Can Earth’s magnetic field be used to maintain a satellite in low orbit ?

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Chosen theme: life in space
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Introduction

After we found out about Mission Space Lab, we wanted to propose an experiment that combines astronomy, physics and computer science: we want to use Earth’s magnetic field to maintain the orbit and the attitude of a low-orbit satellite.
After some research we found out that the magnetic field is already used to control the attitude of miniaturized satellites (magnetorquer), such as CubeSat.
To maintain satellites in low-orbit, there are usually used complicated propulsion systems, which are often environmental harmful (ISS uses about 8700 kg of fuel annually).
Considering a magnetic dipole moment m (generated by the current in a coil; this current can be an induced one, created by the variation of the magnetic field parallel to the coil, or generated by a source), the torque is proportional with the magnetic field perpendicular to the coil, while the force is proportional to the spatial variation of the parallel magnetic field, both being proportional with m. The force is parallel to the coil.
Even if the force is smaller than the torque with orders of magnitude, we saw this as a challenge and we want to find a way to make this force useful.

Method

In the experiment, it was used the IMU sensor (gyroscope, accelerometer, magnetometer), which measures the angular velocity, the acceleration and the magnetic field in the Sense Hat’s frame of reference.
Storage was at 10 seconds interval, which we called "normal storage" and “zoomed", at 500 milliseconds intervals, in zones that we considered special, called "fast storing". The special zones are: Equator, the North-most and the South-most zones, and halfway between those.
Data was stored in csv files with suggestive names.
Stored data:
-primary data (the most important), the components of the IMU sensor on 3 axis;
-attitude data (Euler angles): for every sensor individually and for all together;
-time (date/hour);
-latitude and longitude using time, the TLE for ISS and functions in Python_3;
-polar angle and the dipole magnetic field model;

For data processing we have created a program using Spyder_Phyton_3.8 (Narwhals_total_ver2.py), which takes the measured data, compares it with World_Magnetic_Model’s (WMM) magnetic field, computes the force and the torque and stores the new data in another .csv file.
The graphs were plotted using data from this .csv files, using Excel_Microsoft.

Link GitHub repository:
https://github.com/NarwhalsTeam/Narwhals_Astro_Pi/blob/main/Narwhals_total_ver2.py
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Results
Convention: SR_API –IMU_Sense_Hat reference system(SR), VEC(Velocity_East_Center) - ideal ISS'SR, NEC(North_East_Center) –the SR used by WMM/CHAOS, Va-R – vertical axis Right (Left is implicit), the horizontal axis represents time in seconds.

We want to make sure that our magnetic field measurements match with the World Magnetic Model(WMM).

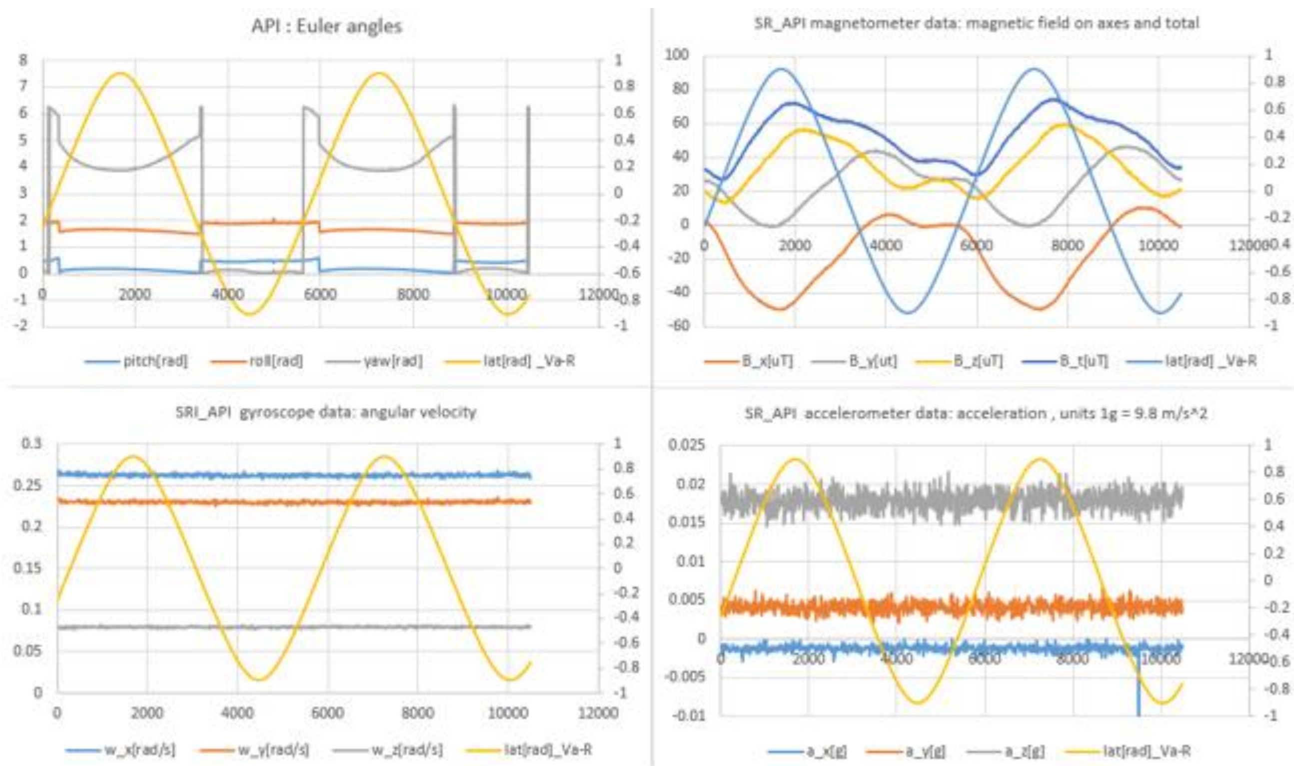

Figure1. Measured IMU sensor data, Euler angles and ISS' latitude

From Figure1, it can be seen that the Euler angles have discontinuities, while the measurements used to calculate them (magnetic field, acceleration, angular velocity), don't. Probably, the attitude function don't work properly in this conditions: proper magnetic field of the ISS, micro-gravity.

We have tried an empirical approach to processing the magnetic field data assuming that:

- the IMU sensor has a fixed orientation to the ISS, so we have taken yaw equal to the angle between ISS' velocity and the geographic North direction;
- the real values of pitch and roll are the mean values of the measured values;

Using the above assumptions we have done transformations from NEC_to_API for WMM, using Euler matrices.
Plotting this results we have concluded that the measured magnetic field and WMM are similar up to some rotation. The results after this rotations can be seen in Figure2. The obtained angles are verified by the position of the Sense_HAT from the available information.

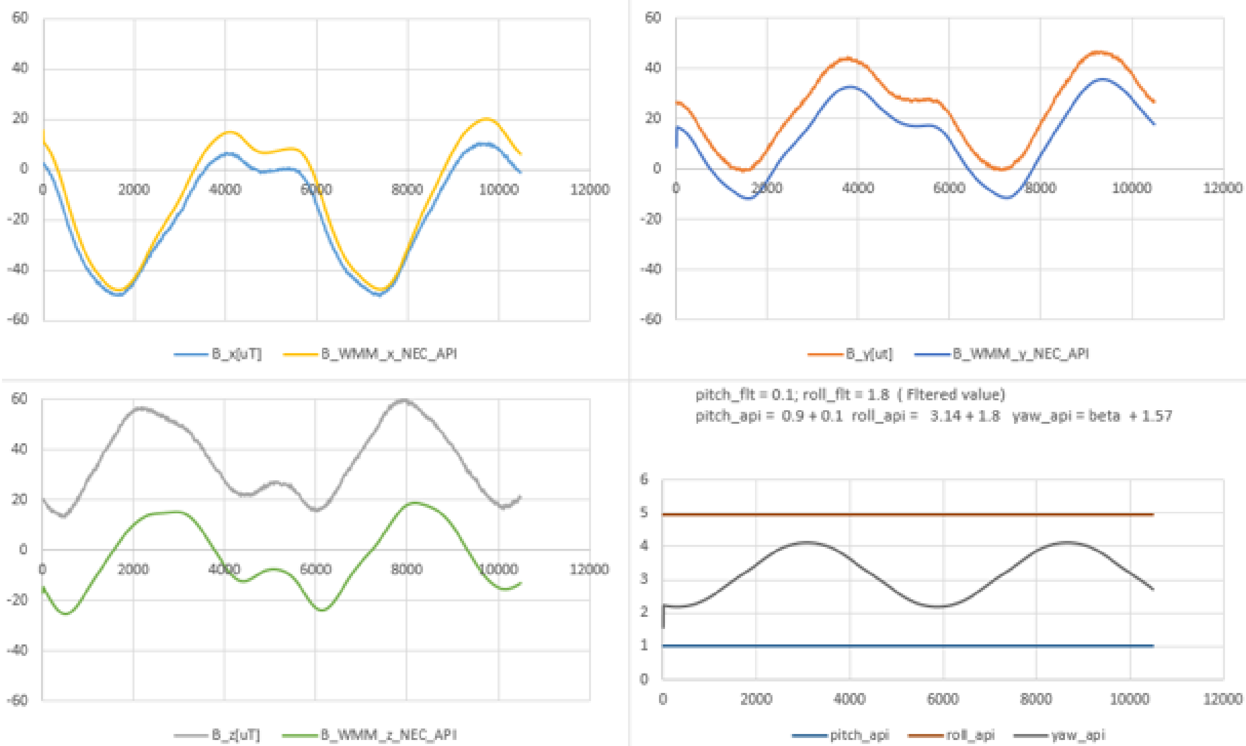

Figure2. Measured magnetic field vs WMM after NEC_to_API transformation

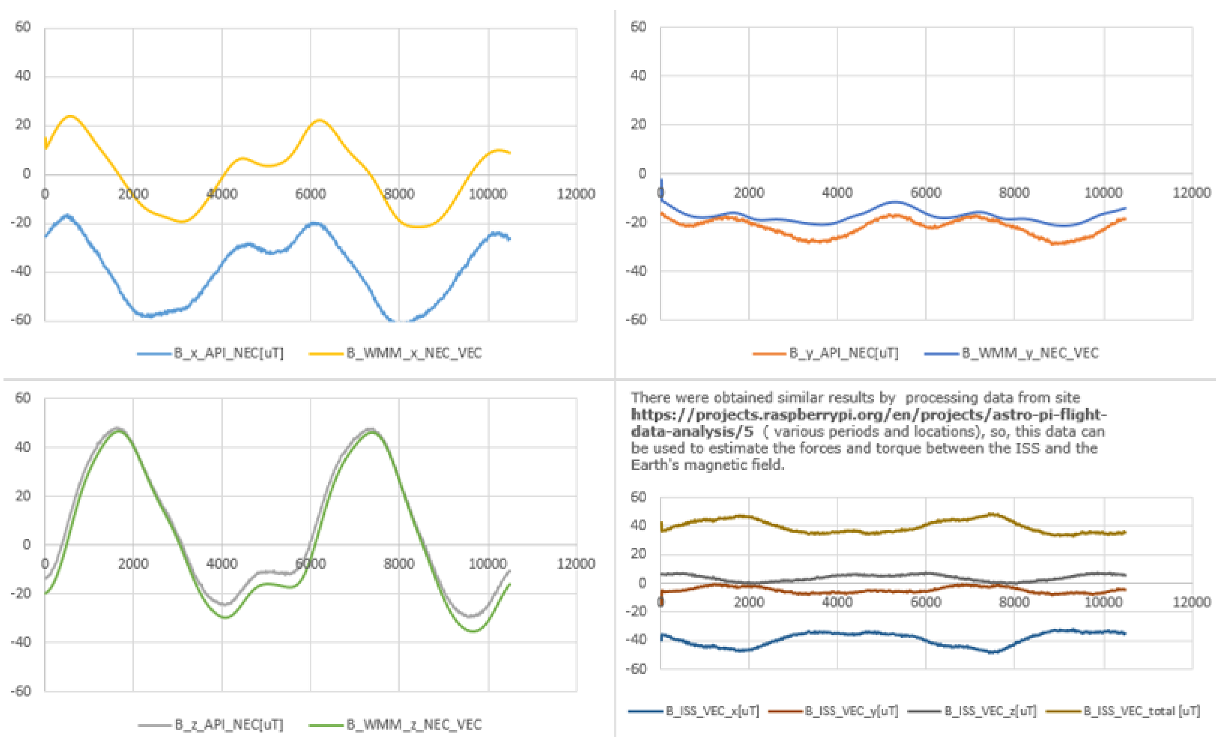

Figure3. Measured magnetic field (API_to_VEC) vs WMM (NEC_to_VEC) . Transformations for consistency check and estimate ISS proper magnetic field

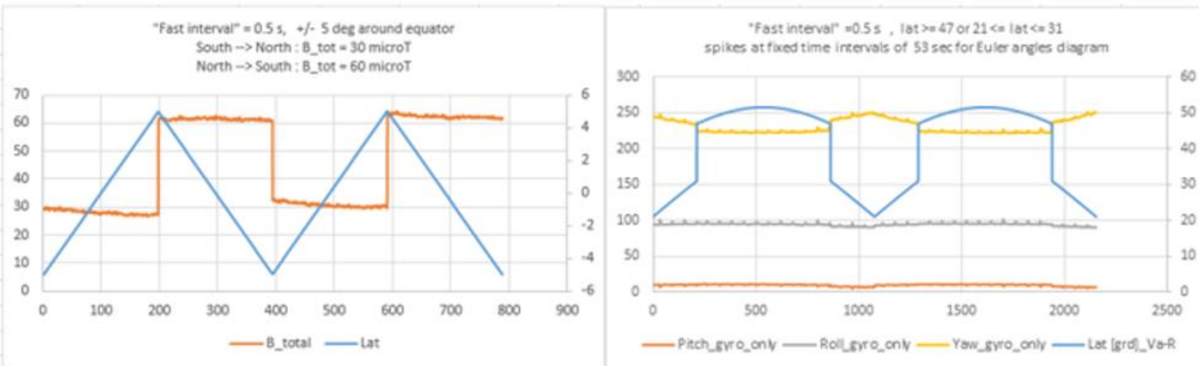

Figure4. Fast storing 500 milliseconds intervals, asymmetry of the magnetic field near the equator and the existence of “spikes” in the graphs for Euler’s angles

ISS’ proper magnetic field is predominant on the direction parallel to the velocity. We used this magnetic field to estimate ISS’ magnetic dipole moment. In Figure5 there are estimates of the magnetic moment, forces and torques for ISS and for two coils with characteristics presented in the table. We estimate for two cases: inducted and 100 A external currents. Unfortunately, the torque is a thousand times bigger than the force, so a satellite with this kind of propulsion would need to have the coil orientated parallel to the magnetic field.

	Magnetic moment [A m^2]	Force [N]	Torque [N m]
ISS induced (X component in VEC)	-4e+10 / -5 e+10	1.5 / -3	-8 e+5 / -2.5 e+6
Coil 1 induced	8 e+8 / -8e+8	0.003 / -0.07	4 e+4 / -3 e+4
Coil 1 source 100 A	1.6 e+10	1.2 / -0.6	8 e+5 / 2.5 e+5
Coil 2 induced	8 / -8	0 / -6 e-10	4 e-4 / -3 e-4
Coil 2 source 100 A	1.6 e+6	1 e-4 / -5 e-5	80 / 25
Coil1 : Length 1 m, Surface 1 m^2, No_Turns = 1.6 1e+8			
Coil2 (CubeSat dimensions): Length 0.1 m, Surface 1 e-2 m^2 No_Turns = 1.6 1e+6			

Figure5. Estimated magnetic interaction (wire 0.025 mm / superconductivity)

Conclusions

- By processing the measured magnetic field data, we concluded that they match with the WMM up to an offset, given by ISS’ proper magnetic field, electronics etc. So, for computing forces and torques, where there are relevant only the variation of the magnetic field, we used WMM and collected data.
- In order to cross-check Figure2 and Figure3, we have also contacted a research team from Institute for Space Science, Bucharest, who confirmed our results by more rigorous, optimization methods.
- The attitude function of the Raspberry_Pi, based on IMU_Sense_Hat doesn’t work well in conditions like those on the ISS, they require additional rotations. The individual sensor measurements gave the same angles, without other meaningful informations.
- The fast storing data gave us interesting information, like in Figure4, we will study this in the future.
- For a coil with dimensions similar to a Cube_Sat we obtain small forces and bigger torques. We believe that with more advanced materials (superconductors - the temperature of the shady side can reach -157C), special geometry and trajectory, the forces can be increase, thus creating a new, cheap and ecofriendly method of propulsion.