One year of Galileo IOV orbit and clock determination

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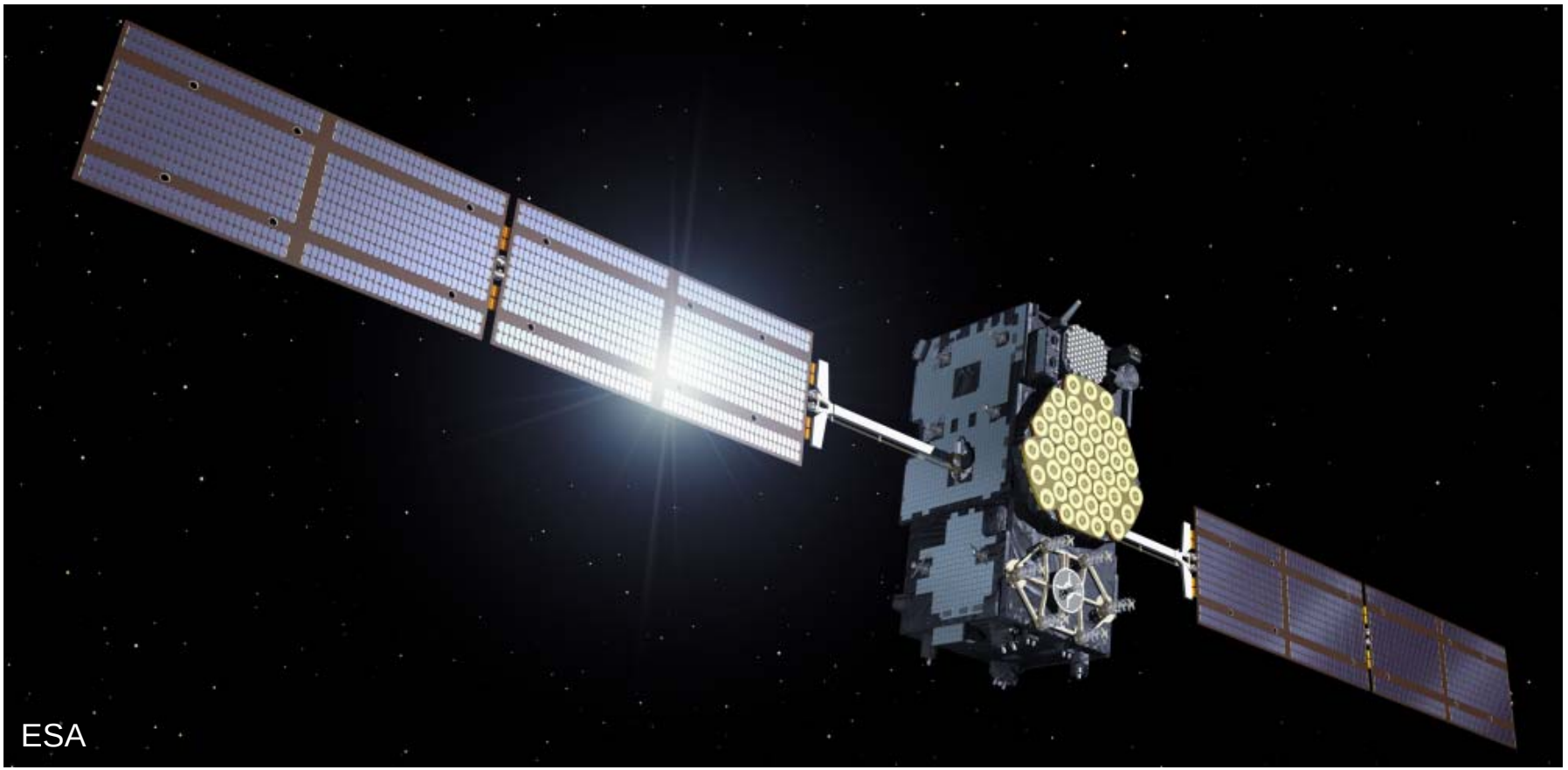
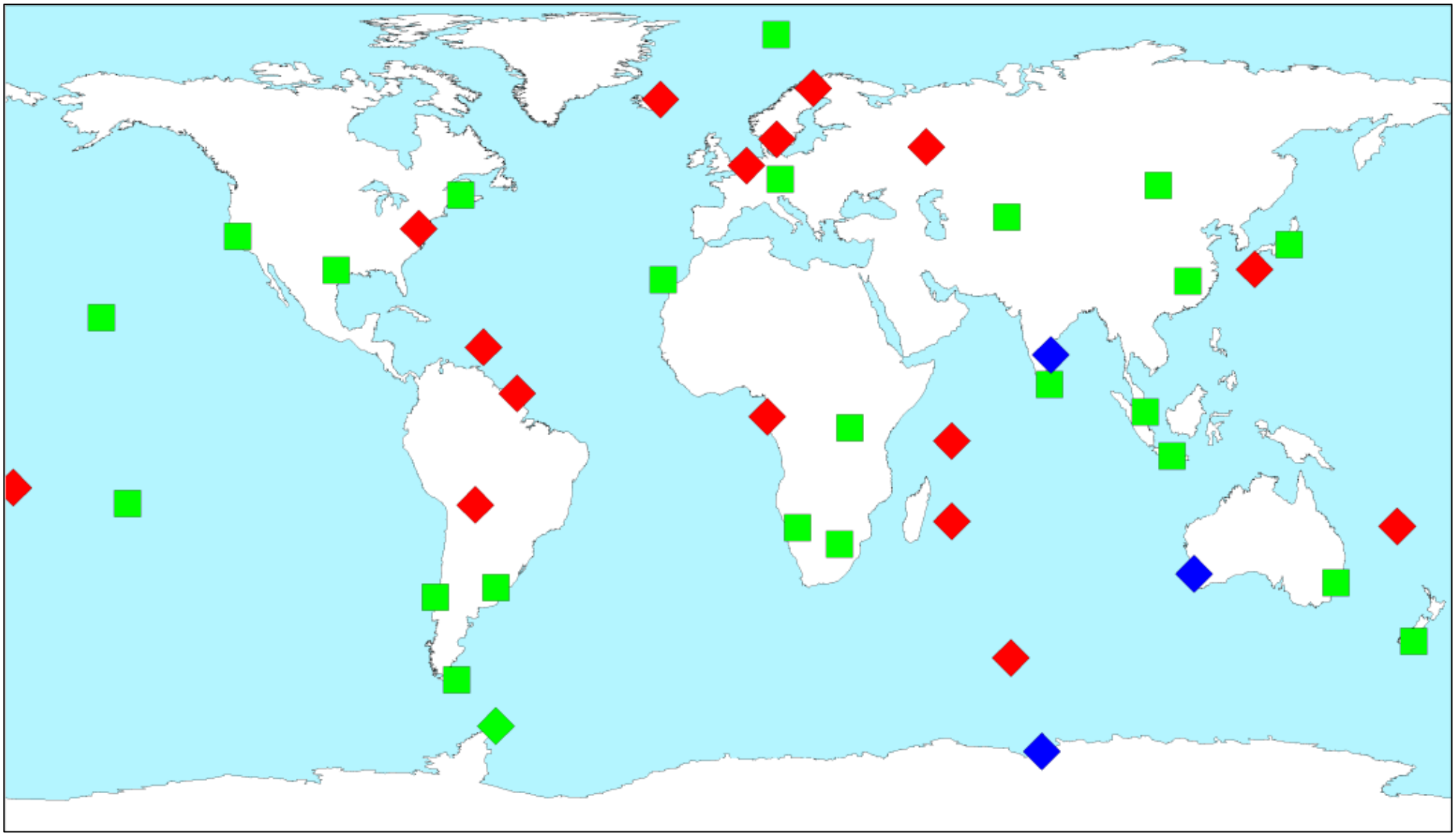
Galileo In-Orbit Validation (IOV)

- First pair of IOV satellites (E11 and E12) launched in October 2011, second pair (E19 and E20) in October 2012
- Frequent outages of E19 and E20 at the beginning of 2013
- Transmission of navigation message started in March 2013



Tracking Network



CONGO MGEX other ☐ Javad receivers ◇ other receivers

Orbit and Clock Determination

- Undifferenced E1 and E5a code and phase observations
- Modified version of the Bernese GPS Software 5.0

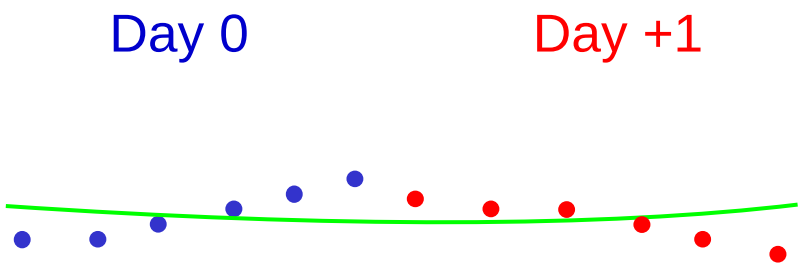
GPS:
- Station coordinates
- Troposphere parameters
- Receiver clock parameters

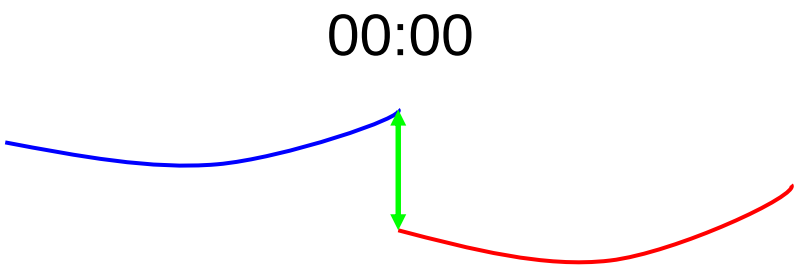
GAL:
- Orbit parameters
- Satellite clock parameters
- Differential code biases

- Anechoic chamber calibrations for selected receiver antennas provided by TU Darmstadt
- <u>Assumptions due to lack of information</u>
  - Conventional satellite antenna offsets (+0.2m,0.0m,+0.6m) as proposed by IGS MGEX (see http://igs.org/mgex/Status_GAL.htm)
  - GPS L1/L2 receiver antenna calibrations for Galileo E1/E5a if no chamber calibrations available
  - E19 and E20 SLR offsets set to E12 values

Internal Orbit Consistency

- Middle day of 5-day arcs with 5 radiation pressure parameters
- Analysis period: 1 January 2012 – 18 March 2013





RMS of 2-day Orbit Fits

Sat.	Mean [cm]	Median [cm]
E11	1.94	1.19
E12	1.95	1.16

Day Boundary Discontinuities

Sat.	Mean [cm]	Median [cm]
E11	14.91	6.21
E12	12.57	5.98

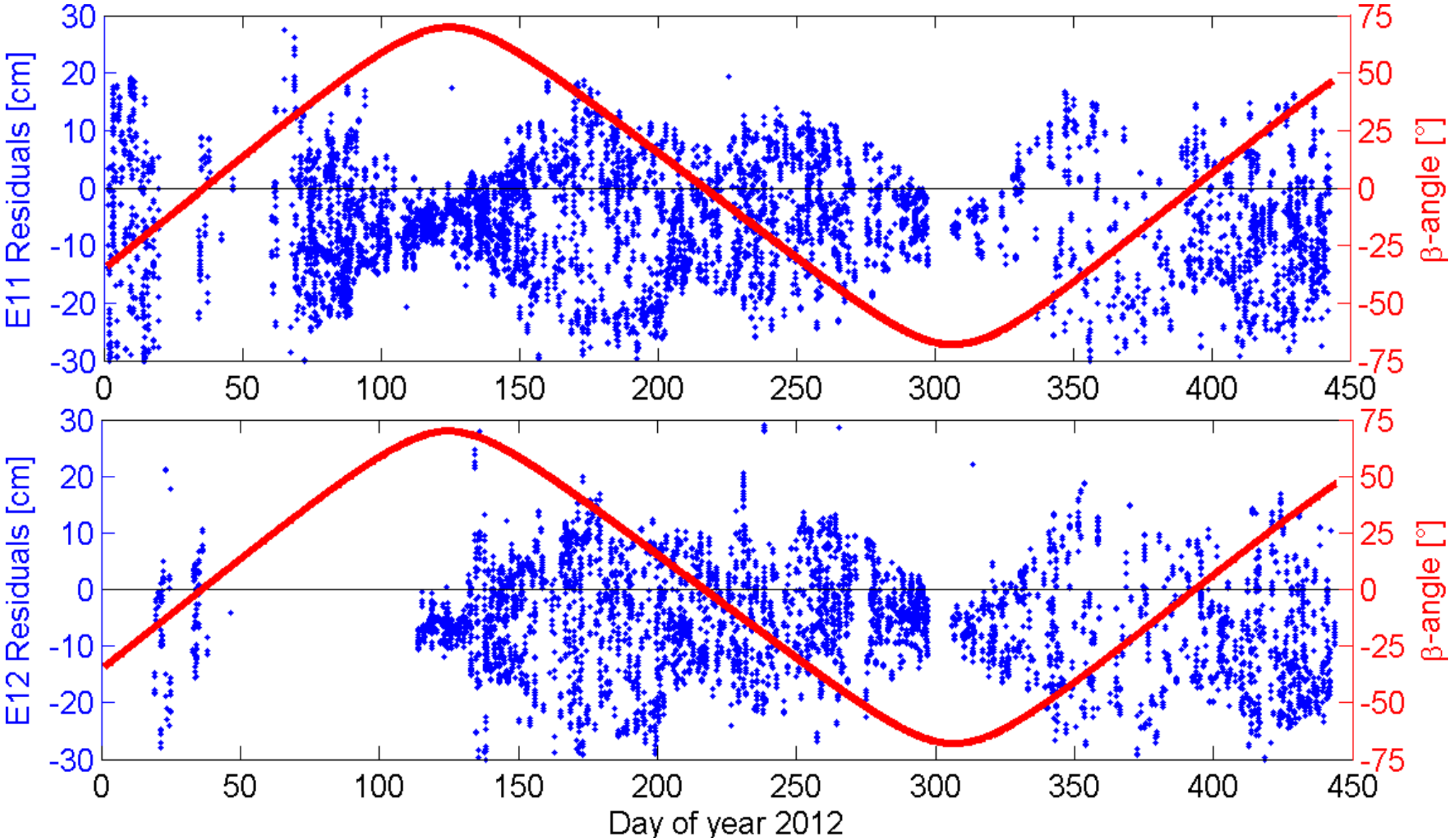
Elevation of the Sun Above the Orbital Plane β_0

- Systematic errors depending on β_0 already known from GPS
  - Satellite Laser Ranging (SLR) as independent validation method helps to identify these errors

Galileo IOV corner cube reflector
Dell'Agnello et al. 2011

Urschl,2006

SLR Residuals

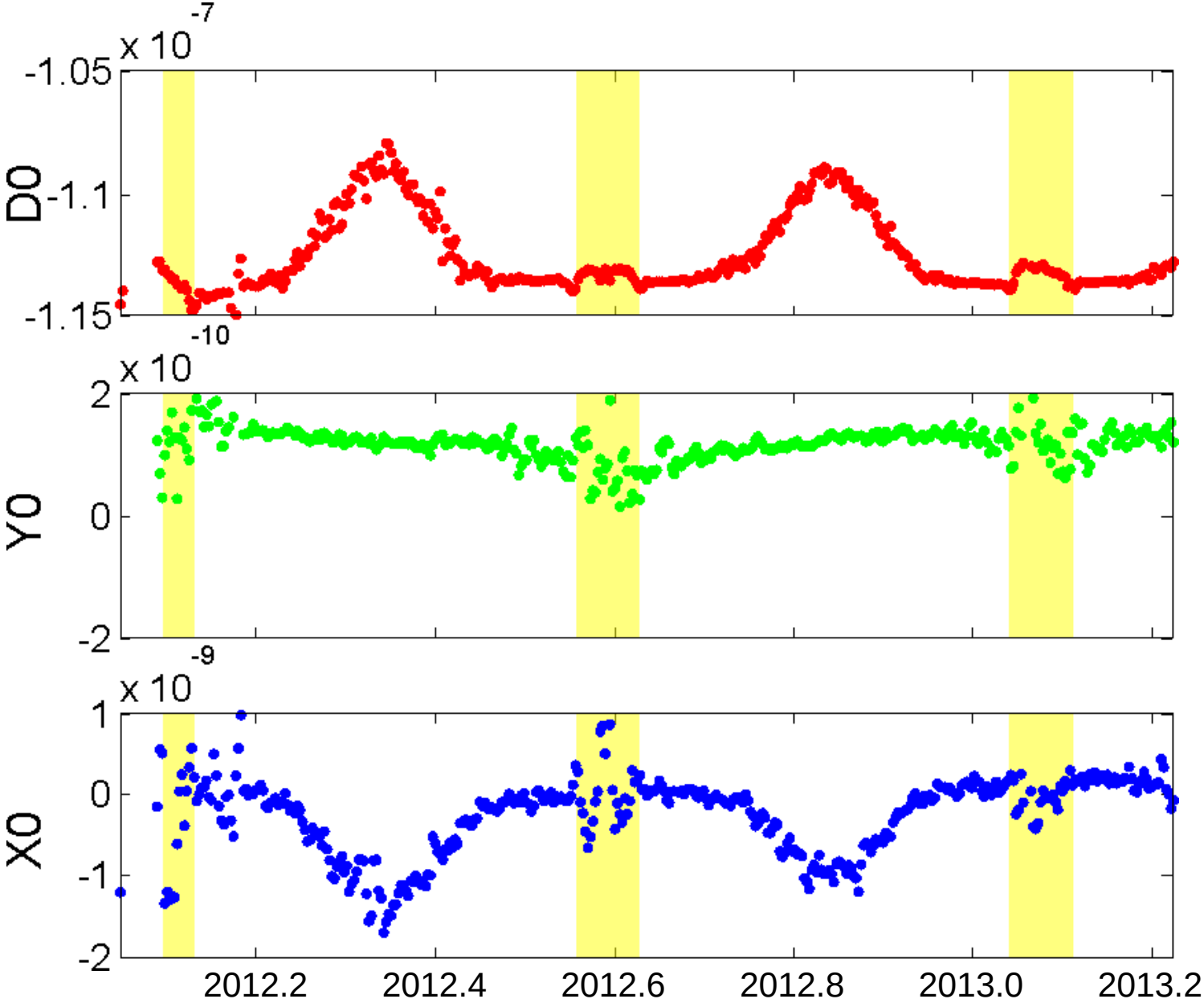


SLR Statistics

Satellite	# NPT	Offset [cm]	STD [cm]
E11	7106	-6.12	10.50
E12	5725	-5.54	10.29
E19	667	-3.35	7.24
E20	796	-4.10	10.22

- Systematic **offset** of about **-5 cm** present for all IOV satellites
- Correction of SLR offset by 5 cm in combined GNSS/SLR analysis results in orbit improvement
- Hackel et al. “Galileo Orbit Determination using Combined GNSS and SLR Observations”, submitted to GPS Solutions

Direct Radiation Pressure Parameters E11

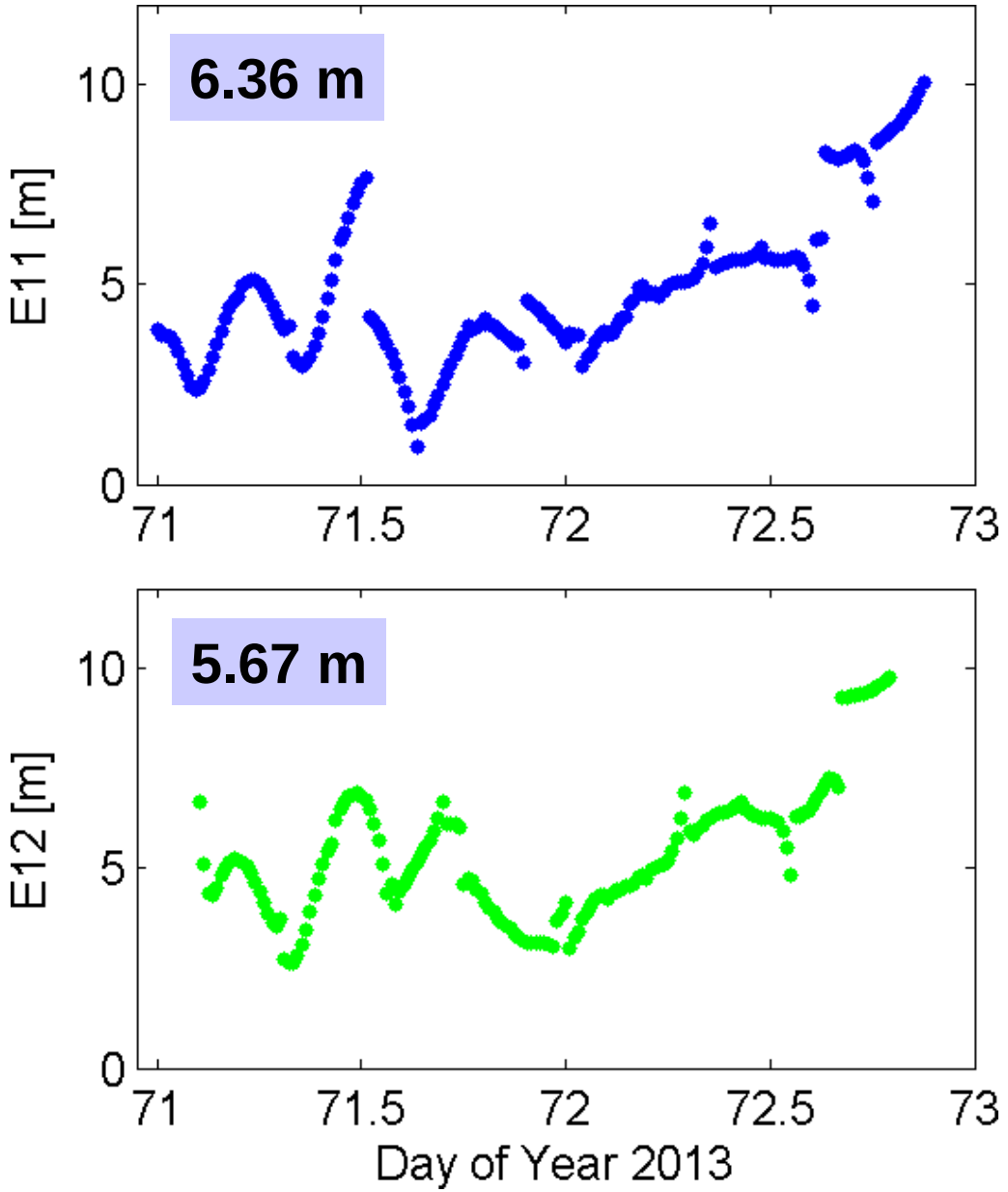


Direction to the Sun

Solar panel axis

Perpendicular to D and Y

Quality of Broadcast Ephemerides



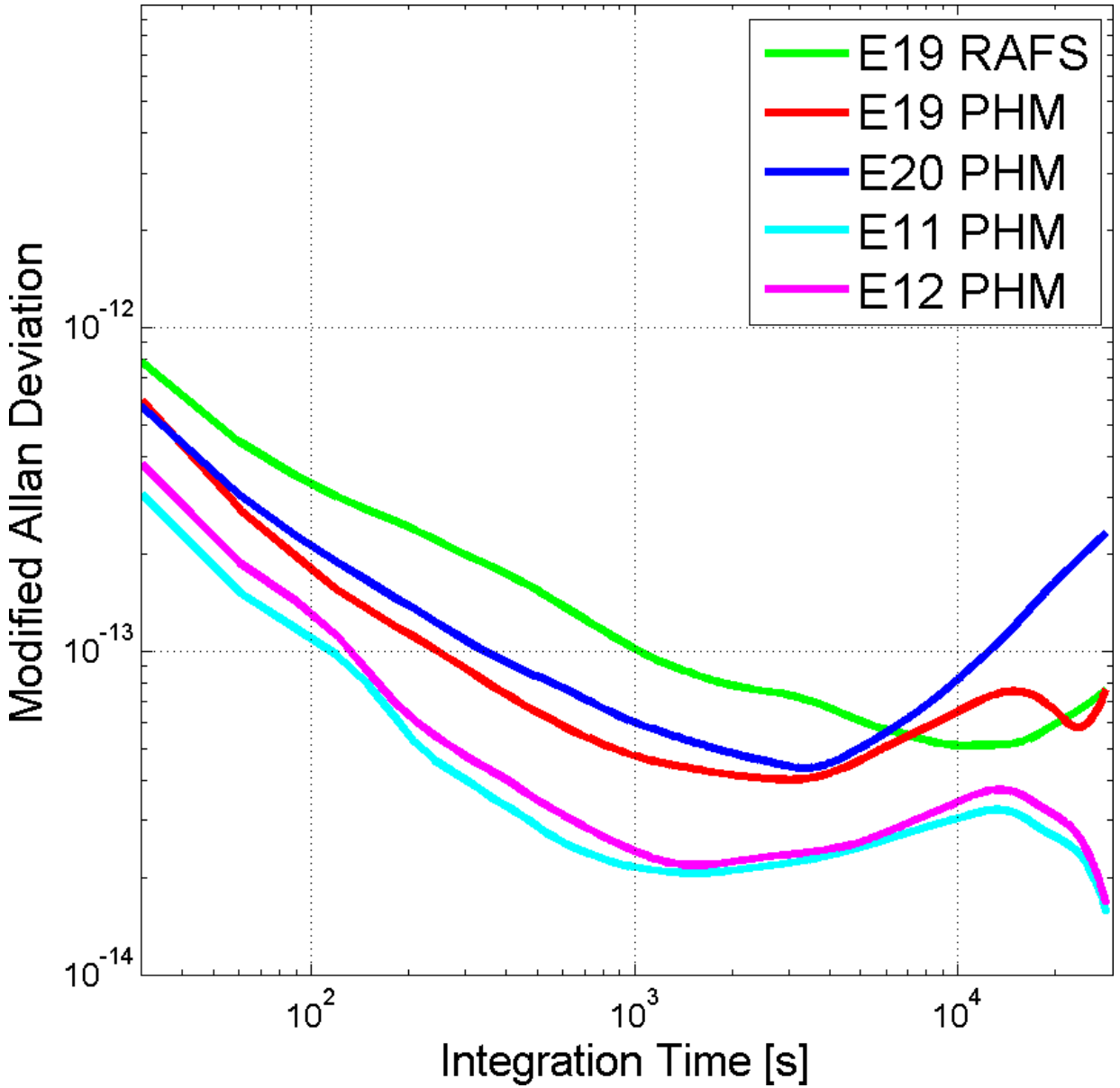
3D Position Differences w.r.t. TUM Orbits

71-83/2013
outliers > 15 m excluded

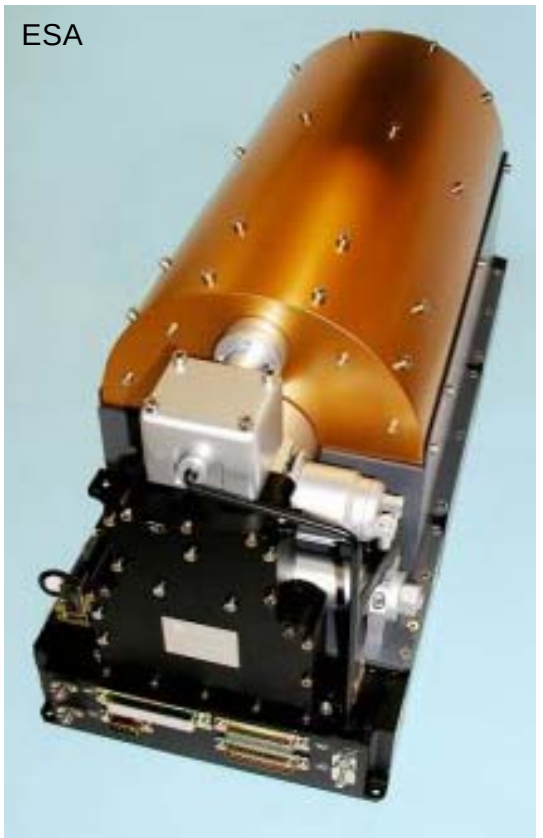
SLR Residuals

Satellite	Offset [m]	STD [m]
E11	0.15	1.99
E12	0.10	0.92
E19	0.65	2.25
E20	-0.40	3.34

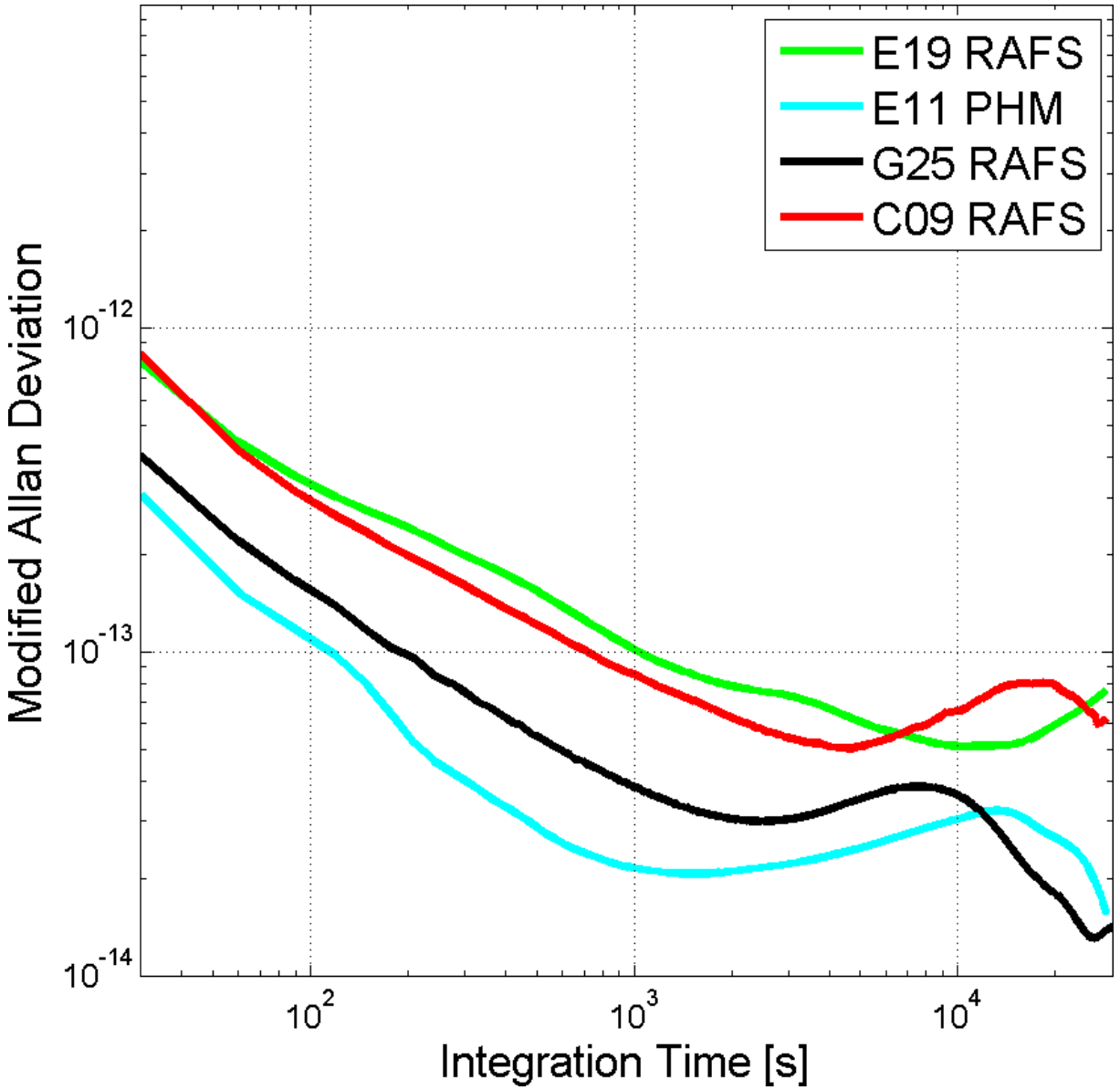
IOV Clock Performance



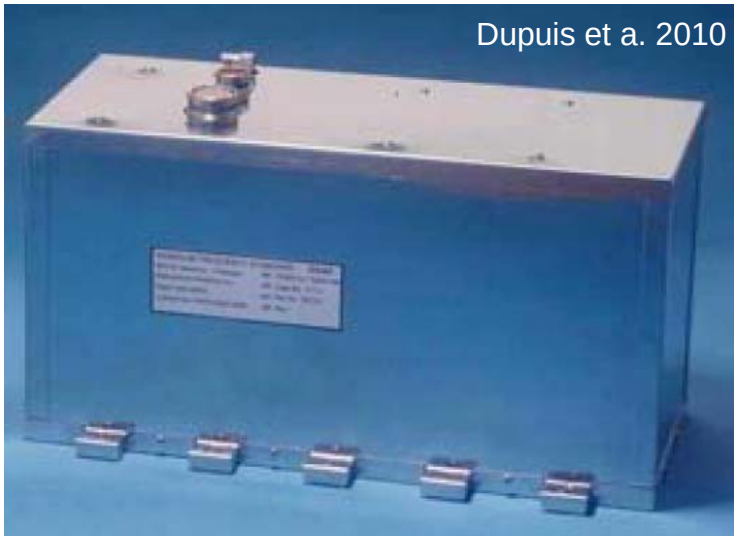
RAFS: Rubidium Atomic Frequency Standard
PHM: Passive Hydrogen Maser



Clock Comparison



G25:
first GPS Block IIF satellite



C09:
BeiDou IGSO satellite
(Inclined Geo-Synchronous Orbit)

Summary and Conclusions

- Quality of **post-processed** Galileo IOV **orbits** is on the **1-2 dm level**
- **Systematic** orbit determination **errors**:
  - depending on the elevation of the Sun above the orbital plane
  - actual cause unclear (SRP model, attitude model, NEQ condition)
  - possible improvement: ambiguity fixing, box wing model
- Quality of experimental **broadcast orbits** presently on the **few meters level** (sparse network)
- **High stability** of RAFS and PHM **clocks**
- **Lack of** spacecraft and antenna **information**:
  - Antenna offsets and phase center variations for all IOV satellites
  - SLR offsets for E19 and E20
  - Receiver antenna calibrations for **all** frequencies and **all** antenna types used within the IGS
  - Surface properties and dimensions for box-wing model