Methodology and Case Studies of Signal-in-Space Error Calculation

Top-down Meets Bottom-up

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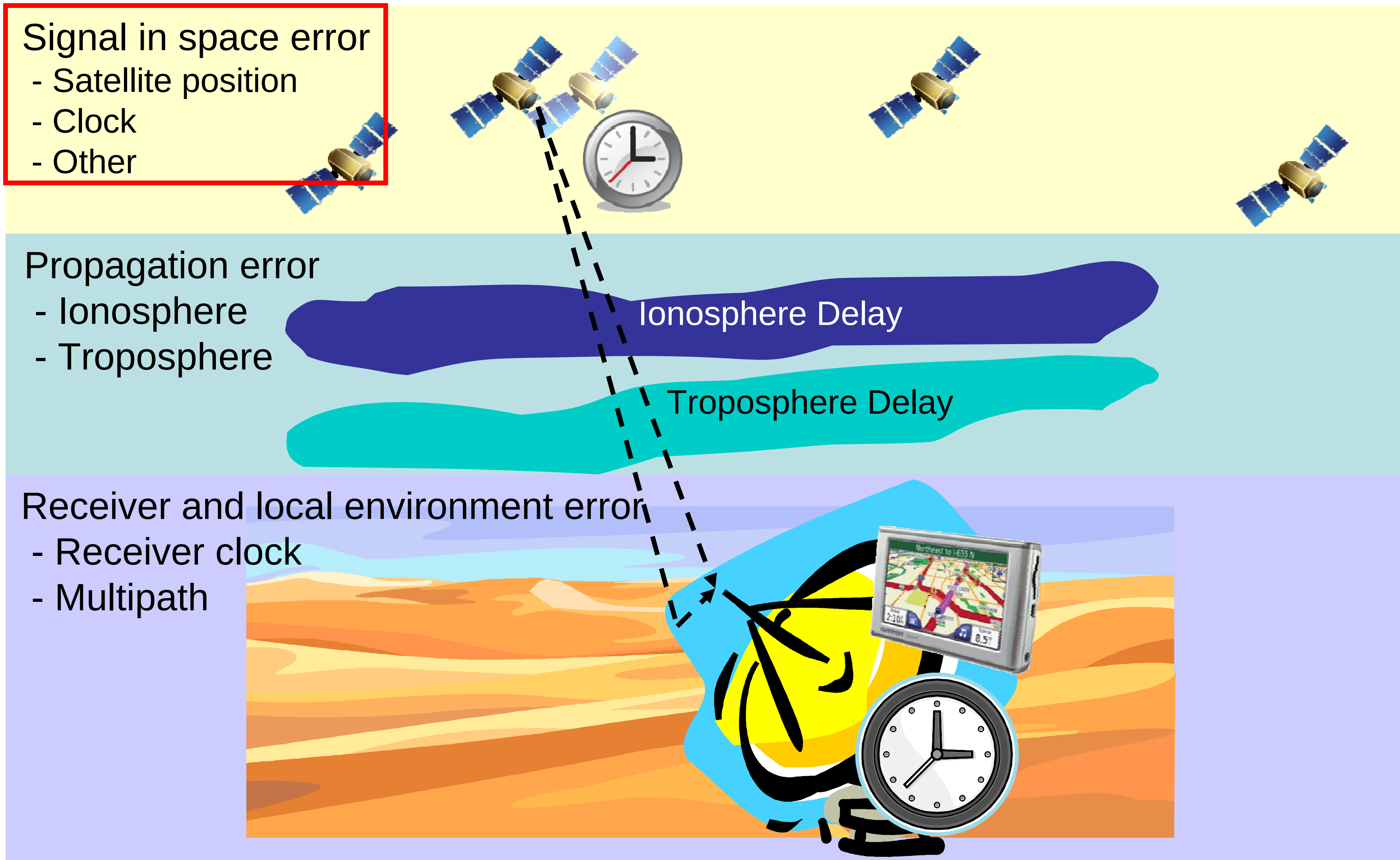
Outline

- Introduction – Signal-in-space error
- Methodology – Top-down
- Methodology – Bottom-up
- Case Studies
  - Planned satellite position outage, PRN 10, Day 39 of Year 2007
  - Unplanned clock anomaly, PRN 07, Day 229 of Year 2007

Error Sources of GPS Signals



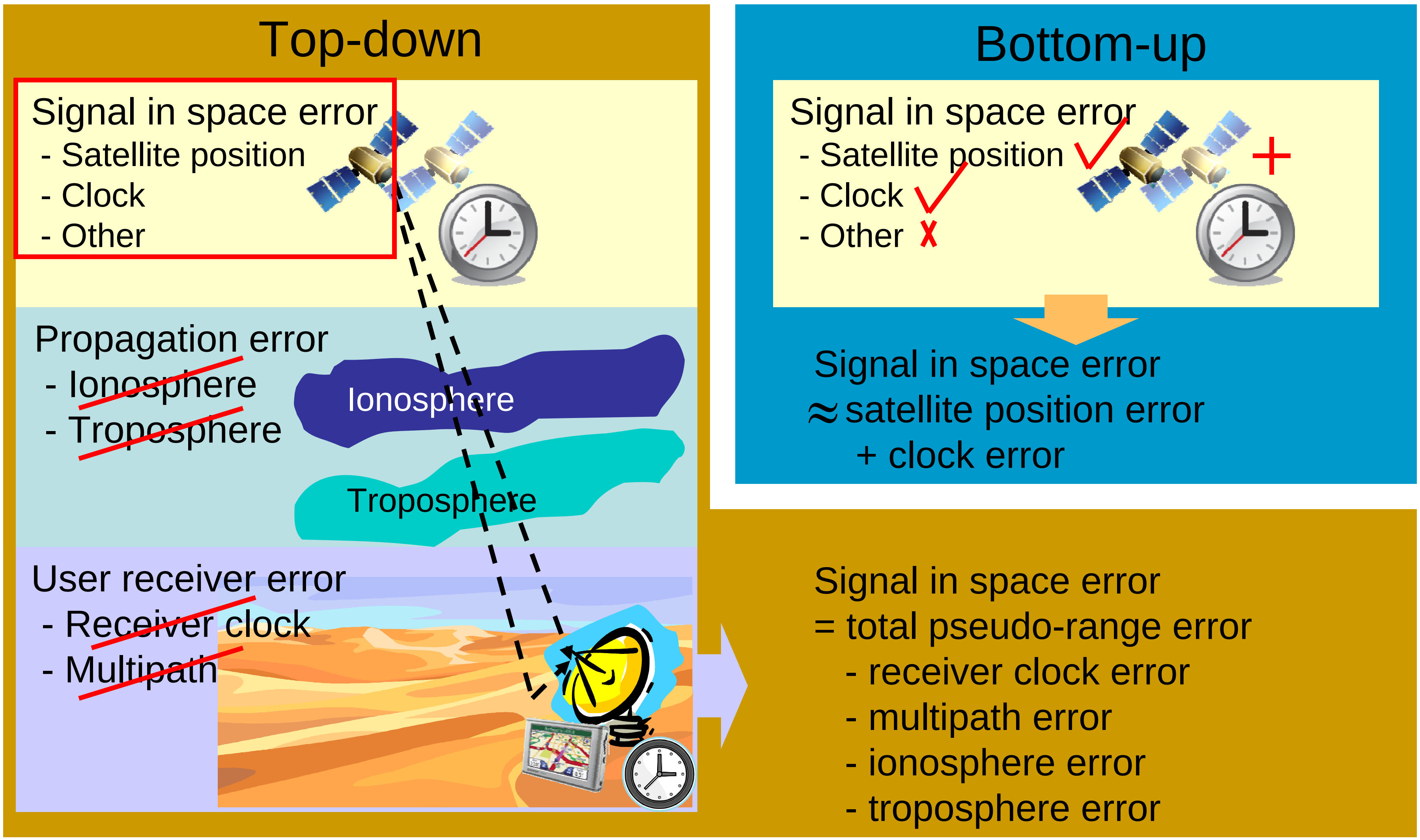
Motivation & Prior Work

- Motivation
  - signal-in-space, propagation and receiver errors have been well studied, but better understanding is still required
  - Essential for GPS integrity
    - Satellite failures are identified if the signal-in-space errors exceed 4.42*URA (User Range Accuracy)
    - The statistics of signal-in-space errors are useful for evaluating URA
- Prior work of signal-in-space error calculation
  - KAIST, Jiyun Lee. GEAS presentations since early 2009
  - Ohio Univ., Frank Van Grass. GEAS presentation 2009
  - FAATC, Tom McHugh for WAAS PAN report
  - IIT, Boris Pervan, et al. GEAS presentation in Sept. 2008
  - Aerospace, Karl Kovach, presented at SCPNT in Nov. 2008
  - David L. M. Warren and John F. Raquet, Broadcast vs. precise GPS ephemerides: a historical perspective, GPS Solutions, 2004
  - Jefferson D, Bar-Sever Y (2000) Accuracy and consistency of broadcast GPS ephemeris data. Proc ION-GPS-2000

Signal in Space (SIS) Errors

- Main errors
  - Satellite position
  - Satellite clock
- Other
  - code-carrier incoherence
  - signal deformation
  - Inter-signal errors
  - satellite antenna phase center variation
  - satellite antenna group delay center variation
  - relativistic correction errors

Methodology Overview: Top-down vs. Bottom-up



Bottom-up Methodology, Flow Chart

Start

↓

Pick proper broadcast ephemerides based on the time of the truth

↓

Propagate broadcast satellite positions to the time of the truth

↓

Propagate broadcast satellite clock error to the time of the truth

↓

Calculate the difference between the propagated broadcast ephemerides and the truth

↓

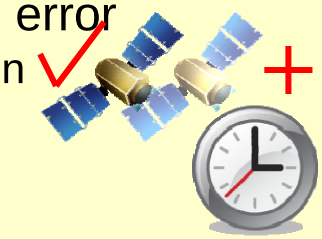
Project the ephemeris error to a certain receiver on Earth

↓

End

Bottom-up

Signal in space error
- Satellite position ✓
- Clock ✓
- Other ✗

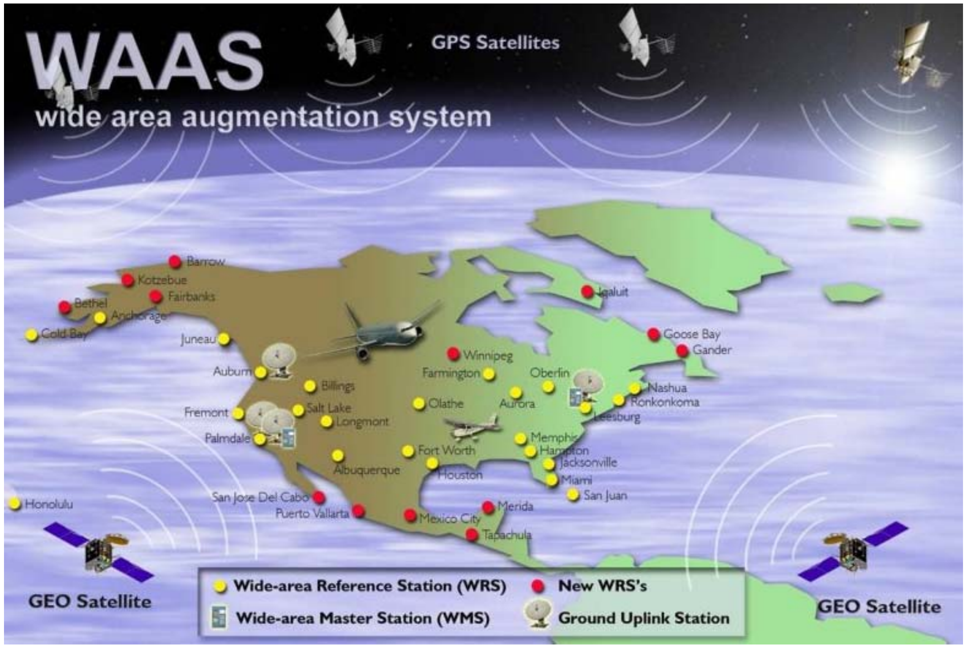


Signal in space error
= satellite position error
+ clock error

Top-down Methodology, Data Source

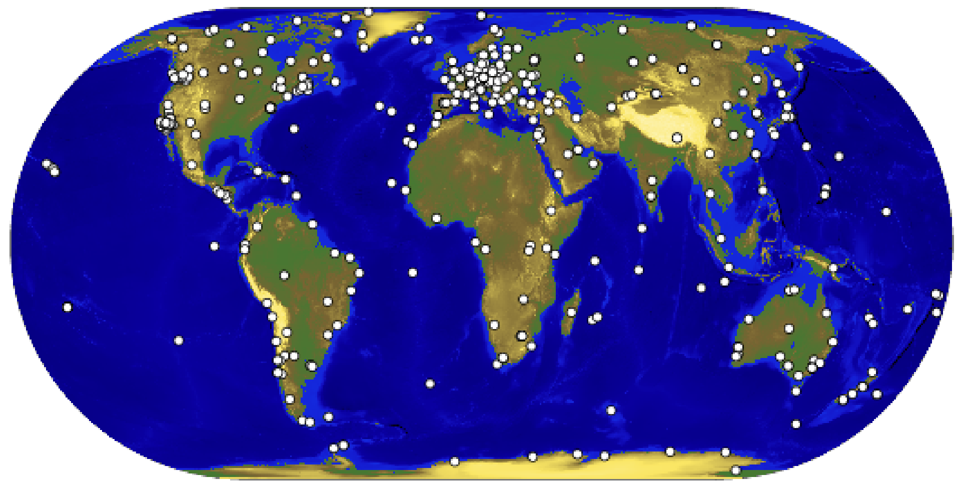
Data Source: Wide Area Augmentation System (WAAS) /
National Satellite Test Bed (NSTB) Network

- 38 stations in North America, with 3 receivers per station
- Data update rate: 1 Hz
- Output pseudo-range measurements and navigation messages



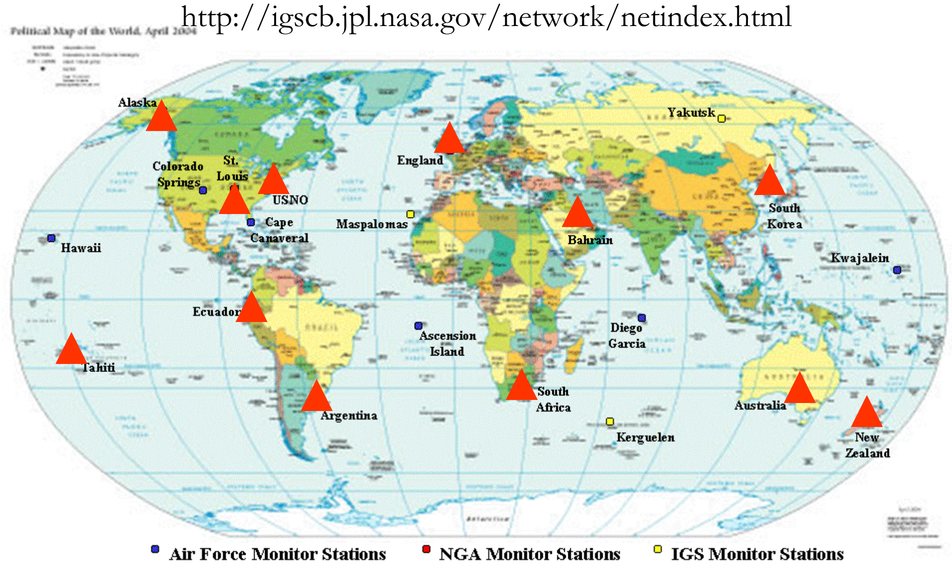
Bottom-up Methodology, Data Sources

Broadcast ephemeris: International GNSS Service (IGS) network



http://igscb.jpl.nasa.gov/network/netindex.html

Precise ephemeris: National Geospatial-Intelligence Agency (NGA) network



http://earth-info.nga.mil/GandG/sathtml/StationMap.gif

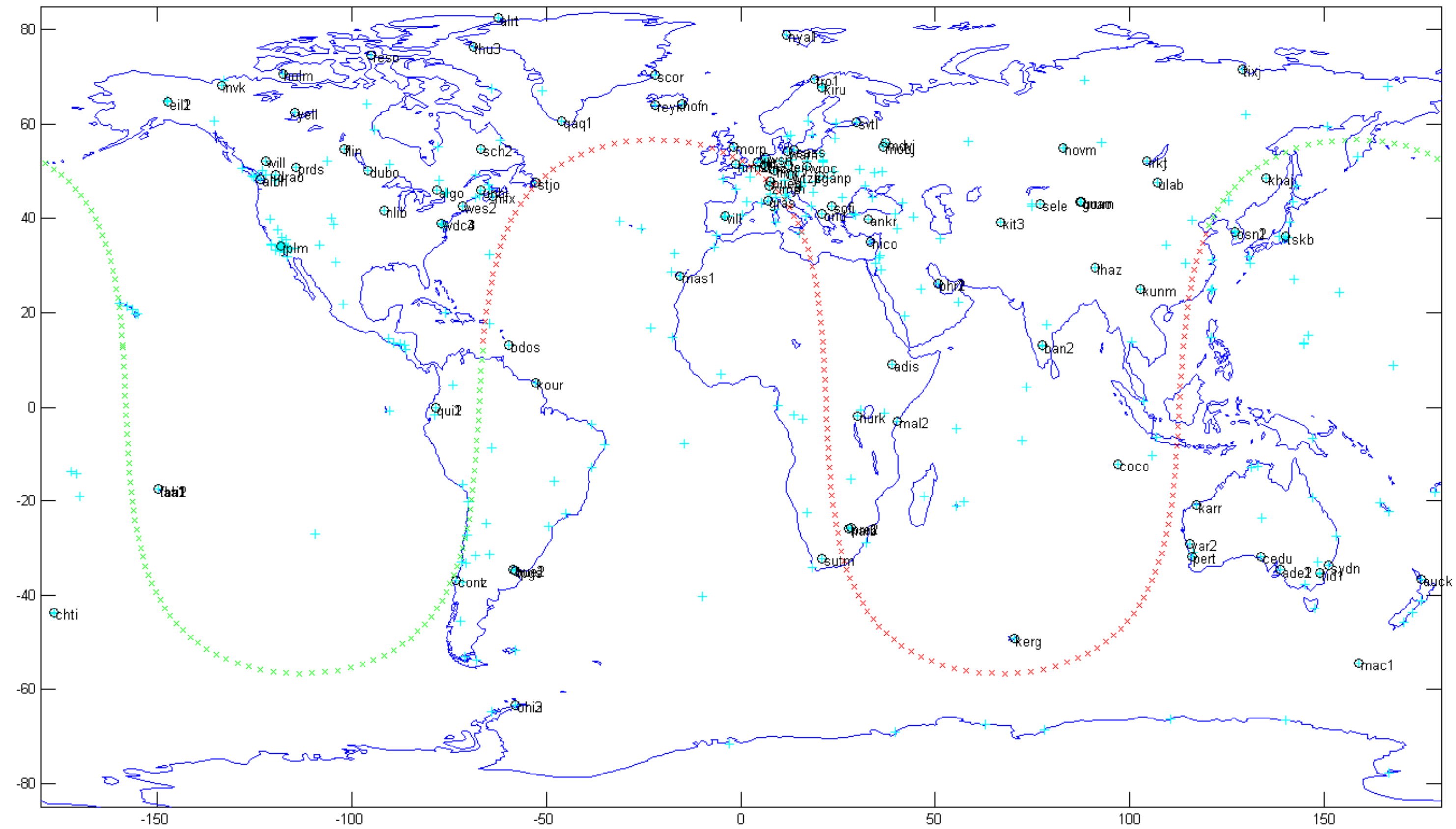
Methodology Comparison: Top-down vs. Bottom-up

	Top-down	**Bottom-up**
Data Source	WAAS & NSTB	IGS & NGA
Control of data source	Yes	No
Data update rate	High, every 1 sec	Low, 15 min
Depend on post-processed truth	No	Yes
Include all SIS errors	Yes	No
Receiver glitches	No for WAAS	Yes
Remove all non SIS errors	No	Yes
Receiver coverage	Limited (CONUS)	Worldwide, but not even
Data availability	Difficult to retrieve past data	Available

Case Studies

Planned satellite position outage,
PRN 10, Day 39 of Year 2007

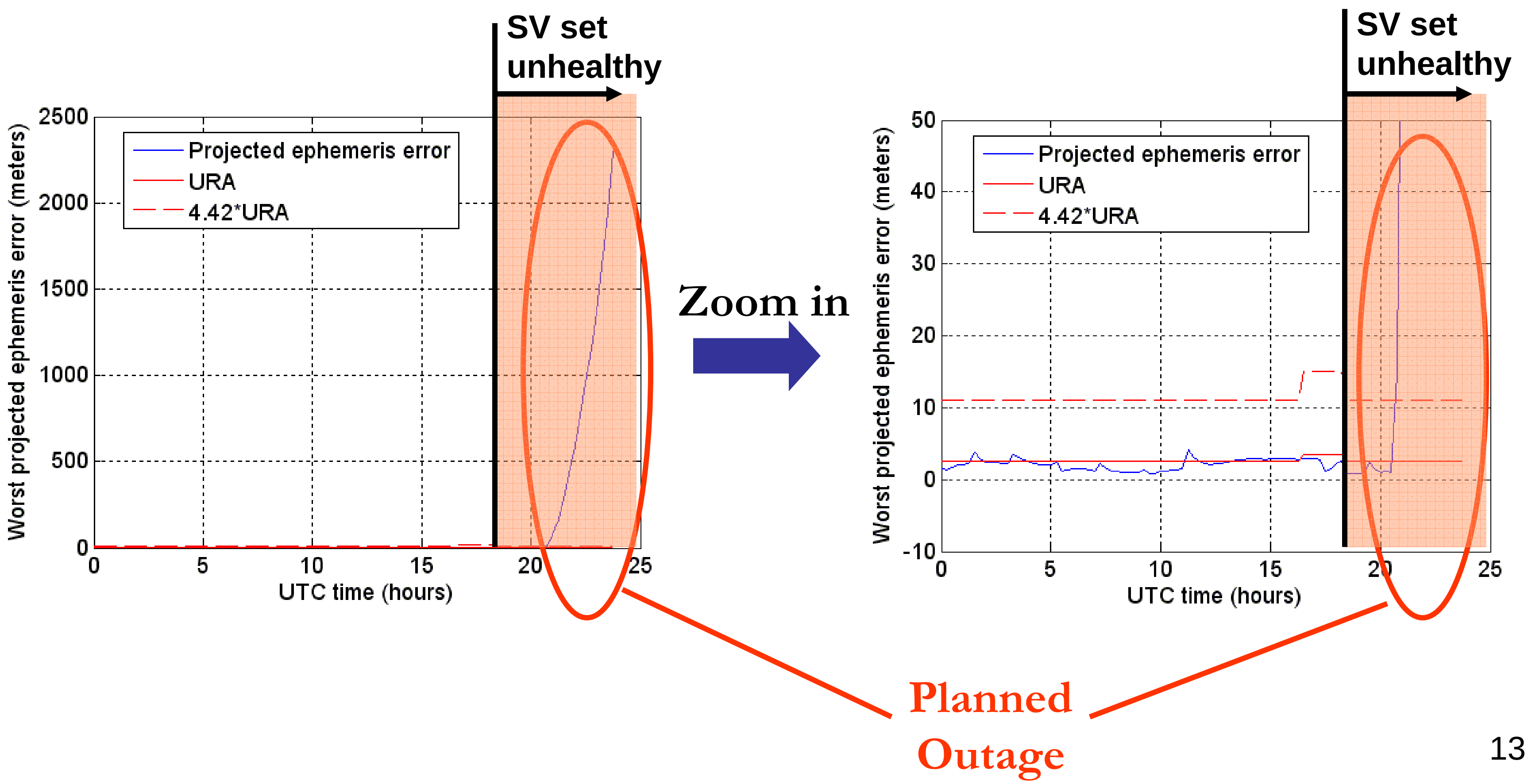
Ground Track of PRN 10, Day 39-40 of Year 2007



Worst Projected Ephemeris Error

PRN 10, Day 39 of 2007

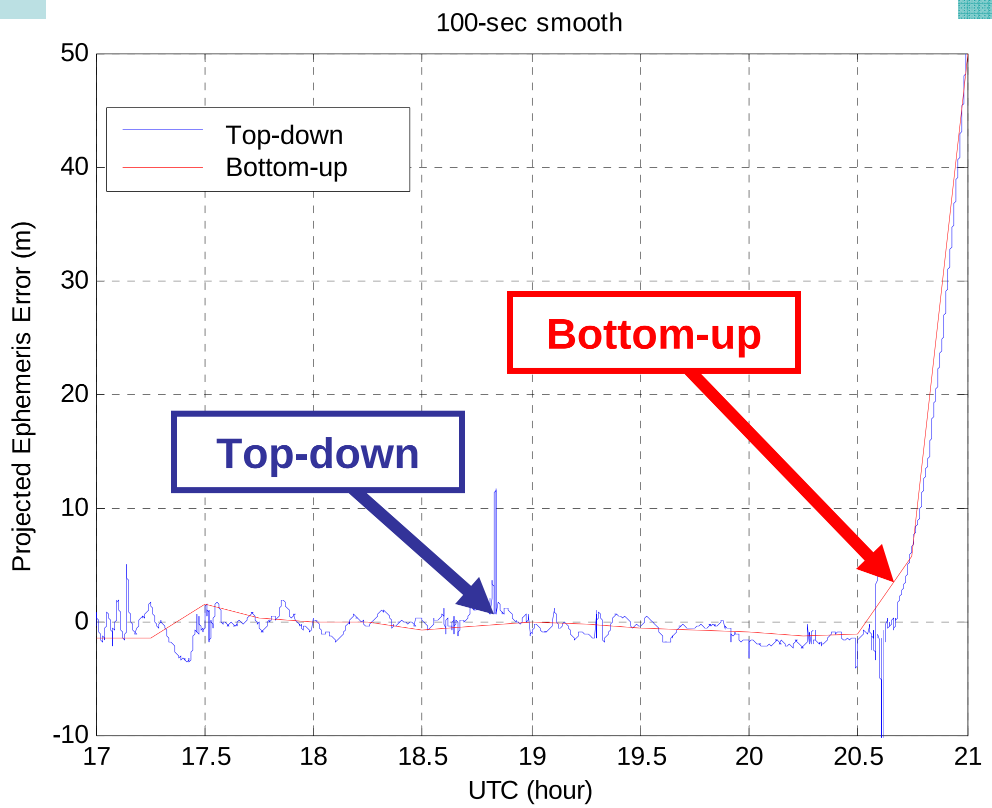
Worst projected ephemeris error ($\Delta X, \Delta Y, \Delta Z, \Delta b$)



Top-down vs. Bottom-up, 100-sec Smoothing

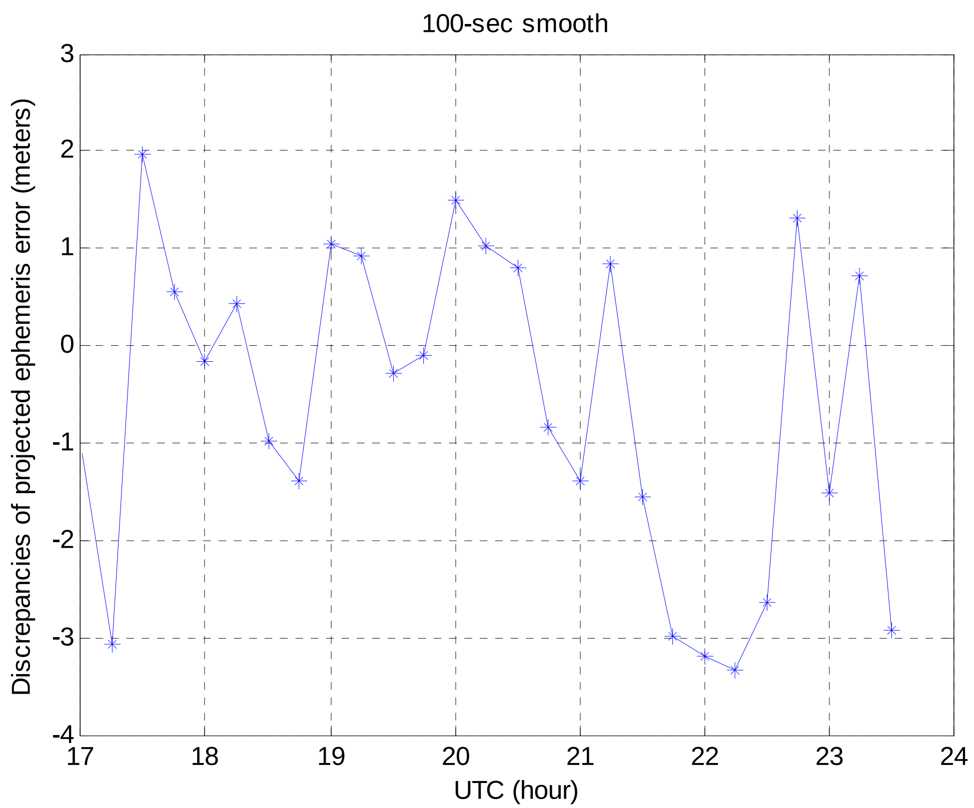
PRN 10 Day 39

100-sec smoothing



Atlantic City NJ, 39.44º N 74.56º W

Discrepancies of Top-down vs. Bottom-up, 100-sec Smoothing

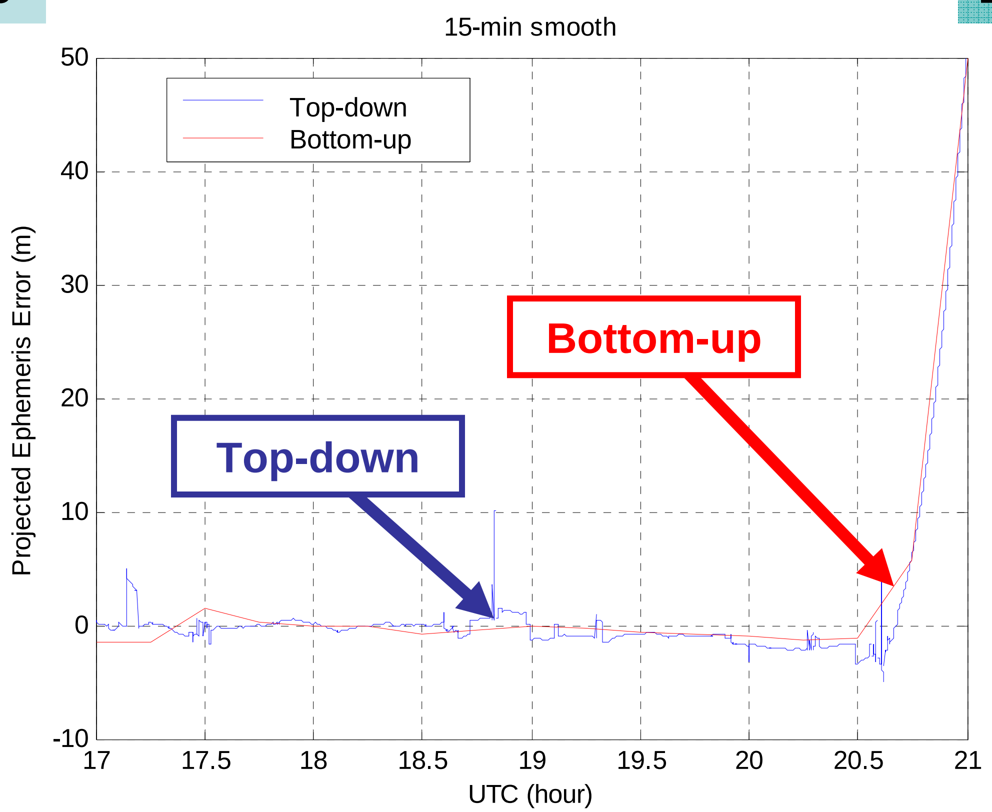


Atlantic City NJ, 39.44º N 74.56º W

Top-down vs. Bottom-up, 15-min Smoothing

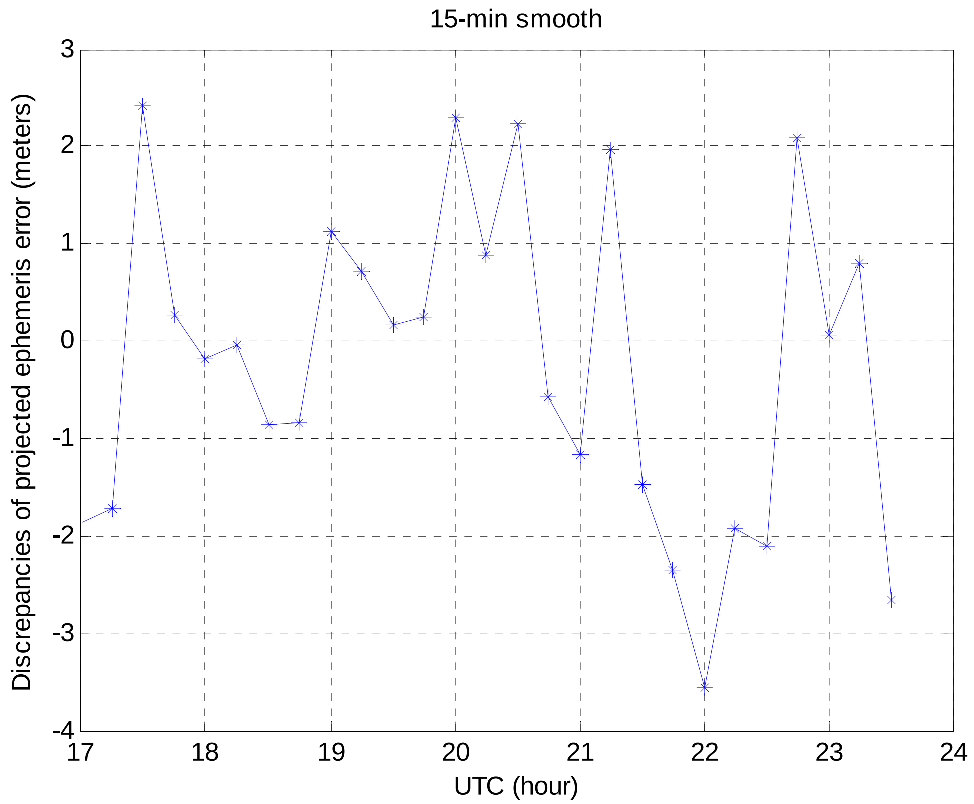
PRN 10 Day 39

15-min smoothing



Atlantic City NJ, 39.44º N 74.56º W

Discrepancies of Top-down vs. Bottom-up, 15-min Smoothing



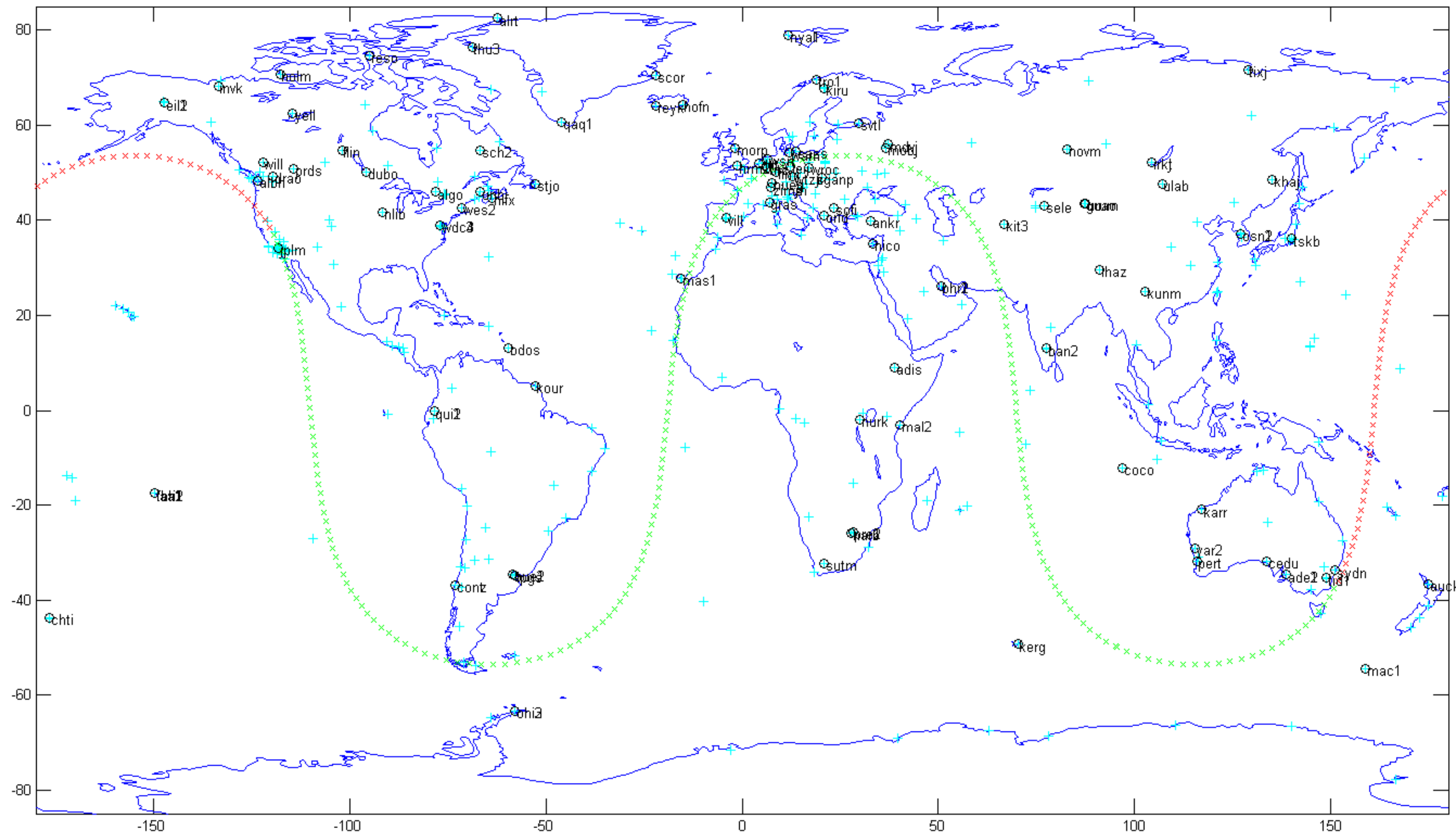
Atlantic City NJ, 39.44º N 74.56º W

Case Studies

Unplanned clock anomaly,

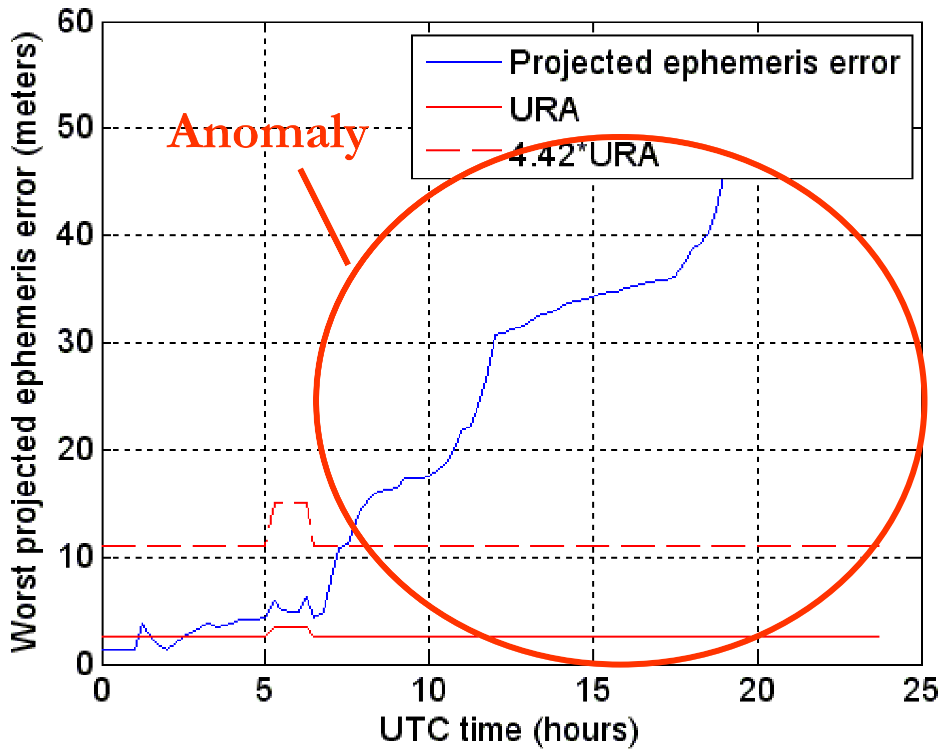
PRN 07, Day 229 of Year 2007

Ground Track of PRN 07, Day 229 of Year 2007

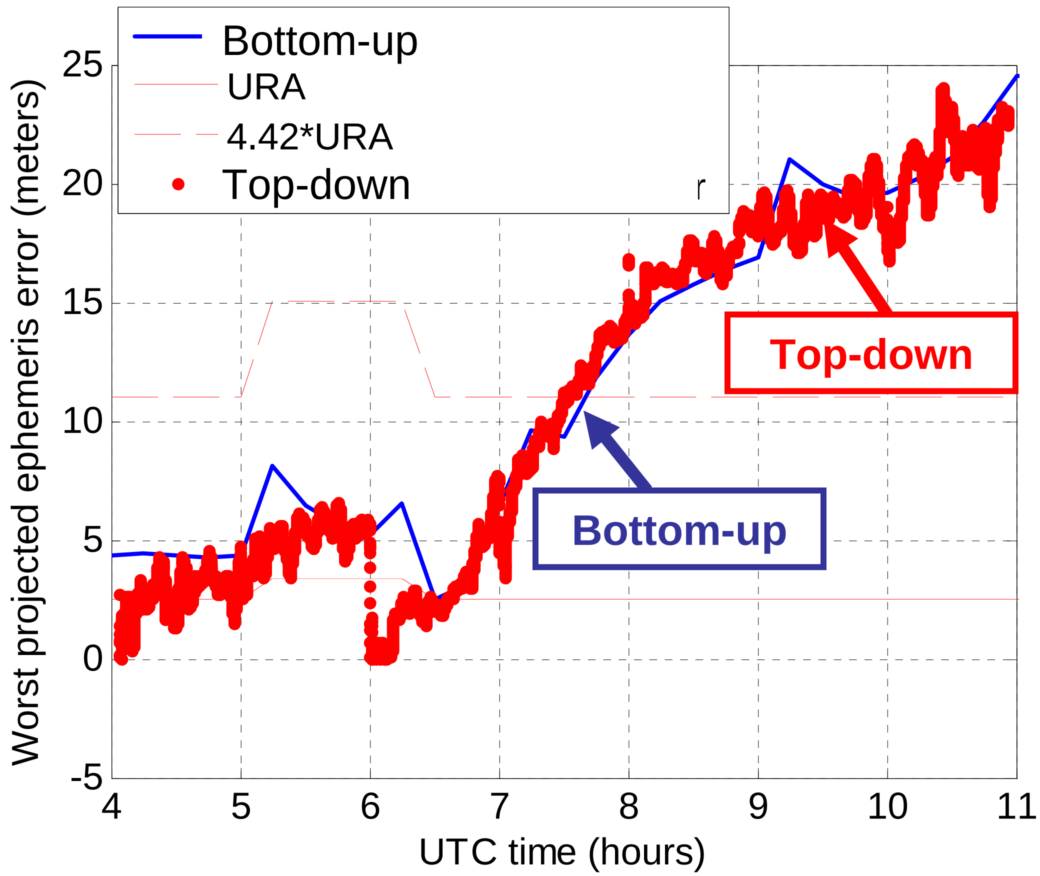


Worst Projected Ephemeris Error

PRN 07, Day 229 of 2007
Worst projected ephemeris error ($\Delta X, \Delta Y, \Delta Z, \Delta b$)

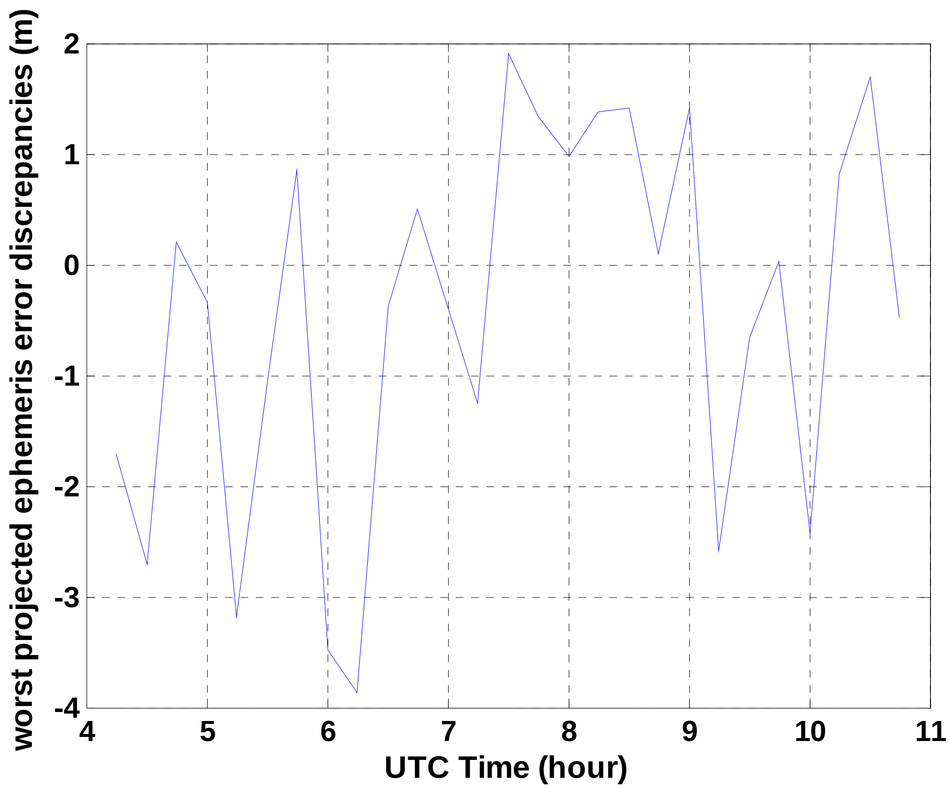


Top-down vs. Bottom-up, Arcata CA, 100-sec Smoothing



Arcata CA, 40.97º N 124.11º W

Discrepancies of Top-down vs. Bottom-up, 100-sec Smoothing



Arcata CA, 40.97º N 124.11º W

Conclusion (1/2)

- Compared two approaches to calculate signal-in-space error
  - Top-down: strips off all other errors from the pseudo-range errors, leaves alone signal-in-space errors
  - Bottom-up: builds up signal-in-space errors from satellite position errors and clock errors
- Top-down and bottom-up both have pros and cons

	Top-down	Bottom-up
Data Source	WAAS & NSTB	IGS & NGA
Control of data source	Yes	No
Data update rate	High, every 1 sec	Low, 15 min
Depend on post-processed truth	No	Yes
Include all SIS errors	Yes	No
Receiver glitches	No for WAAS	Yes
Remove all non SIS errors	No	Yes
Receiver coverage	Limited (CONUS)	Worldwide, but not even
Data availability	Difficult to retrieve past data	Available

Conclusion (2/2)

- Two case studies

	PRN 10, Day 39 of Year 2007	PRN 07, Day 229 of Year 2007
Planned outage?	Yes	No
Outage type	Satellite position	Satellite clock
Site investigated	Atlantic City, NJ	Arcata, CA

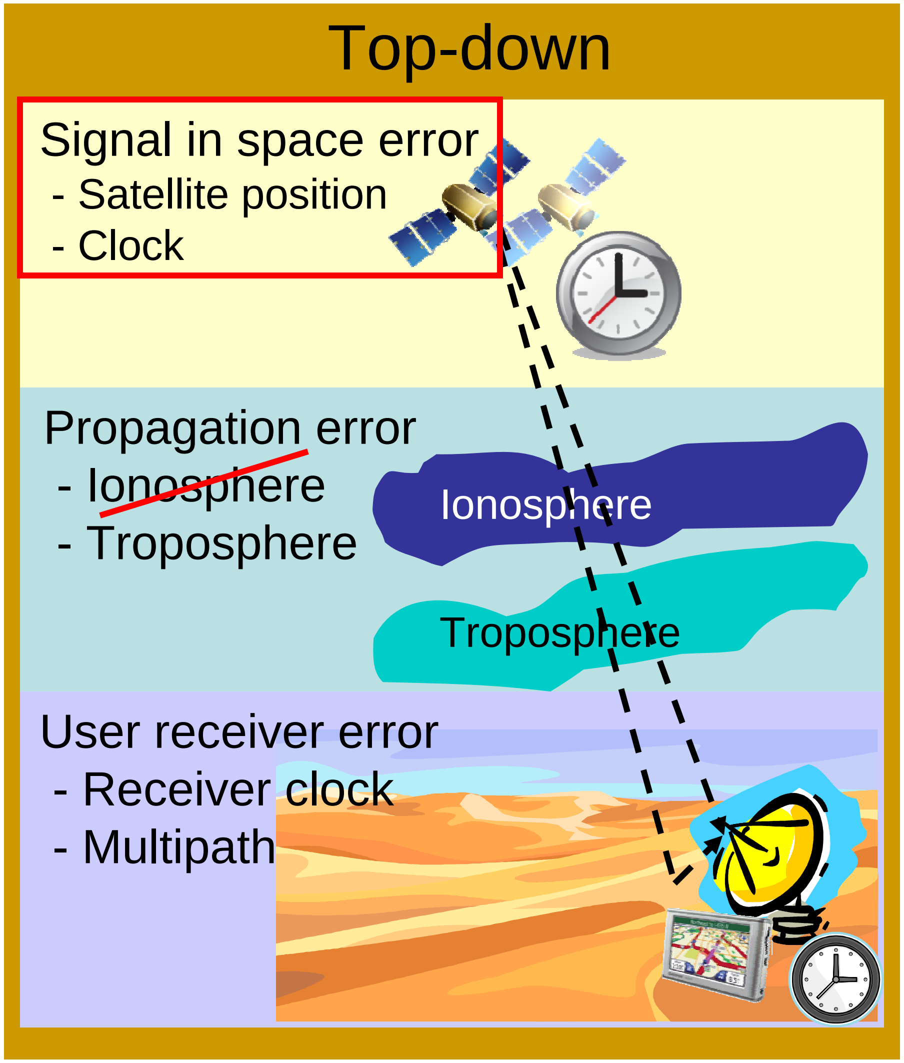
- Top-down and bottom-up match well for both normal and abnormal cases
- The discrepancies are independent of the filter length of carrier smoothing
- The discrepancies are due to
  - Inaccurate estimate of iono/tropo/multipath/receiver clock errors
  - Other error sources, e.g. code-carrier incoherence, signal deformation, Inter-signal errors, satellite antenna phase center variation, satellite antenna group delay center variation, relativistic correction errors, etc
  - Inaccuracies in precise ephemerides
  - Incorrect choice of active broadcast ephemeris
- The discrepancies are within +/-4 meters as a starting point
- Near term goal: better than 1 m

Thank You!

The authors acknowledge Tom McHugh from the FAA Tech Center for providing the WAAS/NSTB data of the 2007 outages.

Back-up Slides

Top-down Methodology in Detail: Removing Ionosphere Error



Dual-frequency iono-free combination:

$$\rho_{IF} = \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2}\rho_{L1} - \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2}\rho_{L2},$$

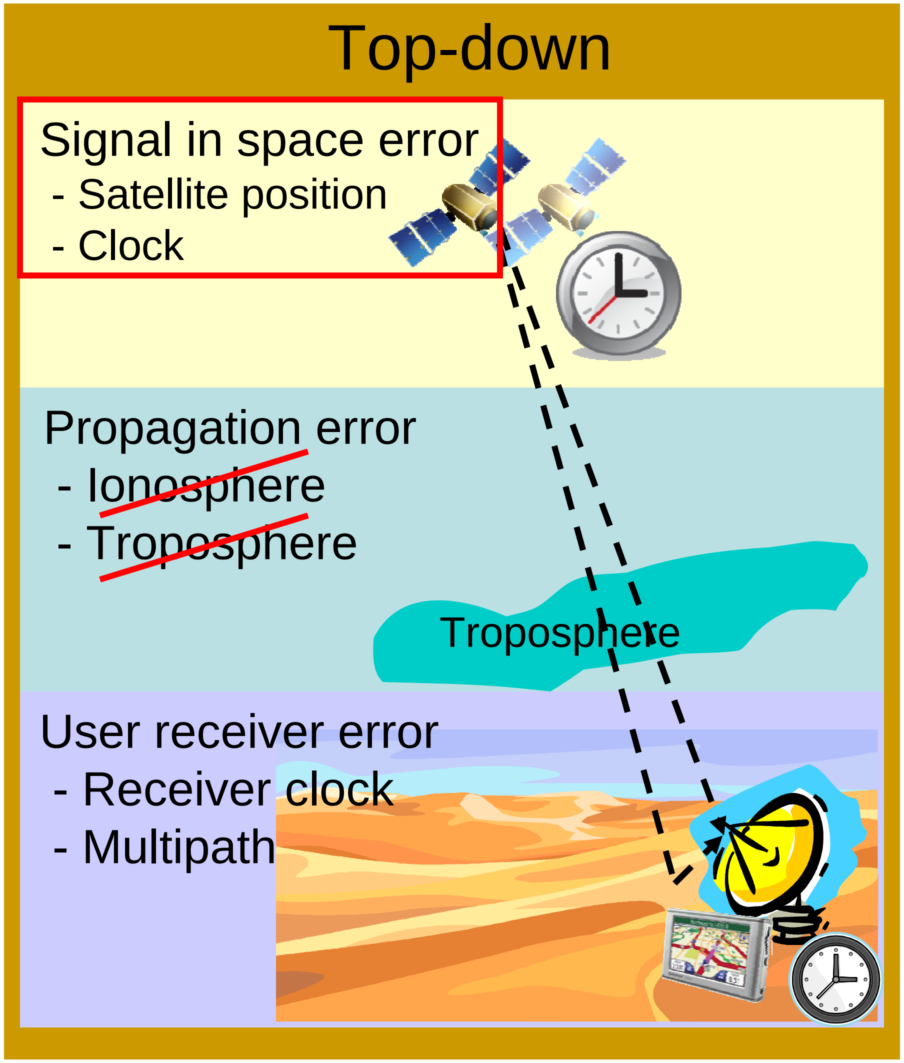
$$\Phi_{IF} = \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2}\Phi_{L1} - \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2}\Phi_{L2},$$

ρ: Code measurement

Φ: Carrier measurement

ρ_{IF}: Iono-free combination of code measurements

Top-down Methodology in Detail: Removing Troposphere Error



Estimate and removal of troposphere error based on WAAS Minimum Operational Standard (MOPS) :

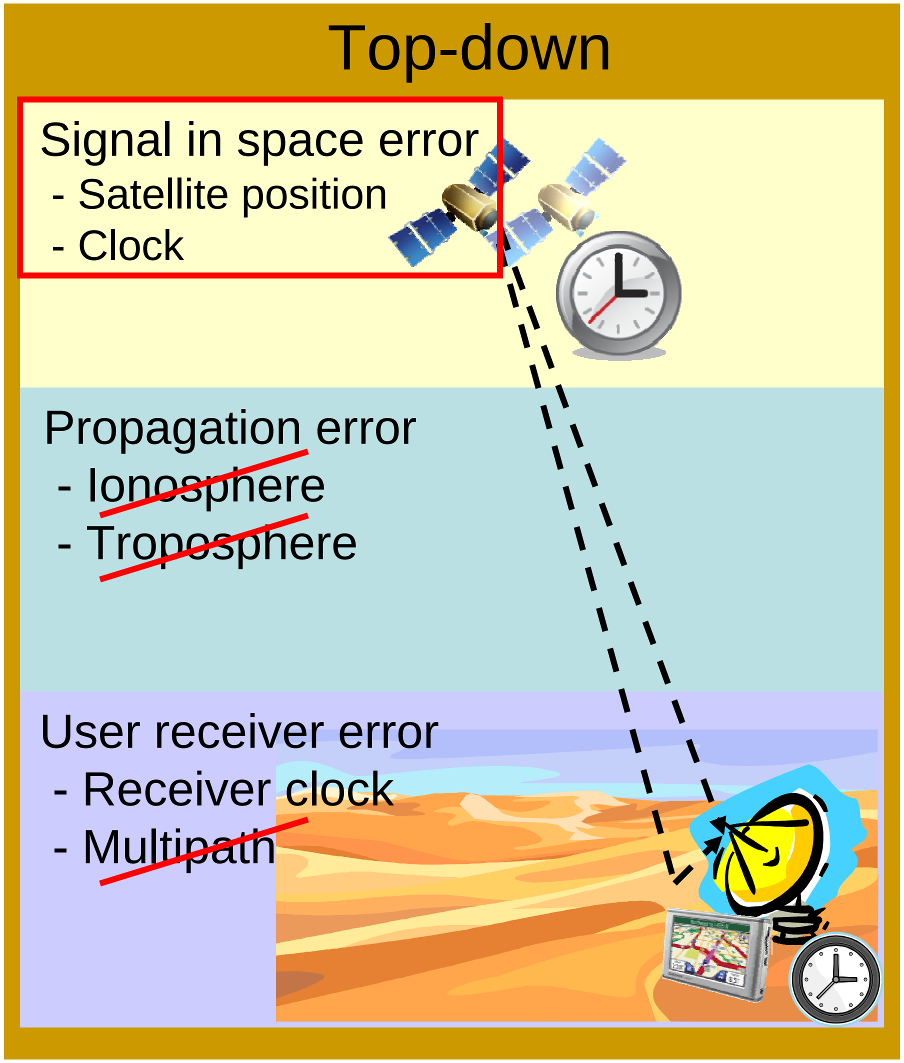
$$\sigma_{i,tropo} = \sigma_{TVE} \cdot m(El_i)$$

Troposphere delay for satellite i

Troposphere Vertical Error

Troposphere mapping function for satellite i

Top-down Methodology in Detail: Removing Receiver Multipath Error



Carrier smoothing:

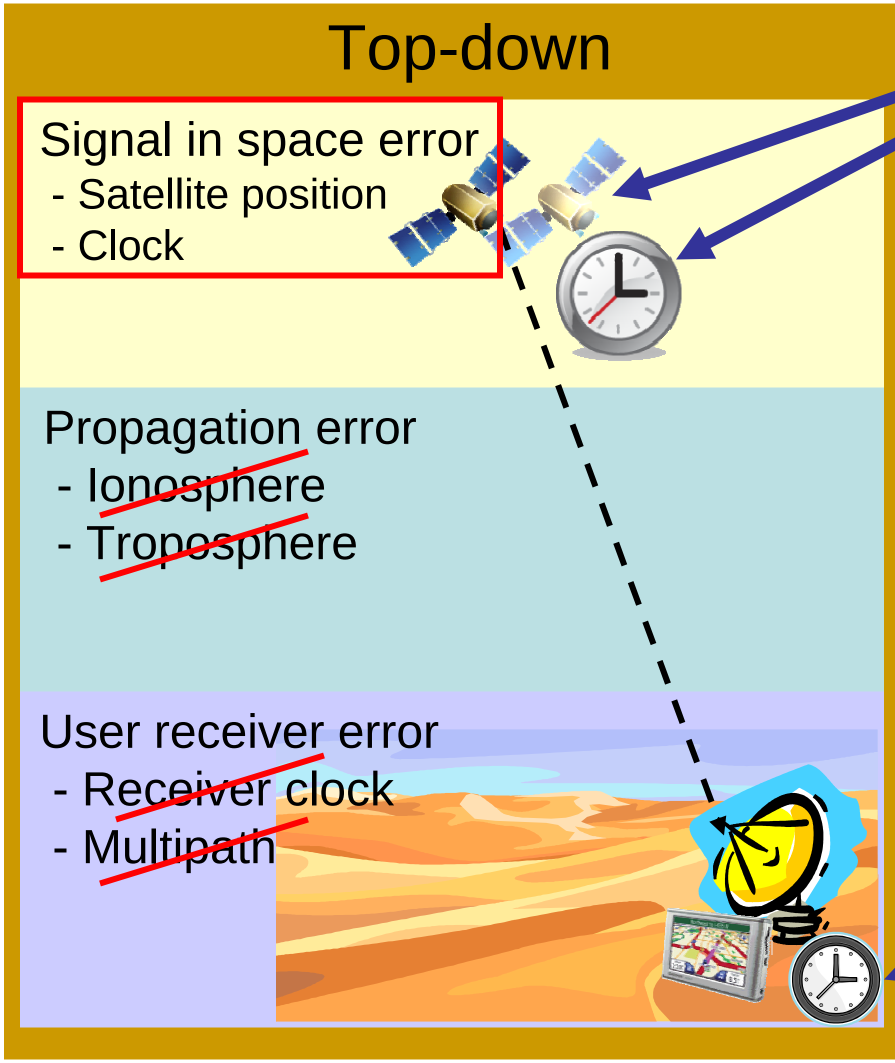
$$\bar{\rho}(t_i) = \frac{1}{M}\rho(t_i) + \frac{(M-1)}{M}[\bar{\rho}(t_{i-1}) + (\Phi(t_i) - \Phi(t_{i-1}))],$$
$$\bar{\rho}(t_1) = \rho(t_1).$$

$\rho(t)$: Code measurement

$\Phi(t)$: Carrier measurement

$\bar{\rho}(t)$: Smoothed pseudo-range measurement

Top-down Methodology in Detail: Removing Receiver Clock Error



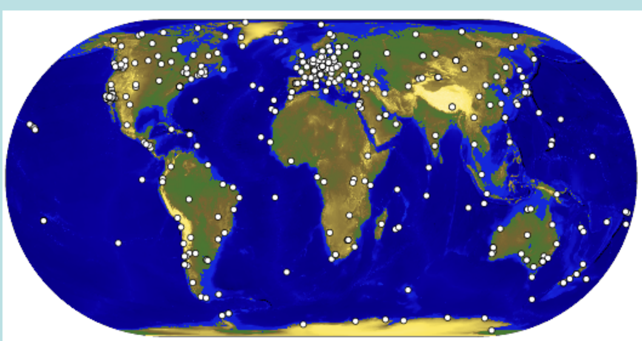
Different among satellites, cancels out after averaging

- Receiver clock error is a common error for pseudo-ranges from all satellites
- For healthy satellites, the signal in space error is zero-mean i.i.d.
- Averaging the remaining errors from those healthy satellites cancels out satellite in space errors and leaves alone the user clock bias

Common among satellites, remains after averaging

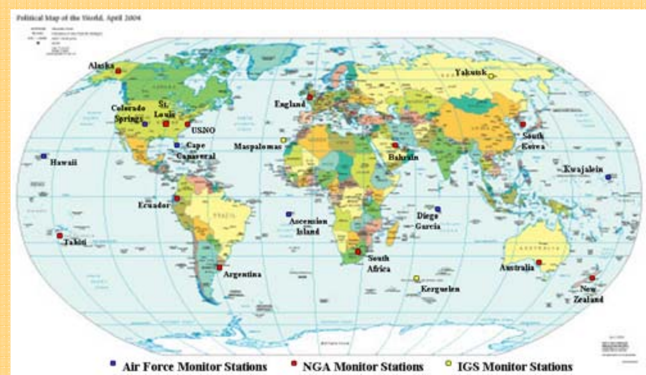
Bottom-up Methodology, Data Sources

- International GNSS Service (IGS) network
  - Provide broadcast ephemeris
  - 350+ receivers worldwide
  - Output pseudo-range measurements and navigation data in RINEX format
  - Data update every 2 hours



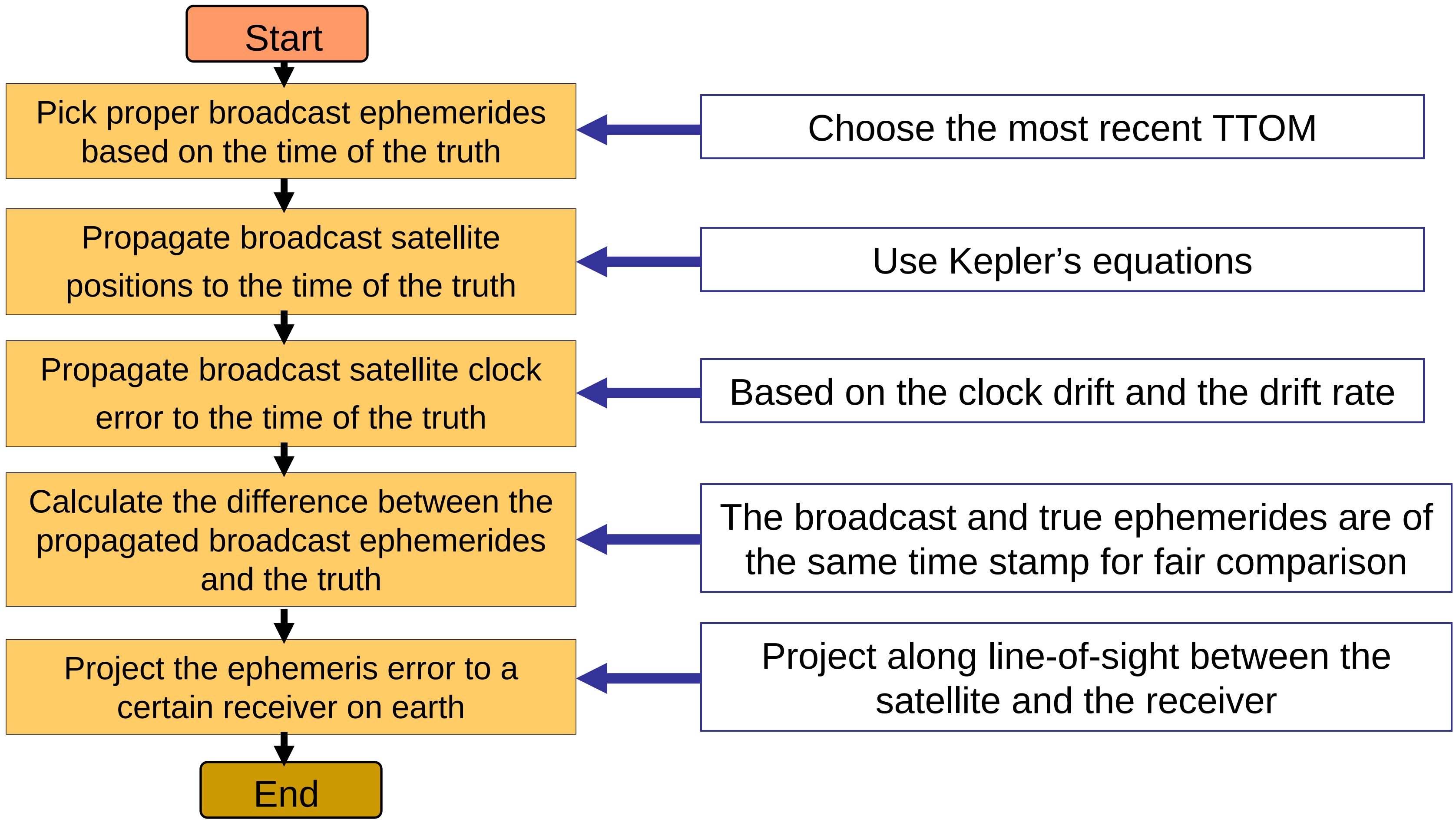
http://igscb.jpl.nasa.gov/network/netindex.html

- National Geospatial-Intelligence Agency (NGA) network
  - Provide post-processed true ephemeris
  - 10+ receivers worldwide
  - Output satellite position and clock information
  - Data update every 15 minutes



http://earth-info.nga.mil/GandG/sathtml/StationMap.gif

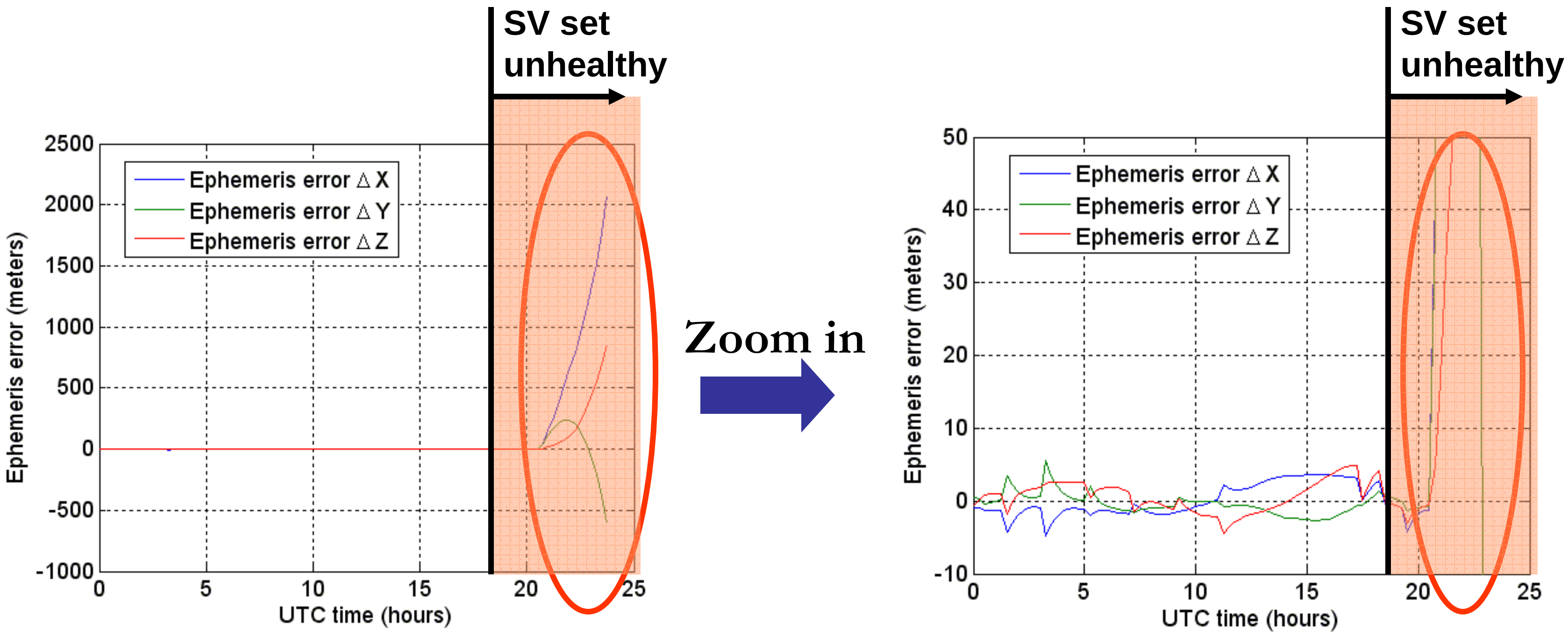
Bottom-up Methodology in Detail



Ephemeris Error – Satellite Position

PRN 10, Day 39 of 2007

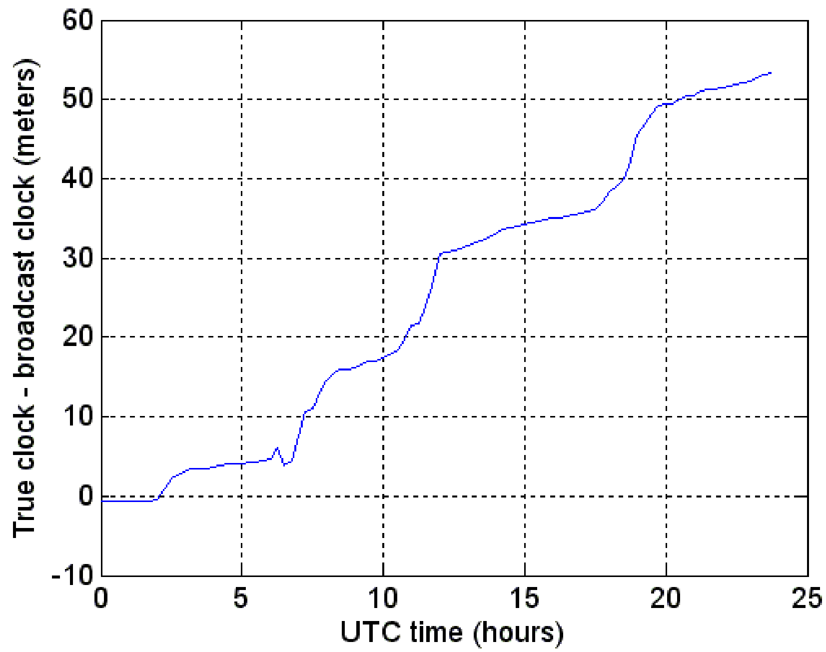
Ephemeris error ($\Delta X, \Delta Y, \Delta Z$)



The ephemeris anomaly of PRN 10 on Day 39
is due to satellite position errors.

Ephemeris Error – Clock

PRN 07, Day 229 Year 2007



The clock error is the cause of the anomaly.