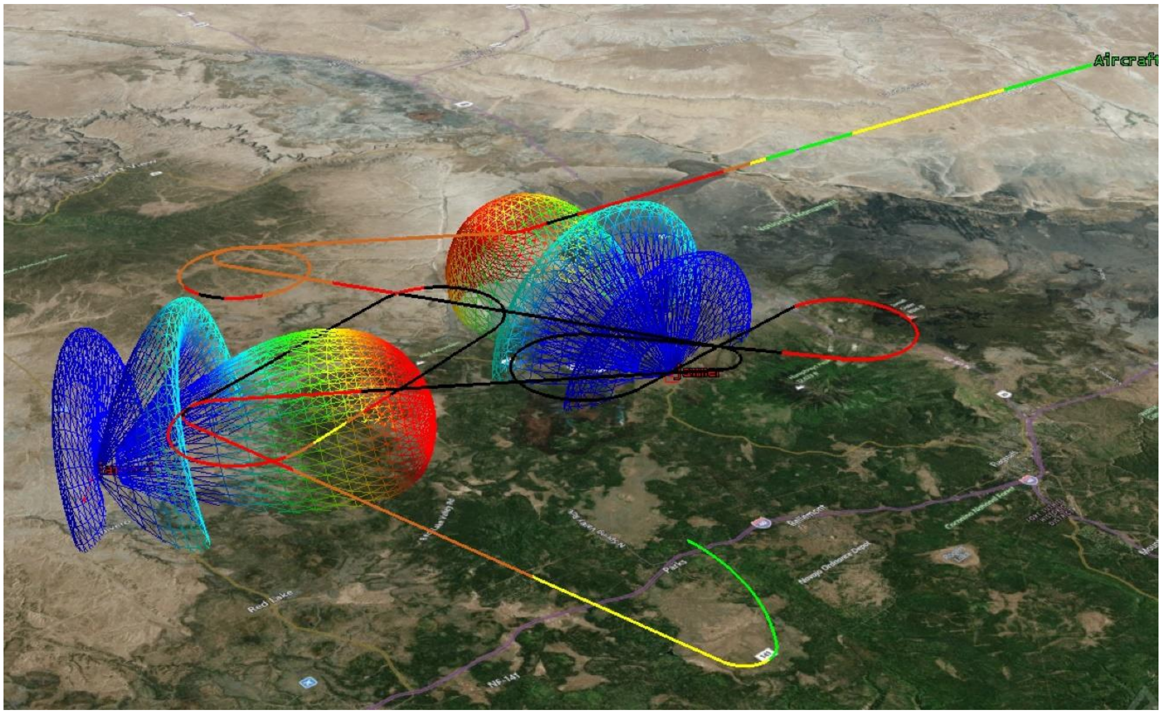


**Figure 5 – GPS Jammed Route**

*Jamming Examples.* In August 2012[†‡], a construction worker in New Jersey, who was trying to protect his privacy, decided to foil his companies attempts at tracking his movements by purchasing a GPS jammer. The company had recently installed GPS tracking devices in their company trucks. This worker inadvertently took down the GPS system at the Newark Airport on several occasions, until August 2013, when he was identified by engineers trying to locate the interference source. The worker subsequently lost his job and was fined over $31,000. This is not a one-off case, but the start of continued GPS jamming efforts to prevent the use of satellite navigation systems. These include nearly 80 incidents reported between 2013 and mid-2016[§], as well as incidents in Syria[**] and the Persian Gulf[††]. This is not limited to military landscapes. In October of 2019, during a

[*] https://www.insidegnss.com/pdf/GNSS_in_Denied_Environment_Webinar_slides_5_2_13.pdf, slide 12
[†] https://insidegnss.com/fcc-fines-operator-of-gps-jammer-that-affected-newark-airport-gbas/
[‡] https://www.nj.com/news/2013/08/man_fined_32000_for_blocking_newark_airport_tracking_system.html
[§] https://www.aviationtoday.com/2017/01/31/are-gps-jamming-incidents-a-growing-problem-for-aviation/
[**] https://www.maritime-executive.com/editorials/military-hardware-proves-vulnerable-to-gps-jamming
[††] https://www.satellesinc.com/shipping-industry-faces-gps-jamming-in-persian-gulf/

drone show in Hong Kong, many of the drones dropped out of the sky because their navigation signals were being actively jammed*.

*FCC Ligado Decision*. On April 19, 2020, the Federal Communications Commission approved a request by the company Ligado, to broadcast 5G signals near the GPS frequency band†. Ligado, a company formed from the bankrupted company Light-Squared, made a few concessions from their original broadcast plan, which the FCC deemed sufficient for approval. Ligado reduced their transmit power to 9.8 dBW, and they put in place a 'guard band' of 23 MHz; separating their 5G broadcast band from the GPS L1 frequency band. Figure 6 lays out the GPS and Ligado band structure between 1500 and 1600 MHz. Note that while the widths of the bars in the graph are correct, the heights (representing power of the signals) are not. If the GPS L1 power value height is left as is in the graph, the height of the 5G band should go approximately to the height of the orbiting International Space Station.

There is a heated debate currently, regarding this approval. The Department of Transportation VOLPE Center, after conducting tests based on the specs for the Ligado 5G system, presented the results at the 2020 Civil GPS Service Interface Committee (CGSIC) meeting in September‡. Their results showed widespread interference, given the approved minimum spacing for Ligado 5G base stations, for commercial-grade GPS receivers at the 1 dB level, and stating that this is essentially authorized interference.

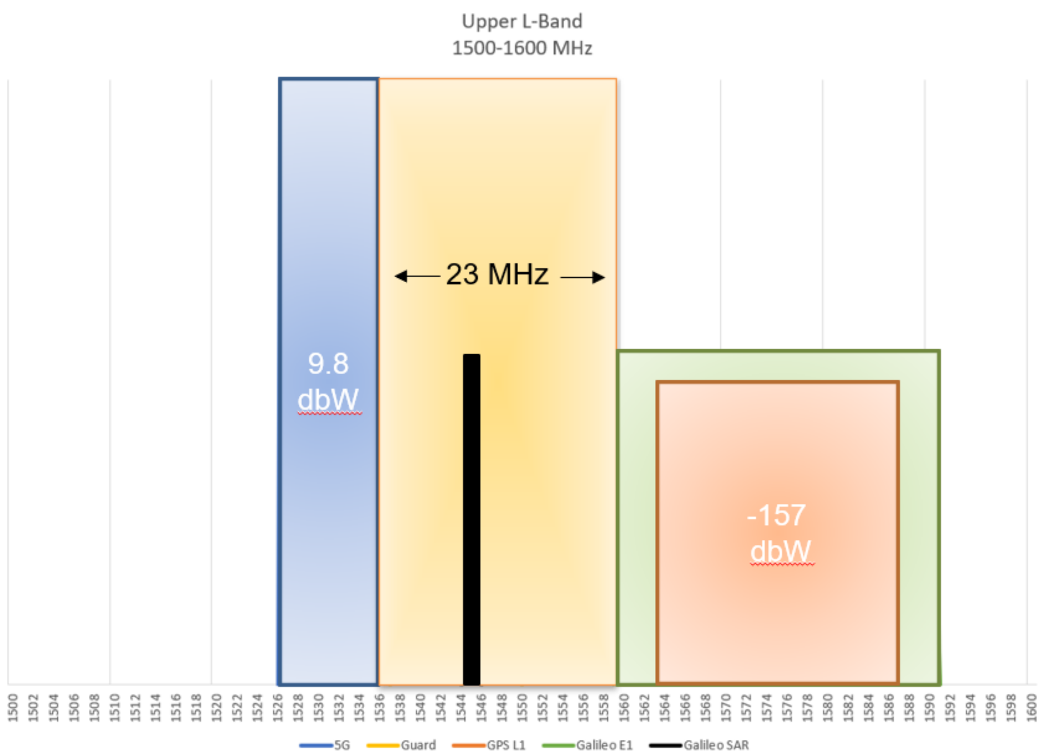


**Figure 6 – GPS and Ligado Frequency Structure**

*https://insidegnss.com/criminal-investigation-underway-in-gps-jamming-incident-that-crashed-drones-caused-hk1m-in-damage/

† https://docs.fcc.gov/public/attachments/FCC-20-48A1.pdf

‡ https://www.ion.org/gnss/virtual-schedule.html#cgsic

One other effect that can cause signal loss in your receiver is ionospheric scintillation. Scintillation is an effect that distorts the GPS signal to a point where it is no longer trackable. A good way to think about scintillation is to imagine a laser being pointed into a calm swimming pool. When the surface of the pool is still, the laser reaches the bottom of the pool. But, if the surface is disturbed, the laser light in the pool scatters erratically. Scintillation tends to happen in bands roughly parallel to Earths' equator. Outside of those regions, it is not seen as much. Additional references have more in depth information on scintillation*.

Understanding radio visibility for GPS is a deep topic and cannot be covered in depth in this paper. Texts in the field are replete with overviews, examples, problems and additional references [Parkinson, Spilker 1996, Vol I, Ch.20; Kaplan, Hegarty, 2006, Ch.6; Misra, Enge 2006, Ch.13]. My aim here is to show the ease with which radio visibility can be interrupted, and the complexities encountered when modeling these environments. Going back to the original thesis for the paper, if a signal is jammed, that signal is not there for your receiver to use in making a position determination, so your DOP value will rise. The next question then becomes, how can these effects be mitigated?

## MITIGATION

For our purposes, mitigation strategies are ways to increase the number of satellites we can track and generate positioning information from. Reducing our position error can be accomplished by reducing the magnitude of the product in equation (3). There are different strategies to do that, some of which are explored below. The strategies include ways to increase the number of satellites in the **H** matrix from equation 3, or to find ways to reduce the value of the User Range Error in equation (4). There are ways to combine GPS with other position determination equipment and refine your position that way as well. Finally, there are location determination methods that do not involve GPS and should be investigated as well.

### Modeling and Simulation

Before we discuss physical or algorithmic strategies for mitigation, I want to discuss modeling. Using a simulation to understand your hardware, its components and your environment is a critical step in the testing process. After system design and test, modeling software can be used to plan missions and visualize results as well. Digital Mission Engineering (DME) techniques are tightly coupled to successful product design and mission success in many aerospace products. The same will be true for the UAV industry. Through digital mission engineering processes, you build a digital twin and try many what-if scenarios before implementing any of them. You perform trade studies on different component types, different operations concepts, and mission profiles. Using your digital twin model, you can then apply constraints to your mission, such as communication link availability, fuel usage and navigation accuracy.

For example, you might implement a model for a GPS receiver antenna type you would like to use on your vehicle. To test the boundaries of operability for that antenna in the presence of jamming, you would fly your digital vehicle through a modeled contested environment and look at the receiver jamming to signal performance. This critical data may lead you to choose a different set of hardware or change your mission parameters.

Software tools such as Systems Tool Kit (STK) provide a platform to design and develop your digital model and run these analyses. These critical steps provide a way to avoid in-field mistakes and drastically decrease the time to production for operational systems.

---

* https://web.stanford.edu/group/scpnt/gpslab/website_files/sbas-ion_wg/sbas_iono_scintillations_white_paper.pdf

### Terrain Mitigation

Physical barriers to satellite signals represent a large error source. When using a single constellation only, there are not many satellites above the horizon, and the number that can be tracked drops rapidly as physical barriers get in the way. Within a challenging terrain environment, the number of tracked satellites can drop significantly, causing vehicles to lose their positioning and change their flight state. What happens then is determined by the vehicle manufacturer. Whether the terrain is natural or artificial, the more satellites you can choose from, the more you can track, so using more than one GNSS constellation is ideal. Figure 1 shows how the dilution of precision value from **H** reduces with additional constellations. Using multi-constellation navigation is becoming the norm in GPS receiver chips because of this fact. One navigation chip manufacturer has chips that can track two, and up to four different constellations simultaneously. This capability helps significantly when flying in terrain-challenged environments. This mitigation strategy simply adds additional satellites to your position solution.

Another technology that helps in terrain-challenged environments is Assisted-GPS (AGPS). This capability downloads critical navigation data from a non-challenged location and sends it to GPS receivers in cellular devices or other capably equipped devices over cellular or VHF frequencies. Additional signal code information can be obtained this way as well, helping receivers that receive only bits and pieces of satellite signals maintain lock. [Misra, Enge 2006, Ch.13 Sec.13.4].

### Jamming Mitigation

When signals are jammed, we need to look for ways that will allow us to maintain signal tracking or reacquire signals. This can be achieved in different ways. In the GPS system, additional signal power can be applied for military users using newer satellites, but generally, civilian users will need to address the issues on the ground. One effective strategy is to employ active antennas. These antennas actively control their gain pattern, sometimes sensing the direction where additional signal energy emanates from and decreasing the gain in that direction. Additionally, since the receiver knows the approximate positions of the satellites, it can adjust the gain to be higher in those directions only (Figure 7). These antennas are called active because satellite geometries change in time, and the gain patterns must respond in kind. Whether these antennas will help enough to maintain mission thresholds in contested environments can be determined by using DME techniques as mentioned above.

Other effective strategies for mitigating jamming consist of using algorithmic methods within the receiver that process out signals with unexpected power levels. The use of Inertial Measuring Units (IMUs) to aid adaptive antenna pointing can be used as well.

*Inertial Aiding.* Using an IMU can help your navigation solution when GPS is experiencing radio frequency interference (RFI) issues [Groves, 2008, Farrell, 2008]. IMUs are not susceptible to RFI and cannot be harmed by it, but IMUs also have no external absolute location reference, so their errors grow in time. IMUs measure acceleration and rotation instantaneously, and then through integration, develop the position and attitude information. Calibrating IMUs before a mission keeps their errors small as the mission begins, but without continual re-calibration, their errors grow beyond what can be used as a sole source for a navigation solution. Tactical grade IMUs will experience errors of one meter or so after one minute, while IMUs for automotive grade use will experience errors over 500 meters in that same time [Misra, Enge 2006, Fig.13.25]. Some GPS chips have IMUs built into them and can perform dead reckoning as well. Using these chips can help vehicles navigation through RFI, but close attention to the chip's limits should be looked at.

Both Terrain and Jamming mitigation strategies described above try to minimize the loss of satellites in the **H** matrix from equation (3). There are ways to step around equation (5) and provide a receiver with insight to errors in the GPS system. Differential GPS (referenced in this paper's introduction) is one method and real-time kinematic (RTK) processing is another. Both techniques rely on a separate system defining errors in GPS signals via some method. These errors are then sent to appropriately equipped GPS receivers, and removed from the position solution. These errors are valid only within a certain radius of the base station determining the errors, and at large distances from the base station, a receiver may undergo spatial decorrelation – whereby the error corrections it receives from the base station are not as applicable at the receiver's location.

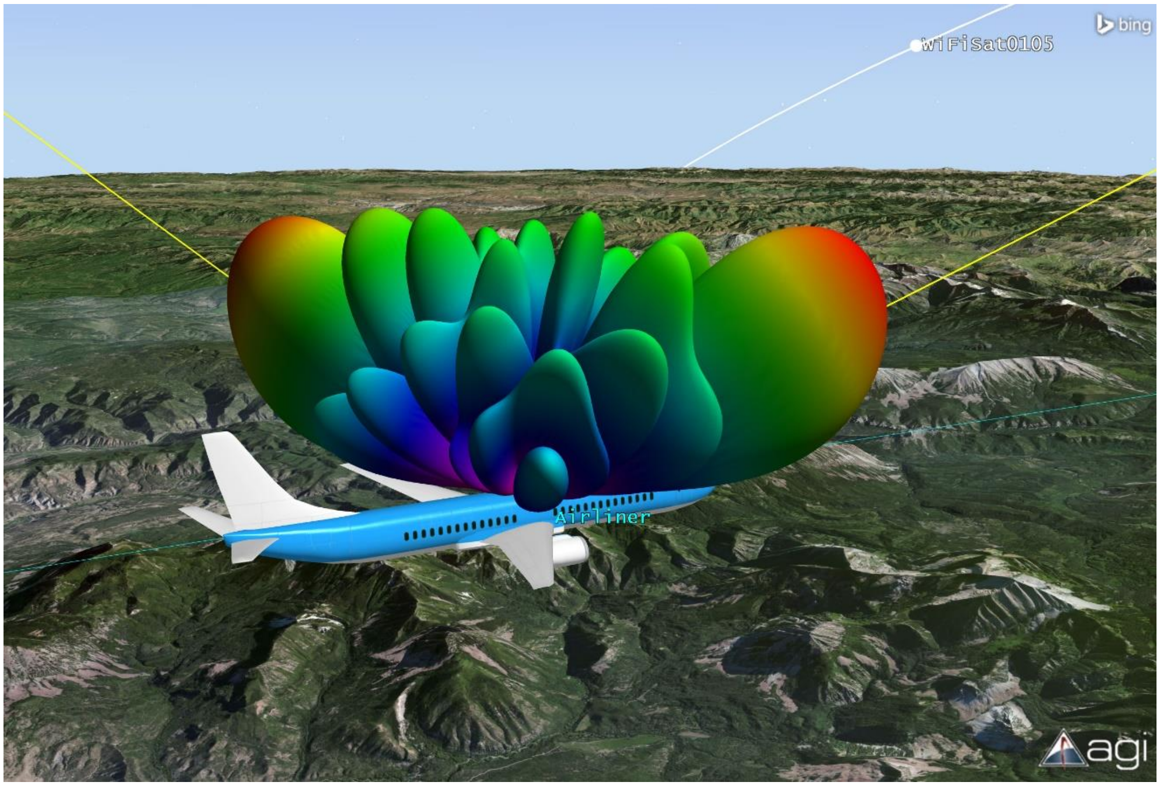


**Figure 7 – Controlled Radiation Pattern (CRPA) Antenna**

## Alternate Navigation Technologies

When GPS is available, and differential systems are used to provide centimeter level accuracy, precise location determination is at its best. Unfortunately, unintentional signal degradation will continue to occur. Even if we could track down all erroneous transmissions (which we must continue to strive for), in the time it takes to do so, they have already affected missions in operations now. The time to fix a given interference problem far outweighs the timeline of the mission experiencing the issue, and new problems will continue to occur.

The current general sentiment towards unidentified drones is trending negative[*], and with that sentiment there will be attempts to disrupt them. Employing Remote ID will help with this, but not in the near term, and not in all cases. Learning from the cyber industry, intentional jamming will also increase as the general population understands how the technology works. In this type of environment, and with an absolute need for precise positioning, it is critical to identify ways to ensure we have correct positioning information as we fly.

[*] https://www.cpr.org/2020/01/10/drone-mystery-spreads-more-sightings-close-calls-no-answers/

One alternate navigation technology is Enhanced Long Range Navigation (eLoran). eLoran is a newer version of the Loran technology initially developed during WWII. Loran uses hyperbolic positioning techniques to determine 2-dimensional locations by measuring the time difference of arrival from signals radiated by Loran towers at known locations. [Misra, Enge 2006, Sec. 1.3.1]. In 2010, the United States cancelled plans for an eLoran system that would serve as a backup to GPS. This system was considered unnecessary at the time, but recently, there is interest in bringing the system back[*]. Companies like Hellen Systems are developing eLoran capabilities for use soon. eLoran has error statistics showing that 95% of the errors are less than 9 meters, with an average in the four-meter range[†]. When used in combination with other location technologies, this will be a good alternative technology.

Other rising technologies include Computer Vision and Simultaneous Location and Ranging (SLAM) techniques. With computer vision, maps of the mission area are preloaded into the vehicle and visual sensors aboard the vehicle record the scene as the vehicle moves. The recorded scenes are compared to the preloaded scenes, to determine positioning information. SLAM uses a similar approach, but instead of preloading data, Light Detection and Ranging (LIDAR) is used to sense the scene at a fast rate, comparing differences from each scan.

Pseudolites are another type of location technology. They are essentially GPS satellites that are placed at specific locations and are used as additional navigation signals in the receiver. Non-GPS beacon technologies are gaining traction as well, such as using signals of opportunity to perform time difference of arrival (TDOA) calculations. Signals such as Wi-Fi, AM/FM, TV and cellular can be used like this. Signals of opportunity can also be used to constrain IMU drift errors[‡§].

When alternative technologies are used to measure position, those disparate measurements can be used together in a fused algorithm to provide a single measurement of position and velocity, with well-defined covariances [Kaplan, Hegarty, 2006, Ch.9] Kalman Filter and other filter algorithms can model states with different force and process models, combining measurements for many different types of measuring equipment [Groves, 2008, Grewal, Weill, Andrews 2007]

Thought needs to be put into combinations of and alternatives to native satellite navigation that will provide robust, jam-resistant, and accurate navigation in densely populated areas. Location determination is a critical, fundamental building block of UAV and UAM technologies and we must maintain that foundation for the market to grow.

## CONCLUSION

In the paper, I have shown how GPS errors are used in practice and broken that down into a simple equation that we can use to understand GPS accuracy. By maximizing the number of satellites in our DOP calculation, we can decrease our positioning error.

I looked at ways that we may lose satellites in our DOP calculation, physical and radio visibility concerns were addressed. I also dived into the definition of heights in the GPS system, because another source of error lies not within the system itself but within us occasionally.

Understanding how the system works, some mitigation strategies were suggested, that may allow us to work through RFI events. Because GNSS systems are so susceptible to jamming, there

[*] https://arstechnica.com/gadgets/2017/08/radio-navigation-set-to-make-global-return-as-gps-backup-because-cyber/
[†] http://web.stanford.edu/group/scpnt/jse_website/documents/Enhanced_Loran_rv2-short.pdf
[‡] https://pdfs.semanticscholar.org/180a/d1839f004ca32f6ffe6d7998fc1f9d98fe52.pdf,
[§] http://kassas.eng.uci.edu/papers/Kassas_Distributed_Signals_of_Opportunity_Aided_Inertial_Navigation_with_Intermittent_Communication.pdf

will always be the threat of losing them during operations. This is why I stressed that alternate navigation technologies must be used in addition to GPS when in operations. Our industry is built on the idea of having precise positioning always available, but we will have to work to make that a reality in the future. This new, combined technology should excel where satellite navigation falls short – in high terrain urban locations, and in active radio landscapes.

## NOTATION

| | |
|---|---|
| **H** | Bold capital letter represents a matrix |
| $\vec{U}$ | Arrow above represents a vector |
| $\Delta$ | Signifies a small change in a value |

## REFERENCES


Kaplan, Elliot D., and Hegarty, Christopher J., Editors, 2006, *Understanding GPS Principles and Applications*, second ed.

Misra, Pratap, and Enge, Per, 2006, *Global Positioning System: Signals, Measurements and Performance,* second ed.

Parkinson, Bradford, and Spilker, James J., Editors. 1996, *Global Positioning System: Theory and Applications,* Progress in Astronautics and Aeronautics, Volume 163

Farrell, Jay A., 2008 *Aided Navigation*

Grewal, Mohinder S., Weill, Lawrence R., Andrews, Agnus P. 2007, *Global Positioning Systems, Inertial Navigation and Integration*

Groves, Paul D., 2008, *Principles of GNSS, Inertial and Multisensor Integrated Navigation Systems*