UNIDATA AND THE SYNERGY BETWEEN GEODESY AND METEOROLOGY

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WHY GEODESY?

• UNIDATA wishes to expand it services beyond its traditional core discipline - meteorology - but can't obtain a lot of additional resources to drive this expansion.

• It should therefore prioritize new disciplines (such as hydrology and geodesy) that readily synergize with UNIDATA's meteorological expertise and services. That is, UNIDATA should choose target areas with high impact/cost ratios.

• Geodesy is already playing a significant role in weather analysis and water vapor climatology, but these connections and benefits could be intensified and expanded.

• Geodesy plays an important infrastructural role many geosciences, including glaciology, hydrology, oceanography, geomorphology, seismology, tectonics, and space physics. In most cases these roles are steadily expanding. Helping geodesy implies helping (and connecting to) a wide range of geosciences.

• While past interactions between geodesy and meteorology were focused on geodesy serving meteorology, geodesists could really use some help from the meteorological community and UNIDATA. Mutually beneficial relationships have more staying power. Geodesy needs more meteorological input.

• If meteorology improved its support of geodesy, geodesy could improve its support of meteorology. Major benefits would arise from coupling numerical weather models and operational GPS geodesy in nearly real-time.

• GPS networks are rapidly expanding worldwide, and most of the data is 'free'.

Geodesy plays a vital infrastructural role in many geosciences, including activities with obvious connections to meteorology and climatology:

- Modern ice mass balance studies
  - Improving the ‘PGR correction’ for GRACE
  - ‘Weighing’ the ice sheets directly with GPS
  - Airborne LIDAR measurements (kinematic GPS)
    - including dH/dt for glaciers and ice sheets

- Surface water hydrology
  - Kinematic GPS for hydrological (river) gradients
  - ‘Weighing’ river basins using GPS
  - Reference frame for altimetry of continental surface water

- Oceanography
  - Absolute versus relative sea level change
  - Refining geoid models

- Paleoclimatology
  - Measuring the postglacial rebound field place constraints on ice history.

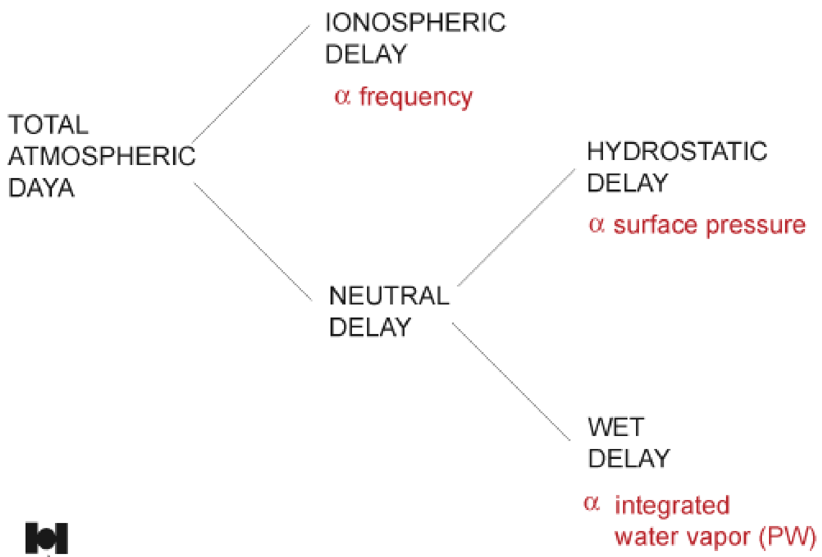
- Ionospheric physics
  - TEC determination, observing TIDs, space weather, etc.

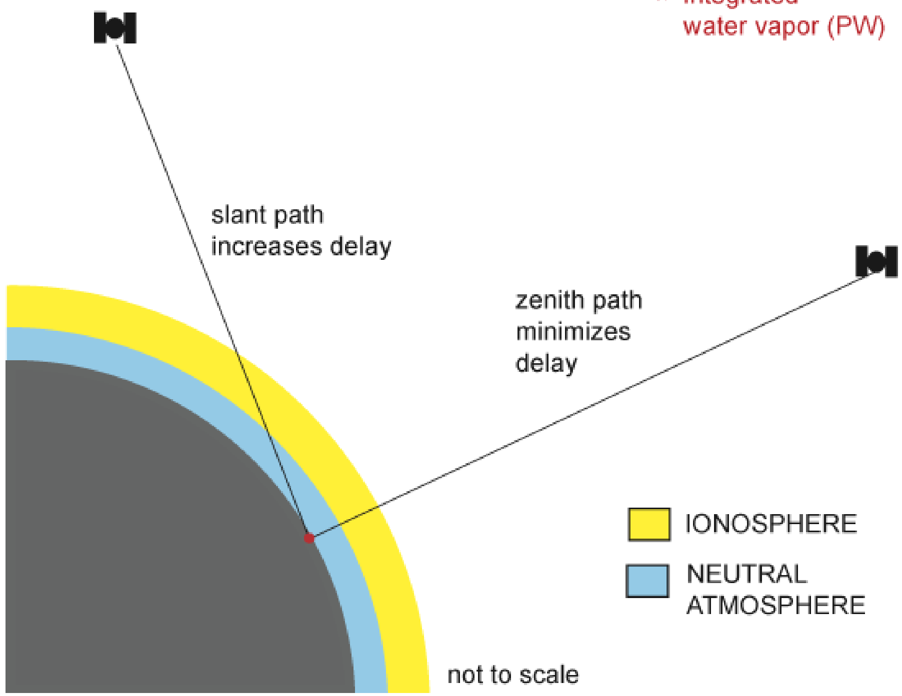
The Basics of Ground-Based

GPS Met

THE BASICS OF GPS MET

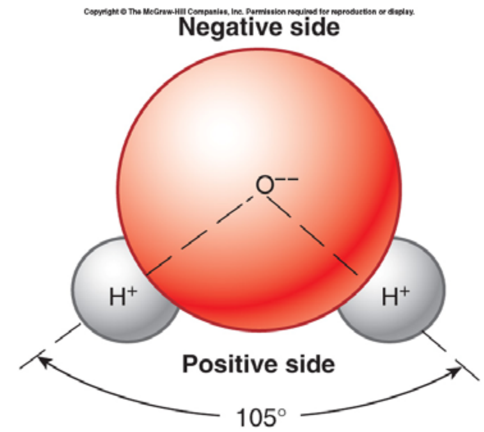
STRUCTURE OF THE GPS SIGNAL DELAY





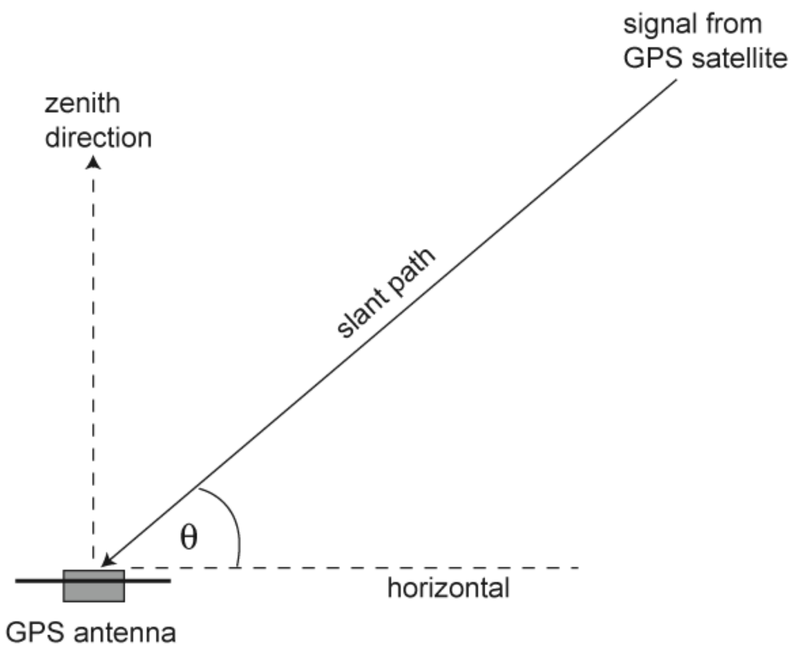
The hydrostatic delay is associated with the *induced* dipole moment of all atmospheric components (including water vapor).

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



The polar structure of the water molecule endows it with other extraordinary properties, including very high heat capacity and very high latent heats - properties that explain the critical roles that water vapor plays in both weather and climate.

ZENITH DELAY, SLANT DELAY & THE MAPPING FUNCTION



The neutral atmospheric delay $D(\theta)$ 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, $\theta = 90°$).

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

For a flat earth with a laterally homogenous atmosphere $m(\theta) = \text{cosec}(\theta)$. Since earth and its atmosphere is curved, the mapping function is more complicated that this.

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 meters at sea level, but decreases with height

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

near the eye of a hurricane	70 cm
subtropical ocean environment	40 cm
typical midlatitude	10 - 30 cm
artic desert	<1 cm

NASA/JPL

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Mapping functions used in geodesy

$$D = Zm(\theta)$$

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

and more complicated expressions that also parameterize the azimuthal asymmetry of the neutral delay (a 2nd order effect)

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

GPS meteorology involves 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 good approximation (Bevis et al., 1992; 1994)

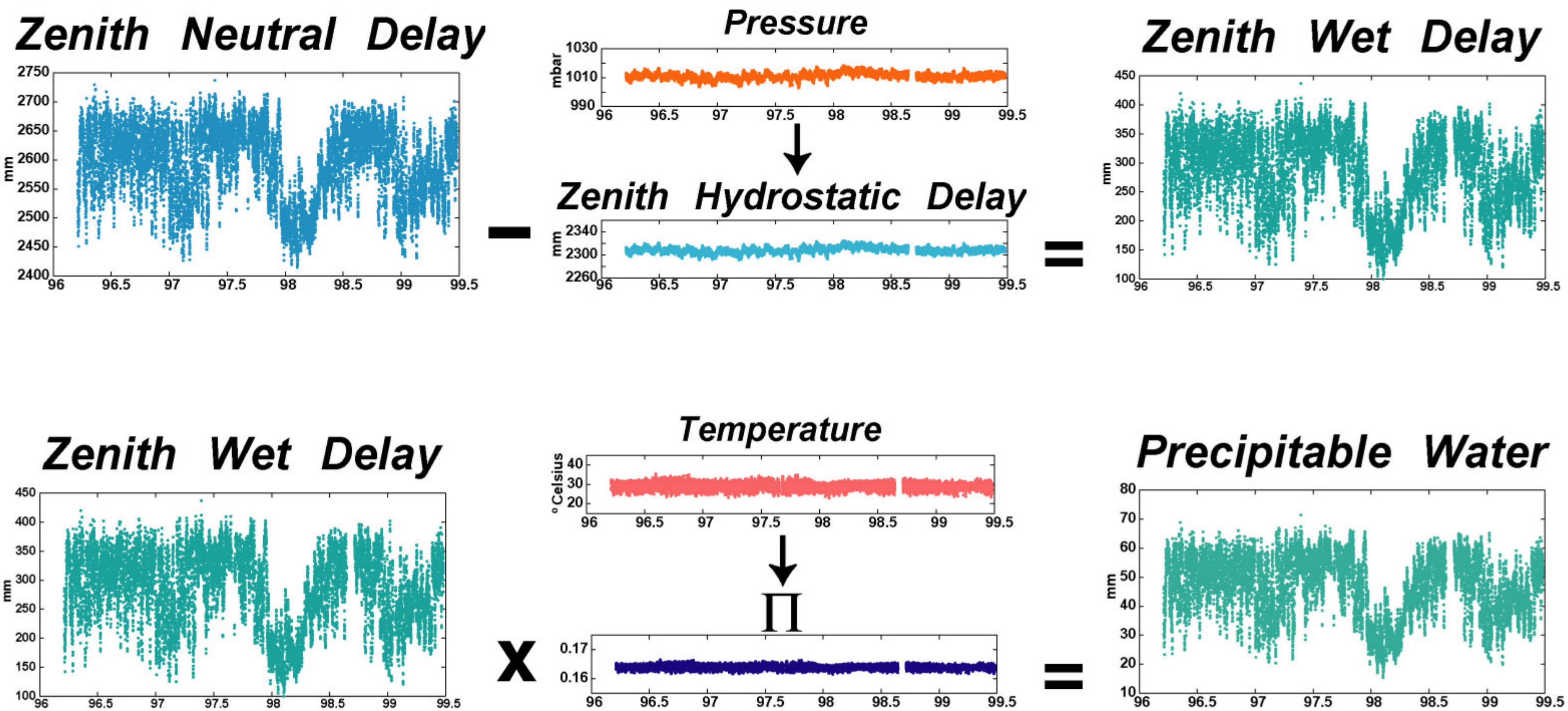
RULES OF THUMB:

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

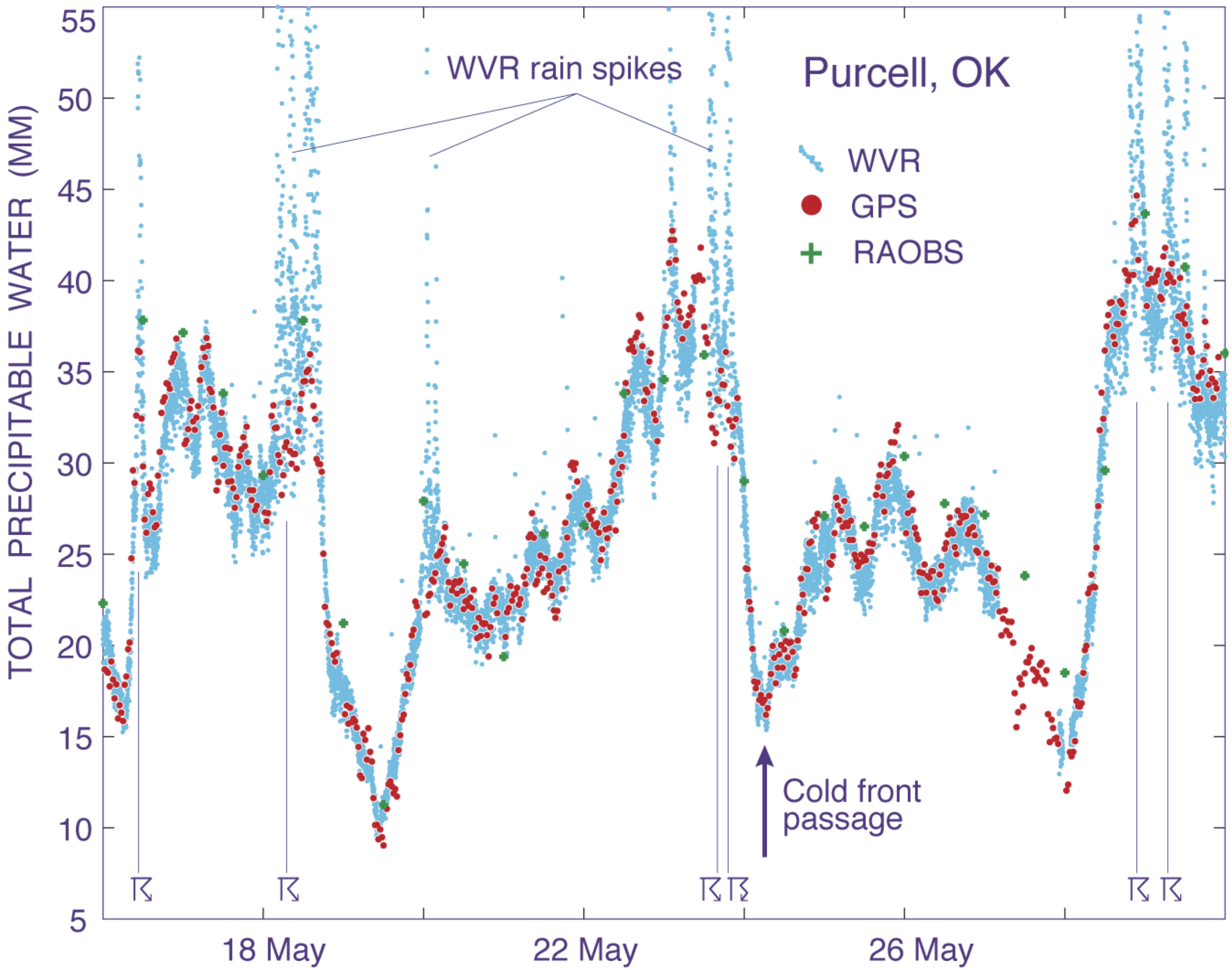
$Z_w \sim 6.5$ PW

PW $\sim 0.15 \; Z_w$

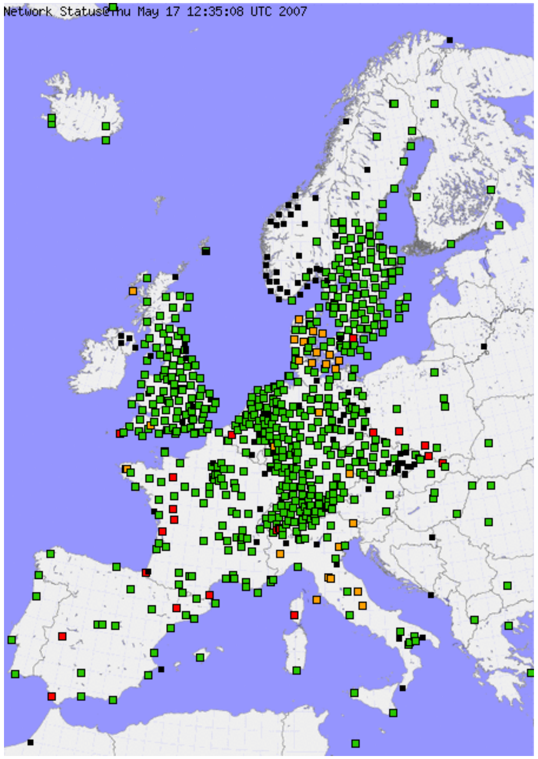
Transformations of GPS Meteorology

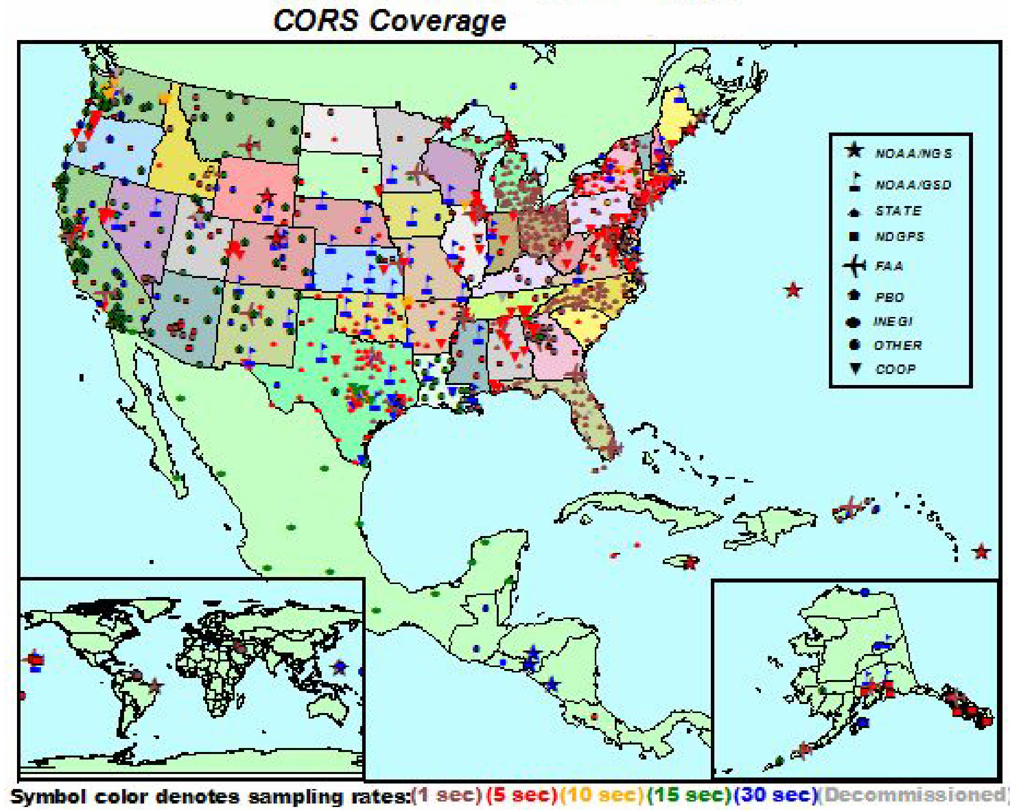


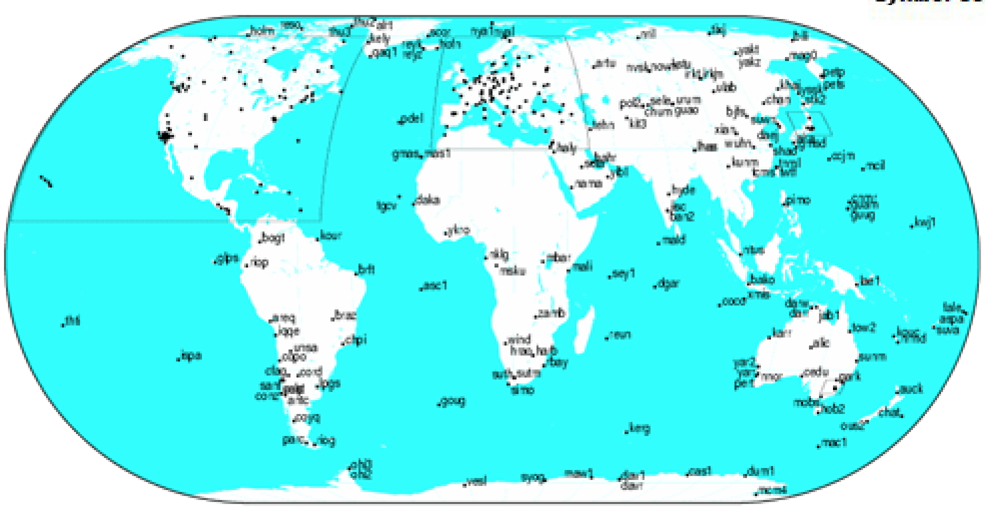
Proof of Concept Experiment: ‘GPS STORM’ May 1993



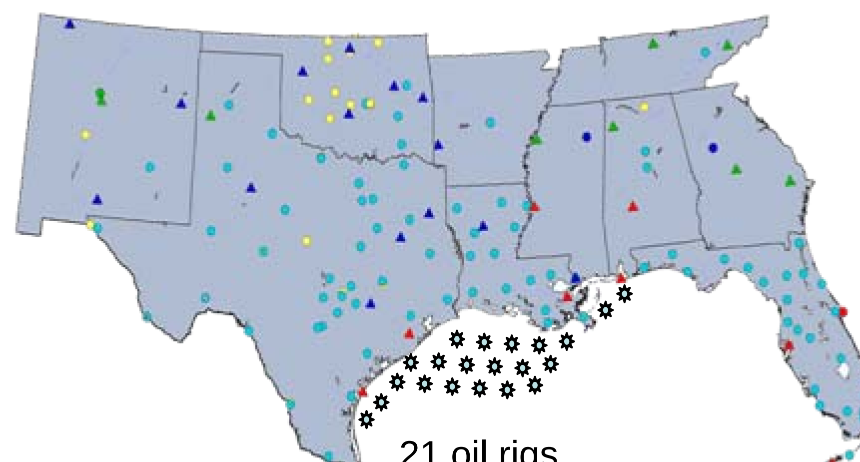
after Duan et al. (1996)







Global Tracking Network of the IGS



21 oil rigs.
Nominal spacing ~100 km

The US invented GPS, and it invented GPS Met…

So why has the US fallen behind Japan and Europe in developing and exploiting GPS Met?

• Coordination. The main US efforts at NOAA FSL and UCAR SuomiNet have been poorly coupled, and FSL has always been poorly funded. The academic community has virtually been left out. Contrast this to the Japanese GPS Met project which integrated efforts by their national geodetic survey (and their 1200 station national GPS network), the JMA, and about 30 different university research groups, each of which were funded for two 5 year cycles.

• The minimal participation in by academic geodesists and meteorologists means that US R&D in the basic technique has been fairly minimal in the last 10 years, potential applications have gone unexplored, logistical synergies with academic GPS projects (e.g. POLENET, PBO) are largely ignored, and the FSL and UCAR efforts have few academic customers and little academic support.

• The confusion between space-based (‘occultation’) and ground-based GPS Met has hurt the later. They have different strengths and weaknesses and the later technique is *vastly* cheaper since most of the resources come for free.

• Tunnel vision on the application of GPS ZD and PW time series:

  + Too much emphasis on NWP. Fully assimilating GPS ZD/PW in NRT is very challenging. Weak assimilation diminishes the impact of the time series.

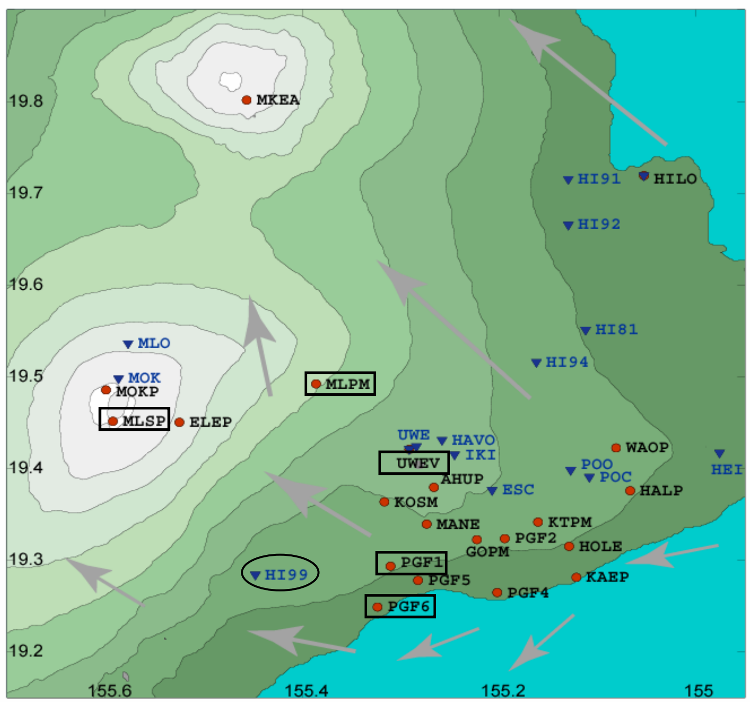
  + Not enough emphasis on nowcasting. No data assimilation required.

  + Not enough emphasis on climatological applications. No NRT requirement.

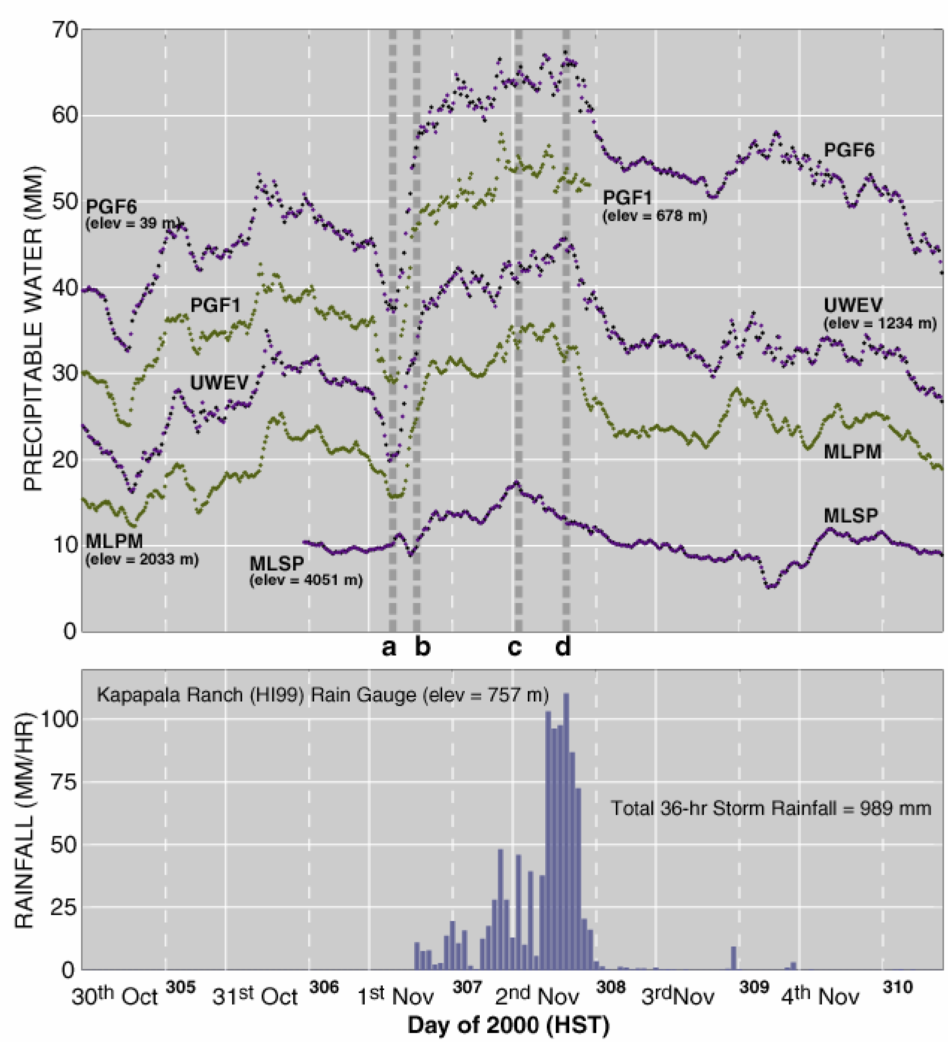
GPS Met and its Potential Impact on Nowcasting and NWP

The Ka`u Storm, Hawai'i
2^{nd} November 2000

- **Record rainfall & flash floods**
- **Common natural hazard in Hawaii**
- **Heaviest rainfall over Big Island GPS network: opportunity to examine how PW evolved during the storm**
- **Investigate the performance of the Mesoscale Spectral Model (MSM) which failed to predict this 50- year flooding event.**

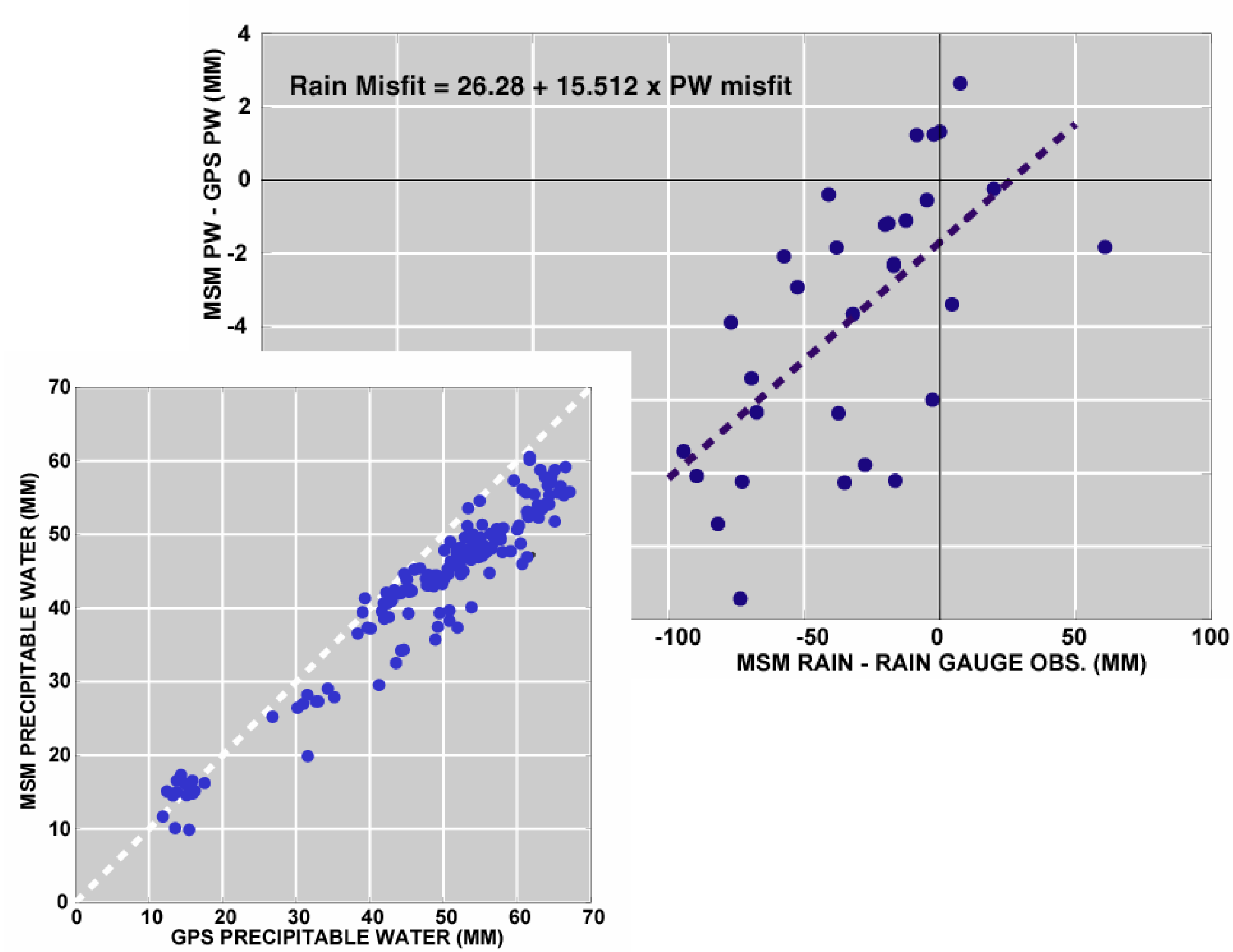


NRT PW from BIGAMY

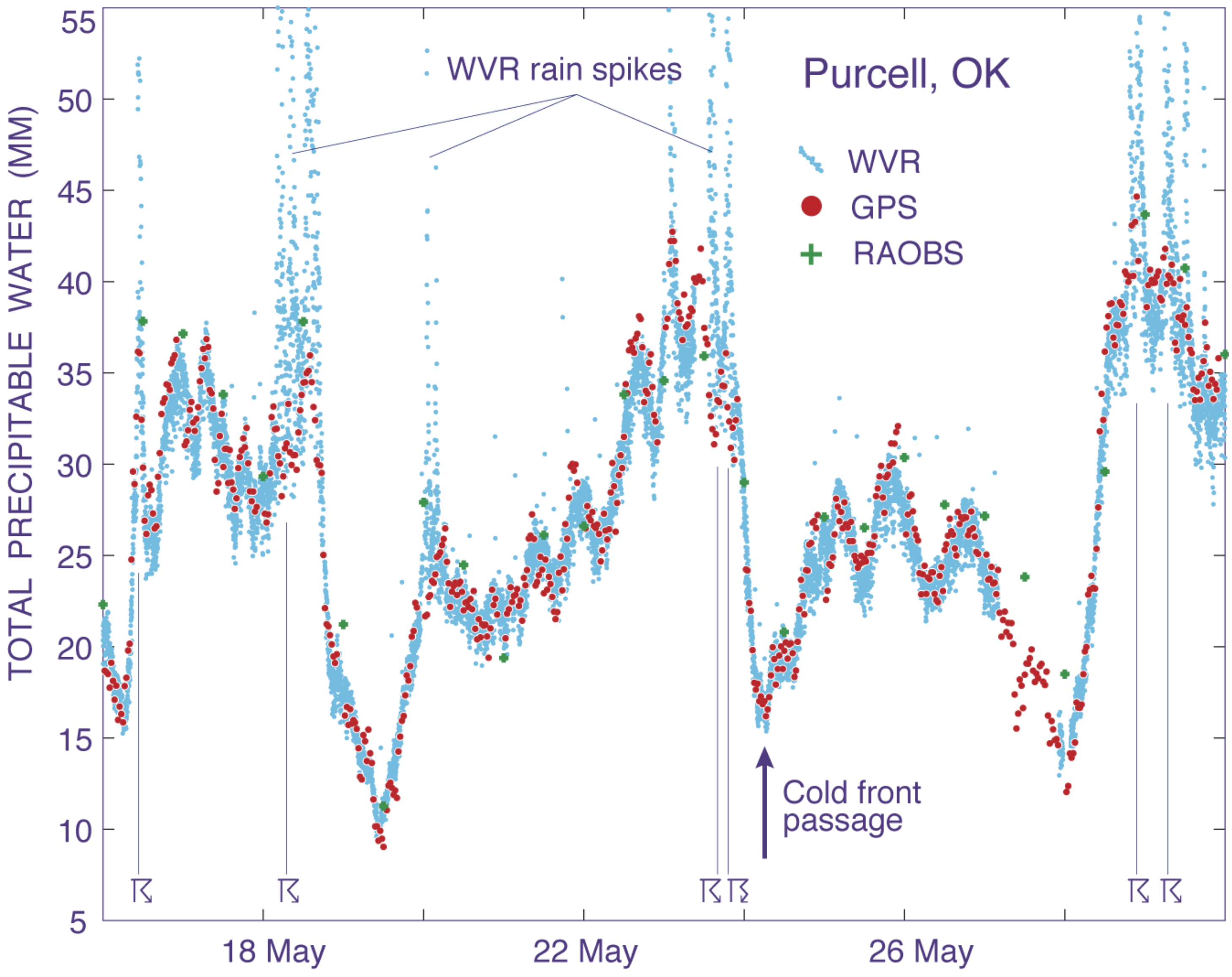


Non-meteorologists in the Pacific GPS Facility watching the PW time series on their website knew severe weather was likely, the NWS workers next door did not.

MSM's underestimate of rainfall was linearly proportional to its underestimate of precipitable water



‘GPS STORM’, Oklahoma, May 1993

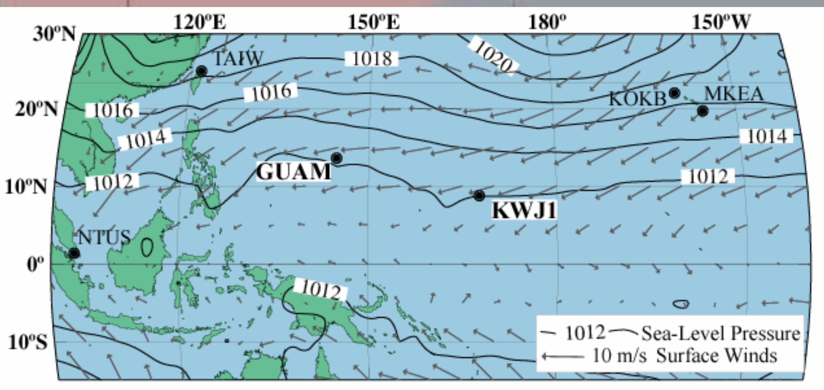


GPS Met and its Potential Impact on Climatology

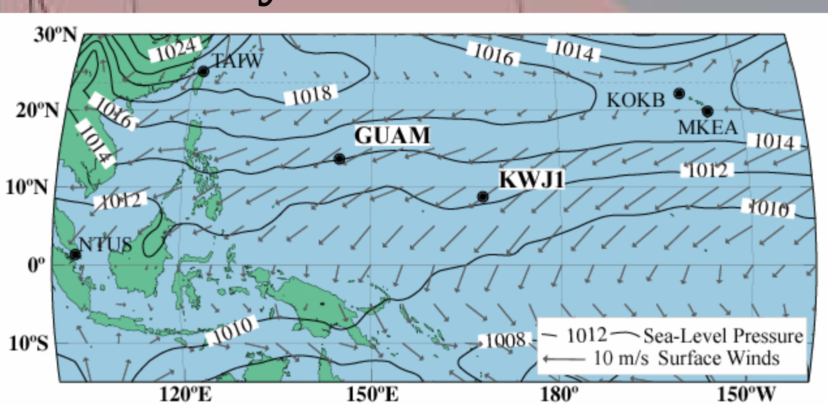
The 1997 - 1998 El Niño

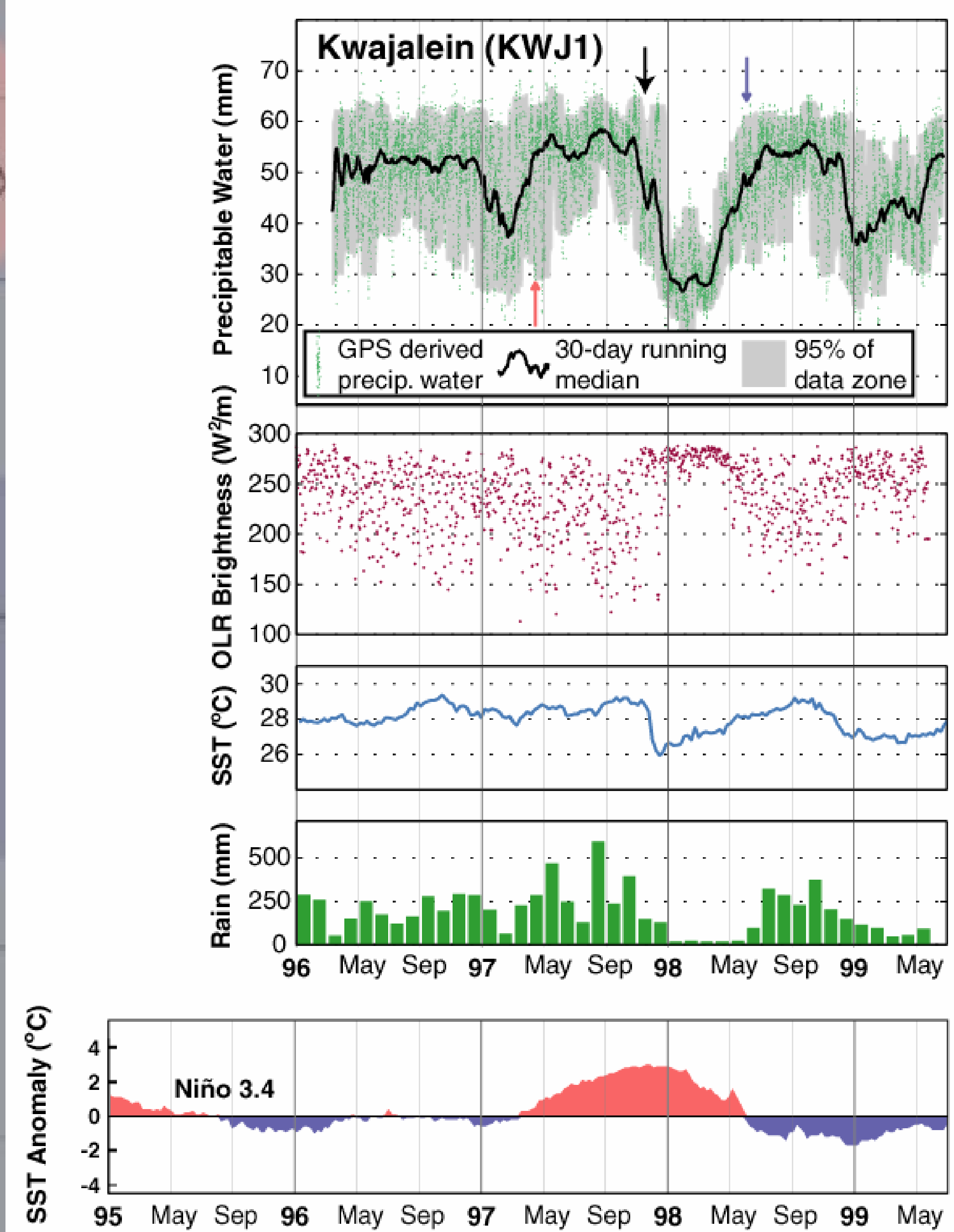
GPS PW at KWJ1 (Kwajalein Atoll)

November 1997



January 1998

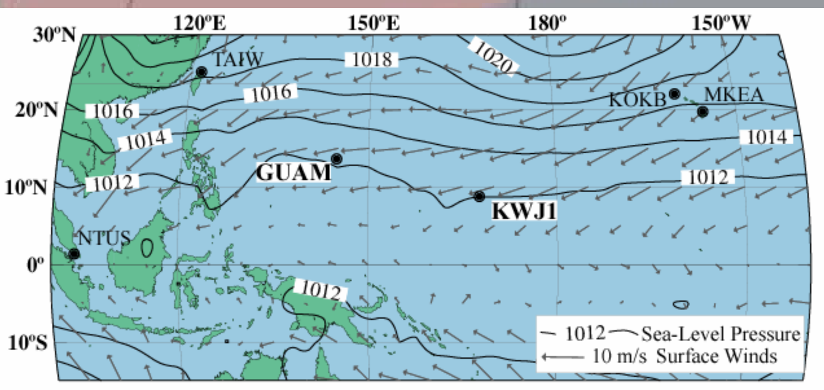




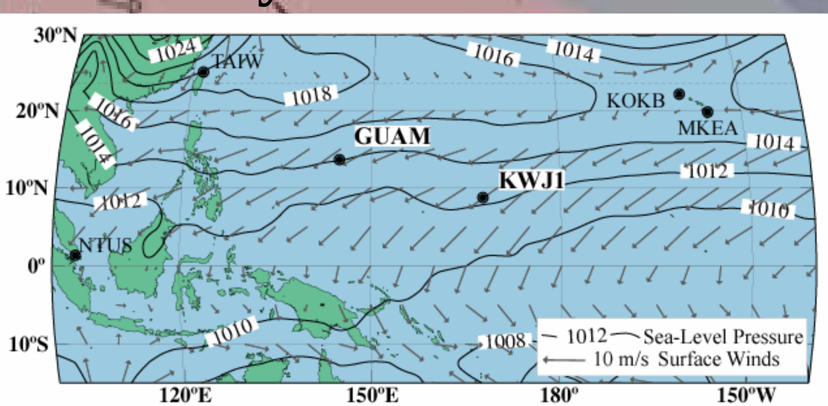
The 1997 - 1998 El Niño

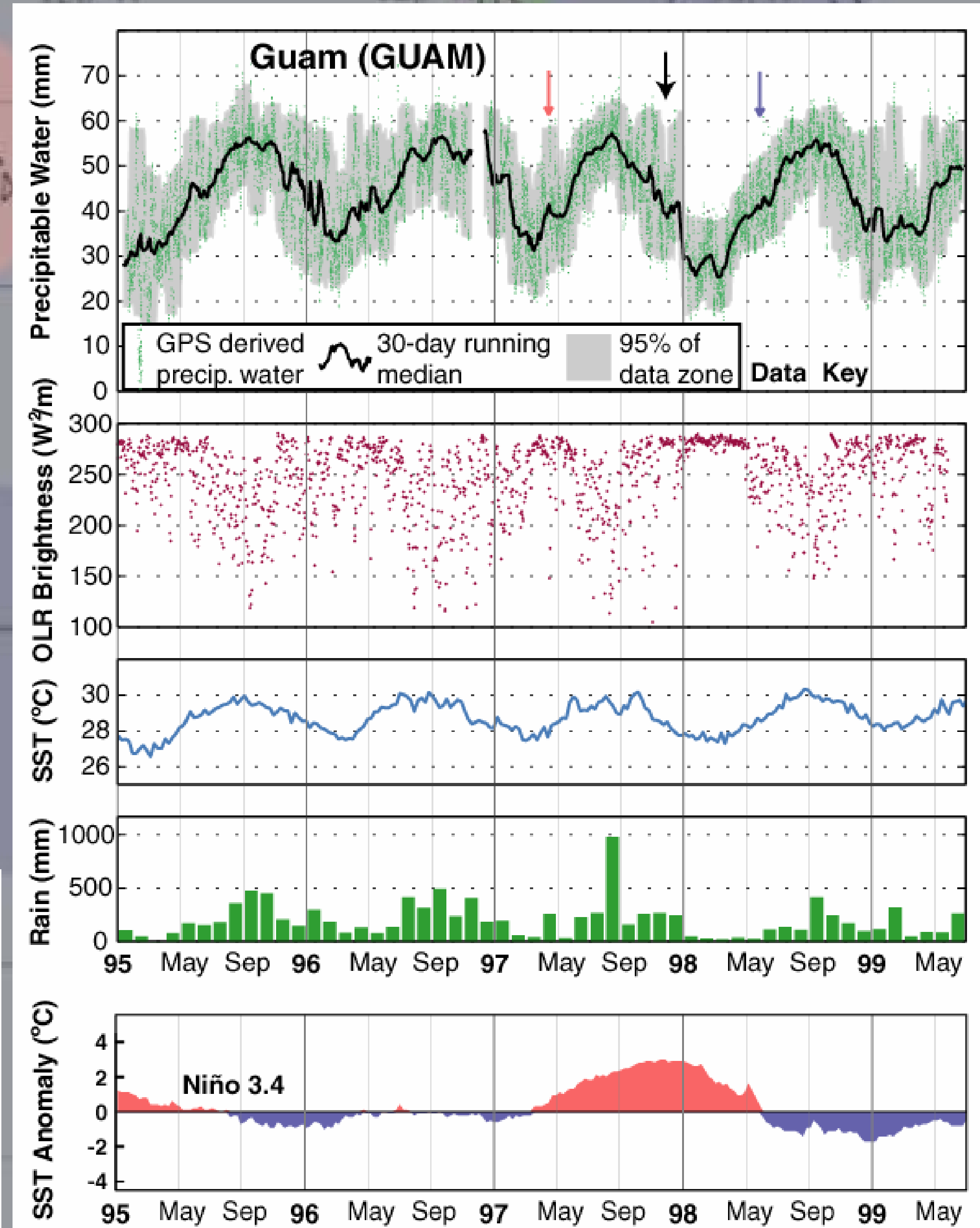
GPS PW at GUAM

November 1997

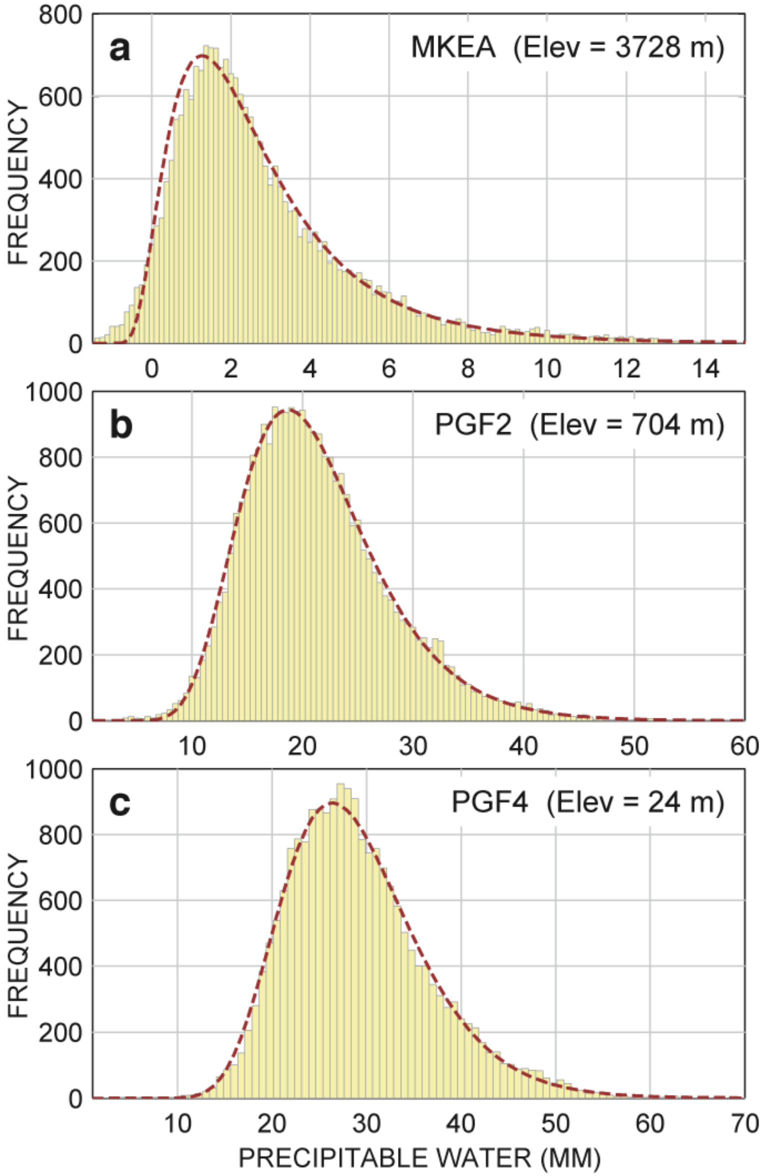


January 1998

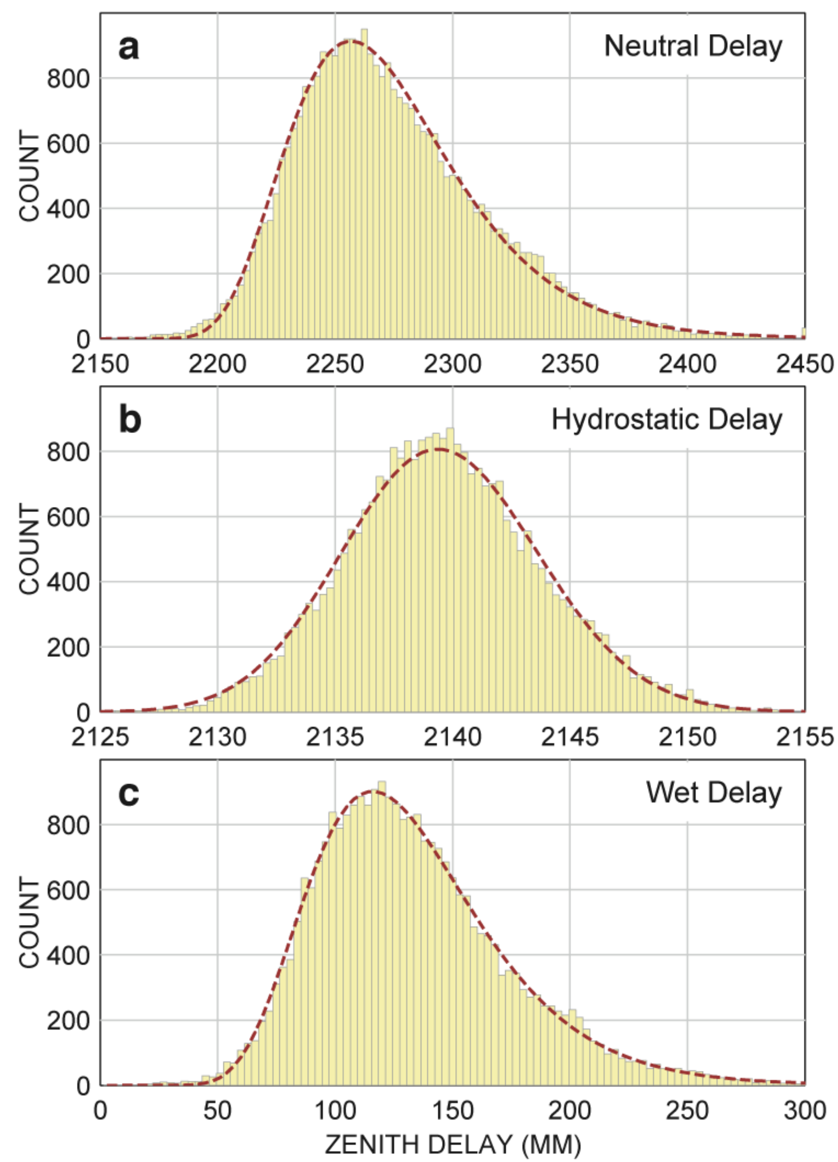




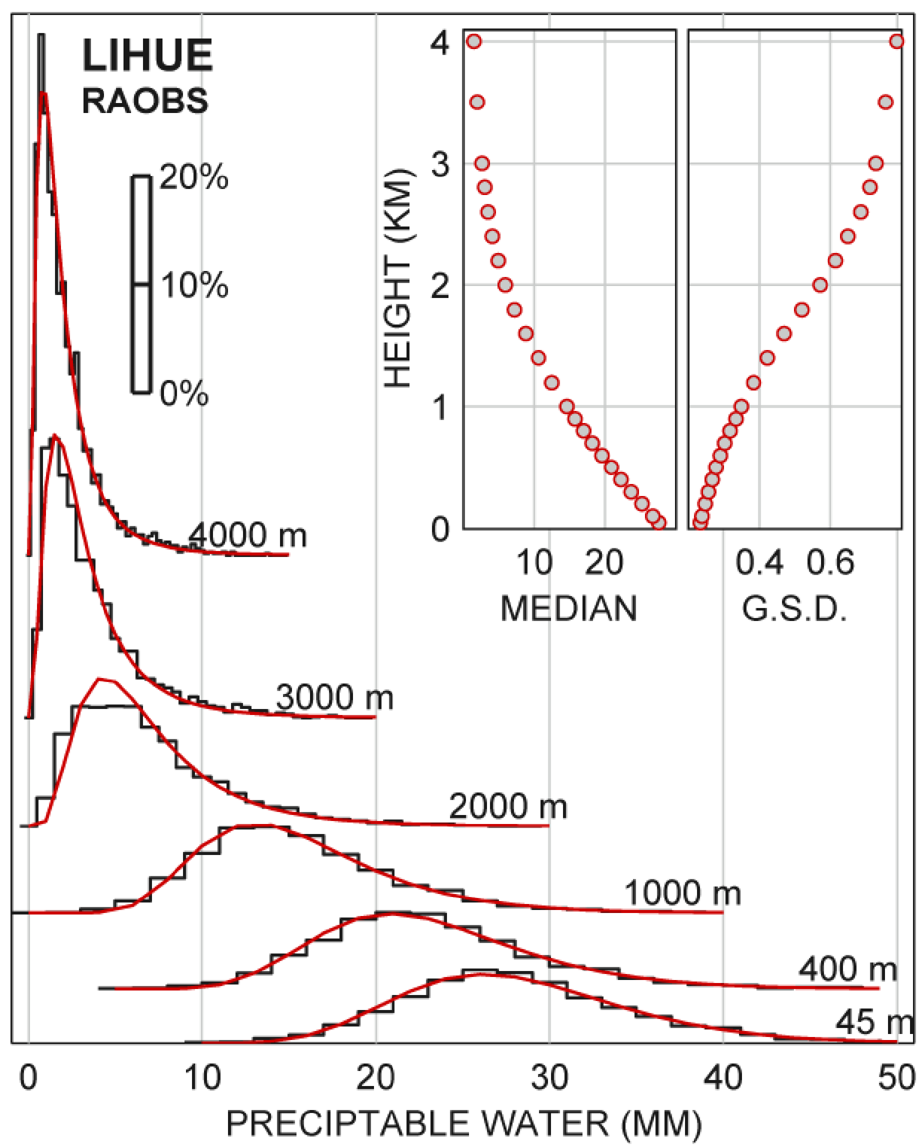
PW Distributions



Delay Distributions at PGF2



(from Foster and Bevis, 2003)



LIHUE
RAOBS
20%
10%
0%
4000 m
3000 m
2000 m
1000 m
400 m
45 m
0
10
20
30
40
50
PRECIPTABLE WATER (MM)
HEIGHT (KM)
4
3
2
1
0
10
20
MEDIAN
0.4
0.6
G.S.D.

In the tropical warm water pool
an *inverse* or *reverse* lognormal distribution

Generalized
lognormal distributions

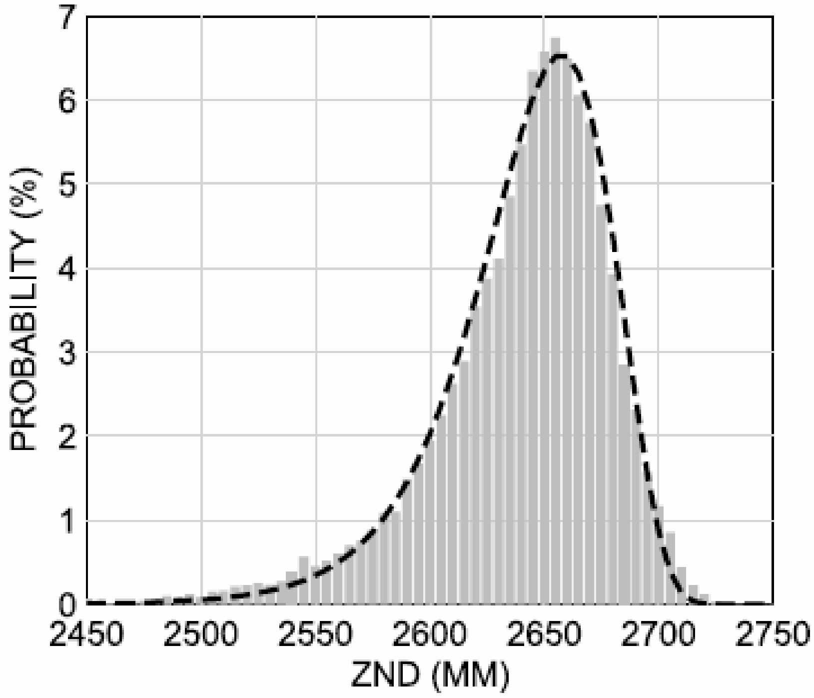
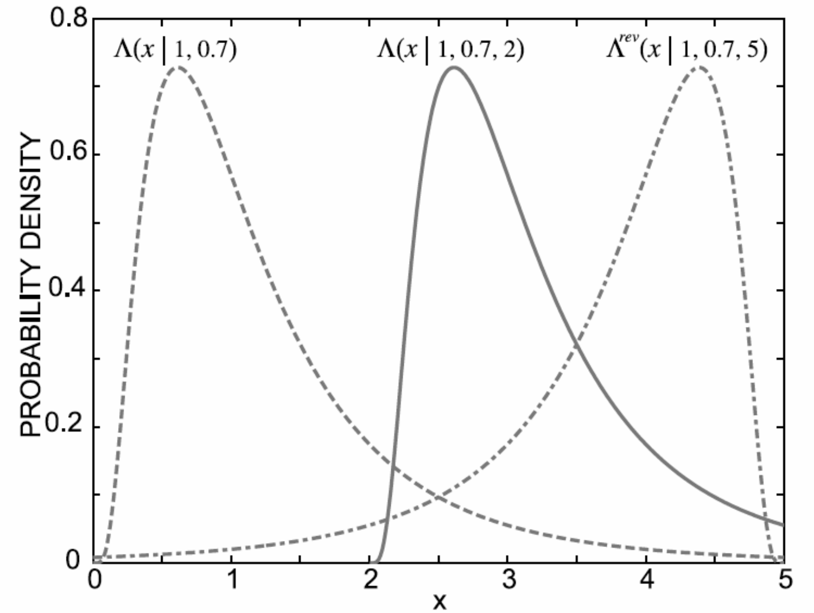


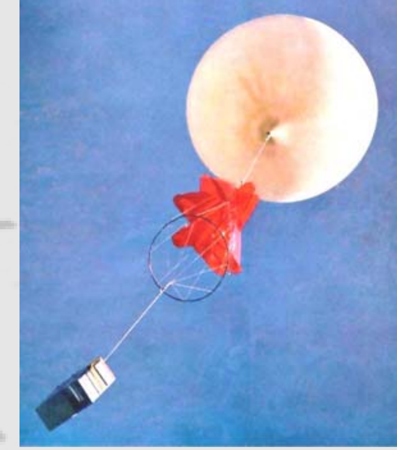
Figure 6. Histogram of zenith neutral delay estimates from GPS site NUSA, Solomon Islands. *M*, *s*, and *t* for the fitted reverse-lognormal curve are 2647.5, 0.33, and 2745.0, respectively.

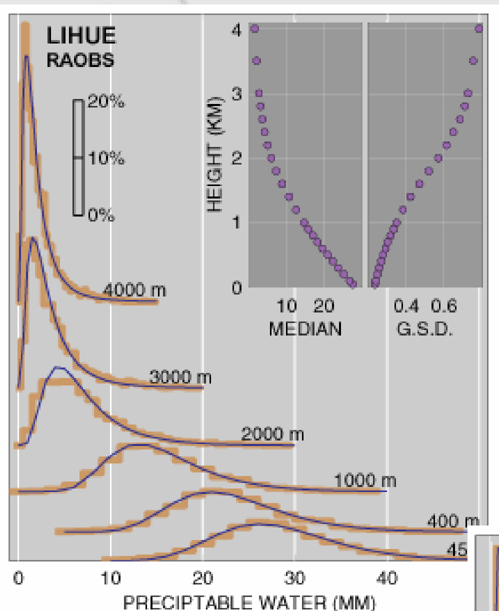
$$\Lambda(x|M,\ s,\ t)$$



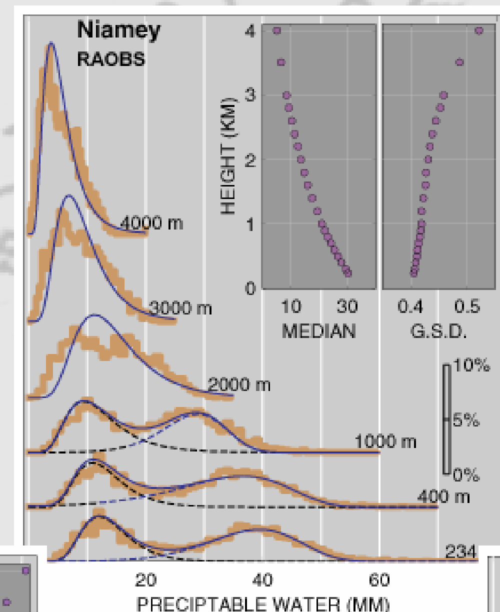
Global vertical PW distributions using radiosonde (RAOBS) profiles

(from Foster et al., 2006)

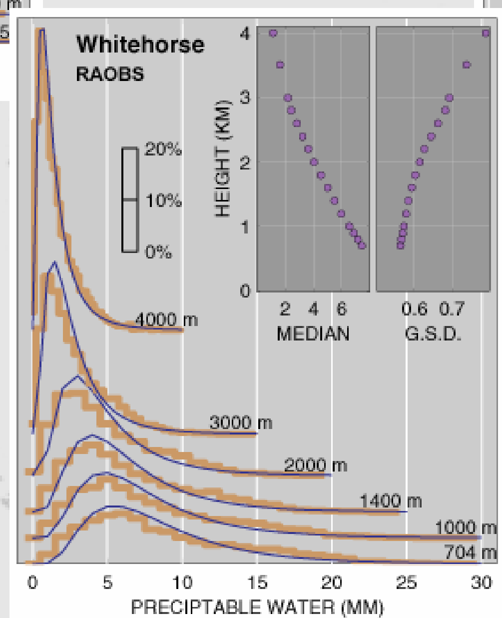




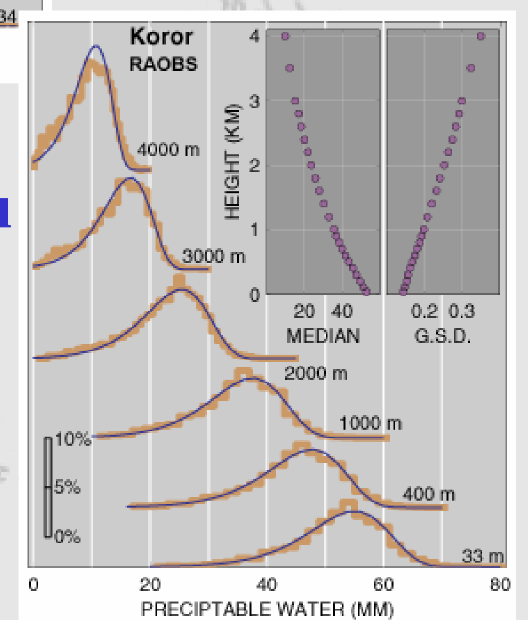
Lihue (tropical oceanic): Lognormal



Niamey, Niger (tropical monsoonal): Bimodal



Whitehorse, Canada (mid-latitude continental): Lognormal



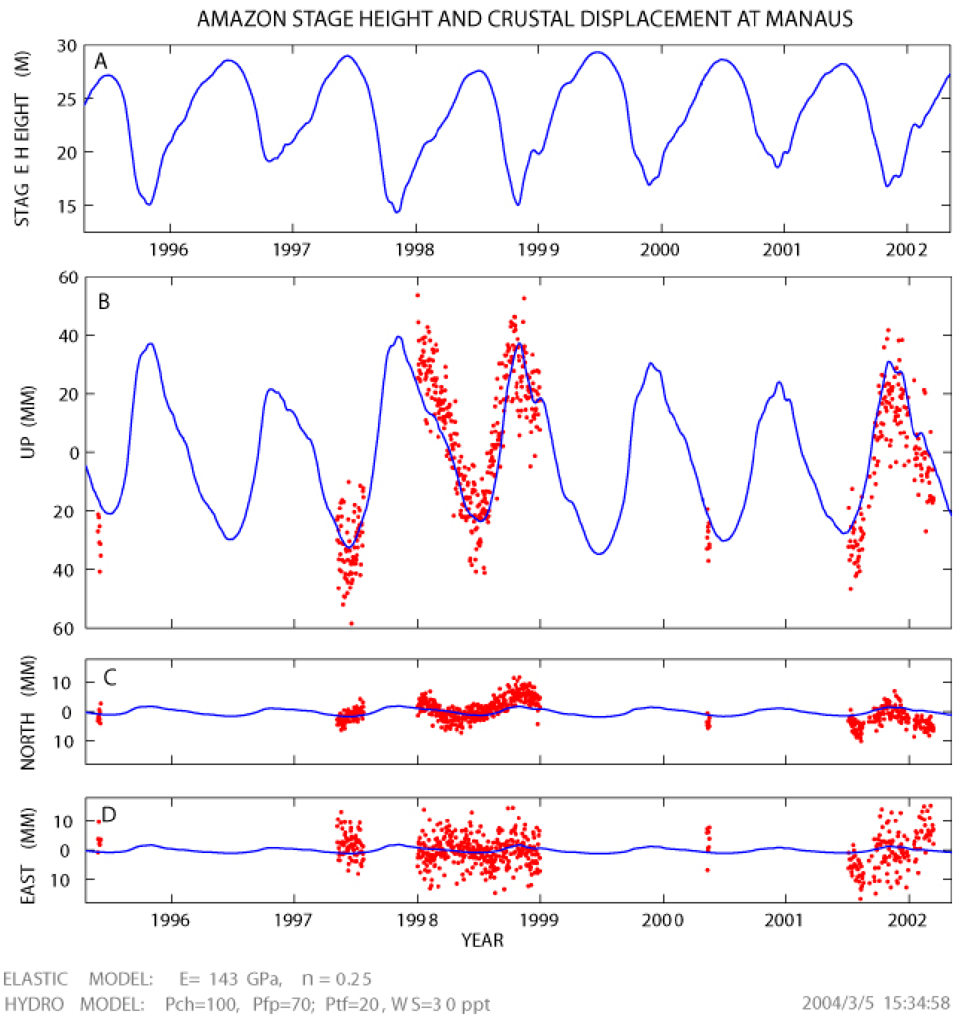
Koror, Palau (equatorial oceanic): Inverse-Lognormal

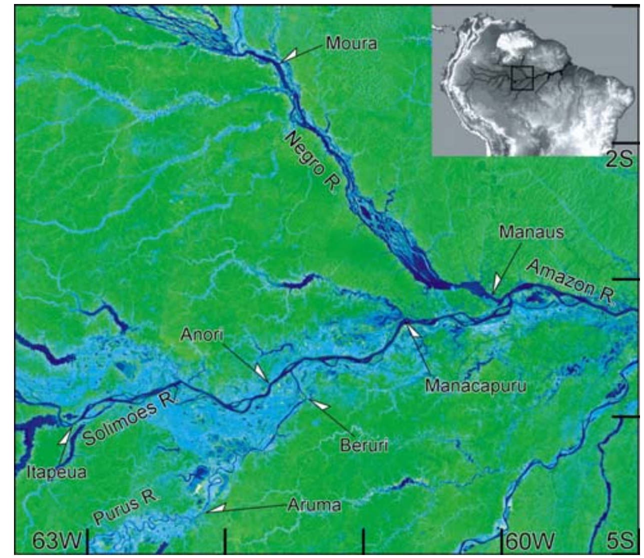
GPS Drives

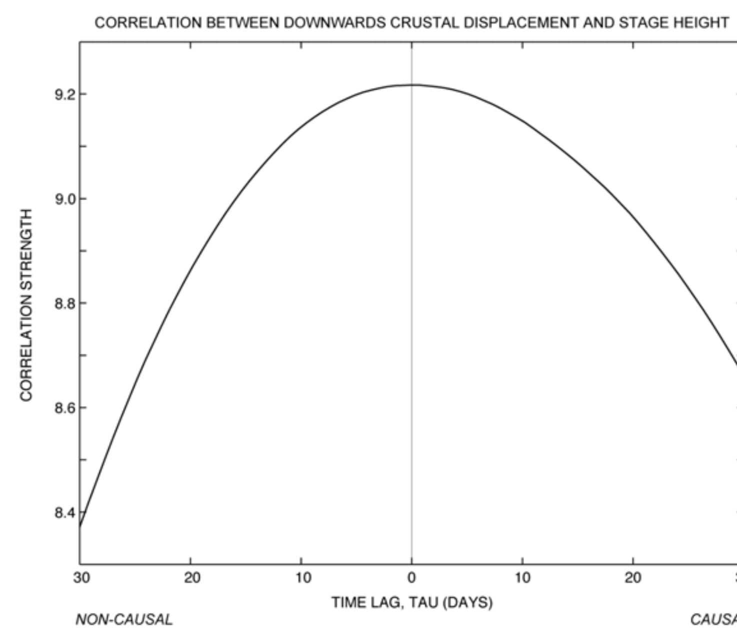
Unexpected or Unusual Synergies

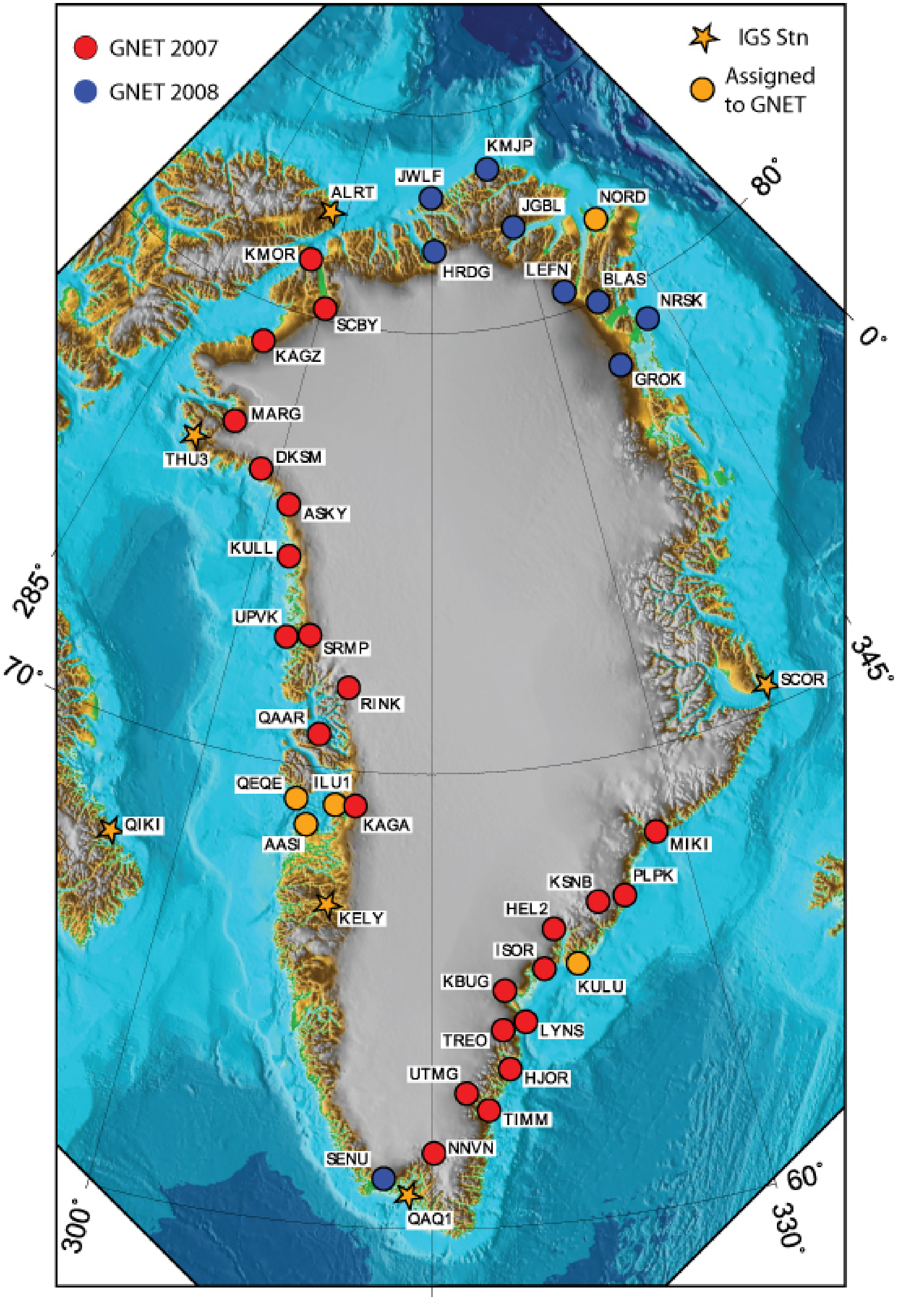
Hydrology/Geodesy Synergy: "Weighing" the Amazon River

Seasonal hydrological loading observed at Manaus (Central Amazon Basin). At one year periods, the earth responds purely elastically, or very nearly so, to the loads associated with the hydrological cycle.









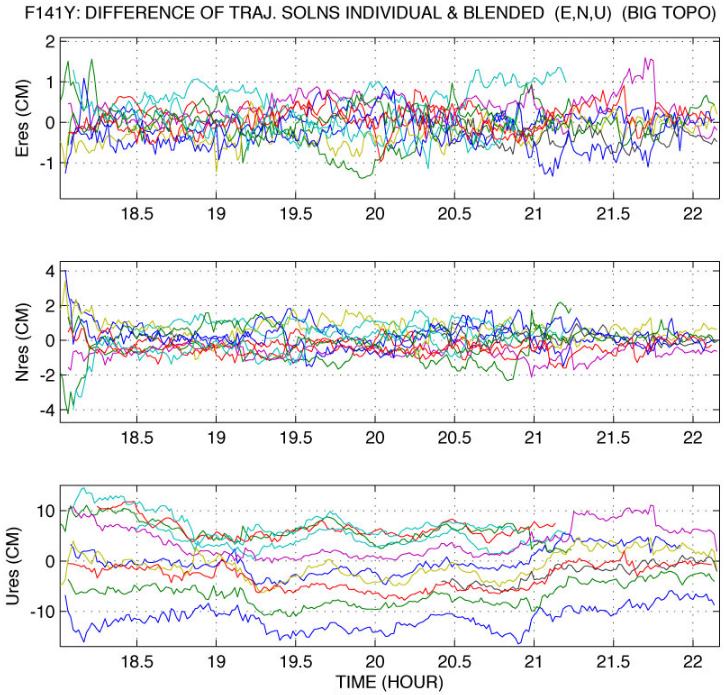
LOGISTICAL SYNERGIES

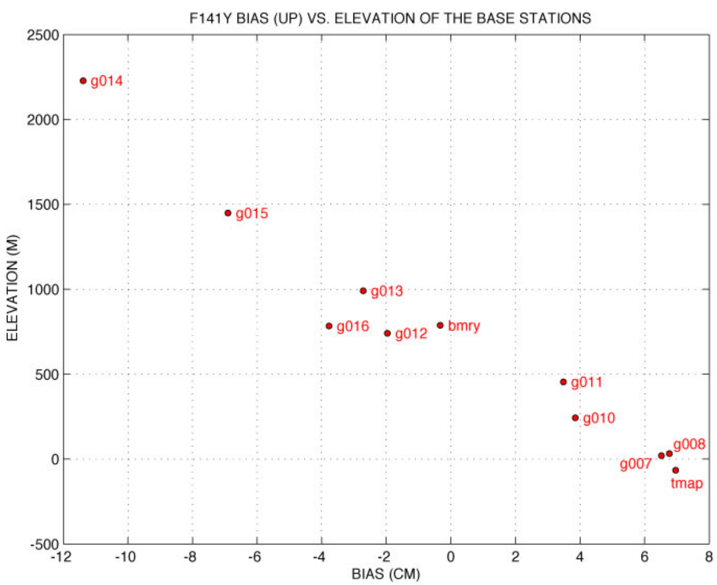
The primary functions of GNET, the Greenland GPS Network, are to

- improve PGR models and thus GRACE's "PGR correction"
- detect earth's instantaneous elastic response to accelerating ice loss

But GNET could also be used to improve the water vapor field in numerical weather models, and thus improve our understanding of water vapor convergence, and precipitation over the ice sheet.

GNET stations will also be used to position aircraft engaged in repeat LIDAR surveys (dH/dt for ice sheet).

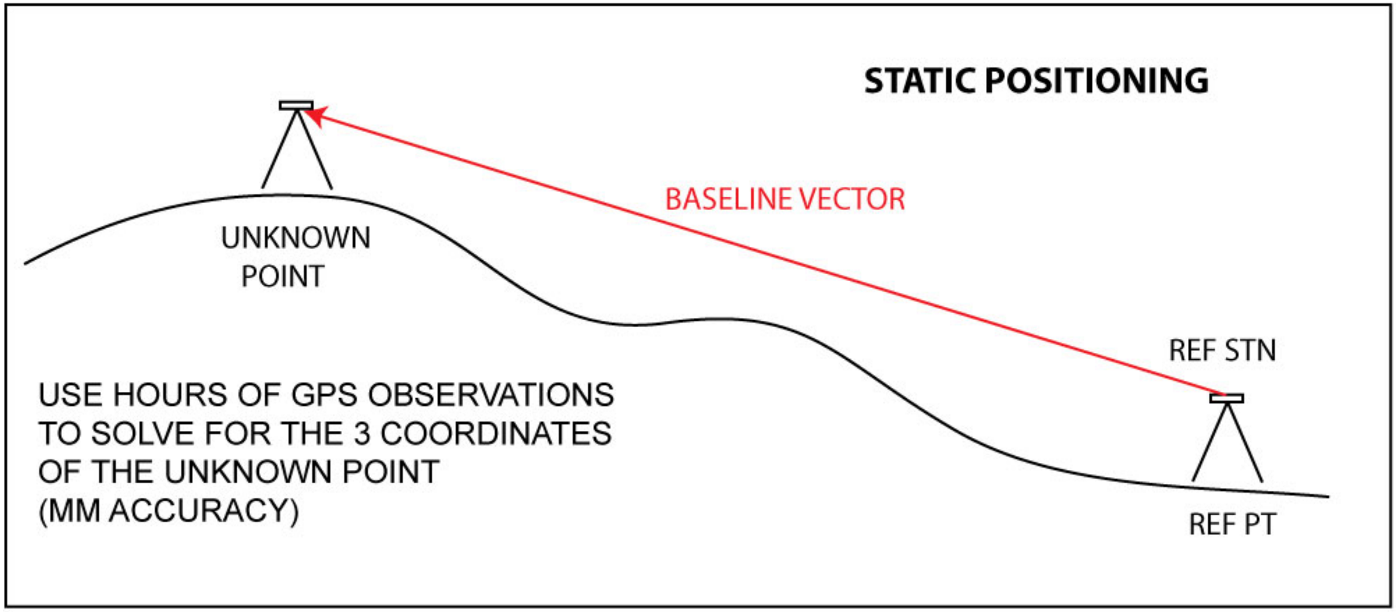


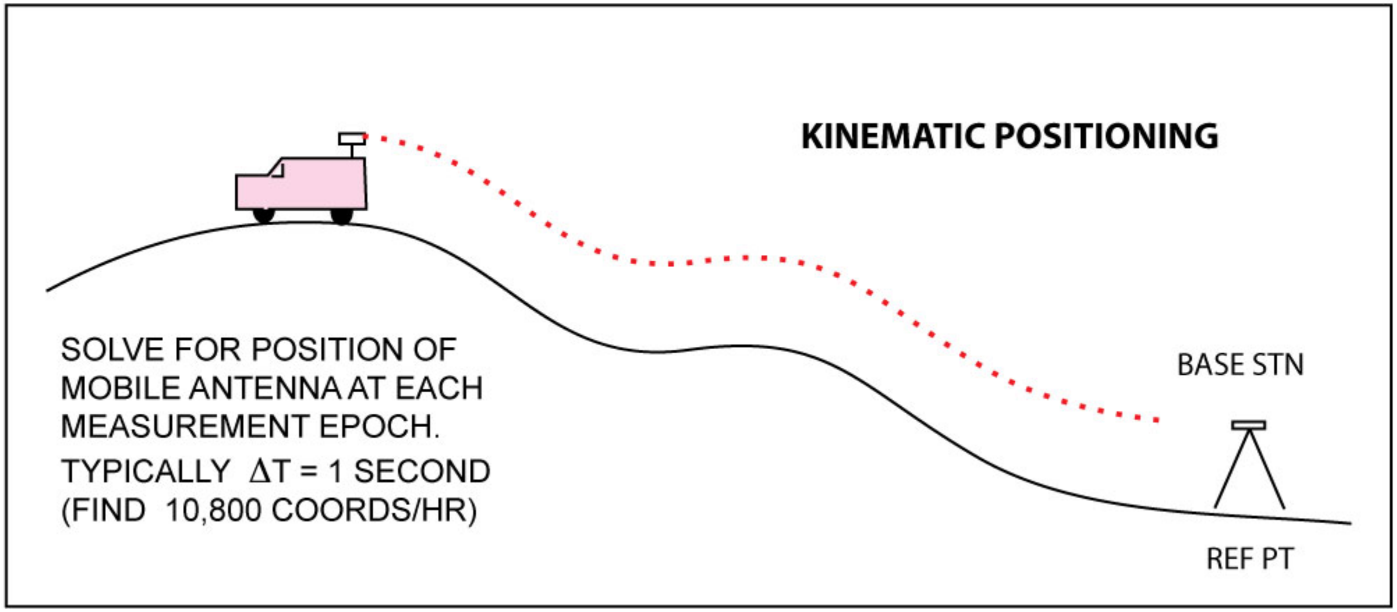


The fundamental problem:

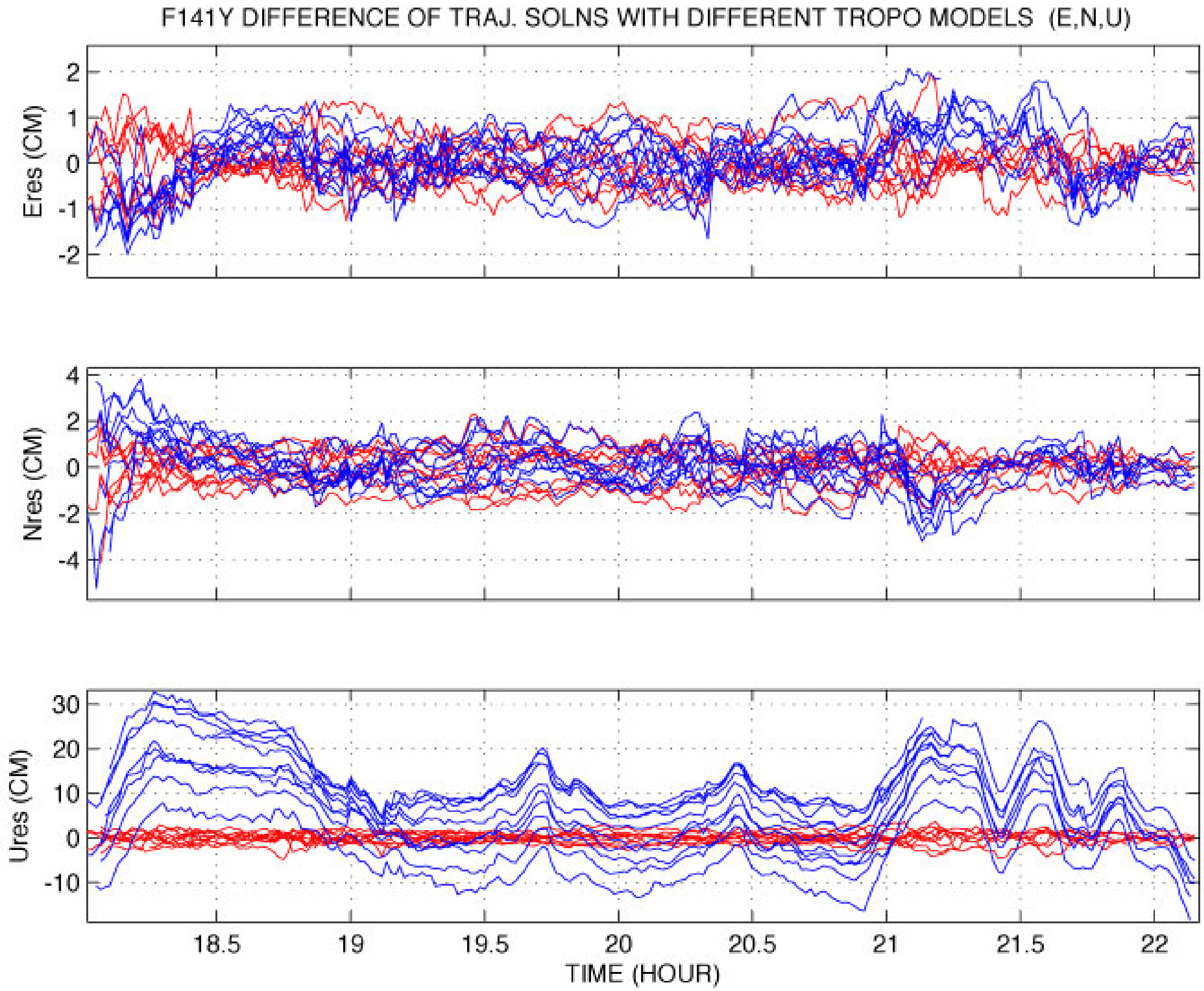
$$\text{Error}_H \quad = \quad 3\text{-}6 \quad \text{Error}_{ZD}$$

CLASSES OF GEODETIC GPS POSITIONING





After estimating ZD(height) and forcing the kinematic positioning software to respect this profile, the height biases were greatly reduced!



ZND calibration has little impact on horizontal positioning

ZND calibration has a big impact on vertical positioning.

How can Meteorology and UNIDATA help

GPS and GPS Met?

Provide geodesists with estimates of Zh and Zw for use in kinematic GPS surveys