A multi-sensor approach to estimation of tropospheric delays

Y. Bar-Sever (1), S. Byun (1), R. Haas (2), S. Keihm (1), Tim Munson (1), Al Tanner (1), Larry Young (1)

(1) Jet Propulsion Laboratory, California Institute of Technology
(Yoaz.Bar-Sever@jpl.nasa.gov), (2) Onsala Space Observatory, Chalmers University of Technology (haas@oso.chalmers.se)

We will discuss techniques for optimal integration of atmospheric measurements from collocated GPS receiver, pointed WVR, and a barometer, capitalizing on the unique strength of each sensor, and minimizing the impact of the sensor’s weaknesses. The goal is to improve our ability to estimate line of sight (LOS) total atmospheric delay, which is required in support of certain high precision applications, such as radio science, and deep space navigation. The benefits from improved atmospheric sensing extend to many other applications such as geodesy and time transfer.

The WVR’s strength is its unparalleled accuracy in sensing the water vapor content along a given LOS, which produces the “wet” delay of a radio signal. But WVRs are incapable of measuring the contribution of the dry atmosphere to the delay, the fluctuations of which are a significant error source for certain radio science applications. GPS data is directly sensitive to the total tropospheric delay (wet plus dry). However, GPS analysis has so far failed to demonstrate comparable sensitivity to the WVR in resolving LOS delays. By using WVR to calibrate the line of sight wet delays affecting a collocated GPS receiver we will be able to tune the GPS estimation strategy to extract only the slowly varying dry delay component, improving the GPS retrieval accuracy. Barometric measurements may be used to further reduce the number of estimated parameters by modeling the zenith dry delay. The combined total delay provides the best estimate of the LOS total delay.

We assess the performance of these techniques primarily by examining time transfer performance across long baselines, using special experimental setup with pointed
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Yoaz Bar-Sever, Sung Byun, Steve Keihm, Tim Munson, Al Tanner, Larry Young

Jet Propulsion Laboratory, California Institute of Technology

and Rudiger Haas
Onsala Space Observatory
Sweden
Motivation

Challenging requirements of NASA/JPL missions:
- 1 mm accuracy in relative total path delay over 10° azimuth variations, at 10° (deep space navigation, Cassini Gravitational Wave Experiment, and other radio science experiments)
- 30 psec (~1 cm) time transfer (Primary Atomic Reference Clock in Space - PARCS)

Significant portion of the error budget is traced to GPS-based trop delay
- Clock errors are typically 3 times as large at zenith delay errors.

The required performance may be beyond the capability of GPS alone, but may not be achievable without GPS
The Concept

Investigate optimal processing of complimentary measurements from several sensors
- Wet delay measurements from pointed Water Vapor Radiometer (WVR)
  - Best for line of sight wet delay retrievals
- Zenith dry delay from surface pressure measurements
  - Highly accurate if well calibrated and operated (modulo bias)
- Dry delay gradients from GPS
  - Uncertain quality
  - No simple alternative

Liberating GPS from the need to estimate highly variable quantities enables retuning of the estimation process to optimize dry gradients retrieval

Demonstrate improvements to:
- Total LOS delay
- Clock estimate
- Everything
Experimental Testing and Validation

Verification of time transfer improvements require two sites instrumented with pointed WVRs, barometers, and atomic clocks
- JPL is currently constructing one such site in Goldstone, California
- Seeking a twin site

Exploit available experimental data to partially test and validate the approach: Lamont, Oklahoma, July - August 1999

GPS: AOA Benchmark
WVR: Radiometrics
Met: Paroscientific MET3

No atomic frequency reference

Poor monumentation

No objective analysis available yet

=> Truth is not available
Data Processing

**WVR data:**
- The WVR points to all GPS satellites in succession
  - 2 sec dwell time in July, 10 sec dwell time in August (~5-7 min cycle)
- 10° elevation angle cutoff
- Interpolate zenith-mapped WVR LOS delays to GPS measurement epochs (5 min)
- Edit out data with liquid water indication

**GPS data:**
- 24 hour arcs centered on noon of each day
- 5 minute data interval
- Up to 12 satellites tracked simultaneously
- 7° elevation angle cutoff (effectively 10° to match WVR measurements)

**Combined processing**
- Use only measurements for which good WVR measurements and surface pressure are available (also for GPS-only processing)
- Eliminate non consecutive days, and epochs during large gaps is WVR data
- Overall we processed 11 days in July and 11 days in August
Estimation and Validation Approach

Estimation approaches:
- **Nominal**: GPS-only data, random walk ZWD (9 mm²/hr), random walk grads (0.09 mm²/hr)
- **GPS-WVR-Pressure Calibrations (GWPC)**: Calibrate GPS data with WVR measurements, a-priori dry delay from surface pressure, estimate daily zenith delay, random walk grads (0.09 mm²/hr)
- **Optimized GWP (GWPC-Opt)**: Same as GWPC but with 0.0036 mm²/hr variance for random walk grads
- **GPS-WVR-Pressure Estimates (GWPe)**: A-priori WVR-based estimates of wet zenith delay and wet gradient, dry delay from surface pressure, estimate daily zenith delay, random walk grads (0.09 mm²/hr)
- **Optimized GWPe (GWPe-Opt)**: Same as GWPe but with 0.0036 mm²/hr variance for random walk grads

Validation approach:
- Reduce day-to-day discontinuities of gradients
- Improve site position repeatabilities
Reduction in post-fit residuals (in GWPC) despite added WVR noise and lower degree of freedom is indicative of successful media calibration with WVR and barometric measurements.
Validation - Position Repeatability

- Local condition are fundamentally unstable
- Vertical repeatability may get worse because of inability to soak up mismodeling
The optimized calibration/estimation approaches significantly improve gradient discontinuities across day boundary, and produce more physical (smooth) estimates.
Conclusions:

- This preliminary analysis shows promise for overall improvement by optimally incorporating into GPS analysis data from WVR and barometer.

- Incorporating WVR-based zenith delay and gradients is more robust than direct LOS measurement calibration, and performs nearly as well.

- Sensor calibration, and quality control are challenging but essential.

In the future:

- Calibration of antenna phase center is expected to improve overall performance.

- Explore impact on time transfer through specially-configured experiment.

- Use objective analysis to directly validate the dry gradients.