The Surprising Ability of the Global Positioning System (GPS) to Observe the Earth’s Water Cycle

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Topic Overview

- Simple Background of GPS
  - Satellite System
  - Signal structure
  - Geodesy

- Ground Water Loading
  - Primarily retrieval method is position time series analysis

- Atmospheric Water Vapor
  - Estimates derived from same analysis techniques used when estimating positions

- GPS Interferometric Reflectometry (GPS-IR)
  - Soil moisture
  - Vegetation
  - Snow
Satellite Constellation

- **Number of satellites**: 24 (planned), 32 (current)
- **Orbital planes**: 6
- **Satellites per plane**: 4 (planned) 5 or 6 (current)
- **Orbital period**: ~12 hours
- **Orbital radius**: 26,400 Km
- **Inclination**: 55°
- **Eccentricity**: ~0°
GPS Observation Types

<table>
<thead>
<tr>
<th>Observation Name</th>
<th>Frequency Multiplier</th>
<th>Frequency</th>
<th>Wavelength</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/A</td>
<td>$f_0/10$</td>
<td>$1.023 \text{ MHz}$</td>
<td>$300 \text{ m}$</td>
<td>$\sim 10 \text{ m}$</td>
</tr>
<tr>
<td>P1 (Y1), P2(Y2)</td>
<td>$1* f_0$</td>
<td>$10.23 \text{ MHz}$</td>
<td>$30 \text{ m}$</td>
<td>$\sim 3 \text{ m}$</td>
</tr>
<tr>
<td>L1</td>
<td>$154* f_0$</td>
<td>$1575.42 \text{ MHz}$</td>
<td>$19.0 \text{ cm}$</td>
<td>$\sim 1 \text{ mm}$</td>
</tr>
<tr>
<td>L2</td>
<td>$120* f_0$</td>
<td>$1227.60 \text{ MHz}$</td>
<td>$24.4 \text{ cm}$</td>
<td>$\sim 1 \text{ mm}$</td>
</tr>
</tbody>
</table>

All GPS signals are derived from a set of atomic oscillators. Their well defined structure makes them a unique observation system to exploit. The need to observe at least 4 satellites at all points on earth makes the signals ubiquitous.

It is an understatement to say that the applications of GPS far exceed the original design objectives of the DoD.
Common GPS Applications

Aviation

Roads

Recreation

Agriculture

Surveying

Timing

http://www.gps.gov/applications/

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GPS as a Tool to Observe the Hydrological Cycle – UT Arlington Seminar – Jan 2012
GPS Station Locations
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P571 Bedrock site in Sierra Nevada Foothills
- Shows secular uplift (~5 mm/yr)
- Annual Cycle peaks in October

P056 Site in Sediments in San Joaquin Valley
- Shows rapid secular subsidence rate (~30 mm/yr)
- Annual Cycle peaks in April
Ground Water

Unconfined aquifer

Confined aquifer

Sand and gravel

Clay and silt (aquitards)

The increased load compresses the skeleton by contracting the pore spaces, causing some lowering of the land surface.

Under the decreased load the pore spaces and the skeleton expand, causing some raising of the land surface.

Depth to water

Time

Fall

Spring

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Groundwater Pumping

Deep-drilled braced in sediments in valley near Sacramento, Calif.

The peak of the annual signal is in March-April and is in phase with water table height.
Hydrologic Loading N. Calif. Mts

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Hydrologic Surface and Lake Loading

Hydrologic surface loading plus lake loading fits vertical GPS signal to sigma ~2 mm. Shasta Lake level data from Calif. Dept. of Water Resources.
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Simplistic GPS PW Explanation

\[ N = 77.6\left(\frac{p}{T}\right) + 3.73 \times 10^5\left(\frac{e_w}{T^2}\right) \]

\[ \Delta L = 10^{-6} \int_s \left[ 77.6\left(\frac{P}{T}\right) + 3.73 \times 10^5\left(\frac{e_w}{T^2}\right) \right] ds \]

\[ ZTD = ZHD + ZWD = \frac{SHD}{m_h(\ )} + \frac{SWD}{m_w(\ )} \]

\[ PW = \frac{IWV}{\gamma} = ZWD \]

or

\[ PW = \frac{1}{\gamma} \cdot IWV = \frac{1}{\gamma} \int v \, dz \]
Example of GPS Water Vapor Time Series

GOES IR satellite image (left) with location of GPS station shown as red star. Time series of temperature, dew point, wind speed, and accumulated rain shown in top right. GPS PW is shown in bottom right. Increase in PW of more than 20mm due to convective system shown in satellite image.
GPS and MWR PW Comparisons

Arctic
rms = 0.73 mm

Mid-Latitude
rms = 0.93 mm

Tropics
rms = 1.65 mm

SG27_B50_gfsNwZ
LMNO_GFSn_MD
SA40_B50_gfsNwZ
Suominet Jan 23-26, 2012
Fig. 2. NFI [as defined by Eq. (1)] for the 3-h RH forecast error (using RUC60) from assimilation of GPS-IPW data. Impacts at 850, 700, 500, and 400 hPa averaged by year for 1999–2004 are shown. Forecast error is assessed by computing forecast minus observed RH difference with rawinsonde observations at 17 stations in the south-central United States (within rectangle in Fig. 1).

Smith, et. al. 2007, Monthly Weather Review

Fig. 6. IPW RMS error (mm) for RUC20 IPW analysis/forecast grids against GPS-IPW observations at ~275 sites in the RUC continental United States (CONUS) domain. Statistics are for the 3-month period from 1 Mar to 31 May 2004. RUC20 with GPS is solid; RUC20 without GPS is dashed.
Beijing Summer Storms Frequently Induce Flash Flooding
Six-Hour Forecast Using GPS PW

GFS

- Init: 12 UTC Fri 09 Jul 04
- Valid: 12 UTC Sat 10 Jul 04 (20 LDT Sat 10 Jul 04)
- Total precip. in past 6 h

BMB+PW

- Init: 12 UTC Fri 09 Jul 04
- Valid: 12 UTC Sat 10 Jul 04 (20 LDT Sat 10 Jul 04)
- Total precip. in past 6 h

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Inhibition of the precipitation → Nature of the cases? IC/model problems?

Accumulated rainfall for the 1st afternoon (00~12-hr fcst) (08~20 LST)

Location of the precipitation was wrong

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Multi-year PW timeseries (above)
Hurricane Kalmeaegi (2008) (top right)
One week, 2010 (right)
Diurnal Signal In GPS PW

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Diurnal Signal Feb vs Aug 2009

Diurnal Variability

TATA

May 2010

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PW and Hurricanes

Category 0-2 GPS-PWV (34 - 95 knots)

Results from Vanessa Almanza, SOARS Protegee, San Francisco State University
Hurricane Intensity is Dependent on PW

Correlation coefficient of water vapor and station pressure is 0.71
Storms with winds of 70 mph have coefficient of 0.76
Multi-Disciplinary Natural Hazards Research Initiative Begins Across the Caribbean Basin, EOS (accepted for publication)
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GPS Interferometric Reflectometry (GPS-IR) (collaborative research with K. Larson and E. Small @ CU)
- Soil moisture
- Vegetation
- Snow
Ground Multipath Schematic

Direct signal

Reflected signal

Antenna gain pattern

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Satellite Position and Fresnel Zones
Changes in SNR and LSP_EST

GPS SNR Data (volts)

A. 

B. Lomb–Scargle Periodogram (power)

Volumetric Water Content
0.05
0.35

C. 

D. Mowing
after
before

E. 

F. no snow
35 cm snow

sine (elevation angle)

effective reflector height (m)
Marshall Field Soil Moisture

Water Content Reflectometers

VWC [cm$^3$/cm$^3$]

Day of Year

Rain (mm)

$\phi$ (degrees)

VWC (cm$^3$/cm$^3$)
NDVI and Multipath
GPS-IR and Snow

May 1st, 2011

Sep 24th, 2009

Snow depth (cm)

Oct Nov Dec Jan Feb Mar Apr May

Snow depth (cm)

Oct Nov Dec Jan Feb Mar Apr May
GPS as a Tool to Observe the Hydrological Cycle

Formal Snow Uncertainty: 2.5 cm
Applications of GPS are becoming increasingly imbedded in modern society. Its use as a tool to study the hydrological cycle is one unexpected example.

- Time Series of Positions
  - Snow and reservoir loading (mountains)
  - Ground water depletion

- Atmospheric Delay Estimation
  - Provides total column water vapor
  -Insensitive to condensed (liquid and ice) water

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**Summary**

**The Hydrologic Cycle**

- Precipitation
- Water Storage in the Atmosphere
- Transpiration
- Evaporation
- Condensation
- Water Storage in Oceans
- Water Storage in Ice and Snow
- Snowmelt Runoff to Streams
- Surface Runoff
- Freshwater Storage
- Ground Water Storage
- Ground Water Infiltration
- Ground Water Discharge

**Snow**
What was not Discussed