Real time precise GPS constellation and clocks estimation by means of a Kalman filter

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Introduction

Kalman filtering: a new approach for real-time orbits and clocks determination

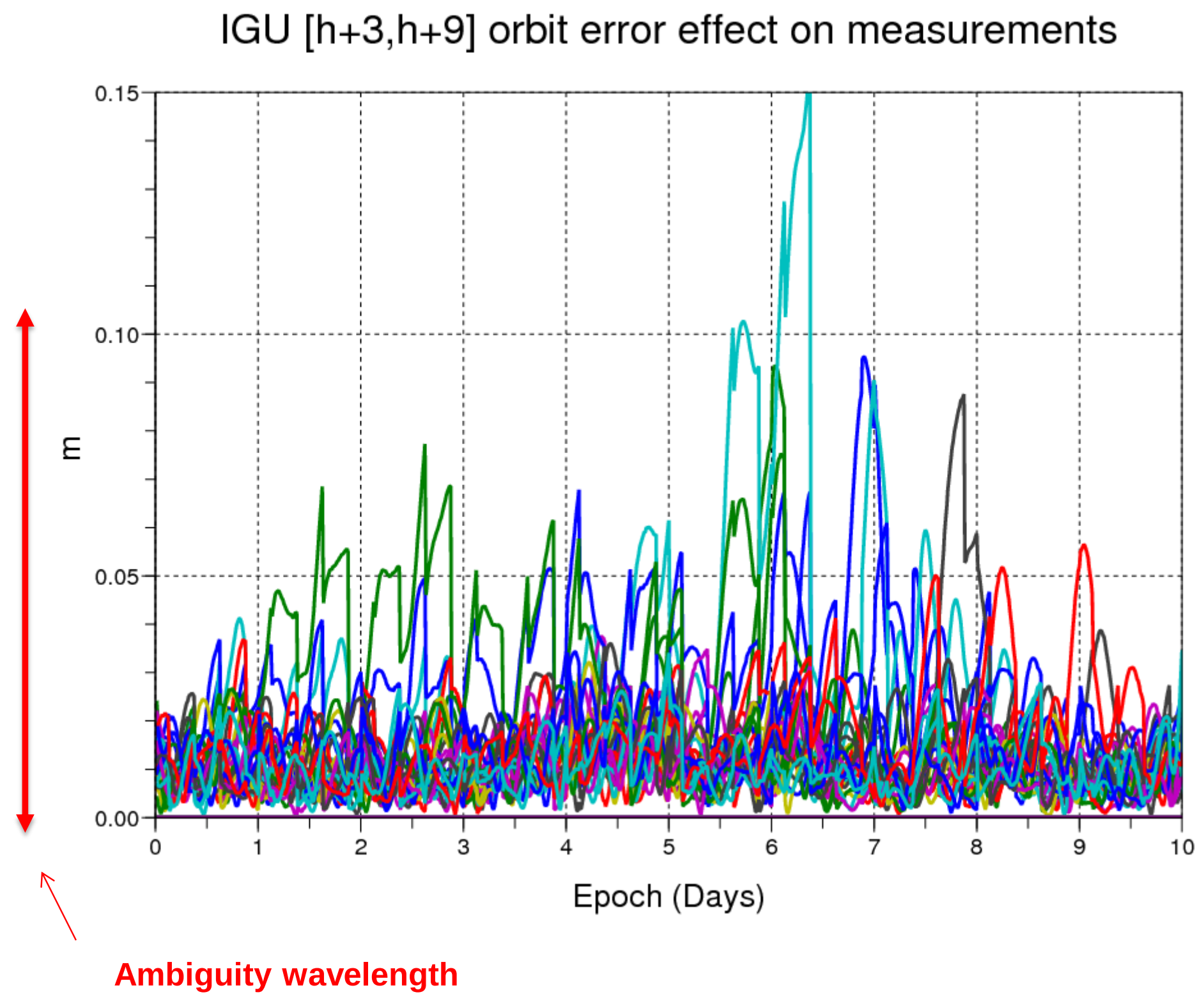
Real time GNSS orbits and clocks computation is routinely performed, for example in the framework of the Real Time IGS project. Most of the RTIGS analysis centers use a Kalman filter to compute the clocks, orbits are in general estimated using a least-squares filter based on past data, and extrapolated by a model, such as predicted IGS orbits (IGUs). By nature, this method is not optimal and limits the precision of the orbits.

We present a study to implement clocks and orbits estimation in real time by means of a Kalman filter, the orbital dynamics being included in the state vector of the filter.

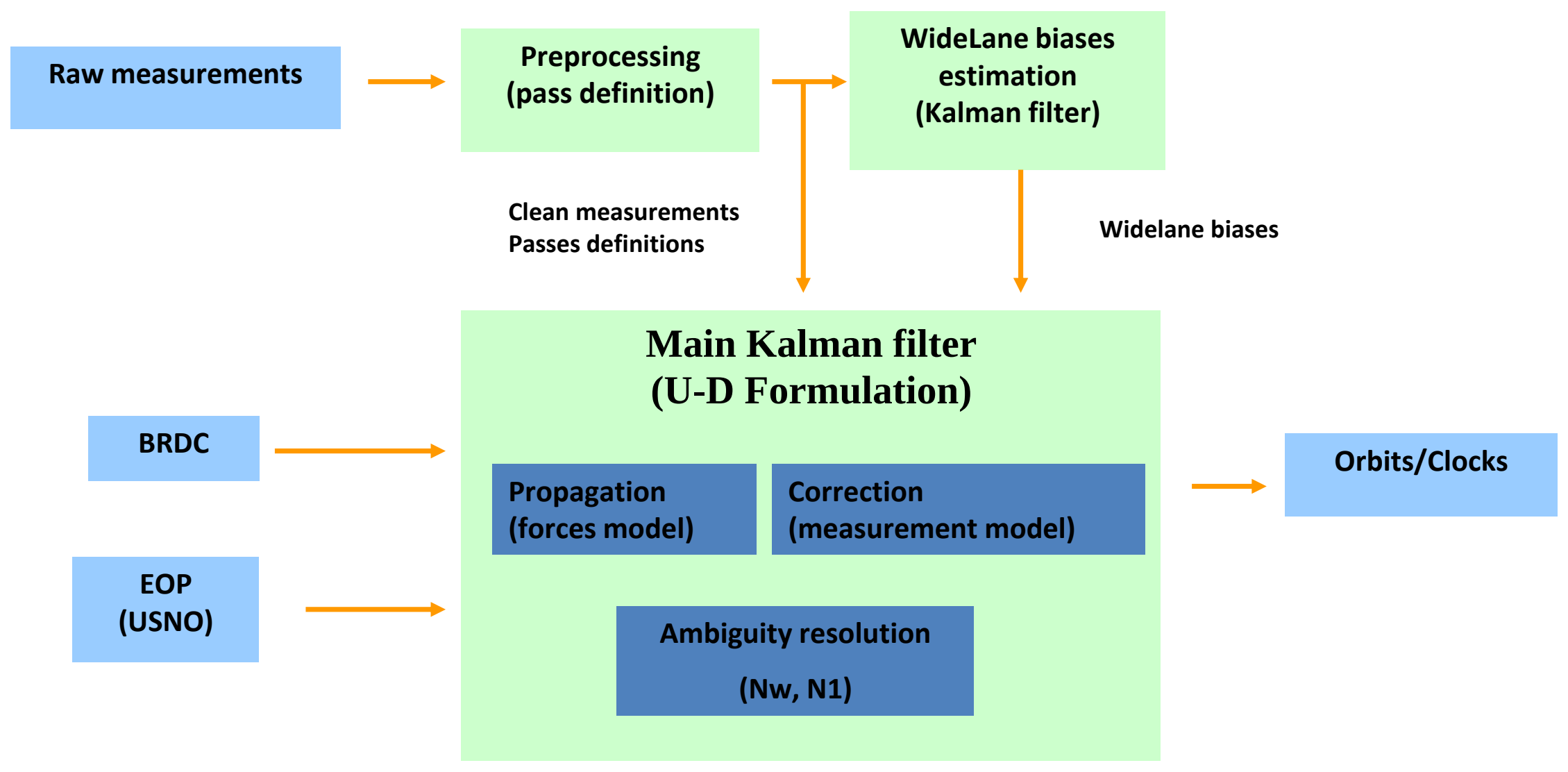
This approach is routinely applied by JPL and Trimble for their respective applications (cf references)

Motivation for this study

- The CNES IGS Real Time analysis center uses a-priori orbits
  - Ex. IGU: 6 hours batches extrapolated to obtain the real-time part of the orbit [h+3, h+9]
  - Like most real time analysis centers
- In addition, CNES promotes a new technique for ambiguity resolution
- Ambiguity resolution requires an accurate measurement model
  - A-priori orbit error is the main contributor to the error budget
  - Error is mainly due to extrapolation
  - Orbit error impact on measurement model error is roughly ~ horizontal errors / 4
  - Should be < ¼ N1 wavelength (2,5 cm)



- The current management of a priori orbits is not fully satisfactory
- Decision was taken to improve the Kalman filter
  - To compute both clocks AND orbits
  - To minimize external interfaces, a-priori information and thus improve robustness
- New software architecture


Raw measurements
Preprocessing (pass definition)
WideLane biases estimation (Kalman filter)
Clean measurements
Passes definitions
Widelane biases
Main Kalman filter (U-D Formulation)
BRDC
EOP (USNO)
Propagation (forces model)
Correction (measurement model)
Ambiguity resolution (Nw, N1)
Orbits/Clocks

Implementation of the Kalman filter for orbits and clocks estimation (1)

Orbit propagation

Elaborate force model and 6th order Runge-Kutta integrator

Force	Amplitude (m/s²)	Model
Geopotential	0.5	EIGEN RL02 bis Degree and order 12 Secular and periodic terms
Third body	10^{-6}	Moon, Sun, Venus JPL DE 405
Direct solar pressure radiation	10^{-8}	Sphere
Solid tides	10^{-9}	Anelastic Earth model
Y bias	10^{-9}	
Empirical forces	10^{-9}	Orbital frame, constant and 1/rev (sub-solar phased)
Ocean tides	10^{-10}	FES 2004
Relativity	10^{-10}	Schwarzchild

Orbit correction

Goal: measurement model accuracy < 5 mm

Model term	Amplitude (m)	Remark
Propagation distance	10^{7}	Incl. Sagnac effect
Ionosphere	10	Corrected for 1st order using dual frequency measurements
Solid earth tide	0.10	Routine dehanttideinel.f
Phase Wind-Up	0.10	Wu & al.
Troposphere	0.10	Zenithal delay Mapping function: Stanag
Attitude law	0.10	Nominal
Satellites and stations PCV and PCO	0.01	igs08_wwww.atx
Ocean tide loading	0.01	Routine hardisp.f http://www.oso.chalmers.se/~loading
Relativistic effects	0.005	2nd order correction on clocks gravitational time delay

Earth orientation

- Frames
  - Inertial: GCRF
  - Terrestrial: ITRF2008
- Interconnection
  - Precession: IAU2000
  - Nutation: IAU2000 (dx and dy corrections from IERS Bulletin A)
- Sub-daily Earth orientation variations
  - Applied diurnal and semidiurnal variations in x,y, UT1 (IERS 2003 interp.f)
- Estimated parameters
  - Polar motion
  - UT1 (not observable with GNSS, a priori value taken from gpsrapid.daily bulletin at USNO)
  - LOD

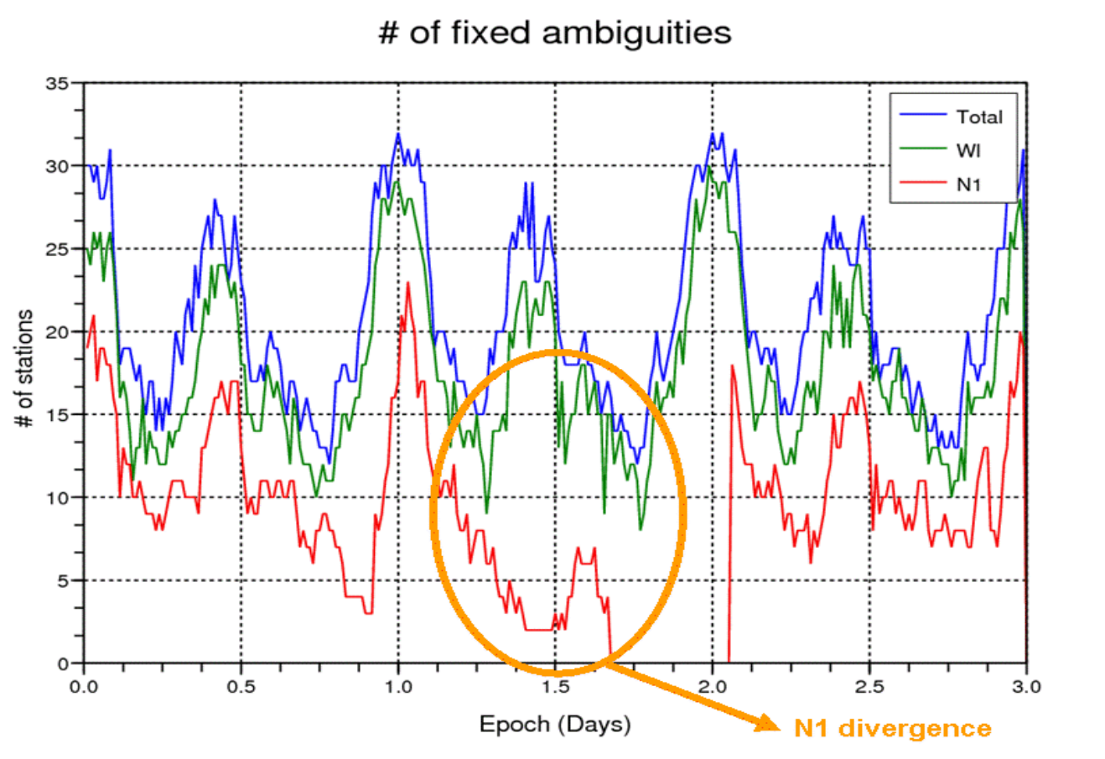
Implementation (2)

Ambiguity resolution

- Ambiguity resolution follows an undifferenced formulation (see ref)
- Widelane + Narrowlane scheme
- No explicit difference in the resolution process
- Ambiguity resolution improves orbits accuracy and outputs clocks compatible with direct ambiguity resolution for isolated receivers
  - PPP-AR

Fault detection

- Preprocessing
  - Detects phase jumps and eliminates erroneous measurements
- Kalman Filter
  - Removes high residual measurements (20 m code and 5 cm phase cut-offs)
  - Implements of a downdating algorithm
- Maneuver detection
  - Based on pseudorange residuals
  - Resets all satellite parameters
- Ambiguity fixing
  - Monitors N1 ambiguity fixing ratio
  - Resets satellite ambiguity vector state



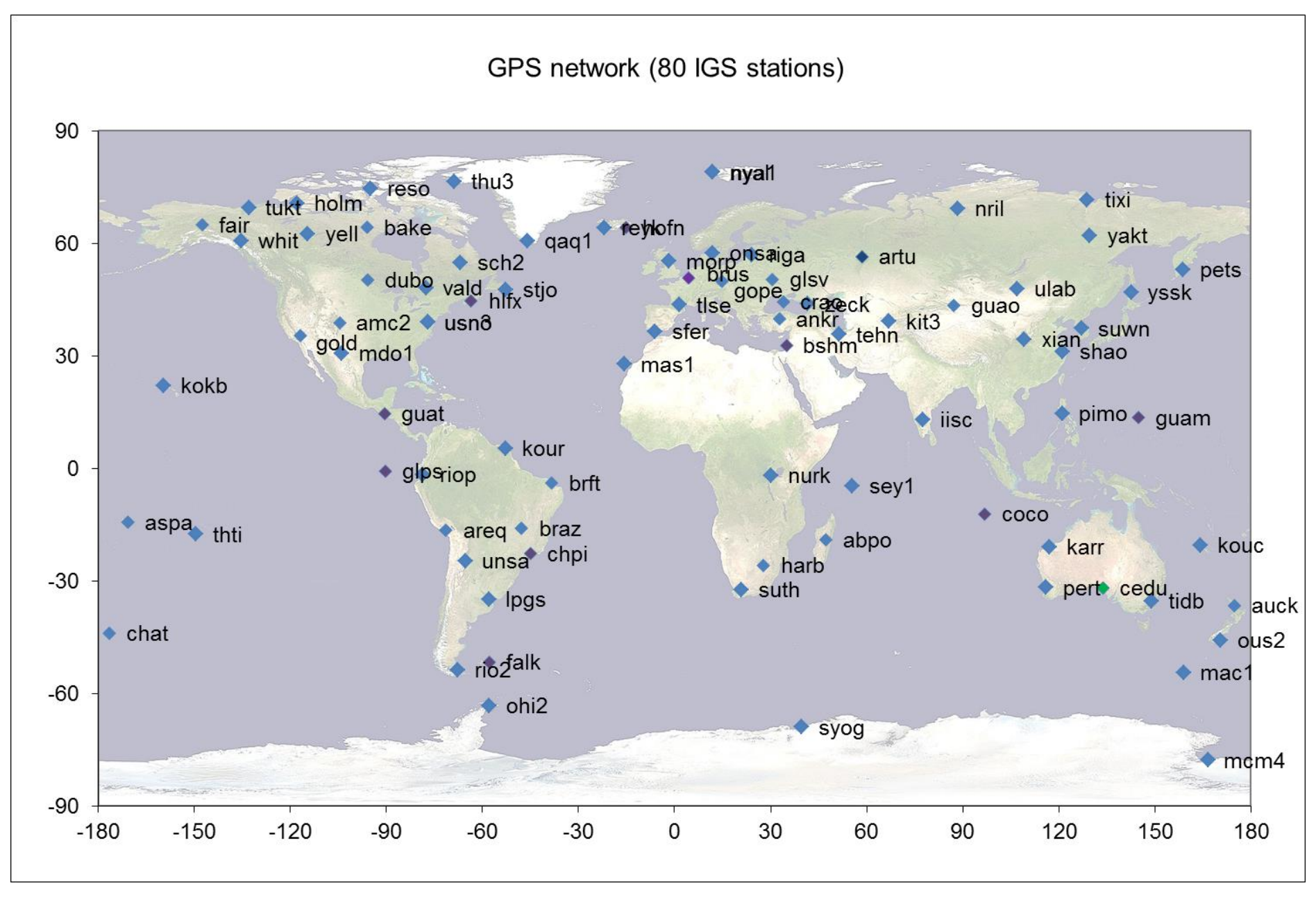
Typical parameterization (32 satellites, 70 Stations)

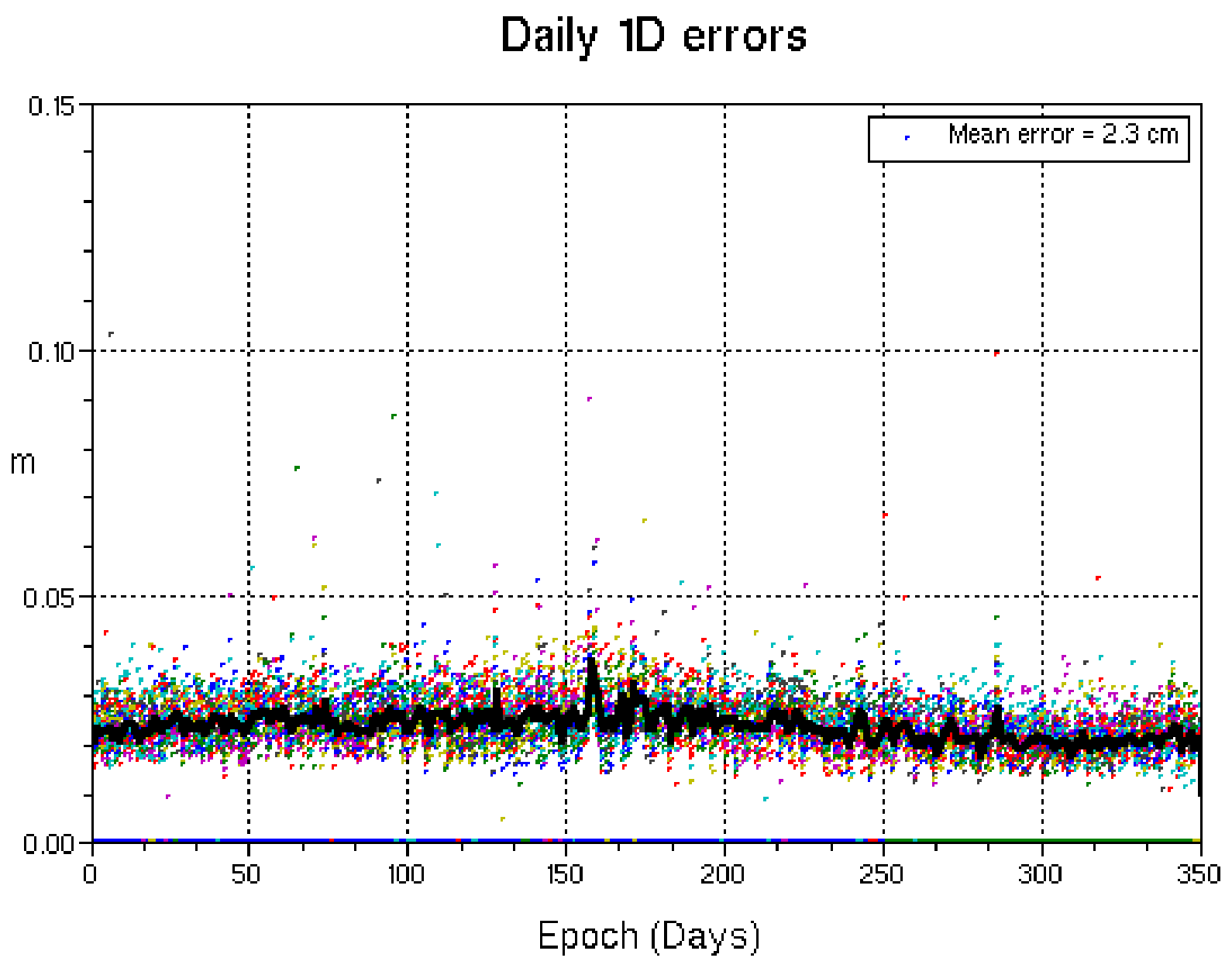
Parameter	Quantity	Typical number	Initial covariance	Model noise 900 s	Model noise 60 s
Positions	3 per satellite	32*3	1 m	0	0
Velocities	3 per satellite	32*3	0.001 m/s	0	0
Solar pressure coefficient	1 per satellite	32	1	10^{-5}	$2.5\ 10^{-16}$
Y Bias	1 per satellite	32	10^{-13} m/s²	10^{-13} m/s²	$2.5\ 10^{-14}$ m/s²
Radial acceleration (cst, sin, cos)	3 per satellite	32*3	(0, 0, 0) m/s²	(0, 0, 0) m/s²	(0, 0, 0) m/s²
Along-track acceleration (cst, sin, cos)	3 per satellite	32*3	$(10^{-10}, 10^{-10}, 10^{-10})$ m/s²	$(10^{-13}, 10^{-12}, 10^{-12})$ m/s²	$2.5(10^{-14}, 10^{-13}, 10^{-13})$ m/s²
Cross-track acceleration (cst, sin, cos)	3 per satellite	32*3	$(10^{-10}, 10^{-10}, 10^{-10})$ m/s²	$(10^{-13}, 10^{-12}, 10^{-12})$ m/s²	$2.5(10^{-14}, 10^{-13}, 10^{-13})$ m/s²
Polar motion (u, v)	2	2	5.10^{-4} arcsec	5.10^{-5} arcsec	10^{-5} arcsec
UT1	1	1	0	0	0
LOD	1	1	10^{-8} s/s	10^{-11} s/s	10^{-12} s/s
Satellite clock	1 per satellite	32	inf	inf	inf
Satellite bias (code-phase)	1 per satellite	32	1 m	1 mm	0.1 mm
Station clock	1 per station	70	inf	inf	inf
Station bias (code-phase)	1 per station	70	1 m	1 m	1 m
Zenithal tropospheric delay	1 per station	70	0.5 m	1 mm	0.25 mm
Phase ambiguities	12 per station (max)	70*12	1 m	0	0
		1662			

- 800 pseudorange + 800 phase measurements at each epoch
- Complete epoch processing: extrapolation + correction ~ 10 sec CPU time

Actual results

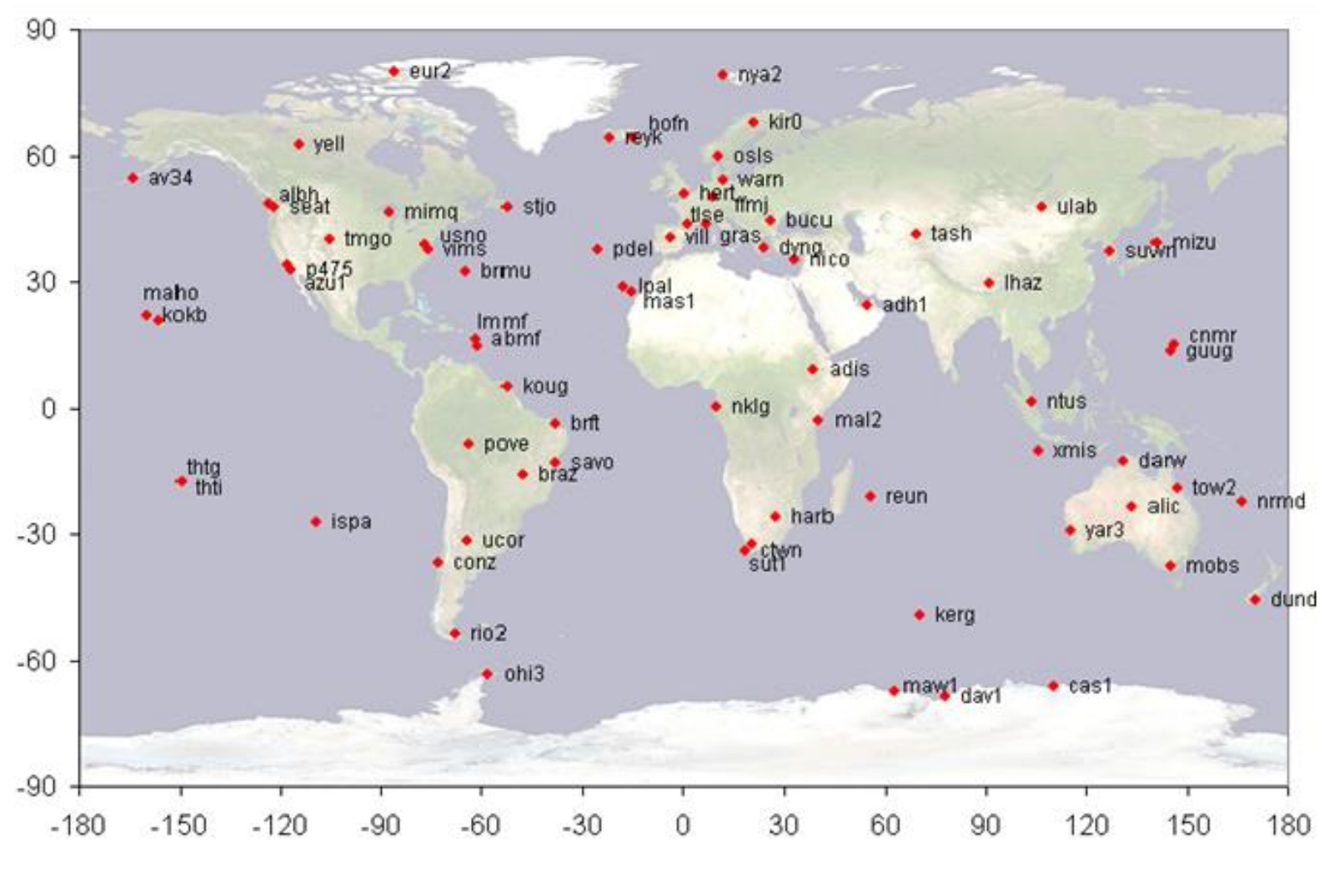
Results over a full draconitic year (09/2010 to 08/2011)
(replay with IGS measurements)

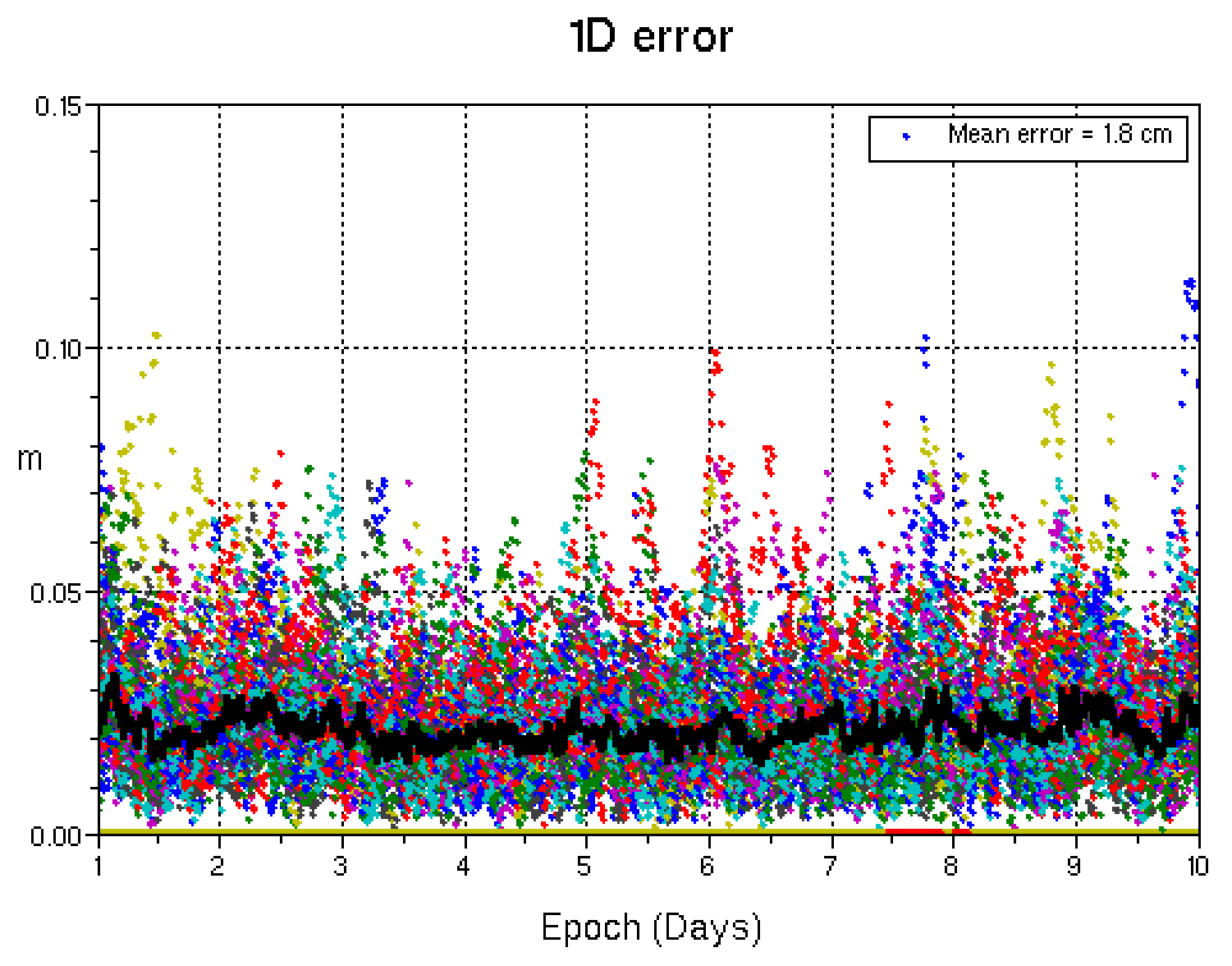




Results using actual real-time measurements

- Real-Time network (65 stations), IGS RT Service framework
- Use of several casters: igs-ip, gfz, NrCan, ign, unavco, (noaa)
- Timespan: 10 days (01/14/2013 to 01/23/2013)





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Formulation

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Real time applications

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Other implementations

Xiaoming Chen and al., " Trimble RTX, an Innovative New Approach for Network RTK ", Trimble white paper

Willy Bertiger and al., « First orbit determination performance assessment for the OCX navigation software in an operational environment », proceedings of ION GNSS 2012