Understanding GPS in Contested Environments

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October 8, 2020

Overview

- Understanding GPS position error
- Dilution of precision and user range errors
- Physical and radio visibility
- Terrain heights and field results
- Mitigation techniques
- Alternative navigation technologies

Introduction - Ted Driver

- Architect and developer of the OneSky analytical SDSP services
- Navigation SME and algorithm developer at Analytical Graphics Inc.
- Lead analyst at the GPS Operations Center (GPSOC)

Precise location is ubiquitous

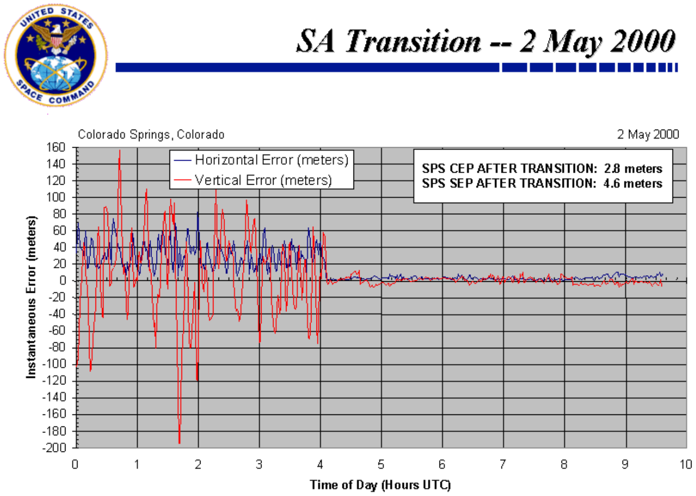
Civilian access to precise location since May 2, 2000

GPS receivers turned into chips

- Location services in every type of device now

Industries now rely on knowing location

- UAM/UAS systems built upon this



Understanding your Position Error

$$\vec{r}_t = \vec{r}_m + \Delta\vec{r}$$

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

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

$$\mathbf{H} = (\boldsymbol{G}^T\boldsymbol{G})^{-1} \qquad \vec{\mathrm{U}} = \boldsymbol{G}^T \cdot \Delta\vec{\rho}_c$$

$$\boxed{\Delta\vec{r} = \mathbf{H} \cdot \vec{\mathrm{U}}}$$

Position measurements have errors

GPS measurement errors result from satellite geometry and errors in ranging to each satellite

The quality of your position measurement is based on this product

Reducing your error

$$\boxed{\Delta\vec{r} = \mathbf{H} \cdot \vec{\mathrm{U}}}$$

H is the Dilution of Precision (DOP) matrix

unitless – a multiplier

U is the User Range Error (URE) vector

Reducing the magnitude of H or U or both will reduce your position error

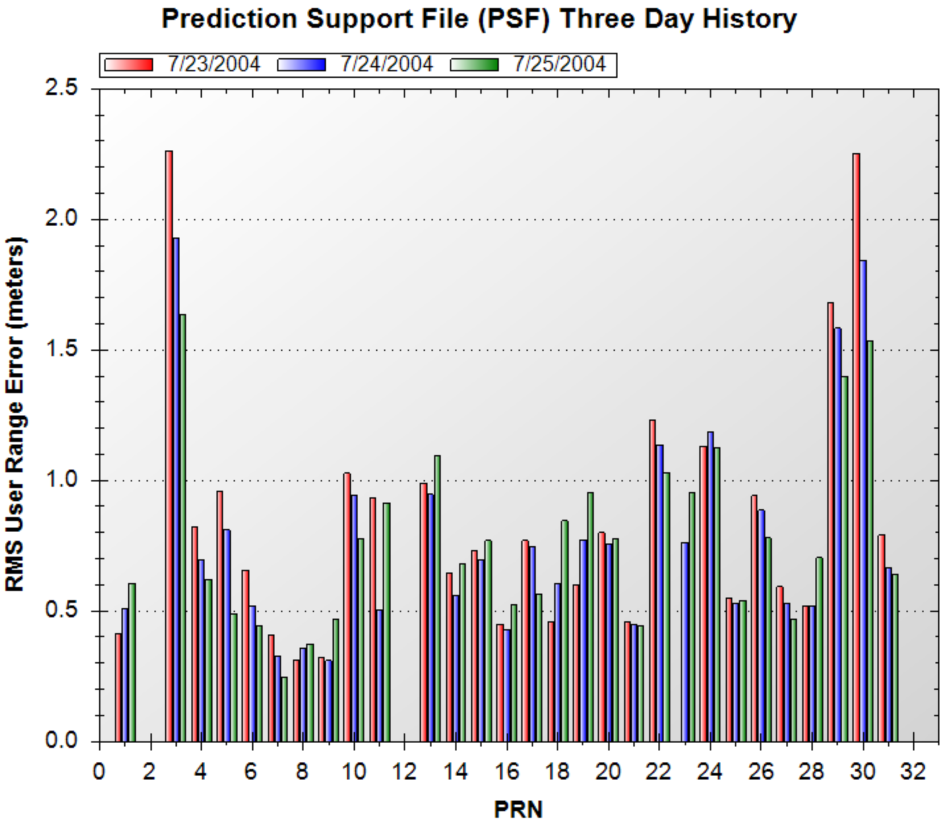
User Range Errors

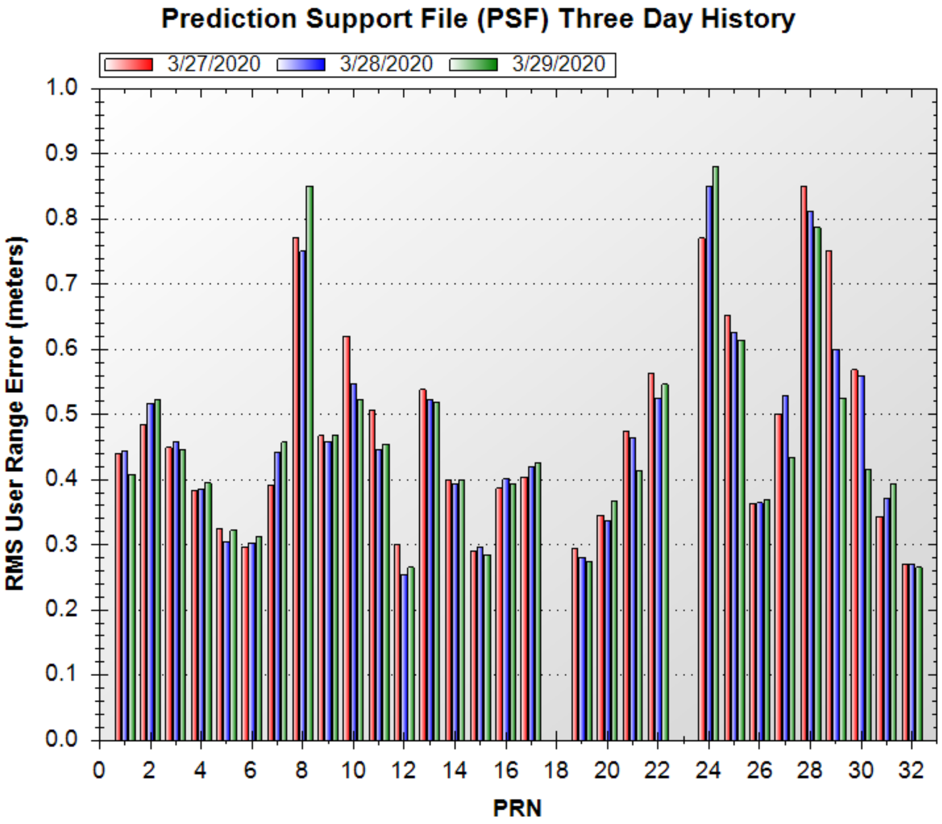
- Signal in space errors (0.5 - 3 meters)
  - Satellite ephemeris and atomic clock prediction errors
  - Control segment controls these
- Atmospheric mis-modeling
  - Ionospheric errors for single frequency users, or scintillation (4+)
  - Tropospheric errors for thick atmosphere, close to the horizon (0.7+)
- Multi-path errors (0-1.5+)
  - In environments with signal reflection issues
- Receiver errors (0.8+)
  - Noise

RMS URE error

6 - 9+ meters

RMS GPS Signal In Space URE





Dilution of Precision - **H**

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

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

$$\boldsymbol{H} = \begin{array}{cc} \begin{bmatrix} H_{11} & \mathrm{H}_{12} & \mathrm{H}_{13} & H_{14} \\ H_{21} & H_{22} & H_{23} & H_{24} \\ H_{31} & H_{32} & H_{33} & H_{34} \\ H_{41} & H_{42} & H_{43} & H_{44} \end{bmatrix} & \begin{matrix} X \\ Y \\ Z \\ T \end{matrix} \\ \begin{matrix} X & \quad Y & \quad Z & \quad T \end{matrix} & \end{array}$$

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

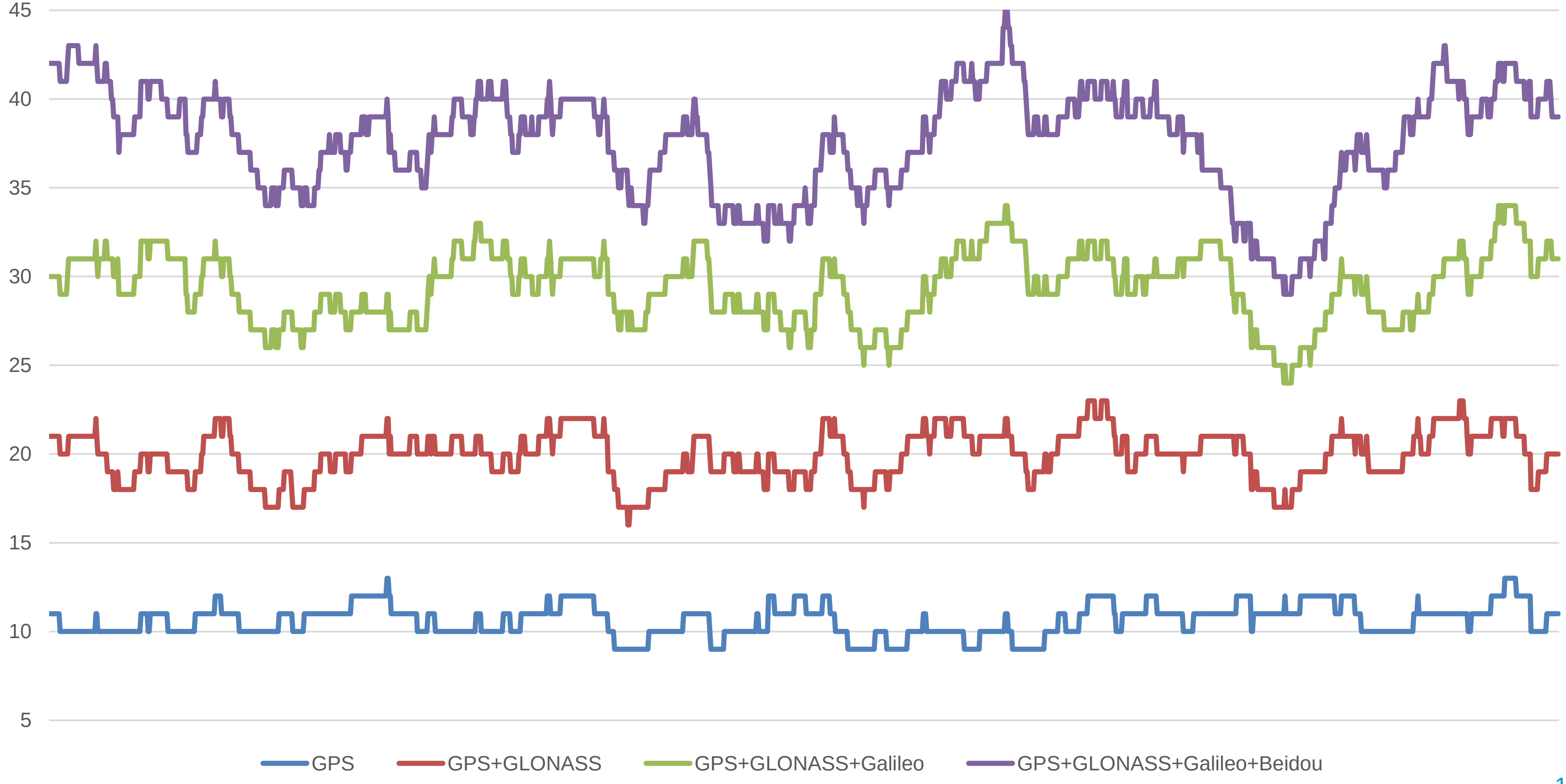
$$VDOP = \sqrt{H_{33}^2}$$

$$PDOP = \sqrt{H_{11}^2 + H_{22}^2 + H_{33}^2}$$

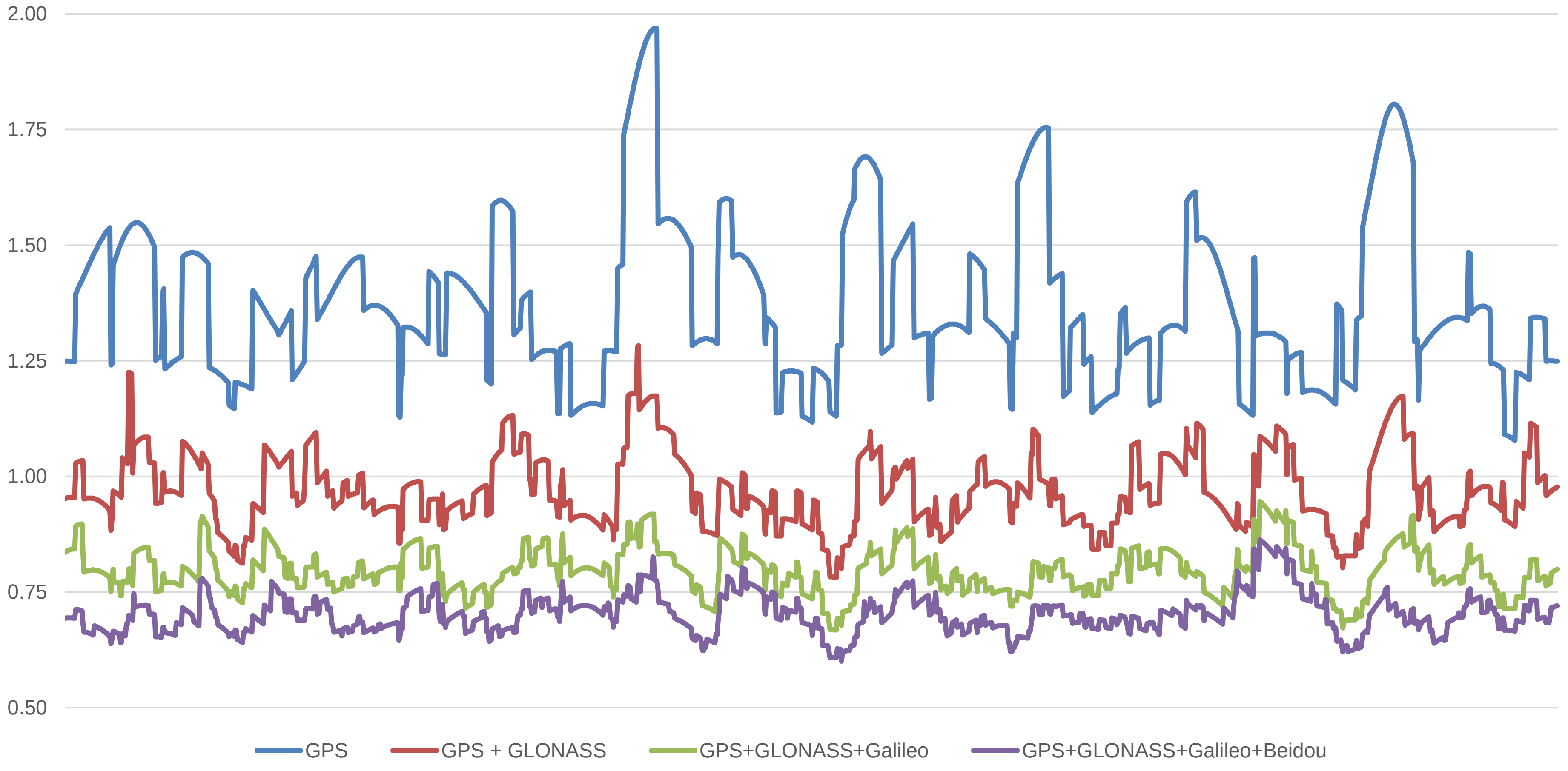
$$TDOP = \sqrt{H_{44}^2}$$

$$GDOP = \sqrt{H_{11}^2 + H_{22}^2 + H_{33}^2 + H_{44}^2}$$

Number of Satellites Above the Horizon



Multi-Constellation Geometric Dilution of Precision (GDOP)



Visibility

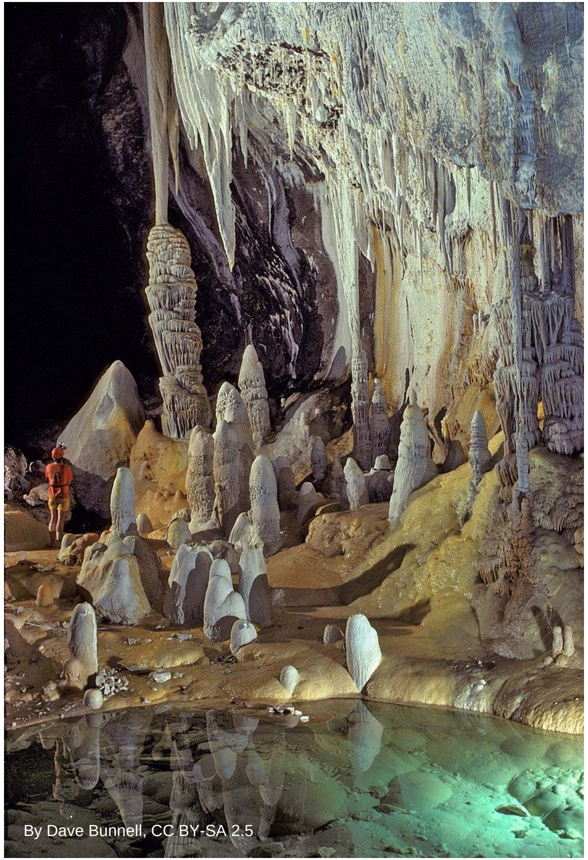
Reducing the number of satellites in **G**

- Increases the magnitude of **H**, which
- Increases your error

So, what will reduce the number of satellites visible to your device?

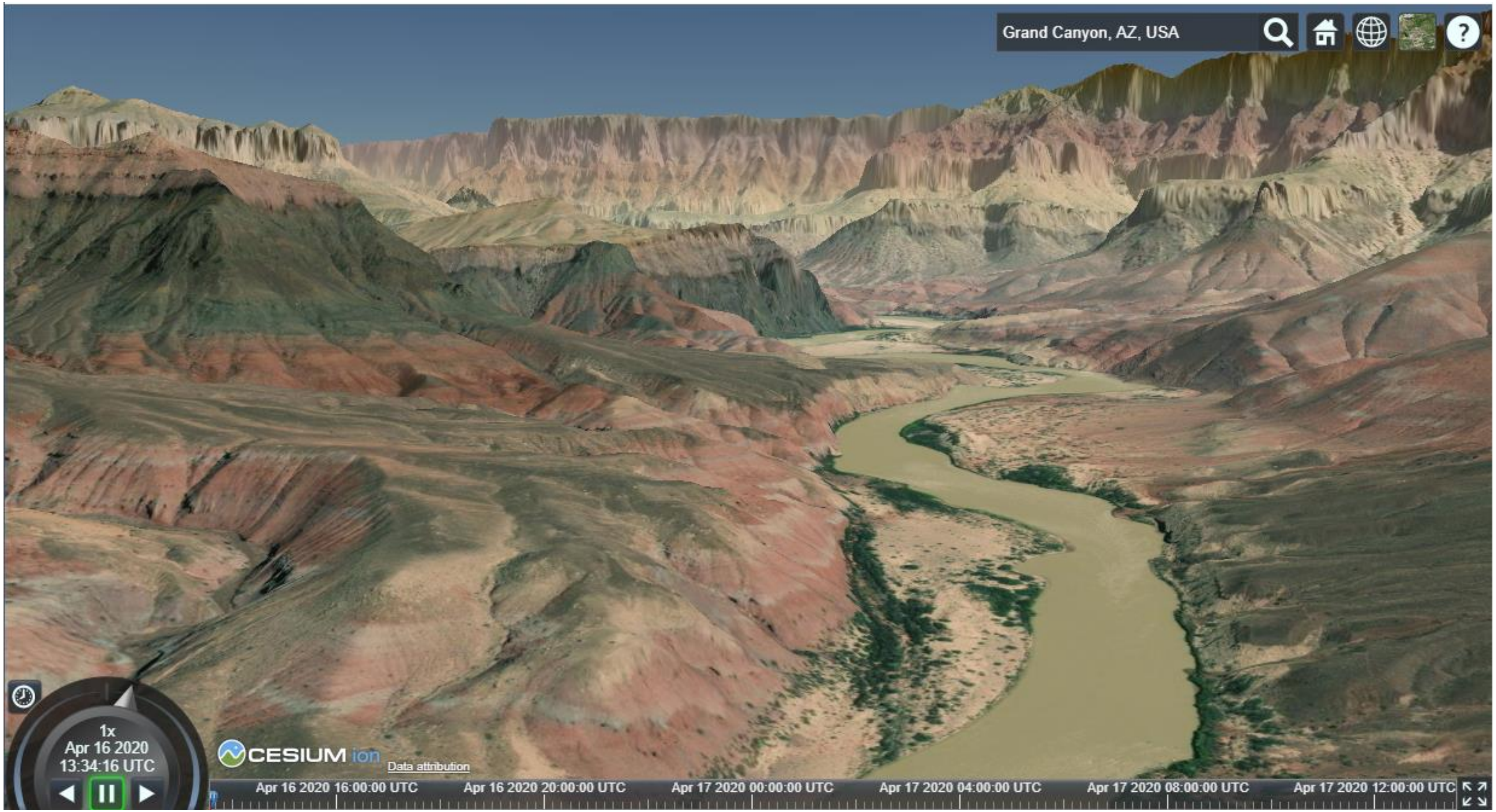
Physical Visibility

DenisTangneyJ/Getty Images

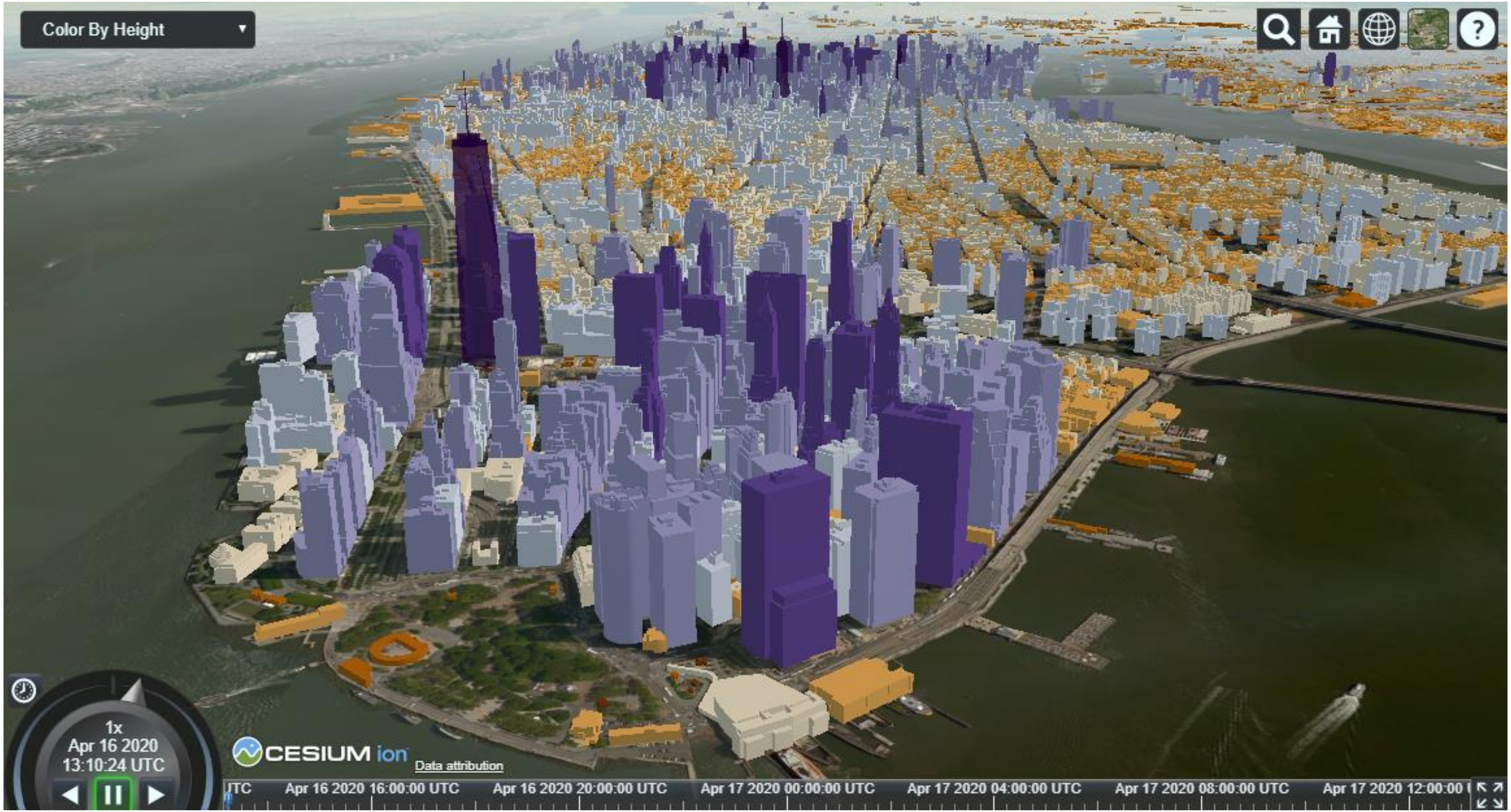


By Dave Bunnell, CC BY-SA 2.5

Physical Visibility



Physical Visibility



Singapore Test flights

Radio Visibility

Signals must be received with enough power to demodulate PRN code and data

- Typical value for tracking is 35 dB-Hz

When signals are not tracked, they are not part of the **G** matrix

Radio Visibility

GPS signal strength is below the noise floor

Transmitted signal:

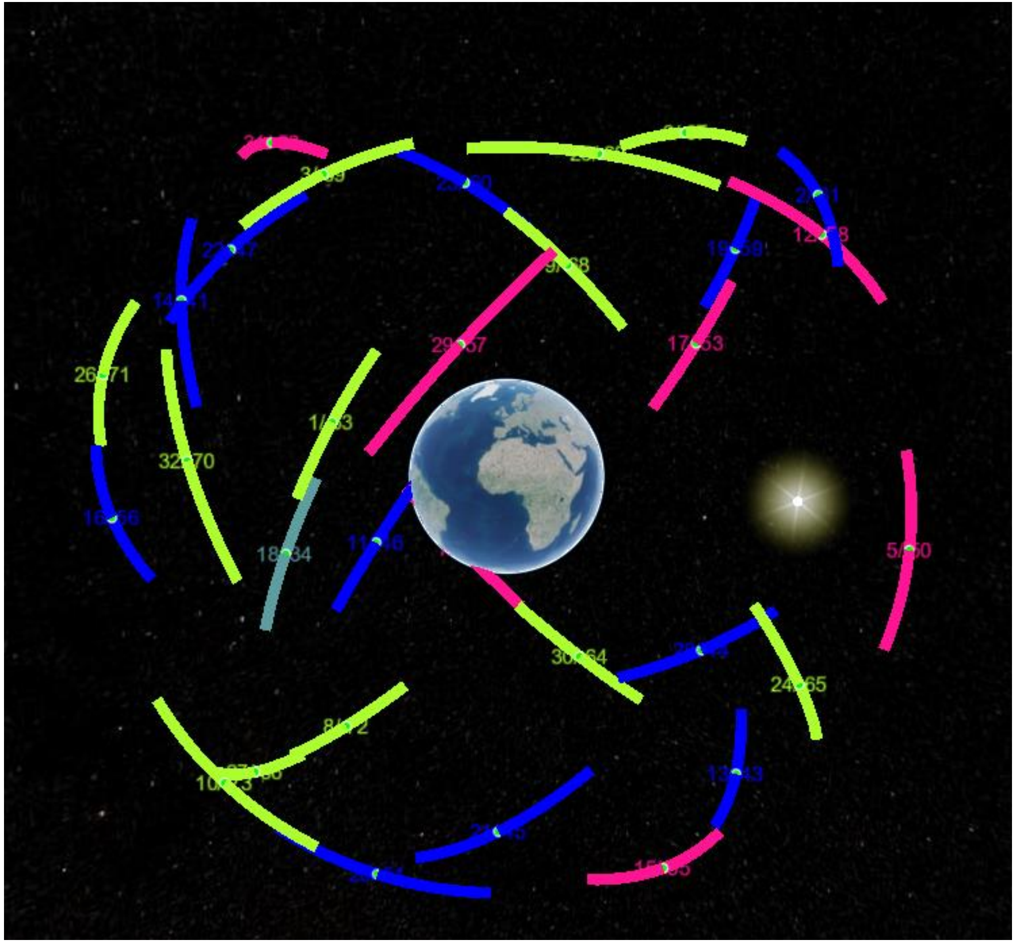
- 25 watts

Distance:

- 20200 km

Power at the Earth

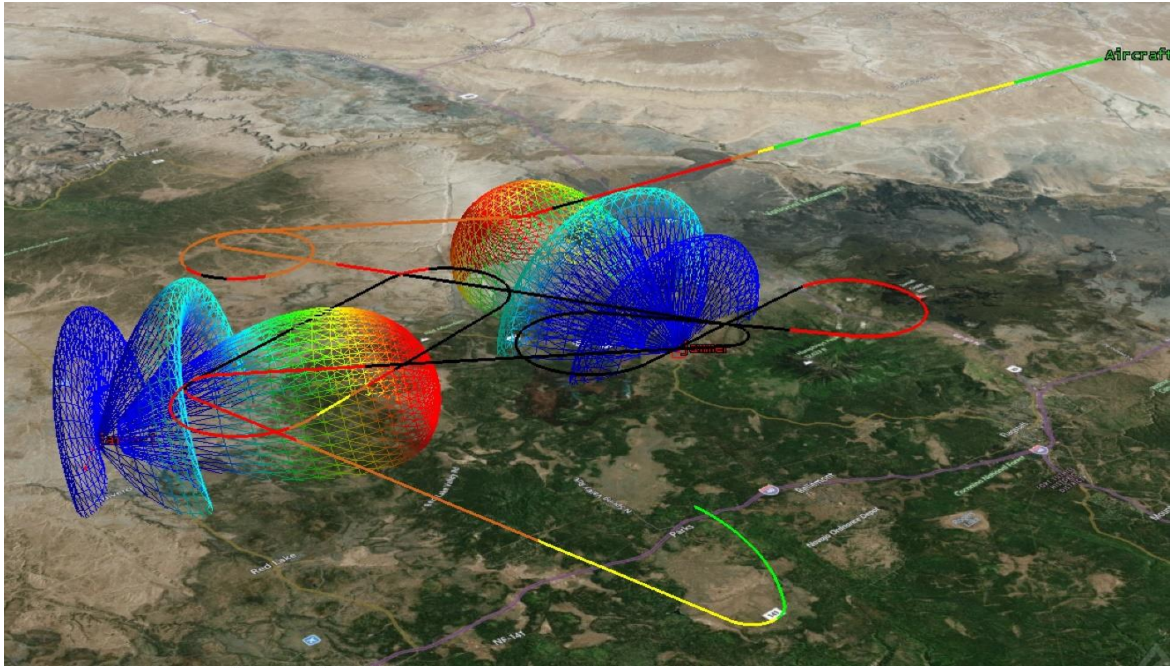
- -157 dBW



Radio Visibility

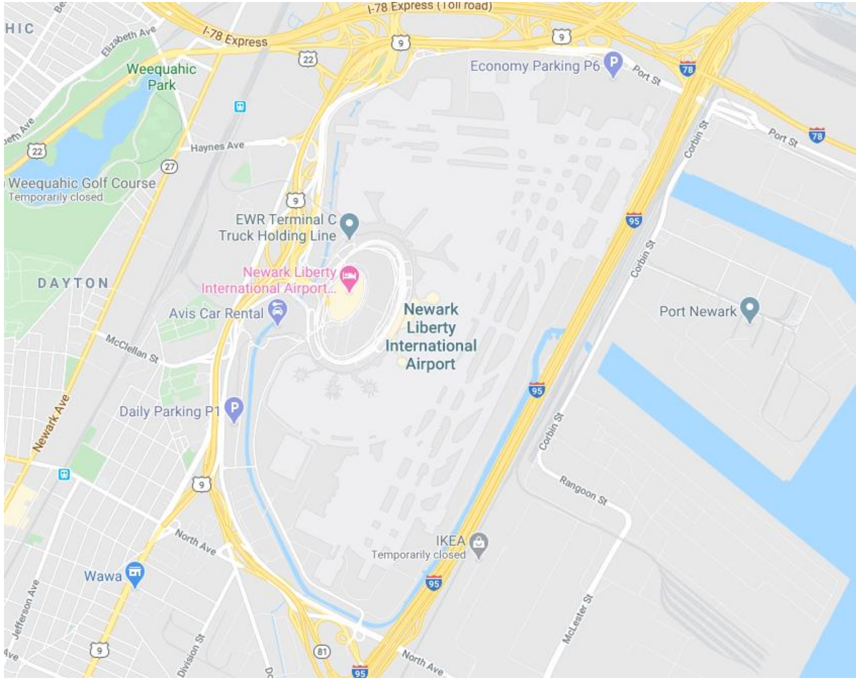
GPS signals are easily jammed

1 watt jammer can disrupt GPS within 30 miles



Jamming Examples

- 2012: New Jersey construction worker



Jamming Examples

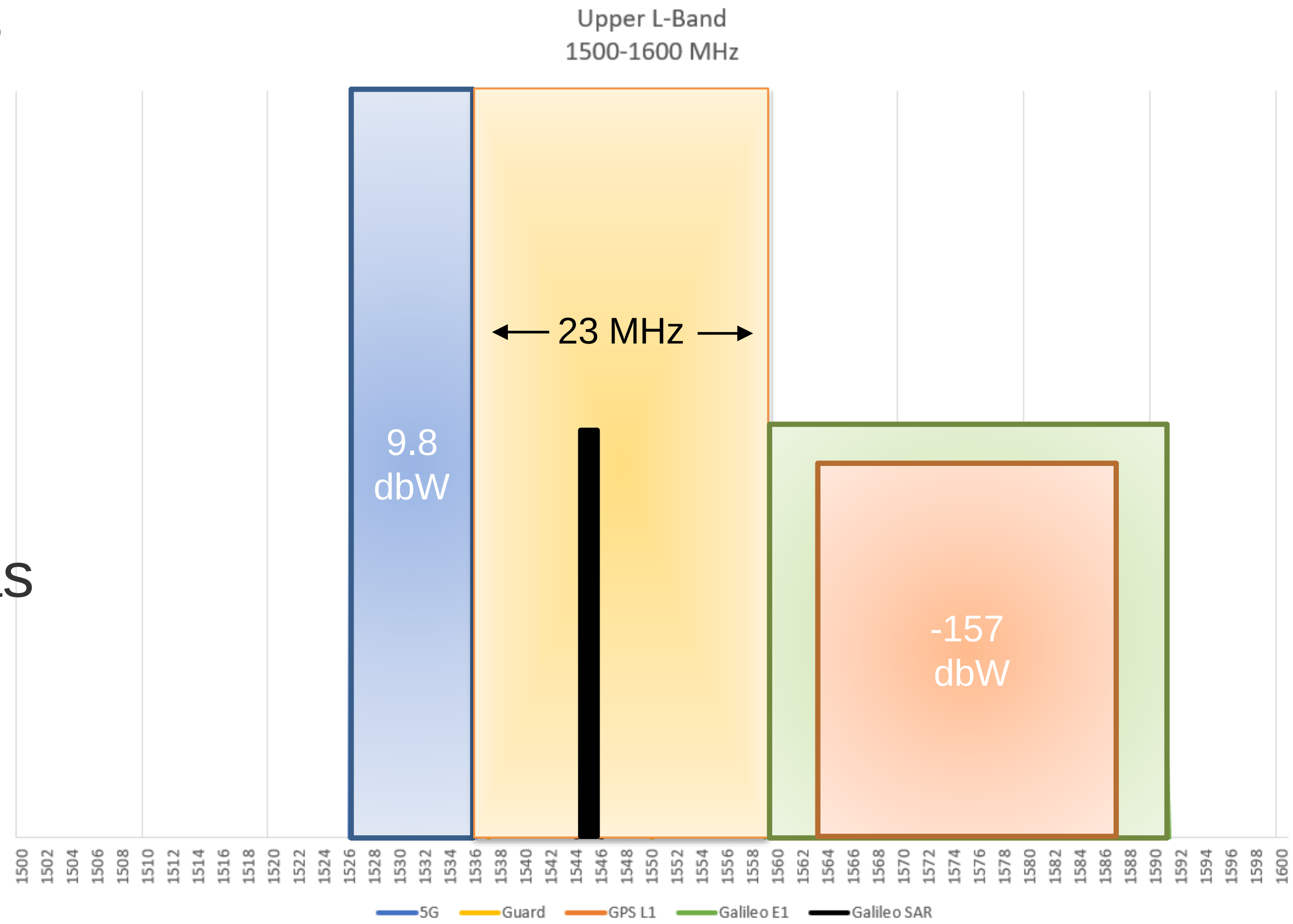
- 2012: New Jersey construction worker
- 2013-2016: 80 incidents reported
- 2019: Hong Kong drone show

Date of Disruption	Location	Date of Disruption	Location
09/08/2019	Shanghai, PRC	3/7/2019	Dongguan, China
09/02/2019	Shanghai, PRC	11/17/2018	Egypt, Straits of Tiran
09/02/2019	Shanghai, PRC	11/04/2018	Egypt
08/14/2019	Alexandria, Egypt	11/01/2018	Haifa Port, Israel
08/12/2019	El Shaikh Mobarak, Egypt	10/29/2018	Strait of Hormuz
08/06/2019	Mediterranean Sea, South of Sicily	10/13/2018	Jeddah Port, Saudi Arabia
08/01/2019	Mediterranean Sea, East of Malta	10/15/2018	Jeddah Port, Saudi Arabia
06/20/2019	Tripoli, Libya, Malta	10/01/2018	Port Said, Egypt
07/24/2019	Sabratha Oilfield - Offshore Libya	08/11/2018	50 miles from Qingdao, China
07/23/2019	Mediterranean	07/23/2018	Port Said, Egypt
07/16/2019	Shanghai, PRC	07/04/2018	Port Said, Egypt
07/10/2019	Port Said, Egypt	07/04/2018	Port Said, Egypt
07/03/2019	Libya	05/18/2018	100NM off Port Said, Egypt
06/26/2019	Port Said, Egypt	05/18/2018	35 NM North of Egyptian coast
06/20/2019	Sabratha Field - Offshore Libya	05/10/2018	Port Said, Egypt
06/12/2019	Ukraine, South of Odessa	04/18/2018	Eastern Mediterranean Sea
05/20/2019	Port Said, Egypt	04/16/2018	Port Said, Egypt
05/15/2019	Larnaca, Cyprus	03/22/2018	Mediterranean
5/12/2019	Port Said, Egypt	03/21/2018	Port Said, Egypt
05/06/2019	Port Said, Egypt	03/21/2018	Suez
04/27/2019	Damietta, Egypt	03/19/2018	Cyprus
04/25/2019	Port Said, Egypt	03/18/2018	Port Said, Egypt
03/19/2019	Pireaus, Greece	10/24/2017	Sea of Japan
02/09/2019	Hodeidah, Yemen	06/22/2017	Black Sea, Novorossiysk, Russia
11/18/2018	Hadera, Israel		

Recent news

April 2020, the FCC approved Ligado to broadcast 5G near GNSS frequencies

5G signal power ~155 million times as strong as GPS



CGSIC DOT Briefing – Sept 21, 2020

Effect On GPS of One Ligado Base Station (1 dB) Based on DOT ABC Testing

- 9.8 dBW base station placed in Lower Manhattan

High precision GPS receivers degraded (used, e.g., for surveying, construction)

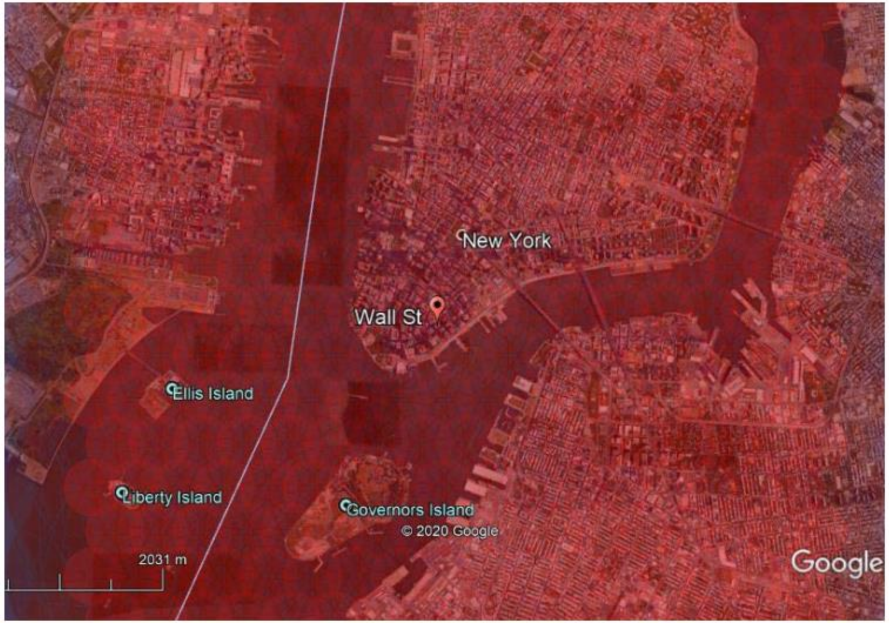
General-purpose GPS receivers degraded (used, e.g., by personal navigation, emergency response, UAVs)

Timing GPS receivers degraded (used, e.g., by cell towers, Communications/ IT, finance, energy, Federal mission systems)

* For illustration only.

CGSIC DOT Briefing – Sept 21, 2020

Effect On GPS of Many Ligado Base Stations (1 dB) Based on DOT ABC Testing



- 9.8 dBW base station separated by 433 m in hexagonal grid*
  - Blanketed Impact for All Receiver Categories

High precision GPS receivers degraded (used, e.g., for surveying, construction)

General-purpose GPS receivers degraded (used, e.g., by personal navigation, emergency response, UAVs)

Timing GPS receivers degraded (used, e.g., by cell towers, Communications/ IT, finance, energy, Federal mission systems)

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U.S. Department of Transportation 4

Other Issues

- Misunderstandings can cause operational errors

🤔

Corpus Christi TCL-4 Results

Corpus Christi TCL-4 Results

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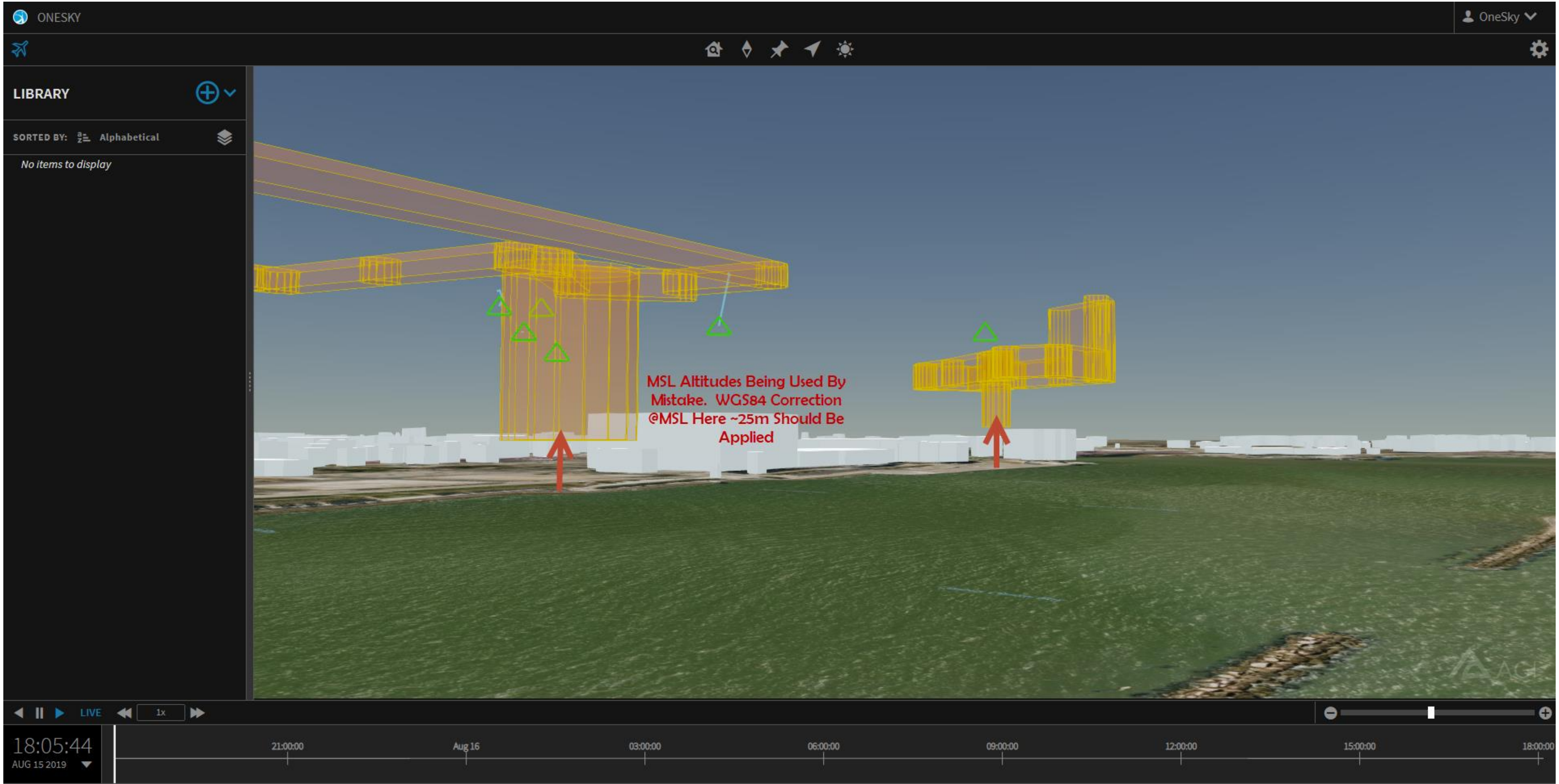
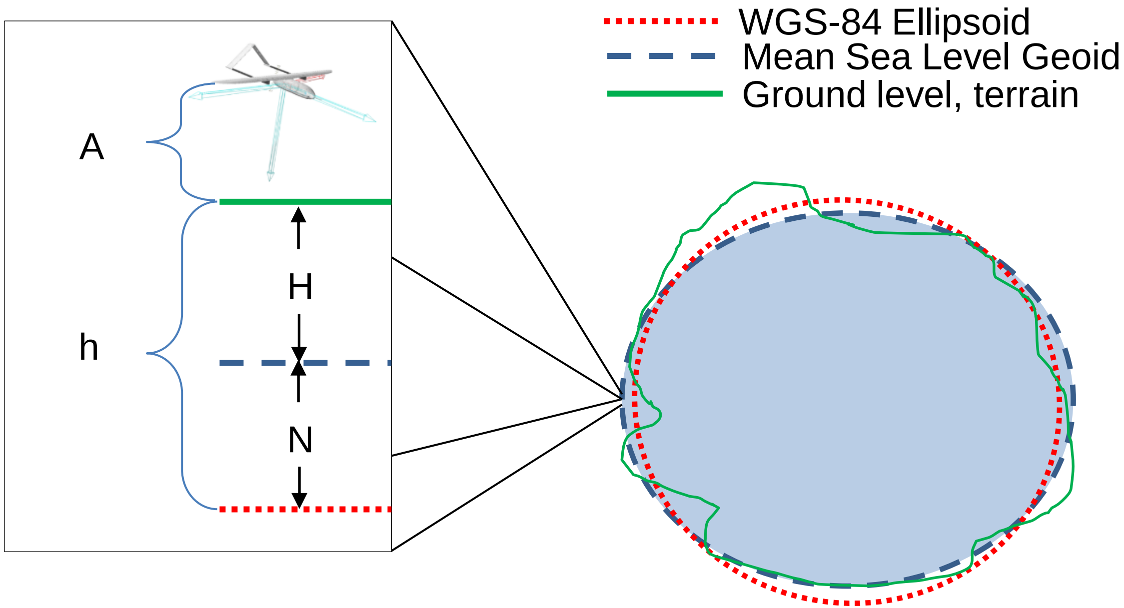


Terrain Heights and Datums



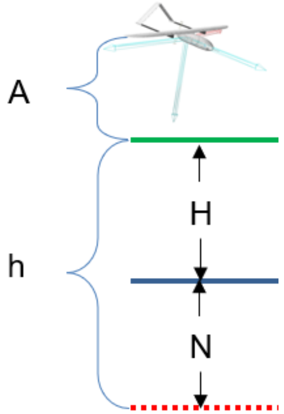
$$h = H + N$$

$$A = \text{AGL height}$$

A Height Example

From a OneSky terrain height service*:

```
    {
h       "TerrainHeightFromWgs84": 4283.1394147693254,
N       "MeanSeaLevelHeightFromWgs84": -16.108077610647548,
H       "TerrainHeightFromMeanSeaLevel": 4299.247492379728
    }
```



*https://saas.onesky.xyz/SDSP/Documentation/Terrain#heights

A Height Example

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h
N
H

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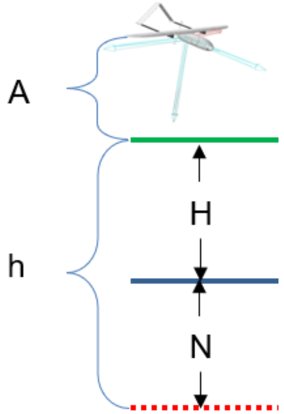

You're flying at altitude: A = 250 ft AGL

What will GPS report your altitude as?

h + A = GPS altitude

*https://saas.onesky.xyz/SDSP/Documentation/Terrain#heights

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From a OneSky terrain height service*:

```
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H     "TerrainHeightFromMeanSeaLevel": 4299.2474923799728
  }
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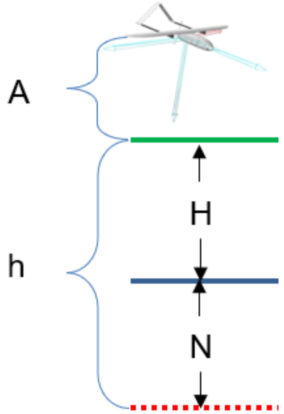

You’re flying at altitude: A = 250 ft AGL

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

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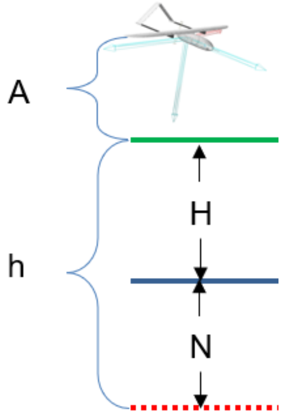


You’re flying at altitude: A = 250 ft AGL

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

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

*https://saas.onesky.xyz/SDSP/Documentation/Terrain#heights

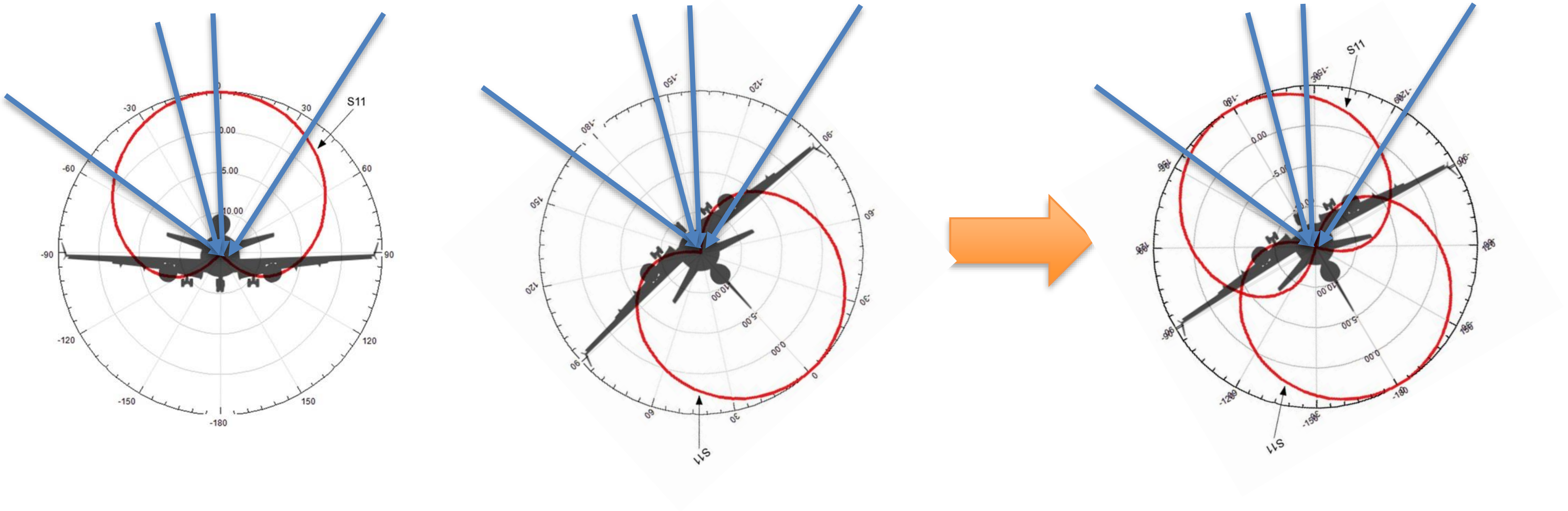
Mitigation

- Modeling and Simulation
- Strategies to increase the number of satellites in **G**
  - Terrain and jamming mitigation
- Ways to find precise locations without using GPS
  - Alternative navigation solutions

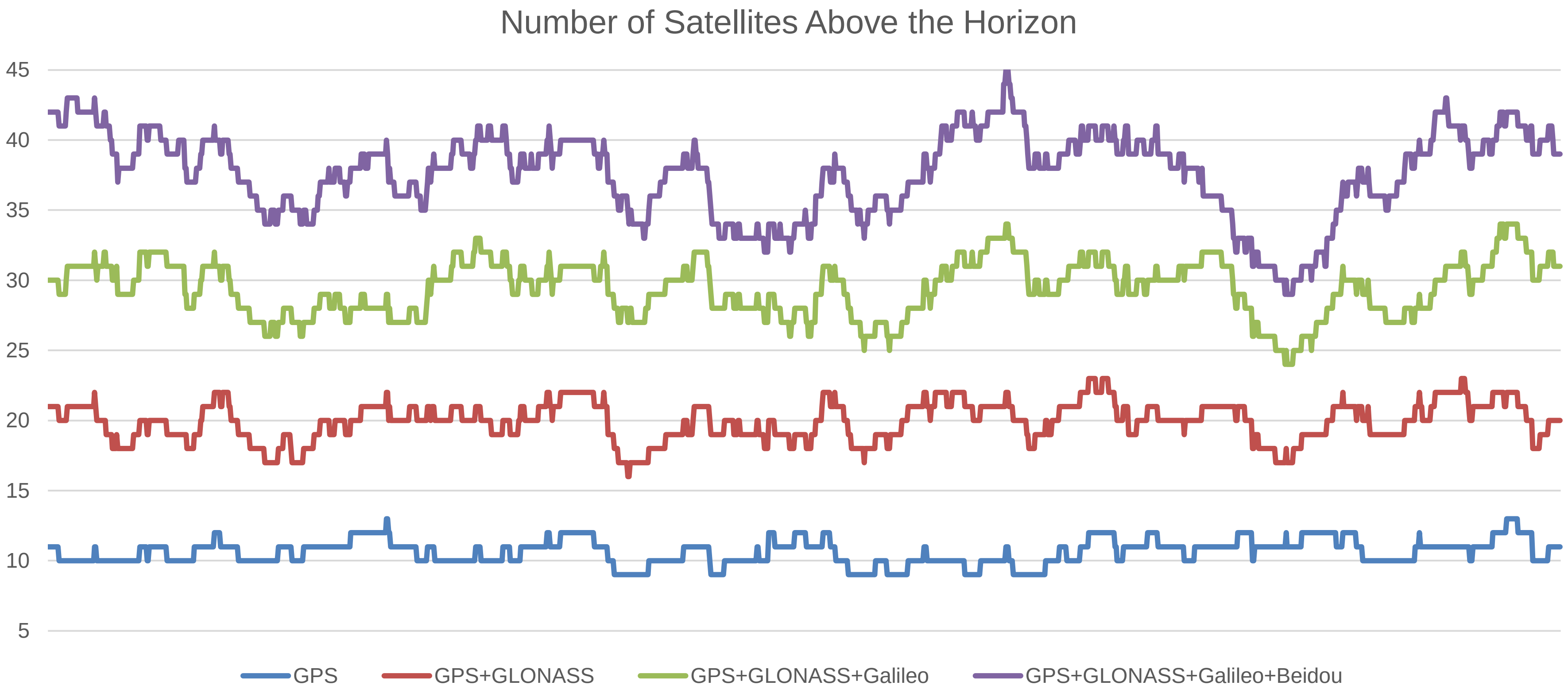
Modeling and Simulation

- Understand your situation
  - How is your mission affected?
- Apply model-based systems engineering
  - Try before you fly
  - Digital twin
  - What-if scenarios

Modeling and Simulation – Antenna Gain



Terrain Mitigation – more satellites

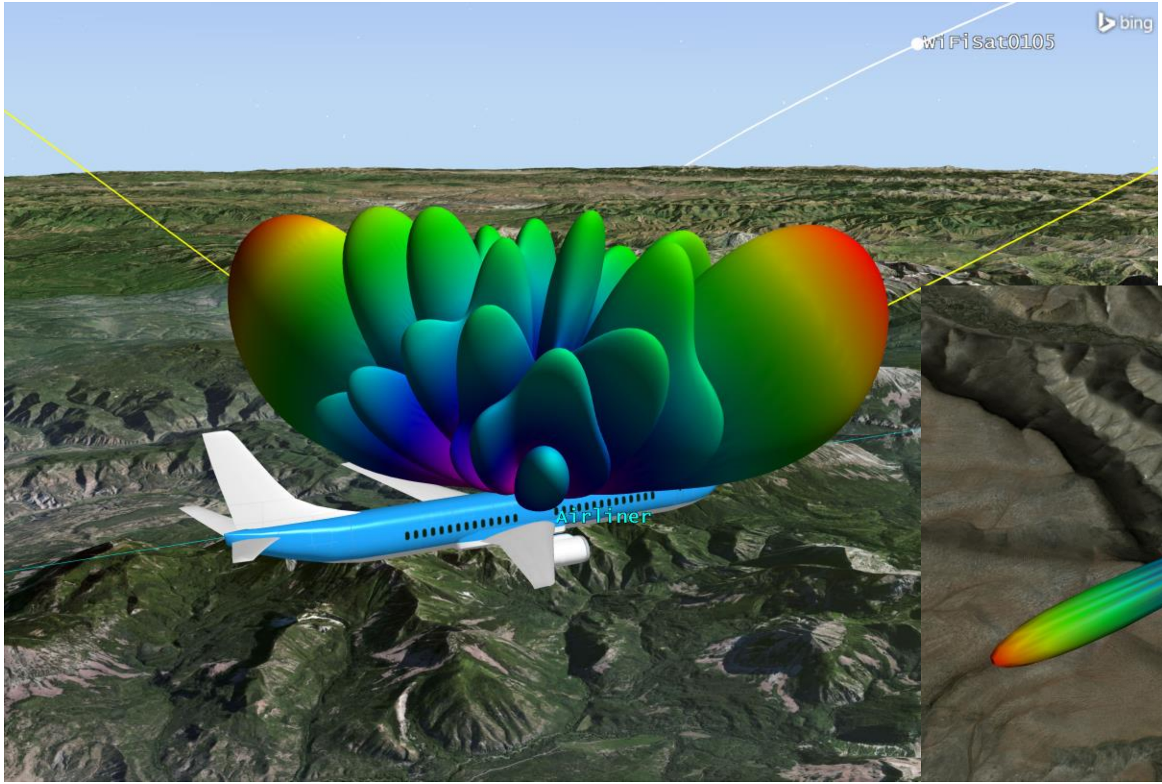


Terrain Mitigation - Assisted GPS

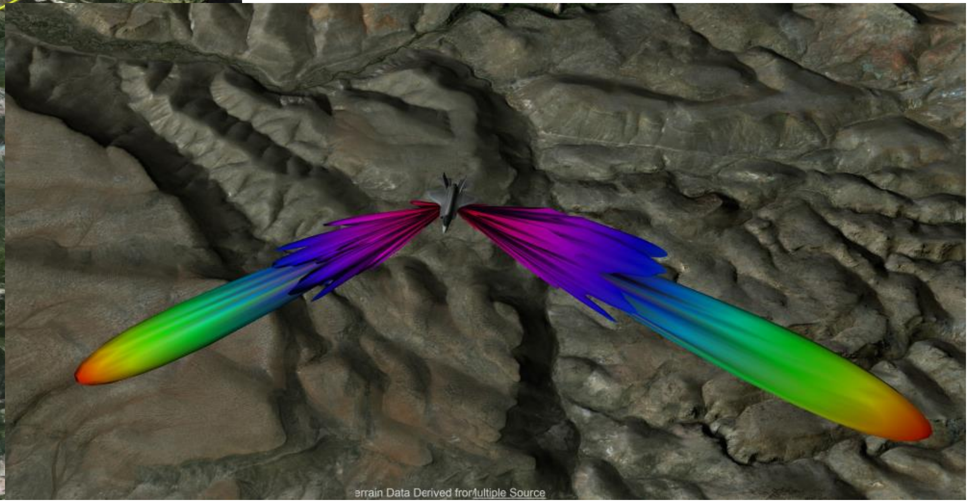
- Critical data downloaded in a clear environment
  - Transmitted over cell network to platform in a contested environment with GPS chip

OneSky®

Jamming Mitigation – Controlled Antennas



Also, some receiver’s have processing that can detect out-of-family signals, excluding them



Inertial Measurment Units (IMUs)

- Inertial aiding can help when GPS is temporarily lost
  - Without updates, errors will grow
  - Signals of opportunity can help bound errors
- Both a jamming mitigation and alternative nav technique

Alternative Navigation Technologies

- Precise location is an absolute need
- GNSS is not universally reliable
- Other location technologies are available

E-LORAN

- Enhanced Long-Range Navigation
  - Hyperbolic positioning
- 2D positioning, ~8 m accuracy
- Contains auxiliary data, including DGPS corrections
- DOT testing Hellen Systems solution now

Pseudolites

- Pseudo-satellites
  - Navigation beacons that act as GPS satellites
- Placed optimally, they can minimize **H** matrix for designated flight routes
- Solutions exist for indoor nav as well

Computer Vision and SLAM

- CV techniques use predefined locations combined with sensors on the UAS
- SLAM uses LIDAR to map the area around the UAS, to update its position
  - SLAM = Simultaneous Location And Mapping
  - LIDAR = Light Detection And Ranging

The need for alternatives to GNSS

- We cannot rely on GPS/GNSS navigation alone
- Along with communications and weather prediction, precise location is a critical enabling technology for the UAS industry
- Combinations of navigation technologies are required to support the need for continuous, precise location information

Summary

- The **G** and **H** matrices help us understand navigation errors
- Knowing height references are crucial for safe operations
- Jamming is a prevalent concern
- Several mitigation techniques were reviewed
- Many alternatives to GNSS exist
- A combined system of navigation technologies is needed to provide continual, precise location

Thank you!

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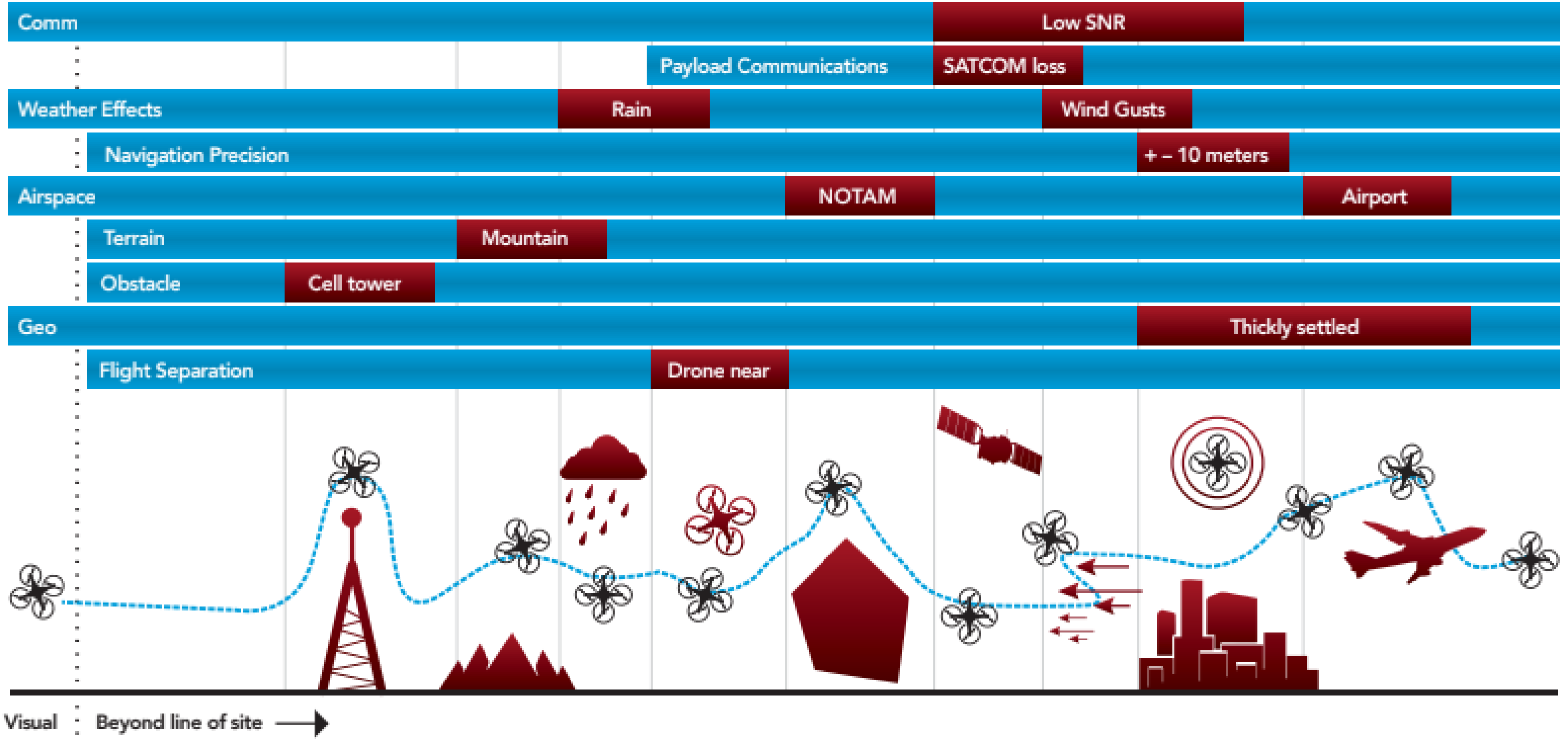

GPS Issues: Contact

- https://www.gps.gov/support/user/
- Suspect jamming?
  - Non-Aviation related:
    - https://www.gps.gov/spectrum/jamming/
  - Aviation related:
    - http://www.faa.gov/air_traffic/nas/gps_reports/