Volume Raycasting of GNSS Signals through Ground Structure Lidar for UAV Navigational Guidance and Safety Estimation -- Video

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Outline - Volume Raycasting of GPS

- Brief overview of the physics of GPS degradation and state of the art
- GPS quality investigated at two flight ranges (video)
- Prototype GPS fidelity calculator
- Discovery: the attenuation vs. foliage-depth curve
- A survey method for heavily wooded flight ranges

Conclusions

1. It is possible to forecast navigation fidelity in urban and arboreal canyons
2. Flight ranges in forests can be surveyed to calibrate the severity of GPS attenuation

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At low altitudes, GPS degradation is all too common

Computing the underlying physics is a 2020's development

UAS navigation is often hindered by degraded GPS position quality. This is caused by

1. Blockage and reflection by buildings
2. Blockage and attenuation by foliage

A useful GPS quality calculator must compute the physics rapidly and realistically using detailed surveys of ground structures

Three research groups (one at Google[1] and two at NASA[2,3]) are computing GPS quality by tracing from the receiver to orbiting satellites

- Building blockage is addressed by all three
- Foliage blockage is addressed by one (this report)

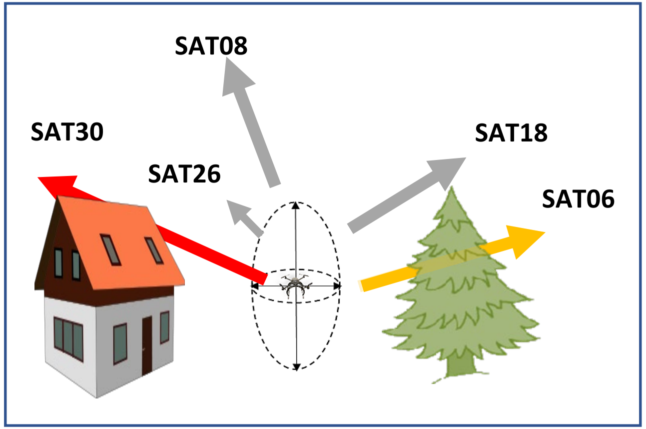
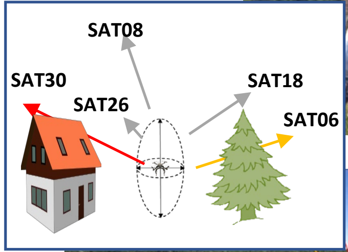


Fig. 1 Tracing the ray blockage from a UAS to five orbital satellites. The left ray is completely blocked (red), the right ray is attenuated (yellow), while the remainder (grey) are free of intersection with ground structures. ***©Graphics: NASA, NOAA, USDA***.

1. F. van Diggelen, *End Game for Urban GNSS: Google's Use of 3D Building Models*, Inside GNSS, 2021.
2. E. Dill et al., *A Predictive GNSS Performance Monitor for Autonomous Air Vehicles in Urban Environments*, ION GNSS+ 2021, 2021
3. A. Moore et al., *Volume Raycasting of GNSS Signals through Ground Structure Lidar for UAV Navigational Guidance and Safety Estimation*, AIAA Scitech, 2022

Visualize GPS fidelity at two sites

Flight ranges known to have intermittent navigation loss



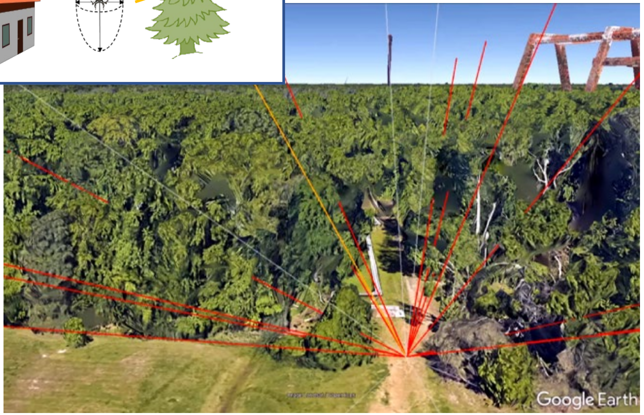
1. **Lunar Lander Research Facility**
   - Aerial lidar, 2015 survey

     17 cm average point spacing

2. **Arboreal canyon** (pipeline corridor)
   - Aerial lidar, 2018 survey

     10 cm average point spacing
   - Ground (tripod) lidar, 2018 survey

     8 cm average point spacing



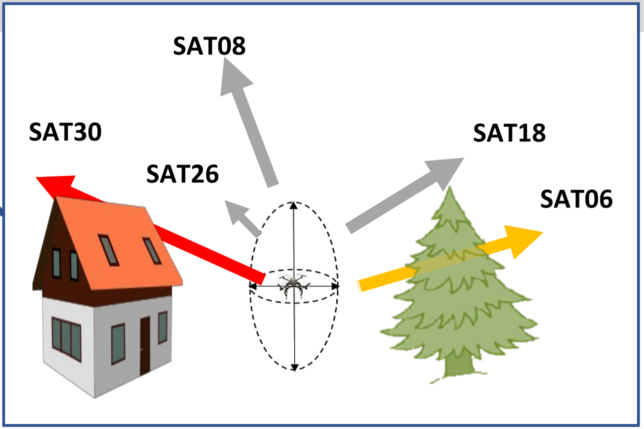
©Graphics: NASA ©Map data: Google Earth (Landsat, Copernicus)

Steps in visualization and analysis

Transform lidar coordinates from local frame to global (satellite) frame, and place in 3D array

Look up orbital constellation at flight time[a]

Sum[b] lidar blockage along the ray from the UAV location to each satellite
  Weight blockage differently for buildings vs. trees

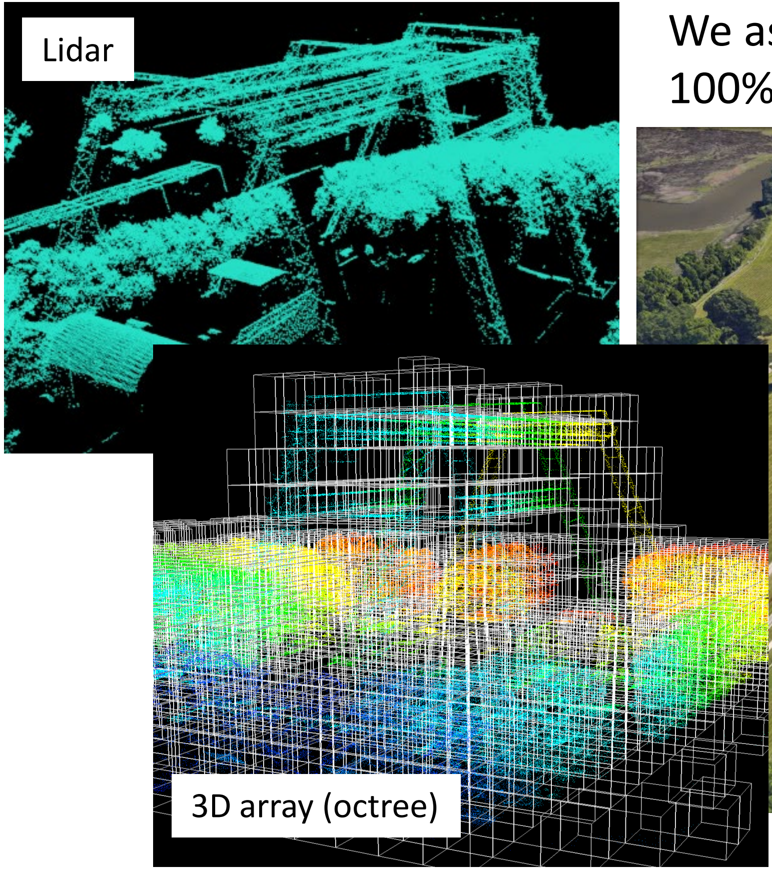


a. NASA's Archive of Space Geodesy Data, cddis.nasa.gov
b. Point Cloud Library, v1.7.2

Site 1. NASA Langley Lunar Lander Research Facility

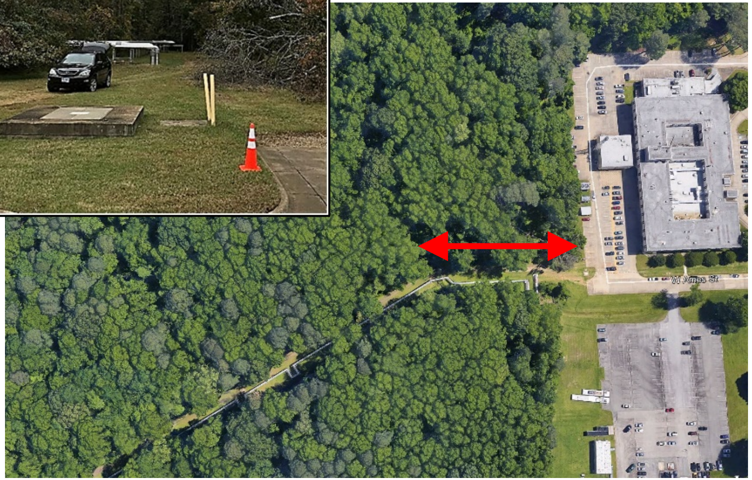
March 2018 flight.

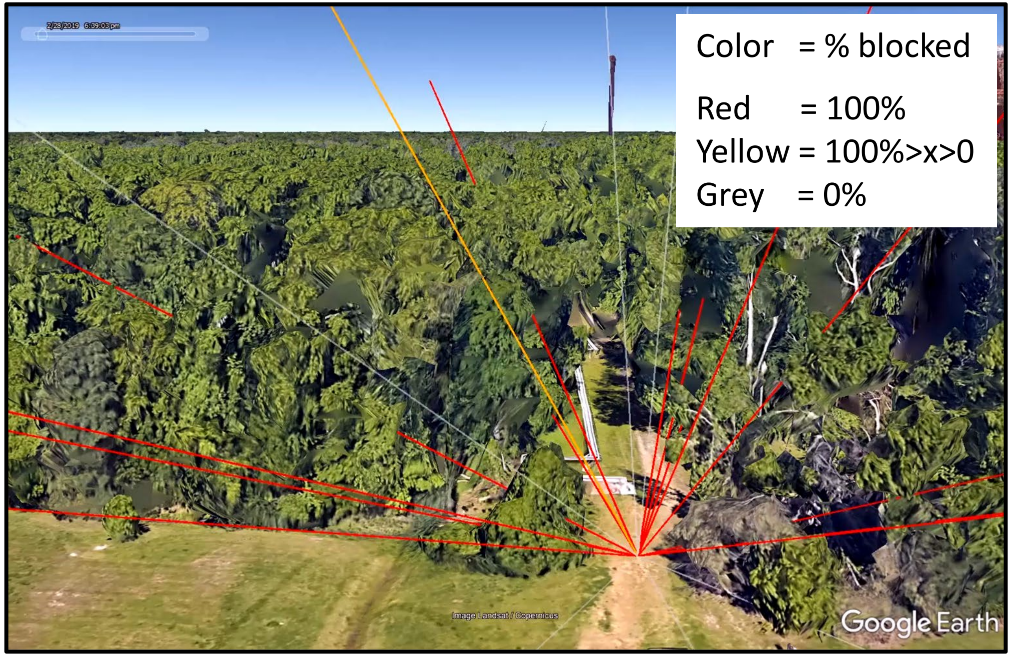
We assumed buildings block 100% and 5m of foliage block 100% of the ray.



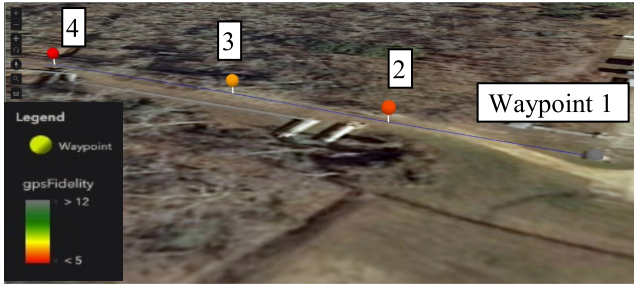
Site 2. Arboreal canyon with steam pipeline

February 2019 flight at 15m altitude.
We assumed buildings block 100% and 5m of foliage block 100% of the ray.





Prototype GPS fidelity calculator



Color	# satellites with clear line of sight
Red	*≤ 5*
Orange	*6-7*
Yellow	*8-9*
Green	*10-11*
Grey	*≥ 12*

Computed on a virtual machine running at Katherine Johnson Compute Facility at the NASA Langley Research Center:

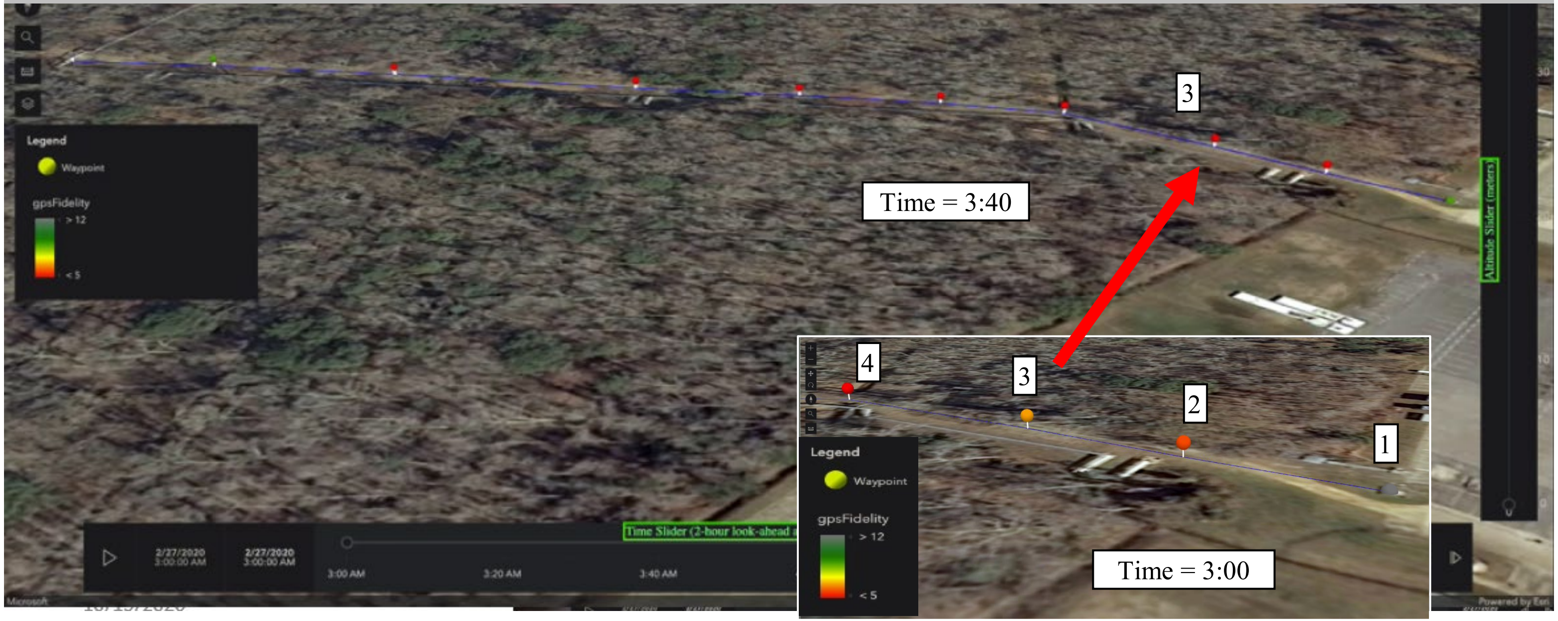
- 12 CPU cores and 42 GB RAM
- 650 fidelity estimates in 52 seconds

- 2 hours forecast = Thirteen 10-minute intervals
- 1.1 GB lidar point cloud
- Ten flight waypoints 30-50 m apart
- Five altitudes (0,10,20,30,40 m)

Prototype GPS fidelity calculator

How does the number of unobstructed GPS satellites change over 2 hours?

At waypoint 3, the satellite count changes from high (foreground image) to dangerously low (background image).



# Satellites	
Red	*≤ 5*
Orange	*6-7*
Yellow	*8-9*
Green	*10-11*
Grey	*≥ 12*

What is the *real* attenuation by trees?

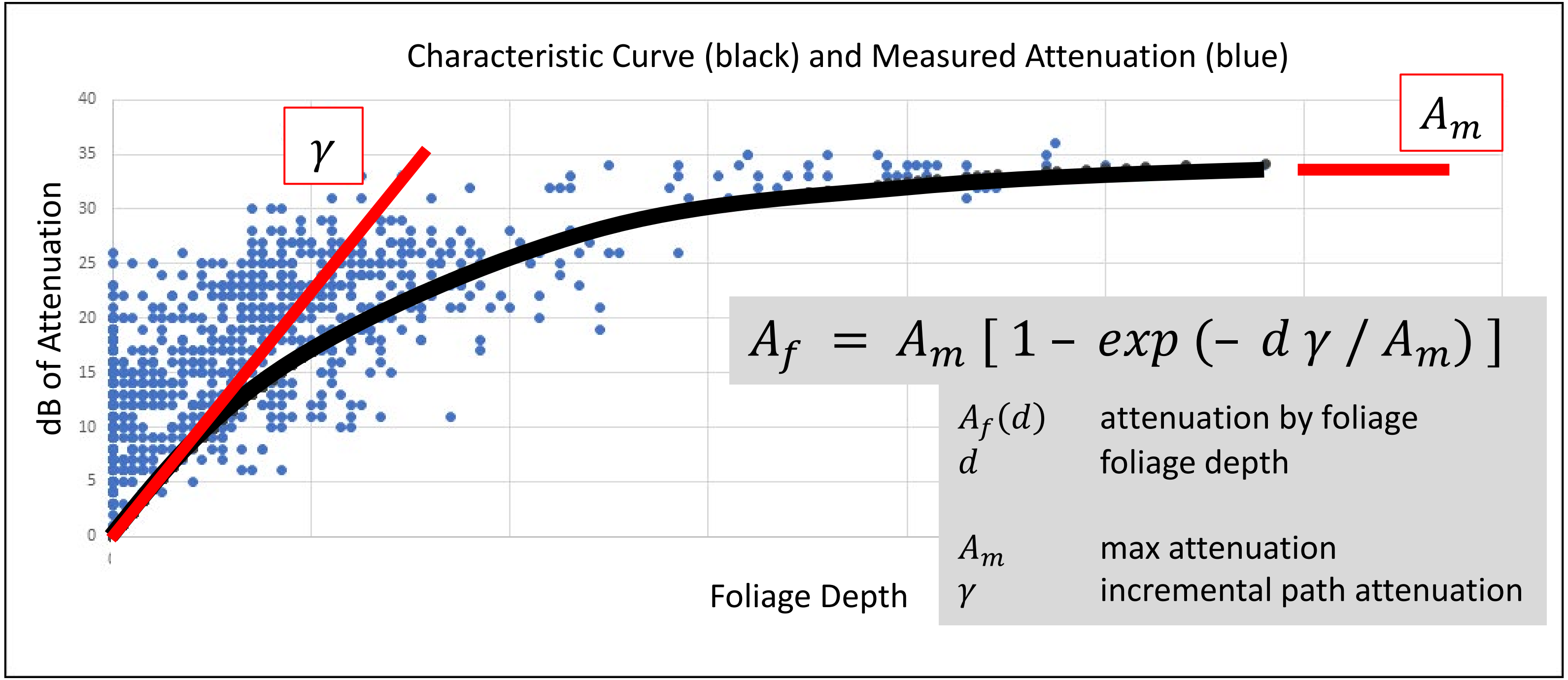
Up to now we assumed linear summation along the ray and nominal (20%) attenuation per meter.

- Is GPS (c/N0) attenuation of foliage linear with depth?
- What is the real attenuation value?

To compare satellite signal strength to foliage depth, we conducted research flights and recorded GPS on 14 days from November 2018 to February 2021.

- Collected 55 recordings, yielding thousands of signal measurements
- Varied constellation (time of day)
- Varied altitude (ground walk, flights at 5m-40m altitude)

Consistent result: GPS signals are attenuated by vegetation according to a saturating exponential



- X axis: Meters of foliage between UAV and satellite
- Y axis: Drop in signal strength from ‘clear sky’ sample

A characteristic curve for GPS attenuation by foliage

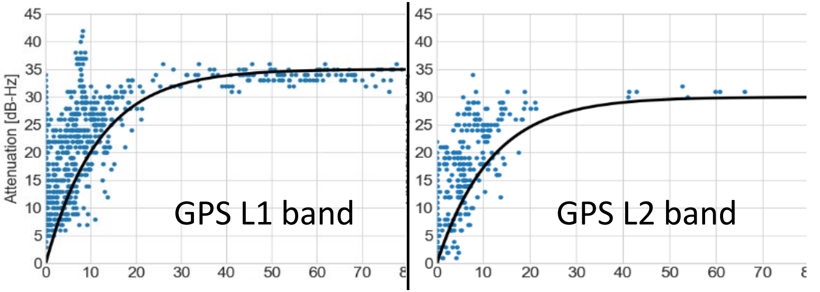
Experimental result

- Left: GPS L1 results. A representative single measurement (top) and all L1 results (bottom).
- Right: GPS L2 results. A representative single measurement (top) and L2 results (bottom).

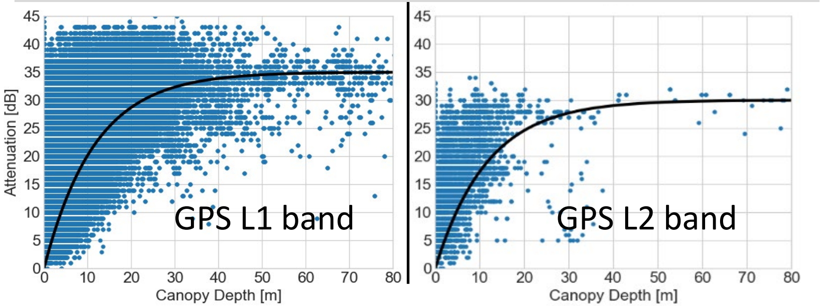
Consistent finding: results follows continuous-wave radio attenuation curve[2] – but with 10X steeper γ (dB/m)

- $A_f = A_m[1 - \exp\left(-\frac{d \cdot \gamma}{A_m}\right)]$
- $A_{m,\text{GPS}} \sim A_{m,\text{continuous-wave}}$
- $\gamma_{\text{GPS}} \sim 10 * \gamma_{\text{continuous-wave}}$

Data from a single recording[1]



All data acquired across 2 years



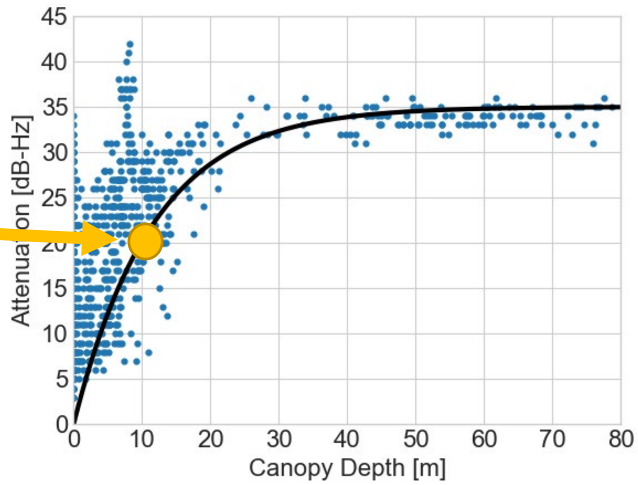
1) February 10, 2021
2) International Telecommunication Union "Attenuation in Vegetation" ITU-R Recommendation P833-9, Geneva, September 2016

Implications for flying in arboreal canyons

What kinds of flights are impacted by foliage degradation of GPS?

- Infrastructure inspection
- Property survey
- Storm recovery
- Search and rescue

- *For this mixed hardwood canyon**, after about 30m of foliage blocking, the attenuation is near the maximum.
  - 60% of signal lost in first 10m
  - Max loss (~ 30dB) will usually knock out a satellite's signal
- Loss of satellites at low elevation angles greatly impairs vertical position quality (VDOP). We observe horizontal (HDOP) degradation as well.



©Graphics: NASA

** We expect that the curve depends on the tree species, as for continuous-wave radio attenuation*

Summary

Computing the physics of GPS loss realistically is a 2020's development

GPS quality was investigated at two flight ranges

1) Visualized GPS reception using nominal attenuation value for foliage
2) Measured actual attenuation in a series of flight experiments

Developed a prototype GPS fidelity calculator/forecaster

There is a characteristic GPS attenuation vs. foliage depth curve ☆

Conclusion

- ❖ It is possible to forecast navigation fidelity in urban and arboreal canyons
- ❖ Flight ranges in forests can be surveyed to calibrate the severity of GPS attenuation

- Infrastructure inspection
- Storm recovery
- Property survey
- Search and rescue

BACKUP

Sources of error for this new survey method

See paper for more details

- Simplified physics (no multipath or lensing at present)
- Inherent errors in surveys of buildings and foliage, e.g., positional error in survey lidar
- Representational error from spatial sampling and binning lidar into 3D voxel array
- Nonuniform receiver antenna sensitivity
- Assumes known receiver position as the origin of the ray to trace to each satellite -- most reliable for preflight planning

Flight experiments to survey foliage attenuation

What is needed:

1. A lidar survey of the area
2. A GPS unit that can report satellite number and signal strength
3. A sidecar processor to store the readings

Sensor: uBlox M8T

Processor: Arduino Teensy

Compact ~size of a pack of chewing gum
Inexpensive ~$400

Solver: RTKLIB, custom C++ and Python

Raycasting: Point Cloud Library, custom C++ and Python