Orbit Modeling and Multi-GNSS in the IGS

G. Beutler
Astronomical Institute, University of Bern
O. Montenbruck, P. Steigenberger
DLR, German Space Operations Center

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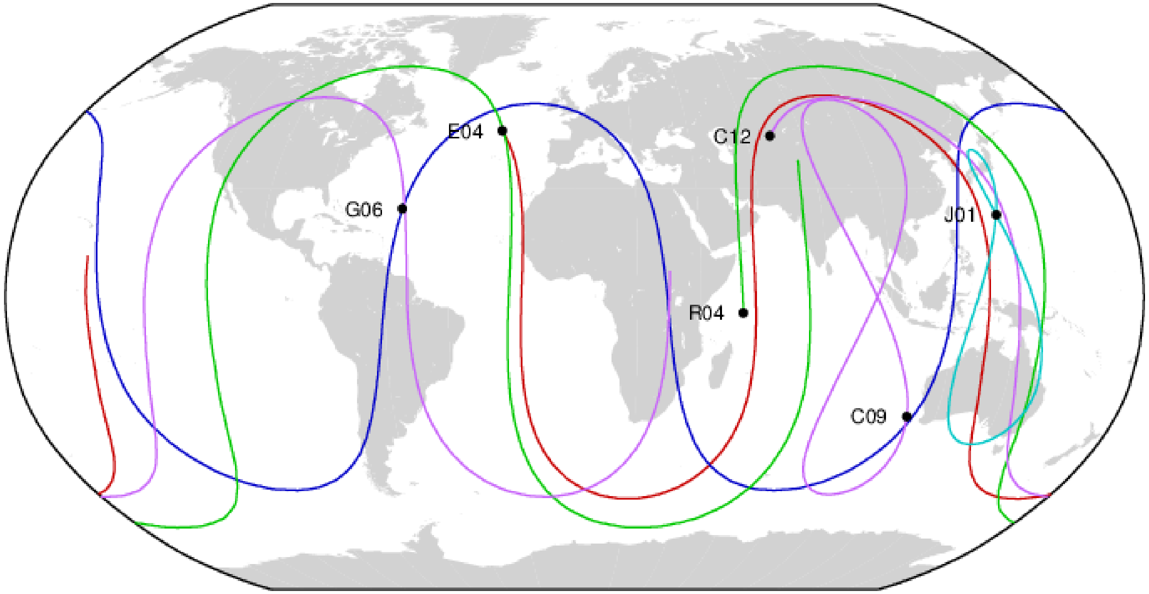
GPS, GLONASS, Galileo, BeiDou, QZSS

System	Revolution Period	Inclination	# Orbital Planes
GPS	11^h58^m	55 deg	6
GLONASS	11^h16^m	65 deg	3
Galileo	14^h05^m	55 deg	3
BeiDou	12^h53^m	55 deg	3
QZSS	23^h56^m	43 deg	3

GPS, GLONASS, Galileo, BeiDou, QZSS



Daily Groundtracks of GPS, GLONASS, Galileo, BeiDou, QZSS (geosynchronous, GPS augmentation).

(GPS, QZSS), GLONASS, Galileo have 1-day, 8-days, 10-days repeat cycles. BeiDou MEOs one of 7 days.

The IGS

The creation of the IGS was **initiated in 1989** with I.I. Mueller, G. Mader, B. Melbourne, and **Ruth Neilan.**

The IGS became an **official IAG service** in 1994.

The IGS first was a pure **GPS Service**, it was renamed as the **International GNSS Service** in 2004.

Today the IGS is a truly **interdisciplinary, multi-GNSS service in support of Earth Sciences and Society**.

Since its creation the **IGS Central Bureau** is located in the USA with **Ruth Neilan** as director – who stands for providing **continuity** and **leadership**.

IGS Workshop 2014 in Pasadena was a key event for GNSS orbit modeling.

Modeling GNSS Orbits

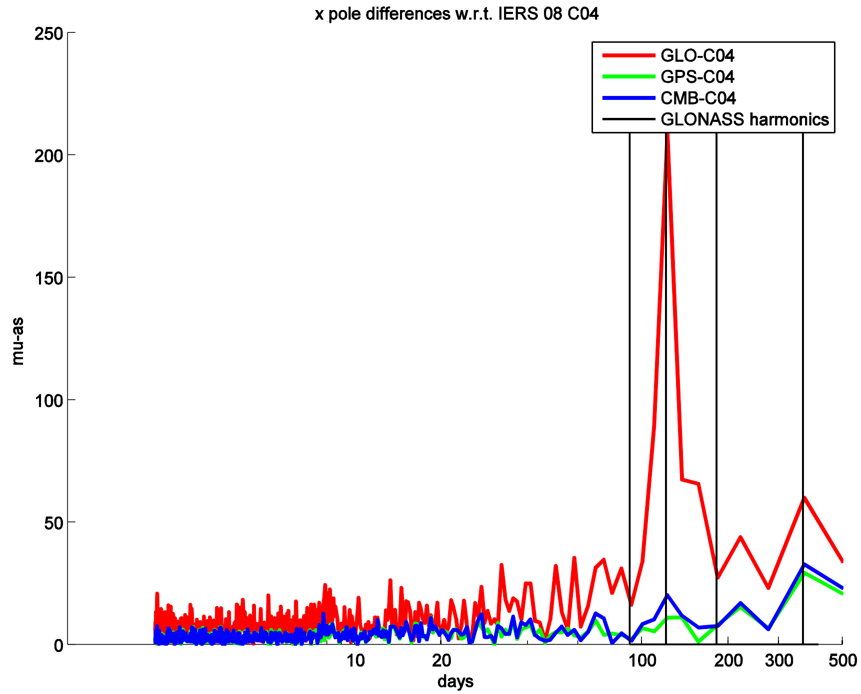
- Lageos (LAser GEOdetic Satellite); spherical, diameter 60cm, mass 405kg
- GNSS satellite: Body 2 x 2 x 2 m^3, “wings” 20 x 2 m^2, mass 500-1000kg
- Satellites for science are simple structures, e.g., spheres
- GNSS satellites may have complex structures

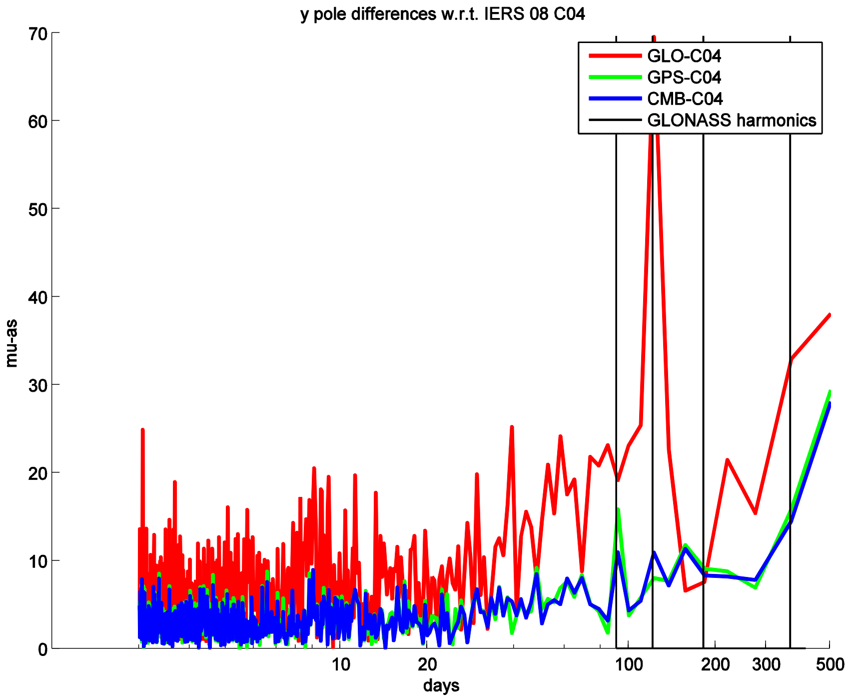
Modeling GNSS Orbits

Ferraris are built to minimize non-gravitational forces, trucks not really (only “to some extent”).

From the p.o.v. of orbitography the Lageos is a Ferrari, the GNSS satellite is a truck.

GLONASS-only, GPS-only, combined Analysis





Polar motion components x & y compared to IERS 08 C04.

100 µarc-sec ←→ 3 mm on surface of the Earth

Problem may be cured/mitigated by better modeling of solar radiation pressure for GLONASS

Modeling GNSS Orbits

IGS Workshop in Pasadena in Summer 2014 was of paramount importance for orbitography. It became clear that …

- **… purely empirical SRP modeling is problematic for GLONASS.**
- **... a priori SRP models for GLONASS may cure/mitigate the problem.**
- **... too simple SRP models may bias geophysical parameters like Earth Rotation Parameters and geocenter coordinates.**
- **… GNSS satellites with "spherical bodies" and perfect yaw-steering are best for science**
- **… GPS satellites are close to this ideal case!**

Today …

- **… several solutions to the GLONASS problem are available!**
- **… "unbiased" multi-GNSS becomes a (gets closer to) reality.**

Multi-GNSS Experiment (MGEX)

Multi-GNSS Experiment (MGEX)

- **is an IGS experiment**
- **MGEX call-for-participation released mid-2011 (ongoing)**
- **Steered by Multi-GNSS Working Group (MGWG)**

Some 27 contributing agencies from 16 countries

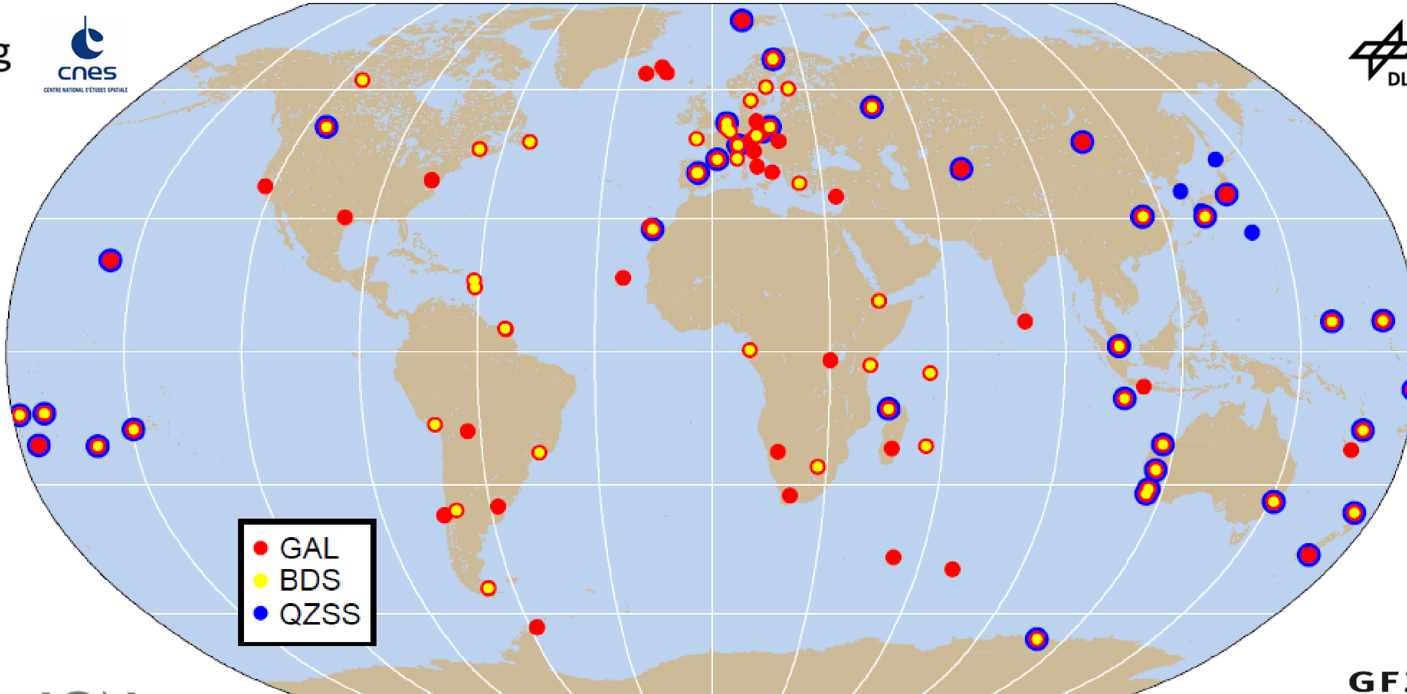
Global tracking network, mostly real-time

- **State-of-the-art receivers and antenna**
- **Tracking of Galileo, BeiDou, QZSS, SBAS (but no IRNSS, yet)**

Free and open access

- **Data archives at CDDIS, IGN, BKG (RINEX 3.x)**
- **Real-time NTRIP caster (RTCM3-MSM)**
- **Product archive at CDDIS**

Multi-GNSS Experiment (MGEX)



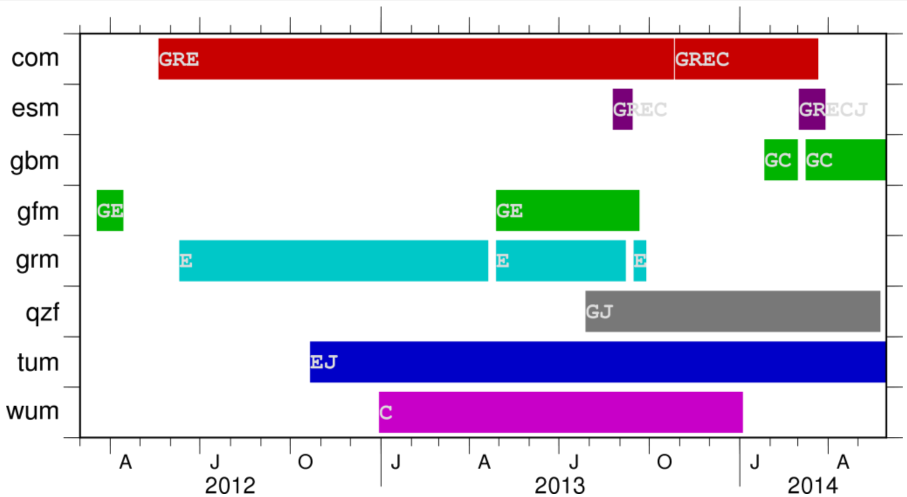
~114 stations, ~95 sites (Oct 2014)

Archive: ftp://cddis.gsfc.nasa.gov/pub/gps/data/campaign/mgex/
Caster: http://mgex.igs-ip.net/

International Association of Geodesy

MGEX Analysis Centers and Products

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



Products provided at ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/

Civil Navigation Message (CNAV)

- The Civil Navigation message CNAV provides
  - a more flexible and more accurate data format compared to the legacy navigation message LNAV
  - Additional information, e.g., inter-signal corrections
- Continuous CNAV transmission started on 28 April 2014 on L2C and L5 for most Block IIR-M and IIF satellites

The Civil Navigation Message CNAV

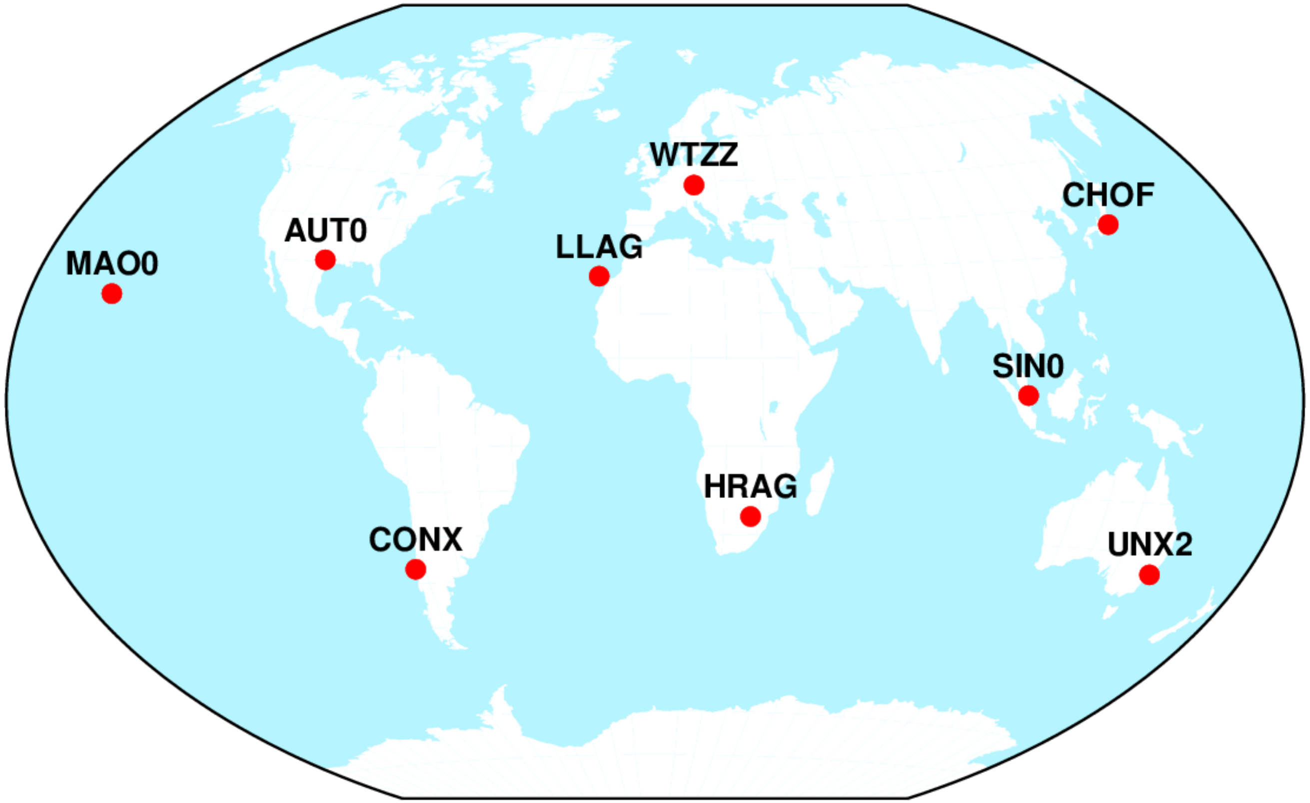
- Compared to LNAV CNAV provides a more flexible structure:
  - Header: preamble, PRN, message type, time of week, alert flag
  - Actual navigation message, currently 14 different types defined
  - Cyclic Redundancy Code (CRC) parity bits

Header | Message | CRC

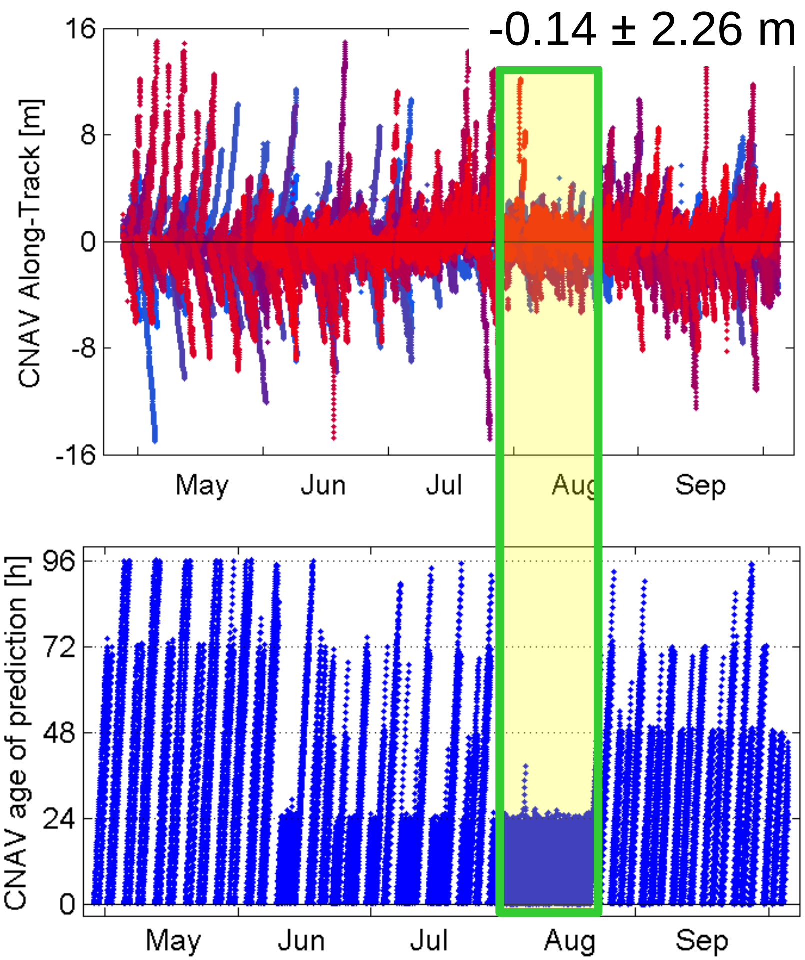
Message Types	Ephemeris 1	Ephemeris 2	Reduced Almanac	Clock Differential Correction
Ephemeris Diffe-rential Correction	Text	Clock, IONO & Group Delay	Clock & Reduced Almanac	Clock & EOP
Clock & UTC	Clock & Differen-tial Correction	Clock & GGTO	Clock & Text	Clock & Midi Almanac

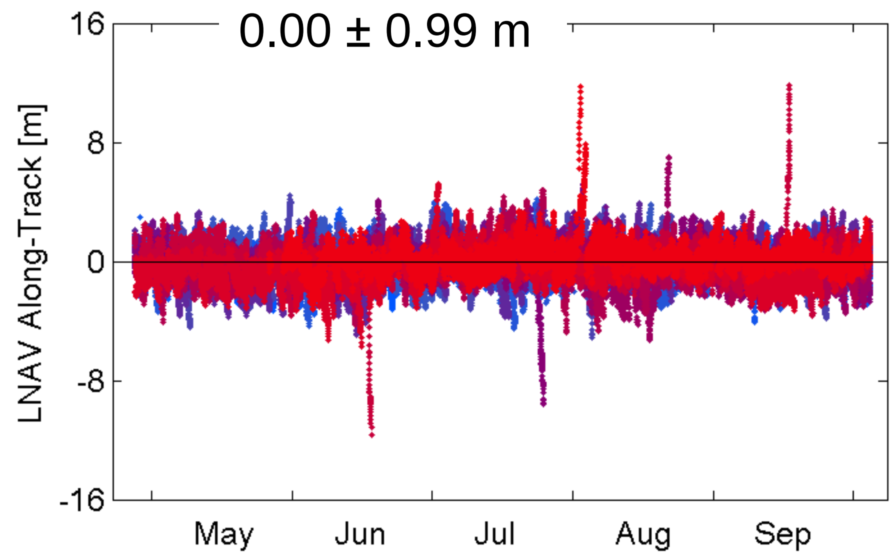
CNAV Tracking Network

- 9 stations with Javad TRE_G2T or TRE_G3TH receivers (CONGO, MGEX)



Orbit Comparisons with IGS



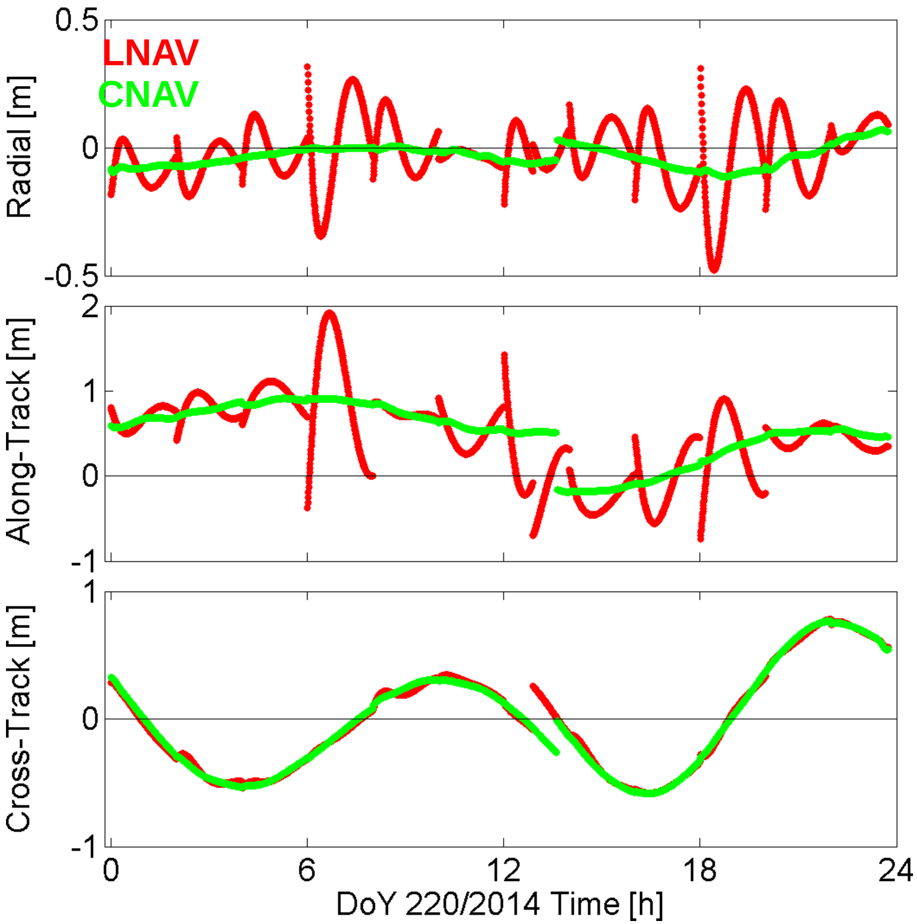


- CNAV performance degraded by prediction times of up to four days
- Similar performance compared to LNAV if age of prediction less than one day

Orbit Comparisons with IGS

- Differences w.r.t. IGS final orbits for PRN 07
- 2 h validity intervals can clearly be seen for LNAV
- LNAV has up to 1 m discontinuities
- Smooth transitions for CNAV except for ephemeris uploads

STD [cm]	LNAV	CNAV
Radial	13	4
Along-Track	49	32
Cross-Track	40	40



CNAV: Inter-Signal Corrections

- Broadcast clocks refer to the ionosphere-free linear combination of L1 P(Y) and L2 P(Y)
- Timing Group Delay (**TGD**) for P(Y) single frequency users already included in LNAV
- Inter Signal Corrections (**ISC**) for users of new signals w.r.t. L1 P(Y) included in CNAV:
  - ISC L1C/A
  - ISC L2C
  - ISC L5I5   L5 data channel
  - ISC L5Q5   L5 pilot channel
- **CNAV** ISCs may be compared to ISCs from Differential Code Biases of
  - IGS Multi-GNSS Experiment (**MGEX**)
  - Center for Orbit Determination in Europe (**CODE**)

  Comparisons are at sub-nanosecond to few nanosecond level.

Single Point Positioning with CNAV ISCs

- Dual-frequency ionosphere-free linear combination
- Kinematic positioning of MGEX station BRUX (Brussels, Belgium)
- IGS final orbits and clocks, ISCs from CNAV, only L2C-capable satellites

Signals	ISCs	RMS [m]			
		North	East	Height	3D
C1W, C2W	–	0.67	0.93	1.72	2.06
C1C, C2L	–	0.83	1.50	2.09	2.70
C1C, C2L	x	0.56	0.76	1.52	1.79

CNAV Summary

- The **Civil Navigation message CNAV** provides a more flexible structure, more precise and additional information compared to LNAV
- Pre-operational CNAV transmission started on **28 April 2014** for most Block IIR-M and IIF spacecraft
- Global CNAV tracking with a network of 9 (10) stations, publicly available CNAV product
- Current CNAV performance suffers from **less frequent updates** compared to LNAV resulting in a degradation by a factor of about two
- For periods with daily CNAV update rate, LNAV and CNAV have a similar performance with a **signal-in-space range error of about 0.6 m**
- L1C/A and L2C dual-frequency single point positioning **improved by about 30%** when taking into account CNAV **Inter-Signal Corrections** (ISCs)
- Full L2C CNAV capability is expected by mid-2016 as part of the Next Generation Operational Control System (OCX)

The Indian Regional Navigation Satellite System

Mixed constellation

- 3 GEOs (λ=32.5°,83°, 131.5°)
- 4 IGSOs (i=27°, λ=55°, 117.75°)

2 Frequency bands

- L5 band (1176.45 MHz, ±12 MHZ BW)
- S band (2492.028 MHz, ±8 MHZ BW)

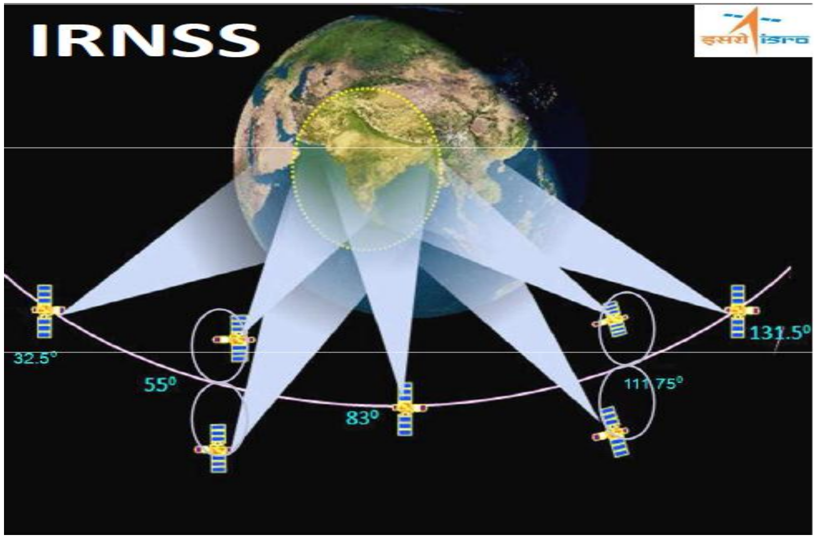
Standard Positioning Service (SPS) and Restricted/Authorized Service (RS)

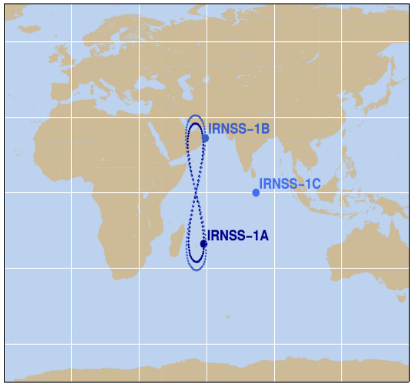
Rubidium clocks (SpectraTime, CH)

Launches

- IRNSS-1A (1 July 2013, IGSO at 55°)
- IRNSS-1B (4 April 2014, IGSO at 55°)
- IRNSS-1C (15 Oct. 2014, GEO at 83°)

SPS Signal ICD published Sept. 2014

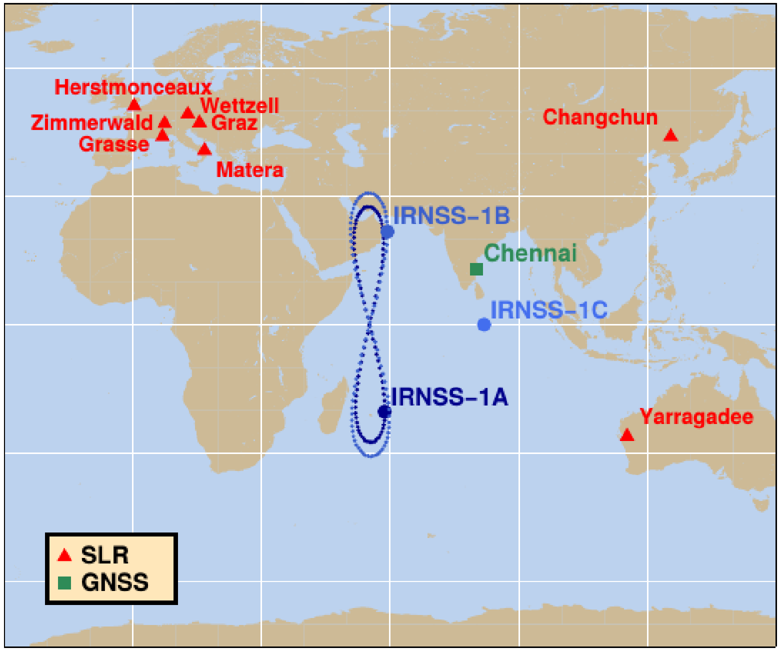




International Association of Geodesy

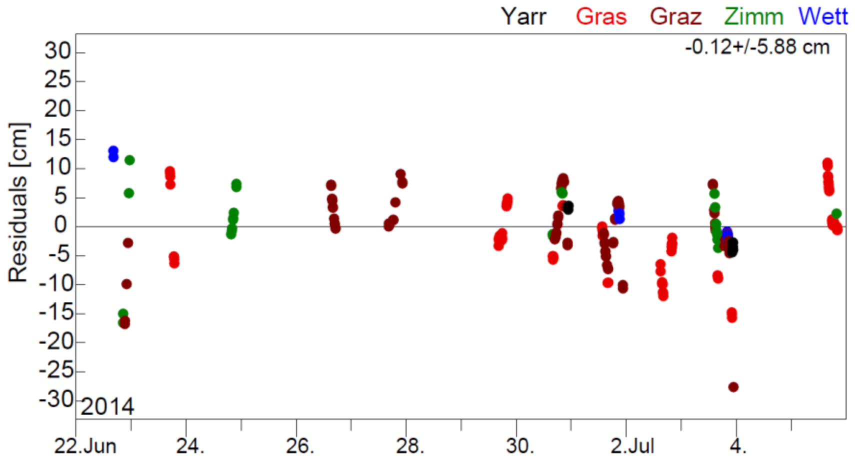
IRNSS Tracking by ILRS

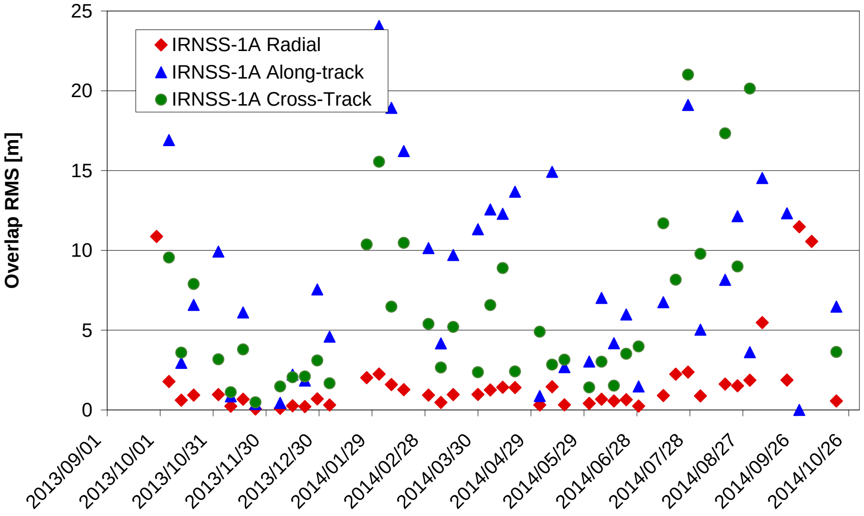
- **SLR is a two-way ranging technique (mm precision, cm acuracy)**
- **All IRNSS satellites carry a laser retroreflector array (LRA)**
- **ILRS = International Laser Ranging Service**
  - **8 participating stations**
  - **„Europe“ plus Yarragadee**
  - **20-40 normal points per week**



IRNSS Orbit Determination

- Sparse SLR tracking, limited geometry
- Long arcs (14 days)
- Dynamical modelling
- Small set of empirical solar radiation pressure (SRP) parameters
- Data cut at maneuvers (~1/month)
- SLR Residuals: 1-10 cm
- Weekly overlap
  - 1-2 m radial
  - 10-15 m along-/cross-track





IRNSS Broadcast vs. SLR Orbits

Orbit errors

- **Meter-level errors in radial direction**
- **10-100 m errors in along-track and cross-track direction**
- **Differences exceed expected uncertainty of SLR orbits**

Signal-in-space range error (orbit-only contribution)

- **Full impact of radial errors**
- **~1/11th contribution of along-track/cross-track errors (*global* average at GSO altitude)**
- **Total SISRE(orb) ~ 5m**
- **Regional SISRE in primary and secondary service area will be much smaller!**

More Information on CNAV and IRNSS

Steigenberger P., Montenbruck O., Hessels U. (2015). Performance Evaluation of the Early CNAV Navigation Message, ION International Technical Meeting, 26-28 Jan. 2015, Dana Point, CA (2015)

Montenbruck O., Steigenberger P., Riley S. (2015). IRNSS Orbit Determination and Broadcast Ephemeris Assessment; ION International Technical Meeting, 26-28 Jan. 2015, Dana Point, CA (2015)