IGS-MGEX:
Preparing for a Multi-GNSS World

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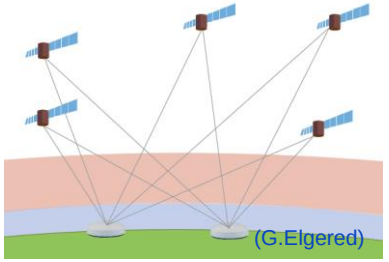
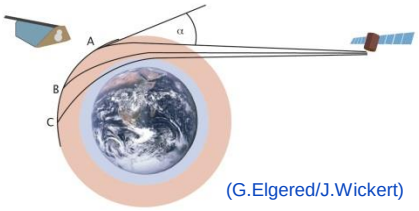
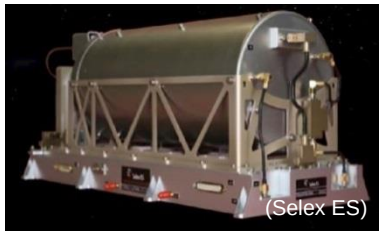
DLR, German Space Operations Center

Why Multi-GNSS?

- More Satellites
  - Improved PPP convergence
  - More pierce points for atmospheric sounding
  - Decorrelation of height, clock, troposphere
- Improved Signals
  - Less multipath
  - Increased robustness (scintillation, weak signals)
- Stable clocks
  - Improved Real-time PPP
  - Orbit improvement
- Diversity
  - Different orbital periods and commensurabilities
  - Decorrelation of estimated parameters (orbits, Earth rotation)

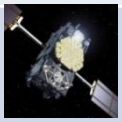
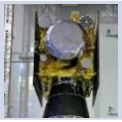






Global and Regional Navigation Satellite Systems

Today‘s „System of Systems”

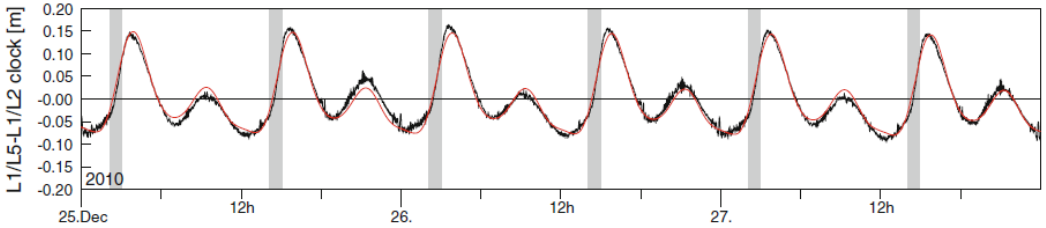
System		Blocks	Signals	Sats*)
GPS		IIA IIR IIR-M IIF	L1 C/A, L1/L2 P(Y) L1 C/A, L1/L2 P(Y) +L2C +L5	3 12 7 9
GLONASS		M M+ K1	L1/L2 C/A+P L1/L2 C/A+P, L3 (CDMA) L1/L2 C/A+P, L3 (CDMA)	23 1 (2)
BeiDou		GEO IGSO MEO 3rd generation	B1, B2, B3 B1, B2, B3 B1, B2, B3 (B1,B3)	5 5 3 (1)
Galileo		IOV FOC	E1, (E6), E5a/b/ab E1, (E6), E5a/b/ab	3+(1) (2)+(2)
QZSS		IGSO	L1 C/A, L1C, SAIF L2C, E6 LEX, L5	1
IRNSS		IGSO	L5, S	4

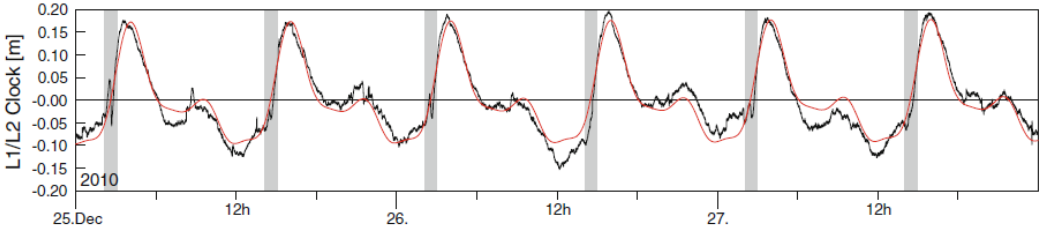
*) Status June 2015; brackets indicate satellites not declared healthy/operational

GPS Status & News

- 9 Block IIF satellites active, only 3 IIA remain
  - Constellation refreshment due to IIF stock clearance
- RAFSs IIF are among the best clocks ever
  - ADEV ~$5 \cdot 10^{-15}$@1d, few 10^{-12}@1s
  - Use of Cs-clock on SVN65 “spoils” average SISRE
  - Thermally-induced bias variations affect apparent L1/L2 clock and L1/L2/L5 phase consistency (0.2m)
- Overall SISRE ~ 0.7m (“Gold standard”)
- New CNAV
  - Transmitted since April 2014
  - Daily uploads since Jan 2015
  - SISRE of IIR-M and IIF CNAV (almost) identical to LNAV (0.6m)
- Gain & Phase patterns for IIR/IIR-M publicly released, IIF pending

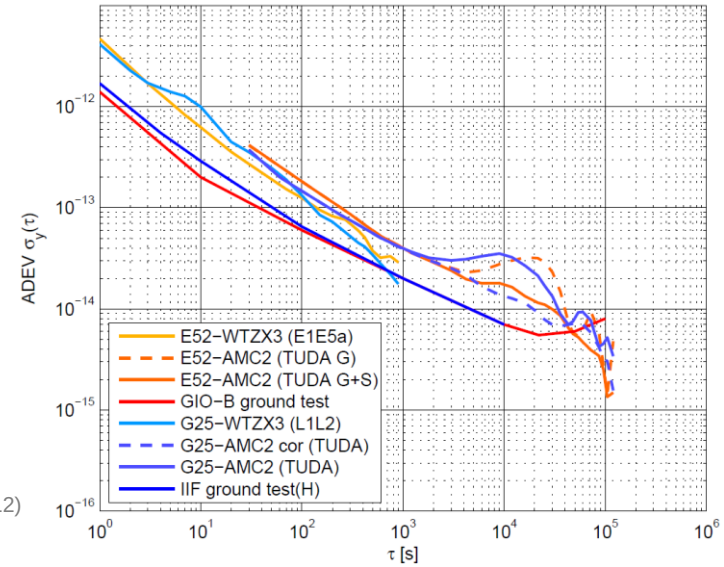
GPS Status & News





Block IIF Clock/Bias Variations

GPS Solut 16:303–313 (2012)

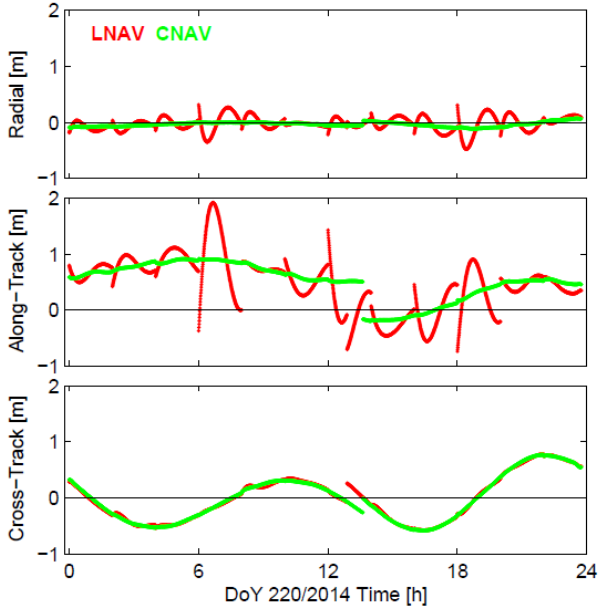


Clock Stability

NAVIGATION 59(4):291-302 (2012)

LNAV/CNAV Orbit Errors

NAVIGATION (in press)



GLONASS Status &News

- Fully operational constellation of 24 GLO-M sats
- Ongoing modernization
  - Two K1 satellites with L3 CDMA and new Rb clocks (?) in testing
  - Latest GLO-M satellites (no. 755) transmits L3 CDMA
  - Microwave and optical links in testing
- Cesium clocks ($5 \cdot 10^{-14}$@1d; 10^{-11}@1s)
- Realignment of GLO system time from Aug. to Dec. 2014 to remove UTC offset
- New SDCM monitoring stations in Antarctica and Brazil
- Current SISRE ~ 1.5-1.9 m

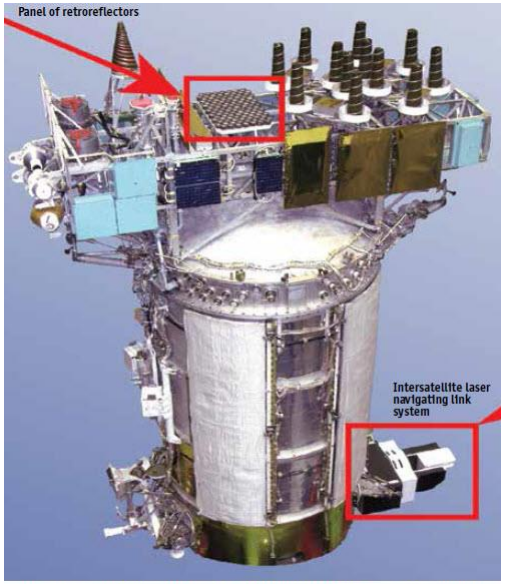
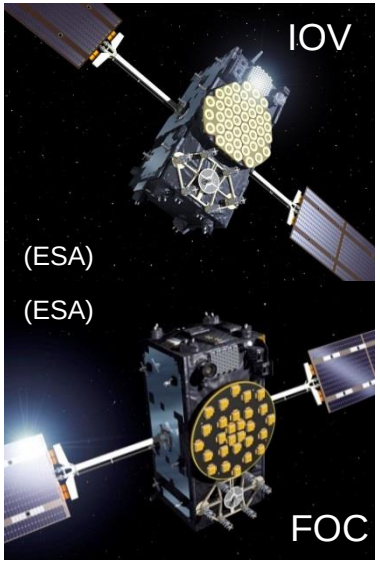


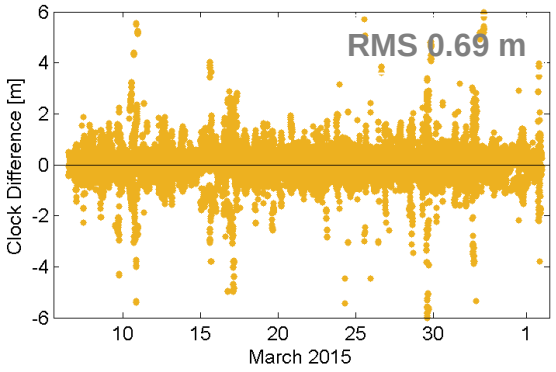
Figure 1. Panel of retroreflectors and Intersatellite laser navigating link system at the SC «GLONASS-M».

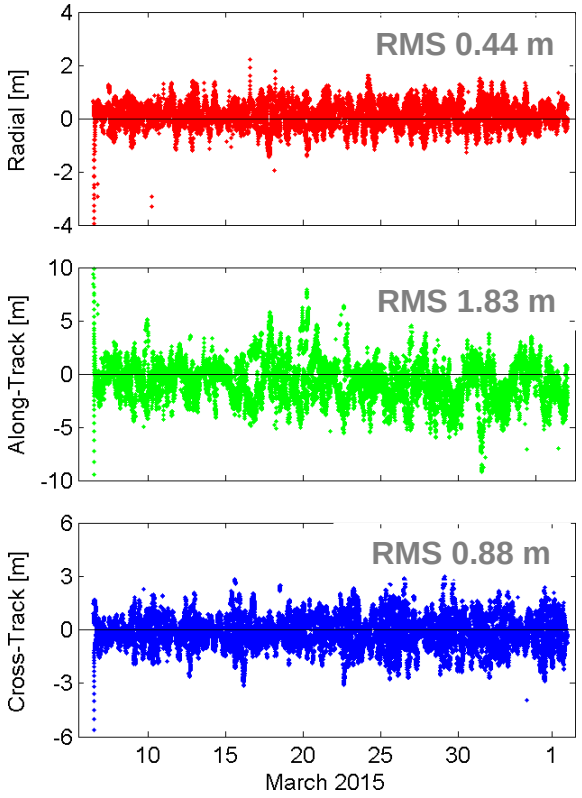
Galileo Status and News

- Four IOV satellites and four FOC satellites launched
  - Loss of E5 on IOV-4, reduced power on IOV-1/2/3
  - Wrong orbit of FOC-1/2;
    no almanac & ephemeris but otherwise fully functional
  - FOC-3/4 signals activated late May 2015
- High-grade clocks
  - Passive H-masers (ADEV ~$5 \cdot 10^{-15}$@1d, few 10^{-12}@1s)
  - Rb clocks (Spectratime, ~$1 \cdot 10^{-14}$@1d)
- Solar radiation pressure modeling needs to account for stretched (non-cubic) body to remove 1/rev orbit determination errors
- SISRE ~1.5m / 0.7 m before/after ground segment update in Feb./Mar. 2015 (currently 10 min update interval)



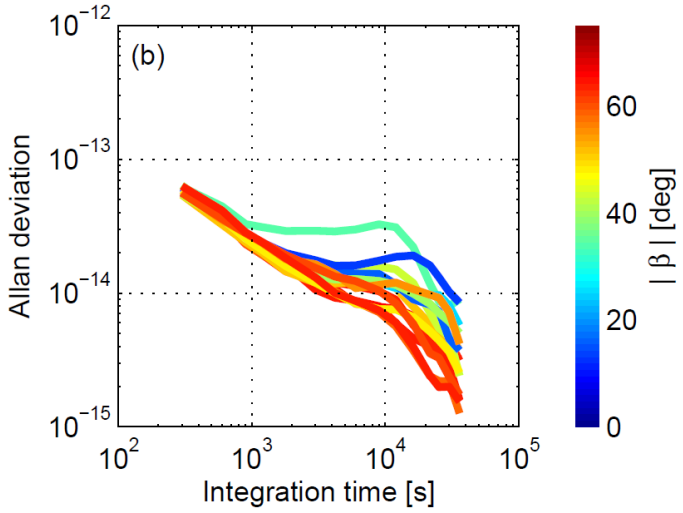
Galileo Status and News





Broadcast Orbit/Clock Errors (IOV)

Steigenberger et al., COST 2015

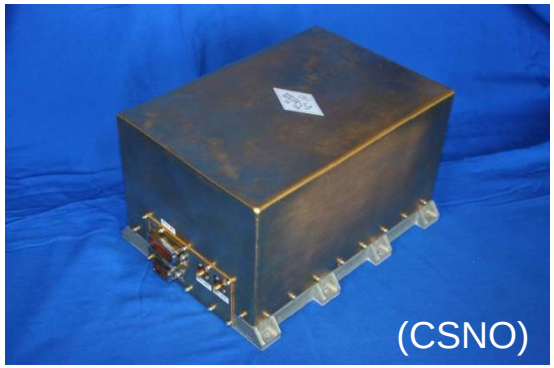


Clock Performance (IOV PHM)

J Geod (2015) 89:283–297

BeiDou Status and News

- Regional system (BDS-2) fully operational
  - 5 GEOs, 5 IGSOs, 3(4) MEOs (M5 terminated in mid 2014)
  - Open service ICD and performance standards released
  - 2 O/S signals on B1, B2; plus “authorized” B3 signal
  - “SBAS”-like real-time corrections (for China) via GEOs
- New BeiDou I1-S satellite launched Mar. 2015
  - Presumably in-orbit-validation satellite for BDS-3
  - Expected to transmit new BDS signals on L1/E1 and L5/E5 (currently B1+B3; wide-band B1+L1 filter)
- Indigenous and European (backup) clocks (10^{-14}@1d, few 10^{-12}@1s)
- SISRE ~1.5 m (~1.0m for MEO & IGSO)



QZSS Status and News

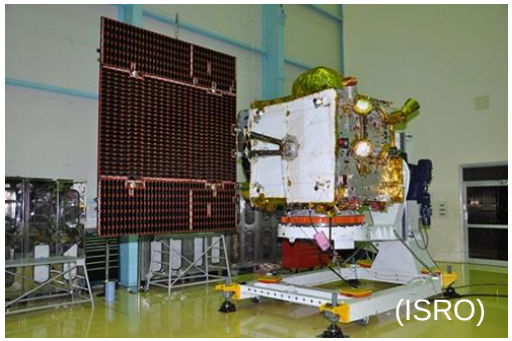
- Regional navigation, augmentation and messaging
  - One spacecraft (QZS-1) launched so far
  - 3 IGSO plus 1 GEO planned for 2018
- Numerous signals and services
  - L1 C/A and L1C, L2C, L5
    (smooth integration with GPS)
  - L1-SAIF and LEX
    (augmentation; “sub-meter”, real-time PPP)
- Yaw-steering and orbit normal mode (ß<20°)
- High-grade RAFS (same as GPS IIF)
- SISRE ~0.6m (15 min updates)

IRNSS Status and News

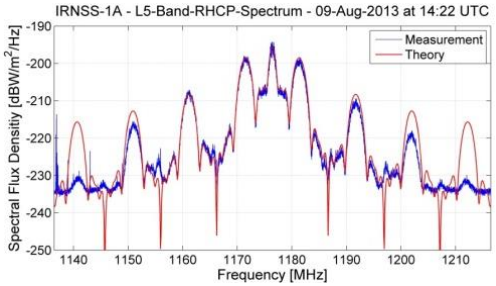
- 4 satellites launched (3 IGSOs, 1 GEO)
- High-performance Rb clocks
  (Spectratime; in-flight characterization pending)
- L5 and S-band open service signals
- Laser retroreflectors (ILRS tracking)

- ICD released (Sep. 2014)
- Pre-operational (signals & nav. msg.)
- Broadcast SISRE few meters

- (Almost) no receivers and data available
  to GNSS community ☹



(Spectratime)



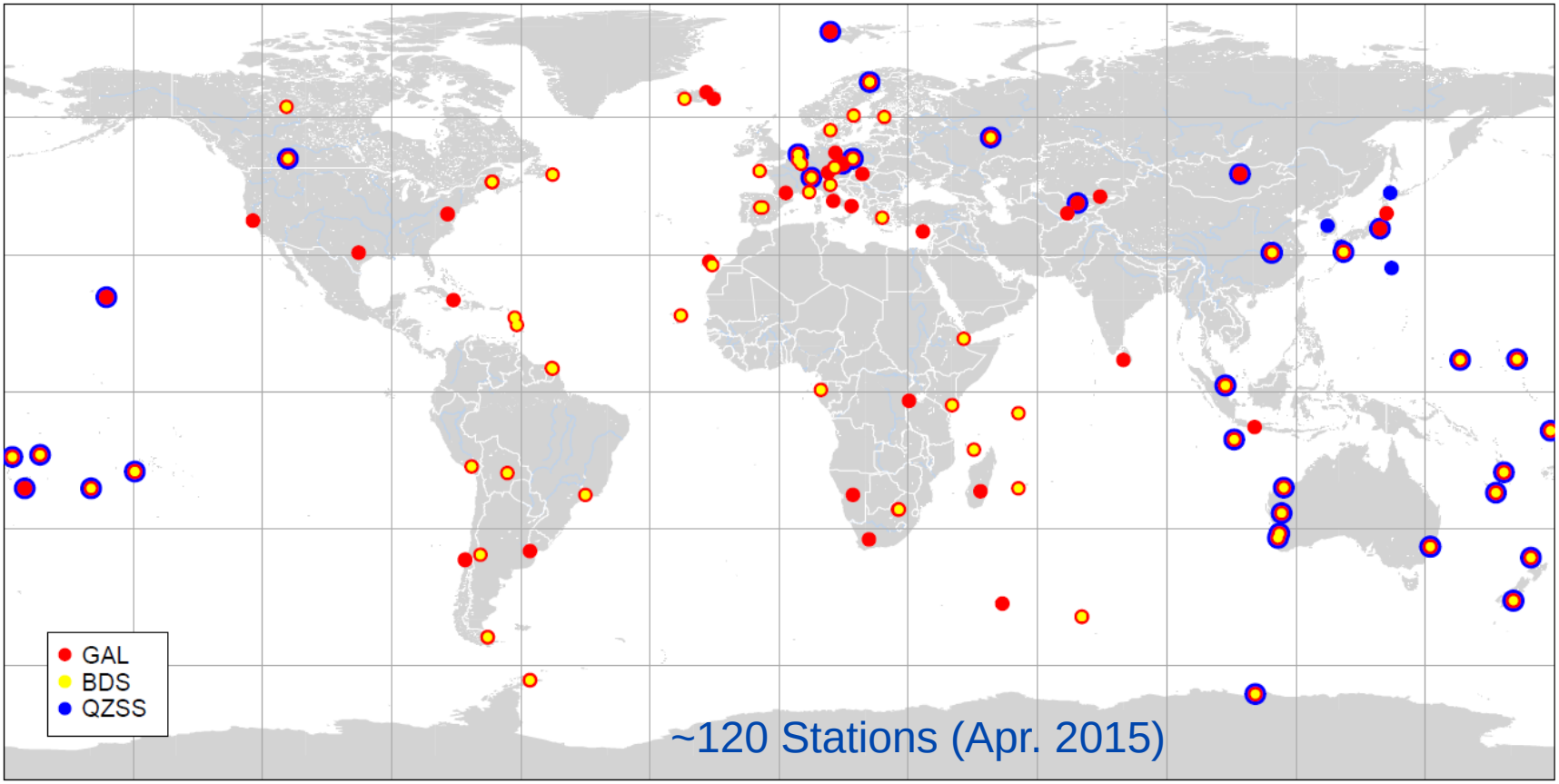
Thölert et al; DOI 10.1007/s10291-013-0351-7

The IGS Multi-GNSS Experiment

Multi-GNSS Experiment (MGEX)

- Multi-GNSS Experiment (MGEX)
  - Call-for-participation released mid-2011
  - Steered by Multi-GNSS Working Group (MGWG)
- About 30 contributing agencies
- About 120 stations worldwide, 75 real-time
  - Diverse equipment (receivers, antennas)
  - Tracking of Galileo, BeiDou, QZSS, SBAS
- Free and open access
  - Data archives at CDDIS, IGN, BKG (RINEX 3.x)
  - Real-time NTRIP caster (RTCM3-MSM)
  - Product archive at CDDIS

The IGS MGEX Network



Offline : ftp://cddis.gsfc.nasa.gov/pub/gps/data/campaign/mgex/
Real-time: http://mgex.igs-ip.net/

The MGEX Network (2)

Features

- Heterogeneous equipment
- Global and continuous coverage (but no guarantee of service)
- Support of 5 GNSSs (GPS, GLO, GAL, BDS, QZS; +SBAS)
- Observations and navigation messages
- Archival and real-time data

Enables

- System characterization
- Product generation
- Science and engineering applications
- System monitoring

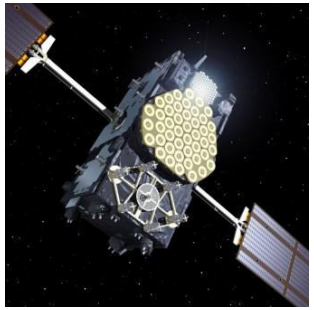
Multi-GNSS Products – Overview

Post-processed

- Precise orbits and clocks
- Broadcast ephemerides
- Differential code biases

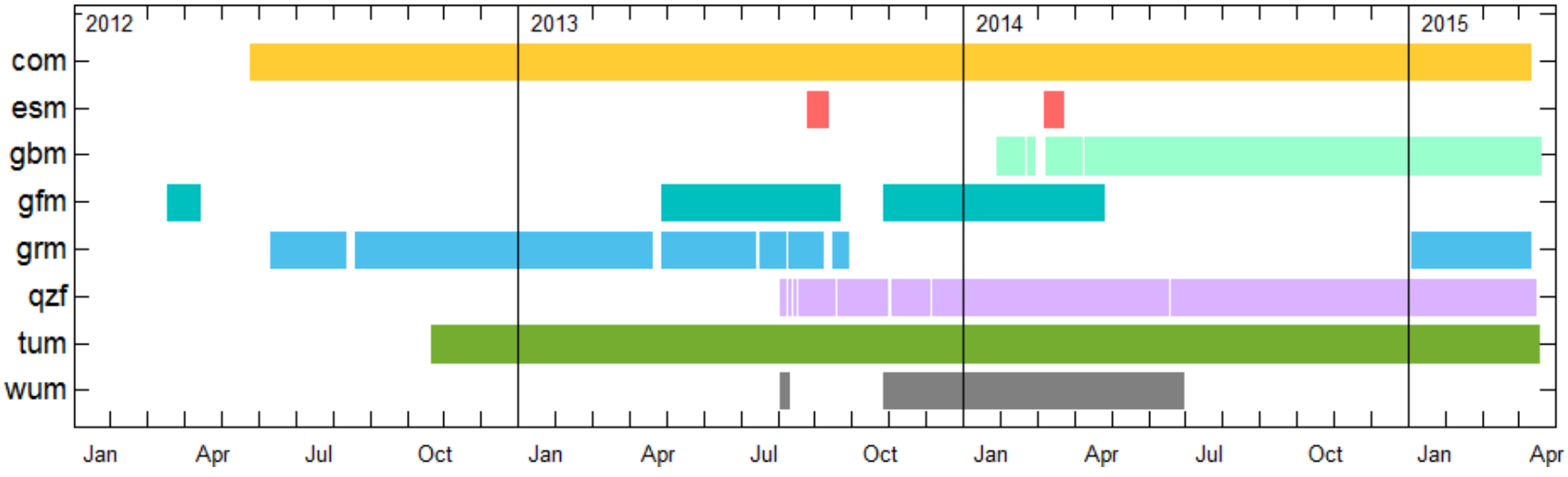
Real-time

- Broadcast ephemerides
- Orbit and clock corrections (Galileo)

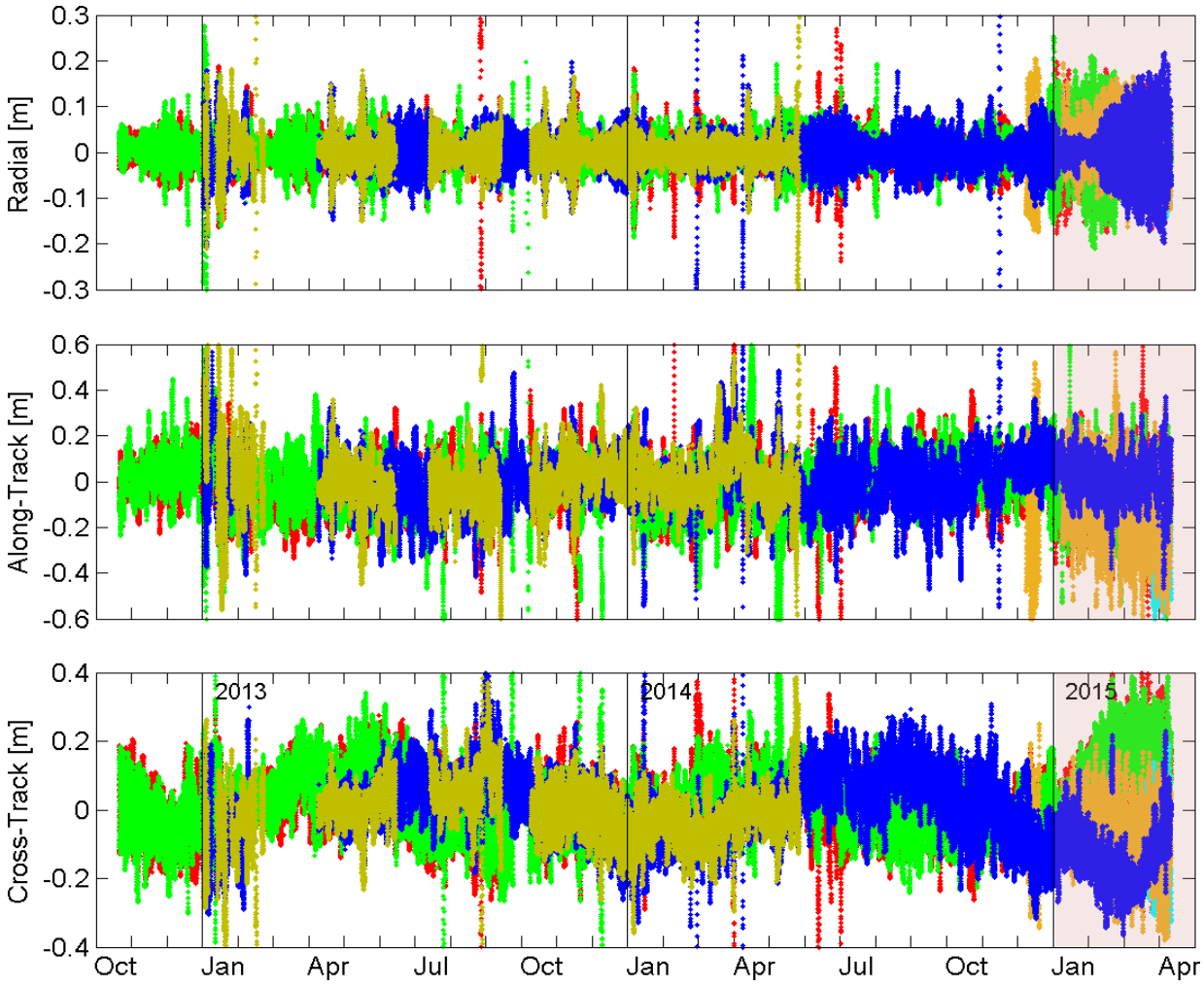


Orbit and Clock Products – Overview

Institution	ID	Systems
CNES/CLS, France	grm	GAL(+GPS+GLO)
CODE, Switzerland	com	GPS+GLO+GAL(+BDS+QZS)
ESA/ESOC, Germany	esm	GPS+GAL(+GLO+BDS+QZS)
GFZ, Germany	gbm	GPS+BDS(+GLO+GAL)
GFZ, Germany	gfm	GPS+GAL (discontinued)
JAXA, Japan	qzf	GPS+QZS
TUM, Germany	tum	GAL+QZS
Wuhan Univ., China	wum	BDS(+GPS+GLO)



Galileo Orbit Comparison **com/tum**



IOV-1 IOV-2
IOV-3 IOV-4
FOC-1 FOC-2

σ = 4 cm

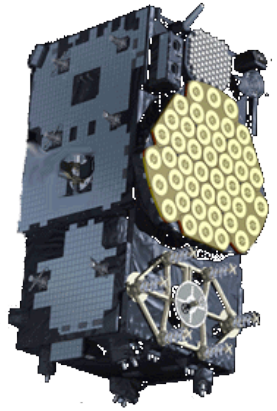
Different orbit model

σ =13 cm

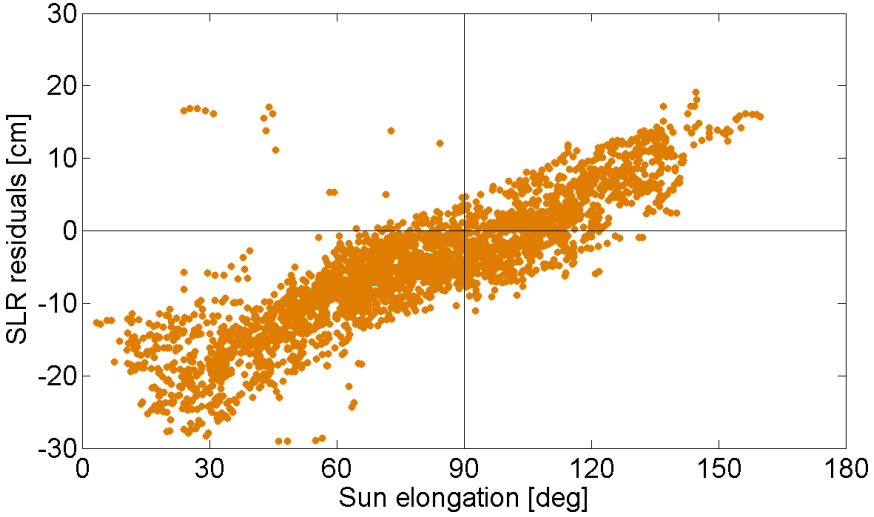
σ = 10 cm

Improved Galileo Orbit Modeling

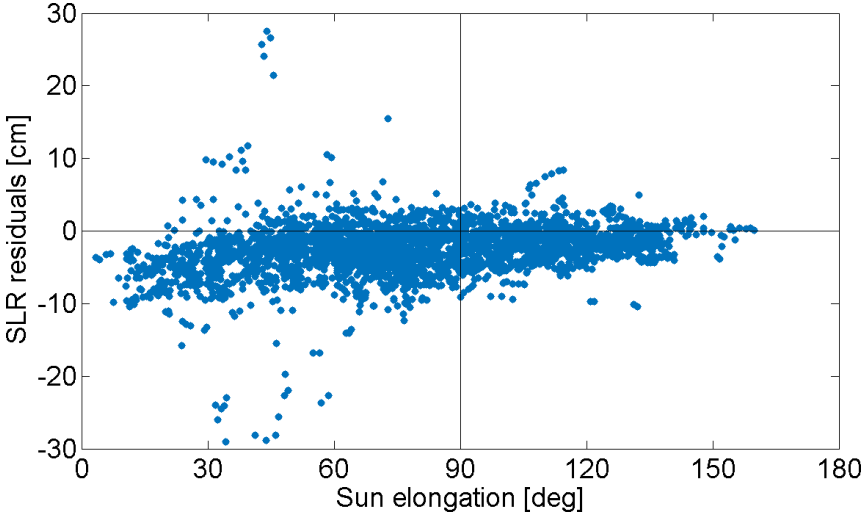
- Galileo satellites have different shape of the spacecraft body compared to GPS
- Classical orbit modeling introduces systematic errors
  - DLR a priori cuboid box model (JGeod 89(3):283-297, 2015)
  - Enhanced ECOM (Prange et al. EGU 2015)



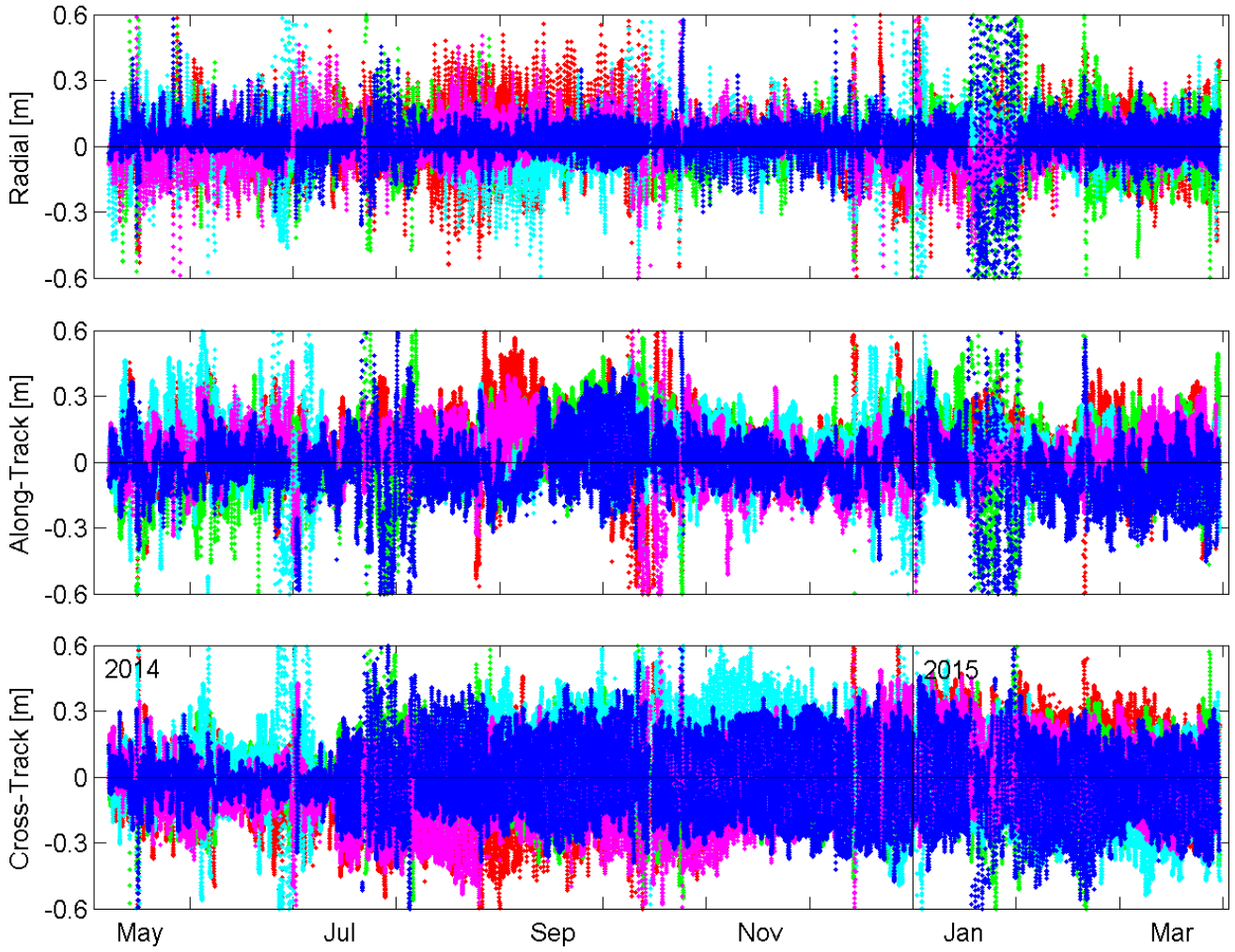
Without a priori cuboid box model



With a priori cuboid box model



BeiDou Orbit Comparison **com/gbm**



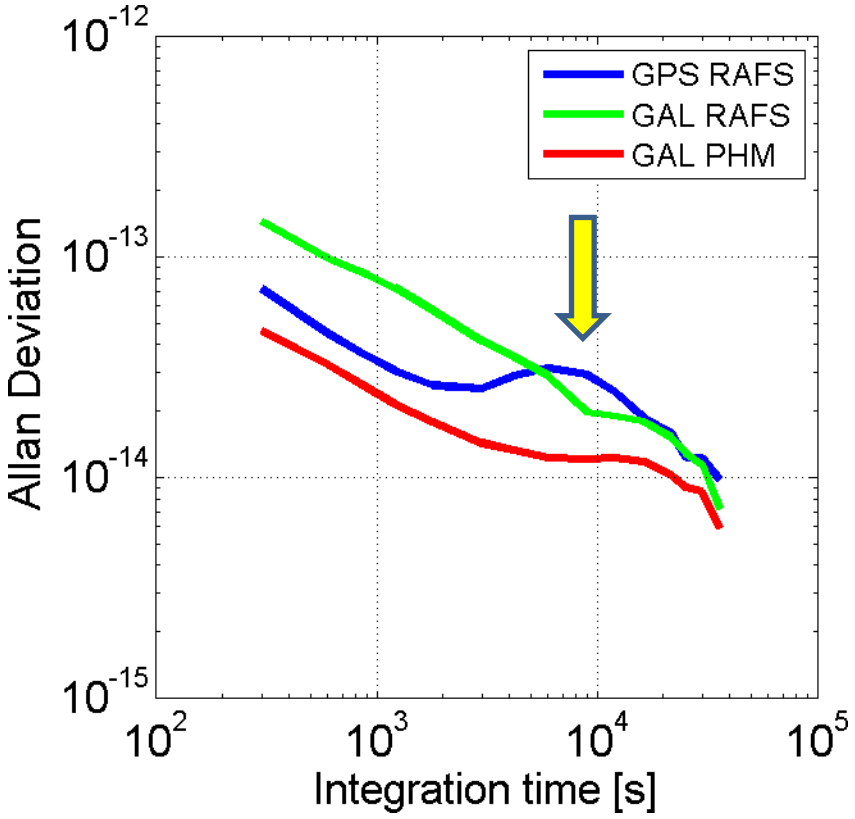
C06 **C07**
C08 **C09**
C10

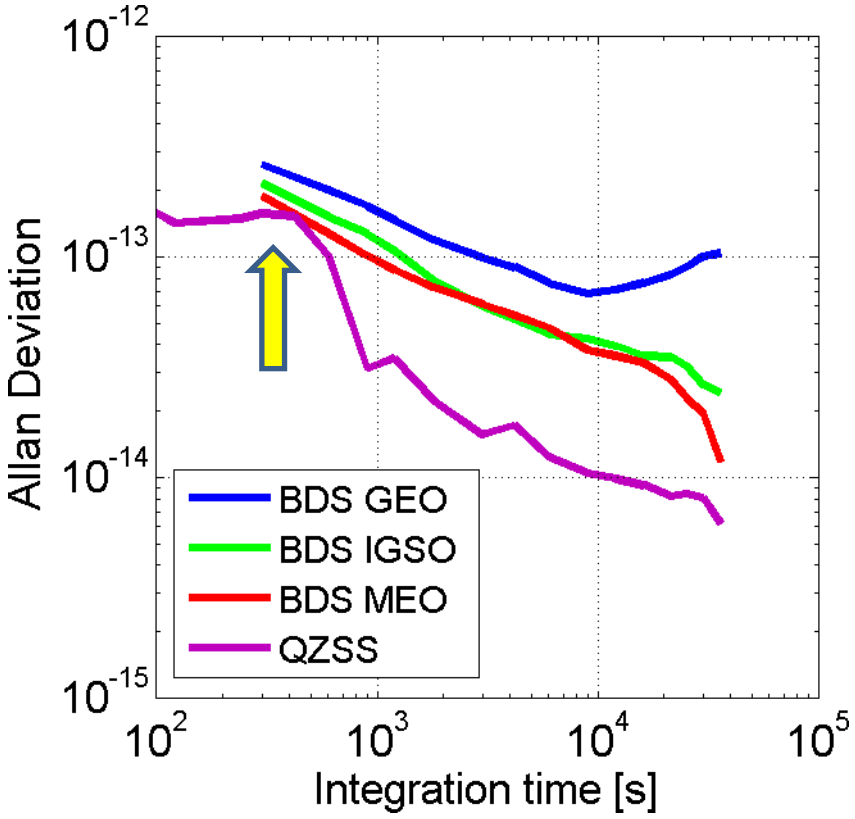
σ = 11 cm

σ = 16 cm

σ = 19 cm

Clock Quality





RAFS: Rubidium Atomic Frequency Standard

PHM: Passive Hydrogen Maser

GPS IIF: thermally induced bias variations

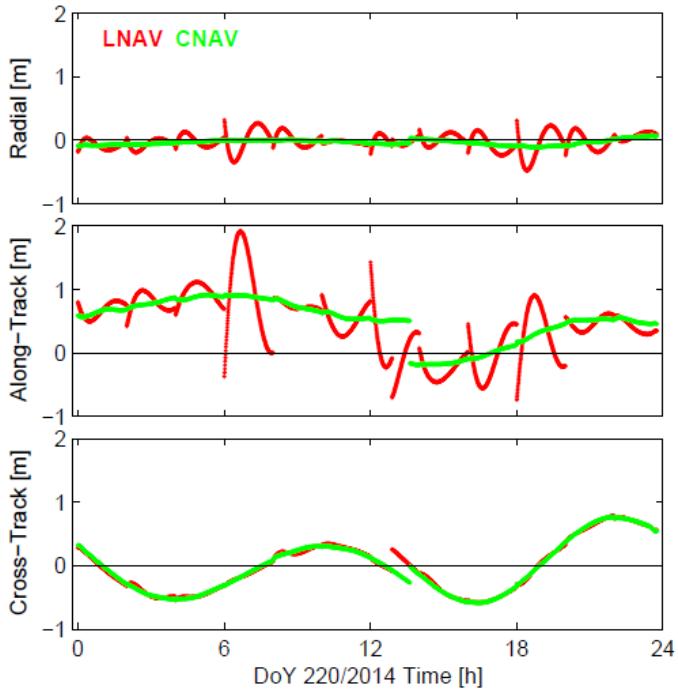
QZSS: short term clock variations (~15 min)

Broadcast Ephemerides – CNAV

- CNAV status
  - Pre-operational transmission on L2C/L5 of GPS Block IIR-M & IIF since April 2014
  - Daily uploads since Jan 2015 (15 satellites, SISRE ~0.6 m)
  - Operational transmission on L2C/L5 of QZSS
- Generated by DLR/TUM from native R/T streams of 10 globally distributed MGEX(CONGO) stations
- Extended RINEX nav format
- Includes group delays (intersystem corrections, ISCs) for civil navigation (L1 C/A + L2C + L5)!
- Daily files available at ftp://cddis.gsfc.nasa.gov/gnss/data/campaign/mgex/daily/rinex3/*yyyy*/cnav

CNAV Performance

Notably improved continuity and smoothness



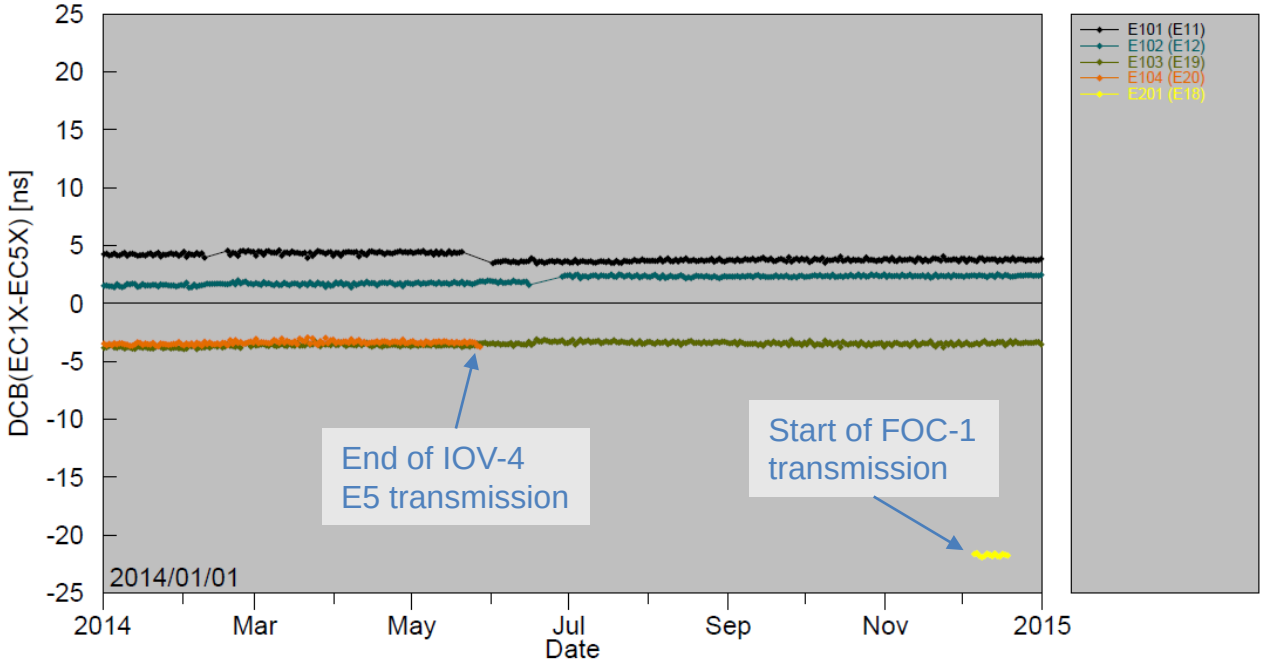
Virtually identical performance of LNAV and Preoperational CNAV after start of daily uploads

1/2015	LNAV	CNAV
Radial	0.17 m	0.16 m
Along-track	1.02 m	1.07 m
Cross-track	0.45 m	0.48 m
Clock	0.50 m	0.57 m
SISRE(orb)	0.23 m	0.23 m
SISRE	0.54 m	0.60 m

P. Steigenberger, O. Montenbruck, U. Hessels; “Performance Evaluation of the Early CNAV Navigation Message”; accepted for: Navigation – Journal of the ION (2015)

Differential Code Biases

- Prerequisite for processing of multi-constellation code observations
- Multi-GNSS DCBs from ionosphere-corrected pseudorange difference
- Generated by DLR on quarterly basis available at ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/dcb
- Includes all tracked signals of GPS, GLO, GAL, BDS

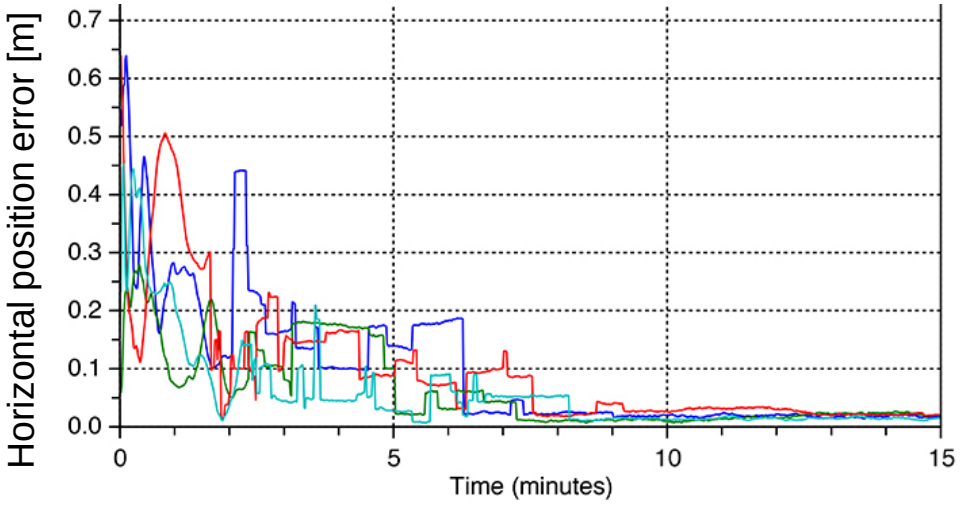


Real-time Broadcast Ephemerides

- Stream RTCM3EPH-MGEX at http://mgex.igs-ip.net
- Generated by BKG from global MGEX real-time network
- RTCM3 ephemeris messages including
  - GPS (msg 1019),
  - GLONASS(mgs 1020),
  - Galileo (msg 1045)
  - BeiDou (msg 63; draft)
  - QZSS (msg 1044)
  - SBAS (msg 1043)
- Data for one s/c of each constellation every 1 sec
- BNC 2.12 software for data extraction and RINEX conversion

Galileo R/T Orbit & Clock Corrections

- Stream CLK93 at http://products.igs-ip.net
- Generated by CNES (D. Laurichesse) using
  - Predicted Galileo orbits from TUM/DLR
  - MGEX real-time observations
- RTCM3 state-space-representation (SSR) messages with orbit/clock corrections relative to broadcast ephemerides
- Signal-in-space range error (SISRE) ~ 5 – 10 cm

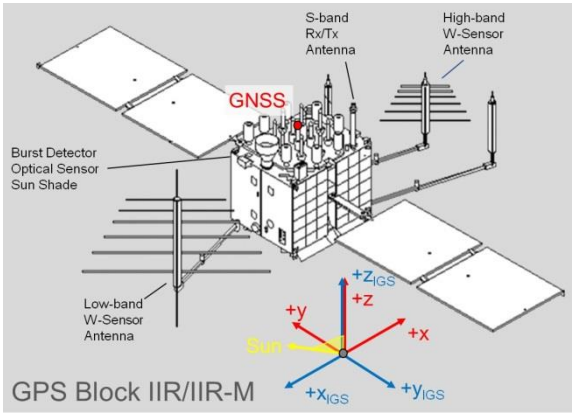


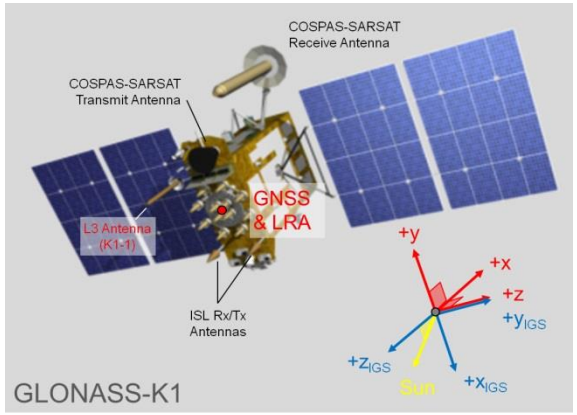
PPP convergence
D. Laurichesse,
GPS World, 2015

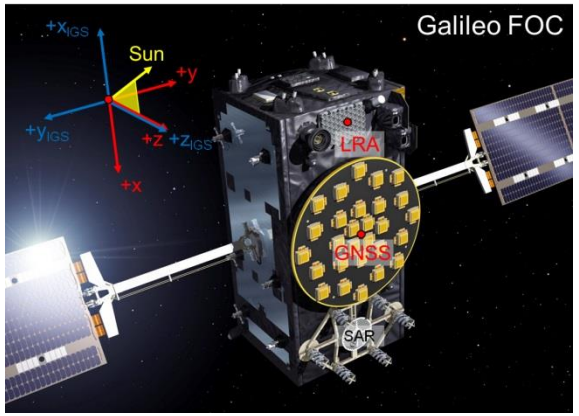
Standardization

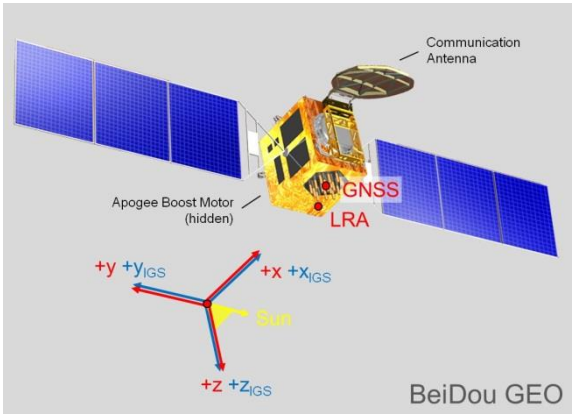
- RINEX
  - Exchange of observation, navigation and meteo data (offline)
  - Version 3.03 (with IRNSS) in preparation; RINEX transition plan
- RTCM3
  - Exchange of observation, navigation and correction data (R/T)
  - Version 3.2 with amendment 2 released
  - Multiple Signal Messages (MSM) for GPS, GLO, GAL, QZSS
  - Ephemerides for GPS, GLO, GAL (SBAS and QZSS in prep.)
  - State Space Representation messages for real-time PPP
- ANTEX
  - Harmonization of spacecraft reference frames (IGS-specific s/c axes, such that +x faces the Sun for all satellites using yaw-steering)
  - Widest possible use of a single reference attitude model for PPP users
  - Except: QZSS & BeiDou orbit normal mode, IRNSS biased yaw-steering

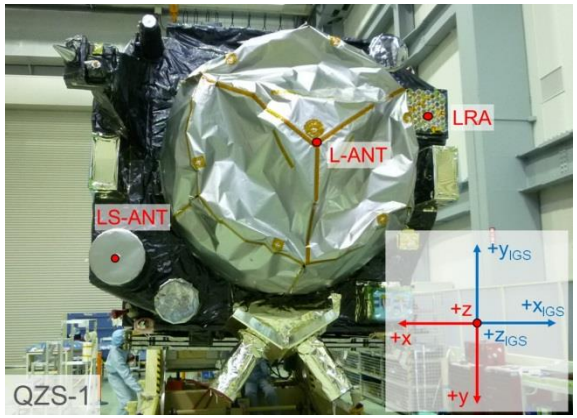
Spacecraft Frames (Examples)

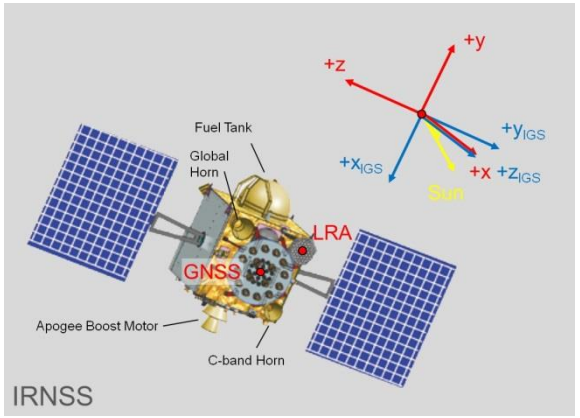












O. Montenbruck, R. Schmid, F. Mercier, P. Steigenberger, C. Noll, R. Fatkulin, S. Kogure, A. S. Ganeshan“, GNSS Satellite Geometry and Attitude Models”, Advances in Space Research (submitted)

Summary

MGEX Achievements

- Global multi-GNSS network with strong real-time component
- Comprehensive products for multi-GNSS work
  (precise orbits and clocks, broadcast ephemerides, differential code biases)
- Standards and models
- Characterize, understand, monitor, and exploit all GNSSs

Challenges

- Integration of MGEX and legacy IGS network
- Exchange of information with GNSS operators and owners
- IRNSS and SBAS support
- Combination of multi-GNSS orbit and clock products
- Pilot Service