Remote Sensing Based Methods to Retrieve UVSQ-SAT Cubesat Attitude to Map the Earth's Radiation Budget.

Adrien Finance[1], Mustapha Meftah[1], Christophe Dufour[1], Thomas Boutéraon[1], and Antoine Mangin[2]

[1]LATMOS Laboratoire Atmosphères, Milieux, Observations Spatiales
[2]ACRI-ST—CERGA

November 24, 2022

Abstract

The terrestrial energy balance represents a measure of the excess energy stored in the climate system. A possible measurement of this variable can be made at the top of the atmosphere by quantifying the imbalance between the incoming solar flux and the outgoing reflected and infrared flux. This is the objective of the UltraViolet and infrared Sensors at high Quantum efficiency on-board a small SATellite (UVSQ-SAT) mission, validating miniaturized technologies on-board a CubeSat with 1U standards (about 11 cm x 11 cm x 11 cm). This satellite was put into orbit in January 2021 by SpaceX's Falcon 9 launcher and is totally functional. In order to measure the various fluxes with accuracy it is necessary to know precisely the orientation of the satellite at each time. Indeed, the knowledge of this orientation makes it possible to dissociate the various fluxes and to correct them from the angle to the considered source (Earth, Sun). To do so, two methods were implemented to retrieve the satellite's attitude based on Sun and Nadir pointing along with inertial measurement unit (IMU) data. To ensure more accurate knowledge of the attitude determination in every configuration (daylight and eclipse), neural networks were implemented based on the available sensors. A multilayer perceptron was thus trained in order to find the orientation of the satellite. Based on the attitude retrieved the different flux were computed at each time from the sensors signals. We present here the development and the outcomes of the neural network applied to in-orbit data recovered from the UVSQ-SAT mission.

Remote Sensing Based Methods to Retrieve UVSQ-SAT Cubesat Attitude to Map the Earth's Radiation Budget.

Adrien Finance[1,2], Mustapha Meftah[1], Christophe Dufour[1], Thomas Boutéraon[1], and the UVSQ-SAT team and INSPIRE-SAT 7 team

(1) LATMOS/IPSL/CNRS/UVSQ, 11 boulevard d'Alembert, 78280 Guyancourt, FRANCE
(2) ACRI-ST---CERGA, 10 Avenue Nicolas Copernic, 06130 Grasse, FRANCE

Contact: Mustapha.Meftah@latmos.ipsl.fr

UMR 8190 - www.latmos.ipsl.fr

Observatoire de Versailles Saint-Quentin-en-Yvelines
CAMPUS DE SAINT-QUENTIN-EN-YVELINES

1 – Abstract

The terrestrial energy balance represents a measure of the excess energy stored in the climate system. A possible measurement of this variable can be made at the top of the atmosphere by quantifying the imbalance between the incoming solar flux and the outgoing reflected and infrared flux. This is the objective of the UltraViolet and infrared Sensors at high Quantum efficiency on-board a small SATellite (UVSQ-SAT) mission, validating miniaturized technologies on-board a CubeSat with 1U standards (about 11 cm x 11 cm x 11 cm). This satellite was put into orbit in January 2021 by SpaceX's Falcon 9 launcher and is totally functional. In order to measure the various fluxes with accuracy it is necessary to know precisely the orientation of the satellite at each time. Indeed, the knowledge of this orientation makes it possible to dissociate the various fluxes and to correct them from the angle to the considered source (Earth, Sun). To do so, two methods were implemented to retrieve the satellite's attitude based on Sun and Nadir pointing along with inertial measurement unit (IMU) data. To ensure more accurate knowledge of the attitude determination in every configuration (daylight and eclipse), neural networks were implemented based on the available sensors. A multilayer perceptron was thus trained in order to find the orientation of the satellite. Based on the attitude retrieved the different flux were computed at each time from the sensors signals. We present here the development and the outcomes of the neural network applied to in-orbit data recovered from the UVSQ-SAT mission.

2 – Introduction

Scientific objective:
There are three components of the Earth Radiative Budget:
- the incoming solar radiation
- the reflected solar radiation
- the outgoing longwave radiation (OLR)

The Earth Energy Imbalance (EEI) is computed from the difference between the incoming and outgoing radiation. It is a metric to quantify climate change. It corresponds to the energy accumulated in the atmosphere per unit of time. Once integrated over a period it corresponds to the amount of energy accumulated from that period (as shown on the Figure 1).
Satellite observation allows retrieval of high-frequency dynamics of the EEI. The UVSQ-SAT satellite is dedicated to the measurements of outgoing terrestrial radiation (shortwave and longwave radiation) that are key to determining the EEI.

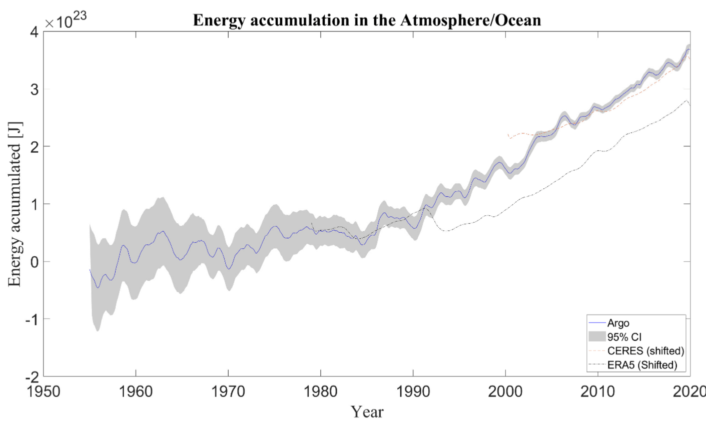

Figure 1: Energy accumulation on Earth.

The UVSQ-SAT mission:
UltraViolet and infrared Sensors at high Quantum efficiency onboard a small SATellite (UVSQ-SAT) also called INSPIRE Sat 5 is a CubeSat that was launched on a Falcon 9 rocket into a Sun-synchronous orbit on the 24th of January 2021.
First results published by Meftah et al. (2021) appear below, they correspond to the outgoing longwave radiation measured by the UVSQ-SAT satellite.

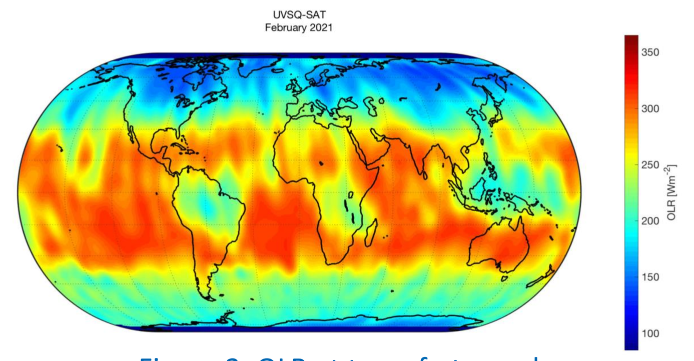

Figure 2: OLR at top-of-atmosphere measured by UVSQ-SAT instruments.

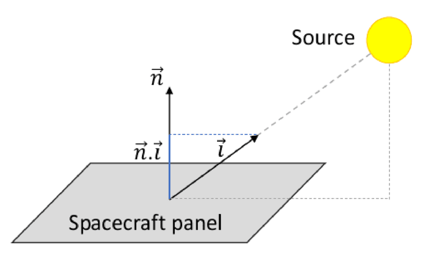

Figure 3: Incidence angle diagram.

UVSQ-SAT main payloads for attitude determination:
- Three-axis gyrometer.
- Three-axis magnetometer.
- Six photodiodes in the visible domain.
- Six Earth radiative sensors (ERS) sensors with an Optical Solar Reflector (OSR).
- Six ERS sensors with carbon nanotubes (CNT).

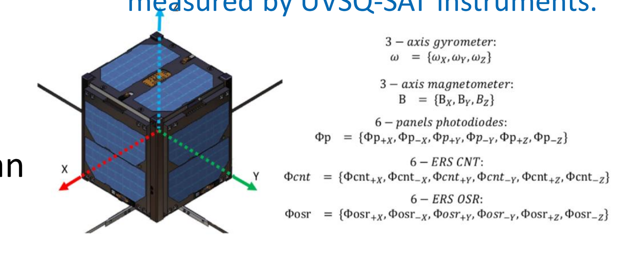
Figure 4: UVSQ-SAT reference frame and instruments.

3 – TRIAD and MEKF methods

The knowledge of the satellite attitude is necessary to determine the different components of the Earth radiation budget as presented by Meftah et al. (2020). Attitude determination can be realized based on different instruments and methods. A global overview of the recent studies (along with the following descriptions of the methods) is presented by Finance et al. (2021b). Two methods have been used. They have an accuracy of 3 degrees in sunlight and 10 degrees in eclipse (at 1 sigma). To improve the results in eclipse we propose the neural network method. This work was initiated by a ground calibration to be able to do a training. However, there were some limitations in the realization of a test in conditions different from those of the orbit. Therefore, we propose to train the neural network in sunlight to improve the accuracy of the nadir determination in eclipse.

Problematic: The main objective is to improve the accuracy of the attitude determination in eclipse.

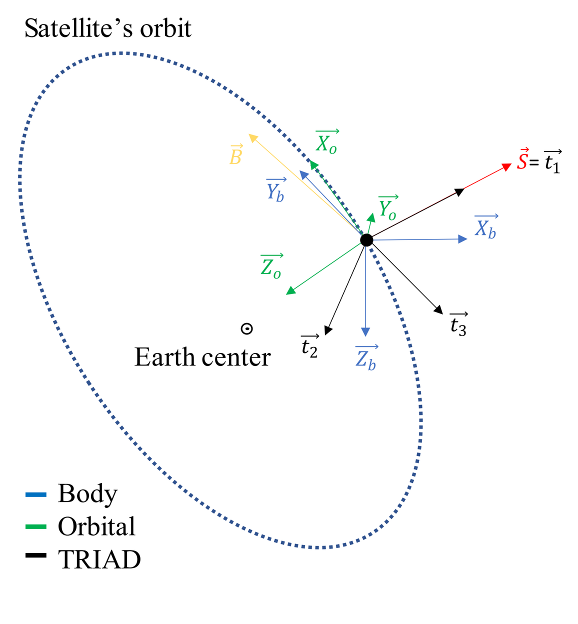

Figure 5: TRIAD reference frame.

Tri-Axial Attitude Determination (TRIAD) method:
The TRIAD method is a determinist and direct method. It consists in creating a new reference frame that can easily be defined from models at the location and time of the satellite. It can also be defined from the measurements onboard the satellite. The magnetometer and photodiodes as Sun sensors are used (or Infrared red sensors for Earth sensors purposes).
- More computationally efficient than other methods.
- Lack of data does not introduce incoherency in attitude determination.
- But it does not include calibration or noise reduction.

Multiplicative Extended Kalman Filter (MEKF) method:
The MEKF method is a recursive method. It consists of the correction of the measurement noise of the instruments by the development of a linearized Kalman filter method.
- Calibrate in real-time the instrument (such as the gyrometer).
- Reduce instrument noise.
- Lack of data introduces divergence of the system and incoherent attitude.

4 – Neural Network Architecture

General method:
The algorithm detailed in this section uses neural networks to predict the UVSQ-SAT attitude based on the instruments onboard and models.
The neural network will be trained based on the attitude determination realized with TRIAD and MEKF methods.
Data processing:
The data processing is realized on-ground. Instruments that can be calibrated are calibrated (based on a magnetic field model for the example of the magnetometer). Once the inputs are available, different methods can be implemented to determine the UVSQ-SAT attitude.
Main objectives:
- To avoid the recursive loop of the Kalman filter
- To improve the accuracy of the attitude determination in eclipse

Inputs and outputs:
- Inputs:
Measurements from the satellite (counting for 136 features)
Data from models at the location and time of the satellite (counting for 6 features)
- Outputs:
Nadir coordinates (counting for 3)
Sun coordinates (counting for 3)

In order to improve the accuracy of attitude determination in eclipse, it is necessary to clearly know what measurements should be used in sunlight, in eclipse and remove the inappropriate ones.
Therefore, features selection is implemented from different techniques:
- Linear regression
- Random Forest regression
- SHapley Additive exPlanations (SHAP)

In sunlight:
- the Sun's direction is computed mostly thanks to the photodiodes.
- the nadir direction appears to be determined mostly from the magnetic field data, photodiodes, and infrared sensors.

Architecture:
A preliminary architecture has been used to obtain the SHAP values described by Shapley (1951). This architecture was presented by Finance et al. (2021a) as tests were realized on-ground before launch. It has been slightly modified since, to allow for a different number of inputs and outputs.
- 5 Hidden fully connected layers
- 143 (max) inputs
- 6 (3 per direction) outputs
- Learning rate of 10−5, determined empirically
- Layers dimensions (width): 143/48/128/256/128/6

Training:
The training of the neural network is done based on results from the TRIAD method for random samples from the first 9 months of data (around 500 000 samples).

5 – First Results and Perspectives

Performance of the UVSQ-SAT Multi-layer perceptron in sunlight:
It is important to mention that the accuracy is estimated based on the TRIAD results and is not absolute accuracy.
Sun vector: 1º (at 1σ) compared to test set.
Nadir vector: 2º (at 1σ) compared to test set.

Results:
Figures representing the performance of the neural network for two different cases. It uses the TRIAD training set based on random samples in the data from launch and the optimized neural network. The continuous blue curve illustrates the ideal case where the observed values exactly match the predicted values.
- Sun's coordinates in sunlight versus the reference coordinates.
- Nadir's coordinates in sunlight versus the reference coordinates.

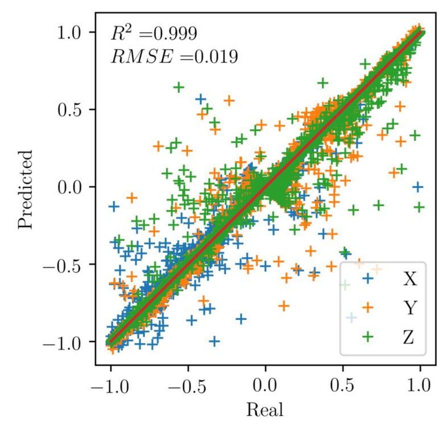

Figure 6: Predicted and real coordinate of the Sun vector in daylight.

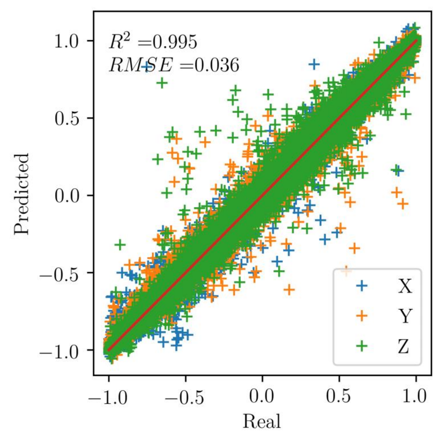

Figure 7: Predicted and real coordinate of the Sun vector in eclipse.

We have tested the ability of the neural network to predict the sun and nadir direction based on the available sensors. Those results are preliminary and allow quantifying the accuracy of the algorithm compared to the values computes from the TRIAD method in sunlight.
Perspectives:

Based on the feature selection presented previously it is possible to select only the information needed for attitude determination in eclipse. Therefore, to train the neural network with only those features in sunlight to improve the attitude determination in eclipse. The methods presented in part 2 are currently used to compute the components of the radiative budget.

Method	Uncertainty (1 σ) Sunlight	Eclipse	Advantage
TRIAD	±3°	±14°	Instantaneous
MEKF	±3°	±10°	Correct noise and calibrate instruments
MLP	±3°*	±3° to ±10°*	Instantaneous and more accurate in eclipse

Figure 8: Attitude determination methods comparison.

References

Hersbach, H, Bell, B, Berrisford, P, et al. The ERA5 global reanalysis. Q J R Meteorol Soc. 2020; 146: 1999– 2049. https://doi.org/10.1002/qj.3803
Loeb, N. G., Doelling, D. R., Wang, H., Su, W., Nguyen, C., Corbett, J. G., Liang, L., Mitrescu, C., Rose, F. G., & Kato, S. (2018). Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Top-of-Atmosphere (TOA) Edition-4.0 Data Product, Journal of Climate, 31(2), 895-918. Retrieved Nov 17, 2021, from https://journals.ametsoc.org/view/journals/clim/31/2/jcli-d-17-0208.1.xml
Cheng, L., & Zhu, J. (2016). Benefits of CMIP5 Multimodel Ensemble in Reconstructing Historical Ocean Subsurface Temperature Variations, Journal of Climate, 29(15), 5393-5416. Retrieved Nov 17, 2021, from https://journals.ametsoc.org/view/journals/clim/29/15/jcli-d-15-0730.1.xml
Meftah, M.; Damé, L.; Keckhut, P.; Bekki, S.; Sarkissian, A.; Hauchecorne, A.; Bertran, E.; Carta, J.P.; Rogers, D.; Abbaki, S.; et al. UVSQ-SAT, a pathfinder cubesat mission for observing essential climate variables. Remote Sens. 2020, 12, 92.
Meftah, M.; Boutéraon, T.; Dufour, C.; Hauchecorne, A.; Keckhut, P.; Finance, A.; Bekki, S.; Abbaki, S.; Bertran, E.; Damé, L.; et al. The UVSQ-SAT/INSPIRESat-5 CubeSat Mission: First In-Orbit Measurements of the Earth's Outgoing Radiation. Remote Sens. 2021, 13, 1449.
Finance, A.; Meftah, M.; Dufour, C.; Boutéraon, T.; Bekki, S.; Hauchecorne, A.; Keckhut, P.; Sarkissian, A.; Damé, L.; Mangin, A. A New Method Based on a Multilayer Perceptron Network to Determine In-Orbit Satellite Attitude for Spacecrafts without active ADCS like UVSQ-SAT. Remote Sens. 2021, 13, 1185.
Finance, A.; Dufour, C.; Boutéraon, T.; Sarkissian, A.; Mangin, A.; Keckhut, P.; Meftah, M. In-Orbit Attitude Determination of the UVSQ-SAT CubeSat Using TRIAD and MEKF Methods. Sensors 2021, 21, 7361. https://doi.org/10.3390/s21217361
Shapley, L.S. Notes on the n-Person Game—II: The Value of an n-Person Game; RAND Corporation: Santa Monica, CA, USA, 1951.