# Satellite Navigation Documentation

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## 1 Introduction

The navigation system or obit-determination and propagation system of the satellite is responsible for determining the position and velocity of the satellite. The position and velocity are required for various other computations for example, outputs from ephemeris models such as IGRF, WMM and Earth reflectivity for albedo are all somewhat dependent on the position and velocity of the satellite as well as its relative position to the sun as well.Thus, an accurate and verified satellite navigation system is a necessity for the computation of reference frame vectors such as sun and magnetic field vectors. Moreover, considering that the payload has high overall pointing requirements, there is a high demand for accurate satellite position and velocity information as it affords greater room for inaccuracy in body frame vector formation as well as to the entire attitude determination and estimation system.

The aim of this document is to record the development of Team Anant's navigation system.

## 2 Methods for Navigation

There exist several methods of orbit determination meant to be used under different kinds of requirements. The broadest classification of these system is done on the basis of the level of autonomy that the satellite has i.e., how dependent a satellite is on other objects such as other satellites or ground stations. On this basis, they can be categorised as follows:

- **Non-Autonomuos:** These were the first navigation systems to be developed for satellites and were completely dependant on ground based processes for generating a state vector. These are considered extremely inefficient and primitive and are thus not considered in modern day navigation systems.
- **Semi-Autonomous:** These systems are considered the optimal choice for most satellites today as it allows for on-board processing of data from either a ground station (TLE) or some other satellite (GNSS). This allows for high precision measurements from specially designed tools that typically would be utilised by several users at any given time. It also allows a degree of autonomy as in the absence of any newer data, the state vector can be propagated on-board the satellite.
- **Autonomous:** These systems are still very much in development and as such, have very poor accuracy compared to semi-autonomous systems. Autonomous systems, as the name suggests, are not dependant on any other artificial object for the creation of a state vector. These are primarily preferred for development of satellites that are of greater strategic importance, making it unaffordable for them to stop working in case of a failure of other satellites or ground stations. Given that all observations are taken from on-board equipment, there remain limitations on the maximum achievable accuracy of these systems.

For the purpose of our navigation system, we have decided that a semi autonomous navigation system would be the best fit for our requirements of high accuracy. There are essentially two different approaches of semi-autonomous orbit determination that could be considered viable under the constraints that a CubeSat design poses on any navigation system. These differ primarily in the method of measurement and the requirementsthey pose on the satellite design.

- **TLE:** Two Line Element sets or TLEs are data sets published by the North American Aerospace Defense Command (NORAD) that list the orbital elements of all objects in space above certain size specifications. These have been used to track all satellites in orbit about the Earth with unclassified satellite missions being made publicly available.
  - **Pros:**

    * Requires no on-board hardware except antenna for uplinking TLEs from ground station.
    * Appropriate propagation models (SGP4, SGP8) publicly available.
  - **Cons:**
    * No error characteristics provided by NORAD.
    * Low update rate of at most 2 times a day for a LEO unclassified satellite.
    * Studies show accuracy of ~1 km at time of measurement with long term propagation of TLEs causing further severe deviations.
    * Necessitates the requirement of a computationally intensive Extended Kalman Filter to run at all times for error reduction.

- **GNSS:** The Global Navigation Satellite System is an international collaboration with a constellation of satellites that provide near-continuous positioning information to the entire world. The most commonly known segment of this system is the American NAVSTAR-GPS constellation. Some other GNSS constellations are GLONASS (Russia) and BeiDou (China). The European Galileo constellation is also partially completed.
  - **Pros:**
    * High degree of accuracy (~10 m)
    * High update rate up to 10Hz
    * Leads to the possibility of not requiring a Kalman Filter for orbit determination.
  - **Cons:**
    * Imposes power, space and weight requirements on the satellite.
    * Requires a receiver and antenna on-board.

  After weighing Pros and Cons of both determination systems and taking power budget and space on board into consideration we have decided to go with a GNSS receiver.

# 3 GPS Basic Functioning

Given that the GNSS Navigation system will be employed, it becomes necessary to understand its basic functioning as well as the requirements it imposes on the rest of the satellite system.

The basic position determination using GNSS is through the concept of trilateration applied in 3D space. All GNSS satellites broadcast a signal that details the time at which the signal was sent. GNSS works on the basis of trilateration of signals from multiple different satellites, each sending a signal that contains the GNSS satellite's own position at a particular time. Given a potential asynchronicity between a receiver clock and a GNSS satellite clock, at least two satellite signals need to be received in order to establish a position in 1 dimension. Thus for 3 dimensional cases, there need to be at least 4 different satellite signals for a receiver to form a state vector. In most use cases however, there are more than 4 satellites whose signal is being received by the user, leading to greater accuracy.

# 4 Reciever and Antenna Selection

In order to make use of GNSS, two major components are required: a GNSS receiver and a suitable antenna. For receiver selection, a short survey of space qualified receivers viable for CubeSats use was done. The survey resulted in reducing the list of receivers to two - Hyperion's GNSS200 and Spacemanic's Celeste.

On contacting Hyperion regarding their GNSS receiver, the Taoglas AP.35A.07.0054A antenna was recommended as one frequently used alongside the GNSS receivers due to its low cost (Rs 1300-1500) and small size.
In order to choose one out of these two we analysed their differences based on specifications and pricing as follows:

| GNSS receiver | | |
|---|---|---|
| **Sr No** | **Hyperion's GNSS200** | **Spacemanic's Celeste** |
| 1 | Accuracy upto 8m | Accuracy upto 2.5m |
| 2 | Average power consumption 160mW | Average power consumption 100mW |
| 3 | Dimensions 67 x 42 x 7.2 mm | Dimensions 20 x 15 x 3 mm |
| 4 | Weight 3g | Weight 25g |
| 5 | It is provided with a single UART interface | It is provided with 5 separate communicating interfaces (I2C, 2 x UART, CAN and RS485) |
| 6 | Costs 8000€(7500€+ 500€) along with user support | Costs 7240€(5290€+ 1950€) along with an engineering model (same as the actual flight model but with COCOM limits) and free user support |
| 7 | Dispatch the product after 12 weeks of payment | Dispatch the product after the 5 weeks of payment |
| 8 | Unwilling to provide a detailed data sheet until we provide 50% of the payment | They have provided the detailed data sheet required for interfacing and whatever we have needed till now before finalizing our GNSS receiver |

Considering all of the above points, we have decided to go with Spacemanic Celeste. As of now we have planned to buy the engineering model, after its proper testing, we will buy the actual flight model from Spacemanic in the next year. We have started working on basic interfacing that can be done before the GNSS receiver arrives.

# 5 GNSS Receiver Celeste

## 5.1 Update Frequency

After analyzing how my error in position affects the attitude of the satellite and the power budget we have on-board, we have decided to keep the GNSS receiver on throughout the journey except of-course satellite enters in any of the emergency mode. The main reason for finalizing this is because of the low power consumption of the receiver and a significantly higher power budget. After analyzing the effects of error in the GNSS receiver readings, the error in attitude was not significant enough. After running a couple on simulations, we can run Orbit-Propagator for around 10-12 hours without updating the position and velocity coordinates (it will result in error of maximum 100m (in magnitude) which lies in tolerable range of error). Therefore we won't be needing a Kalman Filter for GNSS Receiver.

## 5.2 Effect of GNSS receiver on other subsystems

- The GNSS receiver will be kept on throughout the journey, it will consume an average power of 100mW.
- The receiver will consume significant space (67x42x7.2 mm) on-board and will weigh around 25g.
- The receiver can't function alone, it will be accompanied by a patch antenna that must be fixed on the outer surface of the CubeSat. Since the GPS signals are strong enough, the positioning of the patch antenna doesn't affect much as long as it is on the outer surface of the satellite.
- The receiver must be properly interfaced with the on-board computer after which that data of position and velocity received from the GNSS receiver it can then be utilized for further computations and switched modes of operations. The initial data sheet needed for basic interfacing before the equipment arrives is been provided to the OBC and they have started working on it.

## 5.3 Testing of the GNSS Receiver

### 5.3.1 Hardware

- The hardware testing will mainly be carried out by STS in order to ensure that it can withstand space environment and vibrations generated during the launch. STS will also perform tests to calculate the heat generated by the receiver.

- The other tests include the power consumption and maximum current verification by the EPS. This is just to ensure that the data provided by the Spacemanic is correct and also to provide a safety barrier (for maximum current) to the GNSS receiver.

### 5.3.2 Software

This testing will be carried out by ADCS and TTC jointly. This testing will ensure the proper functioning of the receiver and will also provide with data like time taken to cold start, hot start and warm start.
One approach to testing a GNSS receiver is to use real satellite signals. The receiver is equipped with an antenna and receives genuine signals from a navigation system. This approach allows testing of the receiver under real-world conditions including a multitude of effects, but it has also severe disadvantages. The test conditions vary strongly and are unknown to a certain degree. This makes it impossible to repeat a test under the exact same conditions. In addition, the receiver always has to cope with the full range of real-world effects including restricted satellite visibility, multipath propagation and interference, to only name a few. Testing under less complex, well- defined conditions may not be straightforward. In fact, testing with genuine satellite signals can become quite cumbersome, since it is necessary to test the receiver at different times, diverse locations around the world, at high altitudes and at high velocities (as occur e.g. in aircraft) may be practically impossible.
In order to cope up with this problems we simulate the GPS signals received from the satellite according to our test case scenario then generate those signals and feed it to our GNSS receiver, this can be done by many ways:

- Using a Vector Signal Generator: A VSG or a Vector Signal generator is a widely used device for generating various types of satellite signals ranging from a GNSS satellite constellation to any random satellite. The main problem faced here is that it costs too much; it costs around Rs 7-8 lakhs, therefore we decided to look out for any other available options.

- Using MATLAB R2021a: In the latest addition of MATLAB, they have introduced a Satellite communication toolbox which can be used for generating GPS wave-forms which can then be converted to a GPS signal by a RF transmitter. The major problem faced here is that the interfacing of the RF transmitter with MATLAB, it sounds simple but it is quite complex, the another problem faced is that the RF transmitter will transmit the reading to the GPS antenna which then will be sent to the GNSS receiver, this might overlap with the actual signal received from the GNSS satellite constellation and also since the real world scenario is applied, it might also be difficult to reproduce the exact same conditions.

- Using a open-source Github repository: Using this repository it appears quite easy to generate GPS signals. According to the content provided on this repository we will be able to generate GPS baseband signal data streams for a user-defined trajectory specified in a CSV file, which contains the Earth-centered Earth-fixed (ECEF) user positions which can then be converted to a GPS signal using a SDR (Software Defined Radio) like HackRF or USRP (TTC already have those). The main advantage of this is that the signal can either be transmitted using an antenna, then received by the GPS antenna and then fed into the GNSS receiver or it can also be directly fed in to the receiver using cables. Although the problem here is that the repository currently shows 90 pending issues, which is quite significant and since we don't have to make any significant investment we can try it out and try to make sure that it works for us, if not then we could use the complex second option.

Various test scenarios can be generated to test the proper functioning of the GNSS receiver as per our needs. After successfully generating the desired GPS signals we can try to cross check the following data provided by Spacemanic which will be useful for us in many ways:

- Time to first fix:
  - Cold Start: It is the time taken by the GNSS receiver to start providing data without any prior knowledge of the position or velocity, time and ephemeris data. On-board this scenario will take place right after the satellite powers up after the deployment. It is generally around 30-50 seconds and might go up to several minutes.
  - Hot Start: It is the time taken by the GNSS receiver to start providing data with the prior knowledge of the position and velocity, time and ephemeris data. On-board this scenario will take place if the GPS has been turned off for a couple of minutes and then turned back on. It is generally around 1-5 seconds.
  - Warm Start: It is the time taken by the GNSS receiver to start providing data with the prior knowledge of position and velocity and time but not the ephemeris data. It is generally around 30-40 seconds.

- Sensitivity: Minimum level of signal that allows GPS receiver to acquire or track the GPS signal. Sometimes this data is specified in terms of C/No. Sensitivity$_{minimum}$ = -174dBm/Hz + C/No$_{minimum}$ + NF$_{minimum}$
  - Acquisition Sensitivity: Minimum level to successfully perform time to first fix under cold start (typically around -140 to -150 dBm)
  - Tracking sensitivity: minimum level to maintain location fix once it has been attained (typically -150 to -160 dBm)

  These tests requires multi-satellite GPS signal with valid navigational messages for TTFF, and real-time satellite power control to reduce power levels to test sensitivity.

- Location Accuracy:
  - Absolute location accuracy: Closeness of the receiver's calculated location fix to the ideal (simulated) location.
  - Relative location accuracy: Compares location fixes between tests.
  - Moving GPS receiver accuracy: Performing the above 2 tests but with a moving trajectory. Since the tests will be performed on the engineering model now which has COCOM limits, we won't be able to test for a space orbit but instead we could give it a try on a low-altitude, medium velocity airplane.

  These tests require multi-satellite GPS signal for location fix, repeatable testing scenarios, moving GPS receiver scenarios (simulated), and ability to vary power and other satellite parameters to test tracking.

- Secondary Verification tests:
  - Re-acquisition Time: Time required to resume location fix following loss of signal.
  - RF Interference measurements: Measures the ability of the GPS receiver to operate in the presence of interfering (jamming) signals (second RF source will be required).

# 6 Conclusion

This is not yet the final documentation for the navigational system of Team Anant. Till now we have only included the selection of our navigation system along with its GNSS receiver, its testing data is not yet complete, it can only be completed once the GPS arrives and gets properly interfaced with the OBC micro-controller. This documentation just includes the basic introduction to the testing of the GNSS receiver that we have ordered, many unforeseen problems might arrive while its testing, this is just a basic gist of the tests that we will be performing on the GPS receiver. This documentation is subjected to change over time as new problems and solutions arises.