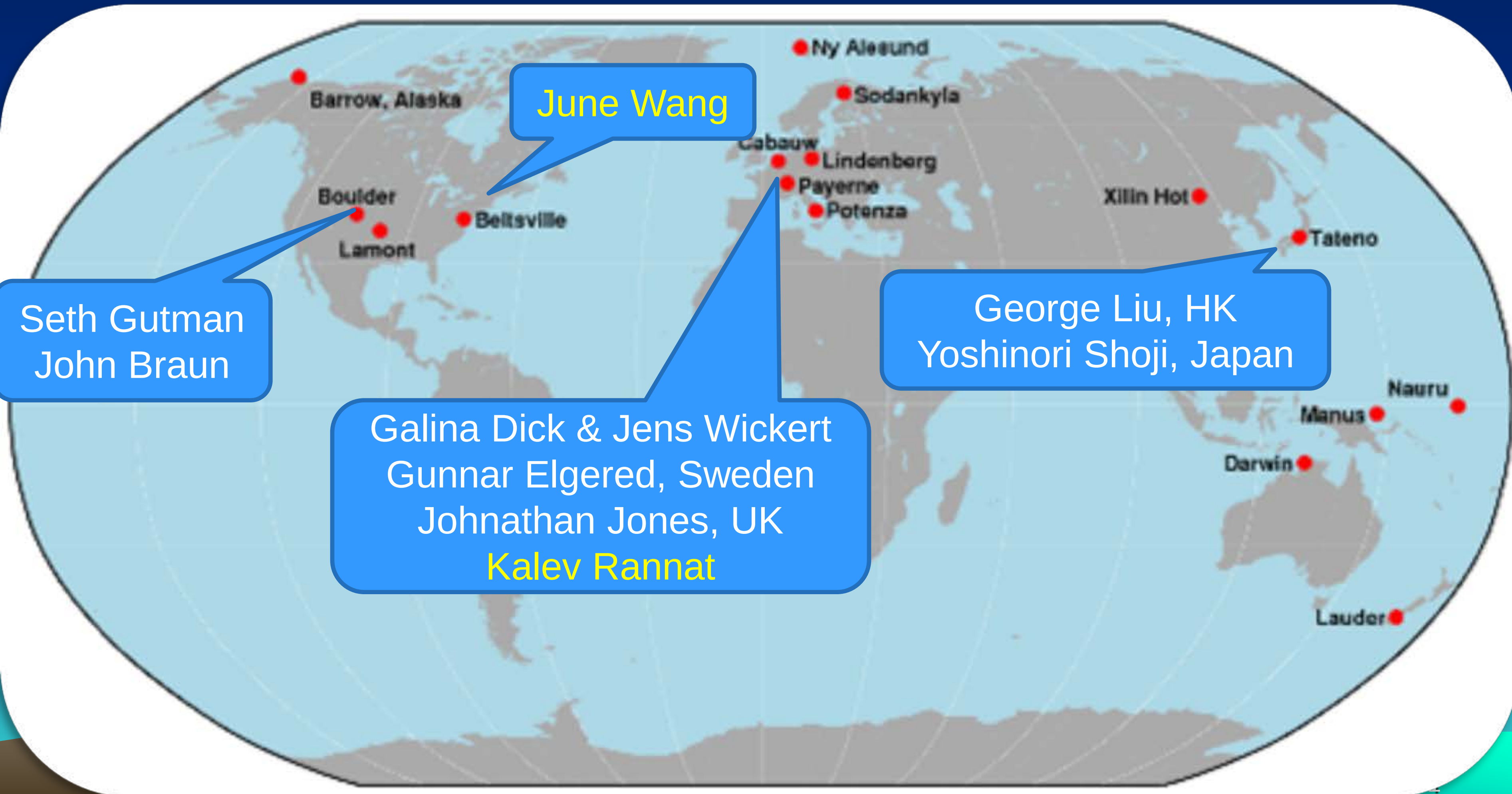
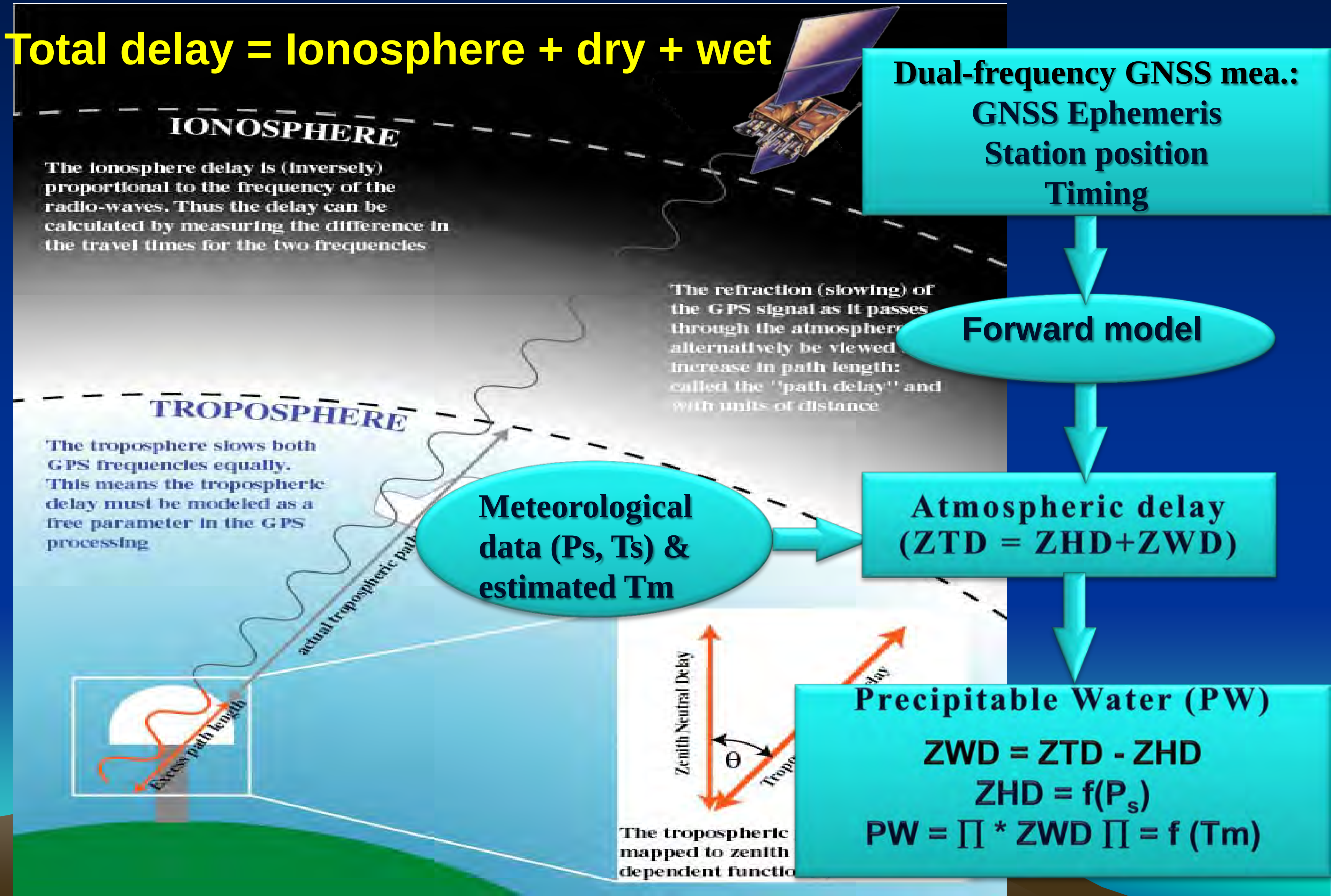
# GRUAN GNSS Precipitable Water (GNSS-PW) Task Team: 10 members from 7 countries



# Outline

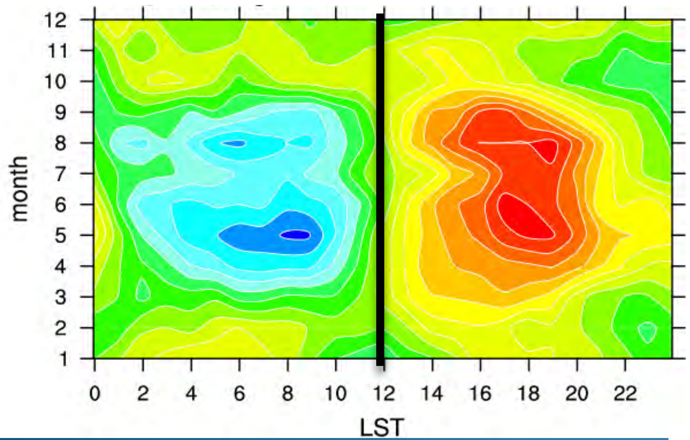
1. ***Guidelines:*** *8 Tasks*
2. ***Implementation:***
   - *GNSS Data Central Processing (GFZ)*
   - *GNSS Data Flow (Kalev)*
3. ***Research:***
   - *Co-locations*
   - *Long-term stability*
4. ***Future of TT***

# How does GNSS estimate precipitable water?

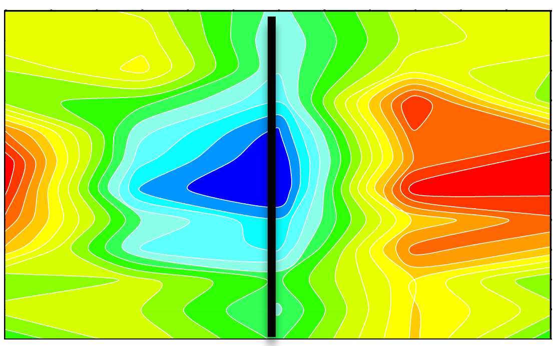


# PW Diurnal Variations (Lindenberg)

GPS



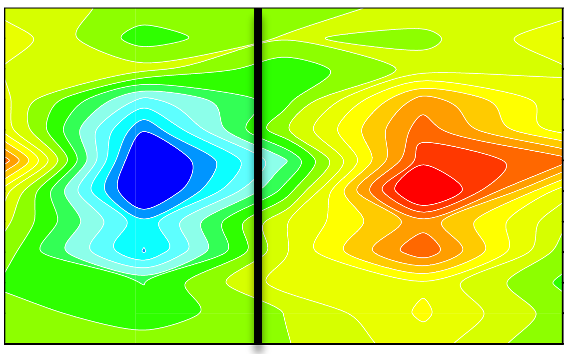

Radiosonde before corr.



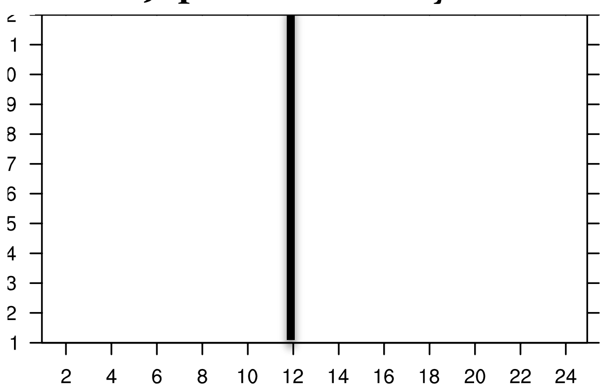
Radiosonde after corr.

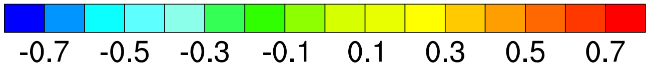



ERA-Interim



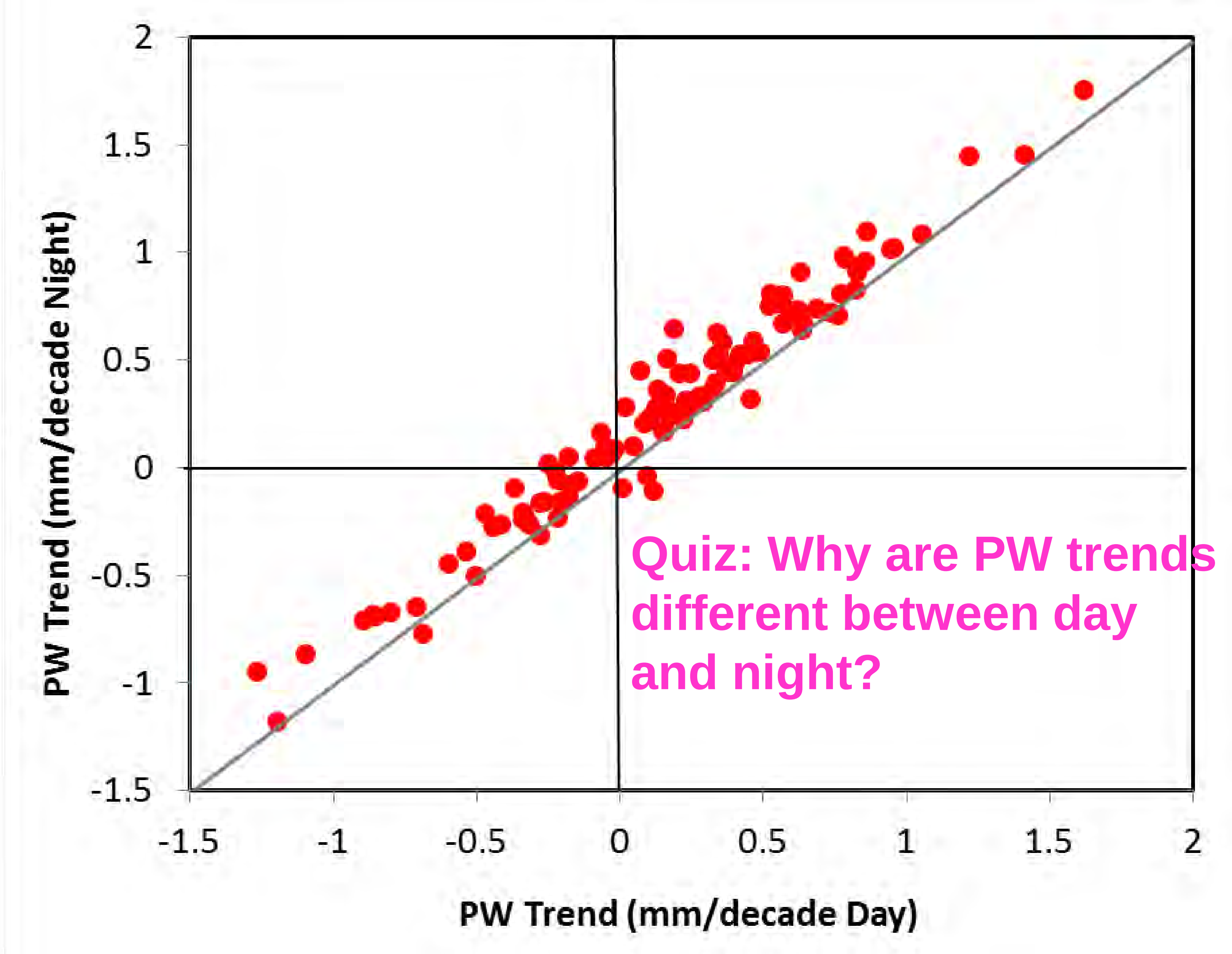
Japanese Reanalysis



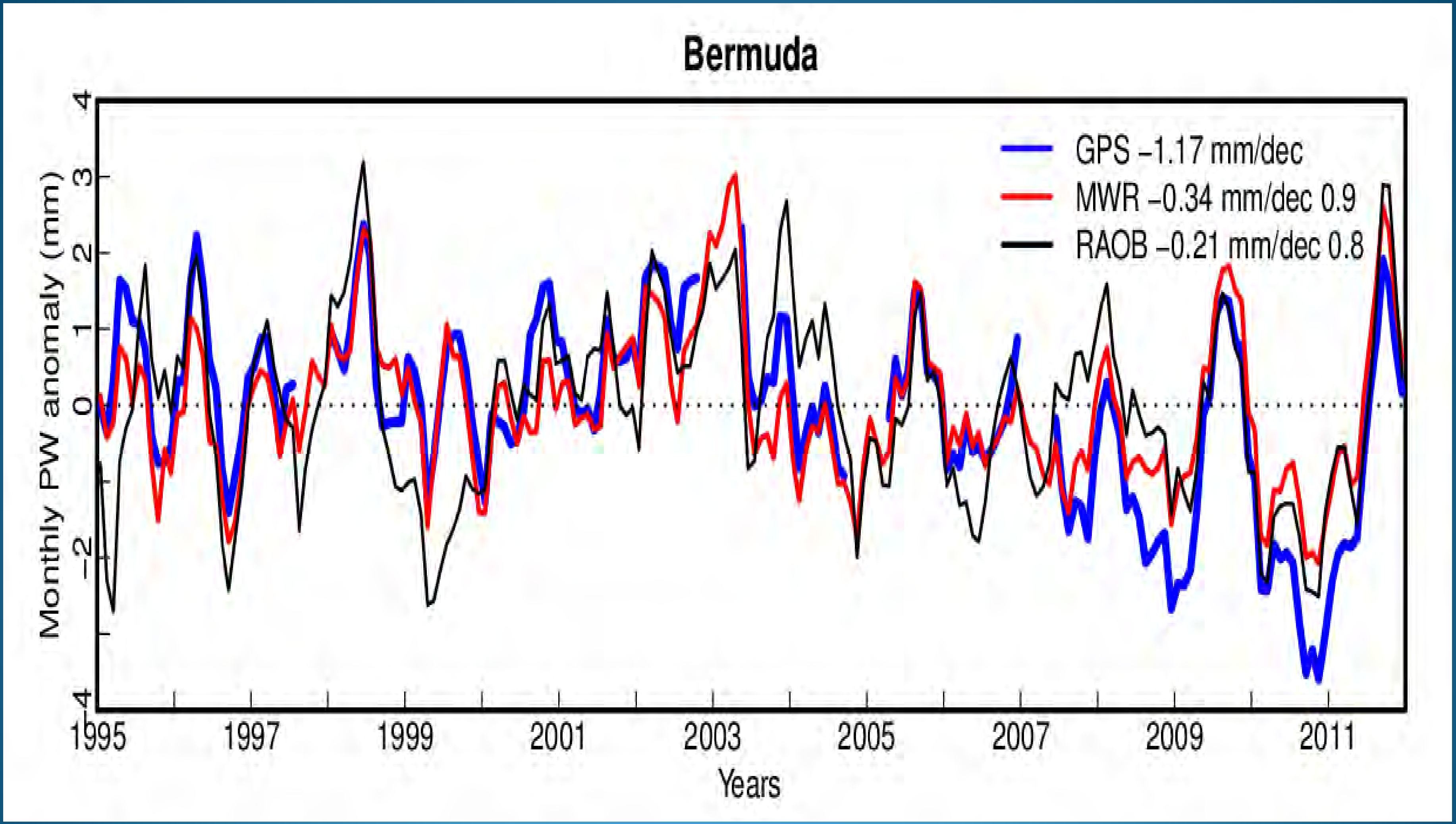

Wang et al. (2013)

# Comparisons of Day & Night Trends (GPS)




**Quiz: Why are PW trends different between day and night?**

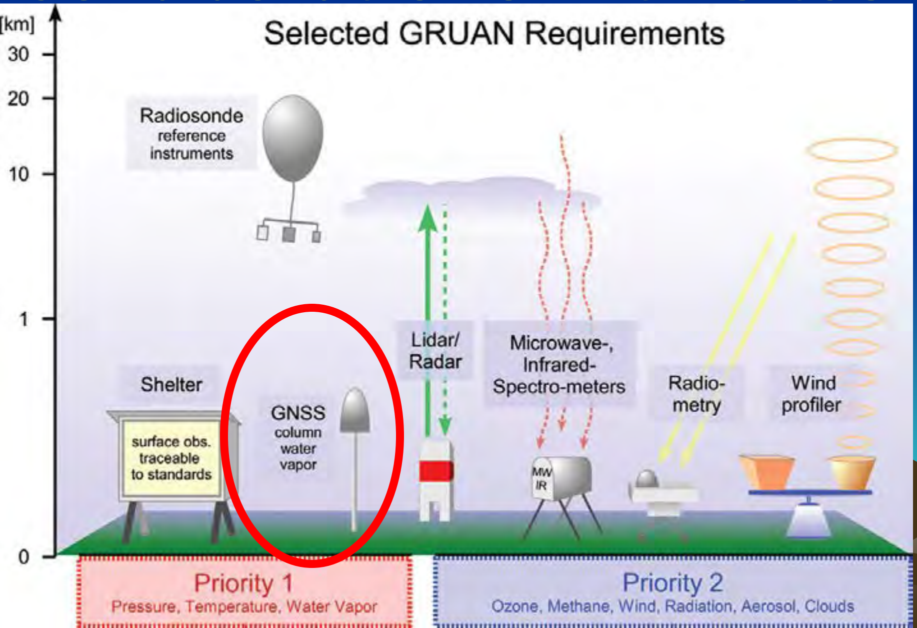
# Redundant Observations

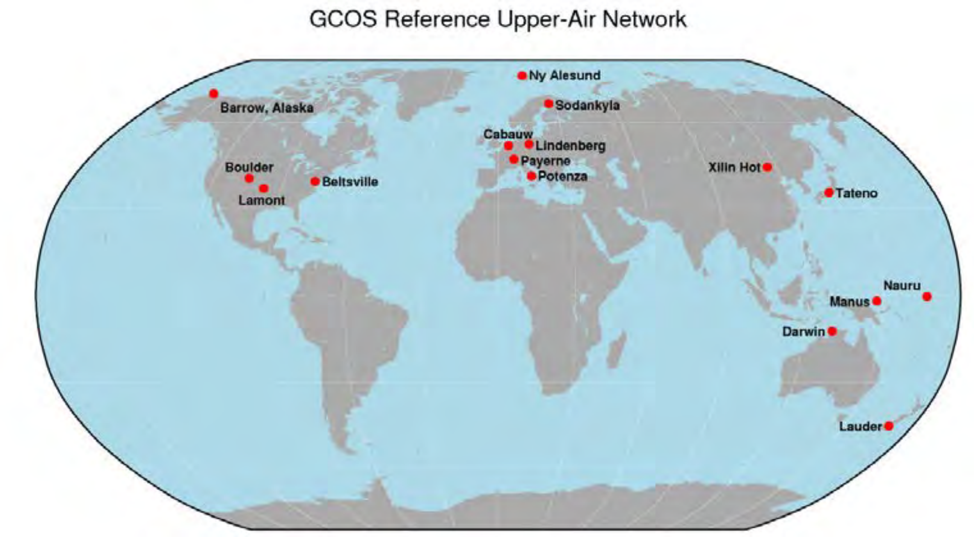


# GNSS-PW Task Team: Motivation, Goal, & Operation

**Goal:** To develop explicit guidance on hardware, software and data management practices to obtain GNSS PW measurements of consistent quality at all GRUAN sites with eight specific Tasks.

**Operation:** Bi-annual conference call, emails, ICMs, sub-teams for each task & documentation, collaborations with sites and GNSS community.



| Task | Milestone | Progress |
| --- | --- | --- |
| #1 To define GRUAN requirements | "GRUAN GNSS Product Requirements" | Done |
| #2 To document and review current status | "GRUAN GNSS Site Survey Table" | Done |
| #3 To prepare "GRUAN GNSS Site Guidelines" | GRUAN TD-6: "GRUAN Ground-based GNSS Site Guidelines" | Done |
| #4 To develop guidance on data | "GRUAN GNSS Data and Product Table" & "Format Specification for COST-716 Processed GPS Data" | Done |
| #5 To identify best practices in making and verifying GNSS observations | "Guidelines on use and data exchange protocols for GNSS water vapour in NWP and climate models" | Done |
| #6 To provide guidelines for GNSS-PW uncertainty analysis | A journal paper | In progress |
| #7 To recommend practices on managing changes | "Managing changes in GRUAN GNSS-PW product" | Done |
| #8 To encourage and recommend experiments and research for resolving the tasks | | On going |

**Measurement**

**the assignment of numbers to objects or events**

- **level of measurement (magnitude)**
- **Dimensions (units)**
- **Uncertainty (Error)**

**No measurement, however carefully made, can be completely free of uncertainties!!!**

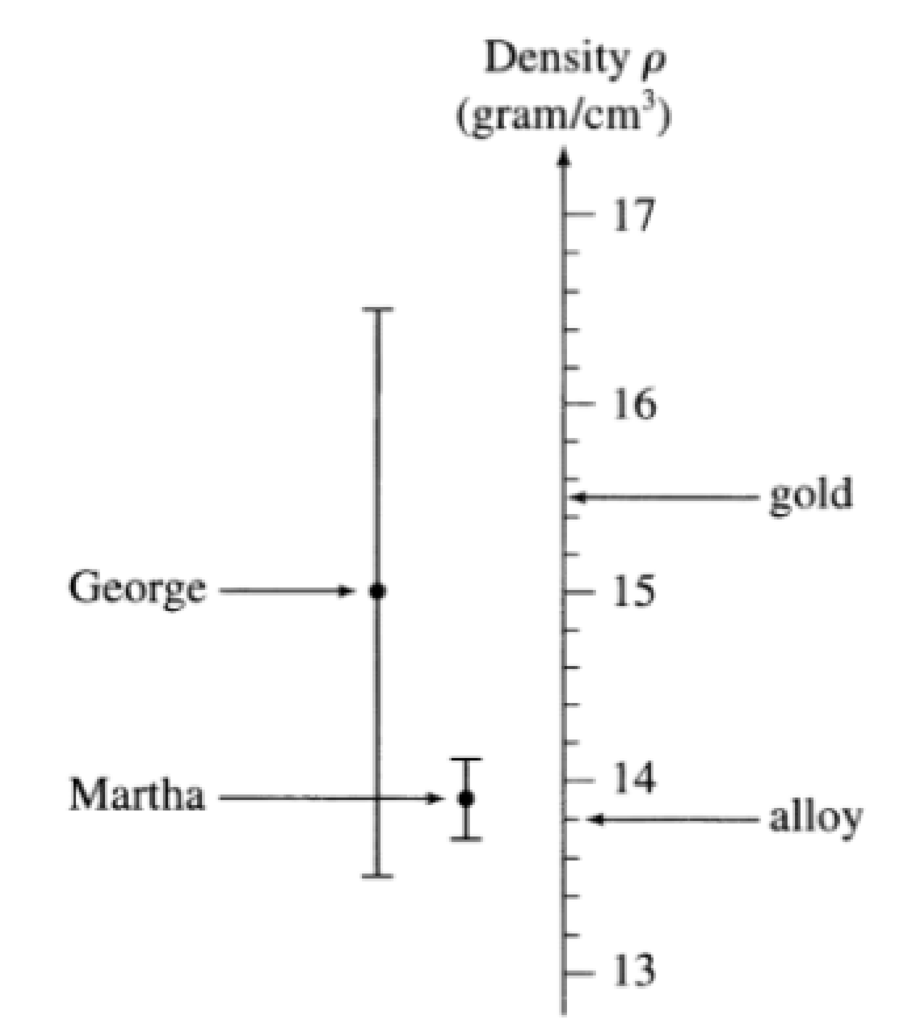
$$(\text{measured value of } x) = x_{\text{best}} \pm \delta x.$$

# Importance of Knowing the uncertainties

- Is a crown made of 18-karat gold or a cheaper alloy?
- Fact:

$$\rho_{\text{gold}} = 15.5 \text{ gram/cm}^3$$

$$\rho_{\text{alloy}} = 13.8 \text{ gram/cm}^3.$$



# PW Uncertainty Estimation

**General Formula for Error Propagation:** If $q = q(x, \ldots, z)$ is any function of $x, \ldots, z$, then

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x}\delta x\right)^2 + \cdots + \left(\frac{\partial q}{\partial z}\delta z\right)^2}$$

(provided all errors are independent and random)

$$V\ (PW) = \frac{ZTD - ZHD}{Q}$$

$$\sigma_V = \sqrt{\left(\frac{\sigma_{ZTD}}{Q}\right)^2 + \left(\frac{\sigma_{ZHD}}{Q}\right)^2 + \left(V\,\frac{\sigma_Q}{Q}\right)^2}$$

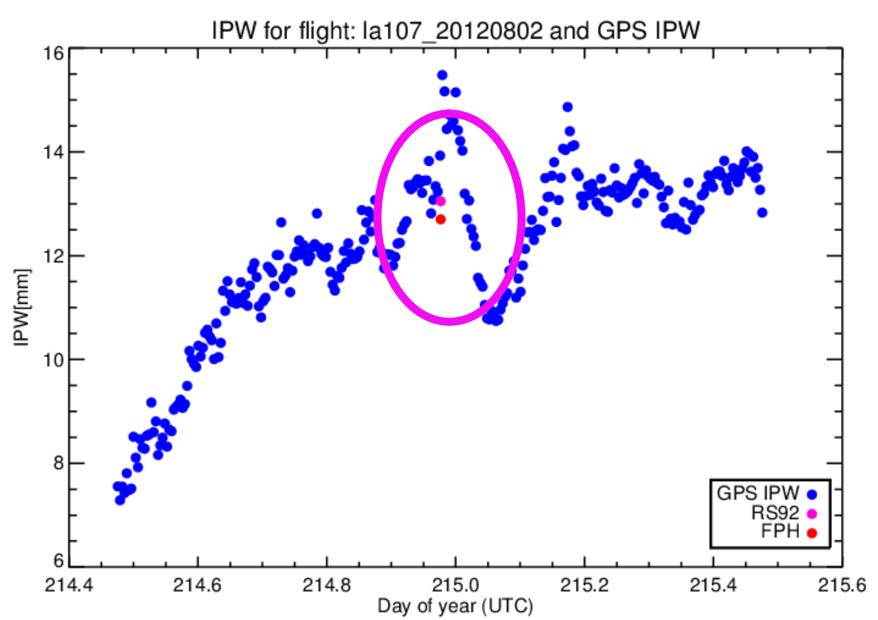
$$\sigma_{IWV} = \sqrt{\left(\frac{\sigma_{ZTD}}{Q}\right)^2 + \left(\frac{2.2768\,\sigma_{P_0}}{f(\lambda, H)\,Q}\right)^2 + \left(\frac{V}{Q}\,10^{-6}\,\rho_w\,R_w\sqrt{\left(\frac{\sigma_{k_3}}{T_m}\right)^2 + \sigma_{k_2'}^2 + \left(k_3\,\frac{\sigma_{T_m}}{T_m^2}\right)^2}\right)^2 \cdots}$$

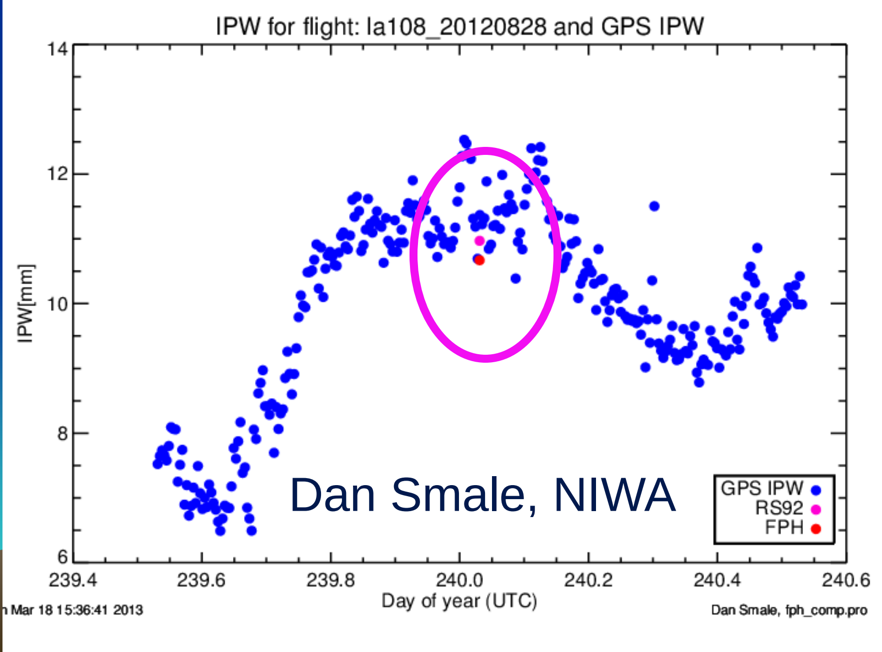
# PW uncertainty estimation

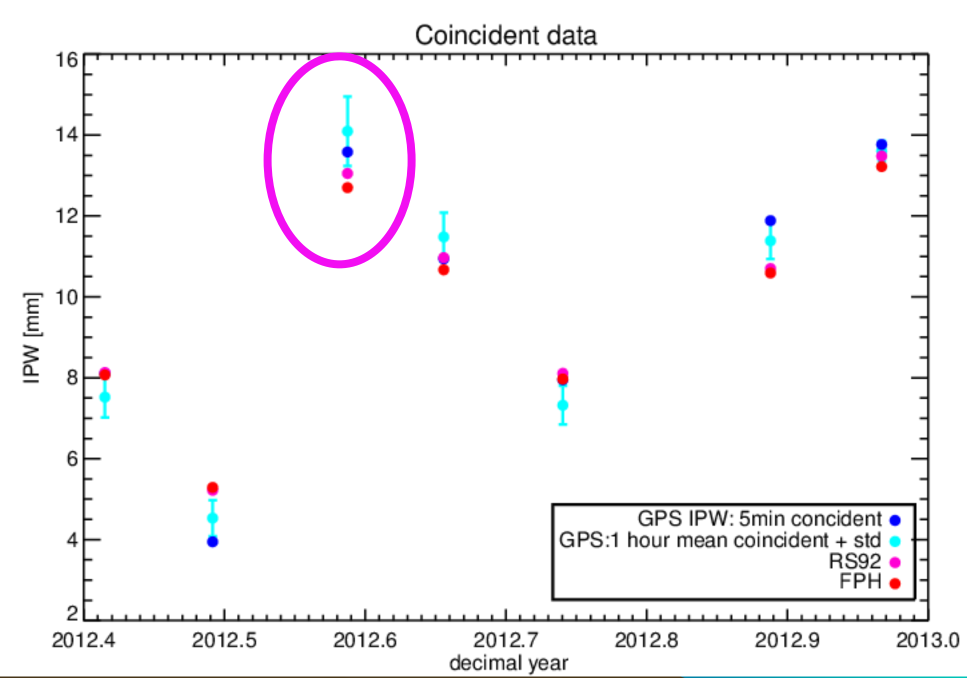
$$\sigma_{IWV} = \sqrt{\left(\frac{\sigma_{ZTD}}{Q}\right)^2 + \left(\frac{2.2768\,\sigma_{P_0}}{f(\lambda, H)\,Q}\right)^2 + \left(\frac{V}{Q}\,10^{-6}\,\rho_w\,R_w\sqrt{\left(\frac{\sigma_{k_3}}{T_m}\right)^2 + \sigma_{k'_2}^2 + \left(k_3\frac{\sigma_{T_m}}{T_m^2}\right)^2}\right)^2 \;(}$$

1. **ZTD and P0 uncertainties dominate (>94%).**
2. **P0 uncertainty: Help from surface obs. group??**
3. **Tm uncertainty: calculated from the input source.**
4. **ZTD uncertainty: formal error from the ZTD product?**
5. **Manuscript on this.**
6. **Collaborations with "COST ES1206 - Advanced GNSS Tropospheric Products for monitoring Severe Weather Events and Climate"**

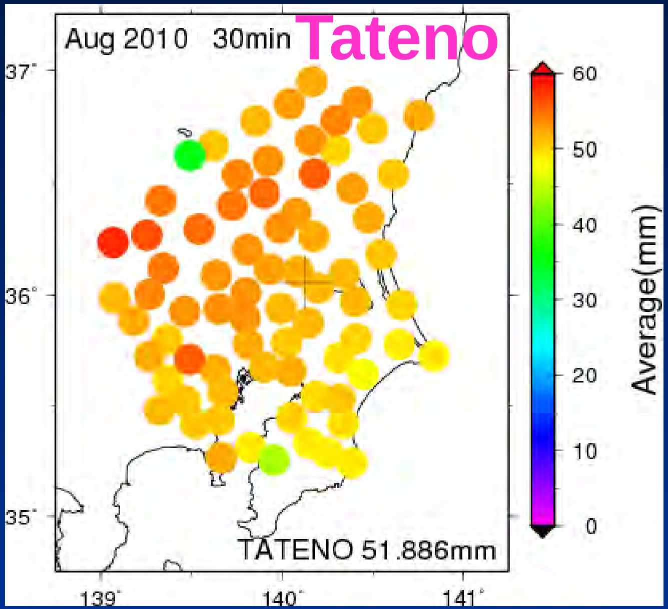
# From Guidelines to Implementation: Lauder site



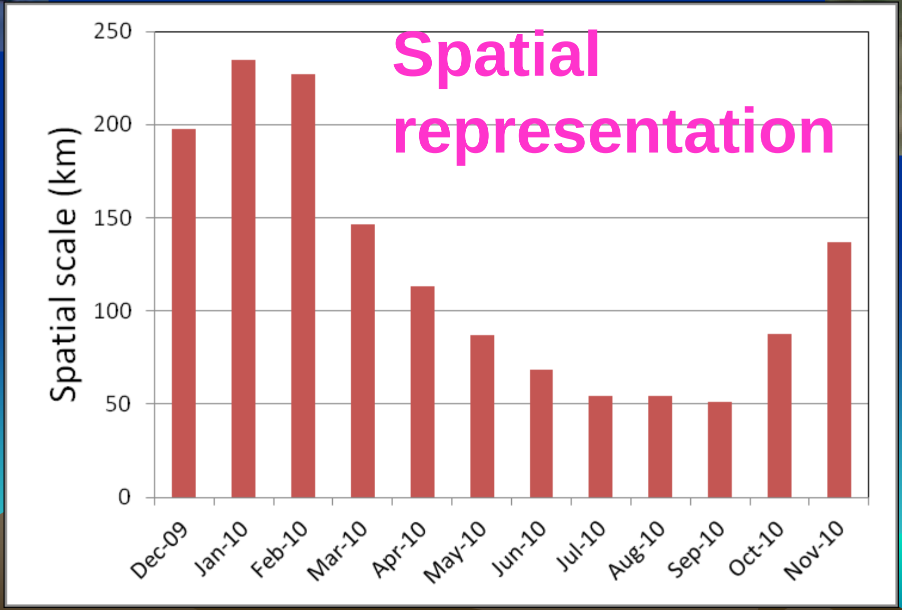



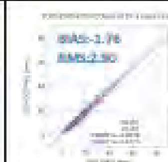
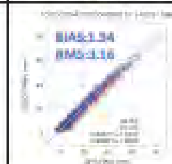
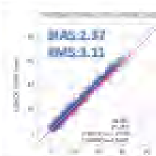
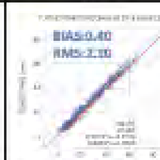
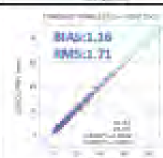
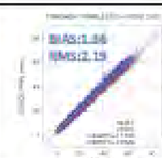
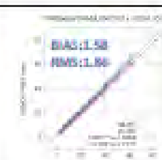
# Closely co-located GNSS receivers at GRUAN sites





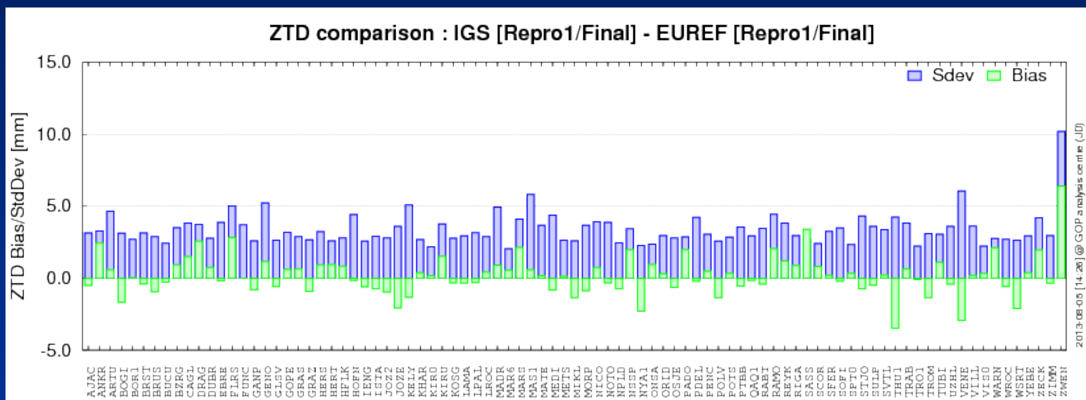
# Redundant Observations & Long-term stability

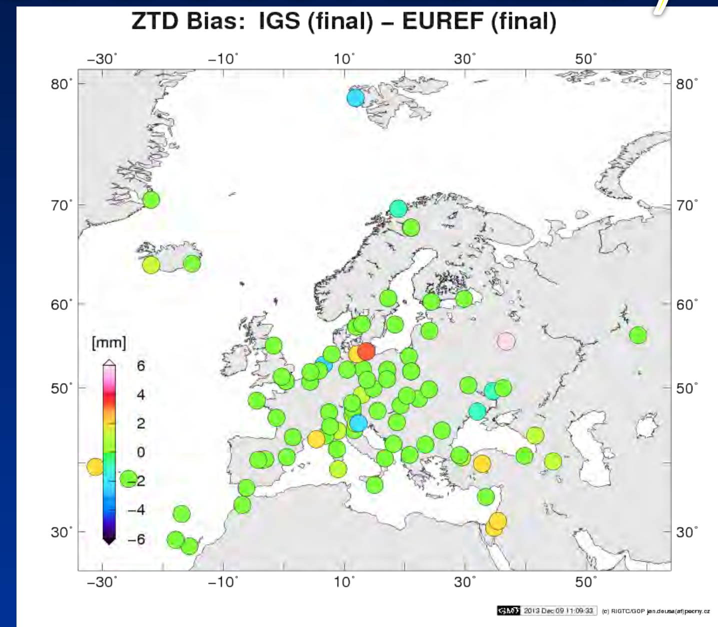
| Sonde | RS2-91 (Meisei) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ant. | AOAD MT | | TRM23903 | | | TRM29659 | | TOP700779A | |
| Rec. | SNR8100 | BENCHMARK ACT | 4000SSE | 4000SSI | 5700 | 5700 | NETRS | GPR1DY | ZXII3 |
| 1994 |  | |  | |  | |  |  | |
| 1996 |  | |  |  | http://www.e-trimblegps.com/images/5700l1mgis.jpg | | http://www.inlandgps.com/Products/NetRS-trimmed-Web-04.jpg |  | |
| 2002 |  |  | |  |  | | |  | |
| 2003 |  |  | |  |  |  | |  | |
| 2009 | http://www.giz.wettzell.de/Infozentrum/Geraetelisten/Positionierungssysteme/MW02-021_1.jpg |  |  | http://image.ec21.com/image/satriamanunggal/oimg_GC04358985_CA04358987/Trimble_4000_SSi_2MB_GPS_Receiver_Accesories_4000SSI.jpg | |  |  | http://x2.aucfan.com/item_data/thumbnail/20140212/yahoo/c/c418691436.jpg  | |

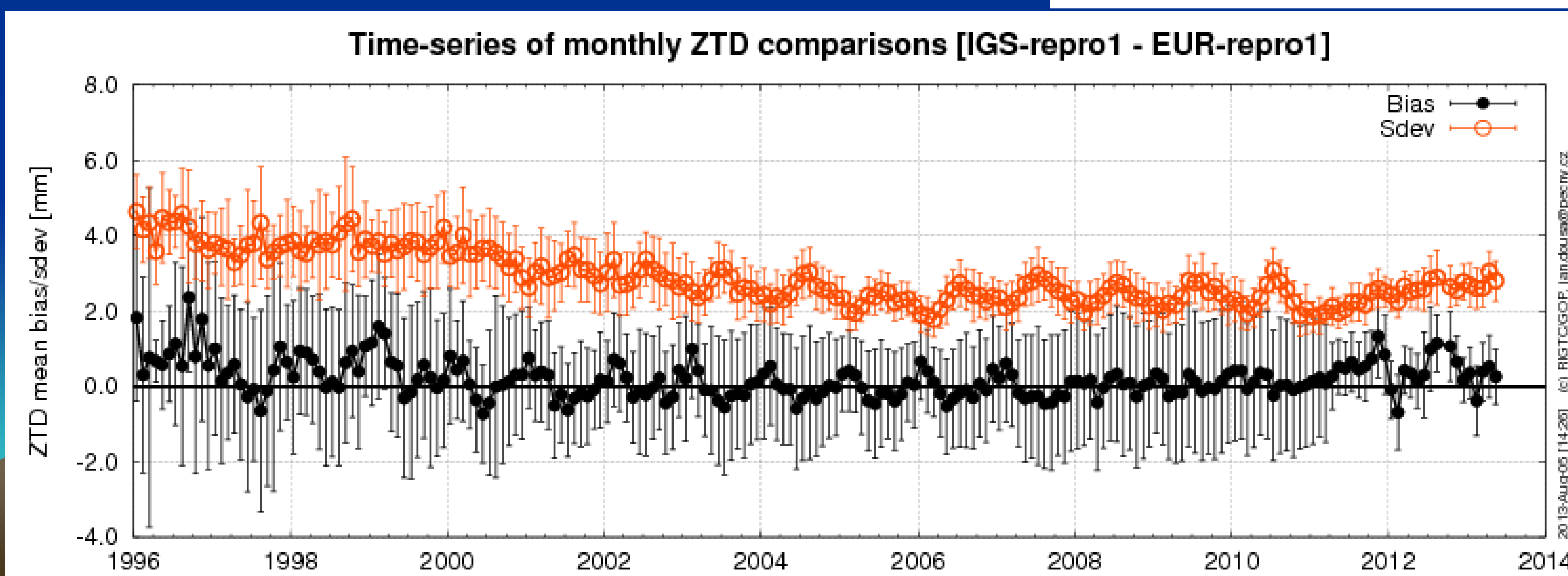
Careful assessment of GPS PWV with considering its antenna type, receiver type and accuracy of ephemerides is indispensable prior to use them for climate study.

# ZTD & PW comparisons from different techniques (IGS & COST ES1206 )

Jan Dousa (Geodetic Observatory Pecny)
(http://pecny.asu.cas.cz/gop/index.php/gnss-mainmenu-200/troposphere-e-gvapii-mainmenu-63/evaluations)



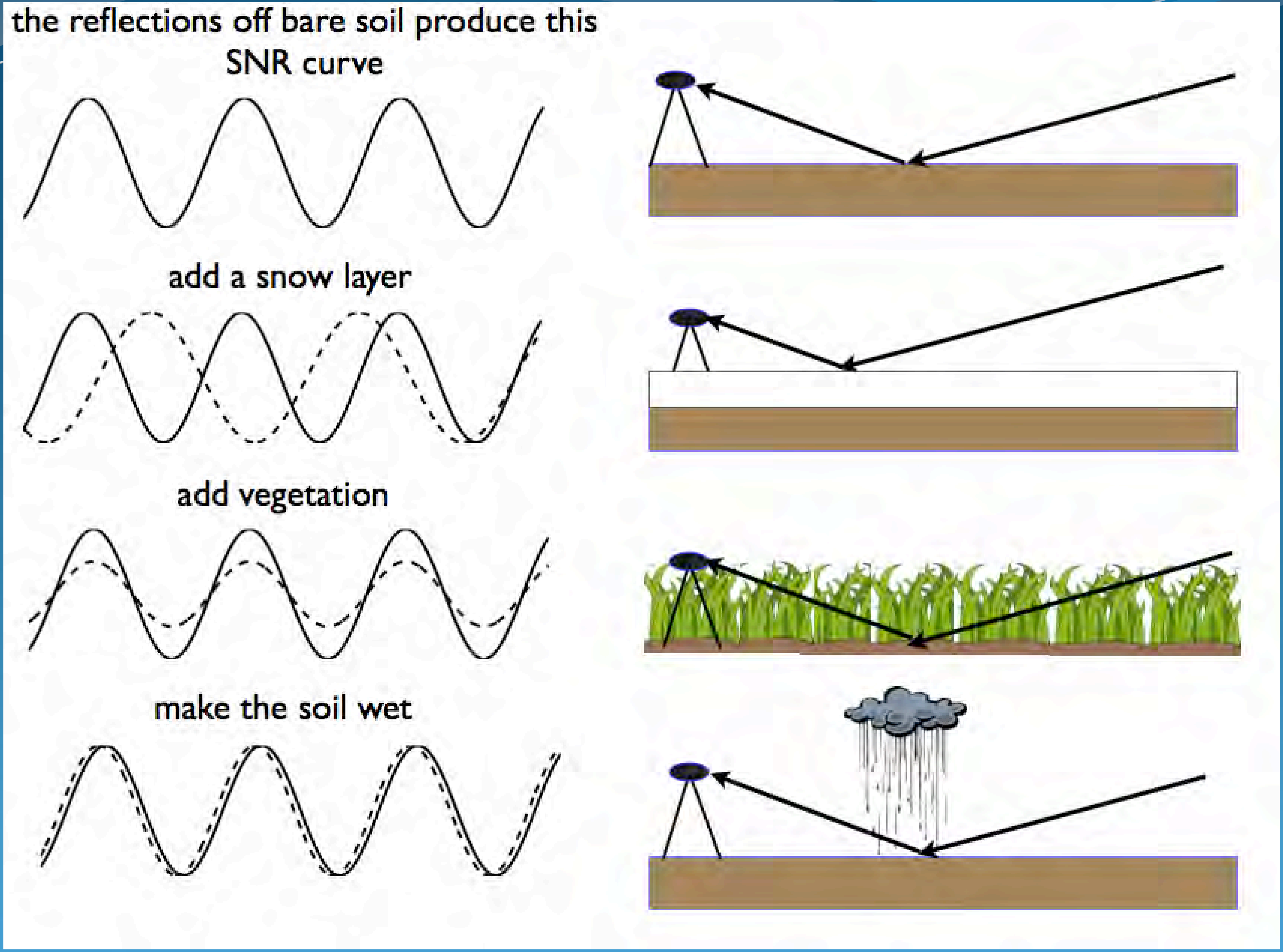



# Future of GNSS-PW TT

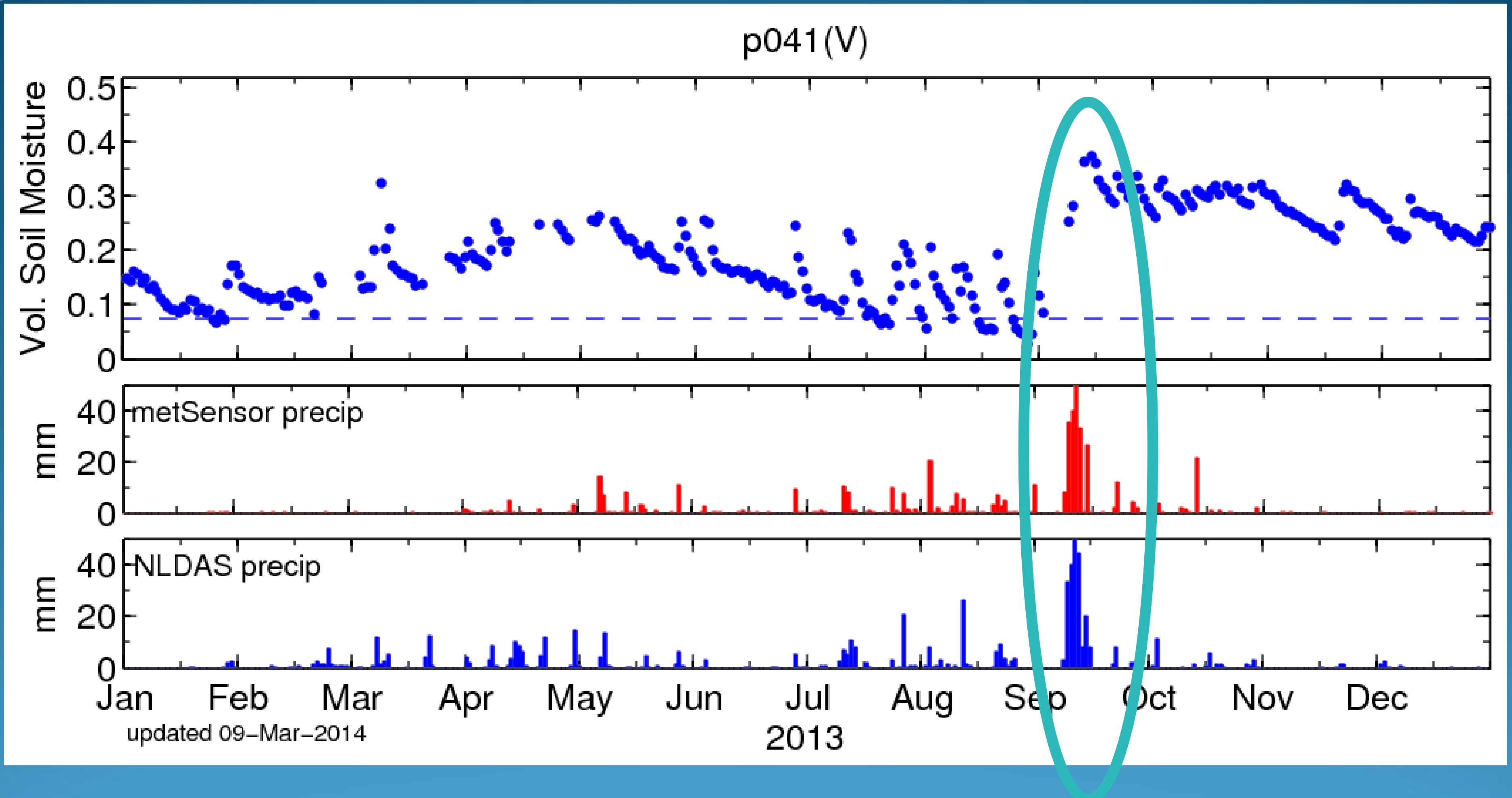
1. Finish un-finished tasks
2. Work with GFZ on updating various guidelines
3. Research: inhomogeneity, reprocessing, …
4. Expanding GNSS measurements and research beyond PW, such as Slant delay, tomography, reflection signals, GPS-RO, DORIS and so on

# Reflected GPS Signals



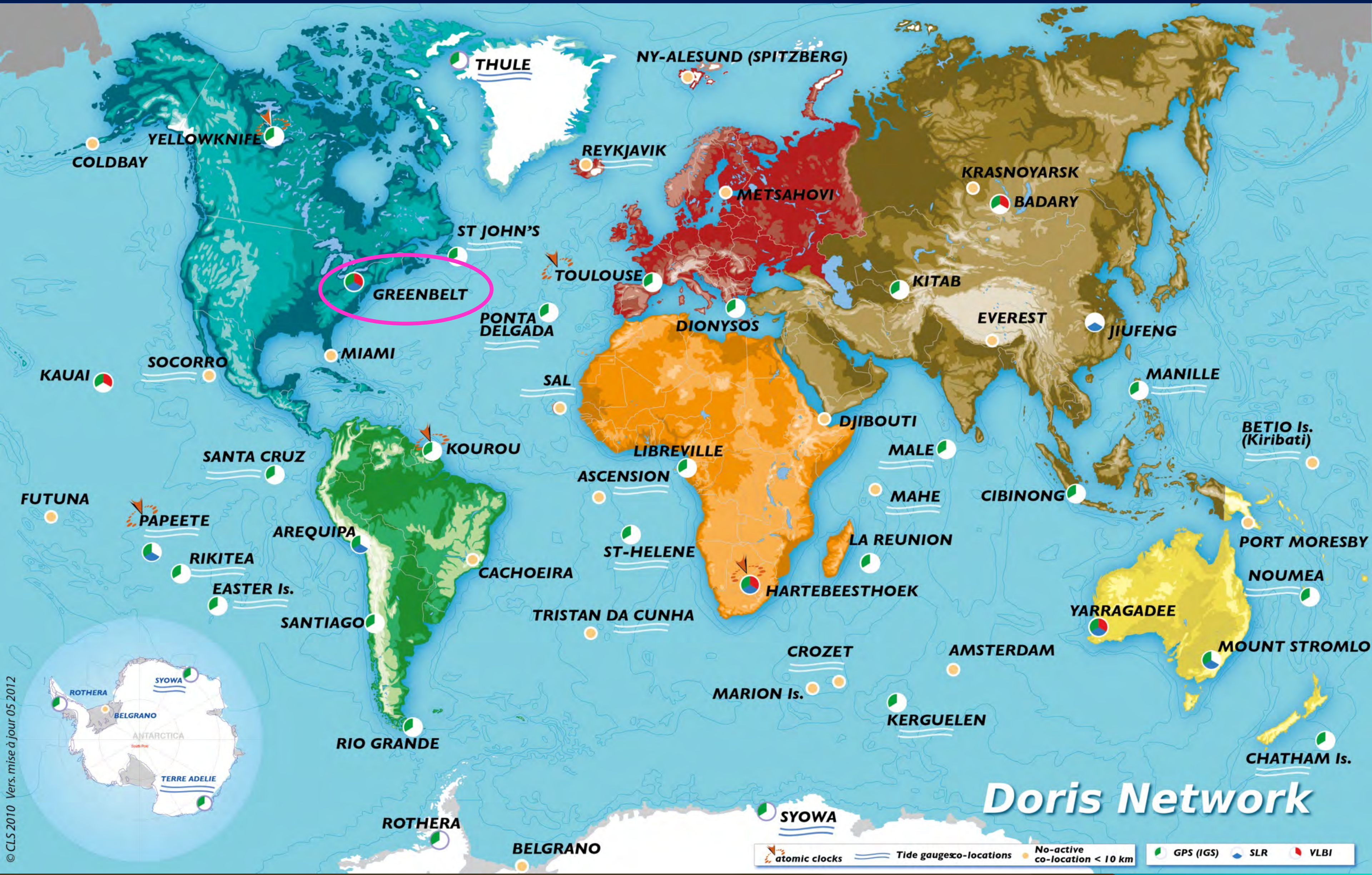

http://xenon.colorado.edu/portal/

# Soil Moisture Data at Marshall, Boulder



# DORIS

## (Doppler Orbitography and Radiopositioning Integrated by Satellite)



# NASA Goddard Geophysical and Astronomical Observatory