IGS Multi-GNSS Working Group Splinter Meeting

Wednesday, 26 April 2016, 08:30-10:00 (Room 2.17)

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DLR, German Space Operations Center

Scope

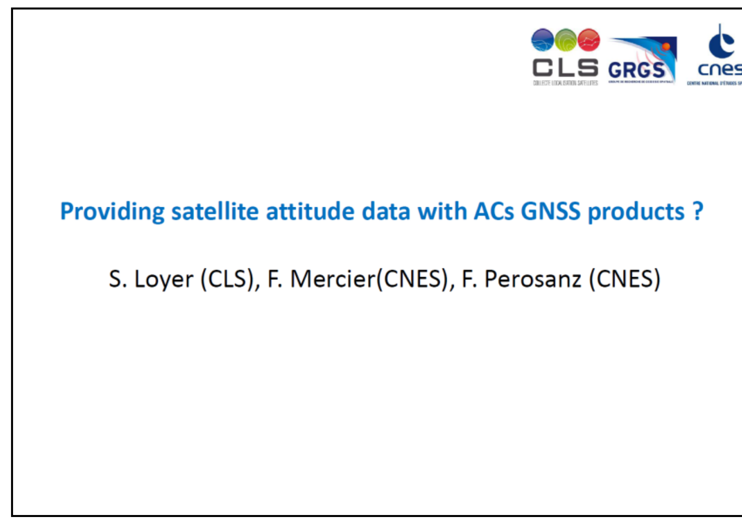
- Advance and harmonize models
  for multi-GNSS orbit and clock products
  - Attitude models
  - Antenna models
  - (Solar) radiation pressure models

  (Note: triggered by, but not limited to release of Galileo metadata)
- Consolidate/promote meta new formats
- Establish new product naming conventions

Part 1
Attitude Models

Attitude Data Product

- Various attitude models (GPS, GLO, GAL) published for eclipse phases
- Need to ensure consistency between product provider and PPP user
- Proposal: dedicated product for provision of attitude data as used in orbit/clock computation
- See separate handout by CNES/CLS AC


Providing satellite attitude data with ACs GNSS products ?

S. Loyer (CLS), F. Mercier(CNES), F. Perosanz (CNES)

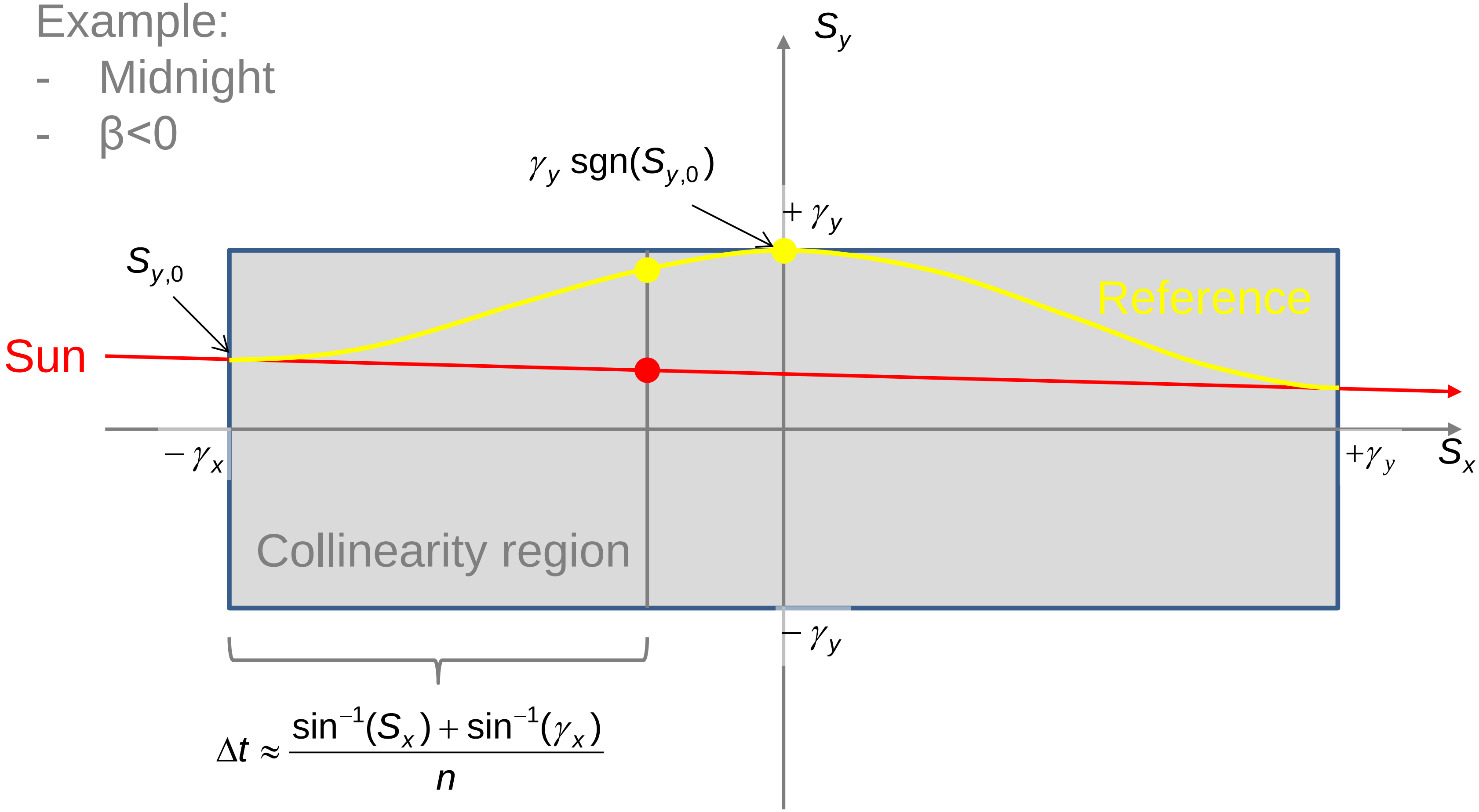
Galileo IOV Attitude Law

- Description of Galileo eclipse attitude provided along with satellite meta data in Dec. 2016
  https://www.gsc-europa.eu/support-to-developers/galileo-iov-satellite-metadata
- Differs from previous assumptions (EADS patent)

- Experience?
- Issues?
- Galileo FOC?

Reference Sun Vector (Example)

Example:
- Midnight
- β<0



Galileo Attitude Law - Formulation

- True Sun direction unit vector in orbit-normal frame

$$\boldsymbol{S} = \begin{pmatrix} S_x \\ S_y \\ S_z \end{pmatrix} = \begin{pmatrix} +\cos\beta\sin\mu \\ -\sin\beta \\ +\cos\beta\cos\mu \end{pmatrix} = \begin{pmatrix} -\cos\beta\sin\eta \\ -\sin\beta \\ -\cos\beta\cos\eta \end{pmatrix}$$

β Sun elevation above orbital plane
μ Orbit angle from midnight
η Orbit angle from noon ($=\mu+\pi$)

- Modified yaw-steering in collinearity region near noon/midnight

$$|S_x| < \gamma_x \,,\; |S_y| < \gamma_y \quad (\gamma_x = \sin 15°,\; \gamma_y = \sin 2°)$$

- “Tweaked” Sun vector for yaw-steering

$$\overline{\boldsymbol{S}} = \begin{pmatrix} \overline{S}_x \\ \overline{S}_y \\ \overline{S}_z \end{pmatrix} \quad \text{with}$$

$$\overline{S}_y = 0.5\cdot(1+c)\cdot\gamma_y \operatorname{sgn}(S_{y,0}) + 0.5\cdot(1-c)\cdot S_y$$

$S_{y,0} = S_y$ at entry into collinearity region

$$c = \cos\left(\pi \frac{|S_x|}{\gamma_x}\right)$$

Cosine weighting factor
(+1 at noon/midnight, -1 at transition)

$$\overline{S}_x = S_x$$

No change of x-component

$$\overline{S}_z = \sqrt{\overline{S}_x^2 + \overline{S}_y^2}$$

Normalization

Galileo Attitude Law – Issues

- Collinearity region is normally entered ~35^m before noon/midnight and left ~35^m thereafter
- Continuity of true and reference Sun vector ensured at entry, but not necessarily at exit
- Non-zero Sun elevation rate $dS_y / dt \approx \dot{\beta} \approx 0.05° / \mathrm{h}$
  - Sun may exit the collinearity region at top or bottom, i.e. $S_x \neq +\gamma_x$
  - Small discontinuity may occur since $c \neq -1, S_y \neq S_{y,0}$
  - Neglect? What about the real satellite?
- How to determine entry into collinearity region?
  - Test permanently and store true entry time?
  - Approximate entry time, e.g. $\Delta t \approx (\sin^{-1}(S_x) - \sin^{-1}(\gamma_x)) / n$ before current epoch, i.e. $\Delta t \approx \sin^{-1}(\gamma_x) / n$ before midnight?
- If Sun elevation is near zero at entry into the collinearity region, the tweaked Sun might have a different sign than computed onboard – how would we know?

Part 2
Antenna Models

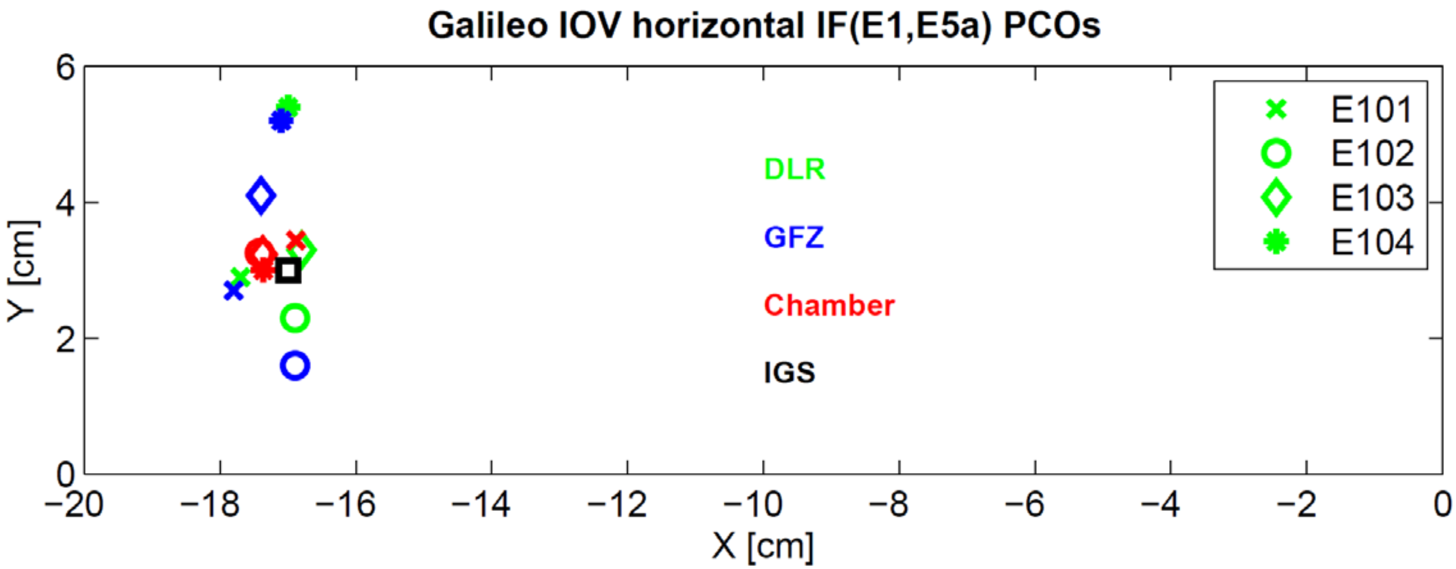
Galileo IOV Antenna Offsets

- ESA/GSC provides
  - Center-of-mass (CoM) location
  - Antenna reference point (ARP)
  - Phase center offset (PCO) w.r.t. ARP (for each frequency)
  - Phase variations (PVs) (for each frequency)
- IGS needs
  - PCO w.r.t. CoM (i.e. $PCO_{IGS}=ARP_{ESA}-CoM_{ESA}+PCO_{ESA}$)
  - PV
- IGS has
  - PCOs of IOV and FOC for E1/E5a (GFZ/DLR campaign)

Erroneous COSPAR-IDs in IOV_NAVANT.atx

- 2011-???A/B for E103/4 instead of 2012-055A/B
- Correction requested via Help Desk of the European GNSS Service Center

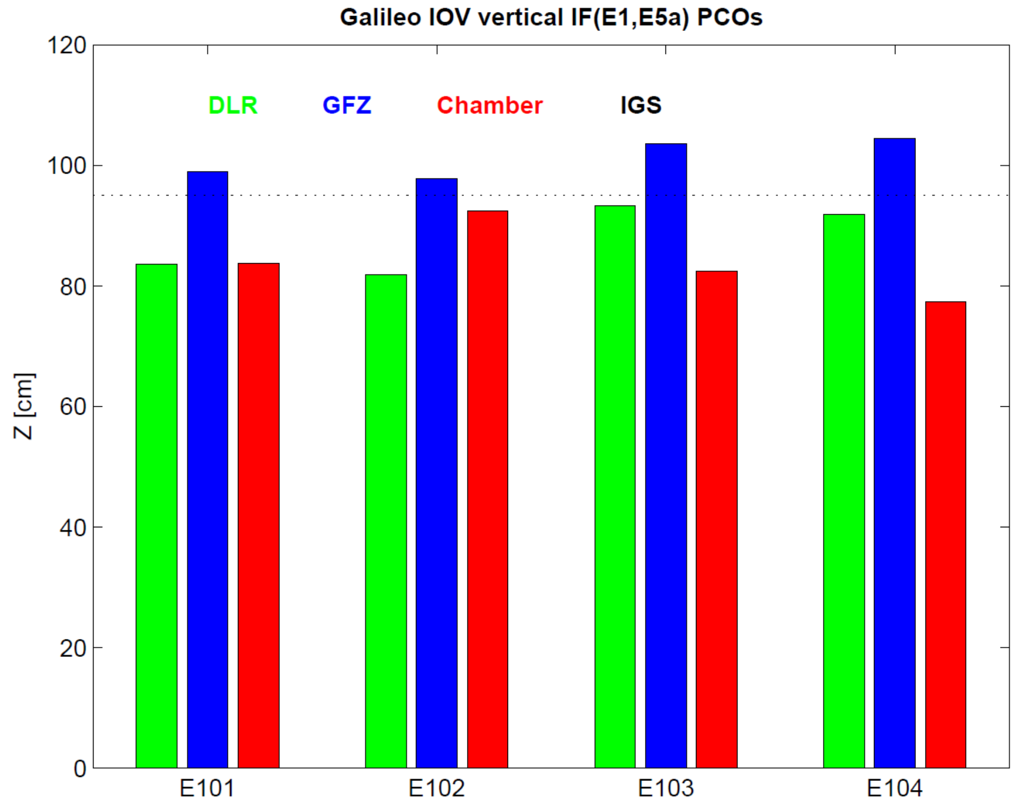
PCO Comparison – Horizontal



- Chamber measurements close to current IGS conventional value
- ±0.5 cm / ±2 cm scatter of observed X-/Y-component
- Good agreement within observational limits

PCO Comparison – Vertical

- Systematic offset (~15 cm) of GFZ and DLR estimates (elev.-dep. weighting?)
- Differences of calibrated and estimated z-PCOs comparable to uncertainty of estimated values
- Use of estimated PCOs promises consistency of IOV and FOC PCOs
- Use of ESA calibrations offers access to single-frequency PCOs



Phase Variations (IOV-1)

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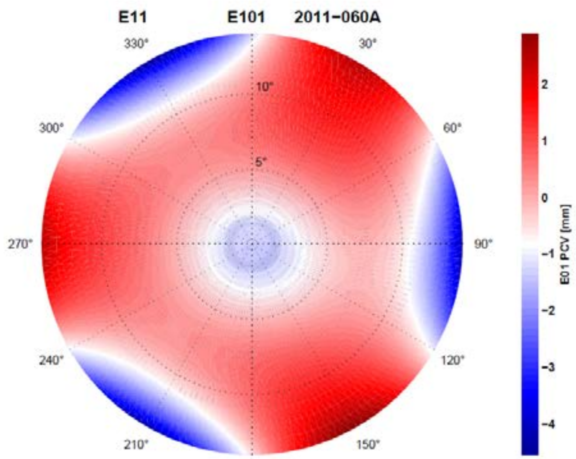
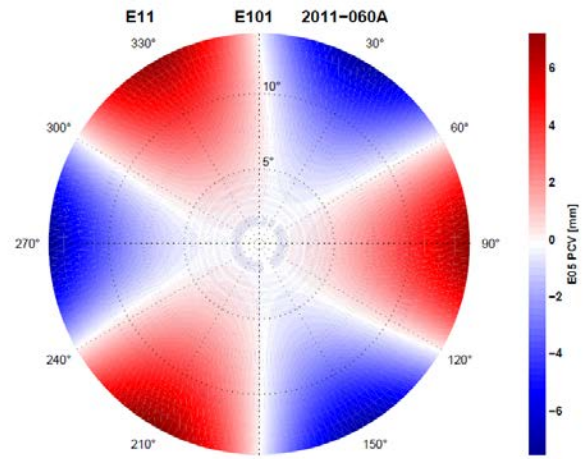
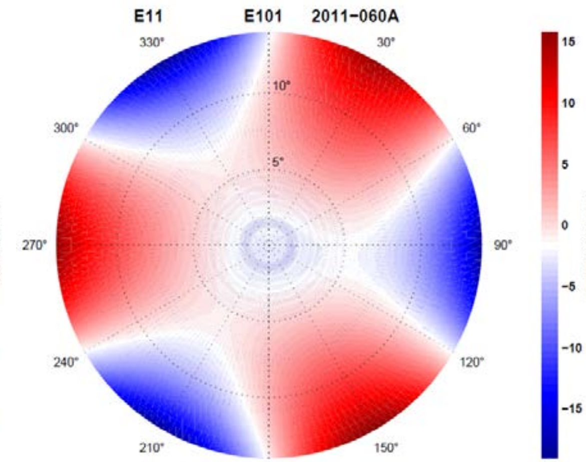
E1



E5a



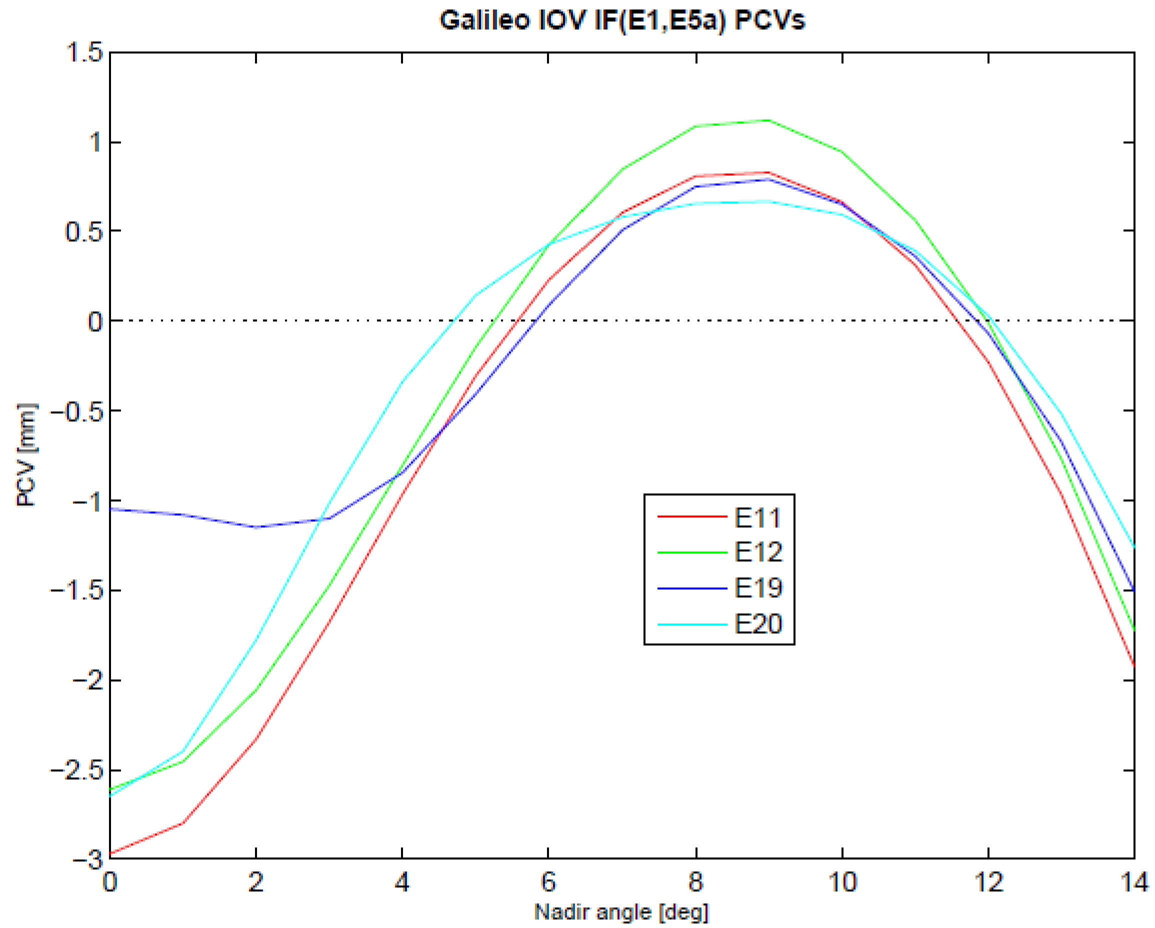
IF(E1,E5a)



- “Wind-mill” pattern, most pronounced on E5a/b/ab
- Up to ±15 mm in ionosphere-free E1/E5a combination
- Fairly flat azimuth-averaged PCV (±2 mm in E1/E5a)

Azimuth-Averaged Phase Variations

- -3 mm … +1 mm in IF(E1,E5a)
- Similar for all IOV satellites except IOV-3



Adjustment of PCOs

- Factory calibrations not fully consistent with observed phase center for ionosphere-free combination
- Re-adjust PCOs to fit observations?
- n equations, n+1 unknowns

$$\Delta PCO_{E1/E5a} = \Delta PCO_{E1} - \frac{f_{E5a}^2}{f_{E1}^2 - f_{E5a}^2}(\Delta PCO_{E5a} - \Delta PCO_{E1})$$

$$\Delta PCO_{E1/E6} = \Delta PCO_{E1} - \frac{f_{E6}^2}{f_{E1}^2 - f_{E6}^2}(\Delta PCO_{E6} - \Delta PCO_{E1})$$

...

- Possible constraints:
    - Reference constraint $\Delta PCO_{E1} = 0$
    - Zero-mean constraint $\Delta PCO_{E1} + \Delta PCO_{E5a} + \ldots = 0$
    - Equal shifts $\Delta PCO_{E1} = \Delta PCO_{E5a}$
    - …
- How to adjust PCOs for unobserved frequencies?

Example PCO Adjustment

	calib [mm]	obs [mm]	A [mm]	dA [mm]	B [mm]	dB [mm]	C [mm]	dC [mm]
E1	812		812	0	844	32	925	113
E5a	792		703	-89	760	-32	905	113
E1/E5a	837	950	950		950		950	
E6	710							
E1/E6a	1009	?						

Correct

- E5a PCO by -89 mm (option A) *or*
- E1 by +32 mm and E5a by -32 mm (option B) *or*
- E1 and E5a by 113 mm (option C)

to change E1/E5a PCO from 837 to 950 mm

Questions on IGS Antenna Model

- General
  - use ESA data for IOV *or* merge these calibrations with GFZ/DLR PCO estimates?
  - use per-frequency data (e.g. E1, E5a, …) *or* ionosphere-free combination (like in GPS/GLO)
- PCO
  - use satellite-specific *or* block mean *or* block mean for *X*,*Y* plus individual *Z*?
- PVs
  - use azimuth+elevation dependent (2-dim) *or*
  - only elevation dependent (1-dim) *or*
  - none?
- Proposal
  - Update current ANTEX data set; “ignore” GFZ/DLR PCO calibrations
  - Insert unabridged ESA data set (individual satellite, all frequencies, 2-dim PV) into next ANTEX release
    Notes: need to add ARP-CoG to PCO; need to double-check orientation
  - Use new ANTEX in MGEX product generation

Part 3
Solar Radiation Pressure Models

New Models

- Galileo IOV
  - Surface areas and properties published by EU/ESA in Dec. 2016
  - https://www.gsc-europa.eu/support-to-developers/galileo-iov-satellite-metadata
  - Experience?
  - Issues?
- QZSS
  - New DLR box-wing model
  - New “ECOM-ON” frame for ECOM parameters estimation in orbit-normal mode
  - http://dx.doi.org/10.1016/j.asr.2017.01.036

Galileo IOV Surface Properties

- Areas and optical parameters for
  - 6 faces of “brick”-like (cuboid) box
  - Solar panels
  - Up to two constituents per surface
- Only +z, +x, -z-faces and solar panels (SP) need to be considered in nominal yaw-steering

Characteristic Accelerations

Panel	$\alpha+\delta$ [nm/s²]	ρ [nm/s²]	Sum [nm/s²]	DLR model [nm/s²]	Notes
+z	17.8	1.8	19.6	19.5	
-z	19.5	0.0	19.5	19.5	
+x	7.7	0.9	8.6	9.5	
zx	13.2	0.9	14.1	14.5	"Cubicness"
Δzx	5.5	0.0	5.5	5.0	"Strechedness"
Δzx	-0.9	+0.9	0.0	0.0	
SP			74.5	87.0	No immediate (or symmetric) reemission of absorbed radiation
SP*			87.2	87.0	With α=0.75, δ=0.04, ρ=0.21

Montenbruck O., Steigenberger P., Hugentobler U.; *Enhanced Solar Radiation Pressure Modeling for Galileo Satellites*; Journal of Geodesy 89(3):283-297 (2015). DOI 10.1007/s00190-014-0774-0

Galileo IOV Box Wing Model

- Box contribution
  - Assume spontaneous reemission of absorbed radiation (only sum of $\alpha+\delta$ matters)
  - Good overall match with flight calibrated DLR cuboid model
  - Benefit of explicit modeling of specular reflection unclear
  - Modeling of *y*-contribution of interest for non-nominal yaw-steering
- Galileo IOV Solar panel parameters
  - “Standard” model does not account for reemission of absorbed radiation (=symmetric emission from front and back of panel)
  - Can only be used in combination with additional model for (asymmetric) thermal reemission (but no temperature data provided) or (more simply) by modified specular reflectivity

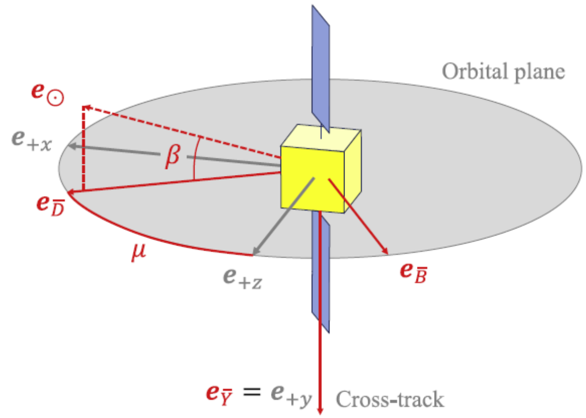
Discussion

- Galileo IOV
  - Which ACs can (plan to) make use of BW model?
  - How to best treat solar panels?
  - Need for ECOM1 on top of a priori BW model?
  - Improvement compared to current modeling?
  - Benefit (and applicability) for non-nominal attitudes?
    - Only short phase (~1h) and small incidence angles
    - QZSS analysis suggests “anomalous” *y*-acceleration outside the nominal yaw-steering

QZS-1 SRP Model

- Surface areas and adjusted "characteristic accelerations" for all six body faces plus solar panels
- For use with complementary ECOM-1
- Dedicated ECOM-ON frame for orbit-normal mode

Parameter	Value [nm/s²]	Parameter	Value [nm/s²]
$a_{zx}^{\alpha\delta}$	20.0	$a_{+z}^{\alpha\delta}$	14.0
a_{zx}^{ρ}	0.0	a_{+z}^{ρ}	0.0
$\Delta a_{zx}^{\alpha\delta}$	−7.0	$a_{-z}^{\alpha\delta}$	12.0
Δa_{zx}^{ρ}	0.0	a_{-z}^{ρ}	0.0
$\Delta a_{z}^{\alpha\delta}$	0.0	$a_{+x}^{\alpha\delta}$	27.0
Δa_{z}^{ρ}	0.0	a_{+x}^{ρ}	0.0
$\Delta a_{x}^{\alpha\delta}$	0.0	$a_{-x}^{\alpha\delta}$	27.0
Δa_{x}^{ρ}	0.0	a_{-x}^{ρ}	0.0
$a_{y}^{\alpha\delta}$	7.0	$a_{+y}^{\alpha\delta}$	7.0
a_{y}^{ρ}	15.0	a_{+y}^{ρ}	15.0
$\Delta a_{y}^{\alpha\delta}$	0.0	$a_{-y}^{\alpha\delta}$	7.0
Δa_{y}^{ρ}	0.0	a_{-y}^{ρ}	15.0
$a_{sp}^{\alpha\delta}$	70.5		
a_{sp}^{δ}	0.0		
a_{sp}^{ρ}	21.0		



QZS-1 SRP Model – SLR Validation

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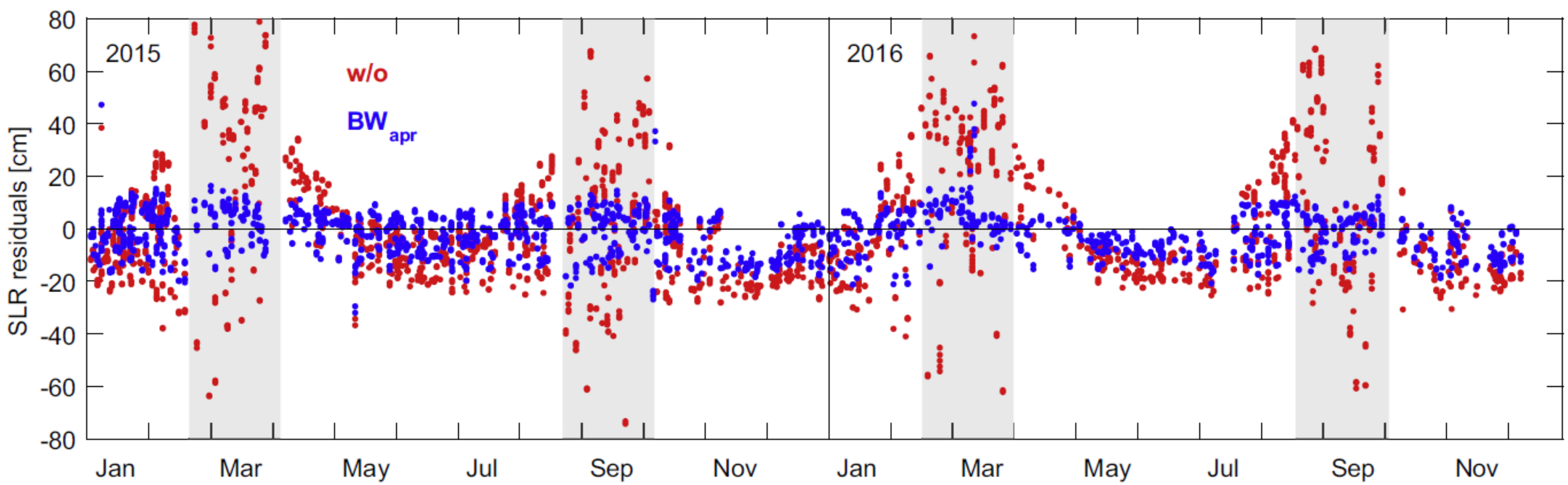
Attitude	No box-wing mean $\pm\sigma$ [cm]	With box-wing mean $\pm\sigma$ [cm]
YS	-5.4 ± 14.0	-2.9 ± 8.0
ON	14.4 ± 33.3	$+2.1 \pm 8.3$
all	-0.5 ± 22.2	-1.6 ± 8.4



Part 4
SINEX Satellite Metadata Format

Background

- Satellite metadata are vital for accurate modeling of GNSS data
  - Unique identifiers: SVN, COSPAR ID, Satellite Catalog Number (“NORAD ID”)
  - PRN/SVN mapping
  - Satellite mass
  - Center of mass
  - Eccentricities of “devices”: transmit antennas, laser retroreflector arrays, …
- ANTEX format includes satellite metadata that is not related to the antenna
  - PRN/SVN mapping → highly redundant antenna records
- **`SATELLITE/ID`** block already available in SINEX format; requires only minor upgrades
  - Add constellation letters in PRN
  - Add Satellite Catalog Number
  - Transition from 2-digit year to 4-digit year
  - Replace *antenna* name by *satellite block* name

Option A: Satellite ID including PRN/SVN

```
+SATELLITE/ID
* SVN PRN COSPAR ID SATCAT   VALID_FROM...TO______________ BLOCK_____
 C017 C15 2016-021A  41434 P 2016:089:00000 2016:285:18000 BEIDOU-2I
 C017 C13 2016-021A  41434 P 2016:285:27000 0000:000:00000 BEIDOU-2I
 E101 E11 2011-060A  37846 P 2011:294:00000 0000:000:00000 GALILEO-1
 E201 E18 2014-050A  40128 P 2014:234:00000 0000:000:00000 GALILEO-2
 G023 G23 1990-103A  20959 P 1990:330:00000 2004:053:86399 GPS-IIA
 G023 G32 1990-103A  20959 P 2006:336:00000 2016:025:86399 GPS-IIA
 J001 J01 2010-045A  37158 P 2010:254:00000 0000:000:00000 QZS-1
 R802 R27 2014-075A  40315 P 2014:334:00000 2016:026:86399 GLONASS-K1
 R802 R09 2014-075A  40315 P 2016:047:00000 0000:000:00000 GLONASS-K1
 R802 R17 2014-075A  40315 P 2016:027:00000 2016:046:86399 GLONASS-K1
       .              .              .              .
       .              .              .              .
       .              .              .              .
-SATELLITE/ID
```

Option B: Separate PRN Block

```
+SATELLITE/ID
* SVN COSPAR ID SATCAT BLOCK_____
 C017 2016-021A  41434 BEIDOU-2I
 E101 2011-060A  37846 GALILEO-1
 E201 2014-050A  40128 GALILEO-2
 G023 1990-103A  20959 GPS-IIA
 J001 2010-045A  37158 QZS-1
 R802 2014-075A  40315 GLONASS-K1
-SATELLITE/ID
```

SATELLITE/ID block only contains unique information that does not require a validity interval

```
+SATELLITE/PRN
* SVN PRN T VALID_FROM...TO______________
 C017 C15 P 2016:089:00000 2016:285:18000
 C017 C13 P 2016:285:27000 0000:000:00000
 E101 E11 P 2011:294:00000 0000:000:00000
 E201 E18 P 2014:234:00000 0000:000:00000
 G023 G23 P 1990:330:00000 2004:053:86399
 G023 G32 P 2006:336:00000 2016:025:86399
 J001 J01 P 2010:254:00000 0000:000:00000
 R802 R27 P 2014:334:00000 2016:026:86399
 R802 R09 P 2016:047:00000 0000:000:00000
 R802 R17 P 2016:027:00000 2016:046:86399
-SATELLITE/PRN
```

SATELLITE/PRN block contains only PRN/SVN mapping

Satellite Center of Mass

- Coordinates of spacecraft center of mass relative to agreed-upon origin (e.g., mechanical reference system defined by manufacturer)
  - Values refer to IGS conventions for orientation of spacecraft body axes[1)]
  - Use zero value if no CoM location is available.
- Example for Galileo IOV-1 (E101) based on data from ILRS
  - Data sets with identical CoM values have been merged

```
+SATELLITE/COM
* SVN VALID_FROM...TO______________ X_[m]____ Y_[m]____  Z_[m]____
 E101 2011:294:00000 2012:277:50560  -1.20590  -0.62890    0.55340
 E101 2012:277:50561 2014:324:63246  -1.20587  -0.62895    0.55343
 E101 2014:324:63247 0000:000:00000  -1.20584  -0.62897    0.55344
-SATELLITE/COM
```

[1)] O. Montenbruck, R. Schmid, F. Mercier, P. Steigenberger, C. Noll, R. Fatkulin, S. Kogure, A. S. Ganeshan (2015) “GNSS Satellite Geometry and Attitude Models”, Advances in Space Research 56(6), DOI 10.1016/j.asr.2015.06.019

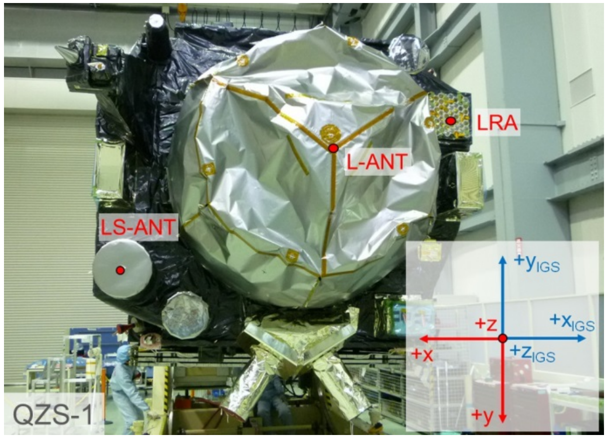
Satellite Mass

- Example for Galileo based on data from ILRS
  - Records with identical mass have been merged
  - Mass increase of +4 g for last record of E201 (bookkeeping uncertainty)

```
+SATELLITE/MASS
* SVN VALID_FROM...TO______________ MASS_[KG]
 E101 2011:294:00000 2012:277:50560   698.815
 E102 2011:294:00000 0000:000:00000   695.328
 E103 2012:286:00000 0000:000:00000   697.632
 E104 2012:286:00000 0000:000:00000   695.652
 E201 2014:234:00000 2014:324:63246   661.030
 E201 2014:324:63247 2015:065:53958   660.973
 E201 2015:065:53959 0000:000:00000   660.977
-SATELLITE/MASS
```

Satellite Eccentricity

- Eccentricities for various devices relative to spacecraft body system
  - IGS axes conventions, same origin as CoM data
  - Device name matches ANTEX code
  - Antenna reference points for different GNSS transmit antennas
  - Laser retroreflector array (LRA) offset
- Example for QZS-1 with two different GNSS transmit antennas and a LRA
  - $ARP_{Z,L\text{-}ANT}$ arbitrarily set to a rounded value of +4.8 m
  - Observation code **T**: **P** – GNSS; **L** – SLR




```
+SATELLITE/ECCENTRICITY
* SVN DEVICE______________ T X_[m]____ Y_[m]____  Z_[m]____
 J001 QZS-1_L-ANT          P   0.00000   0.00000    4.80000
 J001 QZS-1_LS-ANT         P  -1.15000  -0.70000    4.83500
 J001 QZS-1_LRA            L   1.15000   0.55000    4.45030
-SATELLITE/ECCENTRICITY
```

Benefits

- Centralized interface for GNSS satellite metadata
  - Avoids redundancy
  - Facilitates maintenance of satellite database in PPP/POD S/W
- Enables “clean-up” of ANTEX antenna model
- Extendible to further information, e.g.
  - **`SATELLITE/BOX_WING`**
  - **`SATELLITE/TX_POWER`**
  - **`SATELLITE/CLOCK`**
- Extendible to LEO satellite data

Points for Discussion

- Length and choice of satellite (block) names
- Length and choice of device names
- 2-digit vs. 4-digit year
- Field length and width for coordinates
- GLONASS frequency channel
- Extensions for VLBI/SLR/DORIS/LEO?
  - These satellites have no SVN. Use COSPAR ID as unique identifier in **`SATELLITE/COM`**, **`SATELLITE/MASS`**, **`SATELLITE/ECCENTRICITY`**?
  - Add **`SATELLITE/ALIGNMENT`** for orientation of devices on LEO satellites

Implications for ANTEX++

- Remove PRN information, retain only SVN & COSPAR ID
- Provide PCO/PV information only *once* per SVN
- Remove obsolete validity interval
- Refer PCO to ARP rather than CoM; change label

```
                                                            START OF ANTENNA
BLOCK IIA           G01                 G032      1992-079A TYPE / SERIAL NO
                    COD/EMR/ESA/GFZ/MIT      0    25-MAR-11 METH / BY / # / DATE
     0.0                                                    DAZI
     0.0  17.0   1.0                                        ZEN1 / ZEN2 / DZEN
     1                                                      # OF FREQUENCIES
  1992    11    22     0     0    0.0000000                 VALID FROM
  2008    10    16    23    59   59.9999999                 VALID UNTIL
IGS08_1930                                                  SINEX CODE
   G01                                                      START OF FREQUENCY
    279.00      0.00   2380.80                              X / Y / Z  NORTH / EAST / UP
   NOAZI   -0.80   -0.90   -0.90   -0.80   -0.40    0.20    0.80    ...
   G01                                                      END OF FREQUENCY
END OF ANTENNA
```

GLONASS Frequency Channel*)

```
+SATELLITE/FREQUENCY_CHANNEL
* SVN     VALID_FROM     VALID_UNTIL CHN
 R701 2003:344:00000 2009:256:86399   1
 R701 2009:257:00000 2010:117:86399  -4
 R711 2001:335:00000 2006:078:86399   2
 R711 2006:079:00000 2009:347:86399   7
 R712 2004:361:00000 2007:036:86399   4
 R712 2007:037:00000 2011:348:86399   5
 R712 2012:292:00000 2012:304:86399  -6
  .         .              .          .
  .         .              .          .
 R854 2014:101:00000 0000:000:00000  -3
 R855 2014:214:00000 0000:000:00000   4
-SATELLITE/FREQUENCY_CHANNEL
-SATELLITE/ID
```

*) Thanks to Simon Banville!

Part 5
Product Naming Conventions

New File Naming Convention

```
AAAVPPPTTT_YYYYDDDHHMM_LEN_SMP_CNT.FMT[.?*]
GFZ0MGXRAP_20160010000_01D_05M_ORB.SP3.gz

01-03  AAA    3-char AC name (e.g. GFZ)
04       V    1-char version/solution identifier (nominally 0)
05-07  PPP    3-char campaign/project specification (e.g.: "MGX")
08-10  TTT    3-char product type specification
              (here: RAP for "rapid", and FIN for "final")
11            1-char separator (underline)
12-15  YYYY   4-digit year of start epoch
16-18  DDD    3-digit day-of-year of start epoch
10-20  HH     2-digit hour of start epoch (her: 00)
21-22  MM     2-digit minute of start epoch (here: 00)
23            1-char separator (underline)
24-26  LEN    2-digits+1-char intended (nominal) product period
              (e.g. 01D for 1-day)
27            1-char separator (underline)
28-30  SMP    2-digits+1-char sampling interval
              (e.g 15M for 15-min; 000 if not-applicable)
31            1-char separator (underline)
32-34  CNT    3-char content type (e.g.: „ORB")
35       .    1-char separator
36-38  FMT    3-char format extension (e.g.: "SP3")
```

New File Naming Convention (cntd.)

Field	Tags	Description
Analysis center	IGS, COD,EMR,ESA,GFZ,GRG,JPL,MIT,NGS, WUH, …	IGS ACC (for combined products) or individual AC designator
Campaign/project	OPS	Operational IGS products
	RP1, RP2, …	Reprocessing campaigns
	MGX	Multi-GNSS pilot project (MGEX)
	TGA	Tide Gauge Benchmark Monitoring (TIGA)
Product type	FIN	Final
	RAP	Rapid
	ULT	Ultra-rapid
	RTM	Real time streams written to file
Contents type	ORB (or EPH?)	Orbit+(clock) ephemeris (typically in SP3 format)
	CLK	Satellite/receiver clocks
	EOP	Earth orientation parameters
	TRP	Troposphere related product
	ION	Ionosphere product
	SOL	Solutions (typically in SINEX format)
	CRD	Station coordinates/velocities (typically in SINEX format)
	BIA	Biases

Conclusions

Conclusions (Eclipse Models)

- To be supplied at/after meeting

Conclusions (Antenna Models)

- To be supplied at/after meeting

Conclusions (SRP Models)

- To be supplied at/after meeting

Conclusions (Sat Metadata Format)

- To be supplied at/after meeting

Conclusions (Product File Names)

- To be supplied at/after meeting