UAV Attitude Estimation

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3 Global Navigation Satellite Systems

GALILEO The European Union's GNSS: Accuracy of 0.20m (public) and 0.01m (encrypted).

GLONASS The Russian Federation's GNSS: Accuracy within 4.80m and 6.35m horizontally, and 10.52m and 14.08m vertically for military and civilian purposes.

Bei-Dou The Chinese National Space Administration's GNSS: Accuracy of 2 - 4m.

NavIC The Indian Regional Navigation Satellite System: Only covers and operates in India, with an accuracy of 20m over the Indian Ocean and around 10m accuracy in India.

QZSS The Japanese GNSS, SLAS accuracy of 0.38m - 0.84m horizontally and 0.55m - 1.11m vertically. CLAS Accuracy from 1.3cm to 2.7cm horizontally and 3.7cm to 6.3cm vertically.[1]

3.1 GPS architecture

GPS architecture consists of three parts, namely, the space, control, and user segments. The space segment is the constellation of at least 24 satellites that orbit roughly 20,000 km from the Earth's surface and transmit one-way signals to the Earth. The control segment consists of control centers constantly monitoring the satellites' health and updating clocks. The user segment is all the devices that receive GPS signals for calculating their position.[2]

3.2 GNSS error sources

The most dominant source of GNSS error includes ionospheric delay, which is caused by the signal getting refracted by the ionosphere, which can change both its speed and direction. Another significant source is called multipath error, which is caused by the signal reflecting on close surfaces such as walls, mountains, or a body of water. Both these phenomena count for the two most significant sources of error and can be in the order of dozens of meters.[1]

3.3 Dilution of Precision (DOP)

DOP is a value that describes how the precision of a position is affected by the errors in measurement data. The higher the DOP value the worse the accuracy and vice versa.

The DOP value can be divided into the categories GDOP (Geometric), PDOP (Position), VDOP (Vertical), and HDOP (Horizontal) and they deal with the positions of the satellites in relation to the object used for measurements. In general, the more spread out the satellites are, the better the measurement.

3.4 Real Time Kinematic (RTK) GNSS

RTK GNSS is a system used to optimize the precision of localization from meter-precision to centimeter-precision. The system utilizes a stationary base station with a known position to estimate the location of the objects of interest. It is assumed that when the distance is low between the object of interest and the base, the satellites from which they have received data are roughly the same. The base station can then correct the signal values from the nearby satellites due to its known position and send them to the objects of interest thus obtaining a higher precision. When receiving data from a satellite, the base station receiver can measure the phase of the transmitted satellite signal with high precision, but it doesn't know how many wavelengths have passed since the signal started. This is what is called integer ambiguity,

[1] `https://gssc.esa.int/navipedia/`

[2] `https://www.gps.gov/systems/gps/`

and it is solved by the base station using complex algorithms. By knowing the full number of wavelengths along with the phase, a high positional precision can be obtained.[3]

3.5 GNSS accuracy

3.5.1 Standard Positioning Service (SPS)

The GPS is divided into two levels of access, namely SPS and PPS, where SPS is the first level accessible with no direct charge. This system provides a horizontal accuracy of 9m and 15m vertically. PPS, which requires authorization by the US government, provides an improved accuracy of 2.7 meters horizontally and 4.9 meters vertically. Both system accuracies are given with a 95% confidence of the result.[4]

3.5.2 Differential GPS (DGPS)

DGPS utilizes the same concept as RTK with a base station correcting satellite errors which are then broadcast locally. The precision obtained is lower than RTK since they don't try to solve the issue with integer ambiguity to signal length but instead do pseudo calculations. This system achieves sub-meter precision.[5]

3.5.3 RTK float

RTK float uses 4 common satellites to find a region where the object of interest is located and then uses probabilistic calculations to approximate its location. The accuracy is 20cm at best. RTK float is calculated continuously even if the more precise RTK fixed is used instead.

3.5.4 RTK fixed

RTK fixed uses 5 common satellites and has a sub-10cm accuracy. It utilizes the phase of the carrier wave to obtain an improved accuracy.[6]

4 Coordinate systems

4.1 Universal Transversal Mercator (UTM) accuracy

The reference position is defined according to the exercise description as $N55.47° E010.33°$. Using the same reference point is important since the geodetic error is not evenly distributed across the globe due to the coordinate convention wrongly assuming the Earth to be perfectly spherical. It is also noteworthy that the East coordinate is prepended with a zero. This structure, where the numbers are padded with leading zeros, allows for easier automation using computer systems. Here a zero is only visible on the East coordinate since its range is $\pm 180°$ whereas the range of the North coordinates $\pm 90°$.

We define two new positions in UTM, as 1km East and 1km North w.r.t. the reference position. We transform these UTM positions back to geodetic coordinates and evaluate their errors. The result from this is shown in figure 1. Here the longitudal error is shown to be $1000\text{m} - 996.92\text{m} = 3.08\text{m}$ while the latitudal error is $1000\text{m} - 999.08\text{m} = 0.92\text{m}$. These values are calculated using the Great Circle Distance formula

[3] https://www.e-education.psu.edu/geog862/node/1787

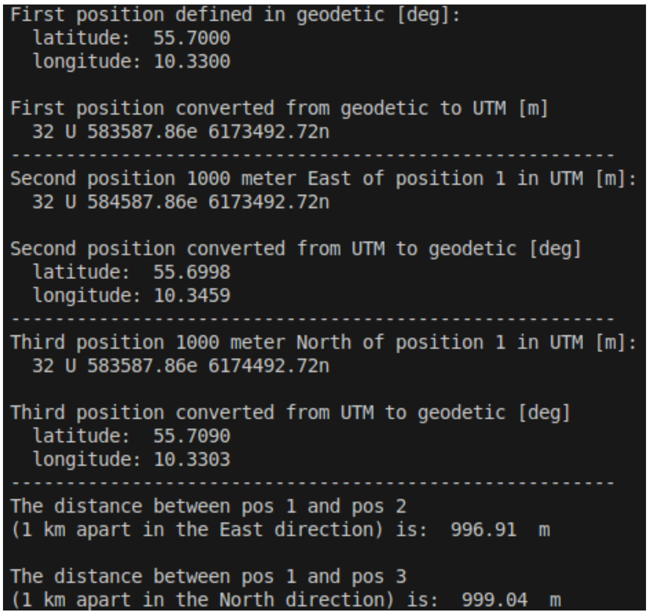
[4] https://www.cnmoc.usff.navy.mil/Our-Commands/United-States-Naval-Observatory/Precise-Time-Department/Global-Positioning-System/Global-Positioning-System-Overview/

[5] https://en.wikipedia.org/wiki/Differential_GPS

[6] https://www.oxts.com/rtk/

$$d = 2 \cdot R \cdot \cos^{-1} \sqrt{\sin^2\left(\frac{\mathrm{lat}_1 - \mathrm{lat}_2}{2}\right) + \cos\left(\mathrm{lat}_1\right) \cdot \cos\left(\mathrm{lat}_2\right) \cdot \sin^2\left(\frac{\mathrm{lon}_1 - \mathrm{lon}_2}{2}\right)}. \tag{1}$$

Where $R \approx 6371$km is the earth's radius. This reference point shows that the error is three times larger in the East direction. This can be explained by this specific reference point on the globe deviating more from the assumed radius of the Earth in this direction.



```
First position defined in geodetic [deg]:
  latitude:  55.7000
  longitude: 10.3300

First position converted from geodetic to UTM [m]
  32 U 583587.86e 6173492.72n
---------------------------------------------------------
Second position 1000 meter East of position 1 in UTM [m]:
  32 U 584587.86e 6173492.72n

Second position converted from UTM to geodetic [deg]
  latitude:  55.6998
  longitude: 10.3459
---------------------------------------------------------
Third position 1000 meter North of position 1 in UTM [m]:
  32 U 583587.86e 6174492.72n

Third position converted from UTM to geodetic [deg]
  latitude:  55.7090
  longitude: 10.3303
---------------------------------------------------------
The distance between pos 1 and pos 2
(1 km apart in the East direction) is:  996.91  m

The distance between pos 1 and pos 3
(1 km apart in the North direction) is:  999.04  m
```

Figure 1: Geodetic error from UTM movement

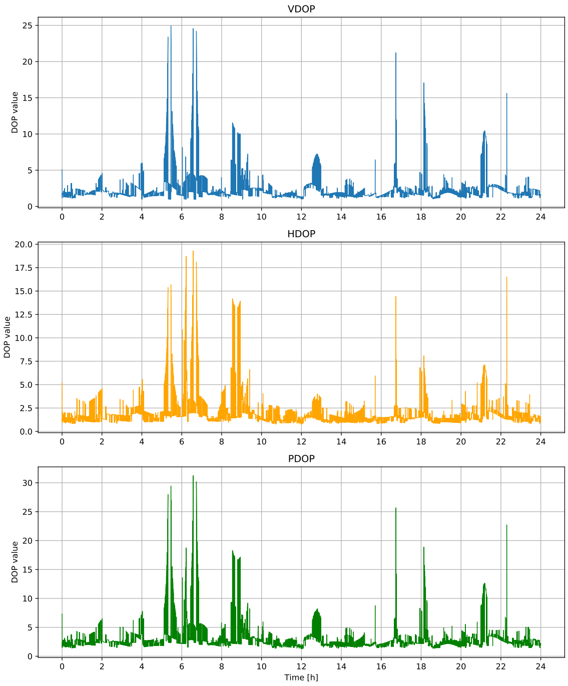


Figure 2: DOP values for the last 24 hours

4.2 National Marine Electronics Association (NMEA) 0183 data

The following plots have been made for the drone flight. Altitude above mean sea level is shown in figure 3, number of satellites in figure 4 and a map of the flight path in figure 5. It can be seen that the drone flies at around 16 to 26 meters above sea level, south of SDU TEK, where it is seen by 8 - 14 satellites. Figure 2 shows how VDOP, HDOP and PDOP values vary throughout a 24H period. The graph shows the values ranging from 3-4 and sometimes spiking into a range of 25-30. A DOP value larger than 4 indicates that the measurement should be discarded.

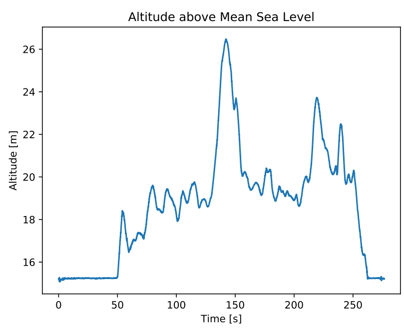


Figure 3: Altitude above sea level

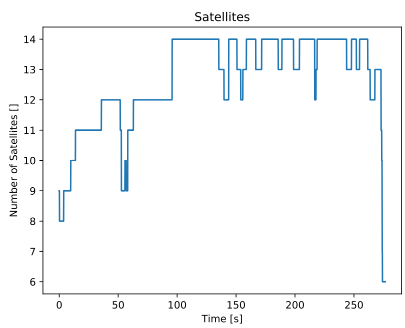


Figure 4: Number of Satellites

Figure 5: Map of path (path in red)

References

[1] R.B. Rustamov and A.M. Hashimov. *Multifunctional Operation and Application of GPS*. IntechOpen, 2018. ISBN: 9781789232141. URL: https://books.google.dk/books?id=knqQDwAAQBAJ.