WeakHEO : GNSS/INS/Star Tracker Integrated Navigation System For Earth Moon Transfer Orbits

Summary
The WeakHEO proof of concept project aims to validate the use of Global Navigation Satellite System (GNSS) constellations, potentially with other systems such as an Inertial Navigation System (INS), for the navigation of a space vehicle in Highly Elliptical Orbits (HEO). The project is based on a simulation phase and an FPGA realization phase.

Although several sensors and technologies are available to estimate the kinematic state of a space vehicle, there is a growing interest in GNSS-based navigation systems. Originally designed as military navigation systems for land, sea and airborne users, nowadays GNSS can also be considered for Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) applications. Moreover, if integrated with additional sensors, they can become an essential part of an accurate, robust, autonomous multi-sensor navigation system for High Earth Orbit (HEO) up to Moon altitudes. For this project, an high-sensitivity GNSS receiver is “ultra tightly” integrated with an INS, because their synergistic integration overcomes their individual drawbacks and provides a more accurate and robust navigation solution than either could achieve on its own. A Star Tracker is also integrated to support the INS rotational propagation and to provide an accurate attitude estimation as well. All the sensors measurements are finally fused with the translational and rotational state prediction of an on-board orbital forces model through a non-linear Kalman filter.

Integration Architecture

Fig. 1: Integration architecture of the multisensory proof-of-concept system for space navigation.

A GNSS receiver and an Inertial Measurement Unit (IMU) are integrated to provide an high rate, high sensitivity, high accuracy and driftless navigation solution. The standalone GNSS provides a high long-term position accuracy with errors limited to a few meters, but low output rate (typically around 10 Hz), high short-term noise (for a code-based position solution) and they rely on the GNSS satellites signals availability. INS operate continuously, autonomously, with high-bandwidth output (at least 50 Hz) and low short-term noise; however, their accuracy degrades with time as their errors are integrated through the navigation equations. As the benefits and drawbacks of INS and GNSS are complementary, by integrating them, the advantages of both technologies are combined to give a continuous, high-bandwidth, complete navigation solution with high long- and short-term accuracy. In the above block diagram, the GNSS receiver is used as absolute reference to calibrate the position provided by the IMU (by integrating doubly the accelerometers measurement \( \mathbf{f} \)) and it is assisted by the IMU in the acquisition and tracking processes. A Star Tracker is also integrated to align the attitude outputted by the IMU (by integrating the gyros measurement \( \mathbf{\omega} \)). The Integrated GNSS/INS \( \mathbf{P}, \mathbf{V}, \mathbf{T} \) and the integrated Star Tracker/INS \( \mathbf{R}, \mathbf{\omega} \) are fused via Kalman filter with an on board orbital forces model, that takes into account the orbital trajectory constraints.

Preliminary results: analysis of Standalone GNSS performances in MEO, GEO and HEO

The standalone GPS and GPS-Galileo-combined performance in MEO, GEO and HEO up to Moon altitude were investigated, in terms of availability, pseudorange factors, geometry factors, Doppler shifts and Doppler rates. By using our multi-GNSS full constellation simulator “Spirent GSS8000”, we accurately modeled the atmosphere layers, the GPS and Galileo satellites constellations, the GPS L1 and Galileo E1 signals and the 3D transmitter and receiver antenna patterns.

The following four orbital cases (illustrated in figure 2) have been studied:

- MEO under GPS constellation.
- MEO above GPS constellation.
- GEO.
- HEO highly elliptical as lunar transfer orbit, from 185 km earth orbit parking to 100 km lunar orbit parking

All the results were published in the proceedings of the International Astronautical Conference 2013 [V. Capuano, C. Botteron, P.-A. Farine, “GNSS Performances for MEO, GEO and HEO”, IAC 2013]. In particular, we have shown that the reception of GNSS signals in space can be very challenging, with received signals weaker than 10 dB-Hz at Moon altitude, Doppler shifts and Doppler rates respectively higher than 30 kHz and 15 Hz/s in LEO, and a geometric dilution of precision (GDOP) above 1000 at Moon altitude.

Fig. 2: Matlab plot of the four investigated orbit and of the GPS and Galileo satellites orbits.