ESA's Non-Gravitational Force Models for One-Centimeter Orbit Determination Accuracy of Galileo Spacecraft

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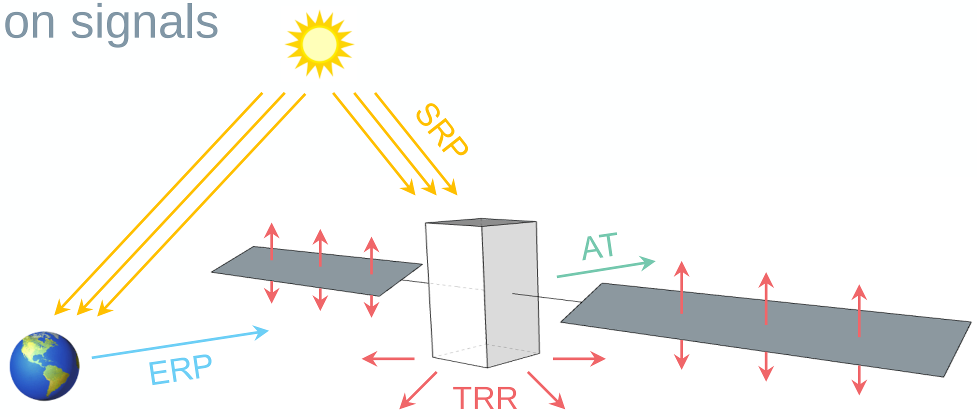
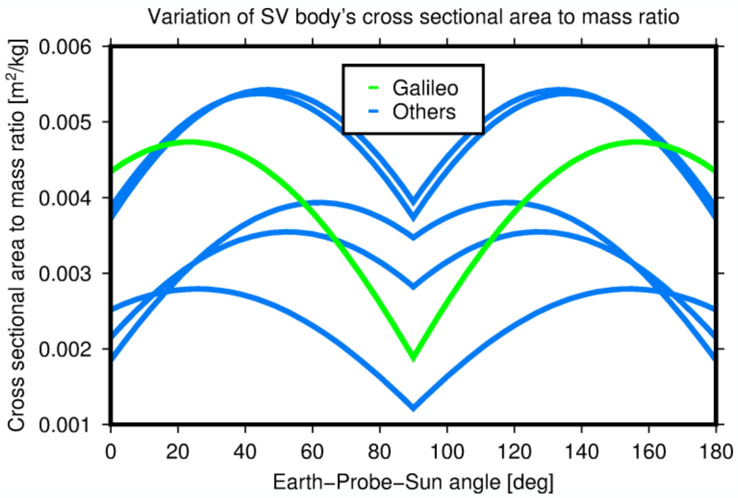
Introduction

- Knowledge of precise GNSS satellite orbits is key for a wide range of high accuracy applications such as navigation, geodetic reference frame (ITRF) realization, Earth rotation monitoring, sea level monitoring, atmospheric modelling, etc.
- Non-gravitational force models are playing an important role in the context of dynamic orbit determination/propagation of GNSS satellites with centimeter–level accuracy
- Non-gravitational forces most relevant to GNSS satellites:
  - Solar radiation pressure (SRP) – the force due to electromagnetic radiation from the Sun
  - Earth radiation pressure (ERP) – the force of reflected visible and emitted IR light from Earth
  - Thermal re-radiation (TRR) – the force due to anisotropic emission of heat from the spacecraft
  - Antenna thrust (TR) – the force due to transmission of navigation signals
- Two basic types of models – empirical and analytical
  - Both having their pros and cons
  - Most common is the empirical scaling or augmentation of an a-priori background model



GNSS satellites’ sensitivity to solar radiation

- Galileo SV relatively lightweight and elongated in X compared to other GNSS satellites
  - 700 kg on-orbit mass, Z-panel more than twice as large as X-panel
- Estimate effect varying cross section of SV body has on SRP
  - Difference maximum minus minimum radiated area divided by mass
  - Sensitivity factor is highest for Galileo compared other GNSS SVs, underlines strong need for a-priori background model



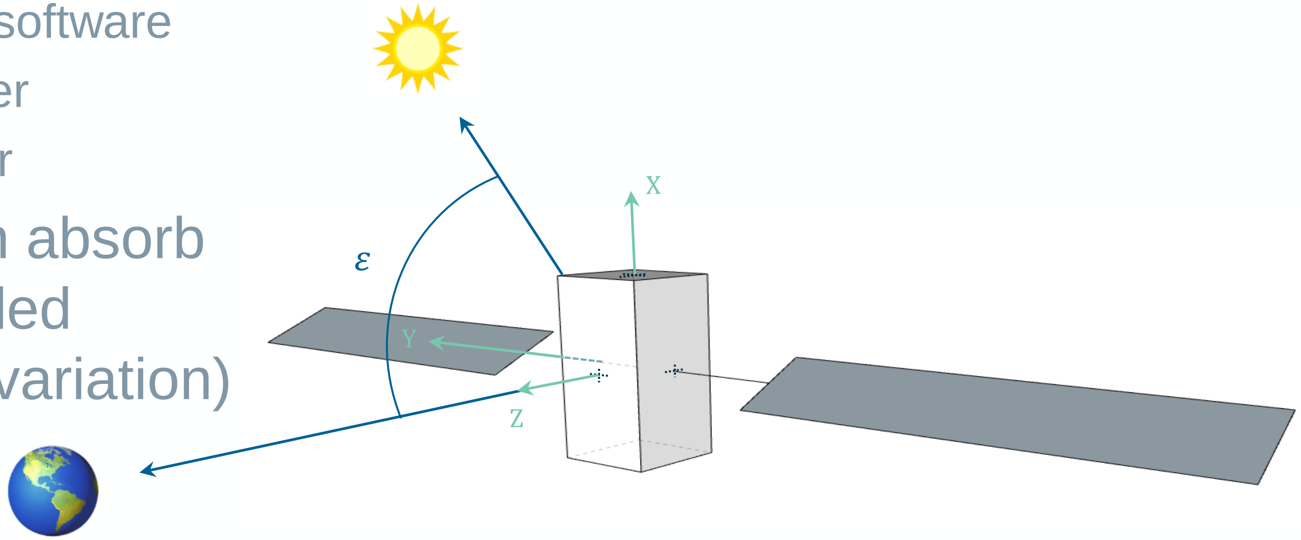
GNSS SV	x-panel [m^2]	z-panel [m^2]	$A_{max} - A_{min}$ [m^2]	m [kg]	$\Delta A/m$ [m^2/kg]
Galileo FOC	1.32	3.04	1.99	700	0.0028
GPS III	7.50	4.00	4.50	2161	0.0021
GPS IIR	4.11	4.25	1.80	1080	0.0017
BDS-3 SECM	1.25	2.59	1.63	1030	0.0016
GPS IIF	5.72	5.40	2.47	1633	0.0015
BDS-3 CAST	2.86	2.18	1.42	1014	0.0014

Analytical force model improvements at ESA

- Spacecraft models undergoing continuous refinements and improvements
- Recent upgrade of analytical radiation force model for Galileo FOC:
  - Separation into subgroups (SVN 201-213, SVN 214, SVN 215-223)
  - Additional structural details for antenna panel (NAVANT, SARANT, MISANT, LRR, IRES)
  - Addition of infrared properties for all surfaces
  - Addition of material properties for solar array back side
  - Update of optical properties of OSR material
  - Grid-based TRR force model for NAVANT
  - TRR force model for +Y and -Y panel (“Y-bias”)
  - TRR force model for clock radiator panel
  - TRR force model for solar array
  - Instant re-radiation for MLI-covered surfaces
  - …

Empirically-derived radiation force model (1/2)

- Technique/parametrization similar to JPL's GSPM approach (Bar-Sever and Kuang, 2004)
  - Dynamical long (5-day) arc fitting to precise orbit data
  - Force represented as truncated Fourier expansion about Earth-Satellite-Sun angle (Fliegel and Gallini, 1992)
  - Iterative adjustment of Fourier coefficients together with orbit state, Y-bias and along-track CPR parameters
  - Combination on normal equation level to form robust set of satellite-group-specific force models
- Advantageous in several aspects over physics-based analytical models
  - Does not require spacecraft surface dimensions or any optical/thermal properties
  - Straightforward to implement into existing POD software
  - All in one – SRP, ERP, TRR, AT lumped together
  - Better reflects satellites' actual in-orbit behaviour
- As a disadvantage, model parameters can absorb effects of other un-modelled or mis-modelled processes (e.g. Earth rotation, geocenter variation)

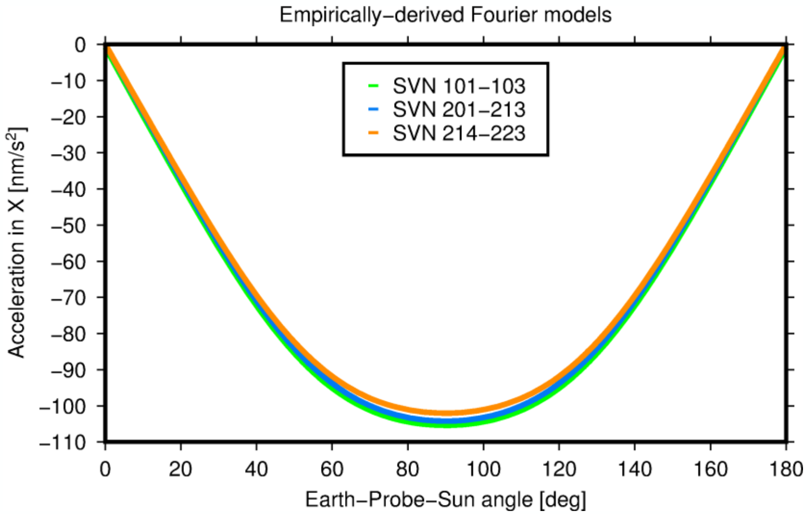


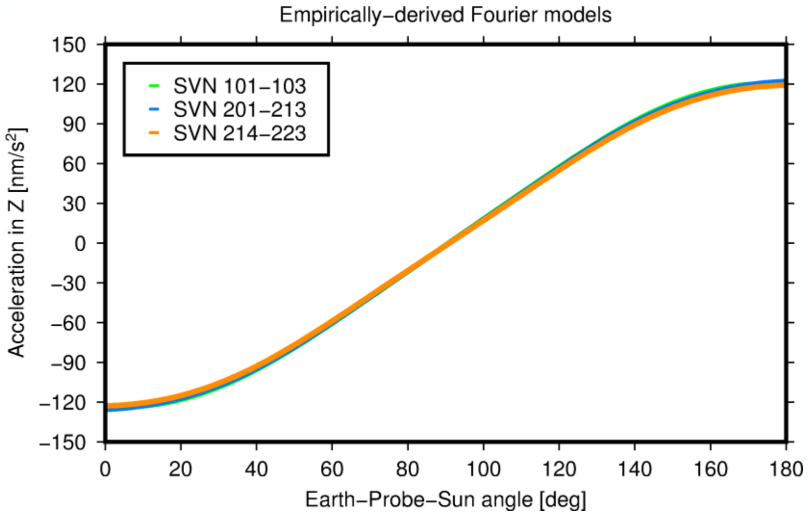
Empirically-derived radiation force model (2/2)

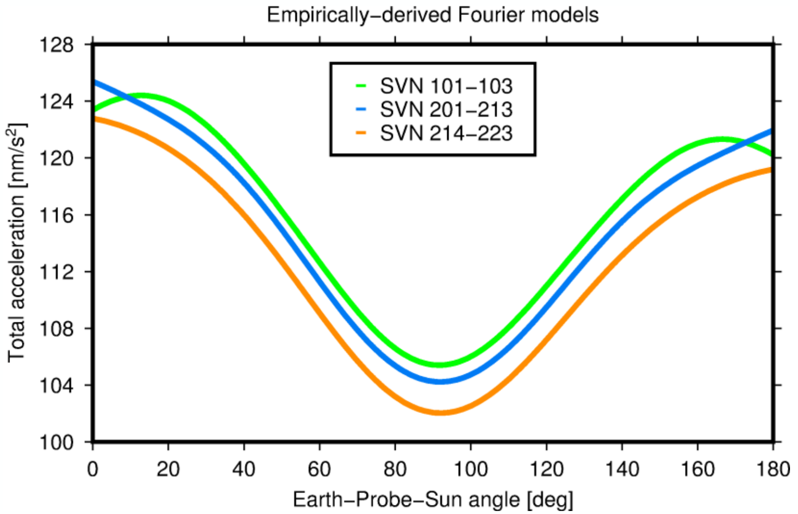
- Models developed based upon one year of daily Galileo orbits from ESOC's MGNSS Final processing and the following low-order Fourier series in body-frame XZ plane:

IOV	$X = XS1\sin(\epsilon) + XC2\cos(2\epsilon) + XS3\sin(3\epsilon) + XS5\sin(5\epsilon)$ $Z = ZC0 + ZC1\cos(\epsilon) + ZS2\sin(2\epsilon) + ZS4\sin(4\epsilon)$
FOC	$X = XS1\sin(\epsilon) + XS3\sin(3\epsilon) + XS5\sin(5\epsilon)$ $Z = ZC0 + ZC1\cos(\epsilon) + ZS2\sin(2\epsilon) + ZC3\cos(3\epsilon) + ZC5\cos(5\epsilon)$

- Fourier terms selected based on "trial-and-error" Fourier fitting of box-wing model output







Model evaluation at ESOC

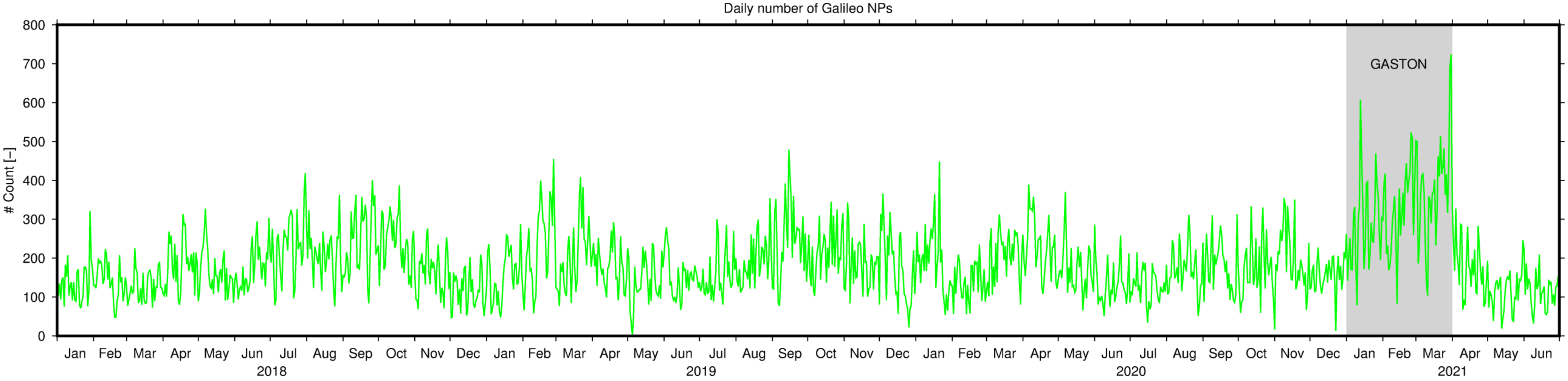
- Generate 24-hour arc test solutions spanning January 1 to March 31, 2021
  - 280 station global network
  - Six solutions based on identical data, the only difference being the force model applied (see below)
- Evaluation by means of several internal and external performance metrics
  - SLR residuals, orbit residuals, empirical radiation parameter estimates, narrow lane residuals

	Force model	Parameterization
1	ECOM-1 only	Five-parameter ECOM (D0, Y0, B0, BC, BS) plus three tightly constrained along-track CPRs (A0, AC, AS) and no a-priori model
2	ECOM-2 only	Same as strategy 1 but with additional twice-per-revolution terms (D2C, D2S) in satellite-Sun direction
3	ECOM-1 + BW_PUB	Same as strategy 1 but with a-priori box-wing model built on public metadata*
4	ECOM-1 + Fourier	Same as strategy 1 but with a-priori Fourier model
5	ECOM-1 + BW_NEW	Same as strategy 3 but based upon the new metadata (see slide 4)
6	ECOM_LIGHT + BW_NEW	Same as strategy 5 but with reduced set of ECOM and CPR parameters

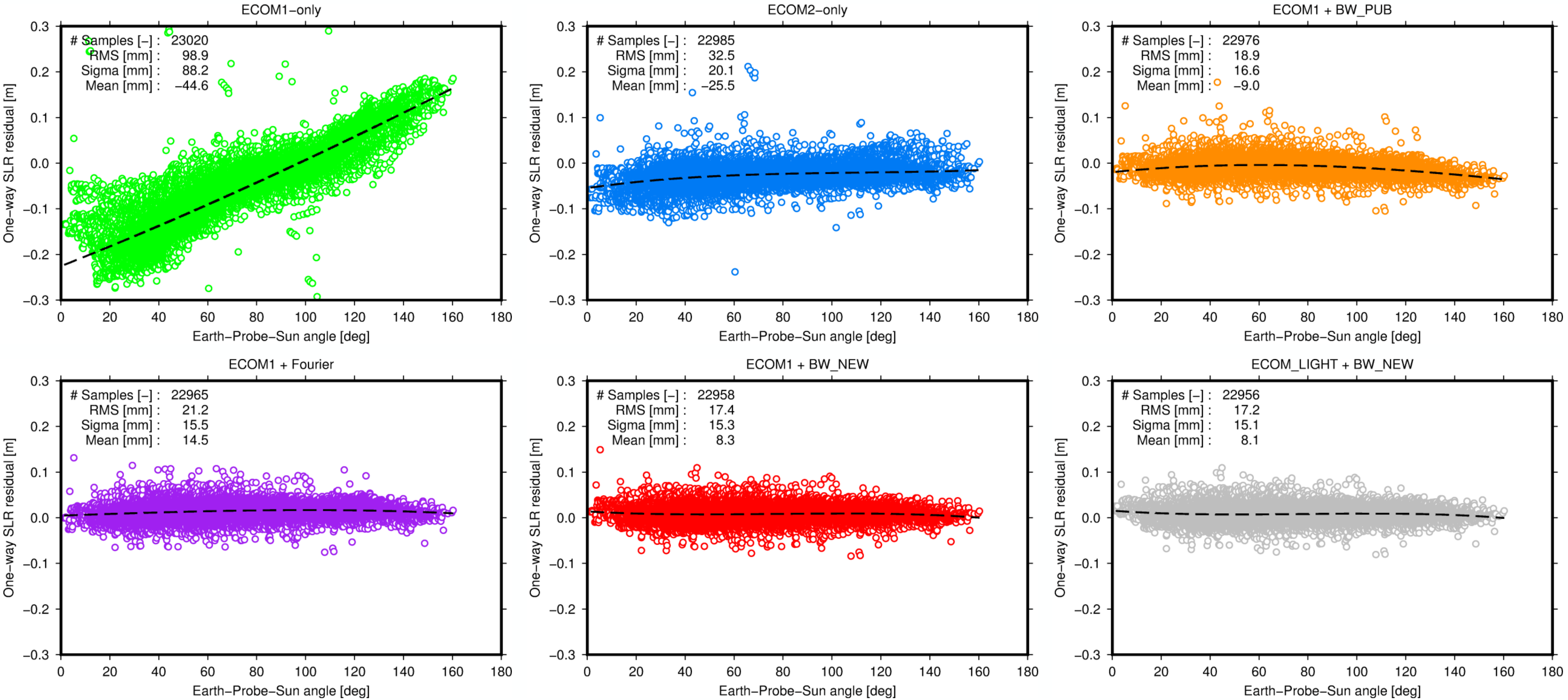
* https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata

GASTON SLR campaign

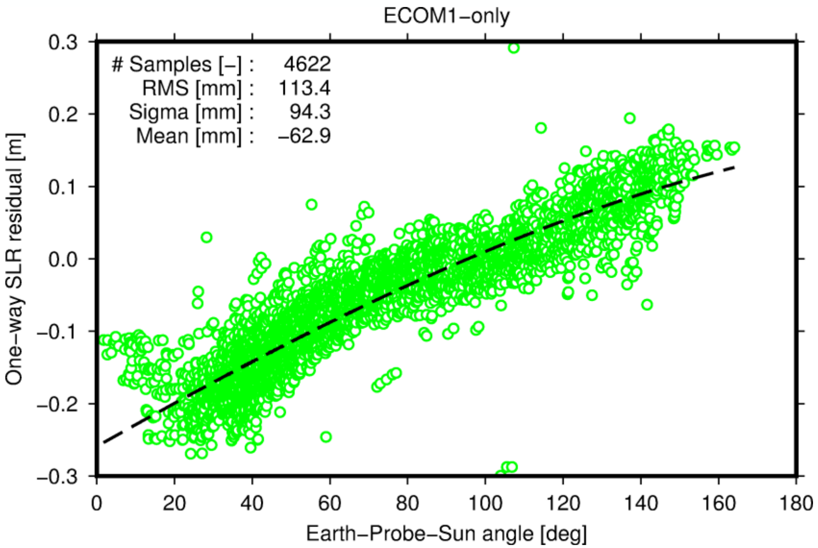
- Three-month ILRS tracking campaign from January 1 to March 31, 2021
- Initiated by ESA in support of GASTON, the “GAlileo Survey of Transient Objects Network”
- Staggering amount of Galileo SLR data
  - Total of ~11.000 passes and ~28.000 normal points from 28 stations
  - Major contributors providing half of all data are Grasse, France (30%) and Yarragadee, Australia (19%)

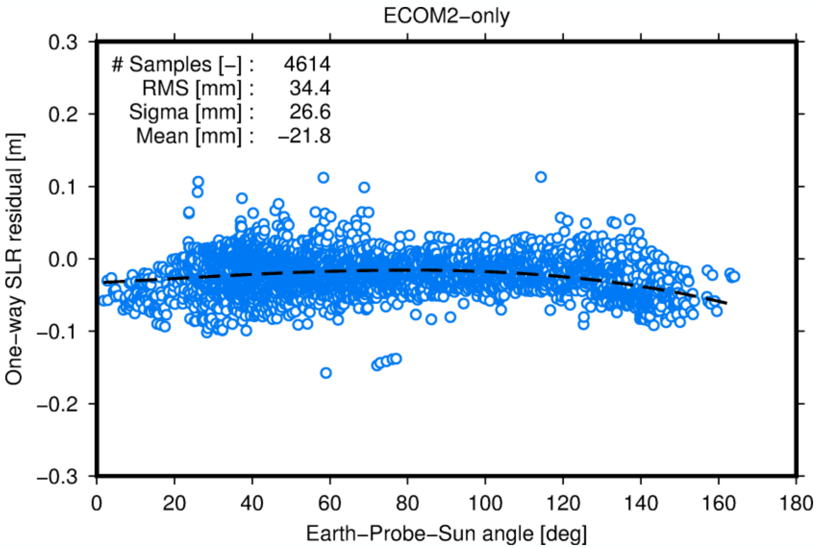


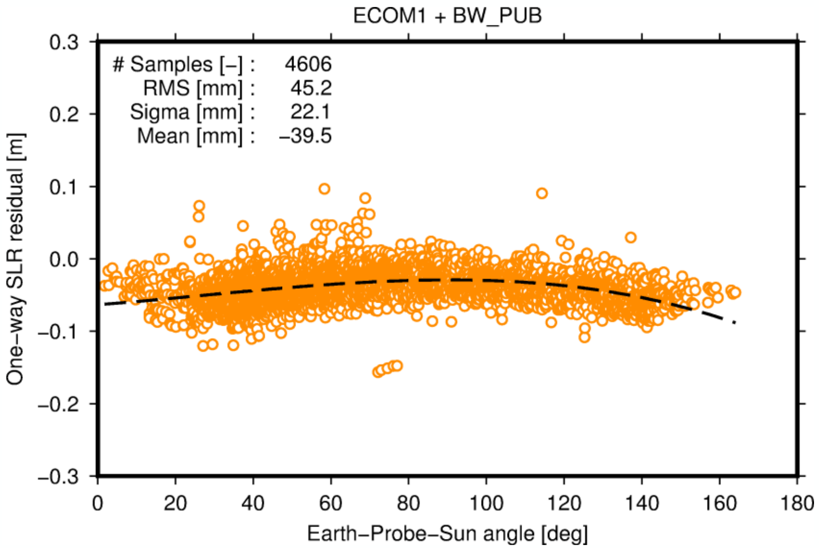
SLR residuals of Galileo FOC orbits

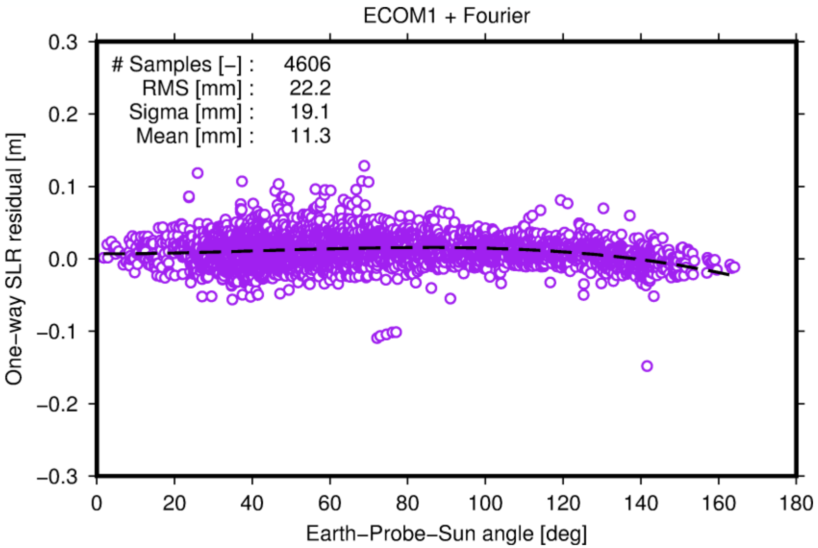


SLR residuals of Galileo IOV orbits


ECOM1–only


ECOM2–only

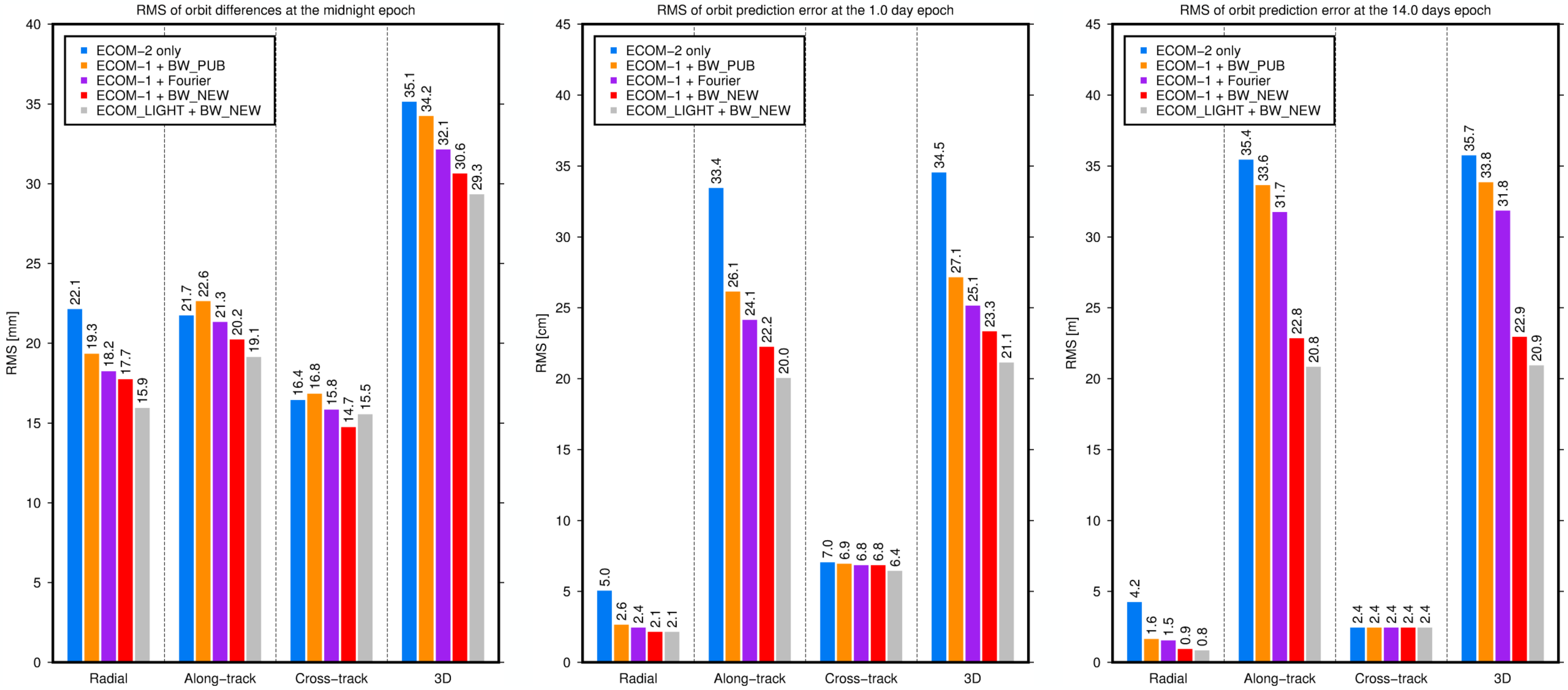

ECOM1 + BW_PUB


ECOM1 + Fourier

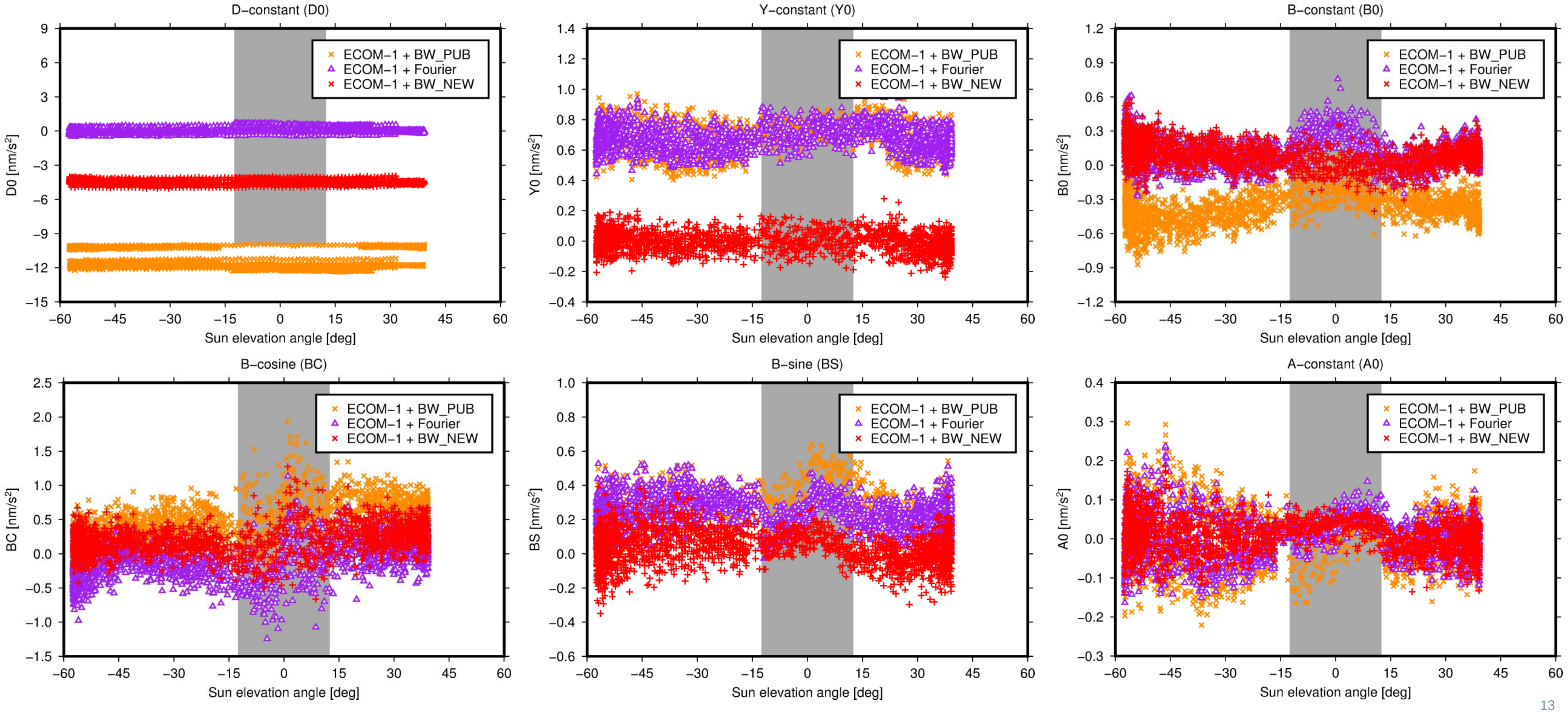
Galileo SLR residuals for “ECOM_LIGHT + BW_NEW”

Location	CODE	Monument	# NPs [-]	RMS [mm]	Sigma [mm]	Mean [mm]	Min [mm]	Max [mm]
Grasse, France	GRSM	7845	8306	12.4	9.3	8.2	-57.3	84.5
Yarragadee, Australia	YARL	7090	5239	9.1	9.1	-1.1	-57.4	68.6
Changchun, China	CHAL	7237	2650	18.6	16.4	-8.8	-80.7	87.8
Graz, Austria	GRZL	7839	2394	27.2	9.0	25.7	-10.0	73.2
Herstmonceux, United Kingdom	HERL	7840	2174	20.7	9.5	18.3	-9.5	61.5
Shanghai, China	SHA2	7821	1363	12.0	12.0	-1.0	-38.2	70.9
Zimmerwald, Switzerland	ZIML	7810	1108	20.8	13.9	15.5	-52.0	97.5
Beijing, China	BEIL	7249	873	20.0	16.8	10.9	-71.8	98.7
Wettzell, Germany	WETL	8834	762	26.4	9.7	24.6	-1.9	56.8
Potsdam, Germany	POT3	7841	595	14.9	9.5	11.5	-34.6	34.4
Matera, Italy	MATM	7941	472	13.6	7.6	11.3	-13.7	38.7
Wuhan, China	JFNL	7396	418	40.9	16.2	37.5	-10.6	88.2
Greenbelt, USA	GODL	7105	332	28.0	10.8	25.9	-1.4	62.1
Mt Stromlo, Australia	STL3	7825	303	14.3	10.1	10.2	-27.1	45.4
Monument Peak, USA	MONL	7110	210	22.7	12.4	19.0	-14.8	45.2
Altay, Russia	ALTL	1879	117	20.8	18.0	-10.5	-67.8	57.2
Tahiti, French Polynesia	THTL	7124	69	9.4	8.8	-3.4	-24.2	17.4
Riga, Latvia	RIGL	1884	42	37.8	28.4	25.3	-16.3	68.3
Komsomolsk-na-Amure, Russia	KOML	1868	27	60.9	12.6	59.7	45.1	84.4
Arkhyz, Russia	ARKL	1886	22	75.9	18.3	73.7	43.0	110.4
Irkutsk, Russia	IRKL	1891	19	32.2	15.5	28.4	9.4	62.8
Mendeleevo 2, Russia	MDVS	1874	11	22.4	9.1	20.7	7.8	35.5
Baikonur, Kazakhstan	BAIL	1887	9	37.8	17.7	33.9	9.0	70.9
Badary, Russia	BADL	1890	8	43.0	14.6	40.8	19.9	66.7
Katzively, Ukraine	KTZL	1893	5	75.0	32.5	69.1	28.1	109.5
Tanegashima, Japan	GMSL	7358	4	92.0	10.5	91.5	79.7	104.3
Hartebeesthoek, South Africa	HARL	7501	2	58.9	0.4	58.9	58.6	59.1
			27534	17.8	15.7	8.5	-80.7	110.4

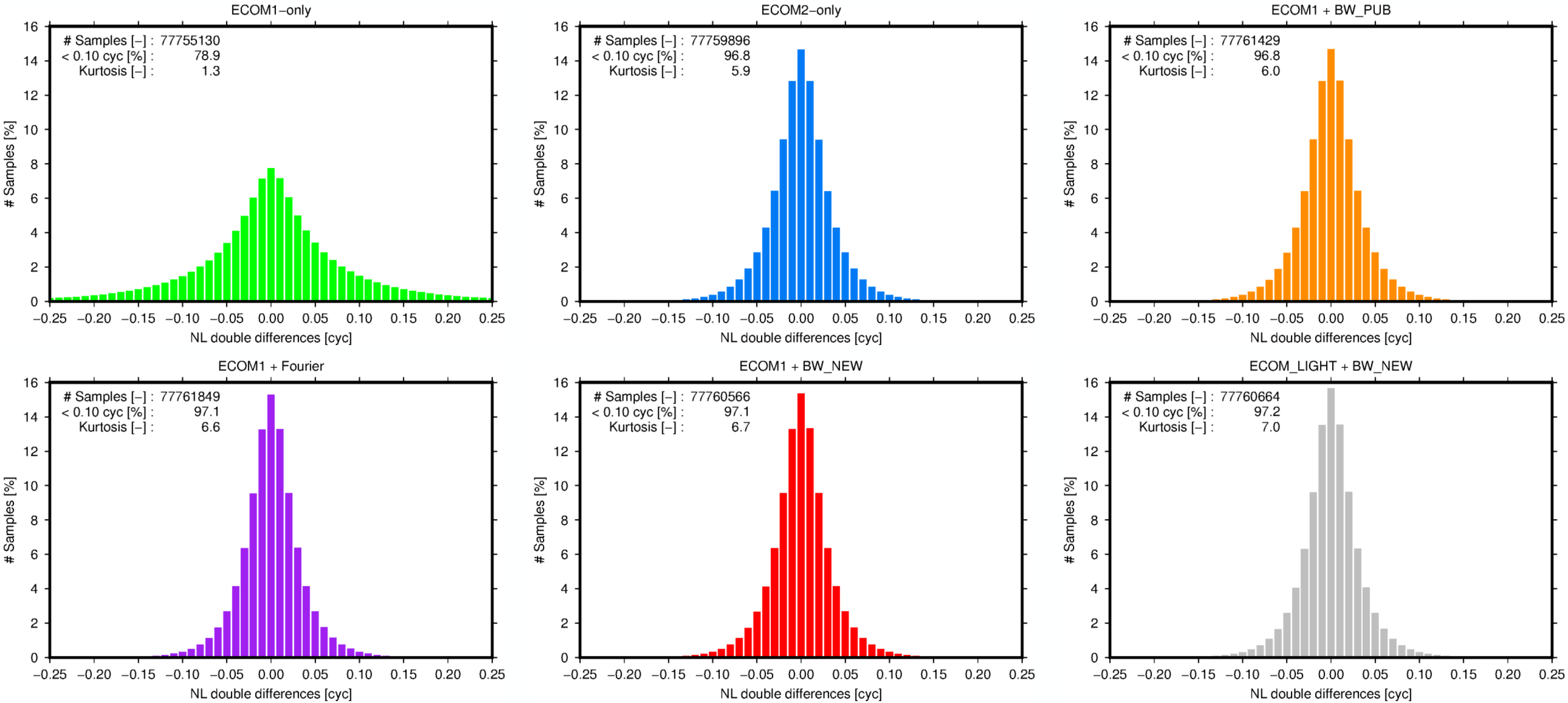
Galileo FOC orbit residuals



ECOM & CPR estimates



Ambiguity fixing statistics



Summary & Conclusions (1/2)

- Galileo satellites are more sensitive to SRP than any other GNSS spacecraft
- New ESA Galileo radiation force models have been developed and thoroughly tested
    - FOC box-wing model based upon most accurate pre-launch engineering information
    - Low-order Fourier models for IOV and FOC satellites from in-flight data
- New ESA FOC box-wing model superior to previous version based on public metadata
    - Significant reduction of empirical radiation pressure estimates, SLR and orbit overlap residuals
    - 14-day orbit prediction error decreasing by more than 30%
    - NL fractionals clustering more tightly around zero
- Less estimated dynamical parameters needed to account for un-modelled force effects
    - No need to solve for all 8 (5 CODE + 3 CPR) terms per satellite anymore
- IOV Fourier model outperforming IOV box-wing model
    - Reduction of SLR residual bias/sigma from -40 mm ± 22 mm to 11 mm ± 19 mm
    - More work needed on IOV box-wing model

Summary & Conclusions (2/2)

- Box-wing model upgrade along with “ECOM_LIGHT” turned out to be superior to all other approaches we have tested for Galileo FOC
  - Overlap RMS of Galileo FOC orbits below 20 mm for each component (radial, along, cross)
  - SLR sigma over all satellites/stations of **15 mm** only
  - SLR sigma for ILRS “core sites” such as Graz, Herstmonceux, Matera, or Yarragadee even **< 10 mm**
- Fourier model for FOC performs good as well but not as good as box-wing
  - 14-day orbit predictions almost 30% worse relative to box-wing
- Development of analytical model takes effort, but it is effort that pays off