

Predicting GPS Fidelity in Heavily Forested Areas

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Outline - Predicting GPS Fidelity in Heavily Forested Areas

- Brief overview of the physics of GPS degradation by foliage: the attenuation vs. foliage-depth curve
- Validation of GPS signal attenuation vs. canopy depth at 3 sites
 - Refinements of measurement technique
- Interpreting the attenuation vs. foliage-depth curve

Conclusions

1. Results replicated at 3 additional sites
2. Radiofrequency fading and receiver limitations explain the attenuation curve
3. Navigation impairments due to blockage and attenuation can be estimated

We are grateful to many NASA Langley colleagues for discussions and assistance in the course of this multi-year development effort, including:

- LaRC GIS Group, UAS Operations Office, and Safety Office
- Scott Dorsey, Evan Dill and Steve Young (GNSS); Russell Gilabert (RTKLIB); Kyle Ellis and Misty Davies (program support). This work was performed with support from the NASA Unmanned Traffic Management program and System Wide Safety Project, which is part of NASA's Aviation Operations and Safety Program.

and to Matthew Peretic and Arthur Scholz of the Mitre Corporation for discussions on multipath phenomena

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, reflection and attenuation by foliage

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

At least four research groups (at Google¹, Spirent², and NASA^{3,4}) are computing GPS quality by tracing from the receiver to orbiting satellites

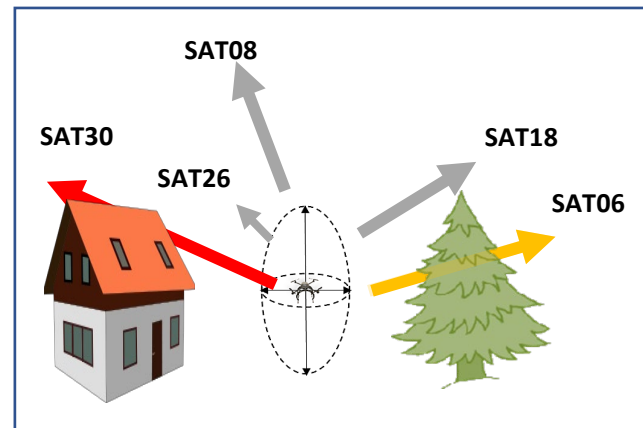
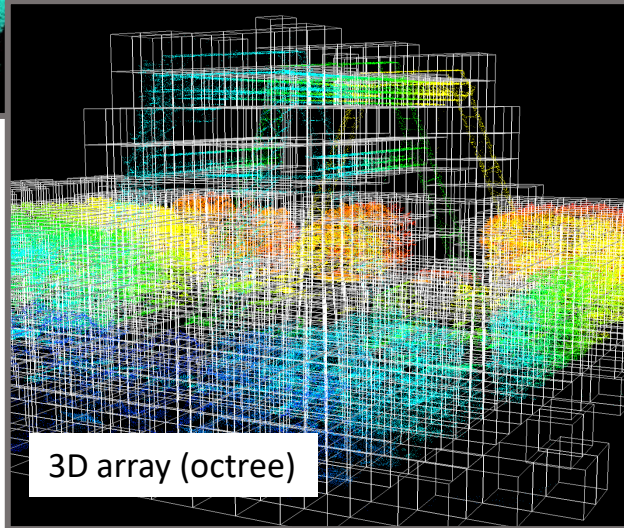
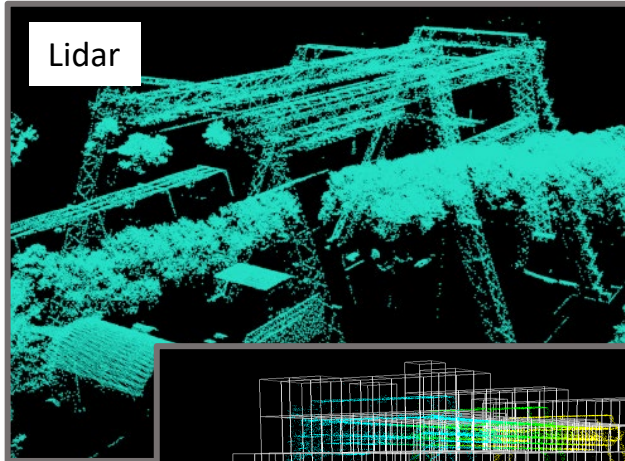


Fig. 1 Tracing the ray blockage from a UAS to five orbital satellites. The left ray is completely blocked (red), the right ray is attenuated (yellow), while the remainder (grey) are free of intersection with ground structures. **@Graphics: NASA, NOAA, USDA.**

1. F. van Diggelen, *End Game for Urban GNSS: Google's Use of 3D Building Models*, Inside GNSS, 2021.
2. Bennett, N., Hunter, M., & Buesnel, G., *Validation of urban multipath models with record and playback simulation*. ION GNSS+ 2021, 2021.
3. E. Dill et al., *A Predictive GNSS Performance Monitor for Autonomous Air Vehicles in Urban Environments*, ION GNSS+ 2021, 2021.
4. A. Moore et al., *Volume Raycasting of GNSS Signals through Ground Structure Lidar for UAV Navigational Guidance and Safety Estimation*, AIAA Scitech, 2022.

Example at NASA Langley Lunar Landing Research Facility

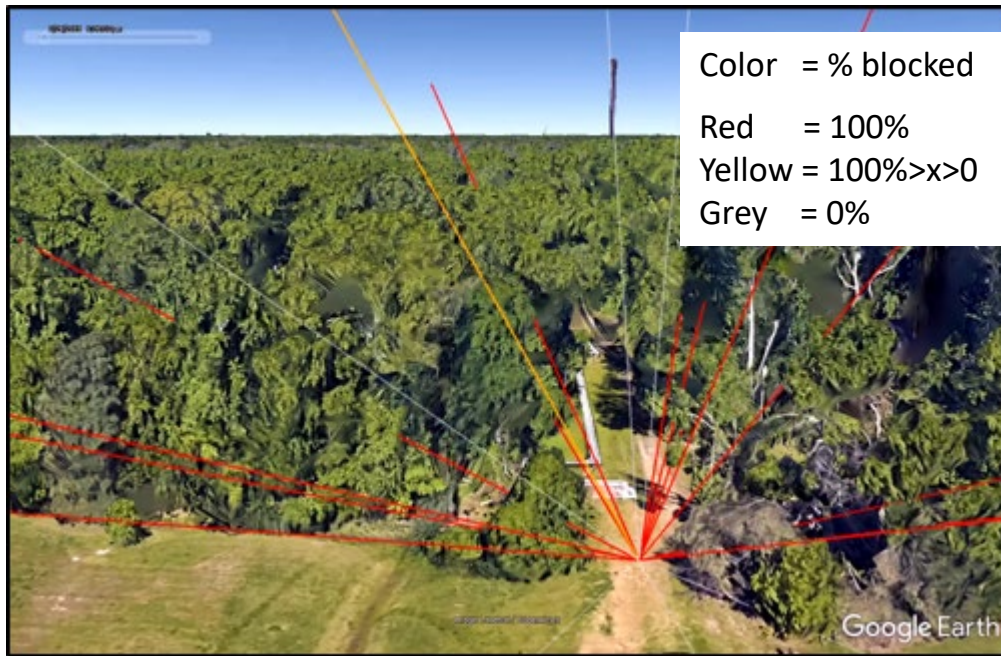
- Lidar point cloud loaded into 3D array of terrain features
- Blockage is summed along each ray from the UAV location to navigational satellite



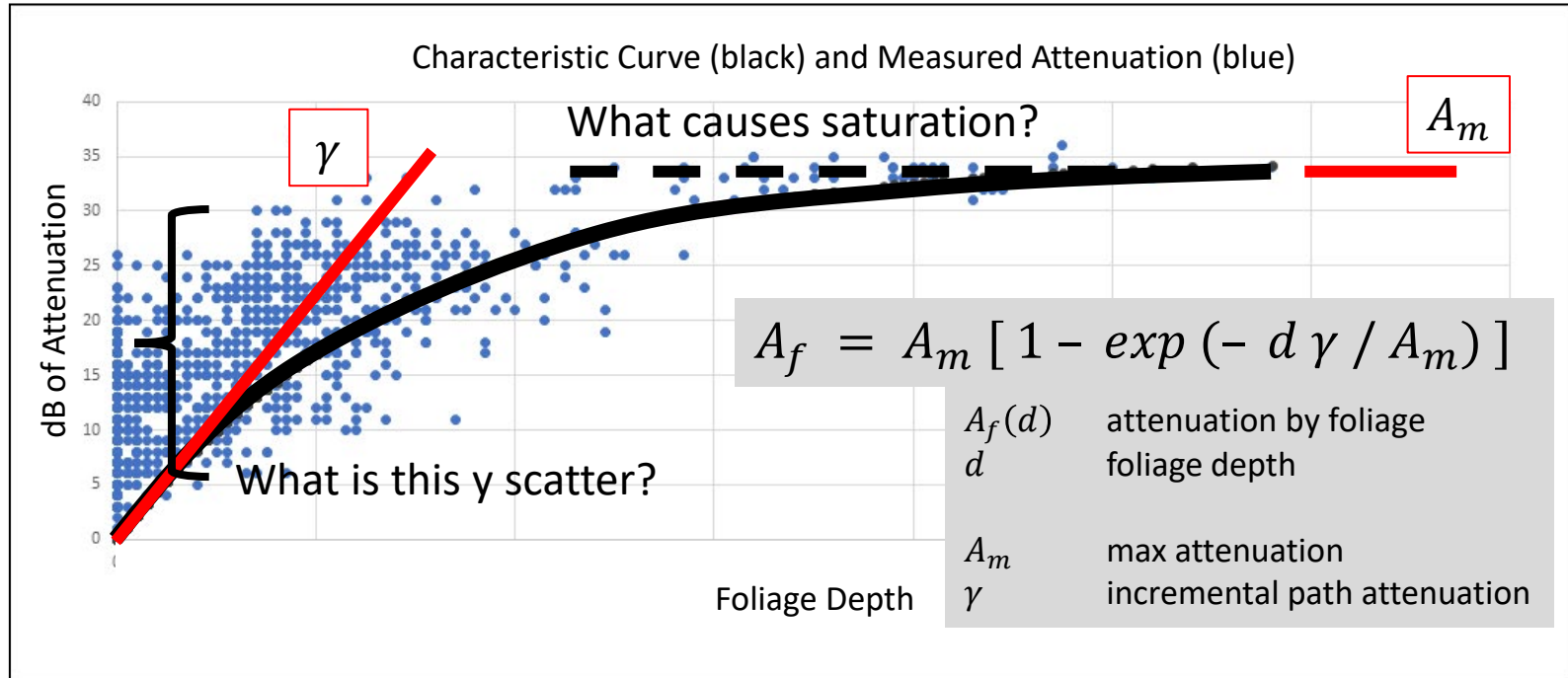
Example at arboreal canyon with steam pipeline

February 2019 flight at 15m altitude.

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

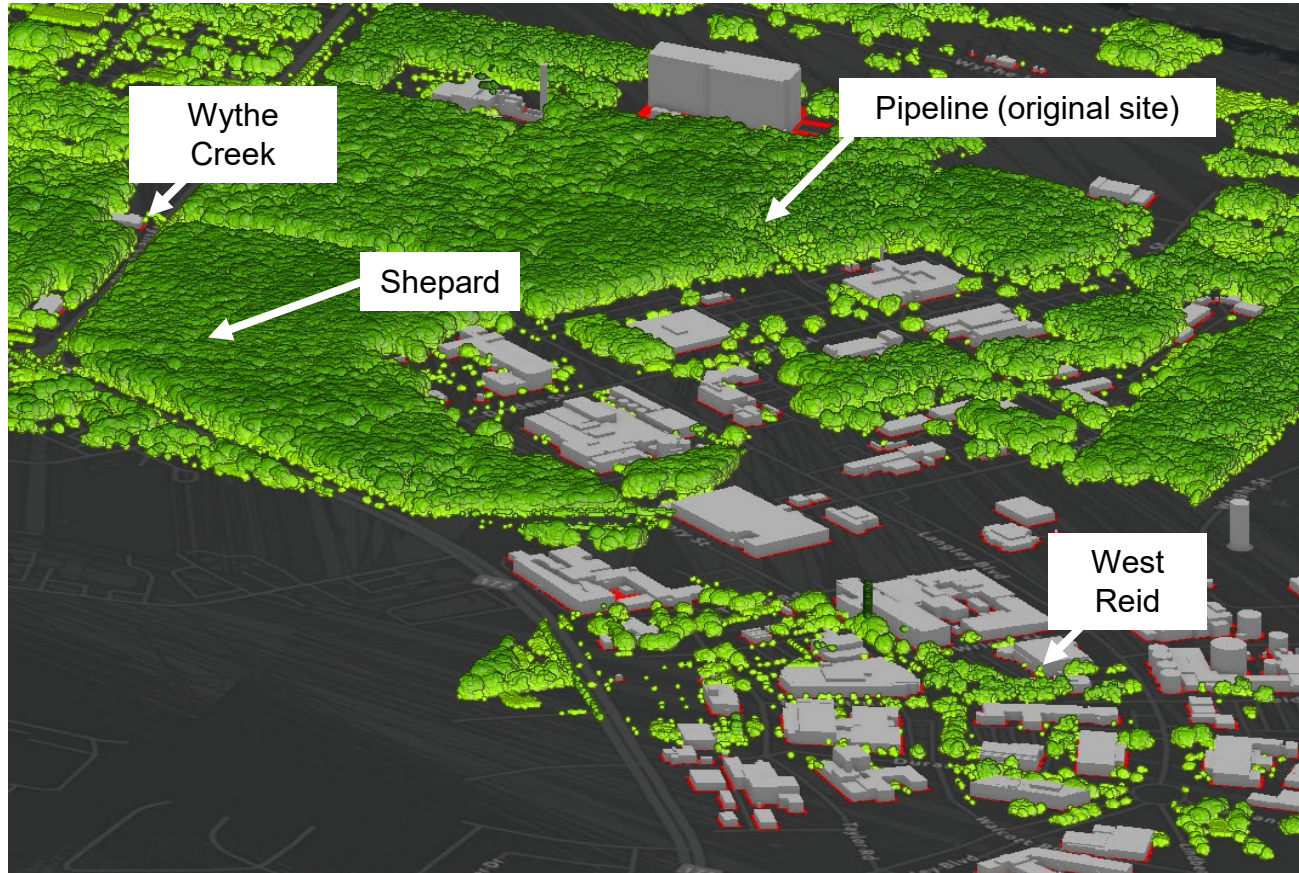


Initial result: GPS signals are attenuated by vegetation according to a saturating exponential

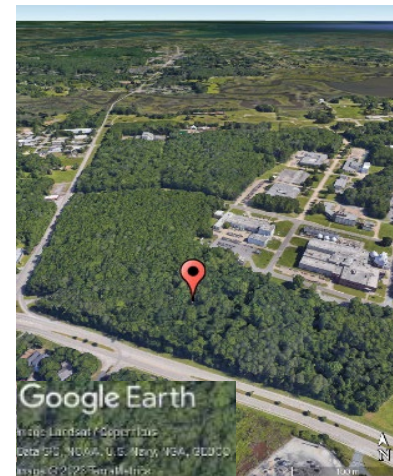
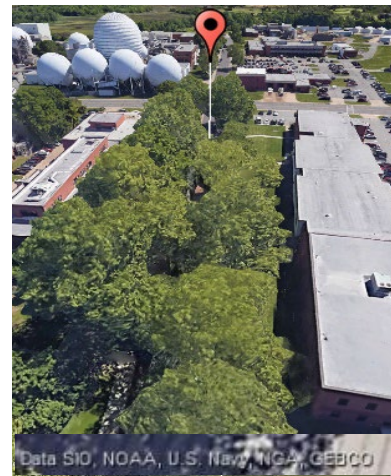
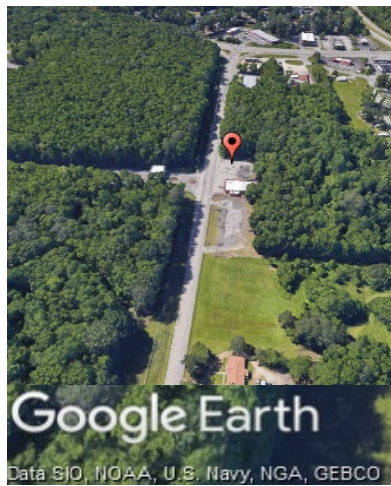
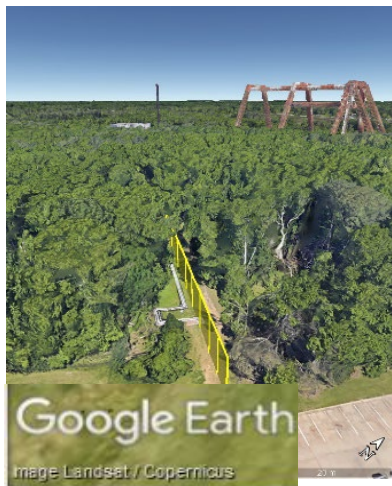


- X axis: Meters of foliage between UAV and satellite
- Y axis: Drop in signal strength from 'clear sky' sample

Validate: Replicate foliage result at 3 additional sites

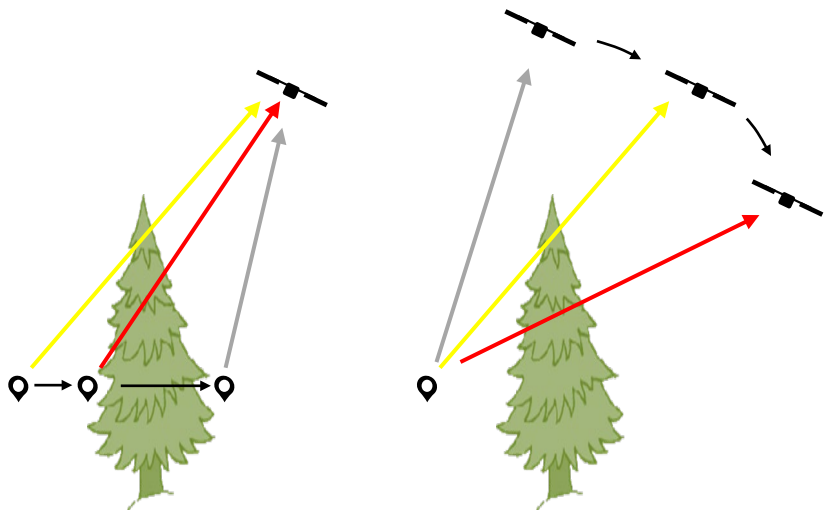


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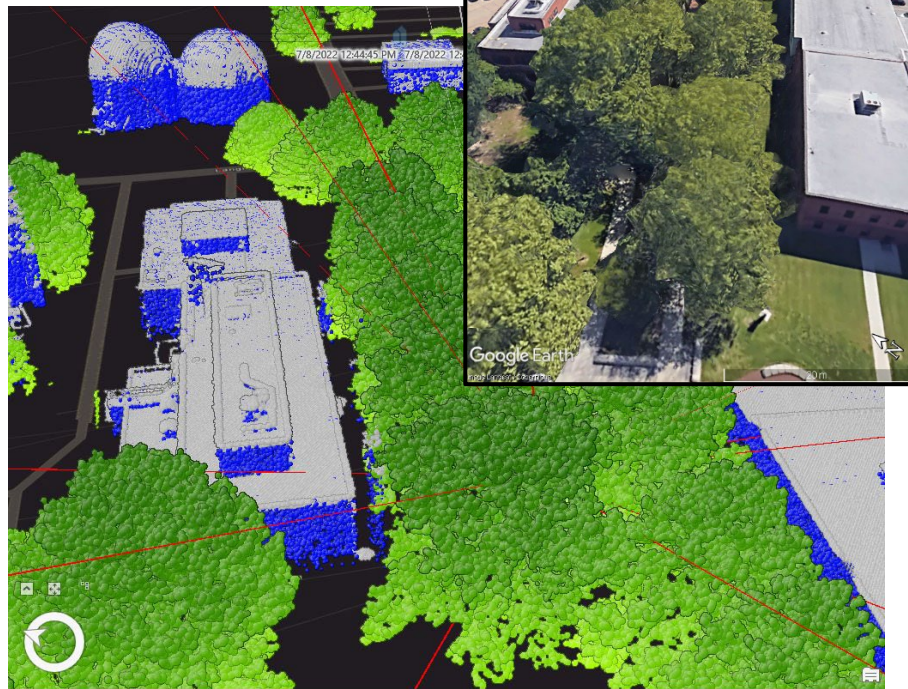


	Pipeline	Wythe Creek	West Reid	Shepard
L1/L2	48/7	4/0	12/6	6/3
Dates	2018/11/02 through 2021/02/10	2020/10/27 2020/11/18	2022/06/30 2022/07/08 2022/07/12	2022/08/24
Method	Moving/fixed	Fixed	Fixed	Fixed

Two methodology improvements



Moving vs. stationary recording



Filling inside buildings

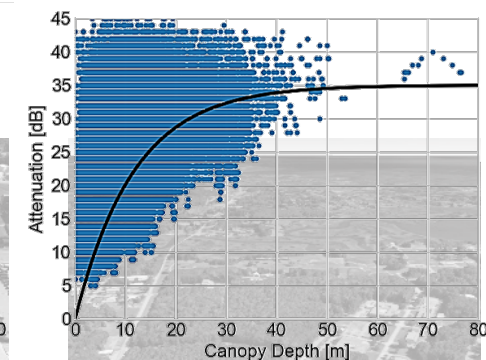
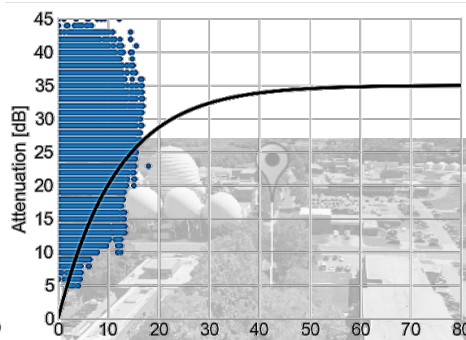
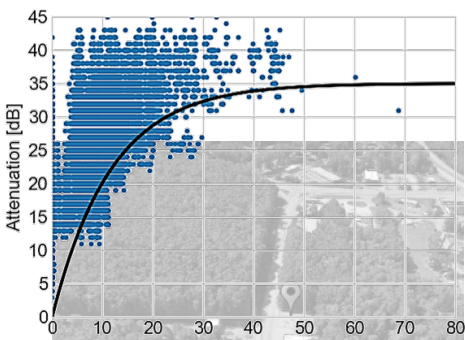
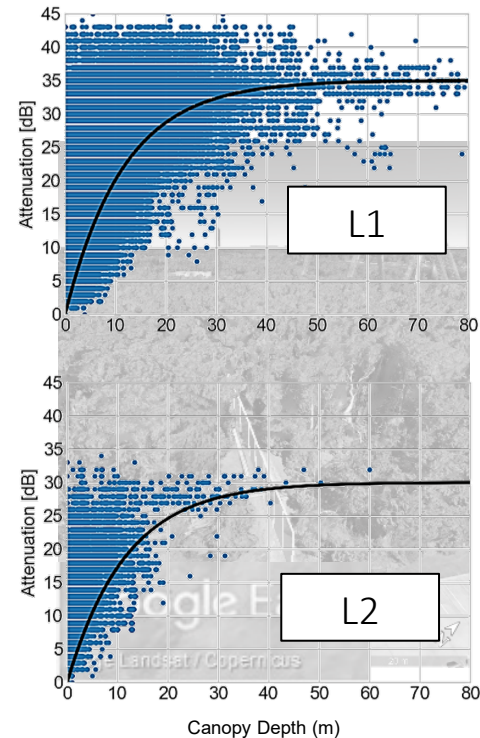
c/N0 vs. foliage depth for the four measurement sites

Pipeline Site (original)

Wythe Creek Site

West Reid Site

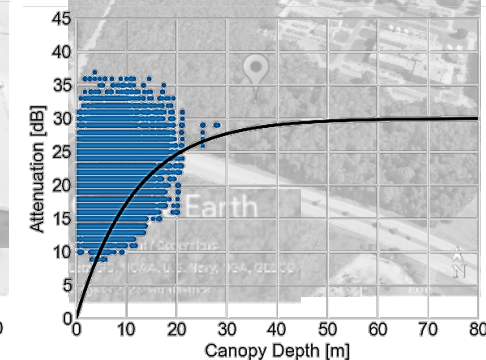
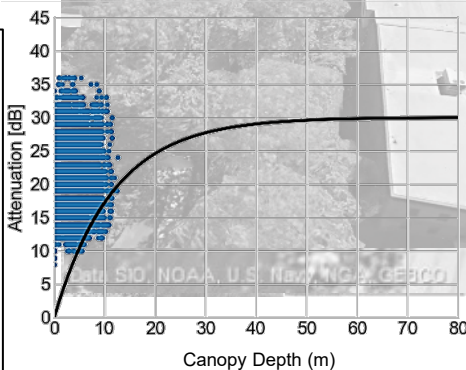
Shepard Site



Replicable result:

- 90% loss @ 20m
- 60% loss @ 10m

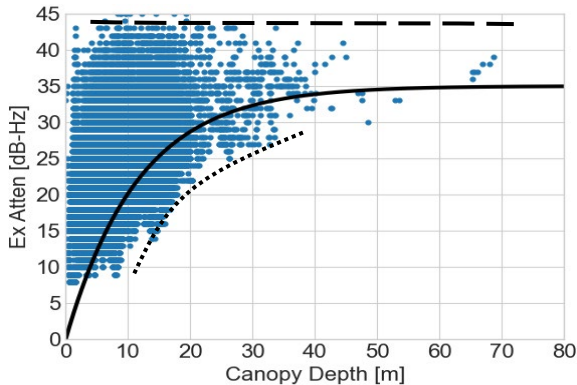
But what is all that noise on y axis? And why does curve tail off?



Fading (interference) explains multiple c/N0 readings

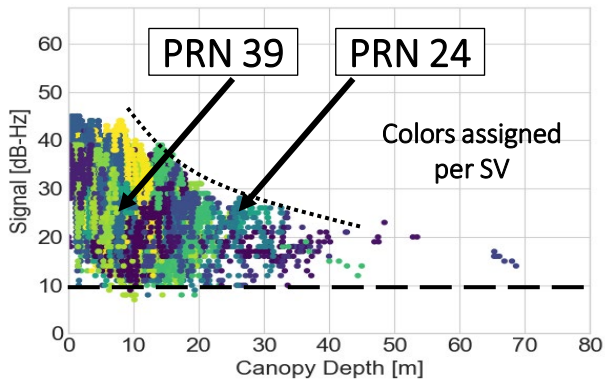
Excess Attenuation

$$A_f = A_m [1 - \exp(-d \gamma / A_m)]$$



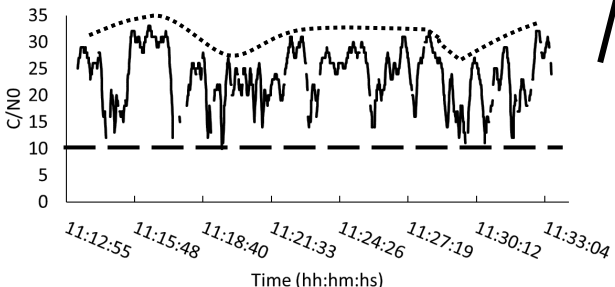
Recorded c/N0 per satellite

$$s = s_{max} * \exp(-k d)$$

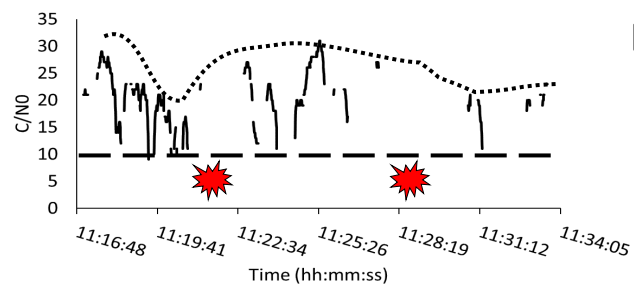


Saturation/narrowing at high canopy depth is due to signal attenuation. With fading, much of the signal drops below the detector minimum of 10 dB-Hz.

PRN 39, ~10m blockage



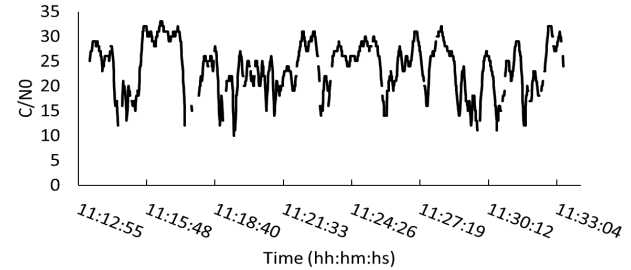
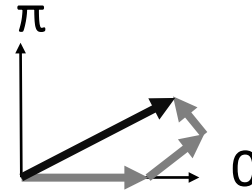
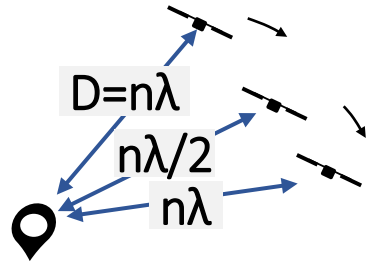
PRN 24, ~25m blockage



Dropouts!

Physics of fading

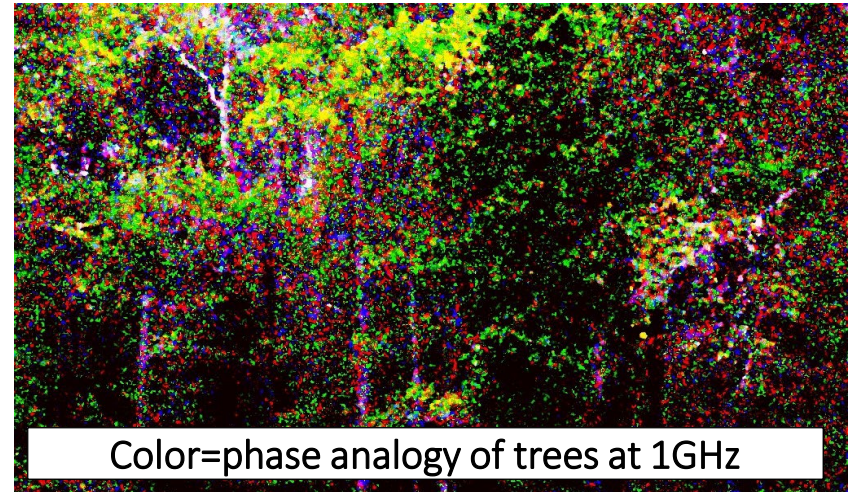
With moving satellites, interference is unavoidable



Moving baseline + complex phase summation = time-varying interference



Trees at pipeline site



Color=phase analogy of trees at 1GHz

Summary

GPS quality was investigated at four wooded locations using

Realistic 3D terrain models from lidar surveys

Intensive geometry computation

As long as measurement data from a reliably located position is used and signal paths that intersect buildings are excluded, results from the technique are consistent across sites.

There is a characteristic GPS attenuation vs. foliage depth curve



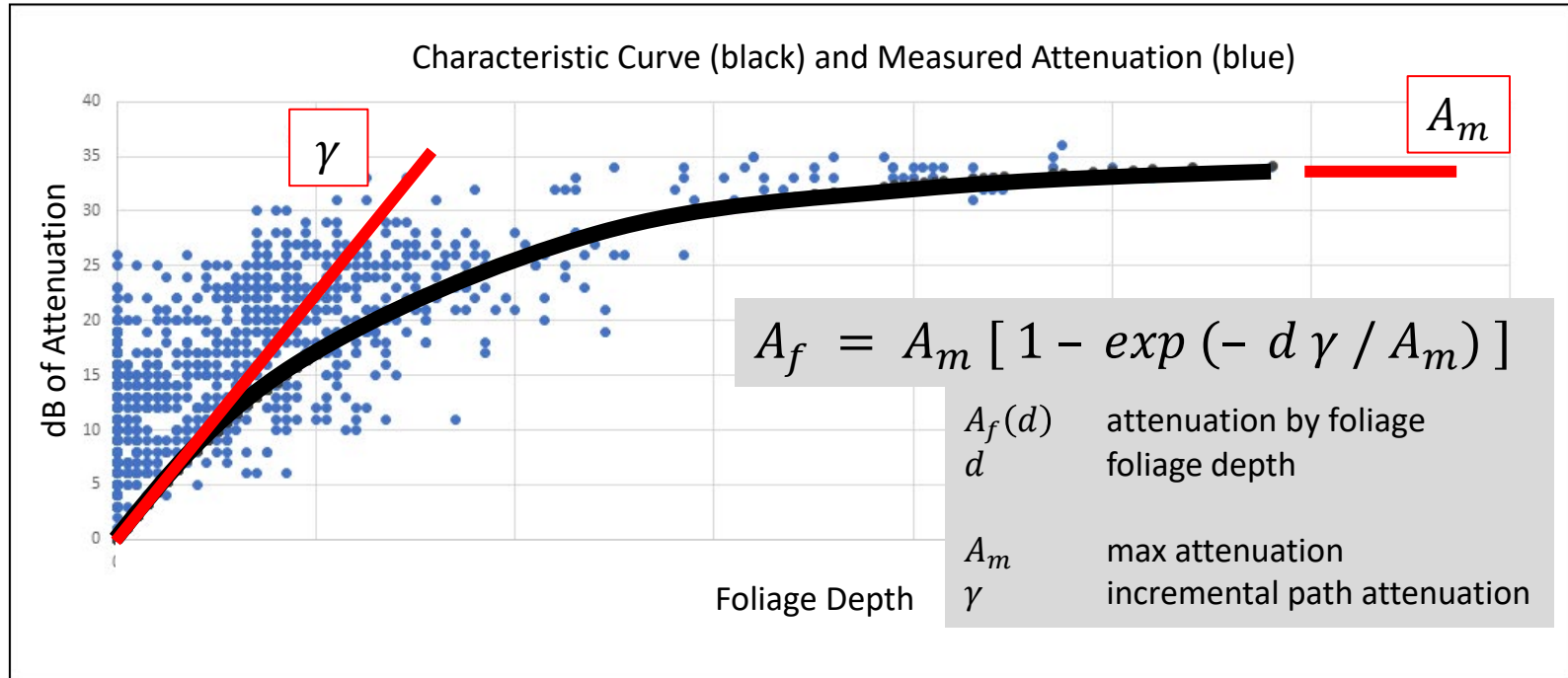
The curve shape is explained by RF fading and receiver detector limits

Conclusion

- ❖ It is possible to estimate **blockage** and **attenuation** impairments to navigation fidelity in urban and arboreal canyons. **Not reflections** though -- yet.
- ❖ Flight ranges in forests can be surveyed to calibrate the severity of GPS attenuation

BACKUP

Initial 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

Sources of error for this new survey method

Listed from most to least severe

1. Ground truth positional error
2. Physics simplification 1: Raycast only; no reflection, diffraction or multipath
3. Imprecise signal strength due to signal fading
4. Receiver-dependent detection threshold
5. Antenna sensitivity vs. elevation assumed uniform
6. Voxel quantization error
7. Physics simplification 2: Season disregarded, in-leaf and out-of-leaf treated the same
8. Positional error in lidar

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

A characteristic curve for GPS attenuation by foliage

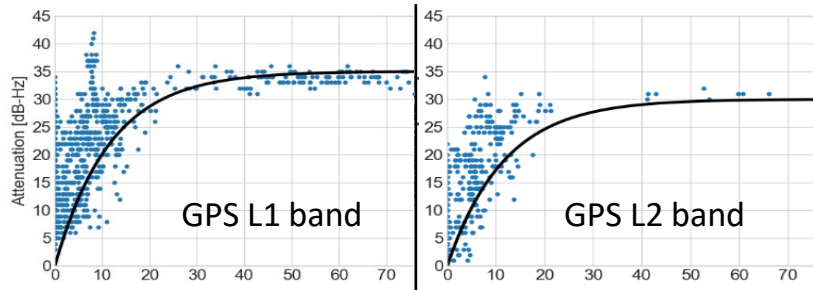
Experimental result

- 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).

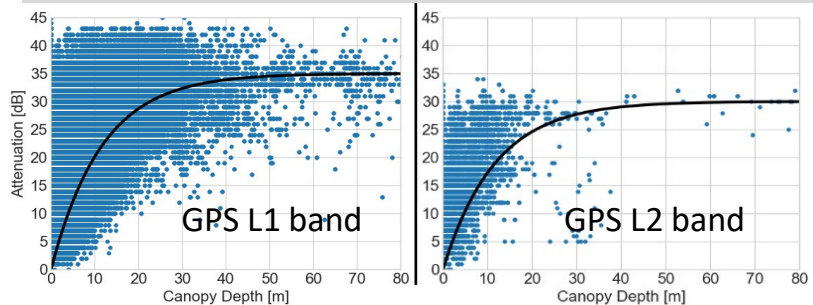
Consistent finding: results follows continuous-wave radio attenuation curve² – but with 10X steeper γ (dB/m)

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

Data from a single recording¹



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

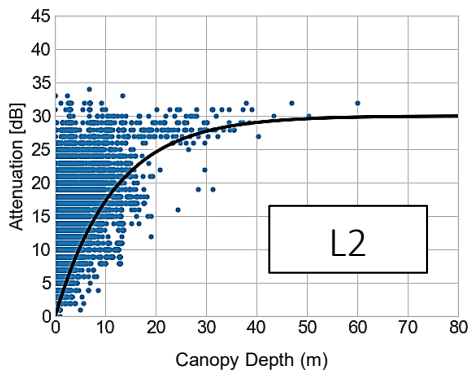
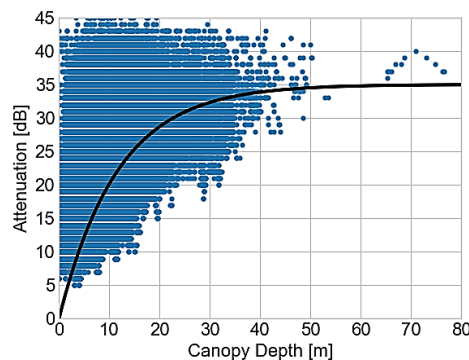
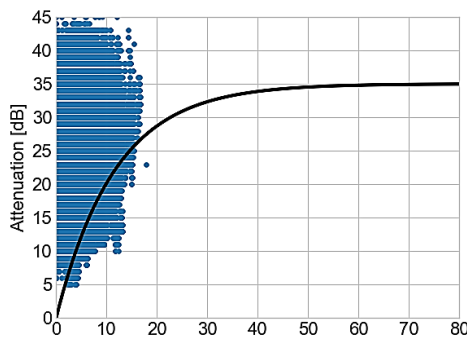
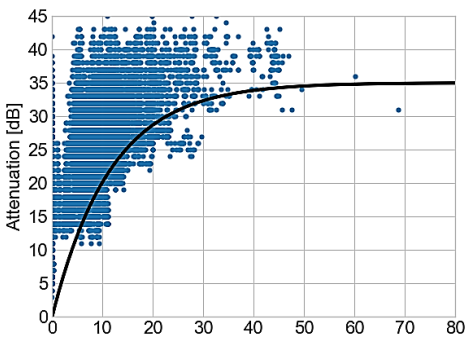
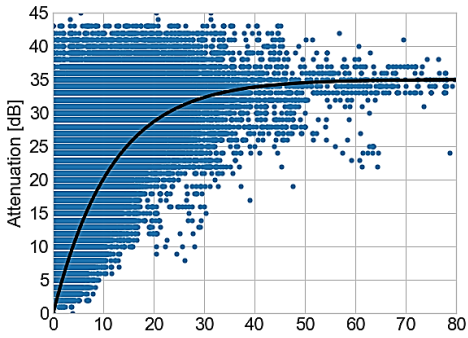
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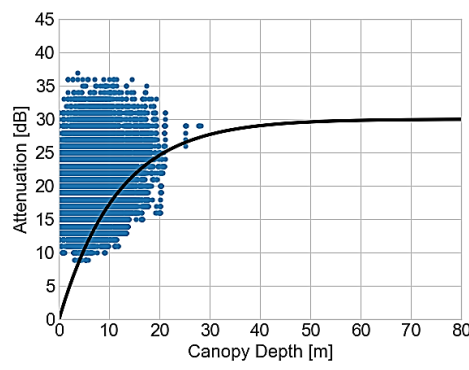
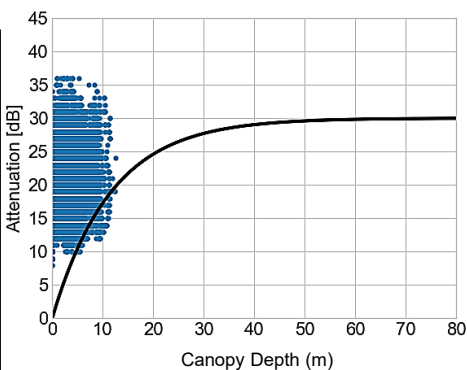
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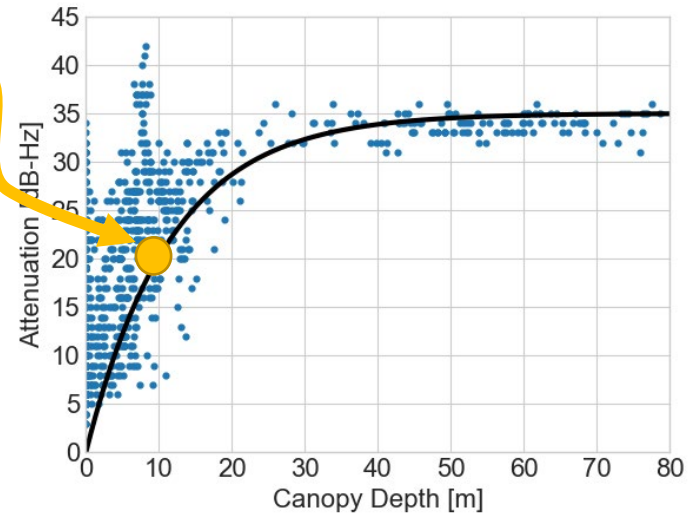
But what is all that noise on y axis?



Implications for flying in arboreal canyons

- *For this mixed hardwood canyon**,
 - 60% of signal lost in first 10m
 - 90% of signal lost in first 20m
- Loss of satellites at low elevation angles greatly impairs horizontal (HDOP) position quality. We observe vertical (VDOP) degradation as well.

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



©Graphics: NASA

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