ESTCube-1 attitude determination: in-flight experience

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Introduction

ESTCube-1 is a one-unit CubeSat launched on May 7, 2013 on board the Vega VV02 rocket [1, 2]. Its primary mission is to perform the first in-orbit experiment of electric solar wind sail (E-sail) technology by measuring changes in the spin rate caused by an ionospheric plasma stream on a charged tether. The E-sail is a propellantless propulsion system concept that uses thin charged electrostatic tethers for turning the momentum flux of a natural plasma stream such as the solar wind into spacecraft propulsion. ESTCube-1 will deploy a 10 m long tether using centrifugal force which is provided by spinning up the satellite to 360 deg·s^{-1}. **The satellite is required to determine the attitude with an accuracy better than 2°.** In order to spin-up the satellite and to estimate the E-sail effect, a precise attitude determination system (ADS) has been developed. The ADS uses three-axis magnetometers, three-axis gyroscopic sensors and two-axis Sun sensors, a Sun sensor on each side of the satellite. The attitude of the satellite is estimated on-board using a Kalman filter. According to pre-launch simulations, the system is able to determine the attitude with an expanded uncertainty (k=2) better than 1.2° [3].

Due to the fact that there is only a single chance to deploy the tether, the ADS has been thoroughly tested and characterised in-orbit to minimise the risk of mission failure. Here we present validation of the ESTCube-1 ADS. The system is validated by comparing the on-board attitude determination results and the attitude determined from on-board images. For both methods we present uncertainty budgets in Tables 1 and 2.

Figure 1 : Images taken by ESTCube-1.

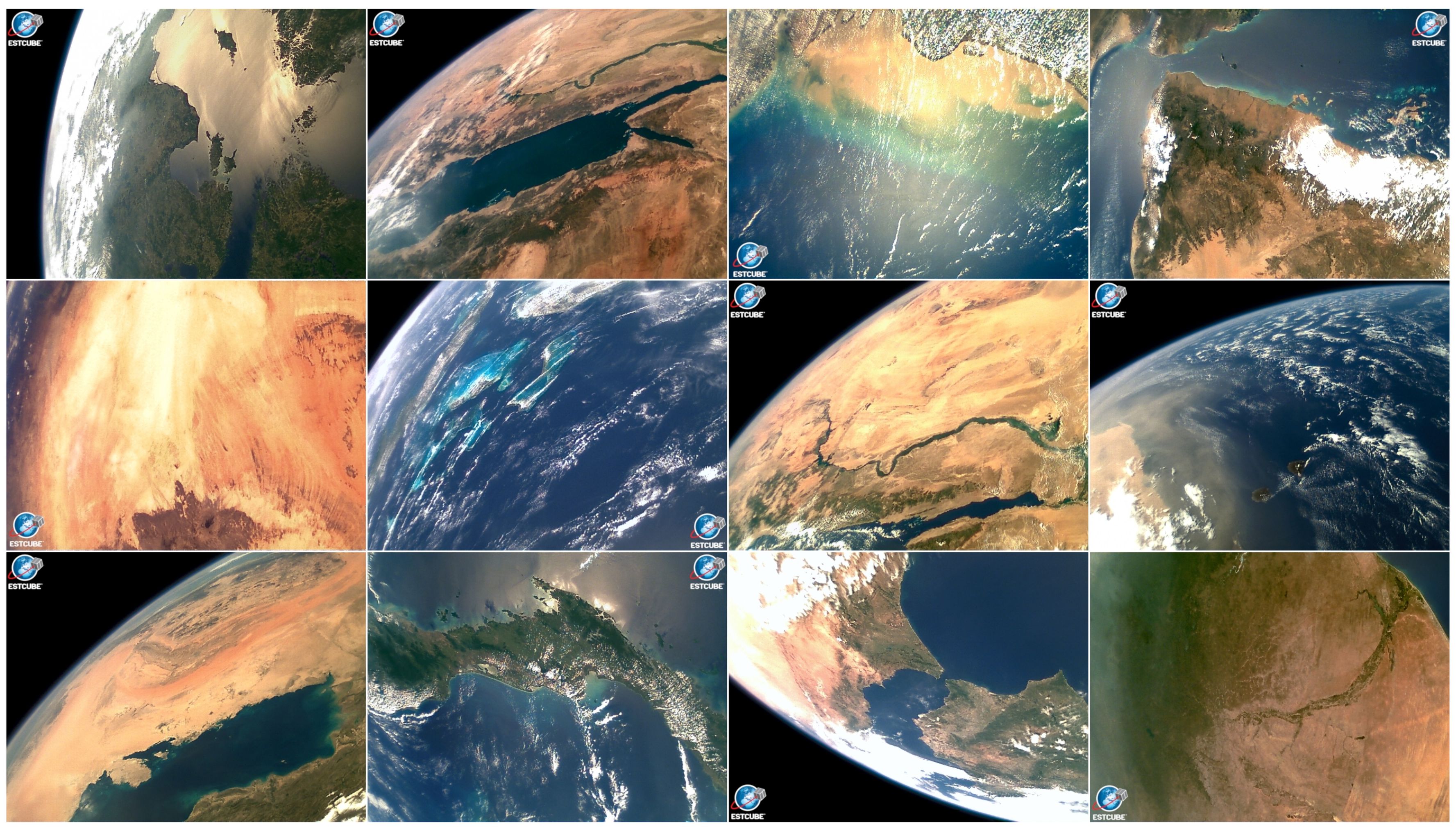

Table 1: On-board attitude determination uncertainty budget

δA_{STD} — Simulation-based uncertainty estimation by standard deviation in parts of the orbit where the experiment will be performed and images are taken [3]
δA_{Sun} — Sun direction model accuracy [4, p. 39]
δA_{Mag} — Magnetic field model accuracy [5]
δA_{Orb} — Orbital model accuracy [6]
δA_{Prec} — Earth spin axis precession [7, p. 27]
δA_{Nut} — Earth spin axis nutation [7, p. 28]

Quantity	Standard uncertainty	Uncertainty contribution, deg
δA_{STD}	0.57°	0.57
δA_{Sun}	0.01°	0.01
δA_{Mag}	390 nT	0.001
δA_{Orb}	6 km	0.13
δA_{Prec}	0.06°	0.06
δA_{Nut}	0.002°	0.002
Combined standard uncertainty		0.6
Expanded uncertainty (95% confidence level, k=2)		**1.2**

Table 2: Image-based attitude determination uncertainty budget

δC_{Res} — Camera resolution
δC_{Lens} — Lens distortion
δC_{Sel} — Point selection uncertainty
δC_{Time} — Time uncertainty

Quantity	Standard uncertainty	Uncertainty contribution, deg
δC_{Res}	0.04°	0.04
δC_{Lens}	0.02°	0.02
δC_{Sel}	0.23°	0.23
δC_{Time}	100 ms	0.4
Combined standard uncertainty		0.5
Expanded uncertainty (95% confidence level, k=2)		**1**

Results

The combined expanded uncertainty (k=2) from both uncertainty budgets is 1.6°. To validate the system, images of the Earth were taken during on-board attitude determination sessions. Images are used as an independent source of the attitude. Differences between the on-board attitude and the attitude from images are presented in the following table.

Sample	1	2	3	4	5	6	7	8
Difference, deg	0.52	0.71	1.96	1.78	1.37	1.74	1.54	1.57
Fulfils mission requirement?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Within uncertainty budget?	Yes	Yes	No	No	Yes	No	Yes	Yes

Conclusions

The ESTCube-1 attitude determination system fulfils the mission requirement to determine the attitude with an accuracy better than 2°. In three samples the difference is slightly bigger then the uncertainty. Most likely it is because δA_{STD}, which is calculated by simulating attitude determination with various disturbances and sensor emulation, does not represent actual sensors and their in-orbit performance. For example, uncertainty of sensors was emulated by applying Gaussian noise to modelled signals without simulating influences like the temperature, the Solar irradiance or the Earth albedo. Uncertainty of on-board attitude determination is also influenced by technical problems of one of the Sun sensors.

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Figure 2 : Artist's impression of the E-sail