Copernicus POD Service – Orbit reprocessing for Copernicus Sentinel-1 satellites

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Session G2.4

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COPERNICUS POD Service

Copernicus POD Service – general information

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EUMETSAT

opernicus
Europe's eyes on Earth

Copernicus Sentinel-1

Copernicus Sentinel-2

Copernicus Sentinel-3

Copernicus Sentinel-6 Michael Freilich

- Sentinel satellites are equipped with various Earth observation instruments
- Mission requirements demand high levels of orbital accuracy (**GPS**, DORIS+SLR only S-3 + S-6 (+GAL)) → **Copernicus POD Service**

Copernicus POD Service

COPERNICUS POD Service

- Consortium led by **GMV**, Tres Cantos, Spain
- **magicGNSS**, external GPS orbit and clock provider (NRT, STC), backup **DLR Reticle**
- **PosiTim**, QWG management, quality control, improvements, scientific outreach …
- **DLR, TUM, AIUB, TUD, GFZ** quality control, QWG members

Copernicus POD Service – general information

Mission	Category	Orbit Accuracy (RMS)
S-1	NRT (predicted)	1 m (2D)
	NRT	10 cm (2D)
	NTC	**5 cm (3D)**
S-2	NRT (predicted)	3 m (2D)
	NRT	1 m (3D)
S-3	NRT (S3PODIPF)	10 cm radial (target of 8 cm)
	STC	4 cm radial (target of 3 cm)
	NTC	**3 cm radial (target of 2 cm)**
S-6	NRT	5 cm radial (target of 3 cm) – compared to POE

Focus of this study is on S-1 (NTC)

Copernicus POD Quality Working Group (QWG)
⇨ **Orbit validation and quality control**

u^b UNIVERSITÄT BERN
DLR
TU Delft
esa
TUM

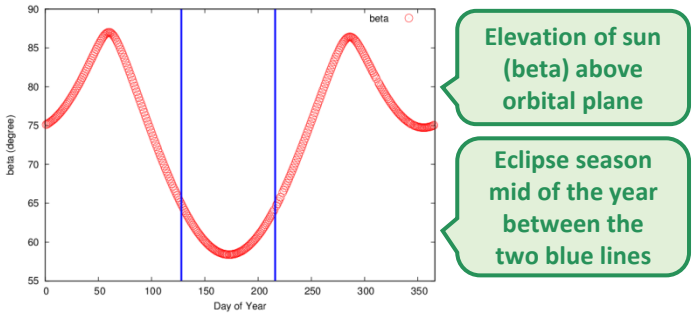
only S-3 + S-6

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES
CLS COLLECTE LOCALISATION SATELLITES
JPL Jet Propulsion Laboratory California Institute of Technology
EUMETSAT
HELMHOLTZ-ZENTRUM POTSDAM DEUTSCHES GEOFORSCHUNGSZENTRUM

- Orbit accuracy requirement for Sentinel-1 is given as 5 cm in 3D RMS in the comparison to external processing facilities [1]
- There are two official orbit providers for the S-3 mission. Copernicus POD Service provides NRT, STC and NTC orbit products. CNES provides STC and NTC orbit products. Operational configuration is NRT (CPOD), STC & NTC (CNES).

CPOD Service – Sentinel-1

- Sentinel-1, C-Band SAR (Synthetic Aperture Radar) mission with two polar-orbiting satellites
  - Altitude: 693 km
  - Inclination: 98.18 deg
  - Mass: ~2150 kg
- Sentinel-1A
  - Launch: 3 April 2014
- Sentinel-1B
  - Launch: 25 April 2016



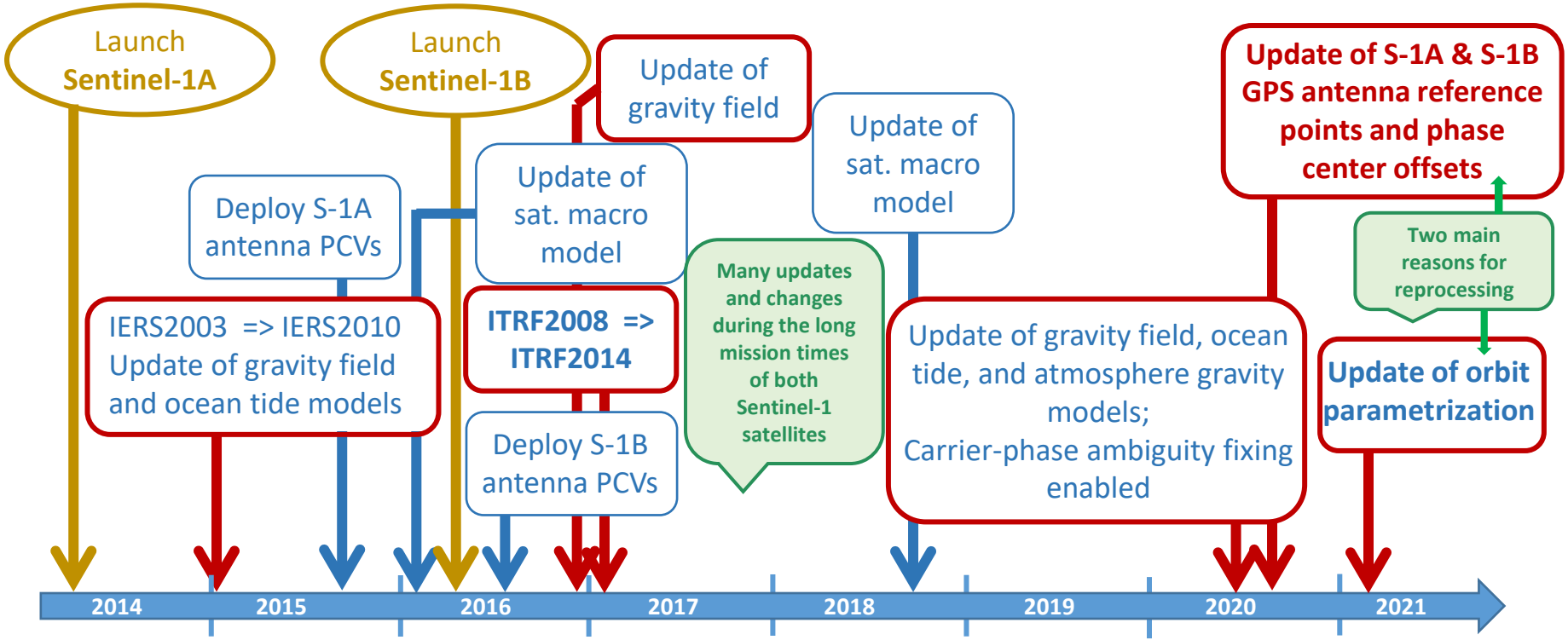
Elevation of sun (beta) above orbital plane

Eclipse season mid of the year between the two blue lines

- Complex satellite structure due to self-shadowing effects
- Fixed solar arrays (30 deg w.r.t. satellite body)

- More information at https://sentinel.esa.int/web/sentinel/missons/sentinel-1 and [2]-[5]

CPOD Service – Selected evolutions for Sentinel-1



CPOD Service – Planning of reprocessing

- ITRF2014 / IGS14 compatible GPS orbit, clock and bias (for integer ambiguity resolution (IAR)) product for the entire mission times is needed => **CODE (Center for Orbit Determination in Europe) provided IGS14-consistent reprocessed time series of GPS orbits, clocks and biases for the years 2014-2019 (doi: 10.7892/boris.146753).**

- For orbit validation and quality control external orbit solutions are needed (no SLR (Satellite Laser Ranging) reflector on the satellites) => **Copernicus POD QWG members (AIUB, DLR, ESOC, TUM, TUD) provided Sentinel-1A & -1B reprocessed orbit solutions based on their s/w packages and orbit determination settings for validation.**

- A combined orbit solution (IGS-like combination based on weighted average) is computed serving as a reference solution.

Sentinel-1 POD solutions – data processing summary

Analysis Centre (Orbit solution ID)	AIUB (AIUB)	CPOD (CPOR)	DLR (DLRR)	ESOC (ESOC)	TU Delft (TUDF)	TUM (TUMM)
Software name and version	Bernese GNSS Software v5.3	NAPEOS	GHOST 2276	NAPEOS 4.2.1	GIPSY-X (v1.5)	Bernese GNSS Software v5.3 (mod)
Arc lengths	24 h	32 h	30 h	30 h	30 h	30 h
Gravity						
Gravity field (static)	GOCO05s (120x120)	EIGEN.GRGS.RL04 TVG (120x120)	GOCO03S (100x100)	EIGEN.GRGS.RL04.MEAN-FIELD	EIGEN.GRGS.RL04.MEAN-FIELD (200X200)	EIGEN GL04C (120x120)
Gravity field (time varying)	IERS 2010 Conventions	Drift/annual/semi-annual terms up to degree/order 90	n/a	Drift/annual/semi-annual terms up to degree/order 80	Drift/annual/semi-annual terms up to degree/order 90	Drift of 20, 30, 40
Ocean tides	EOT11A (50x50)	FES2014 (100x100)	FES2004	EOT11a (50x50)	FES2004	FES2004 (50x50)
Atmospheric gravity	None	AOD1B RL06 (100x100)	n/a	AOD1B RL06 (100x100)	AOD1B RL06 (180x180)	None
Atmospheric tides	None	AOD1B RL06 (100x100)	n/a	Ray-Ponte 2003	n/a	None
Surface Forces and Empirical parameters						
Radiation pressure model	No explicit modelling	Box-wing model	Box-wing model	Box-wing model	Box-wing model	Box-wing model
Earth radiation	No explicit modelling	Albedo and Infra-red	n/a	Albedo and Infra-red	Albedo	Albedo and Infra-red
Atmospheric density model	No explicit modelling	msise00	NRLMSISE-00, drag, lift	msise90	DTM2000	MSISE-90
Radiation pressure coefficient	No explicit modelling	Fixed 1 coefficient to 1.0	1 per arc (estimated)	Fixed	1 per arc (estimated)	1 per arc (estimated)
Drag coefficients	No explicit modelling	1 per arc (estimated)	1 per arc (estimated)	1 per day (estimated)	1 per arc (estimated)	1 per arc (estimated)
1/rev empiricals	n/a	16 sets in along-track and cross-track direction (constant/sine/cosine)	n/a	18 sets in along-track and cross-track direction (constant/sine/cosine)	In along-track and cross-track directions (sine/cosine)	2 sets in along-track and cross-track direction (sin/cosine)
Other empiricals	Piecewise constant empirical accelerations in R,S,W, every 6 min	n/a	Constant empirical accelerations in RTN at 10 min intervals	n/a	Constant empirical accelerations in radial, cross-track and along-track every 10 min (daily biases removed)	Stoch. velocity changes every 15 min
GPS Parameters						
Phase ambiguities	Estimated (integer)	Estimated (integer)	Estimated (integer)	Estimated (float)	Estimated (integer)	Estimated (integer)
GPS orbits & clocks	Fixed (CODE repro/final products(*))	Fixed (CODE repro/final products(**))	Fixed (CODE repro/final products(**))	Fixed (ESOC COP Final)	Fixed (JPL Final / IGS14)	Fixed (CODE repro/final products(**))

(*) The CODE repro products have been used for the interval of time between the start of the mission until 31/12/2018, whereas the CODE final products have been used on 2019/2020.

(**) The CODE repro products have been used for the interval of time between the start of the mission until 31/12/2019, whereas the CODE final products have been used on 2020. The CODE final products have also been used from 9th June to 7th September (both included) 2019 due to a problem with the reprocessed products.

Sentinel-1 POD solutions – data processing summary

Differences to be highlighted

Analysis	CPOD (CPOR)	DLR (DLRR)	ESOC (ESOC)	TU Delft (TUDF)	TUM (TUMM)
Software name and version	Bernese GNSS Software v5.3	NAPEOS	GHOST 2276	NAPEOS 4.2.1	GIPSY-X (v1.5)	Bernese GNSS Software v5.3 (mod)
Arc lengths	24 h	32 h	30 h	30 h	30 h	30 h
Gravity						
Gravity field (static)	GOCO05s (120x120)	EIGEN.GRGS.RL04 TVG (120x120)	GOCO03S (100x100)	EIGEN.GRGS.RL04.MEAN-FIELD	EIGEN.GRGS.RL04.MEAN-FIELD (200X200)	EIGEN GL04C (120x120)
Gravity field (time	AIUB provides fully empirical modelling of non-gravitational forces	Drift/annual/semi-annual terms up to degree/order 90	n/a	Drift/annual/semi-annual terms up to degree/order 80	Drift/annual/semi-annual terms up to degree/order 90	Drift of 20, 30, 40
Ocean tides		FES2014 (100x100)	FES2004	EOT11a (50x50)	FES2004	FES2004 (50x50)
Atmospheric grav		AOD1B RL06 (100x100)	n/a	AOD1B RL06 (100x100)	AOD1B RL06 (180x180)	None
Atmospheric tides		AOD1B RL06 (100x100)	n/a	Ray-Ponte 2003	n/a	None
Surface Forces and Empirical parameters						
Radiation pressure model	No explicit modelling	Box-wing model	Box-wing model	Box-wing model	Box-wing model	Box-wing model
Earth radiation	No explicit modelling	Albedo and Infra-red	n/a	Albedo and Infra-red	Albedo	Albedo and Infra-red
Atmospheric density model	No explicit modelling	msise00	NRLMSISE-00, drag, lift	msise90	DTM2000	MSISE-90
Radiation pressure coefficient	No explicit modelling	Fixed 1 coefficient to 1.0	1 per arc (estimated)	Fixed	1 per arc (estimated)	1 per arc (estimated)
Drag coefficients	No explicit modelling	1 per arc (estimated)	1 per arc (estimated)	1 per day (estimated)	1 per arc (estimated)	1 per arc (estimated)
1/rev empiricals	n/a	16 sets in along-track and cross-track direction (constant/sine/cosine)	n/a	18 sets in along-track cross-track direction (constant/sine/cosine | ESOC and TUDF are using different GPS products cross-track sine)	2 sets in along-track and cross-track direction (sin/cosine)
Other empiricals	Piecewise constant empirical accelerations in R,S,W, every 6 min	n/a	Constant accelerati min interv	ESOC provides single ambiguity-float solution	dial, cross-track and along-track every 10 min (daily biases removed)	Stoch. velocity changes every 15 min
GPS Parameters						
Phase ambiguities	Estimated (integer)	Estimated (integer)	Estimated (integer)	Estimated (float)	Estimated (integer)	Estimated (integer)
GPS orbits & clocks	Fixed (CODE repro/final products(*))	Fixed (CODE repro/final products(**))	Fixed (CODE repro/final products(**))	Fixed (ESOC COP Final)	Fixed (JPL Final / IGS14)	Fixed (CODE repro/final products(**))

(*) The CODE repro products have been used for the interval of time between the start of the mission until 31/12/2018, whereas the CODE final products have been used on 2019/2020.

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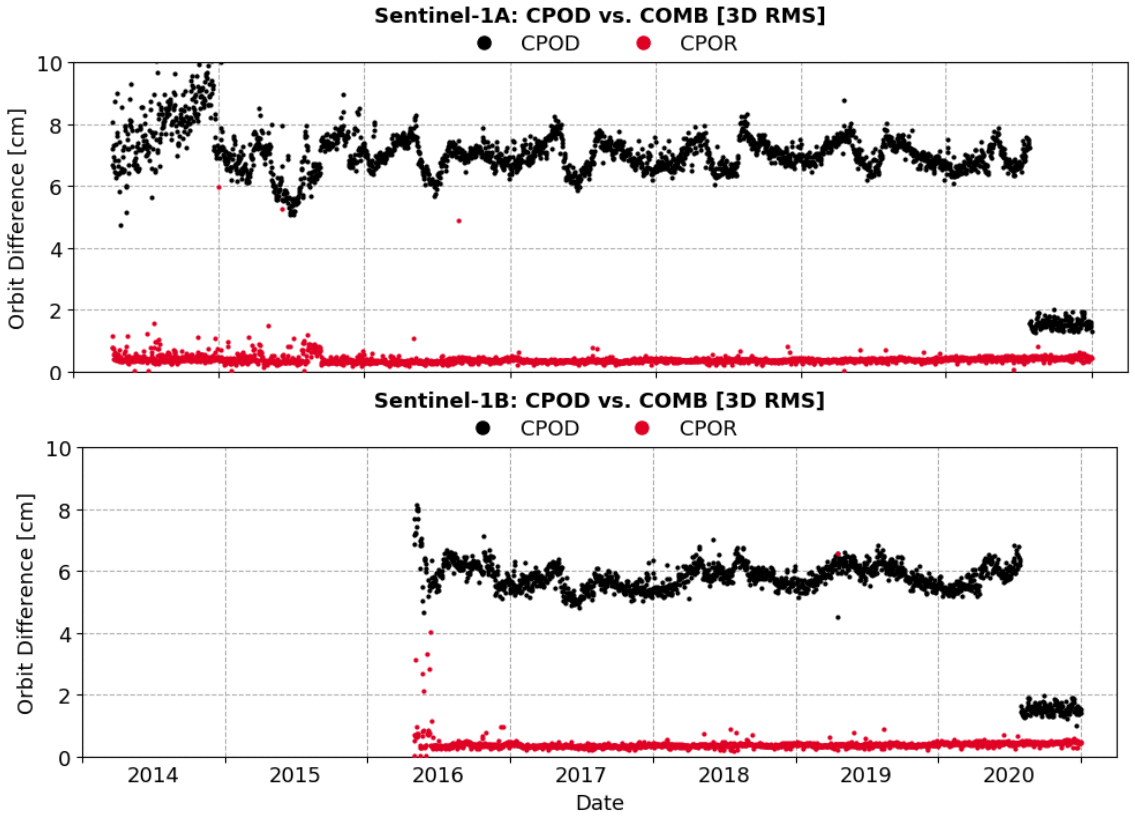
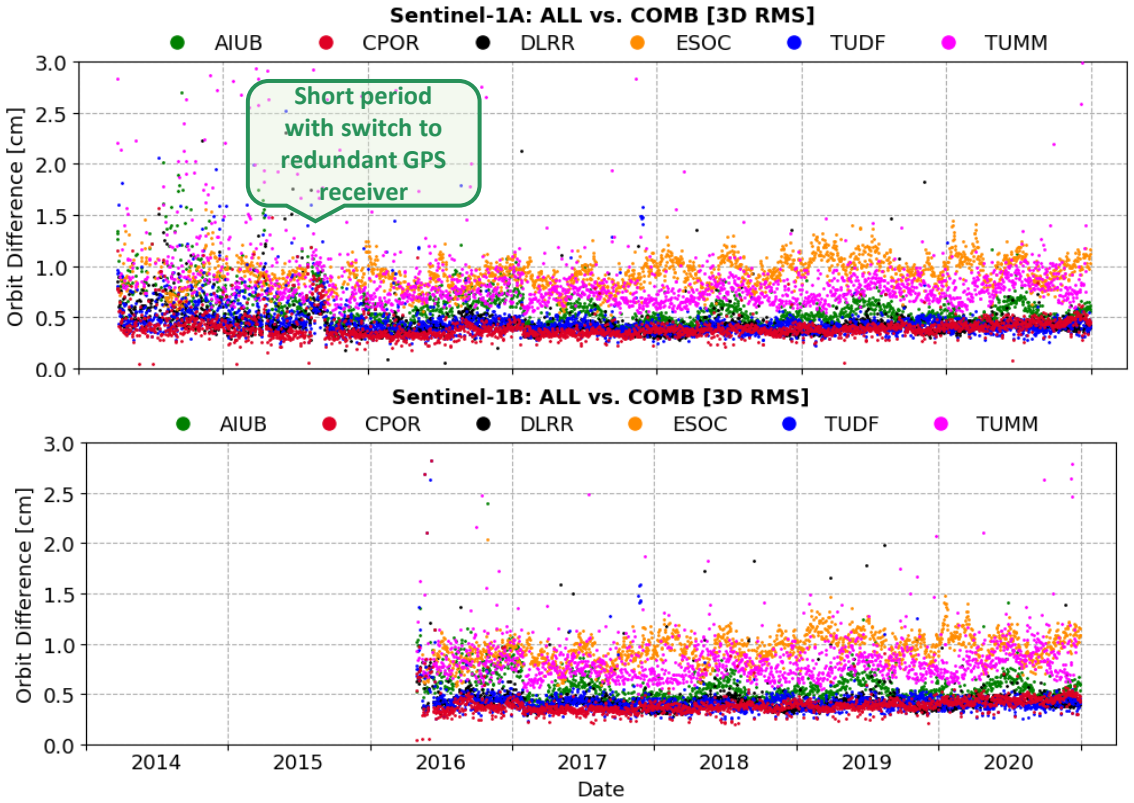
Sentinel-1 reprocessing – orbit comparison – old => new



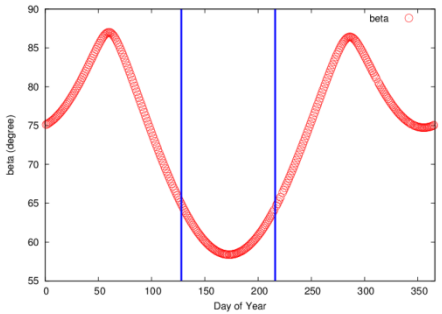
Comparison of combined (based on all reprocessed orbit solutions) vs. operational (**CPOD**) and reprocessed (**CPOR**) orbit solution shows large impact of the correction of the GPS antenna reference point and phase center offsets (done in mid-2020)

=> Need for reprocessing is more than obvious!

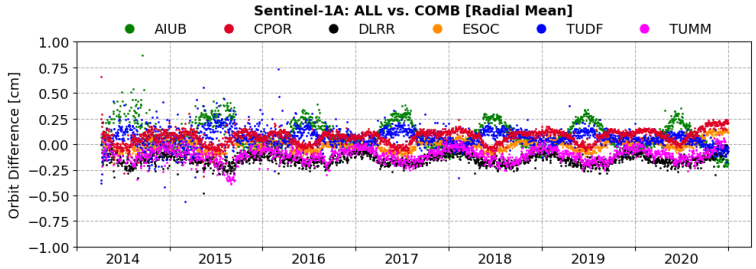
Sentinel-1 reprocessing - orbit comparison – 3D RMS

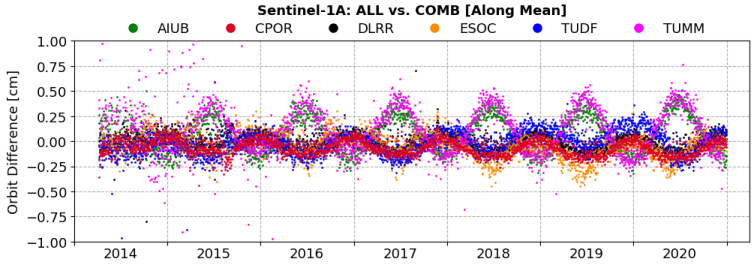


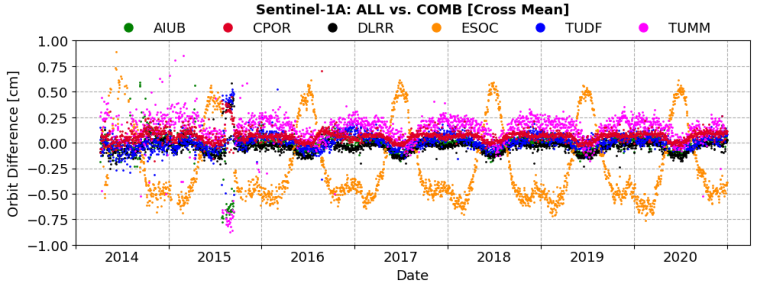
- Comparison of all vs. combined orbit solutions shows an extremely high consistency below 1.5 cm for most of the time.
- Outliers are mainly due to data gaps and manoeuvres, which are handled differently from the groups.
- Seasonal variations dominate orbit differences (eclipse season in summer)



Sentinel-1 reprocessing - orbit comparison – mean diff





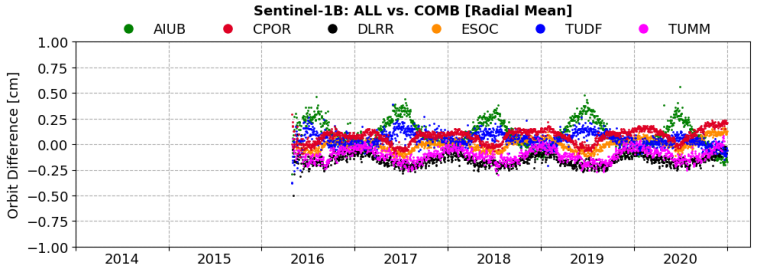


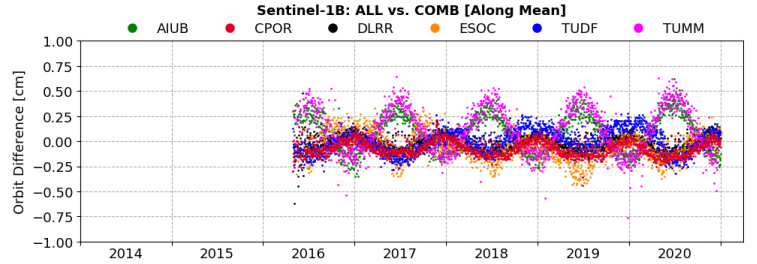
Seasonal differences are visible in all components

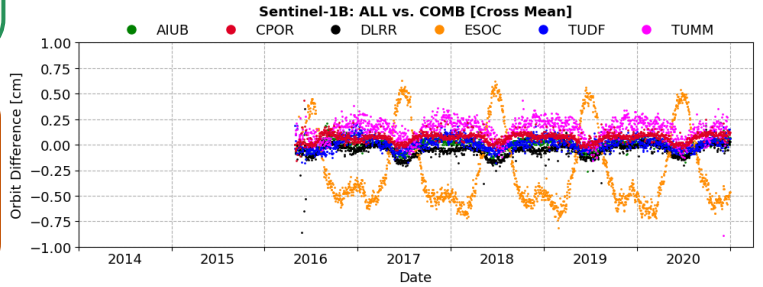
Eclipse season mid-year is more pronounced in radial and along-track direction

ESOC (ambiguity-float) solution shows prominent cross-track mean differences

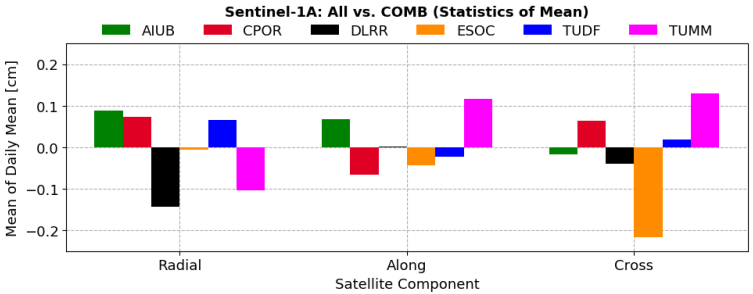
Sentinel-1 has a complex satellite structure => further investigations on the satellite macro model are needed.

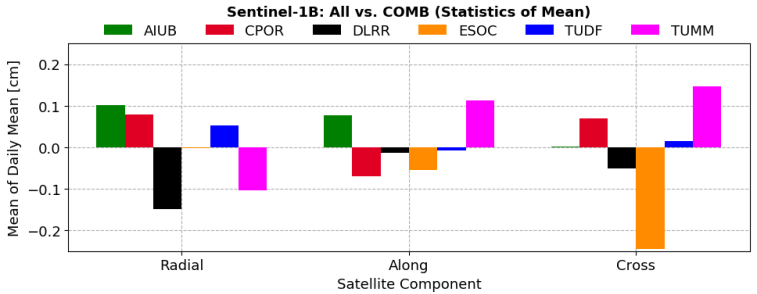


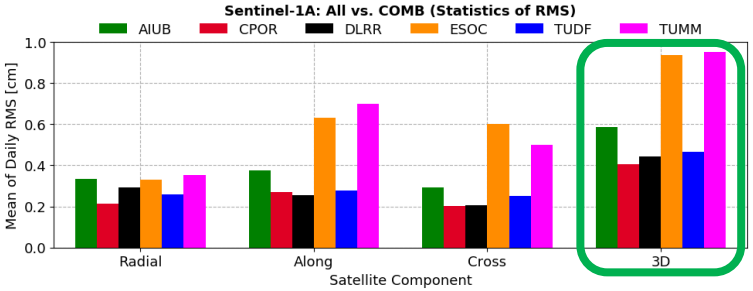


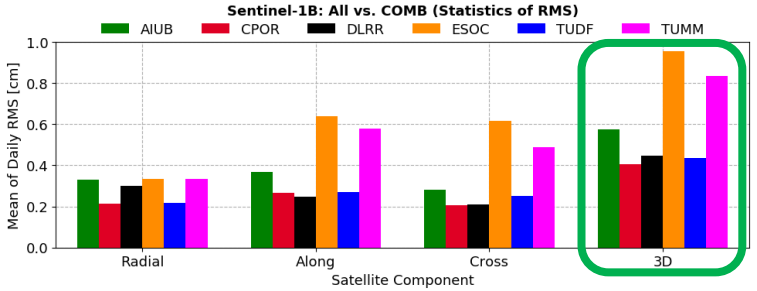


Sentinel-1 reprocessing - orbit comparison







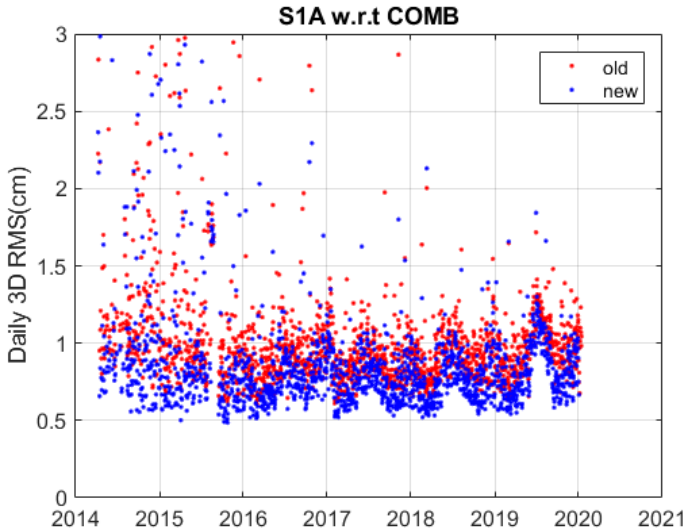


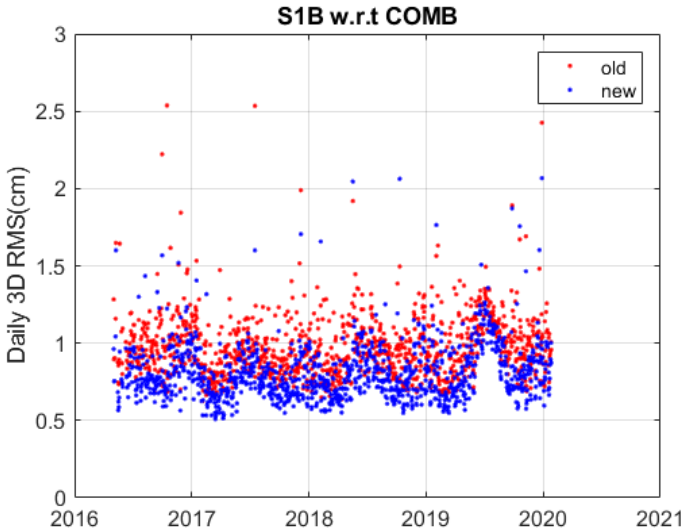
- Despite seasonal systematic differences the overall mean differences are within ± 2 mm.
- The **mean 3D RMS** over the entire mission times for both satellites are **below 1 cm** for all orbit solutions

⇒ Very high consistency of all orbit solutions

⇒ Orbit accuracy requirement of < 5cm 3D RMS w.r.t. external orbit solutions is fulfilled with large margin.

Sentinel-1 reprocessing – updated orbit solutions





- TUM recently updated the reconstruction of the GPS orbit positions in their processing to be more consistent with the original GPS orbit modelling for the CODE GPS orbit products.
- This update led to a significant improvement of the TUM S-1 reprocessed orbit solutions in comparison to the combined orbit.

➢ Not only the Sentinel-1 orbit modelling has to be looked at but also the reconstruction of the GPS satellite positions is important

Summary and Conclusion

- A full mission reprocessing of the precise orbit products has been performed for the two Copernicus Sentinel-1 satellites (in orbit since April 2014 & 2016, respectively).
- Several model and orbit parameter updates during the last years and, in particular, a correction of the GPS antenna reference point and phase center offsets made this reprocessing necessary.
- Orbit validation and quality control is done based on comparison to external orbit solutions delivered by members of the Copernicus POD QWG.
- Although basic input data and settings have to be agreed it is also important to have multiple s/w packages and orbit determination approaches available for validation.
- Small systematic and seasonal variations in the orbit differences are still present. Further investigations on the satellite macro model are needed to even improve the orbit solutions.
- **Reprocessed Sentinel-1 orbit solutions from the Copernicus POD Service are available on the Copernicus Data Hub =>**

  https://sentinel.esa.int/web/sentinel/-/copernicus-sentinel-1a-and-1b-precise-orbital-products-currently-available-for-the-entire-mission/1.2

- More information about the reprocessing may be found at https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-1-sar/pod/documentation => Sentinel-1 Full Mission Reprocessing (2021).pdf

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References

[1] Fernández J., Escobar D., Águeda F., and Féménias P. (2014): Sentinels POD Service Operations, SpaceOps 2014 Conference, SpaceOps 2014 Conference, 5–9 May 2014, Pasadena, CA, doi:10.2514/6.2014-1929.

[2] Peter H., Jäggi A., Fernández J. et al. (2017): Sentinel-1A – First precise orbit determination results, Adv Space Res 60, 879-892, doi:10.1016/j.asr.2017.05.034

[3] Peter H., Fernández J., and Féménias P. (2018): Improved box-wing modelling for the low Earth orbiting Sentinel satellites, presented in session PSD.1 at 42nd COSPAR Scientific Assembly, 14–22 July 2018, Pasadena, CA, USA, available at: https://www.cospar-assembly.org/abstractcd/COSPAR-18.

[4] Fernández J., Calero E., Peter H., and Féménias P. (2019): Copernicus POD Service – Reprocessing of the Copernicus Sentinel-1,-2,-3 orbits, Vol.21, EGU2019-8946, EGU General Assembly 2019.

[5] Peter H., Fernández J., and Féménias P. (2020): Copernicus Sentinel-1 satellites: sensitivity of antenna offset estimation to orbit and observation modelling, Adv. Geosci. 50, 87-100, doi:10.5194/adgeo-50-87-2020.