

Lunar Sun-Synchronous Navigation with Automatic Sun Tracking System

Luigi Ansalone, *GMV Aerospace and Defence*
Fabio Curti, *School of Aerospace Engineering, "Sapienza", University of Rome*
Mariella Graziano, *GMV Aerospace and Defence*

BIOGRAPHY

Luigi Ansalone received a BSc in Aerospace Engineering and a MSc in Astronautical Engineering at "Sapienza" University of Rome. He worked for about one year as research assistant at the Automation, Control and Robotics for Aerospace Laboratory (ARCA Lab) at the Aerospace & Astronautics Dept of "Sapienza" University of Rome. Recently he joined the GMV Aerospace and Defence. He is interested in satellite attitude control, GNC systems and space exploration.

Fabio Curti is Associate Professor at the School of Aerospace Engineering of "Sapienza" University of Rome, where teaches the course of "Space Robotic Systems". He is the director of the Automation, Control and Robotics for Aerospace Laboratory (ARCA Lab) at the Aerospace & Astronautics Dept. He is in the board of the Space Automation and Robotics Technical Committee (SARTC) of the AIAA. He accomplishes research in: space robotics; spacecraft attitude, determination and control; space navigation, rendezvous and docking.

Mariella Graziano is an Aerospace Engineer from the University "Sapienza" of Rome. She is Director of Advanced Space Systems and Technologies at GMV Aerospace and Defence.

INTRODUCTION

The lunar exploration with sun-powered rover is limited in zones where there is a large amount of power and stable thermal conditions. Anyhow, the rover has to survive at the high temperatures during the lunar daylight and to cope with the very low temperatures in the lunar night. Moreover, during the lunar night all unnecessary devices have to be switched off to maintain the stored energy.

The pole sites of the Moon could be visited by using the strategy of the sun-synchronous navigation [1], that is, when the rover travels in the opposite direction of the lunar rotation by maintaining a mean speed fast enough to follow

the sun apparent motion. The advantage of the sun-synchronous navigation is that the rover can operate continuously for a long time without the necessity of designing a complex thermal control and by exploiting the possibility of obtaining a constant source of power. The paper studies a concept of a rover in sun-synchronous navigation with a sun-tracker solar panel.

1 LUNAR SUN-SYNCHRONOUS PATH

The sun-synchronous navigation is a function of the latitude; in fact the mean speed of the rover increases as the latitude is decreasing. As a consequence, at the highest possible latitude the travel speed, the consuming power and the mission risks are minimized. The Moon offers a quite constant distance from the Sun, with a solar constant that varies from about 1320 W/m^2 to 1420 W/m^2 (Figure 1) and, because there is no atmosphere, the Sun offers the entire power at every elevation over the horizon [2].

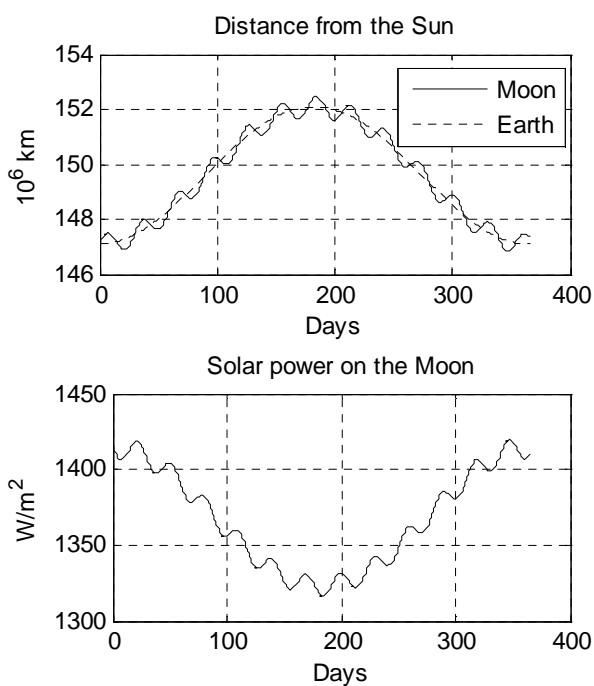


Figure 1: Distance of the Moon from the Sun and the Solar Constant on the Moon

The high latitude is interesting for the exploration because we can circumnavigate the pole, or of a region near the pole while the rover is always powered by the sun rays. In these sites it is possible to visit craters where the bottom has never been illuminated by Sun rays, in these special craters there could be solid water, or there could be installed an infrared telescope for the very low constant temperature.

Some sites (like Mount Malapert in the South pole) could offer an advantageous place to communicate with the Earth, because they could offer a continuous visibility of our planet [3]. The south pole of the Moon seems to be the most suitable place to Sun-Synchronous navigation for the presence of the South Pole-Aitken basin, which offers several scientific aims. It is possible to compute the mean velocity considering this simple law:

$$\bar{v} = \frac{2\pi R \cos(\lambda)}{T} \quad (1)$$

where R is the polar radius ($R=1736$ km), λ is the latitude and T is the synodic period ($T=29.53$ terrestrial days). As it is possible to see in *Figure 2* the mean velocity decreases from 10 km/h to zero km/h as the latitude increases from 50° to 90° . It is simple to think that this mission could be possible only at very high latitude, in order to have low mean velocity. For example at the latitude of 85° , the rover could travel at a mean speed of about 1 km/h.

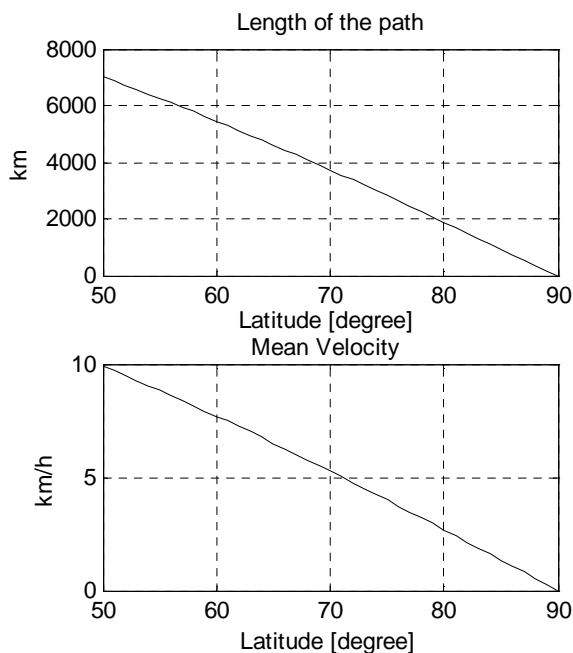


Figure 2: Sun-synchronous length path and mean velocity.

This mean velocity is obtained assuming the navigation in a perfect circular route, but it is not possible to consider it, because there is lot of obstacles that the rover has to avoid to make its travel safe. The travel paths of the rover can be identified by the analysis of high-resolution pictures of the site; these routes are usually called Magellan Routes [4]. By following a Magellan Route the rover travels for a path longer than a circular route or radius r (*Figure 3*).



Figure 3: The Magellan Route

2 POLAR NAVIGATION WITH AUTOMATIC SUN TRACKER

During the travel time, in the sun-synchronous path, the Sun is very low above the horizon, so a horizontal solar panel results to be unusable, because the power would be near to zero for the high angle between the panel normal and Sun direction. If the solar panel was vertical (or slightly tilted according to the latitude of the mission) but fixed, then it could be mandatory to optimize simultaneously a path through the terrain and the amount of solar power received. In this case, the guidance control of the rover has to consider some periods when the panel does not offer the maximum surface to the Sun, and, as a consequence, the guidance strategy should take into account these constraints by using a complex navigation control [5].

The guidance control can be made independent from the power budget by using a sun-tracker solar panel. This device allows an optimal scheduling of the maneuvers, avoiding risks and optimizing the time of the travel; it is only the panel that finds the direction of the Sun in the sky. At the polar latitudes on the Moon, the Sun has very low inclination, so it is convenient to design an azimuthal sun-tracker solar panel. In fact, one degree of freedom is enough to enhance our performances, while a double degree of

freedom provides the maximum power available with an increased complexity of the system against a minimum increment of power (not appreciable in *Figure 4*).

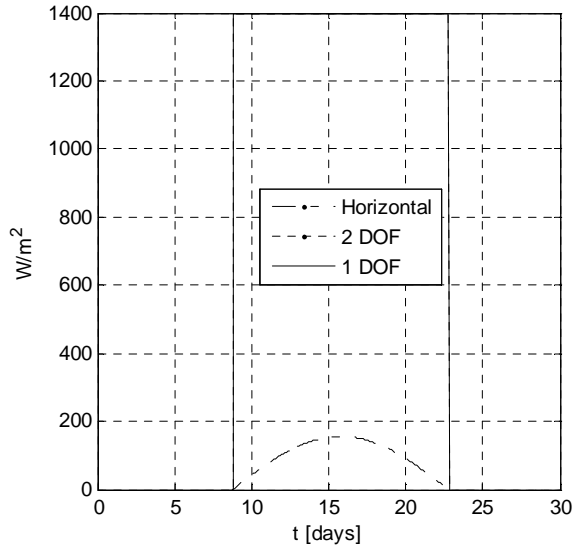


Figure 4: Power availability with horizontal, 1 DOF and 2 DOF solar panels at 85° of latitude.

The tracking panel also allows a high flexibility for the mission planning with respect to the constraint of the sun-synchronous navigation; in fact for a fixed panel it is mandatory to fix a lunar local time to be followed that affects the path planning. If the sun-synchronism is lost with a sun-tracker, it is possible to restart the navigation with a new lunar local time by only using the autonomous tracking of the solar panel.

It is useful to consider the lunar local time following the terminator to obtain intermediate thermal condition (*Figure 5*).

If the local time is at the sunset, the rover has the Sun vector oriented like the antiparallel of the velocity vector, which corresponds to going towards the sun. This is a bad condition for many reasons: first of all if we lose the local time for some problems or delays the rover will be in the dark side of the Moon, with only the battery power but with a high request of energy because the rover has to make up for lost time; in addition the optics used for the navigation have to get filters to avoid sensor problems due to the high incoming of energy.

If the local time is at the dawn, the Sun will be behind the rover and the optics have no problem; moreover if the rover loses the local time, it is possible to fix a new local time correspondent to the old one plus the delay due to problems or to scientific interests that force rover to slow down.

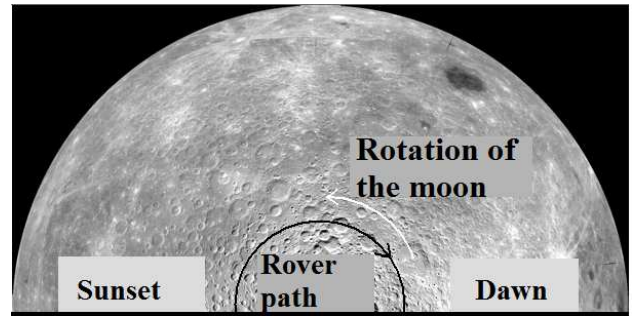


Figure 5: The rover path seen from the north pole

If the rover with a fixed solar panel changes the local time of sun-synchronous navigation, the angle between the normal of the panel and Sun changes of $\Delta\vartheta$:

$$\Delta\vartheta = \frac{2\pi}{T} \cdot t_d \cong \frac{12^\circ}{day_e} t_d \quad (2)$$

In Equation (2) t_d stands for the time of delay, and day_e stands for a terrestrial day. If the rover collects, for example, a total delay of 48 hours, it will lose almost the 10% of the available power, exactly in the time when it needs more power to compensate the delay.

With an automatic sun-tracking system the panel compensates the delay only rotating around a new zero-reference, adjusting the offset of the system. In addition, if the rover is able to cope with the high temperature reachable on the lunar surface, it is possible to think about a rover that travels in a nearly sun-synchronous path with a constant rate of delay in order to slow down the mean velocity of the rover. If the rover travels at a constant velocity equals to $2/3$ of the velocity obtained in the equation (1), it starts its exploration at the dawn and it finishes at the sunset travelling the entire path by only changing the attitude of the solar panel with respect to the rover.

The angular position of the solar panel with respect to the rover is measured by an encoder; this measurement with the output of the azimuthal sensor is used to estimate the Sun direction in the reference frame of the rover. If the condition of sun-synchronous navigation is respected, the Sun position in the sky is constant, providing a good reference for the rover attitude. In particular the elevation of the Sun above the Moon surface is quite constant and it is a function of the selected local time for the navigation. A planetary rover is usually equipped with accelerometers [6] that determine the vector towards the center of gravity of the Moon. Therefore by using the sun-tracker solar panel as

a sun sensor also and the accelerometers, it is possible to estimate the attitude (*Figure 6*). The use of a sun sensor for planetary rovers is well known in literature (see [8] or [9]).

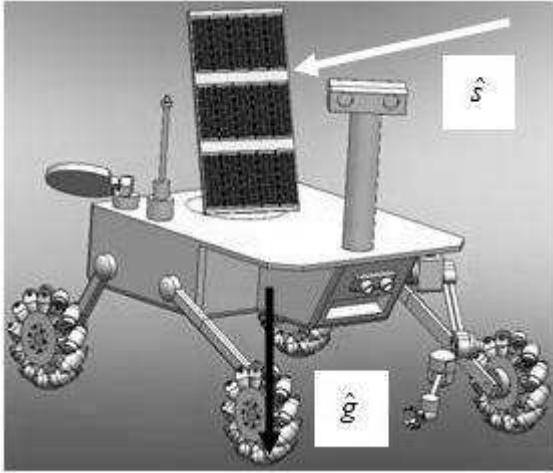


Figure 6: Gravity and Sun unit vectors

The MERs do not have a dedicated sun sensor, but they use their Pancam to find the Sun. When requested the Pancam is pointed to the sky to find the Sun with a dedicated filter (“Sunfind mode” [7]). If the Sun is at zenith, the rover cannot provide no-parallel two vectors, so the rover is obliged to wait ten minutes to permit the displacement of the Sun in the sky [6], ten minutes correspond to an angular displacement of 2.5° . For a lunar equatorial mission for the same angular displacement the rover would wait for about 5 hours, because the synodic period of the Moon is about 30 times bigger than the synodic period of Mars. The MERs propagate their attitude and position with a IMU, or gyro and odometry; when required visual odometry is also performed [7].

In a polar exploration there is no chance that the Sun can be overhead. It is worth noting that for a sun-synchronous lunar rover it is very useful to obtain a continuous reference like the Sun position, so it possible to know position and attitude of the rover with increased accuracy, allowing a velocity much higher than the velocity of the MERs.

In summary the use of the tracking solar panel equipped with a azimuthal sensor yields three main advantages: 1) the navigation is independent from the power; 2) flexibility for the lunar local time of the sun-synchronous navigation; 3) the sun-tracker solar panel can be used as a sun sensor.

3 NAVIGATION FILTER

On the MERs the IMU is not always powered because the rovers are at rest for a lot of time. In

the sun-synchronous navigation the respect of the timeline is essential for the mission, so the IMU will be always powered. The IMU introduces gyro drift errors for the long time propagation of the gyro output, so a global sensor is fundamental to avoid great errors in position and attitude knowledge. Notice that the Sun is fixed in the sky and, with a perfect sun-synchronous navigation, it represents a reference for the East, so it is possible to obtain a sort of “solar compass”.

A Kalman filter is very helpful to integrate the gyroscope and the sun sensor outputs.

Let us consider the motion of the rover in a flat surface; therefore only the heading angle ϑ is needed to know the travelling direction of the rover.

The output of the gyro can be described as:

$$\begin{cases} \omega = \dot{\vartheta} + b + n_1 \\ \dot{b} = n_2 \end{cases} \quad (3)$$

where ω is the output of the gyro as the sum of the real angular velocity $\dot{\vartheta}$, the bias b and a white Gaussian noise n_1 . The bias is modelled as the integration of the white Gaussian noise n_2 .

The output of the sun-tracker can be written as:

$$y = \vartheta + w \quad (4)$$

where w is a white Gaussian noise.

From Equations (3) and (4) we can write:

$$\begin{cases} \begin{bmatrix} \dot{\vartheta} \\ \dot{b} \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \vartheta \\ b \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot \omega + I_{2 \times 2} \cdot \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \\ y = \begin{bmatrix} 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \vartheta \\ b \end{bmatrix} + w \end{cases} \quad (5)$$

where $I_{2 \times 2}$ is the identity matrix 2x2.

Let $\hat{x} = \begin{bmatrix} \hat{\vartheta} & \hat{b} \end{bmatrix}^T$ be the state estimate vector of the state vector $x = \begin{bmatrix} \vartheta & b \end{bmatrix}^T$. The estimation filter can be construct as:

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + B\omega + K(y - \hat{y}) \\ \hat{y} = C\hat{x} \end{cases} \quad (6)$$

where $A = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$, $C = [1 \ 0]$, and K is the filter gain.

Let P be the error covariance matrix of the estimate error $x - \hat{x}$; then by applying the Kalman filter theory [10] the covariance equation of the filter is obtained as:

$$\dot{P} = AP + PA^T + V - PC^T W^{-1} CP \quad (7)$$

where V and W are respectively the covariance matrices of the gyro noises and the sun sensor noise; this equation is the Differential Riccati Equation. It is possible to solve the equation for the steady-state case, so $\dot{P} \rightarrow 0$, yielding the matrix K as a constant:

$$K = PC^T W^{-1} \quad (8)$$

4 NUMERICAL SIMULATION

A simple path is simulated to test the Kalman Filter applied to the rover navigation. For sake of simplicity we consider an example of path shown in *Figure 7*; the rover travels at a constant speed of 0.5 m/s (or 1.8 km/h), for 100 m towards West (y axis) in 200 s, for the next 10 seconds it rotates of 45° towards North (x axis) and then it continues for 100 m. From t=410 s to t=420 s the rover rotates to align its velocity with the West direction and then it continues for 100 m. The sun vector is aligned with the West direction, so the rover has the Sun behind.

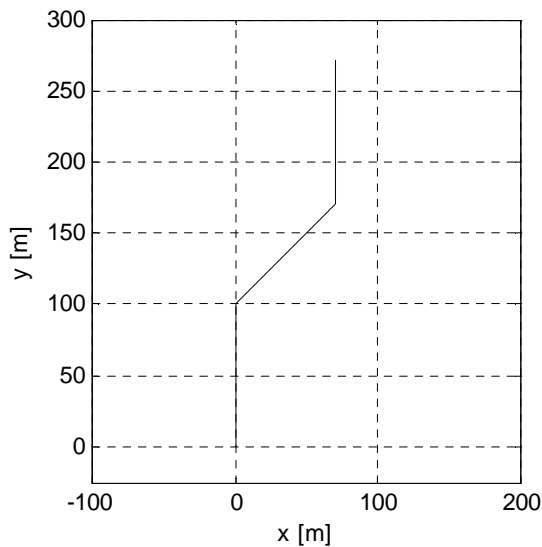


Figure 7: The rover path

In *Figure 8* the profile of angular velocity in the z axis is shown.

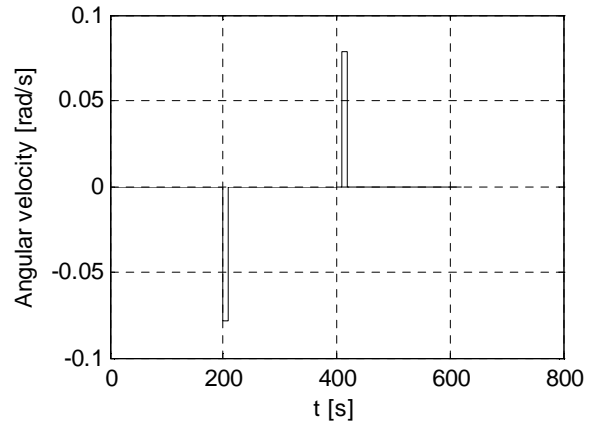


Figure 8: The profile of angular velocity

The values of the standard deviations are assumed as:

$$\begin{aligned} \sigma_{n_1} &= 0.018^\circ / s \\ \sigma_{n_2} &= 1.82 \cdot 10^{-4} / s^2 \\ \sigma_w &= 0.57^\circ \end{aligned} \quad (6)$$

The first and the second values have been taken from off-the-shelf devices while the third value has been assumed from some tests on a simple prototype of azimuthal sensor designed and build with four micro photodiodes at the ARCA Lab (*Figure 9*).

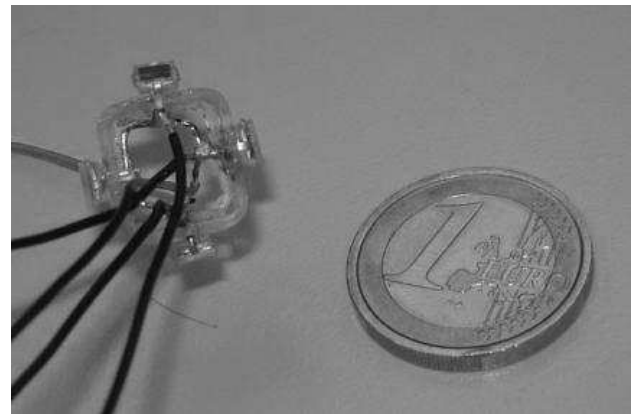


Figure 9: The azimuthal sensor

The azimuth of the incoming sun rays has been computed trough the cones intersection technique [11].

This sensor is mounted on the tracking panel with closed loop control. This panel is equipped with flexible silicon solar cells (*Figure 10*).

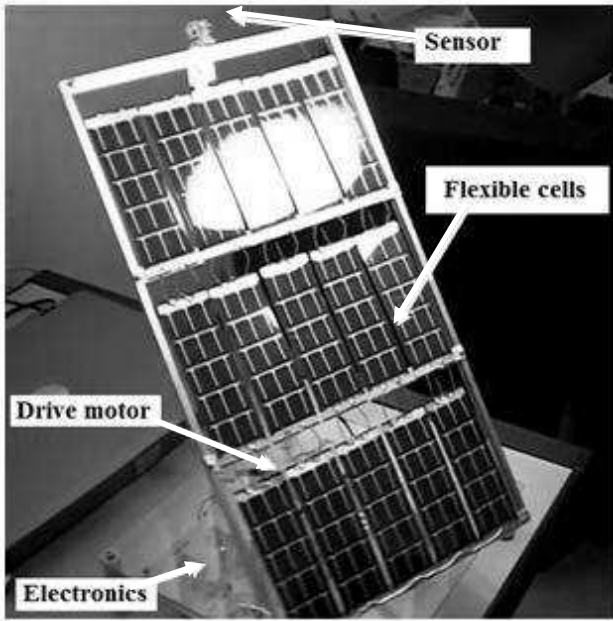


Figure 10: The tracking panel

It is possible to evaluate the improvement of the performances of the navigation system, comparing the errors between a rover with only gyro outputs and a rover with gyro and sun sensor outputs. *Figure 11* shows the error on the heading angle, while *Figure 12* shows the position error. The target

is located in $\left[100 \frac{\sqrt{2}}{2} m, (200 + 100 \frac{\sqrt{2}}{2}) m \right]$. The error can

be subdivided in along track (along the y-axis) and cross track (along the x-axis), in *Figure 13* the two cases are presented, with the estimation on the cross track (C-tr.) and the along track (A-tr.).

The actual and the estimated bias have been shown in *Figure 14*.

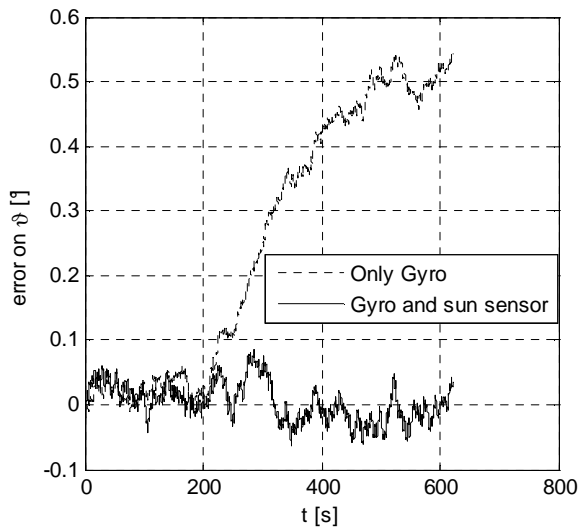


Figure 11: The error on ϑ

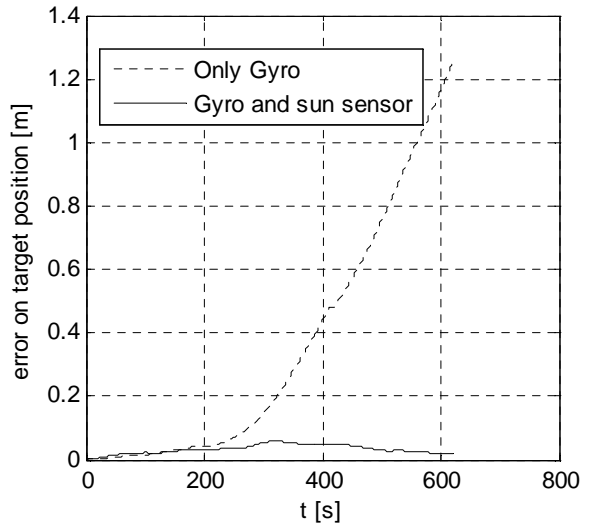


Figure 12: The error on target position

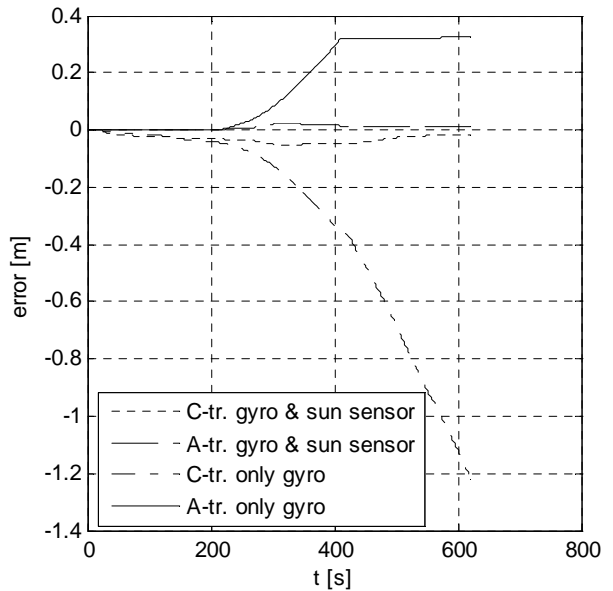


Figure 13: Along track and Cross track errors

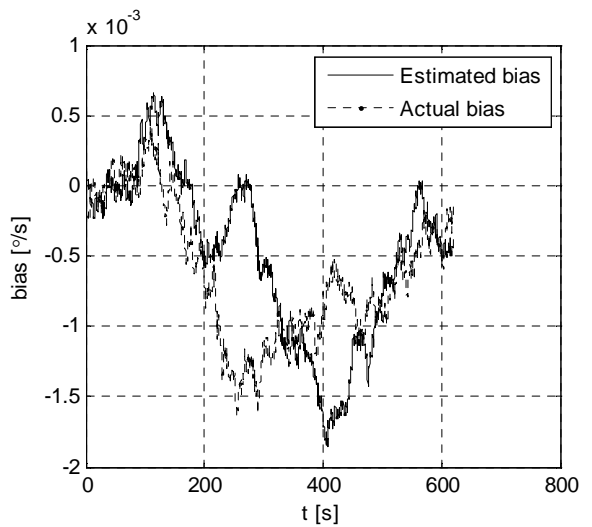


Figure 14: The bias

5 CONCLUSIONS

A new solution for sun-synchronous navigation is proposed by using a sun-tracker solar panel.

As a result the use of a sun-tracker solar panel maximizes the gathered power and provides outputs for the estimation of the attitude and the position of the rover. The future work will be the setting-up of a prototype to test the behaviour of the system.

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