Sentinel-3A/3B orbit determination using non-gravitational force modeling and single-receiver ambiguity resolution

EGU2020-16611
European Geosciences Union
General Assembly 2020
04 May - 08 May 2020, Sharing Geoscience Online

Xinyuan Mao[1*], Daniel Arnold[1], Valère Girardin[2], Arturo Villiger[1], Adrian Jäggi[1]

1. Astronomical Institute, University of Bern, Bern, Switzerland
2. The Space Transportation directorate of the European Space Agency, Paris, France

Introduction

Sentinel-3 is a designated European Space Agency (ESA) Earth observation satellite formation devoted to oceanography and land-vegetation monitoring. Currently two identical satellites are flying at a circular sun-synchronous orbit with an altitude of about 800 km. Their prime onboard payload systems, e.g. radar altimeter, necessitate high-precision orbits, particularly in the radial direction. This can be fulfilled by using the collected measurements from the onboard dual-frequency high-precision 8-channel Global Positioning System (GPS) receivers. The equipped laser retro-reflector allows for an independent validation to the orbits.

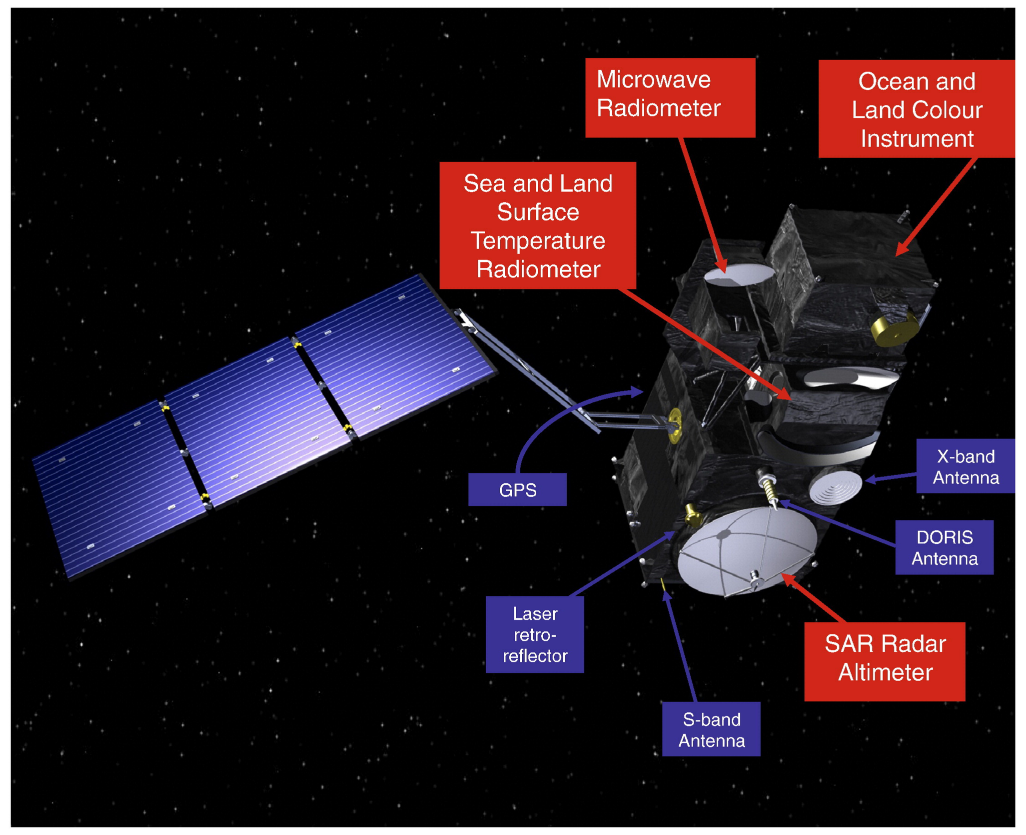

Figure 1: Artist's image of a Sentinel-3 satellite and its prime payloads (credits:ESA).

This research outlines the recent Low Earth Orbiter (LEO) Precise Orbit Determination (POD) methodology developments at the Astronomical Institute of the University of Bern (AIUB) and investigates the POD performances for the two Sentinel-3 satellites. LEO POD based on the Bernese GNSS Software (BSW) was advanced by two main developments: on the one hand, use is made of the GNSS Observation-Specific Bias (OSB) products provided by the Center for Orbit Determination in Europe (CODE), allowing for the resolution of GNSS carrier phase ambiguities for single-receiver (Schaer et al. 2020). On the other hand, a refined satellite non-gravitational force modeling strategy is constructed to reduce the amount of empirical parameters used to compensate force modeling deficiencies. The latter is the focus of this research.

Orbit Solutions

In BSW, a kinematic (*KN*) LEO orbit is described as an epoch-wise trajectory fully independent of force models, whereas a dynamic orbit heavily relies on them. A reduced-dynamic orbit draws a compromise and reduces the strengths of force models using constant and/or periodic empirical accelerations, and the so-called pseudo-stochastic parameters, e.g., Piecewise Constant Accelerations (PCA) (Jäggi et al. 2006). The equation of motion for this nominal (*NM*) reduced-dynamic orbit is given by,

$$\ddot{\vec{r}} = -GM\frac{\vec{r}}{r^3} + \vec{f}(t, \vec{r}, \dot{\vec{r}}, Q_1, ..., Q_d, P_1, ..., P_s) \qquad (1)$$

where, $\vec{r}$ is the geocentric position vector of the satellite center of mass; GM represents the gravitational constant of the Earth; $Q_1, ..., Q_d$ indicate d empirical parameters that are often set as constant accelerations in three directions; a total of s PCA (P) are characterized by the a priori statistical properties, e.g. a priori variances σ_p and spacing time τ, which is fixed to 6 mins in this research. In addition, non-gravitational force models will minimize the heavy dependence on those empirical parameters. The constant accelerations are completely replaced and the PCA can be more tightly constrained towards zeros. The reduced-dynamic orbit based on non-gravitational force models is marked as *NG*.

Poster compiled by Xinyuan Mao, April 2020
Astronomical Institute, University of Bern, Bern
xinyuan.mao@aiub.unibe.ch

Table 1: Four satellite orbit solutions generated in this research (Note that the PCA settings align in the radial/along-track/cross-track directions).

Solution	Ambiguity	Const. acc.	PCA (σ_p, nm/s^2)	Ngrv
FAKN	Float	No	No	No
IAKN	Integer	No	No	No
IANM	Integer	Yes	Yes (5.0/5.0/5.0)	No
IANG	Integer	No	Yes (0.5/0.5/0.5)	Yes

Conventionally, the associated orbit solutions (*KN*, *NM*, *NG*) are computed using the zero-difference GPS observations and the ambiguities remain as float values (*FA*). Since the GPS week 2004 (3/Jun/2018), CODE has been routinely generating the GNSS OSB products, which allows for undifferenced ambiguity resolution and enable BSW to generate an integer ambiguity (*IA*) orbit solution (Schaer et al. 2020).

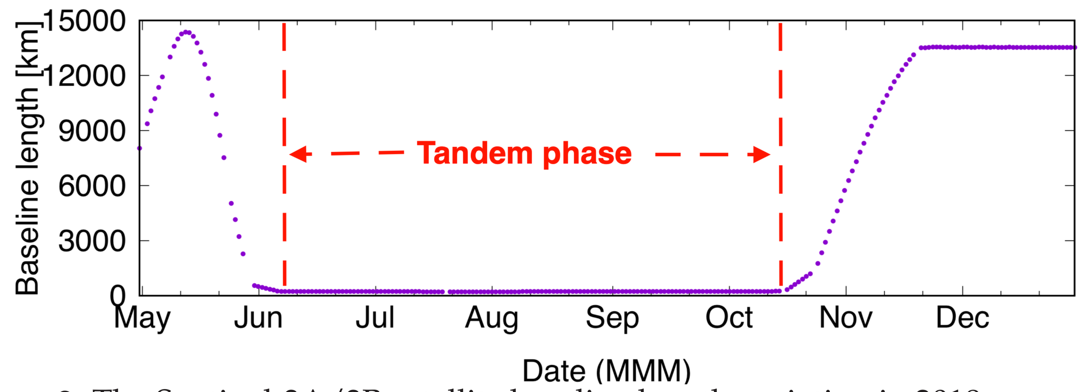

Figure 2: The Sentinel-3A/3B satellite baseline length variation in 2018.

A test period is selected from 7/Jun/2018 to 14/Oct/2018 (Day of Year: 158-287), when the two Sentinel-3 satellites operated in a tandem formation maintained at a separation of about 30 s. This ensures nearly identical in-flight environment for both satellites and thereby enables direct POD performance comparisons.

Non-gravitational Force Models

The non-gravitational forces profile used in Equation 1 can be given by,

$$\vec{f}_{Ngrv} = S_{SRP}\vec{f}_{SRP} + \vec{f}_{REF} + \vec{f}_{EMT} + S_{AF}\vec{f}_{AF} \qquad (2)$$

where, Solar Radiation Pressure (SRP), Earth REFlectivity (REF) and EMissiviTy (EMT) radiation pressure, and Aerodynamic Force (AF) are surface forces acting on the satellite. This research uses a description of the Sentinel-3 satellites in terms of an 8-plate macro-model (Montenbruck et al. 2018). SRP and AF, are scaled by factors S_{SRP} and S_{AF} that are co-estimated in POD.

Table 2: Overview of the non-gravitational force models (Mao et al. 2020).

Aerodynamic Force	Plate-wise lift and drag DTM-2013 atmospheric density model HWM-14 horizontal wind model Goodman accommodation coefficients Scale factor
Solar Radiation Pressure	Plate-wise direct pressure Spontaneous thermal re-emission for non-solar panels Conical Earth and Moon shadow Coefficients for optical radiation Scale factor
Earth Radiation Pressure	Plate-wise reflectivity and emissivity radiation pressure Spontaneous thermal re-emission for non-solar panels Coefficients for optical and infrared radiation Monthly grids based on CERES-S4 radiosity products Interpolation between neighboring monthly grids

Fig.3 shows that SRP is the dominating non-gravitational force for Sentinel-3 due to the large solar panels. AF modeling at this fairly high orbit is close to negligible. The Earth radiation pressure (REF and EMT) mostly projects onto the radial direction and causes a discrepancy of more than 30 nm/s^2 w.r.t the empirical accelerations estimated in the *NM* solution. This suggests orbit shift in the radial direction.

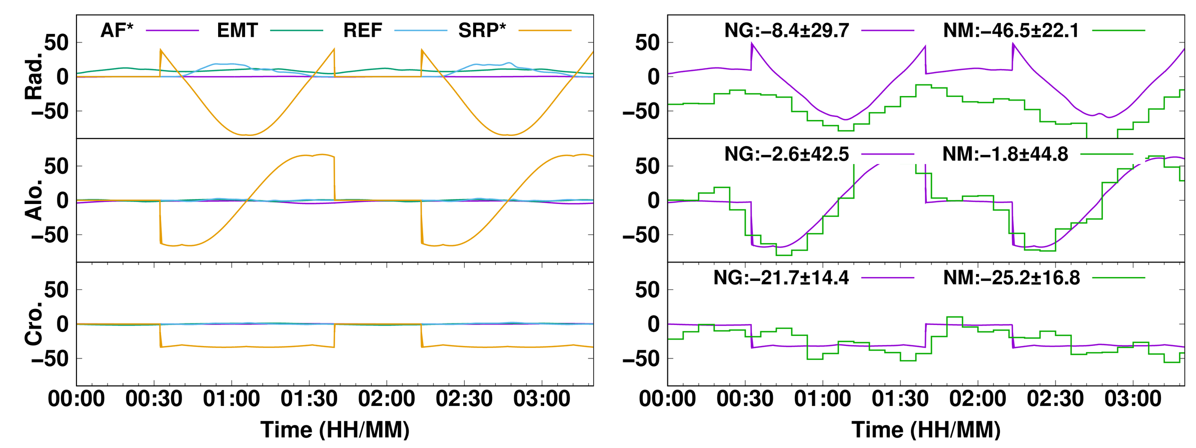

Figure 3: Non-gravitational force modeling for the Sentinel-3A satellite during its first two orbit revolutions on 7/Jun/2018. Left: Each modeled force in the *NG* orbit solution, SRP and AF are scaled. Right: Comparison between the sum of all modeled forces and the empirical acceleration estimates in the *NM* solution. Similar trend also happens to the Sentinel-3B satellite. Unit: [nm/s^2].

Internal Consistency Check

The scale factor estimates for AF and SRP are depicted in Fig.4, which first indicates an over-performed modeling of AF. This is caused by a high orbit and often atmospheric density models are over-performing during the low solar activity seasons. It is interesting to see that the scale factors for SRP slightly differ between the two satellites. Beside that, the *IANG* orbit solution significantly impacts on the scale factors by introducing more geometry constraints, particularly for the Sentinel-3A satellite.

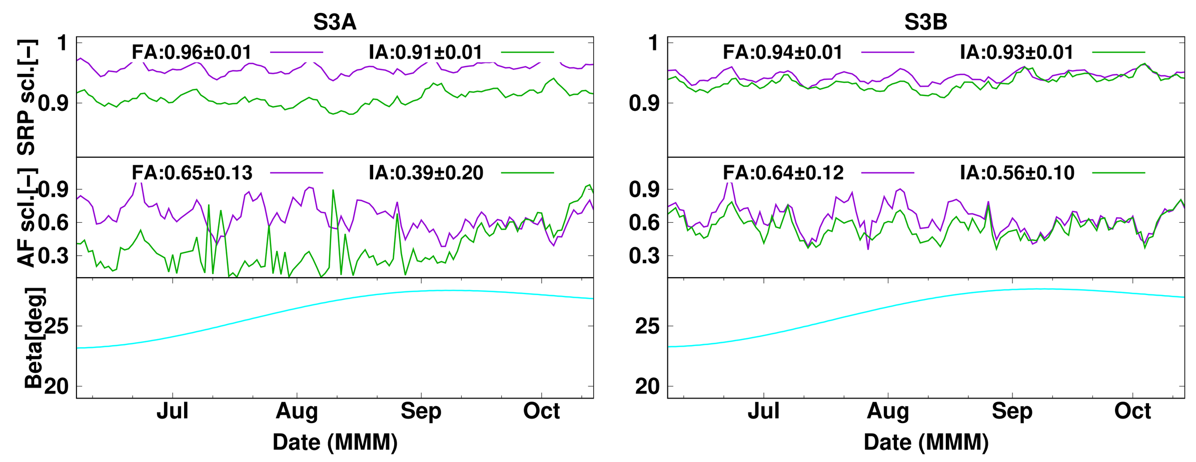

Figure 4: The SRP (top) and AF (middle) scale factors for the Sentinel-3A (left) and -3B (right) satellites. The satellite beta angle (elevation of the Sun above orbital plane) is depicted at bottom.

Fig.5 shows clear orbit shifts due to the non-gravitational force modeling strategy. In addition, the integer ambiguity resolution further constrains orbits in particularly the cross-track direction, agreeing well with the conclusions in (Montenbruck et al. 2018).

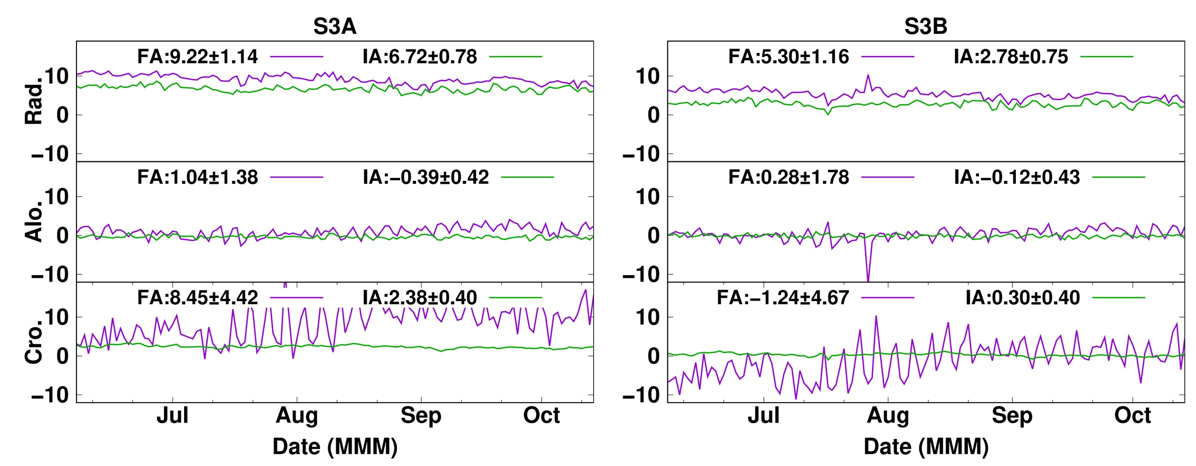

Figure 5: Orbit comparison between the *NG* orbits and their corresponding kinematic orbit for the two satellites. Unit: [mm].

Satellite Laser Ranging Validation

The independent Satellite Laser Ranging (SLR) measurements are used to validate our orbit solutions. Tab.3 and Fig.6 show that the SLR validation residuals decrease significantly after first introducing integer ambiguities, and then the non-gravitational force modeling strategy in POD. The former adds more geometry constraints to the orbit and the latter significantly improves the orbit particularly in the radial direction. The best possible orbit precisions are at levels of sub cm for both satellites.

Table 3: Mean and standard-deviation statistics of SLR residuals in the line-of-sight direction and mean offsets for the two Sentinel-3 satellites using normal points collected by 10 selected stations (elevation cut-off angle: 10 deg, outlier screening: 200 mm) (Arnold et al. 2019). Unit: [mm].

Satellite	Orbit	Nr.obs [-]	Mean	STD	Rad.	Alo.	Cro.
S3A	FAKN	12069	-8.22	17.42	-12.54	-1.36	2.13
	IAKN	12069	-5.49	11.73	-8.20	-2.00	0.67
	IANM	12089	-5.57	10.41	-8.33	-1.93	0.38
	IANG	12089	-0.57	9.97	-0.56	-2.32	2.53
S3B	FAKN	13194	-5.83	18.55	-8.49	3.80	6.31
	IAKN	13194	-3.71	11.37	-5.55	3.23	2.58
	IANM	13203	-3.62	9.96	-5.34	3.44	2.46
	IANG	13203	-1.08	9.46	-1.48	3.07	2.24

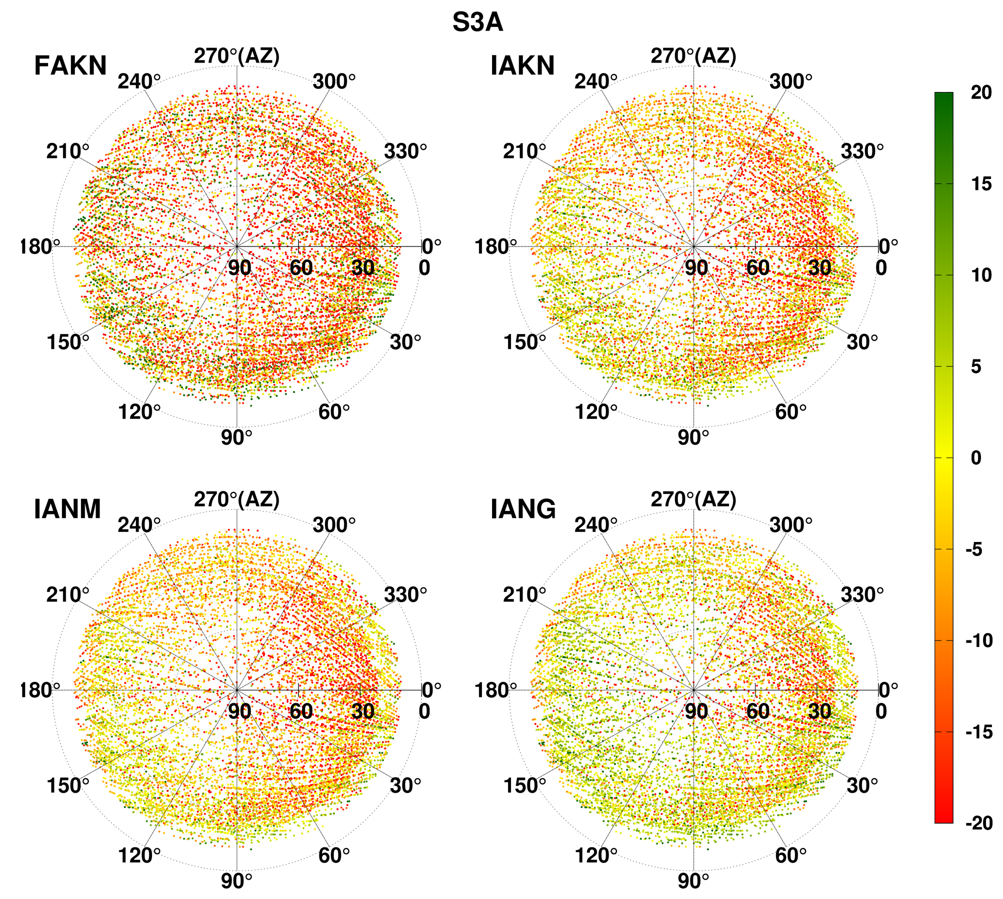

Figure 6: The azimuth- and elevation-dependent SLR residual distributions on sky-plots for the Sentinel-3A satellite. The mean of residuals of the *IANG* solution is the closest to zero. Similar trend also happens to the Sentinel-3B satellite. Note the reference frame is originated from SLR stations. Unit: [mm].

Conclusions

- The single-receiver ambiguity resolution provides significantly more geometry constraints to the orbit solutions.
- The non-gravitational force modeling orbit solution generates the superior orbit quality. In particular the orbit offset in the radial direction is almost mitigated.
- These LEO POD implementations obtain significantly better orbits and are supposed to be released in the new Bernese GNSS Software.

References

Jäggi, A., Hugentobler, U., and Beutler, G. (2006). *Pseudo-stochastic orbit modeling techniques for low-Earth orbiters*. J. Geod., 80(1), 47-60.

Montenbruck, O., Hackel, S., and Jäggi, A. (2018). *Precise orbit determination of the Sentinel-3A altimetry satellite using ambiguity-fixed GPS carrier phase observations*. J. Geod., 92(7), 711-726.

Arnold, D., Montenbruck, O., Hackel, S., and Sośnica, K. (2019). *Satellite laser ranging to low Earth orbiters: orbit and network validation*. J. Geod., 93(11), 2315-2334.

Schaer, S., Villiger, A., Arnold, D., Dach, R., Prange, L., and Jäggi, A. (2020). *The CODE ambiguity-fixed clock and phase bias analysis and their properties and performance*. J. Geod., in preparation.

Mao, X., Arnold, D., Girardin, V., Villiger, A., and Jäggi, A. (2020). *Dynamic GPS-based LEO orbit determination with 1 cm precision using the Bernese GNSS Software*. Adv. Space Res., in preparation.

Contact address

Xinyuan Mao
Astronomical Institute, University of Bern
Sidlerstrasse 5
3012 Bern, Switzerland
xinyuan.mao@aiub.unibe.ch