Development and Testing of a Miniaturized, Dual-Frequency, Software-Defined GPS Receiver for Space Applications

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February 1, 2012

THE UNIVERSITY OF TEXAS AT AUSTIN
RADIONAVIGATION LABORATORY

Outline

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- Goals
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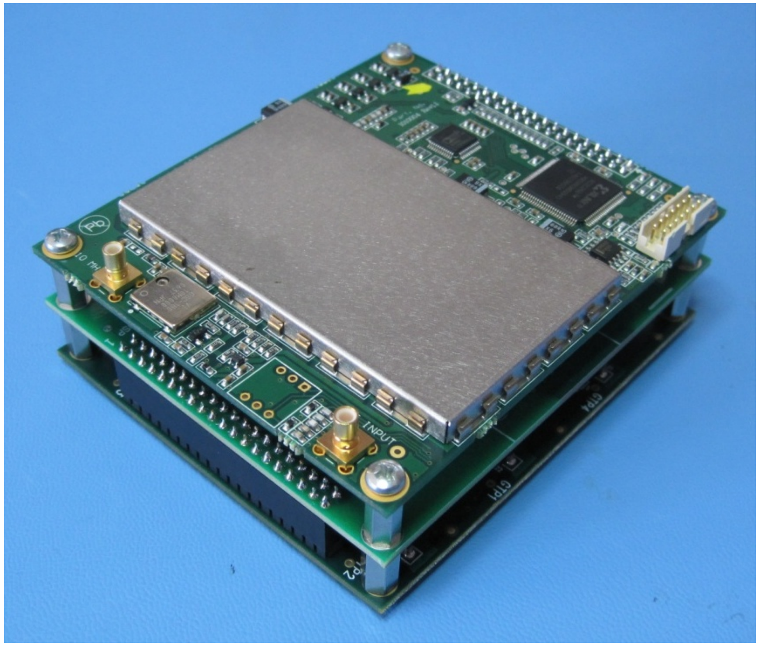
- On-Orbit Acquisition/Duty Cycling
- LEO Navigation
- Radio Occultation Observation
- GEO Navigation
- Hardware/Flight Testing
- Conclusions



Motivation

- Why is there a need for a small, high-precision GPS receiver for space missions?
  - Space science missions often require precise positioning
  - Use of legacy high-precision receivers on small satellites restricted by volume, mass, and power requirements

- Why use small satellites for space science missions?
  - Low cost encourages university involvement
  - Large constellations of small satellites provide more instrument coverage at a fraction of the cost

Goals

- <1 W Orbit-Average Power
- <500 g Mass
- 0.5U CubeSat Form Factor
- Sub-Meter Low Earth Orbit (LEO) Navigation
- Ionospheric Occultation Observation
- Geosynchronous Orbit (GEO) Navigation

Background

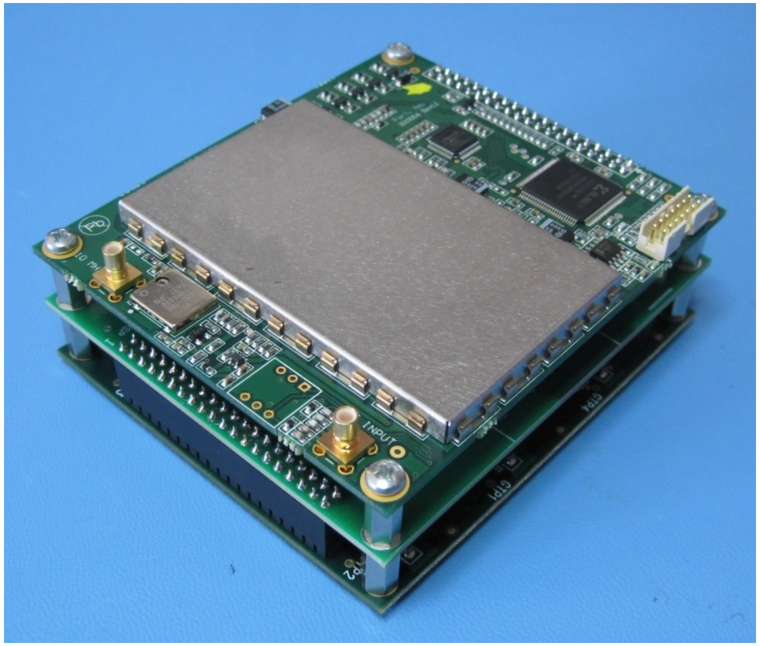
Background: CASES

- CASES: Connected Autonomous Space Environment Sensor
  - Software-defined, dual-frequency receiver
  - Developed by the University of Texas and Cornell University
  - Designed to measure ionospheric scintillation
- Data Output
  - Navigation, observations, raw IQ, TEC, SV data

CASES: A Smart, Compact GPS Software Receiver for Space Weather Monitoring. *2011 ION GNSS Conference*

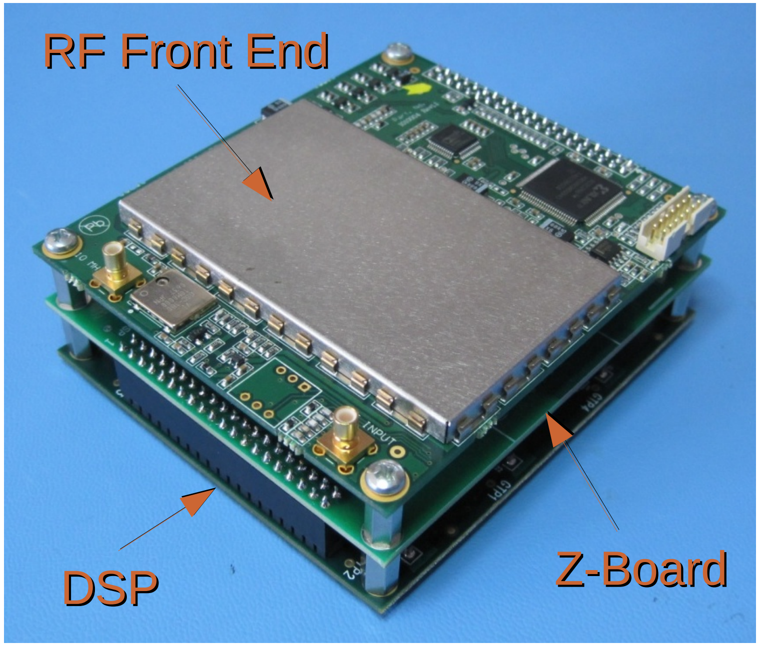
Background: FOTON

- FOTON: Fast, Orbital, TEC, Observables, and Navigation Receiver
  - Space-based, dual-frequency, software-defined receiver
  - Developed from CASES
  - Hardware repackaged into smaller form factor
  - Software altered to allow LEO navigation



Background: FOTON

- Hardware (COTS components on custom boards)
  - Bobyn RF Front End
  - TI C6457 Digital Signal Processor
  - Interface Board (Z-Board)
  - Volume: 0.5U CubeSat form factor (8.3 x 9.6 x 3.8 cm)
  - Mass: 326 g
  - Power: 4.5 W, <1 W orbit average power



- Software
  - Tracks GPS L1 C/A, L2C, and L5
  - Configurable for tracking other L-band signals
  - Arbitrary number of channels, limited by data downlink

Background: Software Changes

- Terrestrial → Space-based Conversion:
  - Release ITAR altitude/speed limits* – Done
  - Widen Doppler range to ±40 kHz (increases memory requirements) – Done
- Radio Occultation:
  - Occultation prediction – In Process
  - Suppress clock fix-up during occultation – Done
  - Open-loop tracking – Done
  - Data bit prediction – Done

*Software uploads/testing done within ITAR-restricted lab

Initial Testing

Initial Testing

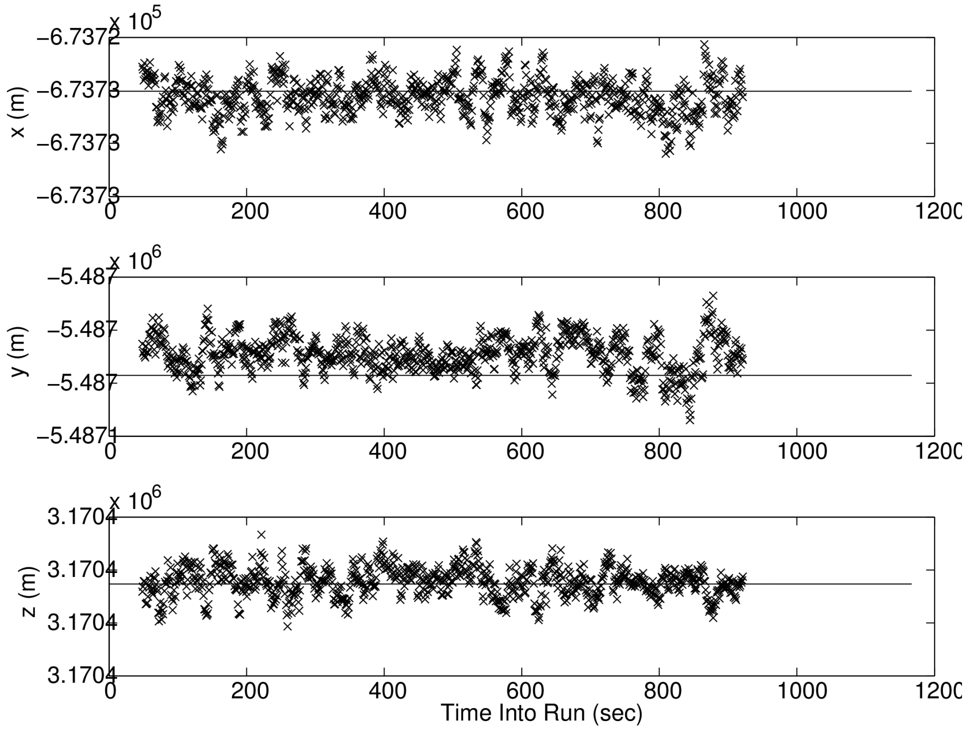
- Testing on Spirent GPS signal simulator
  - Baseline receiver (Rx) testing
  - Ionosphere and Troposphere not simulated
  - Satellite (SV) clock and ephemeris errors not simulated
- Tests include:
  - Static simulation
  - Rectangular track (low-dynamics) simulation
  - Low earth orbit simulations

Initial Testing

Terrestrial Tests

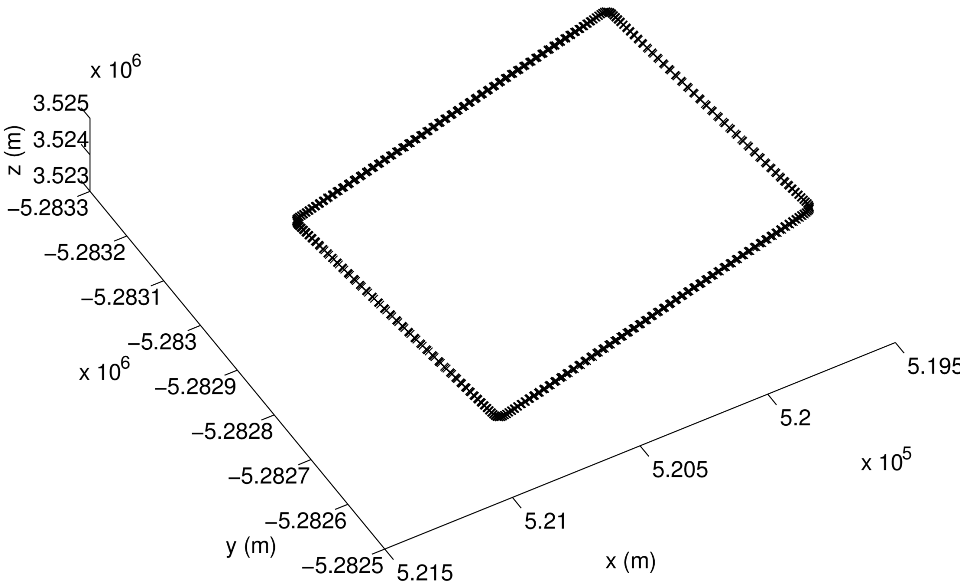
Static Simulation

- 0.46 m RMS error



Rectangular Track Simulation

- 0.83 m, 0.12 m/s RMS error



Initial Testing

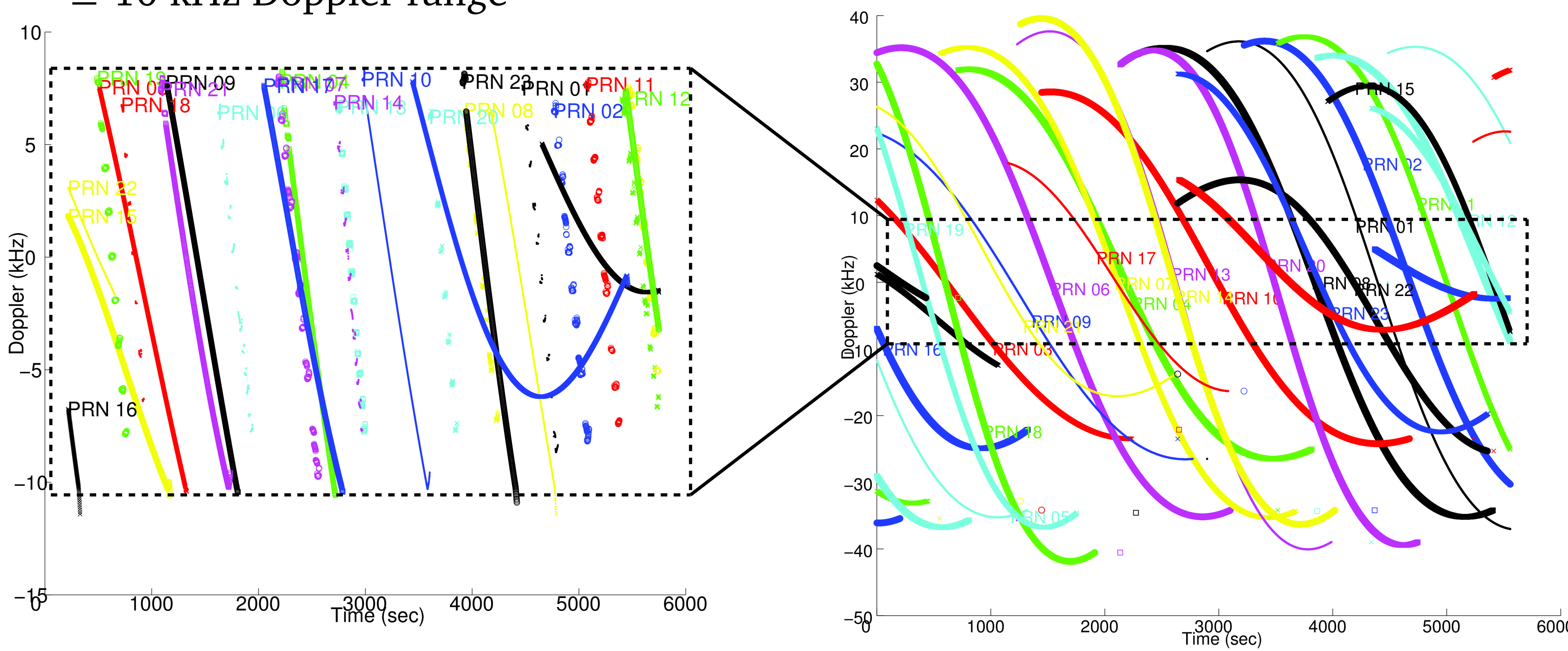
LEO Doppler Test

Tracked Doppler

- **Before** software updates
- Tracked 1-3 signals
- ± 10 kHz Doppler range

Simulated Doppler

- Inclined, 90 min. period LEO
- Produced ± 40 kHz Doppler

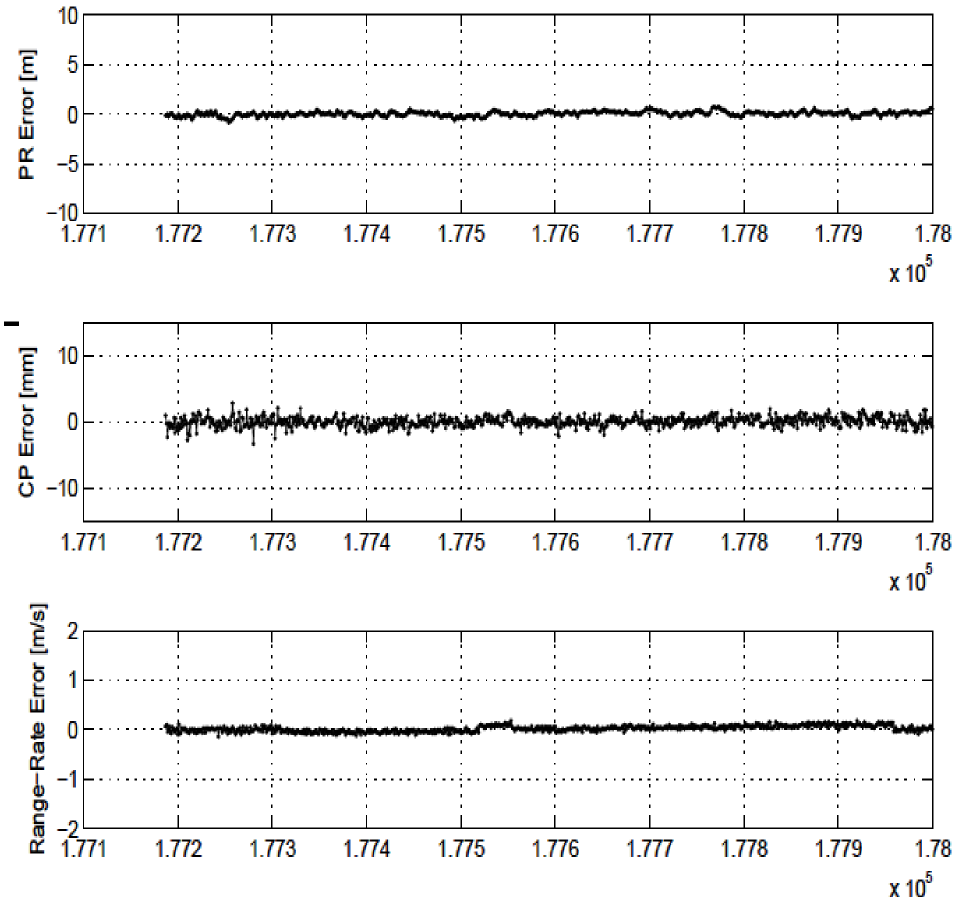


Andrew Joplin
02/01/2012

Initial Testing

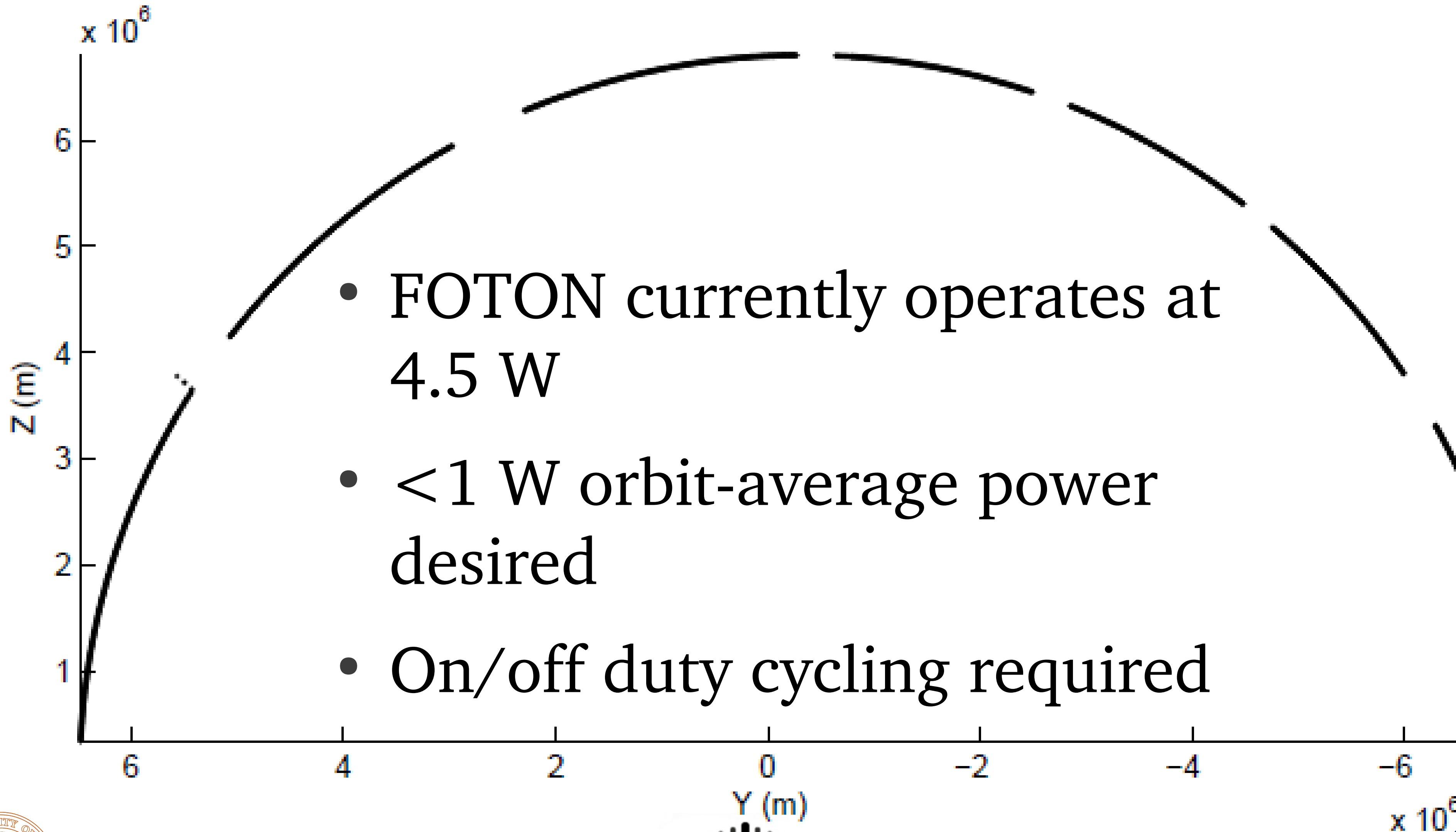
LEO Benchmark Tests

- Simulated polar LEO
- Double-difference of observables
  - Removes geometry and Rx clock effects
  - Leaves only Rx- and channel-specific noise
- RMS Errors:
  - Pseudorange: 0.1616 m
  - Carrier Phase: 0.5973 mm
  - Range Rate: 0.0569 m/s



On-Orbit Acquisition/Duty Cycling

On-Orbit Acquisition/Duty Cycling



- FOTON currently operates at 4.5 W
- <1 W orbit-average power desired
- On/off duty cycling required

On-Orbit Acquisition/Duty Cycling

- Current on-orbit acquisition capability:
  - DSP reset time: 15 sec
  - FFT-based acquisition: <5 sec
  - Ephemeris retrieval: <30 sec
  - Overall time to first fix (TFF): <1 min.
- TFF dominated by DSP reset and ephemeris retrieval
  - Store ephemerides in memory (in process)
  - Operate DSP in low-power mode (in process)
  - TFF of a few seconds attainable
- Duty cycling is possible

LEO Navigation

LEO Navigation
Kalman Filter

- Extended Sequential Kalman Filter (EKF)
- Combine L1 pseudorange and Doppler with assumed LEO dynamics to smooth nav solution
- State: ECEF position/velocity, Rx clock bias/rate
- State dynamics model:
  - Pos/vel: J2 gravity model + noise
  - Clock: 1st order + noise

LEO Navigation
Kalman Filter

- Tested with LEO simulation
- Comparison of EKF with point-wise linear least-squares solutions:

	Kalman Filter	Point Solutions
RMS Position (m)	0.544	0.739
RMS Velocity (m/s)	0.0121	0.247

- Can be improved with higher-fidelity dynamics model

LEO Navigation

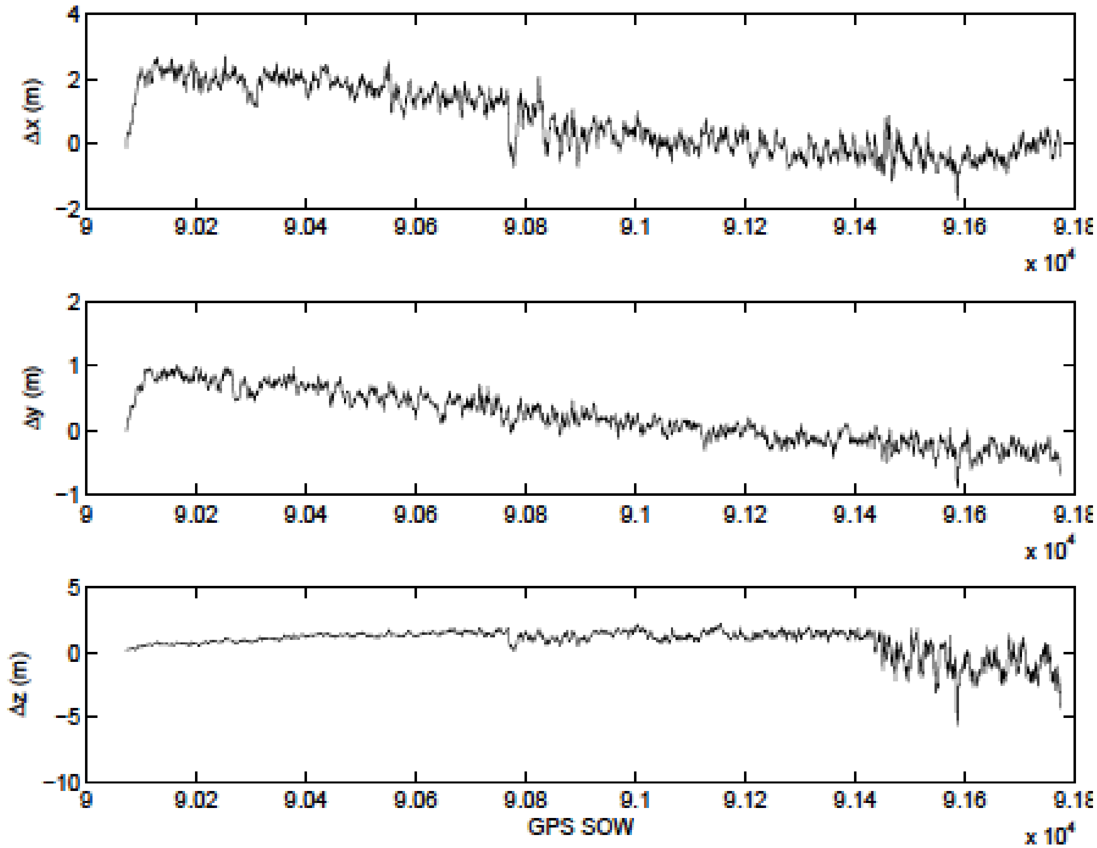
Dual-Frequency Capability

- Ionospheric modelling algorithm:
  - Running estimate of TEC (Total Electron Content) used to model ionosphere real-time
  - L2 pseudorange not otherwise used in nav solution
- LEO Test:
  - Polar LEO simulation
  - Ionosphere, L2C simulated

LEO Navigation

Dual-Frequency Capability

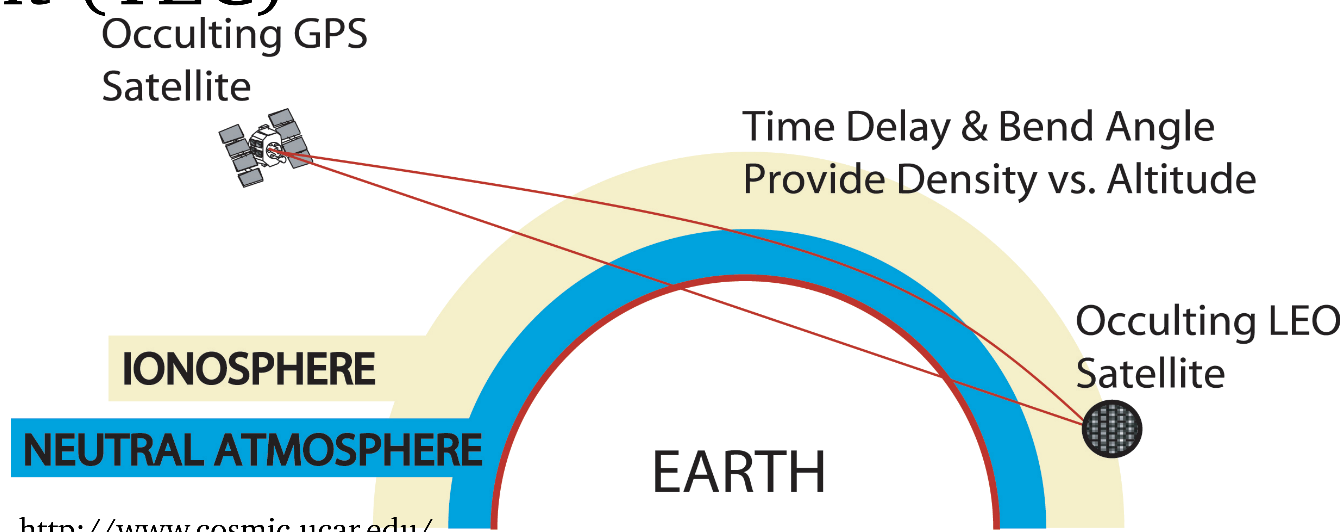
- Point Solution Results
  - RMS Errors:
    - Pos: **1.47 m**
    - Vel: **0.29 m/s**
  - Results can be improved with a Kalman filter that ingests L2C pseudorange



Radio Occultation Observation

Radio Occultation Observation

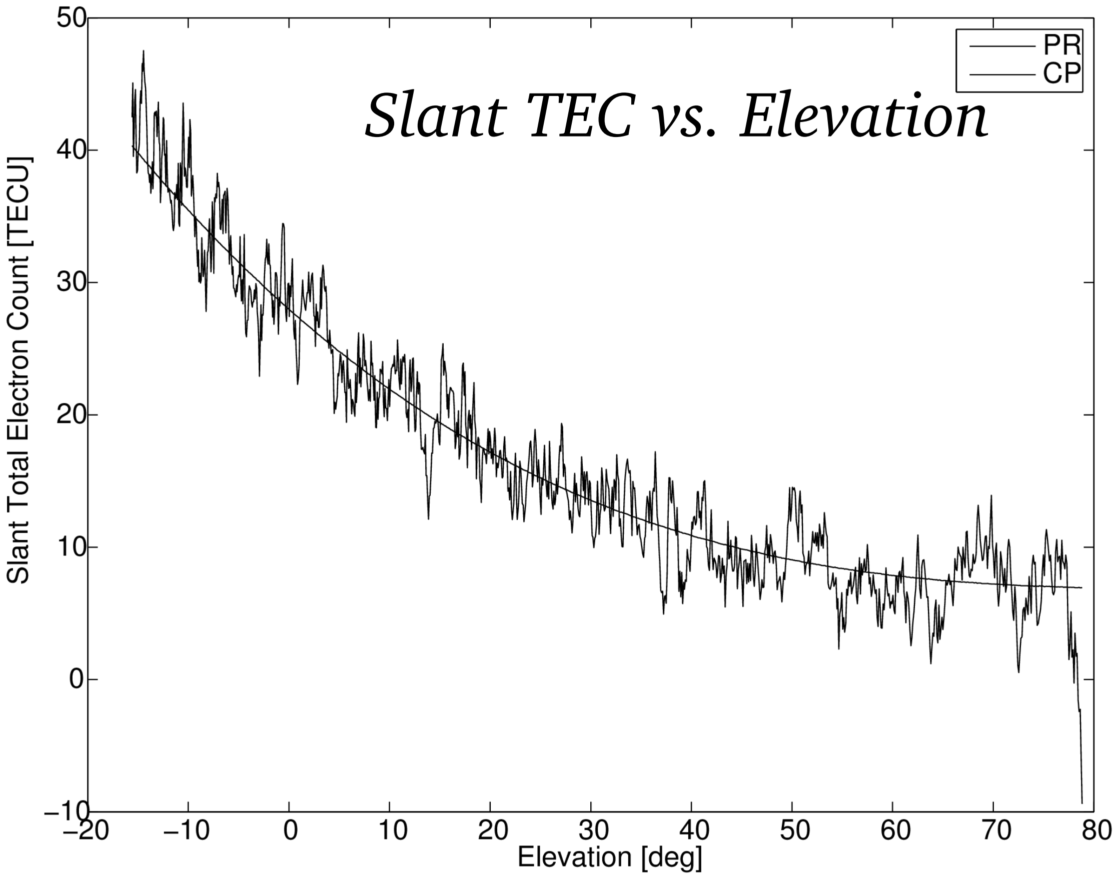
- Rising/setting GPS satellite transmits through multiple layers of ionosphere
- GPS receiver on LEO satellite measures time history of ionospheric delay/total electron content (TEC)



http://www.cosmic.ucar.edu/

Radio Occultation Observation

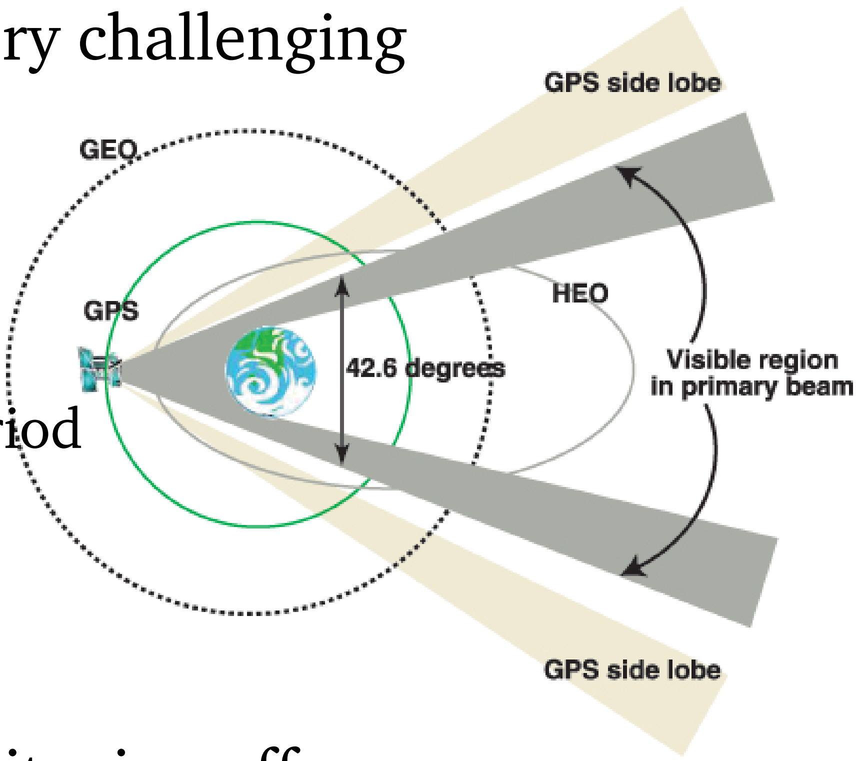
- FOTON software already designed to measure TEC
- Dual-frequency LEO simulation demonstrates:
  - Low elevation tracking
  - TEC estimation
- To do:
  - Occultation prediction



GEO Navigation

GEO Navigation

- Geosynchronous Earth Orbit (GEO) outside of GPS orbit
  - Low signal strength, navigation very challenging
- FOTON GEO Simulation Results
  - Used OCXO + coherent accumulation
  - Unable to pull in side lobes
  - Tracked 2-4 SVs at a time over 2 hr period
  - RMS Errors:
    - 10 m horizontal, 155 m vertical
    - 0.75 m/s horizontal, 15 m/s vertical
- Better results attainable using data bit wipe-off
  - Already implemented, but not tested in GEO



http://www.gpsworld.com

Hardware/Flight Testing

Hardware/Flight Testing

- Completed:
  - Vibration testing
  - Thermal testing
  - Vacuum testing
- Upcoming:
  - Sounding rocket launch (Cornell): March 2012
  - Armadillo CubeSat launch (UT): 2014

Conclusions

- FOTON – a high-precision, adaptable, space-based software receiver
- Duty cycling allows <1 W orbit average power
- 326 g, 0.5U volume small enough for CubeSats
- Kalman filter + dual-frequency → meter-level navigation
- Low elevation tracking, TEC estimation demonstrates occultation observation potential
- Data bit wipe-off + long coherent integration → GEO navigation possible
- Upcoming test flights in 2012-2014

Acknowledgements

- UT Radionavigation Laboratory
  radionavlab.ae.utexas.edu
- UT Center for Space Research
  www.csr.utexas.edu
- UT Satellite Design Laboratory
- Cornell University
  gps.ece.cornell.edu

Backup Slides

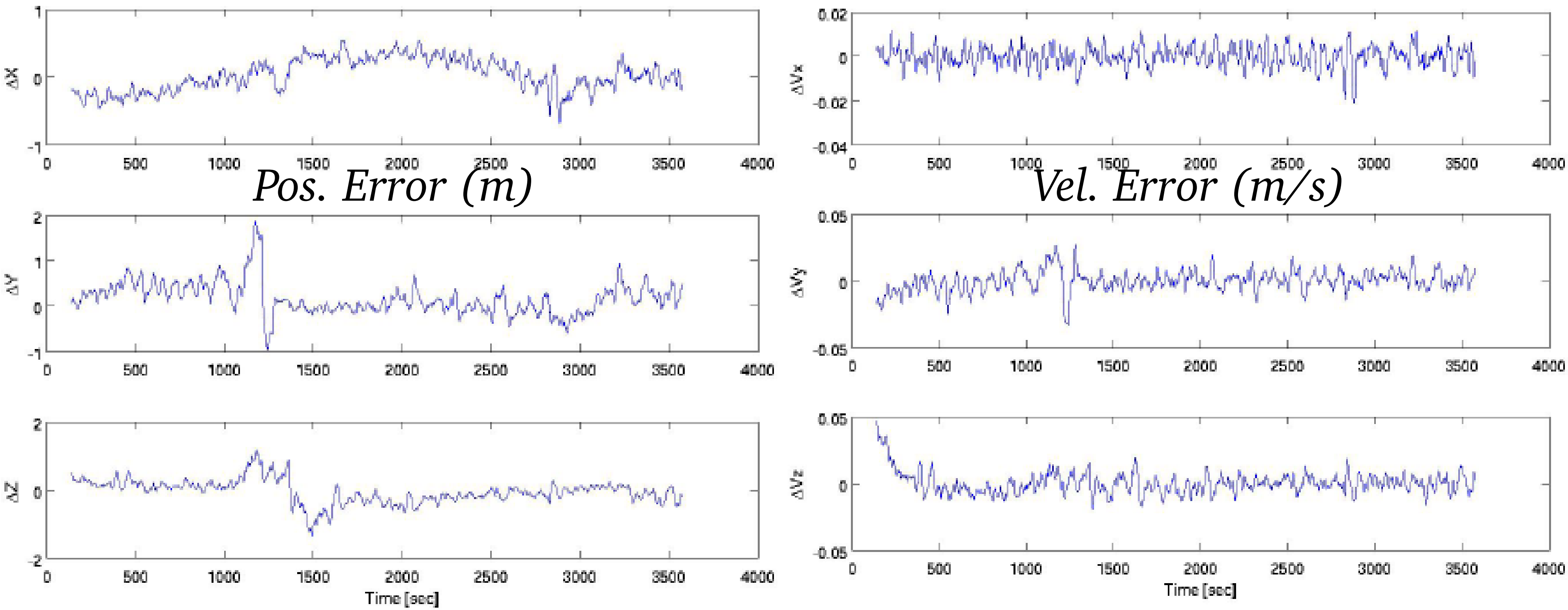
Motivation

- Why dual-frequency?
  - Increased precision using ionosphere-free pseudorange
  - Direct computation of ionospheric delay

- Why software-defined?
  - Quick development – just recompile and test
  - Adaptable – use for navigation, ionospheric sensing, …
  - Reconfigurable on-orbit

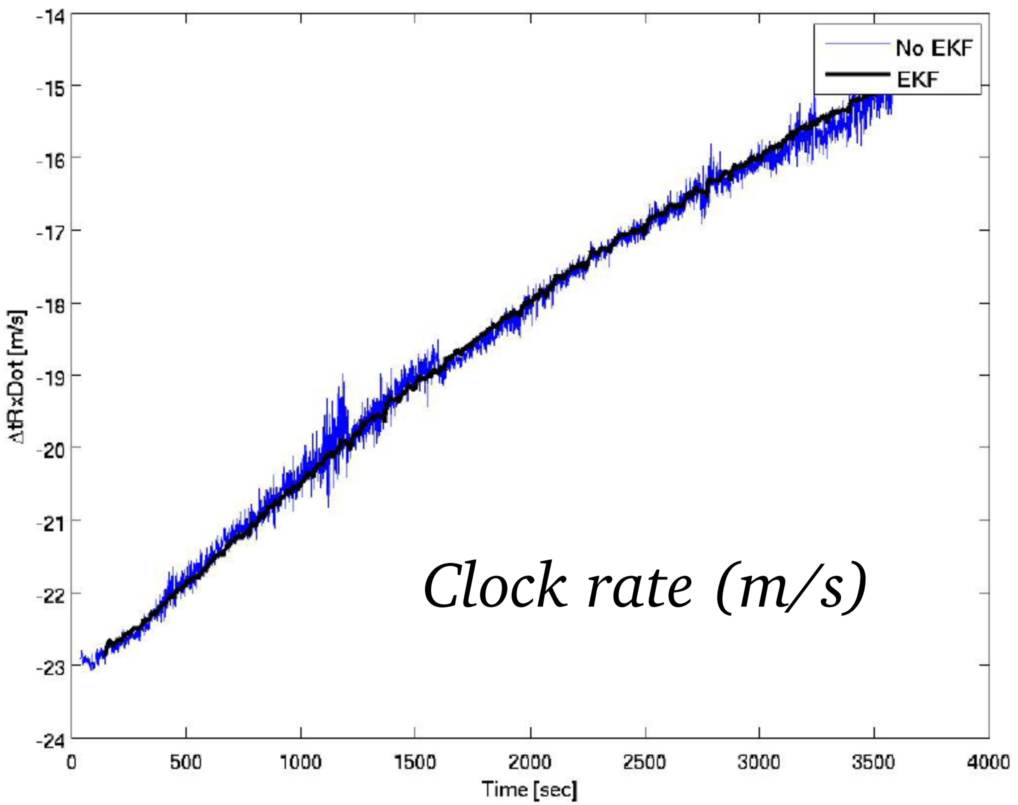
Kalman Filter-Based POD

- LEO Simulation Testing
  - Repeat benchmark test simulation



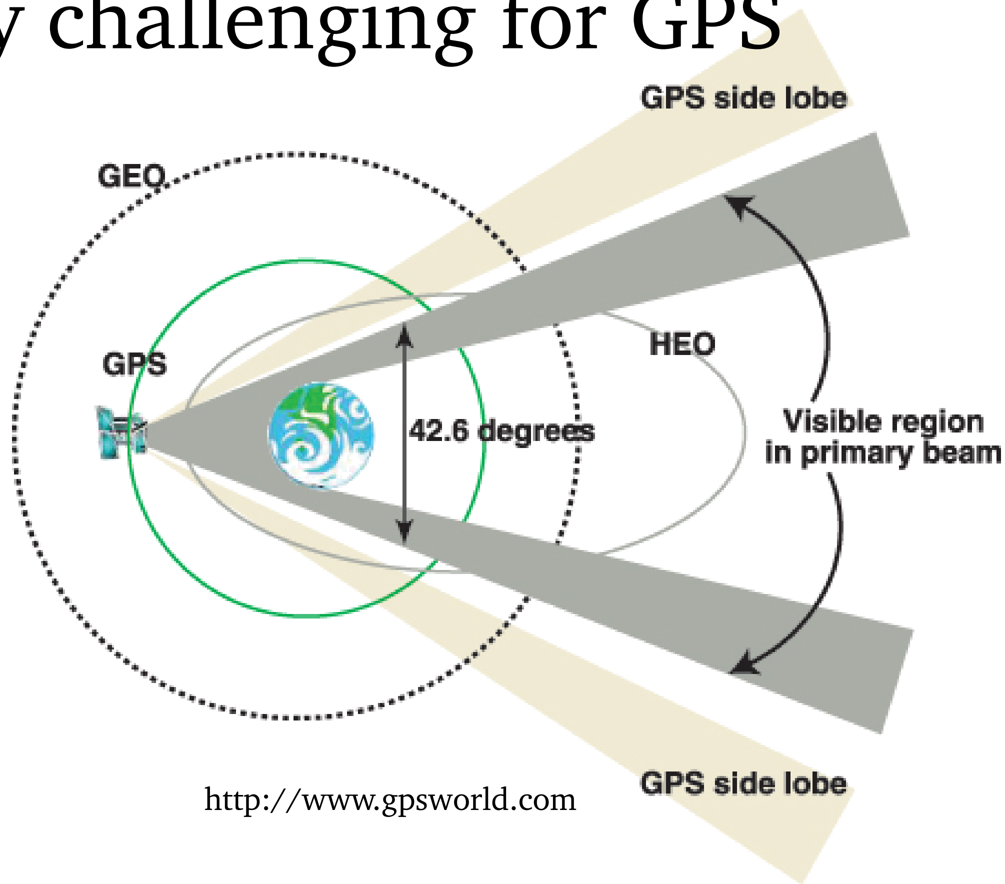
Kalman Filter-Based POD

- RMS Errors:
  - Pos: **0.544 m** (vs. 0.739 m)
  - Vel: **0.0121 m/s** (vs. 0.247 m/s)
- Can be improved with more accurate dynamics model



GEO Navigation

- High Earth Orbits (HEO) and Geosynchronous Earth Orbits (GEO) very challenging for GPS navigation
- Weak signals from GPS transmitter side lobes
- Very slow geometric change



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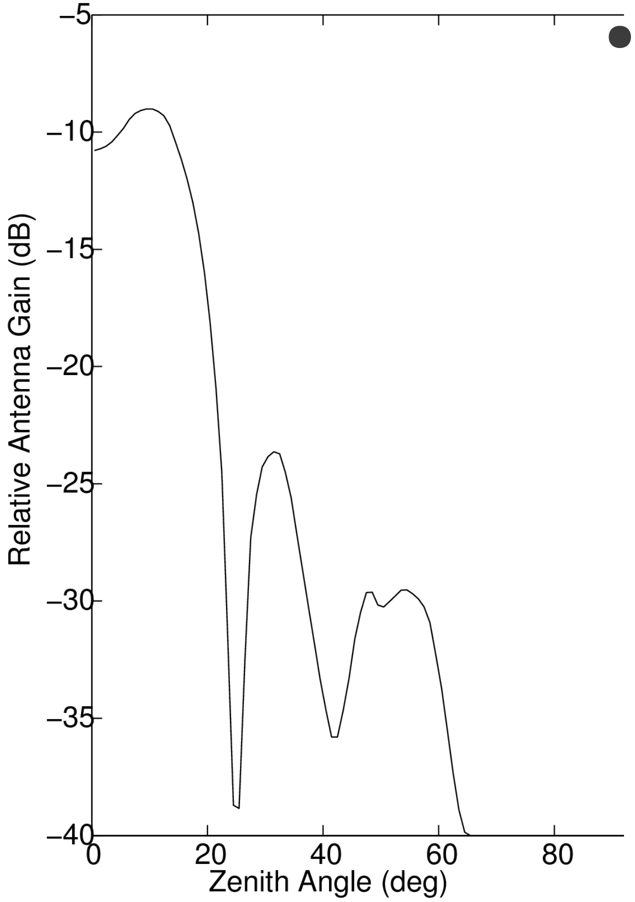
GEO Navigation



- Solutions:
  - More stable clock (e.g. OCXO)
    - Allows smaller PLL bandwidth (increases C/No)
  - Long coherent integration of weak signals
    - Pulls in signal from GPS side lobe
    - Requires data bit wipe-off
  - Kalman filtering

Description and Performance of the GPS Block I and II L-Band Antenna and Link Budget. 1993 Institute of Navigation Conference, 1993.

GEO Navigation

- Results