Driving operational synergies between geodesy, meteorology and climatology

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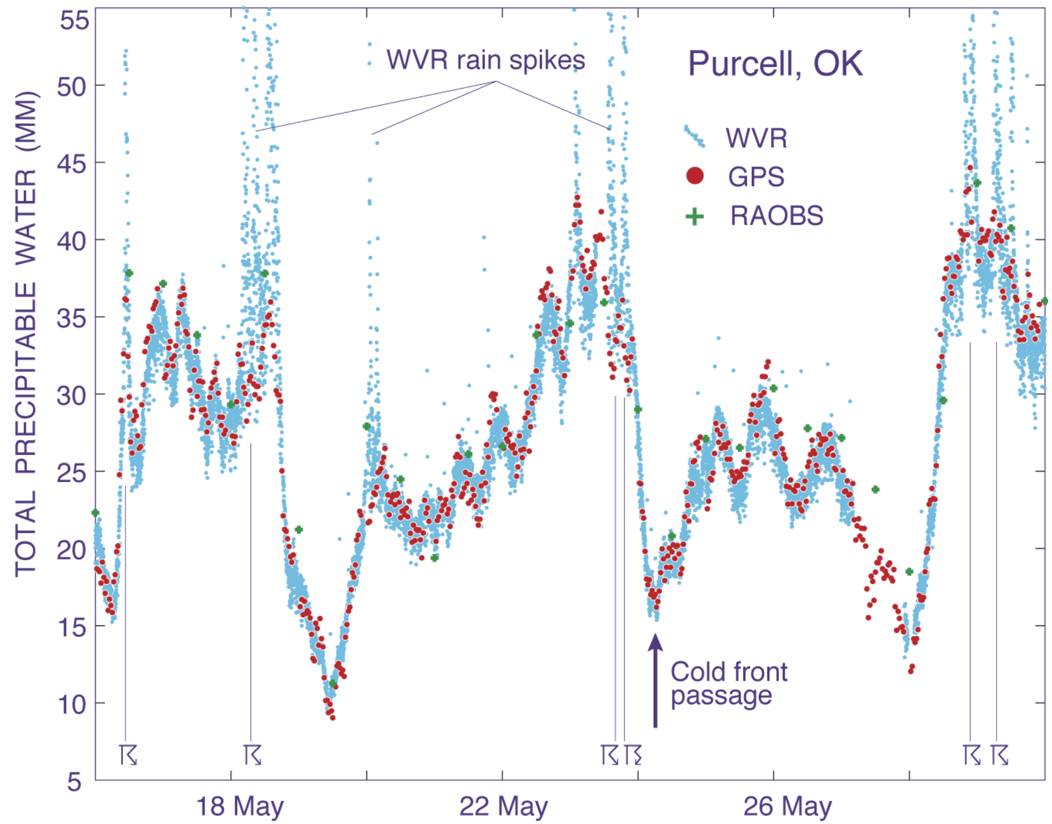
GPS Met proof-of-concept experiment "GPS STORM" (1993)



The Global Positioning System (GPS)

Work on GPS began in early 1970s

The first four GPS satellites were launched in 1978

In 1989 the first commercial hand-held GPS receivers became available

GPS was declared ‘operational’ in 1990 and ‘fully operational’ in 1995

Between 1990 and 1995

- the DOD determined that there was no military application of GPS that required positioning accuracy better than 1 meter. It closed its own geodesy groups, and it led a major US government disinvestment in basic geodetic research
- the geospatial economy began to grow explosively. It now has a global value of at least $ 1 trillion/year
- ground-based GPS meteorology was first proposed in 1992, and successfully demonstrated in 1993

In 1999, GPS technology appeared in a cell phone for the first time. Today 3.5 billion people use GNSS positioning in their cell phones every day.

Themes of this presentation

Geodesy underpins all the other geospatial sciences, geospatial technologies, systems, services and applications

The US geodesy crisis. (google it!)

Using GPS meteorology to illustrate the value of geodesy, and the impending loss of scientific, technological, and practical opportunities as a result of the geodesy crisis

A more productive synergy between geodesy and meteorology in the US can help us drive the future of satellite positioning as well as meteorology and climatology

Structure of this presentation

Some basic meteorology and climatology concepts for geodesists and surveyors

A brief history of GPS and GNSS meteorology

Why did the USA lose its lead in ‘GPS meteorology’ to Europe?

What is the future of satellite positioning (say in 15-20 years) how is it coupled to atmospheric signal delays?

How can we drive a more productive synergy between geodesy, other sciences and technology in the USA?

The US geodesy crisis

See the grass-roots white paper of January 2022

America's loss of capacity and international competitiveness in geodesy, the economic and military implications, and some modes of corrective action

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You can find this position paper on the web (google geodesy crisis), and a recent commentary on it at the Australian website 'Spatial Source'. Or, if you email me at mbevis@gmail.com *, I can send you a copy.*

The geodesy workforce crisis

Geodesists have been warning about the national neglect of geodesy, and an impending workforce crisis, for more than a decade.

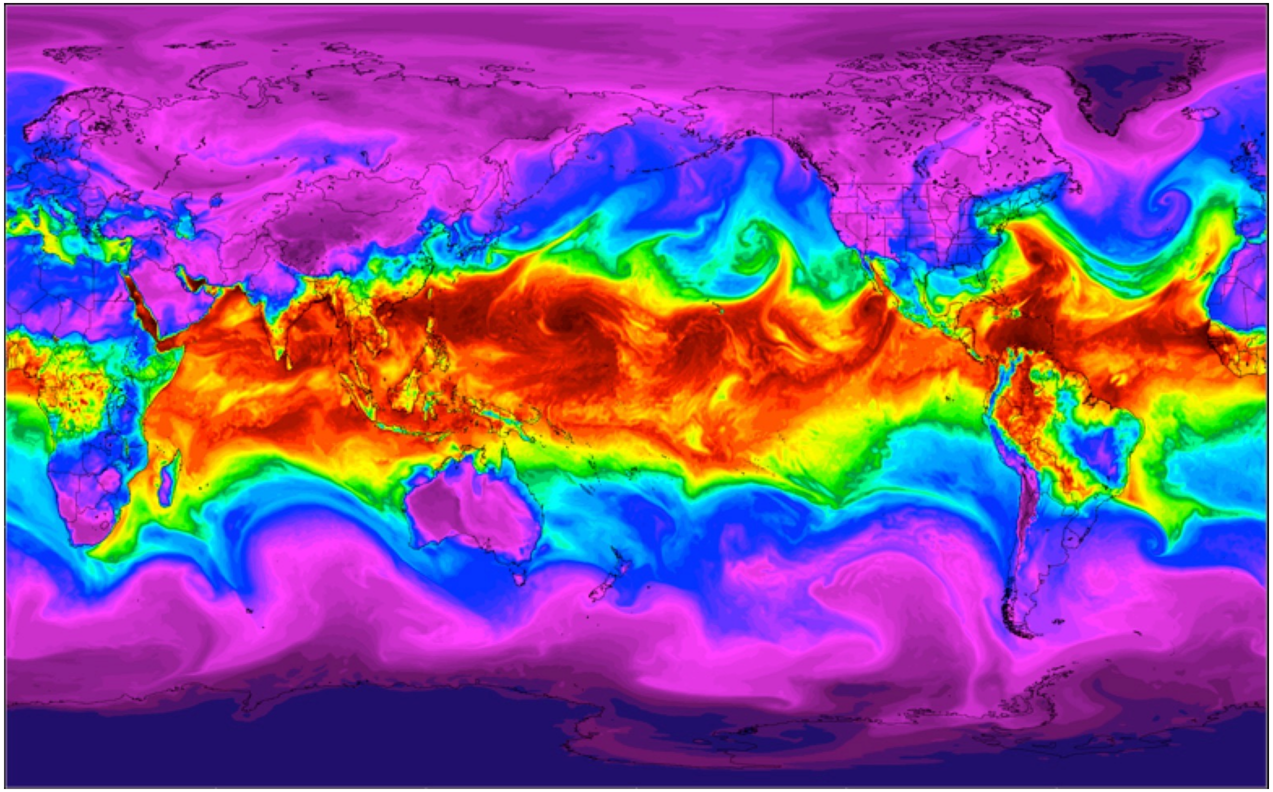
Since the mid-late 1990's, established American geodesists have been retiring more rapidly than American replacements were being trained. NGS, NGA, NASA, USGS and industry now find it very hard to hire American geodesists—because so few exist*.

The disappearance of American geodesists has led to large numbers of young geospatial engineers who are inadequately trained in the scientific underpinnings of their own discipline **.

Tightening accuracy requirements, and a growing emphasis on real-time applications, require constant improvements in geodetic techniques and infrastructure that are increasingly being developed outside of the US.

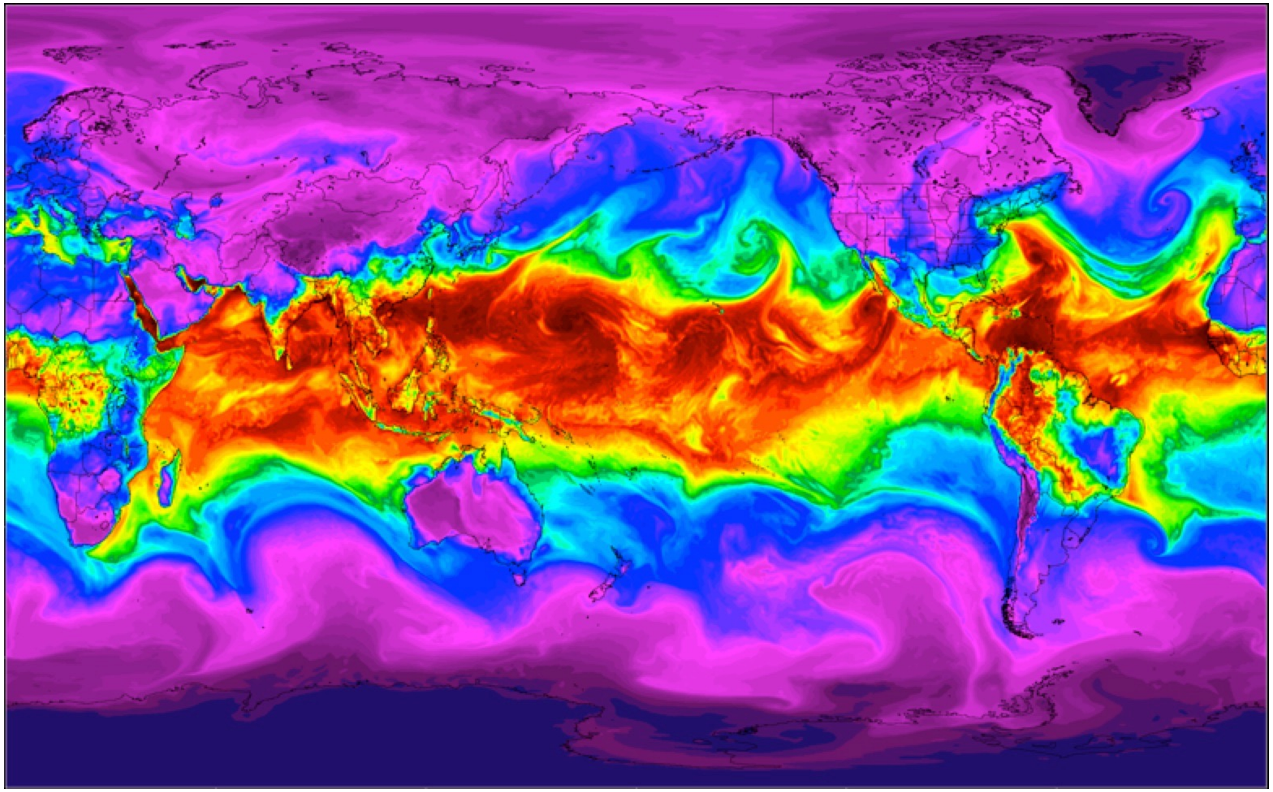
**In 2019, Trevor Greening, CTO of Towill, Inc., a geospatial engineering company, stated: "we have noted that the rapid development of many new technologies has placed a premium on geodetic science knowledge" but "we see graduates insufficiently skilled to comprehend the basis of the new technology including hardware, software, and procedures".

Global atmospheric flow depicted by midlevel water vapor



Water can be solid, liquid or gas under normal atmospheric conditions. The distribution of water vapor is affected by the weather but it also it affects weather. As a result, the distribution of water vapor is highly variable in space and time. This is important, since water vapor carries immense amounts of energy in the form of latent heat, it is a major driver of atmospheric instability, and it is a potent greenhouse gas.

Global atmospheric flow depicted by midlevel water vapor



It is difficult to overstate the importance of water vapor in weather or in the climate system.

Lack of understanding of water vapor distribution is a <u>major</u> source of error in numerical weather prediction.

Climate change is not just about global warming, but also about intensification of the water cycle (more intense storms, more flooding, more droughts, etc) driven by warming.

Atmospheric Refractivity

GPS signals are delayed by the atmosphere because microwaves travel more slowly in air than in a vacuum, and because the atmosphere bends the signal path, increasing its length. Both effects are caused by a variable index of refraction, *n*.

The delay in signal arrival time can be stated as an equivalent increase in path length. This excess path length ΔL is given by

$$\Delta L = \int_L [n(s) - 1]\, ds + [S - G]$$

where *L* is the curved ray path, *S* is the path length along *L*, *s* is distance along that path, and *G* is the length of the straight path that would be taken if the atmosphere was absent.

It is common to restate this equation by defining refractivity $N = 10^6 (n-1)$

There are a number of formulas relating microwave refractivity to air temperature, pressure and humidity, and perhaps the most widely used expression is

$$N = k_1 \frac{P_d}{T} + k_2 \frac{P_v}{T} + k_3 \frac{P_v}{T^2}$$

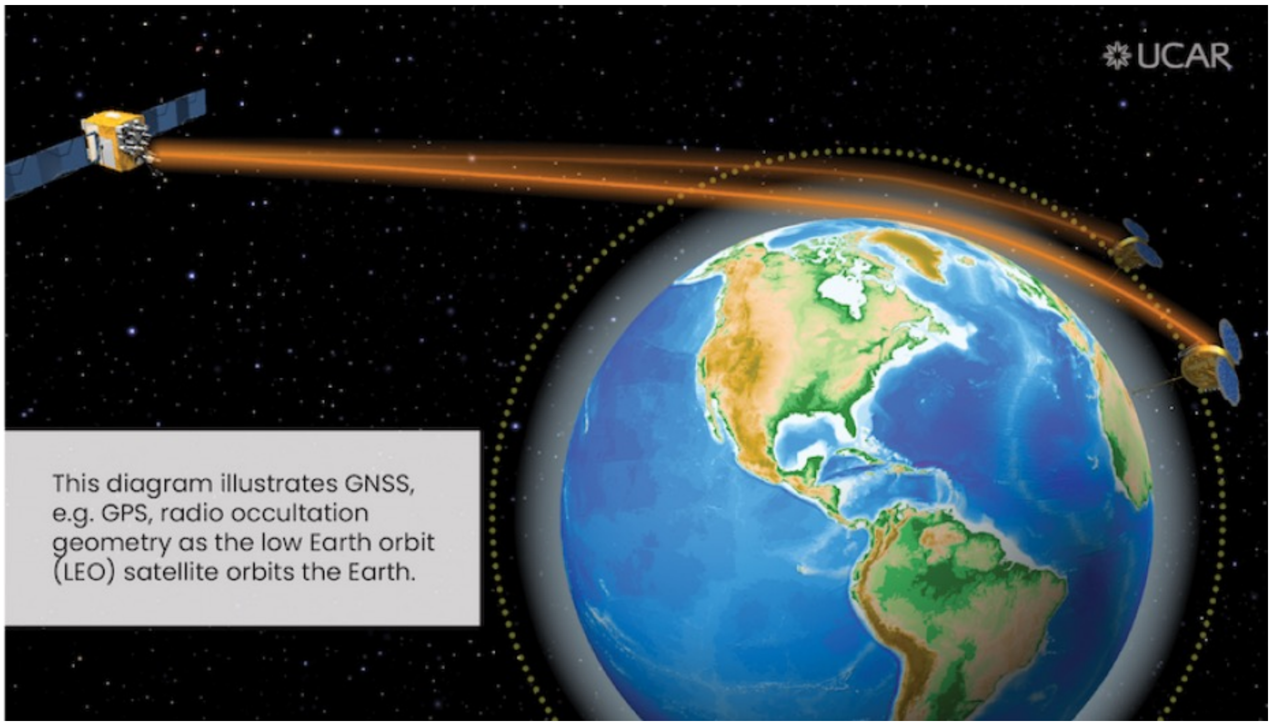
where P_d and P_v are the partial pressures of dry air and water vapor, respectively, and T is absolute temperature.

The constants k_1 , k_2 and k_3 are determined using lab measurements.

It is possible to sense atmospheric refractivity using ground-based or space-based GPS and GNSS techniques. The space-based approach is also referred to as the **radio occultation** or limb sounding method, as exemplified by the COSMIC mission.

Space-based GPS Meteorology

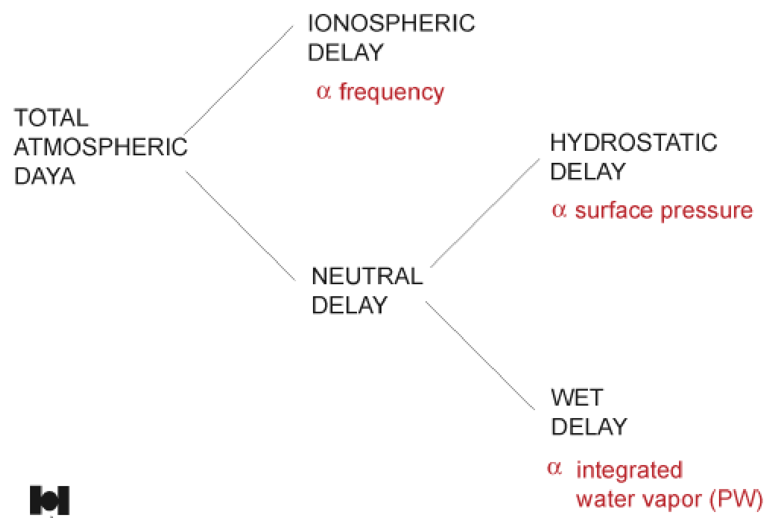
Radio occultation (RO)
or 'limb sounding' techniques (e.g. COSMIC, COSMIC-2)

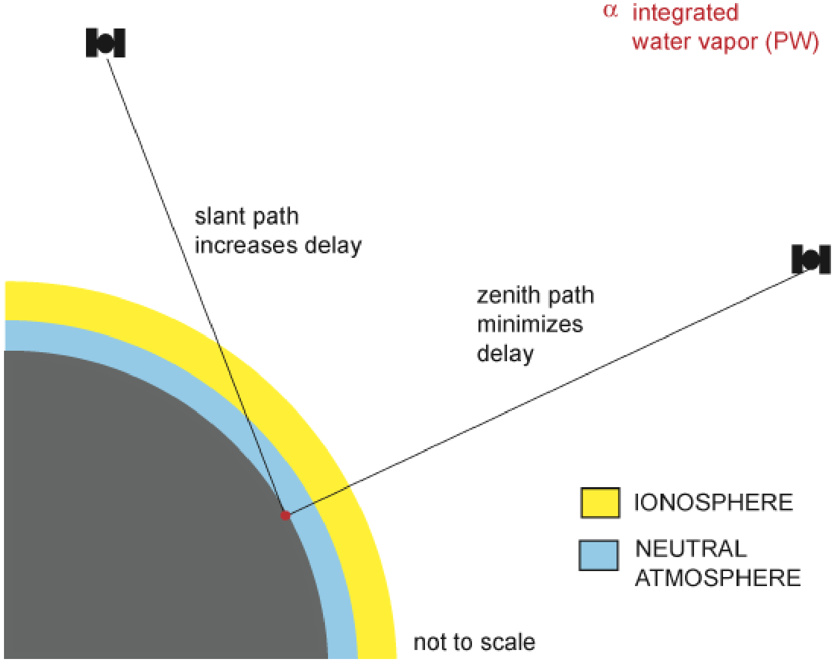


Radio occultation data are obtained by observing signals from the Global Navigation Satellite System (GNSS) using LEO satellites. The path of such signals crossing the atmosphere is bent as a result of refraction, and the bending angle provides information on the atmospheres refractivity structure and hence on the vertical distribution of atmospheric pressure, temperature and humidity. Such occultation events take about 3 minutes.

Ground-based GPS Meteorology

STRUCTURE OF THE GPS SIGNAL DELAY

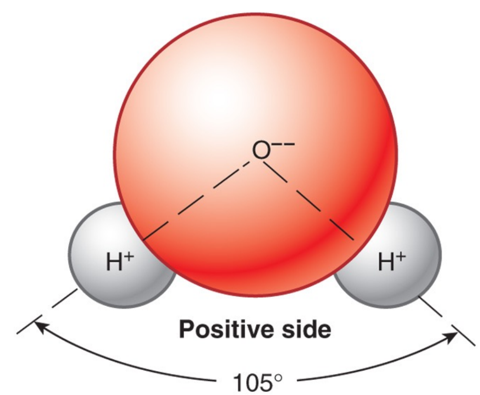




The hydrostatic delay is associated with the *induced* dipole moment of all atmospheric components (including water vapor).

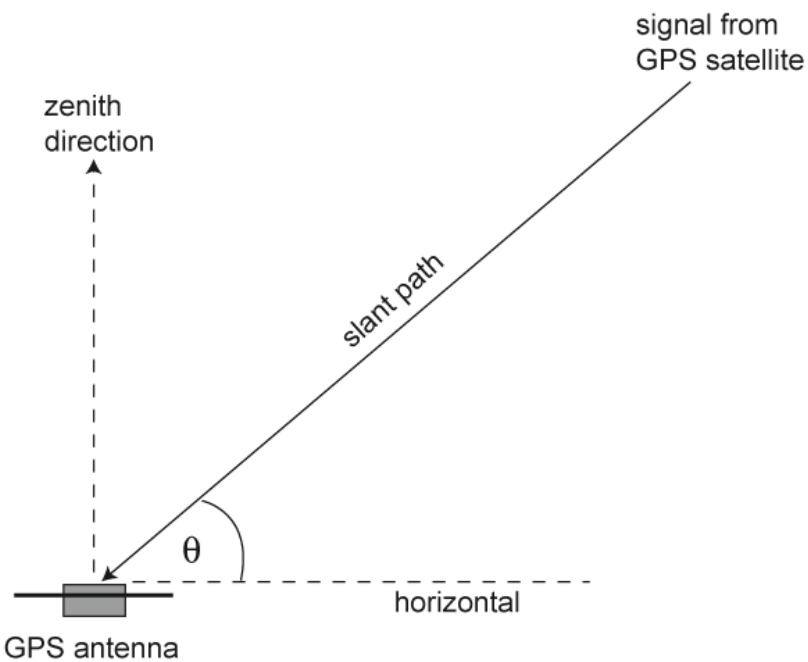
The wet delay is associated with the *permanent* dipole moment of water vapor.

The polar structure of the water molecule endows it with many extraordinary properties



including high heat capacity, extremely high latent heat and its potency as a Greenhouse gas.

ZENITH DELAY, SLANT DELAY & THE MAPPING FUNCTION



The neutral atmospheric delay D(θ) for a GPS signal path with elevation angle θ, can be expressed by the equation:

$$D(\theta) = Z\, m(\theta)$$

where Z is called the zenith delay parameter, and represents the delay that would be associated with a satellite located directly above the GPS station (i.e. in the zenith direction, θ = 90°).

The function m(θ) is called a mapping function since it maps the zenith delay onto the pointed delay D(θ).

For a flat earth with a laterally homogenous atmosphere m(θ) = cosec(θ). Since earth and its atmosphere is curved, the mapping function is more complicated that this.

GROUND-BASED GPS MET

The simplified form of the mapping equation shows how a GPS (or GNSS) stations can estimate the local zenith delay parameter, Z. The station senses all the slant delays D_i to *n* satellites, each of which is at a known elevation angle θ_i. So, the value of Z is overdetermined.

Since the zenith delay changes over time, it is usual to estimate Z every 5 - 60 minutes.

Space geodesists estimated zenith delays long before GPS meteorology was invented in 1992. This is because a typical value of Z is 2.3 meters, and slant delays D will be larger than that. So, if these huge delays are not accounted for, they will mess up mm-level geodetic positioning. These delay parameters were 'nuisance parameters'.

If we did GPS on the moon, we would not need to estimate atmospheric delay parameters.

ZENITH DELAYS

Delay due to the neutral atmosphere is parameterized in terms of zenith delay parameters

Zenith Neutral Delay = ZND or Z_n
Zenith Hydrostatic Delay = ZHD or Z_h
Zenith Wet Delay = ZND or Z_w

ZND = ZHD + ZWD

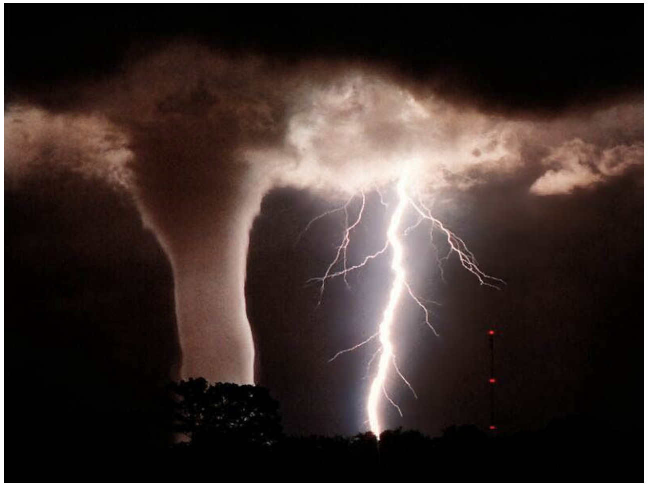
Delays are usually stated in length units (i.e. as equivalent excess path lenghts). Conversion factor is the speed of light.

ZHD is typically ~ 2.3 m at sea level, but it decreases with increasing station height.

ZWD is much smaller, but much more variable in space and time. Some typical values:

Near the eye of a hurricane	70 cm
Subtropical ocean environment	40 cm
Typical mid-latitude	10 – 30 cm
Arctic desert	< 1 cm

Note: ZND is also known as ZPD and ZTD.



The strategy of ground-based GPS Met in the late 1990’s:

Estimate ZND using GPS, compute ZHD using surface pressure, and find

ZWD = ZND – ZHD.

Then convert ZWD into PW.

Today it is more common to assimilate ZND directly into NWMs (along with any coincident measurements of surface pressure).

Mapping functions used in geodesy

$$D = Zm(\theta)$$

$$D = Z_w m_w(\theta) + Z_h m_h(\theta)$$

More complex expressions also parameterize the azimuthal asymmetry of the neutral delay (MacMillan, 1995; Chen and Herring, 1997; Qiu et al., 2020) by adding delay gradient parameters.

Quantity	Abbreviation	Symbol
Zenith wet delay	ZWD	Z_w
Zenith hydrostatic delay	ZHD	Z_h
Zenith neutral delay	ZND	Z_n
Zenith delay (nonspecific)		Z
Satellite elevation angle		θ
Wet mapping function		$m_w(\theta)$
Hydrostatic mapping function		$m_h(\theta)$
Neutral mapping function		$m_n(\theta)$
Mapping function (nonspecific)		$m(\theta)$
Precipitable water	PW	PW

In the 1990s, ground-based GPS meteorology involved using GPS to sense Z, isolate the wet delay Z_w, and transform Z_w to PW (the total vertical column water vapor content of the atmosphere, expressed as the height of an equivalent column of liquid water). This last transformation has the form

$$PW = \Pi Z_w$$

Where $\Pi = f(T_s)$ to a good approximation (Bevis et al., 1992; 1994)

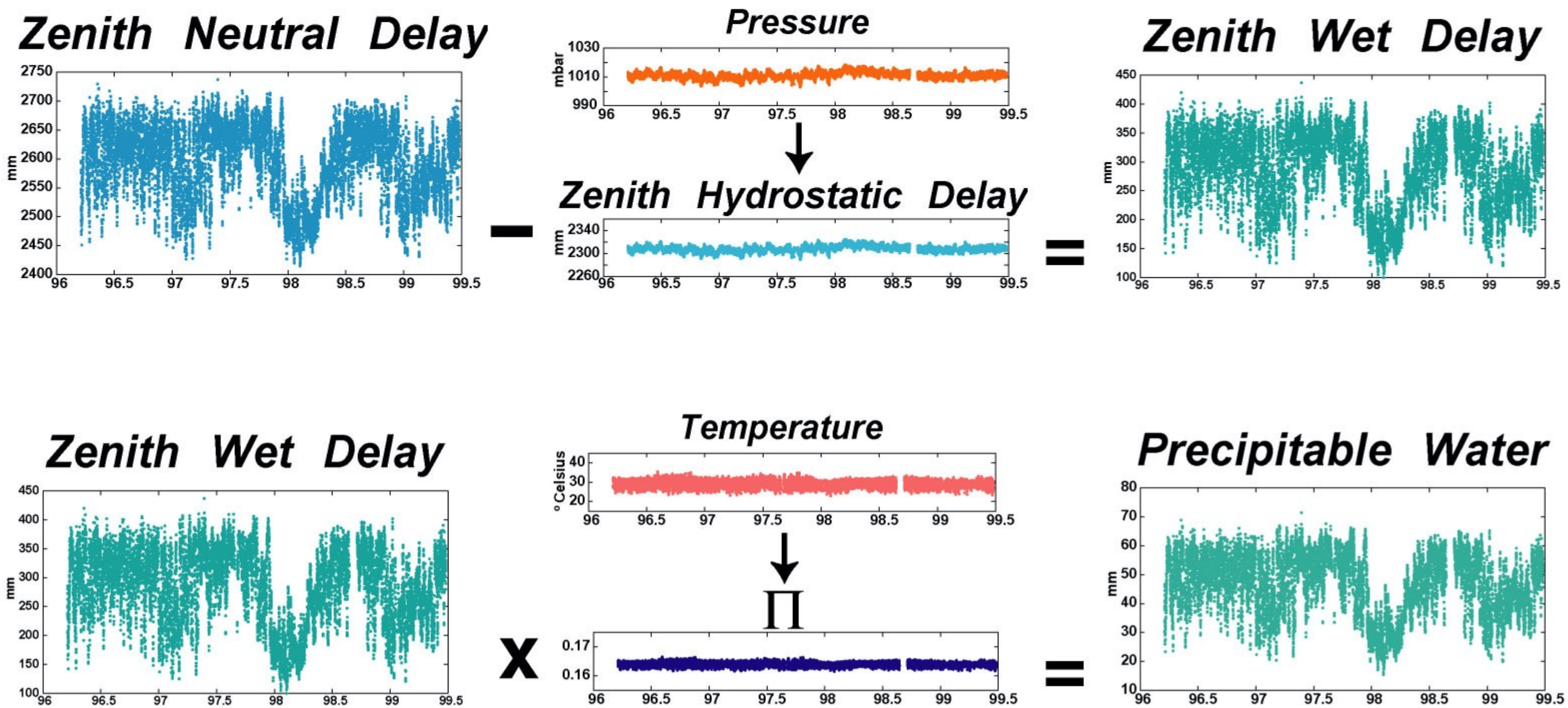
RULES OF THUMB:

(when PW and Z_W are expressed in the same length units)

$Z_w \sim 6.5$ PW

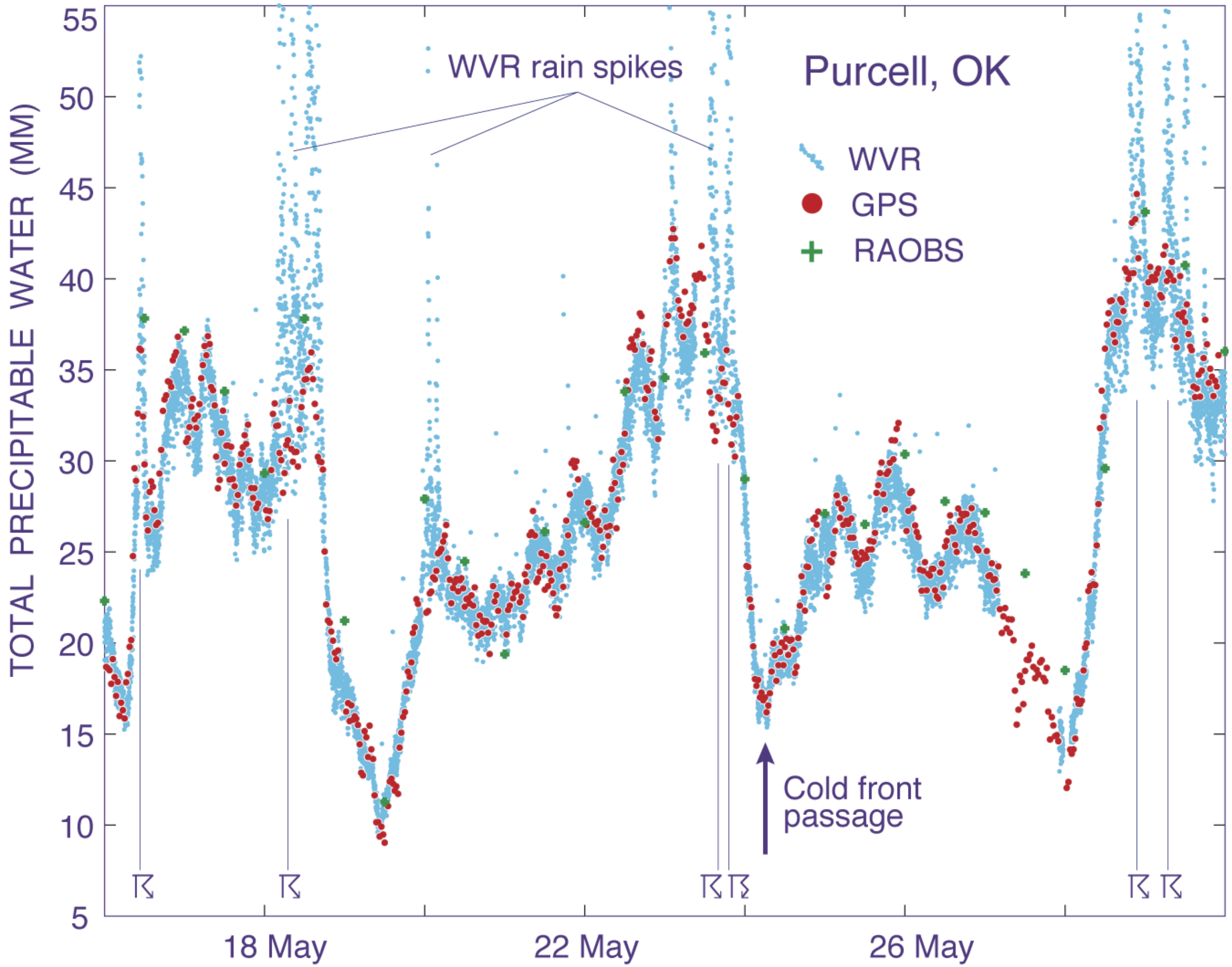
PW ~ 0.15 Z_w

Transformations of GPS Meteorology



PW estimated in this way, is sometimes referred to as GPS PW or GNSS PW. Early attempts to use GPS to assist numerical weather models (NWM) focused on ingesting GPS PW. But eventually it was realized that it was better to assimilate the ZND and collocated pressure measurements separately, and allow the NWM to constrainwater vapor implicitly (and internally), using all of the physics captured by the model.

Proof of Concept Experiment: 'GPS STORM' May 1993



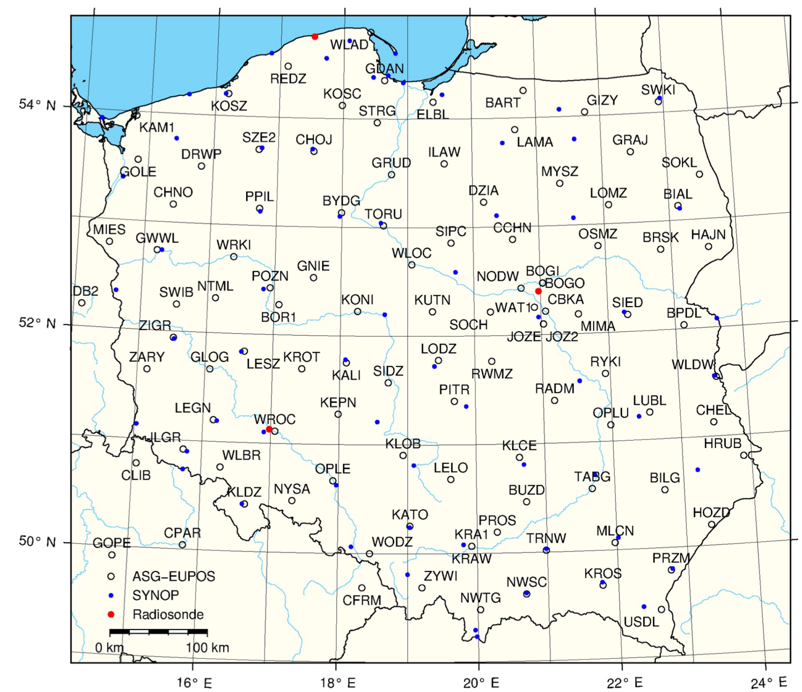
after Duan et al. (1996)

Variational Assimilation of GNSS Delay Parameters

When 4DVAR is used to assimilate GNSS products (typically ZND), it usually leads to improved predictions for precipitation and often for other atmospheric variables such as surface temperature or RH (e.g. Bonniface et al., 2009; Yan et al., 2009a,b; Bauer et al, 2011; Bennitt and Jupp, 2012; Kawabata et al., 2013; Mahfouf et al., 2015; Shoji, 2015; Lindskog et al., 2017; Hdidou et al., 2020; Giannaros et al., 2020; Wagner et al, 2022).

Example: Rohm et al. (2019) assimilated GNSS estimates of ZTD (or ZND) in Poland, along with conventional surface met observations (SYNOP) and radiosonde profiles, into the regional NWM model WRF, using 4DVAR.

They concluded that the GNSS observations improved forecasts in the first 24 h, with the strongest impact starting from a 9 h lead time. The relative humidity forecast in a vertical profile after assimilation of ZTD had a > 20 % decrease of mean error starting from 2.5 km upward.



3DVAR and 4DVAR assimilation schemes extract greater advantage from GNSS troposphere products than did earlier (2000-2010) schemes based on Rapid Update Cycles. ECMWF routinely assimilates GPS delay parameters into their model, as do several national weather agencies.

A brief and rough history of ground-based GPS Met

The original concept was developed and published in 1992. The demonstration project GPS STORM was mounted in May ‘93. This GPS data was used by 4 US university groups to refine the algorithms used to estimate and validate GPS PW. This process was largely completed by 1996.

Late 90’s - early 2000’s Seth Gutman of NOAA FSL develops and runs a much larger GPS Met demonstration network. Only a few geodesists were involved. Data assimilation was mostly via RUC. Only modest improvements in NWM prediction skill were found.

Late 90’s – early 2000’s Japan developed a very large GPS Met project involving more than a dozen universities, GSI (their NGS) which owns a > 1,000 station GPS network called GEONET, and JMA, their equivalent of the NWS.

2000-2010. European geodesists and meteorological agencies form the project E-GVAP. GPS/GNSS data was collected in NRT from all across Europe, it was analyzed simultaneously by many geodetic analysis centers, and a weighted mean time series was provided to the meteorological agencies with a latency of ~ 30 minutes. The delay products were assimilated into operational NWMs run by ECMWF, the UK Met Office, Meteo France and by other national agencies. They emphasized 3DVAR and 4DVAR assimilation techniques from the beginning.

2010-2020 The European collaboration could document that GPS data assimilation significant improvements in the predictive skill of their NWMs. The European literature on GPS Met now dwarfed the US literature.

2015-2022 There has been an explosion of Chinese research on GPS Met. Many different university groups are funded, much along the lines seen in Japan and then Europe.

A brief and rough history of ground-based GPS Met

Since about 2010, Europe has taken a very large lead on GPS meteorology, even though it was developed and first demonstrated in the USA.

Now China is taking large strides and is publishing much more than US scientists in this field. At the rate the Chinese literature is growing, it may soon exceed Europe's.

Why did Europe do some much better than the USA?

The European collaboration was well funded, and it involved a great many geodesy groups, mostly located in academia, as well as multiple meteorological agencies. They copied the geodetic MO of the orbit analysis centers of the IGS.

Once GPS Met was demonstrated, NSF lost interest in the field, and NOAA funding was limited and rather restricted. The US GPS community was shrinking as the European community was growing. This was a mistake given the difficulty of the task.

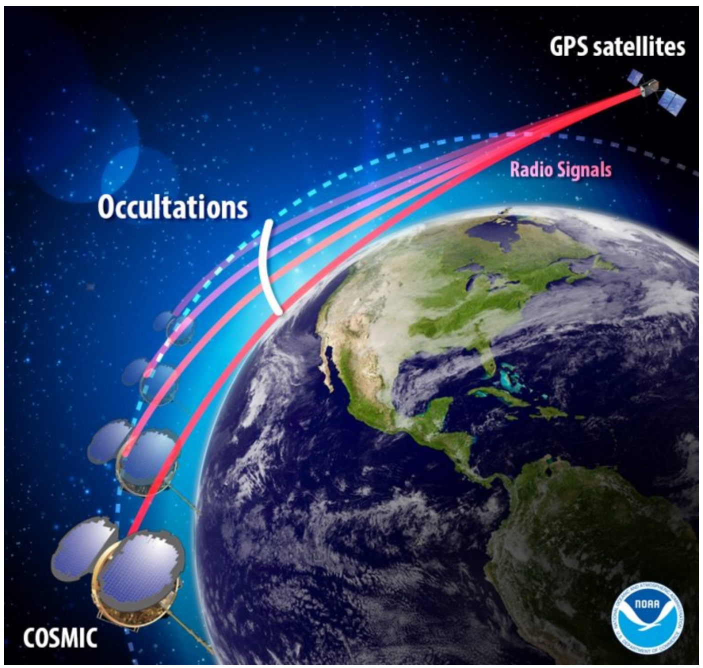
The European meteorologists emphasized 3DVAR, 4DVAR data assimilation techniques from the beginning (and eventually Ensemble 4DVAR). (They did this to assimilate all observations, not just GNSS products). They demonstrated enhanced prediction skill.

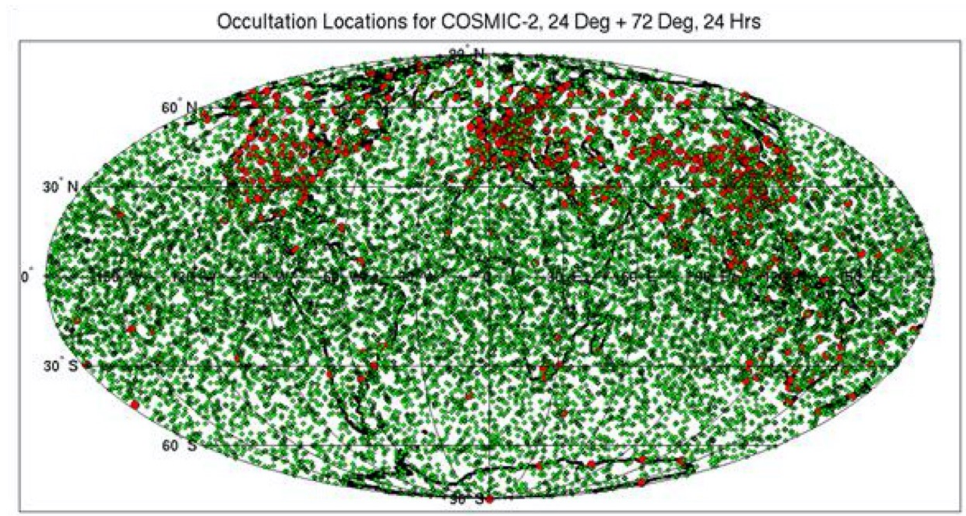
Question
Why did NOAA and NWS fail to engage with NGS to develop GPS Met along the lines seen in Europe? RT GPS/GNSS networks have many applications, including Met.

Radio Occultation Techniques (GNSS-RO)

The Cosmic-2 constellation, presently in operational phase A, has 6 LEO satellites, producing about 5,000 occultations per day between 40 N and 40 S.

The phase B deployment, now cancelled, would have added 6 more LEO satellites in polar orbits, so that the number of occultations would have increased to about 10,000/day, with global coverage.





If Cosmic-2 had completed its phase B (polar) deployments it would have produced about 10,000 events per day allow sensing of the *entire* atmosphere. Each occultation event takes ~ 3-minutes.

Imagine a mega-constellation of LEO satellites like Space-X's Starlink (with many thousands of satellites) equipped for GNSS-RO. There would be millions of occultations per day! It would be possible to characterize the entire atmosphere in 15 – 30 minutes.

The future of satellite positioning

I share a view quite commonly held by European and Chinese geodesists, that the future of satellite positioning will combine an evolved version of our existing GNSS constellations and a mega-constellation of small LEO satellites.

Consider a very large LEO constellation (cf. Starlink), with very sophisticated communications, whose satellites can receive GNSS signals and also range to each other using radio links and/or pointed laser beams. Since the LEO satellites lie above the atmosphere it should be possible to position them to ~ 1 mm in real-time.

If the system can use ground-based GPS met techniques, and the millions of radio occultations per day for limb sounding (cf. COSMIC), it should be possible to image the entire atmosphere with a temporal resolution of 15 - 30 minutes, and use a state space representation of atmospheric refractivity structure to position ground-based users against the LEO constellation with only a minor loss of real-time positioning accuracy.

This agenda would receive additional support if the LEO satellites could also receive DORIS-like signals from ground-based telecomm towers (there are ~ 4 million, now).

Because space-time variability of the neutral delay is dominated by water vapor, and lack of knowledge of water vapor distribution is the single biggest cause of weather model prediction error, such a positioning system would revolutionize operational meteorology, and have a major impact on climate studies too.

Next Gen Satellite Positioning using LEO Mega-Constellations

Consider the advantages of this class of satellite positioning:

Since the LEO constellation would have high-speed, internet-like communication capabilities
- its navigational users could communicate their ultra-accurate positions in real-time
- the system could support a wide range of encryption strategies, and implement a wide variety of access controls
- the LEO satellite signals would be far stronger at ground-level than GNSS signals, so they would be harder to jam or spoof

If the LEO satellites were equipped with downwards pointing antennas, they could acquire and communicate reflected signals, allowing the system to probe terrestrial surface state (e.g. soil humidity, or ice surface melt), sea state, etc.

By virtue of its real-time accuracy and its two-way comms the system could improve the performance of existing geospatial systems (e.g. improve airborne LIDAR or gravity surveys by improving the positioning of the aircraft or drone), allow buoys to better sense tsunamis, or geodetic stations on land to improve warnings of volcanic deformation or earthquake early warning. Collision avoidance systems could be turbo-charged as well.

Such a system would probably support hundreds of new scientific, engineering, military and commercial applications that we are presently incapable of imagining. Its value would be assessed in trillions of dollars.

The US Geodesy Crisis

If the US cannot solve the geodesy crisis in academia, the NGS, NASA, the DOD, etc., it seems very likely to me that next generation satellite positioning systems will be dominated by Europe and China, and that their impact on operational weather analysis and prediction will be better exploited there, as well.

This is only one area of science in which the US geodesy crisis will cause a loss of US competitiveness in geospatial technologies and applications. This crisis threatened US participation in the global geospatial economy and our national security.

In my recent presentation to the National Geospatial Advisory Committee (NGAC) I described how major advances in gravity modeling are needed to improve inertial navigation and global networking of modern atomic clocks and timing systems. (You can email me at mbevis@gmail.com if you would like a copy of that talk.

Thank you.