A star-tracker processor for Sentinel-6: performance and application for radar antenna pitch bias calibration

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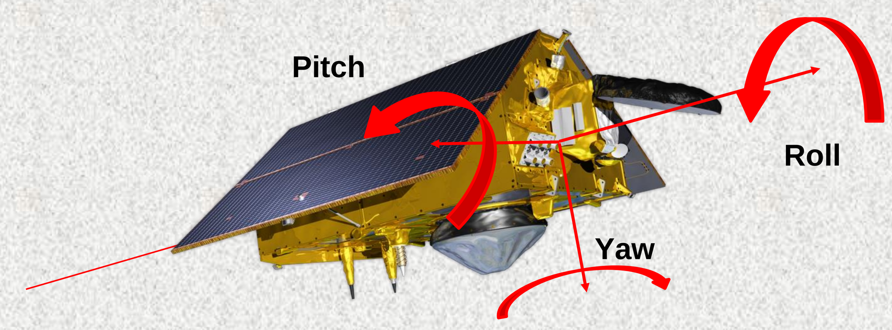
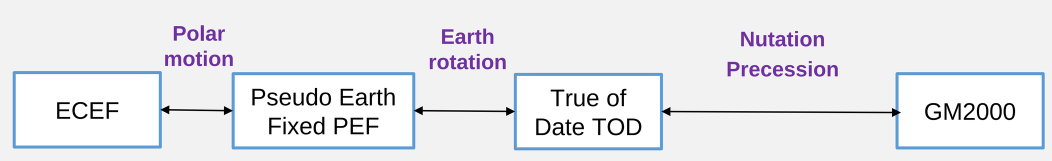


ABSTRACT

In this contribution we present and discuss the overall performance of the star-tracker processor that has been implemented by isardSAT for the Sentinel-6 mission as part of the ESA Sentinel-6 Poseidon-4 (P4) L1 Ground Prototype Processor (GPP). It addresses star-tracker raw measurements on-ground with consolidated orbit data for attitude validation purposes, as well as providing Roll-Pitch-Yaw (RPY) attitude estimates as observed from each star-tracker both independently and in combination. We provide a comparison of the pitch measured by the star-trackers with an independent estimate procured by the radar altimeter, allowing to determine the residual bias in pitch between the star-trackers measurements and the actual radar antenna pointing. Additionally, the long-term variability of thermal loads on the different pitch estimates is discussed.

INTRODUCTION

Earth observation satellites with remote sensing payloads such as altimeters require very precise measurements of their in-orbit 3D orientation (attitude) for accurate antenna pointing. The Copernicus Sentinel-6 satellite includes a suite of 3 star-tracker instruments, which use an internal star reference catalogue to provide attitude estimations with arcsecond accuracy. Estimates are usually provided in quaternions, which allow storing 3-D rotations in a compact way.



The attitude reference frame of a satellite is usually the Satellite Nominal Attitude Frame (SNAF), based on the orbital velocity and the nadir vectors and given in coordinates of an Earth-Centered Earth-Fixed reference (ECEF); the S6 platform attitude is given by the orientation of the Spacecraft Reference Frame (SRF) with respect to SNAF, and the same reference holds for the S6 Poseidon 4 antenna frame. The best-estimate orbital position and velocity of the satellite is required to construct the SNAF, and an inertial reference such as GM2000 is used both as inertial reference for attitude estimations (as complementary to ECEF) and to compute an aberration correction on the attitude coming from the ~37 km/s of speed of the platform with respect of the Solar System barycenter.

THE PROCESSOR

The S6 GPP star-tracker processor is a tool that converts L0 attitude data in quaternion form to platform (SC) and Poseidon 4 (P4) RPY estimates. It uses XML refined orbital files, more precise than the on-board files used to generate the L0 data, and best-estimates of the orientation and disposition of the different reference frames of the satellite as a characterization file.

To begin with, L0 estimates for each STR given in quaternions in inertial GM2000 coordinates are aberration-corrected if required. These are then converted to ECEF coordinates and transformed to the Spacecraft Reference Frame by means of known rotation matrices. Parallelly, using the position and velocity of S6, the SNAF reference in ECEF is constructed. The rotation difference between the SRF and SNAF in a matrix form then represents the satellite/platform attitude.

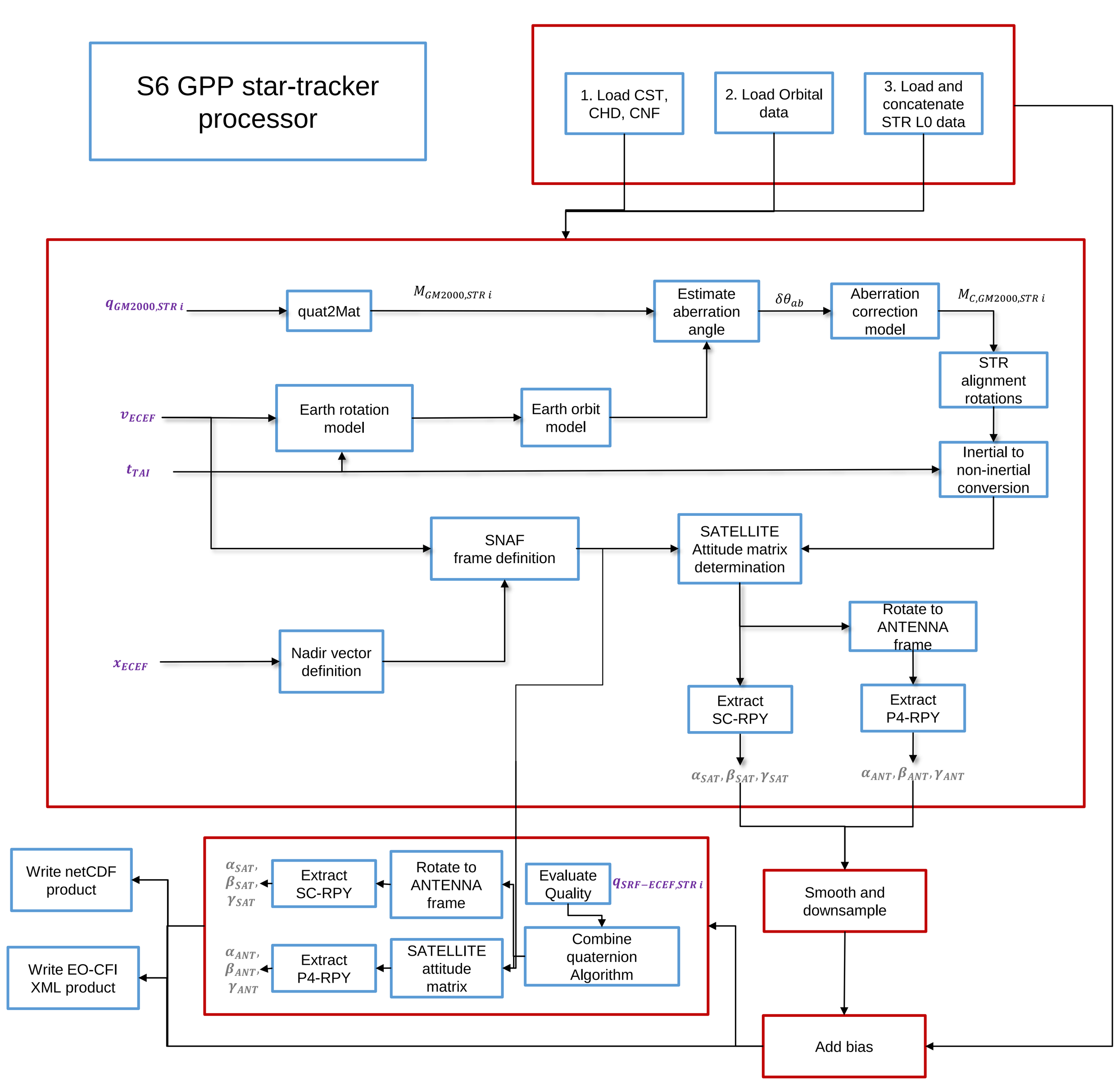


Fig. 1. Layout of operations of the star-tracker processor.

RPY estimates are extracted from these matrices for each STR input, and corresponding pairs in P4 coordinates are also obtained by means of a known mechanical alignment rotation estimate (provided by ESA).

The RPY angles estimated by each STR are given in deg. STR L0 data is originally sampled and processed with a nominal sampling frequency of 10Hz, but the STR processor provides averaged data at 1Hz after downsampling and smoothing.

The processor also provides an additional RPY estimate for the spacecraft and the antenna by adequately merging the quaternion information; STR RPY estimates are re-converted, sorted according to their quality, merged, and then converted back to RPY into a STR-fusion attitude product.

The output are 4 RPY group of angles from both the spacecraft and the P4 antenna; 8 groups in total, a pair for each STR input and one for the STR-fusion. They are provided in a NetCDF product encapsulating other ancillary data and 2 XML files (one for the spacecraft and another for the antenna) complying with the EOCFI convention. A layout of the processor is found in Fig. 1, and a typical P4 RPY example is displayed in Fig. 2.

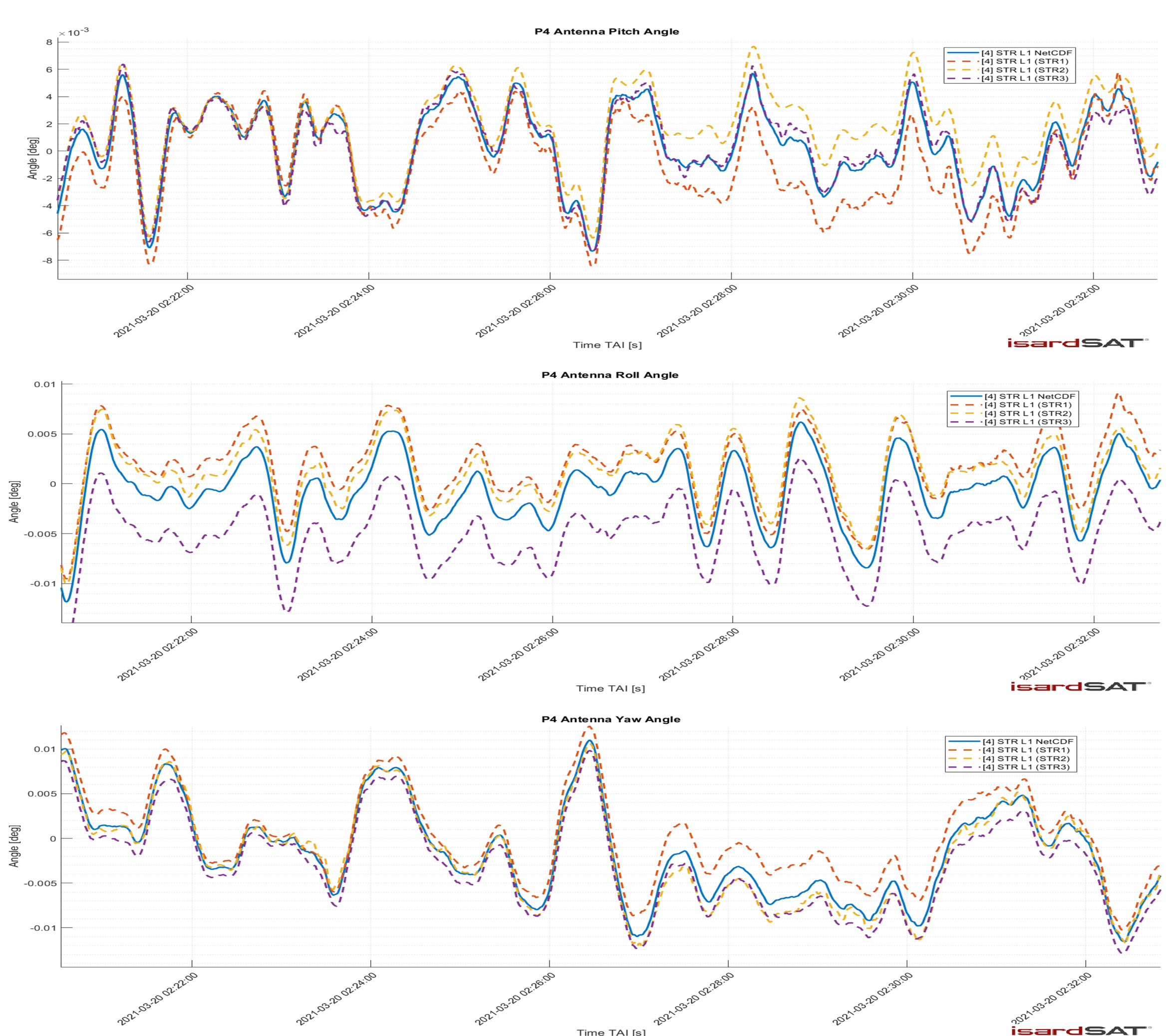


Fig. 2. RPY series from a 3 STR active period on March 20, 2021.

ANTENNA PITCH CALIBRATION

The radar altimeter onboard Sentinel-6 is sensitive to the P4 antenna boresight pitch. This effect is observed in the L1B stack over ocean, where the power of the beams is modulated by the antenna pattern and an eventual pitch shifts the maximum away from the expected zero Doppler beam.

The P4 antenna pattern is usually modelled with a Gaussian function; the expression obtained by integrating in range part of the beams within the stack can be fit with such function. The antenna pitch is found in the location of its maximum.

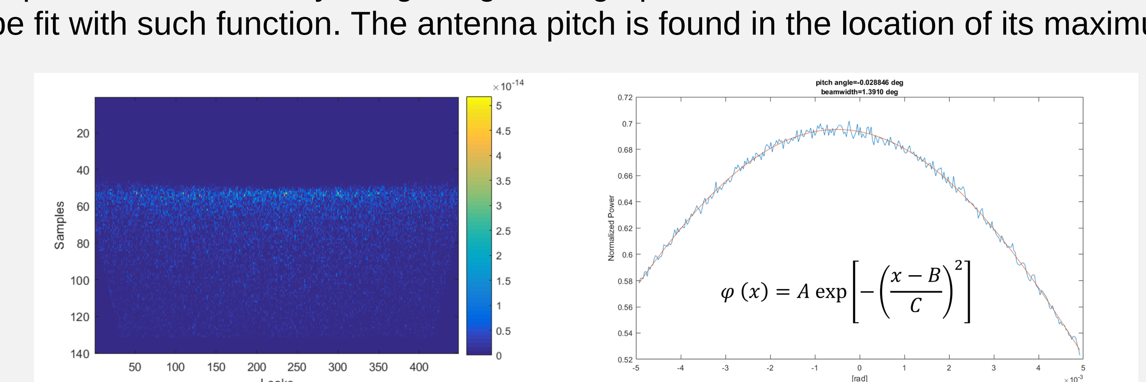


Fig. 3. P4 L1B stack and gaussian fit.

This feature is carefully considered in the GPP processor and allows to generate an independent estimate of the pitch, which serves as a ground truth to calibrate the STR-retrieved pitch estimates. Through dedicated pitch and yaw manoeuvres, antenna pitch and roll biases can be estimated, respectively. Bias in the order of few 10s of mdeg are normally obtained.

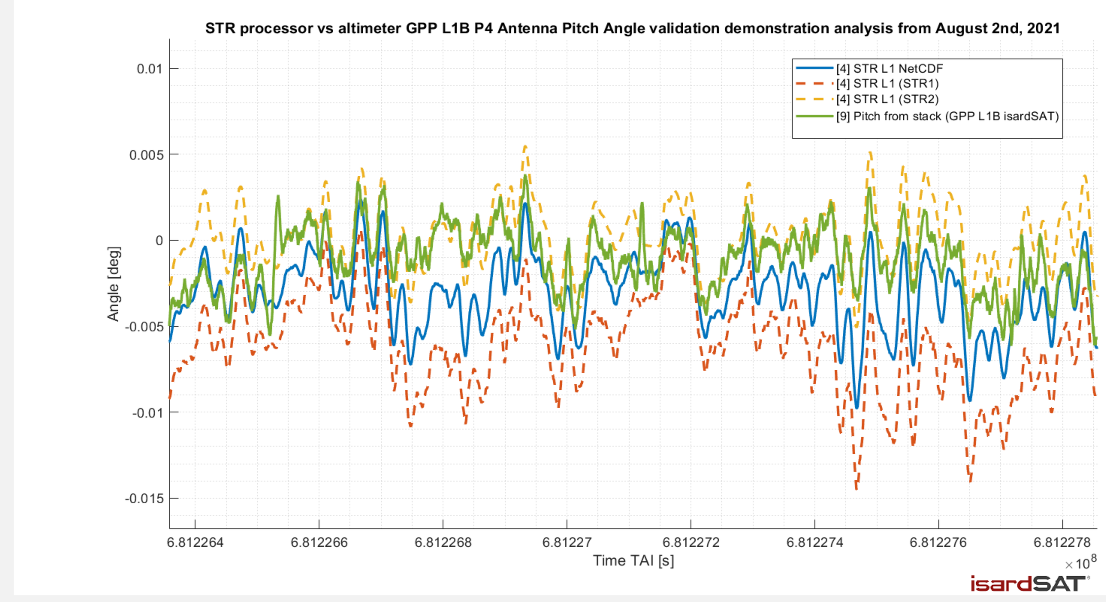


Fig. 4. Comparison of STR processor and altimeter-derived P4 pitch results.

PITCH vs THERMAL VARIATIONS

The Sunlight illumination of the satellite and its star-trackers changes according to the in-orbit position and the Earth's position with respect to the Sun, driving long-term temperature variation cycles. These create a thermoelastic distortion of the star-trackers orientation. In consequence, the attitude determination accuracy of the processor is not constant: there is an evolution of the average RPY values. This long-term evolution appears correlated with the temperature excursions.

The correlation is shown in Fig. 5. A 5-month period of STR processor pitch estimates is shown parallelly with star-tracker detector temperature readings, loaded and processed from housekeeping telemetry. The pitch values have been clipped and smoothed by average moving windows using the orbital period and the terrestrial day period, while the temperature data has been upsampled to match the pitch estimates.

Fig. 5. Long-term P4 pitch evolution correlated with HK detector temperature data.

Quantifying the pitch-temperature evolution can serve to provide a temporal assessment of the processor performance and calibration. One simple approach to this is to calculate coupling factors between each pitch product and each STR temperature in periods of relative stability.

A coupling factor can be regarded as the slope magnitude of a linear regression of the scattered pitch-temperature pair values from a certain period of time; they have been obtained assuming linear behavior between pitch distortion and temperature readout. Fig. 6 displays the results of the coupling factor analysis obtained from the segment corresponding to the first 17 days in Fig. 5. Values up to 0.36 mdeg/ºC are obtained.

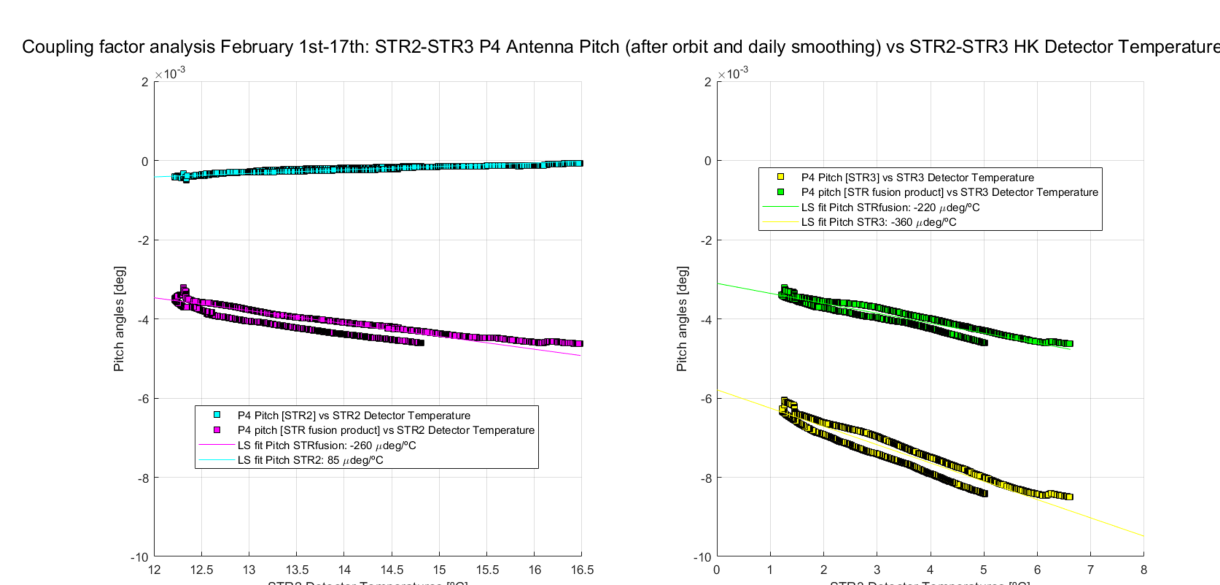


Fig. 6. Coupling factors analysis from the period 1-17 February 2021.

CONCLUSIONS

The S6 P4 L1 GPP star-tracker processor has proven a robust, reliable tool to provide post-processed attitude data to the S6 Michael Freilich mission. It allows STR-independent RPY estimates, providing a framework for relative attitude cross-checks between the star-tracker measurements and other attitude solutions, and includes a series of additional features such as aberration correction. The processor pitch results have been compared to the star-tracker-independent altimeter-derived L1B pitch estimate, which acts as a reference for calibration. Finally, the long-term stability of the P4 attitude pitch has been analyzed and found to be correlated with the varying temperatures of the star-tracker detectors; the first analysis suggest that the relationship can be initially characterized by means of a coupling factor. Future studies will extend this analysis to roll and yaw and longer time series, while also providing long-term pitch calibration using the L1B-derived product.