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Grau en Enginyeria de Vehicles Aeroespacials

Treball de fi de grau

Study of differential GPS system for UAVs

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Contents

List of Figures

List of Tables

1. Aim

The aim of the project is to track an Unmanned Aerial Vehicle (UAV) with a centimetre-level accuracy by implementing a Differential Global Positioning System (DGPS) using a pair of low-cost Global Positioning System (GPS) receivers. DGPS corrections will be applied a posteriori and, if the results are satisfactory, it will be studied the possibility to implement real-time DGPS corrections.

2. Scope

This project involves understanding GPS principles and performance, as well as its sources of error, so an initial learning phase is required. Once the bases are acquired, the stages of the procedure must be defined.

The first step is to communicate with the GPS receivers, so the connections and interface must be specified. Achieved that, receivers have to be set and input data stored and exported into a convenient format to be treated afterward. To do that it is necessary to get familiarized with the work's environment and begin to understand the basics of GPS protocols, as well as the receiver's configuration settings.

At this point, it has been revealed that available GPS receivers do not output raw data, so solution must be found to overcome this problem.

The next stage is to begin the program that will perform all the correction tasks. Which first purpose, must be to read GPS stored data, decode it and extract the information contained inside. Each useful binary message's structure must be known, so a deeper knowledge of UBX and NMEA GPS' protocols is obligate.

Once information is extracted, it must be processed and corrections applied.

All the implemented code must validated and then tested, this will imply some field work.

Finally, results have to be analysed, and if they are satisfactory, the methodology can be implemented for real-time applications.

The optional tasks would include obtaining a communicating system, in order to receive data and transmit corrections in real time. Additionally, it is possible that the original program should be adapted to make it optimal, allowing fast corrections.

3. Requirements

The requirements that this project must fulfil to be considered successfully are:

A. Obtain a centimetre-level accuracy positioning.

B. Low cost of the whole system.

As an optional requirement:

C. The whole system has to be fast enough to be applied in real-time.

4. Justification

The use of Drones or Unmanned Aerial Vehicles in civil applications has grown exponentially in the last years and it currently does. They help society performing tasks that have to be done in the air, at some altitude or that involve flight somehow. Until few years ago, many of these would have been very expensive or impossible. In many of these applications a higher positioning precision than a conventional GPS can offer is required.

In order to improve positioning precision, augmentation systems, such as Differential GPS, are used.

DGPS is not a new concept and it has been used in aviation, coastguard services, marine transport, and so forth, for more than two decades. However, this equipment is complex, expensive and covers large areas. What this project seeks is a low-cost technique based on DGPS that achieves high precision positioning in small ranges in order to satisfy this new demanding.

5. State of the art

Currently, a basic single-frequency GPS receiver can be purchased by approximately 50€ with around 3m of horizontal precision thanks to EGNOS, the Satellite-Based Augmentation System (SBAS) that covers Europe. In those countries where any SBAS service is provided, the horizontal error for standard precision is around 10m, according to [11].

Dual-frequency receivers can achieve centimetre-level accuracy for several thousands of euros.

Another way to improve positioning without expending such quantities of money, is using Differential GPS corrections. DGPS corrections can be performed running the open-source software *RTK solutions*, but with a great computational cost complicating real-time applications or *RTKLIB*, which supports real-time and post-processing corrections reaching until decimetre-level accuracy by a high computational cost. However, *RTKLIB* does not support many receivers such as the *U-Blox NEO* family since they do not provide raw data [13]. This is an important lack since these receivers are very common, for instance are the receivers that *3D Robotics* uses. Raw capable receivers can be obtained by around 70€.

Other alternatives are like *SwiftNav 'Piksi' GPS* that can cost around 450€ each receiver and provide centimetre-level accuracies or applications based on *RINEX* (Receiver Independent Exchange Format), as can be found in [12].

The utility of this project is to supply DGPS corrections to the wide group of unsupported receivers such as the available for the implementation of this project.

6. Proposed procedure

In the following sections, it has been assumed a basic understanding of GPS principles, its sources of error and augmentations such as DGPS. Only the most indispensable aspects are pointed out below. For the interested reader, a more detailed explanation is attached in annex A.

6.1 Approach, issues and solutions

In this project is demanded a low-cost enhancement system based on DGPS that improves basic GPS precision. Recall that, a minimum of 2 receivers with at least one of them at known location, **base station/s** and **rover** respectively, are required to apply DGPS corrections. Using this technique we are able to cancel common errors, between relatively close receivers, that distort positioning. These sources of error are:

GPS sources of error	
Common errors	**Non-common errors**
• Ephemerides errors • Satellites' clock errors • Atmospheric: tropospheric and ionospheric delays.	• Receiver's clock error • Multipath • Noise and interference • Hardware delays

Table 1: GPS sources of error

DGPS methodologies assume that the contribution of common errors to the total positioning inaccuracy is important when receivers are placed at a relatively short distance. The stronger this hypothesis the better the results.

Corrections can be applied in the **pseudorange domain** or in the **position domain**. The first just needs to know the positioning solution and the latter also demands satellites' positions and pseudoranges.

However, the available components for the development of this project are 2 single-frequency receivers **incapable to provide raw data** (restricted by the manufacturer). So, it is not possible to get receivers' pseudorange measurements, which are compulsory for pseudorange domain Differential GPS corrections.

At this point, a decisive controversy is presented. The proposals to overcome this affair are:

- ✗ **Obtain raw data** even it is not officially supported. Measuring pseudoranges is the main feature of GPS receivers and they are used to compute positioning, so these values are contained in the module. There is one configuration message that allows the receiver to output raw data, but it is unknown. It has been found several codes on some forums but for similar receivers (the previous generation of the available devices), and suggestions referred to the used ones, all have been attempted once it has been possible to communicate with the receivers and all failed.

- ✓ **Indirectly estimate raw data.** Pseudorange measurements can be estimated reversing navigation solution's computation process, if navigation solution, satellites' positions and a key parameter called **Range Residuals** (RR) are known.

- ✗ **Buy a pair of raw capable receivers.** This is the last option, since it implies extra costs and time. It will only be considered if none of the above is feasible.

It has been chosen **the second alternative**, since it uses the available resources, most of them granted by the Aerospace Department of ESEIAAT (Escola Tècnica Superior d'Enginyeries Industrial, Aeroespacial I Audiovisual de Terrassa), and allows to perform DGPS corrections to the all models even if they are not raw capable, supplying this way, a feasible enhancement service that can serve the school purposes.

6.2 Development of the project

In this section it is presented the procedure that is followed to accomplish the goals, introducing the tasks that must be executed by hardware components and software, and finally illustrating how all of them are integrated to attain a greater purpose.
First of all, before proceeding to expose the stages, let's recall the main features of the employed DGPS correction method:

Main Features of the Employed DGPS Correction Method
✓ **Absolute Positioning** → Since we want to link rover's position to the Earth and no to the base station. ✓ **Local Area** → as the goal is to cover a small area with high precision. ✓ **Code-based** → such is the only way that corrections can be performed with the available receivers. So they are applied on the pseudoranges. ✓ **Single-reference** → due to the limited number of available receivers and the size of the area to be covered. ✓ **A posteriori** → corrections are not applied in real time via data link but as post-processing in the computer.

Table 2: Main features of the employed DGPS correction method

6.2.1 Implemented DGPS methodologies

Four correction methodologies have been considered to achieve the goal of this project: one in the **position domain** (treats the error as offset) and three in the pseudorange domain. These are, **classical or common DGPS** corrections and a proposal of this study presented as two variants of the same idea. These methodologies are based on navigation solution's correction, and have been called **Navigation Solution– Real SVs** and **Navigation Solution – Virtual SVs**, respectively.

6.2.1.1 Position domain correction

Position domain correction is the simplest one. It does not require any knowledge about Space Vehicles (SV) position neither pseudoranges, only **rover position** and **base station measured and known position**.

Position domain correction consists on the addition of an offset applied directly on the final navigation solution, which is basically the difference between the true location of the base station and the base station navigation solution.

This can be written as:

$$\Delta\vec{r}(t) = \vec{r}_{true} - \vec{r}(t)_{BS} \tag{6.1}$$

$$\vec{r}(t)_{Rcorr} = \vec{r}(t)_{Runc} + \Delta\vec{r}(t) \tag{6.2}$$

Where $\vec{r}$ stands for the position vector and the subscripts *true, BS, Rcorr, Runc* mean true locations, base station, rover corrected and rover uncorrected respectively.

This technique is extremely simple, but several aspects have to be taken into account before applying it. Has to be ensured that both receivers, rover and base station, use the same set of satellites to make pseudoranges measurements all the time. Also, the same solution technique (least squares, Kalman filter, WLS, etc.), with the same parameters (filter tunings, smoothing time constants, etc.), must be warranted.

These conditions make of this, an impracticable real-time method, but can be performed as a post-processing correction.

This methodology assumes that base station and rover final solution errors are similar values. A reading of this, is that the method corrects the error introduced by the atmosphere over the final solution, which seems reasonable, but also errors due to receivers' hardware, noise and interference, and multipath (which is expected to be low but in those cases that it is not, makes the method inapplicable). The latter set of errors is independent from one receiver to another, so the lower weight of these errors the better the performance.

Note that, as the correction is applied over the final solutions, receiver and satellite clock corrections are already done. The same way tropospheric and ionospheric delays are attempted to be corrected by the receivers using models and correction parameters, this method fixes models' limitations.

6.2.1.2 Pseudorange domain corrections

Pseudorange domain corrections differ from the latter on where the corrections are applied. Instead of correcting the final solution, corrections are computed and applied over each pseudorange. That are also expected to be similar if receivers are relatively close.

Once pseudoranges have been corrected, the corrected solution is found by normal triangulation. In this project it has been used the least squares method, presented in section 6.2.1.2.4.

Finally, with the intention of having a measure of the confidence in results, dilution of precision is computed such is defined in section 6.2.1.2.5 or explained in the annex section A.1.2.

The essential parameters for computing pseudprange measurements are:

- ✓ **Rover position**
- ✓ **Base station position**
- ✓ **Base station true location**
- ✓ **Space Vehicles' positions** → computed from ephemerides.
- × **Pseudoranges** → Available GPS receivers do not output pseudoranges, they must be estimated.

Sections 6.2.1.3 and 6.2.1.4 explain how satellites' positions and pseudoranges are computed.

6.2.1.2.1 Common DGPS correction

The common or classic method compares the pseudorange measurement with the real range between the base station *m*, in the known position, to the satellite *k*. The difference, which is the error, is composed by the base station receiver clock delay, ionospheric and tropospheric errors plus a residual error. The correction is applied to the rover receiver *i*, expecting common ionospheric and tropospheric delays.

Let be P_m^k the measured pseudorange, ρ_m^k the geometric range, dt_m the base station clock offset, I_m^k the total ionospheric error from satellite *k* to the receiver *m*, T_m^k the tropospheric error and e_m^k the residual error that the least squares method tries to minimize.

$$P_m^k = \rho_m^k + cdt_m + I_m^k + T_m^k + e_m^k \quad (6.3)$$

The differential correction is:

$$\Delta P_m^k = \rho_m^k - P_m^k = -cdt_m - I_m^k - T_m^k - e_m^k \quad (6.4)$$

The same way, the measured pseudorange between satellite k and the rover receiver *i,* can be written as:

$$P_i^k = \rho_i^k + cdt_i + I_i^k + T_i^k + e_i^k \quad (6.5)$$

Under the hypothesis $I_m^k + T_m^k \approx I_i^k + T_i^k$, the pseudorange correction is applied to the rover GPS receiver pseudorange measurement:

$$P_{i,corr}^k = P_i^k + \Delta P_m^k = \rho_i^k + c(dt_i - dt_m) + e_i^k + (I_i^k - I_m^k) + (T_i^k - T_m^k) - e_m^k \quad (6.6)$$

Note that if the latter hypothesis is acceptable and once dt_i-dt_k is computed, the measured pseudorange will only differ from the real geometric range a distance of value e_i^k-e_m^k.

6.2.1.2.2 Navigation Solution correction – Real SVs

In this project it is proposed an alternative correction method to the classical one. As the goal of the project is to implement post-processing DGPS correction, it has been suggested taking advantage of this fact and compute corrections over the final navigation solution instead on pseudorange measurements.

The idea is to compute the range between the base station final solution and each Space Vehicle and compare it to the range between the real position of the reference and the satellites. Each difference is taken as correction and added to the range between the rover final solution and the satellites. Once each range is corrected the position of the rover is recomputed using the least squares method.

Equations (6.7) and (6.8) illustrate that idea.

$$\Delta R_m^k = \rho_m^k - R_m^k \tag{6.7}$$

$$R_{i,corr}^k = R_i^k + \Delta R_m^k \tag{6.8}$$

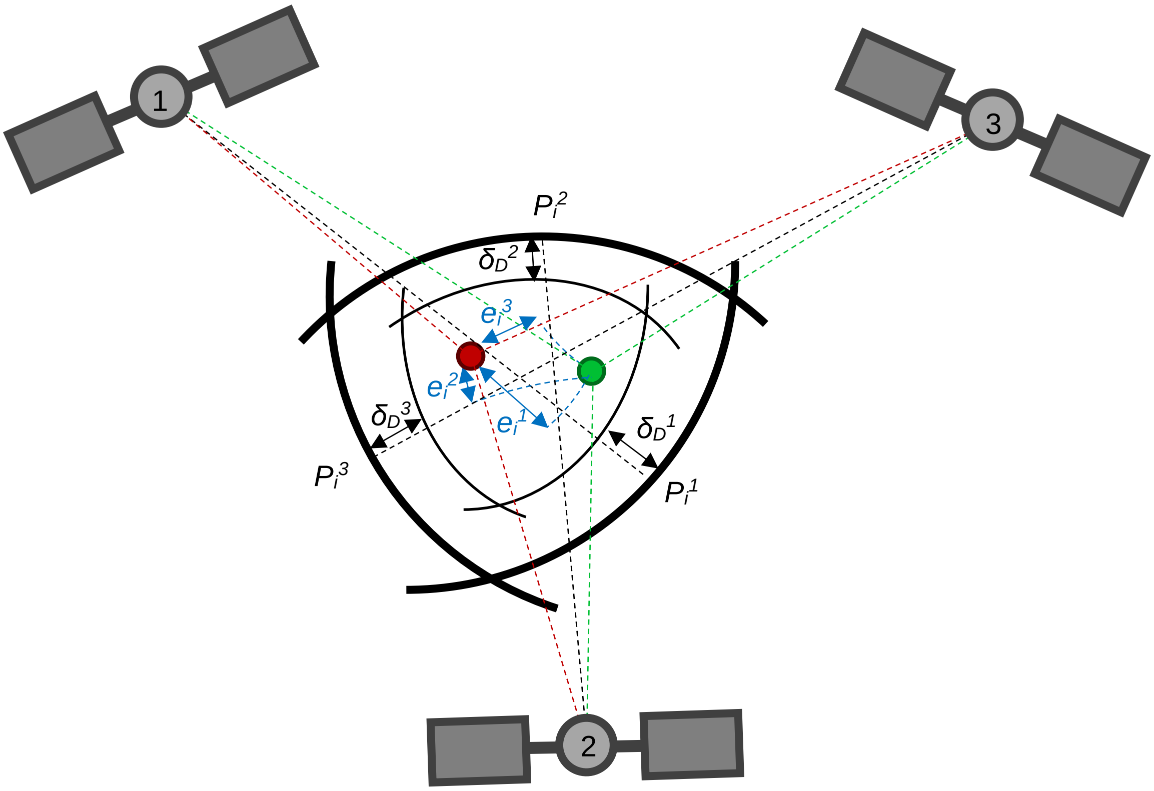
Where R_i^k stands for the range between navigation solution of the *i* receiver and the *k* satellite.

Note that, as ranges proceed from the final solution, receiver's clock delay has already been considered, and therefore this effect must not be taken into account while position is being computed. Otherwise, matrix scaling problems might appear.

Figure 1 illustrates the steps of the whole correcting process:

1. Receiver: pseudorange measurments.
2. Receiver: first corrections.
3. Receiver: computation of navigation solution.
4. Post-processing: computes geometric ranges to navigation solution.
5. Post-processing: computes geometric ranges to reference location.

6. Post-processing: computes the difference.



: Reference Location

: Navigation Solution

Figure 1: Navigation solution correction concept

6.2.1.2.3 Navigation Solution correction – Virtual SVs

It has to be note, that the correction method exposed in the latter section, does not use real pseudoranges, so no measure of the travel time of the signals has to be recomputed[1] and no correction is applied to them. Keeping on that idea, real Space Vehicles are not necessary in order to compute these corrections.

This section exposes an evolution of the latter methodology, where **virtually generated Space Vehicles have replaced real satellites.** This yields a great advantage, so the satellites can be placed wherever the user desires. Allowing an ideal satellite distribution, can fix real problems such as the undesired high Vertical Dilution of precision (VDOP), which is defined later in 6.2.1.2.5, so virtual satellites can be located even inside Earth. Also the number of satellites used is chosen by the user, so **the maximum potential of this proposal can be achieved.**

In this project, when this technique is applied, virtual satellites are located on a sphere surface centred at the real base station position with a radius specified by the user[2]. Note that satellites have a constant ECEF position (Earth-Centered Earth-Fixed coordinates), which means they are rotating with the Earth and we always see them fixed at the same position.

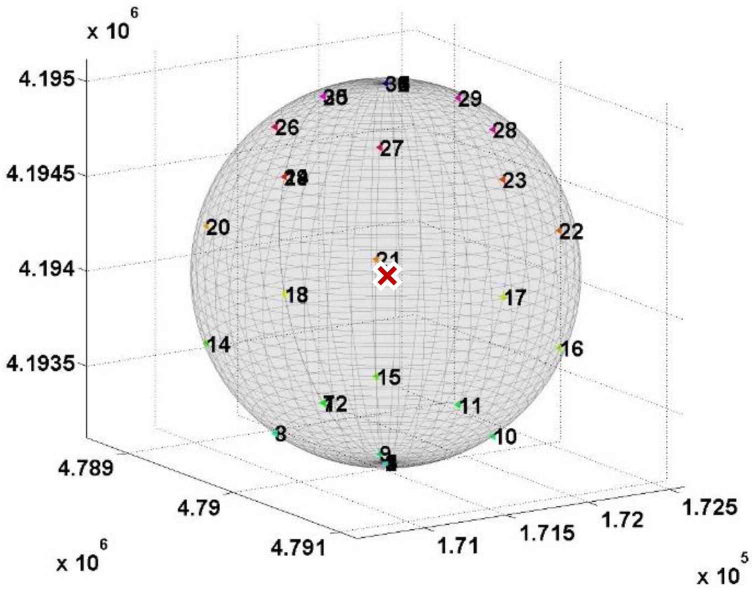


Figure 2: Virtual Space Vehicles' distribution (36 satellites, 1km of radius).

[1] Pseudoranges are used only to find the final navigation solution.
[2] Sometimes, if the radius is too low (~300m) convergence problems may occur.

6.2.1.2.4 Computation of Receiver Position – Least Squares Method

Once al pseudoranges have been corrected, it is time to recompute receiver position. To do that, it has been performed an iteratively process on the linearized least squares method. This process can be described as follows:

Variables legend	
i: receiver *i*	P_i^k: pseudorange from satellite *k* to receiver *i*[3].
k: satellite *k*	ρ_i^k: real geometric range between satellite *k* and receiver *i*.
m: total number of satellites.	dt_i: receiver clock offset
e_i^k: residual error	

Table 3: Variables lengend - Least squares method definition

$$P_i^k = \rho_i^k + cdt_i + e_i^k \tag{6.9}$$

$$\rho_i^k = \sqrt{(X^k - X_i)^2 + (Y^k - Y_i)^2 + (Z^k - Z_i)^2} \tag{6.10}$$

$$P_i^k = \sqrt{(X^k - X_i)^2 + (Y^k - Y_i)^2 + (Z^k - Z_i)^2} + cdt_i + e_i^k \tag{6.11}$$

Where, if common DGPS corrections have been employed, the position of the satellite *k* has to be corrected to compensate the Earth's rotation as it is explained in section 6.2.1.4.

Linearizing equation (6.11):

$$P_i^k = \rho_{i,o}^k - \frac{X^k - X_{i,o}}{\rho_{i,o}^k} - \frac{Y^k - Y_{i,o}}{\rho_{i,o}^k} - \frac{Z^k - Z_{i,o}}{\rho_{i,o}^k} + cdt_i + e_i^k \tag{6.12}$$

Where:

$$\rho_{i,o}^k = \sqrt{\left(X^k - X_{i,o}\right)^2 + \left(Y^k - Y_{i,o}\right)^2 + \left(Z^k - Z_{i,o}\right)^2} \tag{6.13}$$

[3] It has been considered all corrections except for receiver clock offset

Applying equation (6.13) to all satellites and building the matrix equation $AX = B$, an undetermined system is reached, such the imaginary spheres centred on the satellites with radius P_i^k do not converge into a single point. That is why the system shown in equation (6.14) needs to be build. Where $\hat{X}$ represents the best choice in terms of reducing the quadratic error as much as possible.

$$\hat{e} = b - A \cdot \hat{X} \qquad (6.14)$$

$$\left\{\begin{array}{l} \begin{bmatrix} -\dfrac{X^1 - X_{i,o}}{\rho_{i,o}^1} & -\dfrac{Y - Y_{i,o}}{\rho_{i,o}^1} & -\dfrac{Z^1 - Z_{i,o}}{\rho_{i,o}^1} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ -\dfrac{X^k - X_{i,o}}{\rho_{i,o}^k} & -\dfrac{Y^k - Y_{i,o}}{\rho_{i,o}^k} & -\dfrac{Z^k - Z_{i,o}}{\rho_{i,o}^k} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ -\dfrac{X^m - X_{i,o}}{\rho_{i,o}^m} & -\dfrac{Y^m - Y_{i,o}}{\rho_{i,o}^m} & -\dfrac{Z^m - Z_{i,o}}{\rho_{i,o}^m} & 1 \end{bmatrix} \begin{bmatrix} \Delta X_{i,1} \\ \Delta Y_{i,1} \\ \Delta Z_{i,1} \\ cdt_{i,1} \end{bmatrix} = \begin{bmatrix} P_i^1 - \rho_{i,o}^1 \\ \vdots \\ P_i^k - \rho_{i,o}^k \\ \vdots \\ P_i^m - \rho_{i,o}^m \end{bmatrix} \\ X_{i,1} = X_{i,o} + \Delta X_{i,1} \\ Y_{i,1} = Y_{i,o} + \Delta Y_{i,1} \\ Z_{i,1} = Z_{i,o} + \Delta Z_{i,1} \end{array}\right. \qquad (6.15)$$

The latter system, (6.15), has to be solved iteratively, only if $m \geq 4$, until the conversion criteria is achieved. In this project a **maximum variation of 1mm and 1ns for positioning and clock correcting** respectively, is warranted[4].

Note that for those correction methods where receiver clock offset has already been corrected, the latter system might be, if the correction is correct, bad scaled since $dt_{i,1}$ would be a value close to zero. Then, the following system must be applied:

$$\left\{\begin{array}{l} \begin{bmatrix} -\dfrac{X^1 - X_{i,o}}{\rho_{i,o}^1} & -\dfrac{Y - Y_{i,o}}{\rho_{i,o}^1} & -\dfrac{Z^1 - Z_{i,o}}{\rho_{i,o}^1} \\ \vdots & \vdots & \vdots \\ -\dfrac{X^k - X_{i,o}}{\rho_{i,o}^k} & -\dfrac{Y^k - Y_{i,o}}{\rho_{i,o}^k} & -\dfrac{Z^k - Z_{i,o}}{\rho_{i,o}^k} \\ \vdots & \vdots & \vdots \\ -\dfrac{X^m - X_{i,o}}{\rho_{i,o}^m} & -\dfrac{Y^m - Y_{i,o}}{\rho_{i,o}^m} & -\dfrac{Z^m - Z_{i,o}}{\rho_{i,o}^m} \end{bmatrix} \begin{bmatrix} \Delta X_{i,1} \\ \Delta Y_{i,1} \\ \Delta Z_{i,1} \end{bmatrix} = \begin{bmatrix} P_i^1 - \rho_{i,o}^1 \\ \vdots \\ P_i^k - \rho_{i,o}^k \\ \vdots \\ P_i^m - \rho_{i,o}^m \end{bmatrix} \\ X_{i,1} = X_{i,o} + \Delta X_{i,1} \\ Y_{i,1} = Y_{i,o} + \Delta Y_{i,1} \\ Z_{i,1} = Z_{i,o} + \Delta Z_{i,1} \end{array}\right. \qquad 6.16)$$

[4] This criteria is usually achived in 2 or 3 iterations.

Note that equation (6.16) can only be solved if the number of satellites is equal or higher than 3, $m \geq 3$.

Figure 3 illustrates an example of a triangulation problem solved by least squares method.

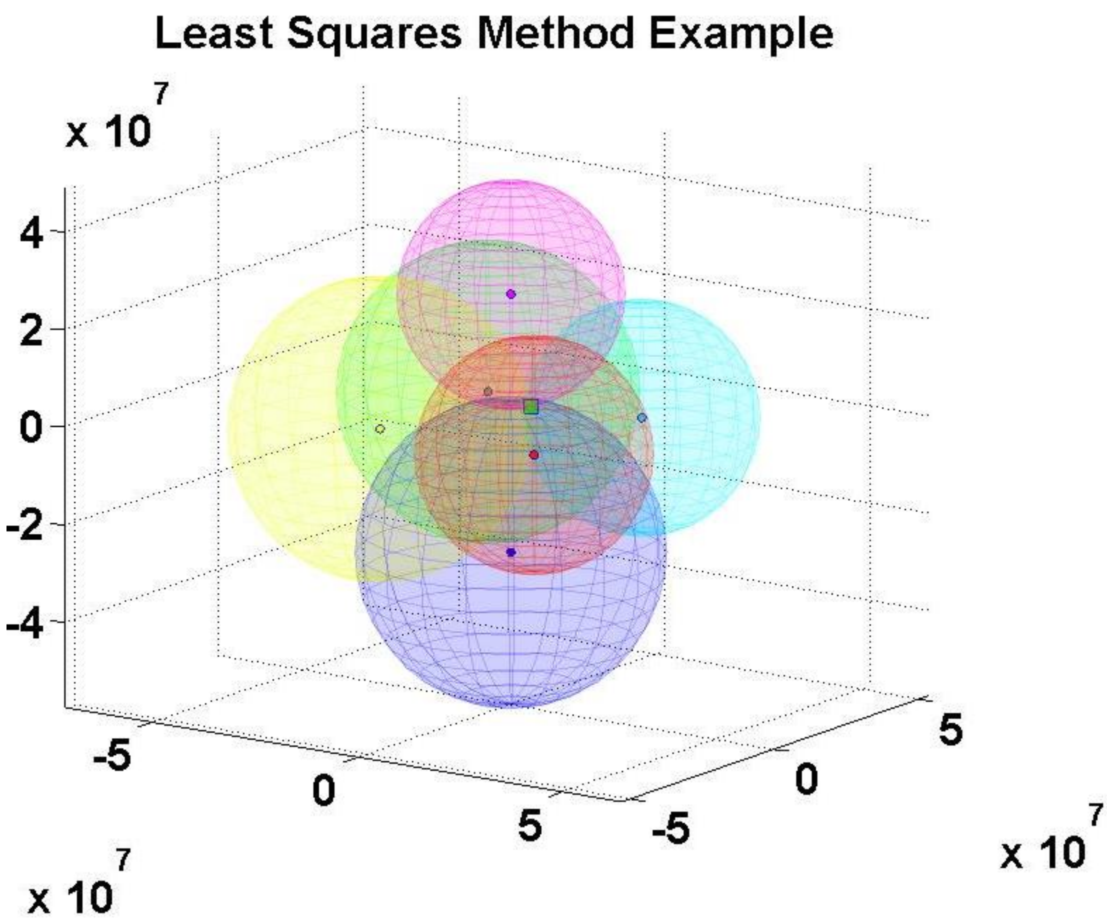


Figure 3: Least squares method example

6.2.1.2.5 Compute Dilution Of Precision

Once the final position has been calculated, Dilution Of Precision parameters can be obtained from their definitions:

$$Q = (A^t \cdot A)^{-1} = \frac{1}{\sigma_0^2} \cdot \begin{bmatrix} \sigma_e^2 & \sigma_{en} & \sigma_{eu} & \sigma_{e,cdt} \\ \sigma_{ne} & \sigma_n^2 & \sigma_{nu} & \sigma_{n,cdt} \\ \sigma_{ue} & \sigma_{un} & \sigma_u^2 & \sigma_{u,cdt} \\ \sigma_{cdt,e} & \sigma_{cdt,n} & \sigma_{cdt,u} & \sigma_{cdt}^2 \end{bmatrix} \quad (6.17)$$

Geometric: $$GDOP = \sqrt{tr(Q)} \quad (6.18)$$

Position: $$PDOP = \sqrt{\frac{\sigma_e^2+\sigma_n^2+\sigma_u^2}{\sigma_0^2}} \quad (6.19)$$

Horizontal: $$HDOP = \sqrt{\frac{\sigma_e^2+\sigma_n^2}{\sigma_0^2}} \quad (6.20)$$

Vertical: $$VDOP = \frac{\sigma_u}{\sigma_0} \quad (6.21)$$

Time: $$TDOP = \frac{\sigma_{cdt}}{\sigma_0} \quad (6.22)$$

Dilution of precision reflects the confidence of the method with its result. High values of dilution of precision implies a wide region of possible solutions, and therefore, low confidence.

6.2.1.3 Satellite positioning

As detailed in section A.1.6 of the annex A, each satellite position is determined by a packet of ephemeris, which allows to estimate the Space Vehicle's path until it is updated.

In this section it is explained how to obtain ephemeris and satellite clock correction parameters from the navigation message, and how to compute Space Vehicles' position.

6.2.1.3.1 Navigation Message - Clock parameters and Ephemeris

The first step to compute the position of a satellite is to get clock correction parameters and ephemeris. These parameters are extracted from the navigation message, which structure is defined in [15], the most relevant information is pointed out in this section and must be complemented with annex C since some tables has been omitted.

The Navigation Message is divided in 5 300-bits long subframes, each of them composed by 10 30-bits words. Each subframe begin with the **Telemetry (TLM)** and **Hand-Over Word (HOW)** followed by 8 data words. Navigation message has a total length of 1500 bits and it is transmitted at rate of 50 bps, where subframes 4 and 5 shall be subcommutated 25 times each, so the complete data message shall require the transmission of 25 full frames.

However, for our purpose subframes 4 and 5 are not of interest. They contain the Almanac, which is not relevant if Ephemerides can be acquired, and ionospheric parameters.

Clock parameters are transmitted as a part of the subframe 1 of the navigation message and **Ephemeris parameters are contained between subframe 2** and **3**. In 6.2.1.3.1.2 it is explained how these subframes of the navigation message are obtained and which words it is possible to access (3 to 10 without parity bits plus the first HOW).

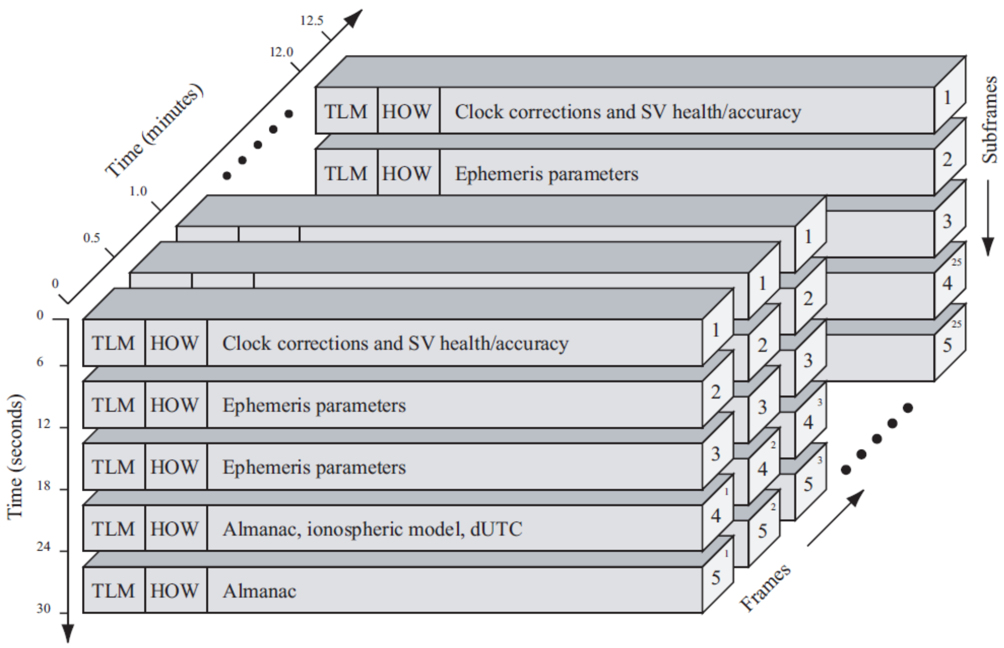


Figure 4: Navigation message frames, image from [4]

6.2.1.3.1.1 Telemetry and Hand-Over Word

Each subframe of the navigation message begins with the Telemetry and Hand-Over Word, recall that in this project we only have access to these words contained in the first subframe. As every word each one is 30-bits long and are structured as shown in figures 5 and 6.

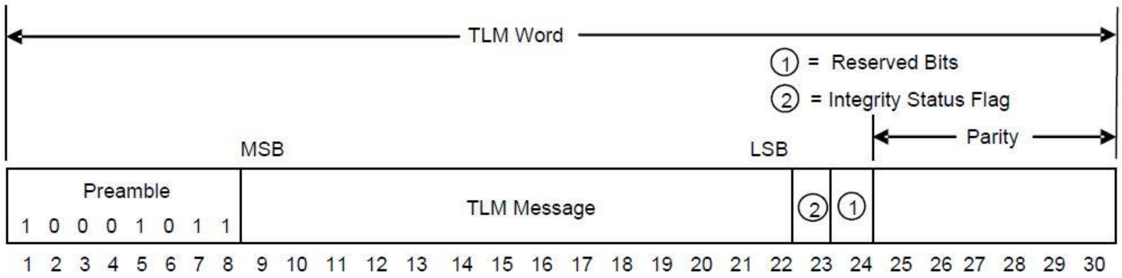


Figure 5: Telemetry word structure. Image from [15]

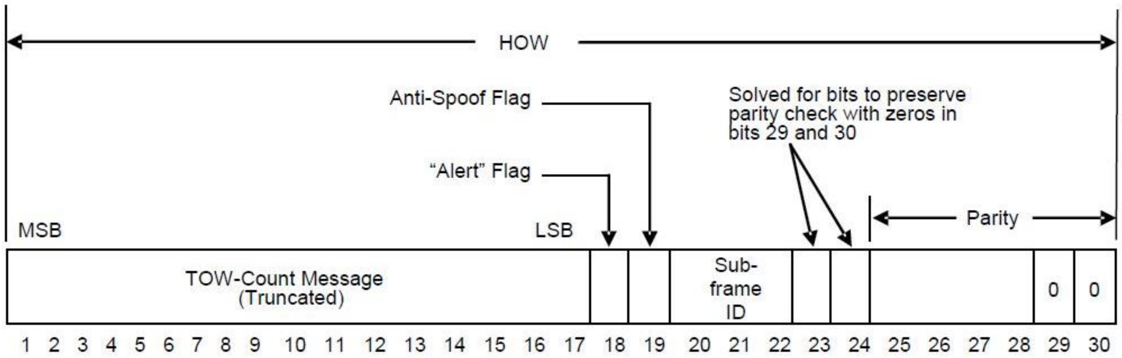


Figure 6: Hand-over word, image from [15]

<u>Telemetry Word (TLM)</u>

If the preamble is correct the following packet of data, preamble included, is taken as a subframe of the navigation message. The TLM message contains key information such as the Transmission Time. Also, as in every word 30-bit, TLM contains 6 bits (LSB) of parity check. Parity check it is used to check for any misinterpreted bit.

Hand-Over Word (HOW)

HOW includes a truncated version of the TOW referred as the truncated Z-count, which is the number of seconds passed since the last GPS week rollover [5] in units of 1.5s and truncated to the 17 MSB. In figure 7, it is shown the relation between GPS time, Z-count and the truncated Z-count.

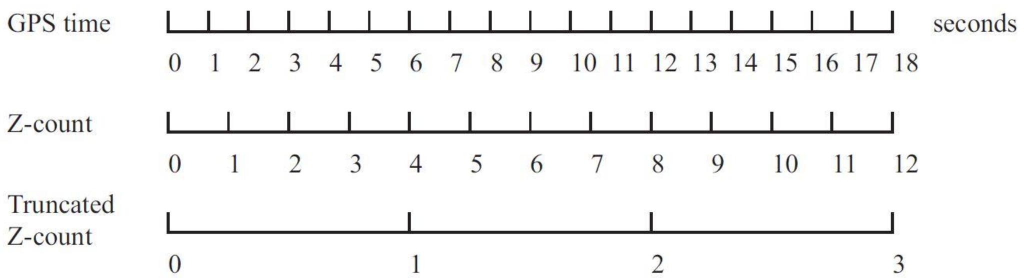


Figure 7: GPS time, Z-count and truncated Z-coount, image from [4]

6.2.1.3.1.2 Subframe 1 – Satellite Health and Clock parameters

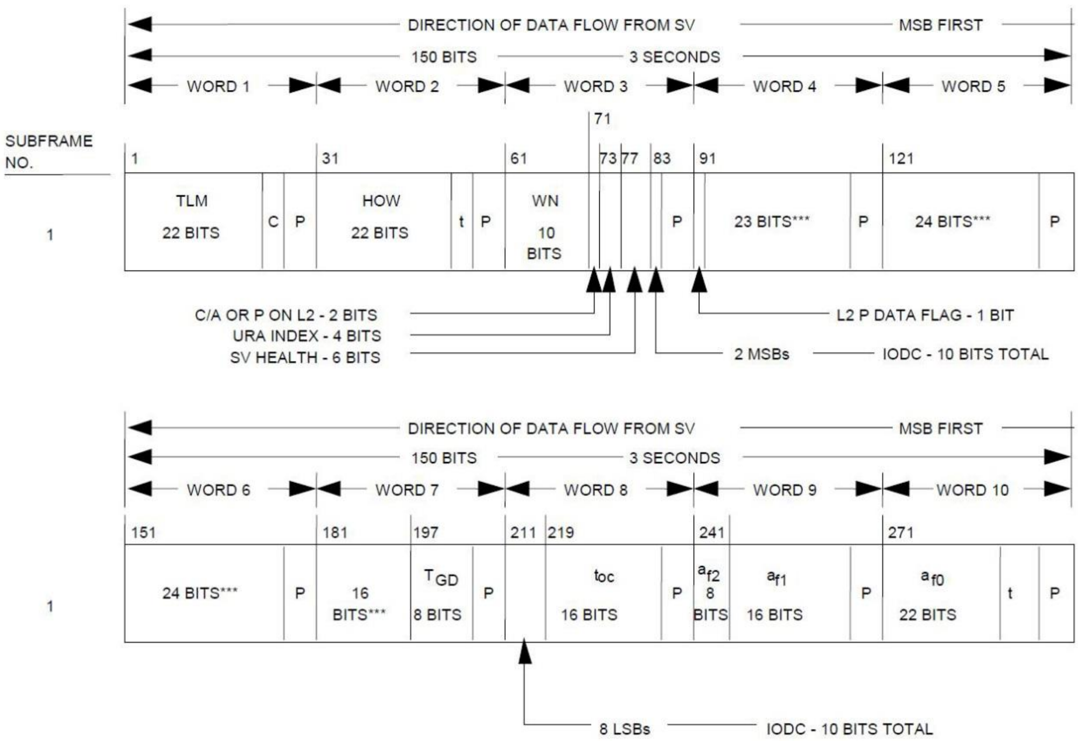


Figure 8: Navigation Message Subframe 1 structure, image from [15]

[5] Rollover occur every week at midnight between Saturday and Sunday. Must not confuse with the moment when the week number emitted by the satellites turns back to zero. This happens after 1023 weeks, such SV week number is emitted in 10 bits, approximately 20 years and it is also called rollover.

6.2.1.3.1.3 Subframe 2 and 3 – Satellite Ephemeris data

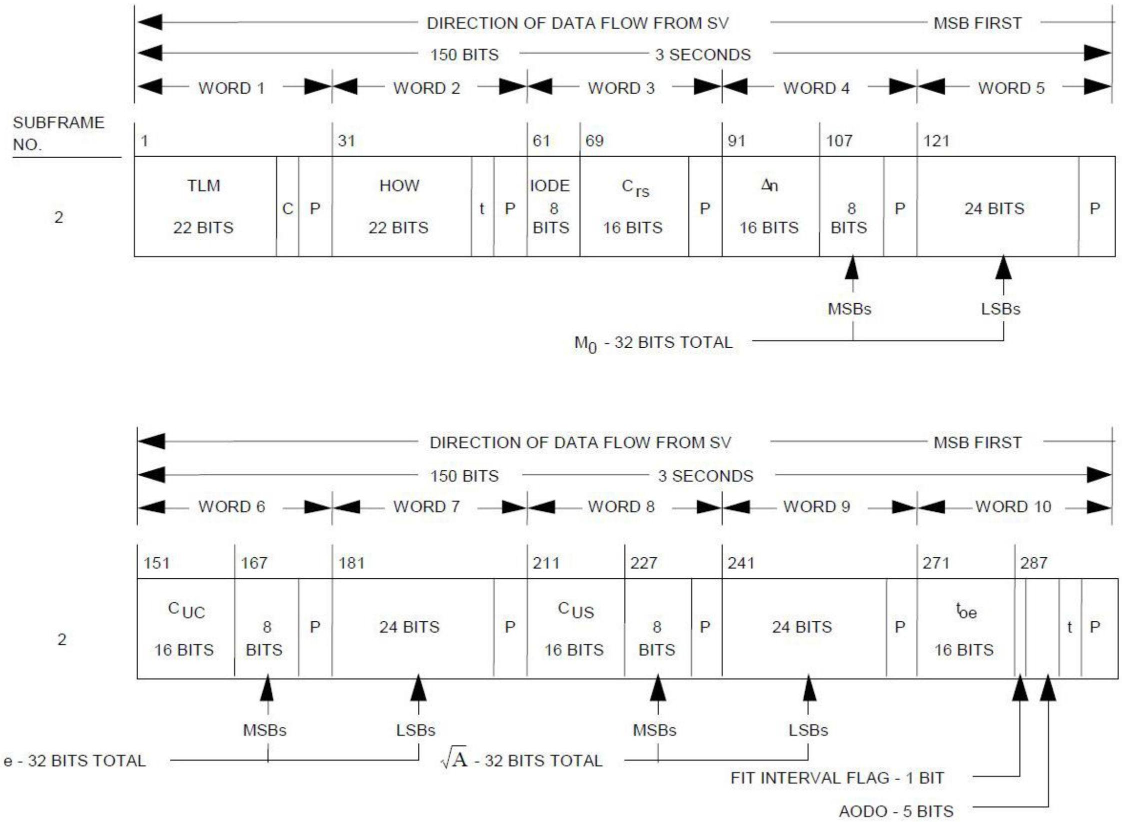


Figure 9: Navigation Message Subframe 2, image from [15]

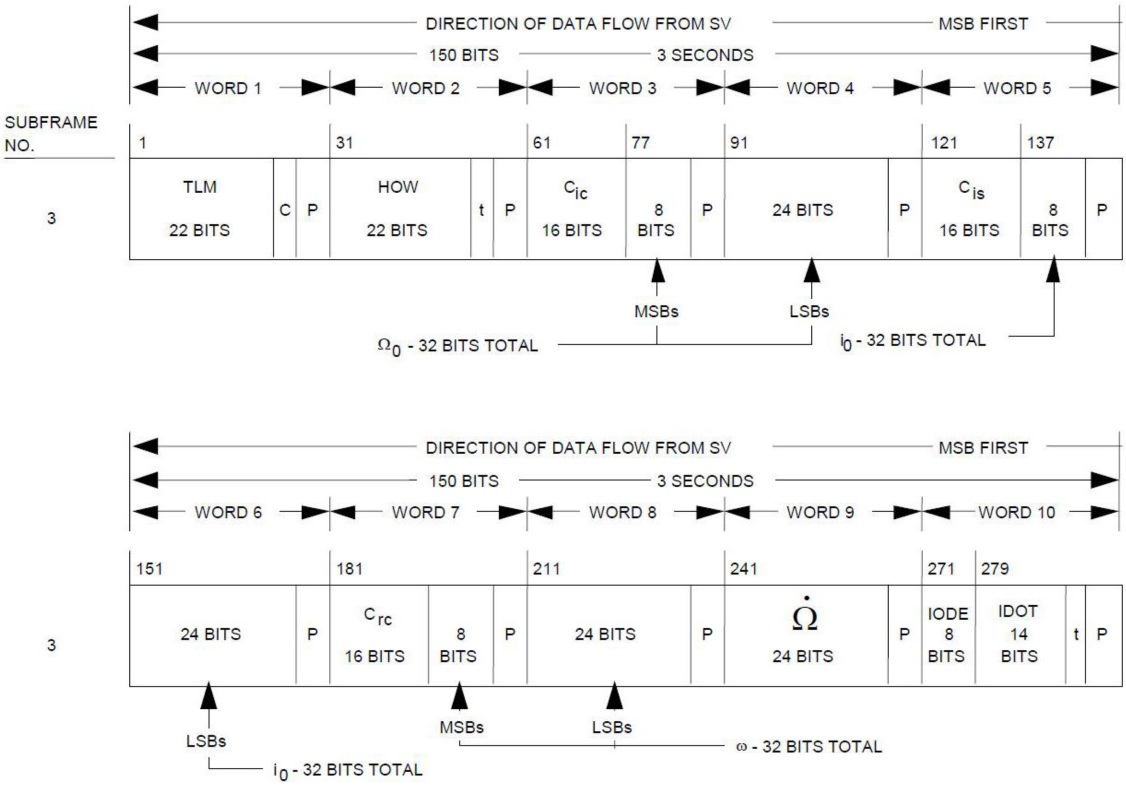


Figure 10: Navigation Message Subframe 3, image from [15]

Subframe 2 and 3 - Satellite Ephemeris Data: Definitions	
Parameter	**Definition**
M_0	Mean Anomaly at reference time
Δn	Mean Motion Difference from Computed Value
e	Eccentricity
$\sqrt{A}$	Square Root of the Semi-Major Axis
Ω_0	Longitude of the Ascending Node or Orbit Plane at Weekly Epoch
i_0	Inclination Angle at reference time
ω	Argument of Perigee
$\dot{\Omega}$	Rate of Right Ascension
IDOT: $\dot{i} = di/dt$	Rate of Inclination Angle
C_{uc}	Amplitude of the Cosine Harmonic Correction Term to the Argument of Latitude
C_{us}	Amplitude of the Sine Harmonic Correction Term to the Argument of Latitude
C_{rc}	Amplitude of the Cosine Harmonic Correction Term to the Orbit Radius
C_{rs}	Amplitude of the Sine Harmonic Correction Term to the Orbit Radius
C_{ic}	Amplitude of the Cosine Harmonic Correction Term to the Angle Inclination
C_{is}	Amplitude of the Sine Harmonic Correction Term to the Angle Inclination
t_{oe}	Reference Time Ephemeris (Time Of Ephemeris)
IODE	Issue Of Data: Ephemeris

Table 4: Subframe 2 and 3. Definition of parameters, according to [15]

6.2.1.3.2 Satellite Clock and Time Correction

Receiver clock delay cannot be globally predicted such depends on each receiver clock, which furthermore, is not very precise[6], and it must be computed as an unknown with the final position. However, the number of Space Vehicles of a GNSS constellation is limited and satellite clocks are so much precise, if besides a correction of their small delay is applied, the error introduced by these components is very low.

As explained in A.2.1 of annex A, each satellite clock delay is corrected with a second-order polynomial which of parameters are given by the ephemeris. Time corrections are applied as follows:

First let's recall that pseudoranges are computes as:

$$P_i^k = c \cdot (t_i - t_k) = c \cdot \tau_i^k \quad (6.23)$$

Where t_i and t^k are the measure of the arrival time to the receiver *i* and the emission time of the satellite *k* respectively, measured by their own clocks. These measures might differ from the GPS time at which that events really occurred. This can be expressed as:

$$t_i = t_i^{GPS} + dt_i \quad (6.24)$$

$$t_k = t_k^{GPS} + dt^k \quad (6.25)$$

Where dt^k is the satellite clock delay given by the ephemeris defined in annex A section A.2.2

$$dt^k = a_{fo} + a_{f1} \cdot \left(t^k - t_{oe}\right) + a_{f2} \cdot \left(t^k - t_{oe}\right)^2 \quad (6.26)^7$$

And equation (7.1) can be rearranged as:

$$t^k = t_i - \frac{P_i^k}{c} = t_i - \tau_i^k \quad (6.27)$$

Combining equation (7.3) and (7.5), t_k^{GPS} can be expressed as:

$$t_k^{GPS} = t_i - \tau_i^k - dt^k \quad (6.28)$$

Where t_k^{GPS} is the signal emission time referred at GPS time and, t_i and τ_i^k are known parameters.

[6] Compared with Space Vehicles' atomic clocks.
[7] Note that relativistic effect is included in the bias parameter (a_0).

6.2.1.3.3 Determining Space Vehicle's position

It is not the goal of this project to dig out in orbital mechanics, the interested reader can expand this topic by reading [2] or the can find a summary in annex C. The computation of the required parameters it is shown in table 5.

Computation of a Satellite's ECEF Position		
Equation No.	**Equation**	**Name**
(7.7)	$a = (\sqrt{a})^2$	Semimajor axis
(7.8)	$n = \sqrt{\frac{\mu}{a^3}} + \Delta n$	Corrected mean motion $\mu = 398{,}600.5 \cdot 10^8\ m^3/s^2$
(7.9)	$t_k = t - t_{oe}$[8]	Time from ephemeris epoch
(7.10)	$M_k = M_o + n(t_k)$	Mean anomaly
(7.11)	$M_k = E_k - e\sin E_k$	Eccentric anomaly[9]
(7.12)	$\sin v_k = \frac{\sqrt{1-e^2}\sin E_k}{1-\cos E_k}$	True anomaly
(7.13)	$\cos v_k = \frac{\cos E_k - e}{1-\cos E_k}$	
(7.14)	$\phi_k = v_k + \omega$	Argument of latitude
(7.15)	$\delta\phi_k = C_{us}\sin(2\phi_k) + C_{uc}\cos(2\phi_k)$	Argument of latitude correction
(7.16)	$\delta r_k = C_{rs}\sin(2\phi_k) + C_{rc}\cos(2\phi_k)$	Radius correction
(7.17)	$\delta i_k = C_{is}\sin(2\phi_k) + C_{ic}\cos(2\phi_k)$	Inclination correction
(7.18)	$u_k = \phi_k + \delta\phi_k$	Corrected argument of latitude
(7.19)	$r_k = a(1 - e\cos E_k) + \delta r_k$	Corrected radius
(7.20)	$i_k = i_0 + \left(\frac{di}{dt}\right)t_k + \delta i_k$	Corrected inclination
(7.21)	$\Omega_k = \Omega_0 + (\dot{\Omega} - \dot{\Omega}_e)(t_k) - \dot{\Omega}_e t_{oe}$	Corrected longitude of node
(7.22)	$x_p = r_k \cos u_k$	In-plane x position
(7.23)	$y_p = r_k \sin u_k$	In-plane y position
(7.24)	$x_s = x_p \cos\Omega_k - y_p \cos i_k \sin\Omega_k$	ECEF x-coordinated
(7.25)	$y_s = x_p \sin\Omega_k + y_p \cos i_k \cos\Omega_k$	ECEF y-coordinated
(7.26)	$z_s = y_p \sin i_k$	ECEF z-coordinated

Table 5: Computation of a satellite's ECEF position from ephemeris parameters, as is defined in [15]

[8] t stands for the current time and t_{oe}, Time Of Ephemeris, is the time at which the astronomical parameters are valid.
[9] Must be solved iteratively for E_k

In figure 11 can be seen a plot of the active visible Space Vehicles' paths. Although it is hard to appreciate from a picture, all satellites' paths are approximately tangential to the mean orbital radius sphere's surface.

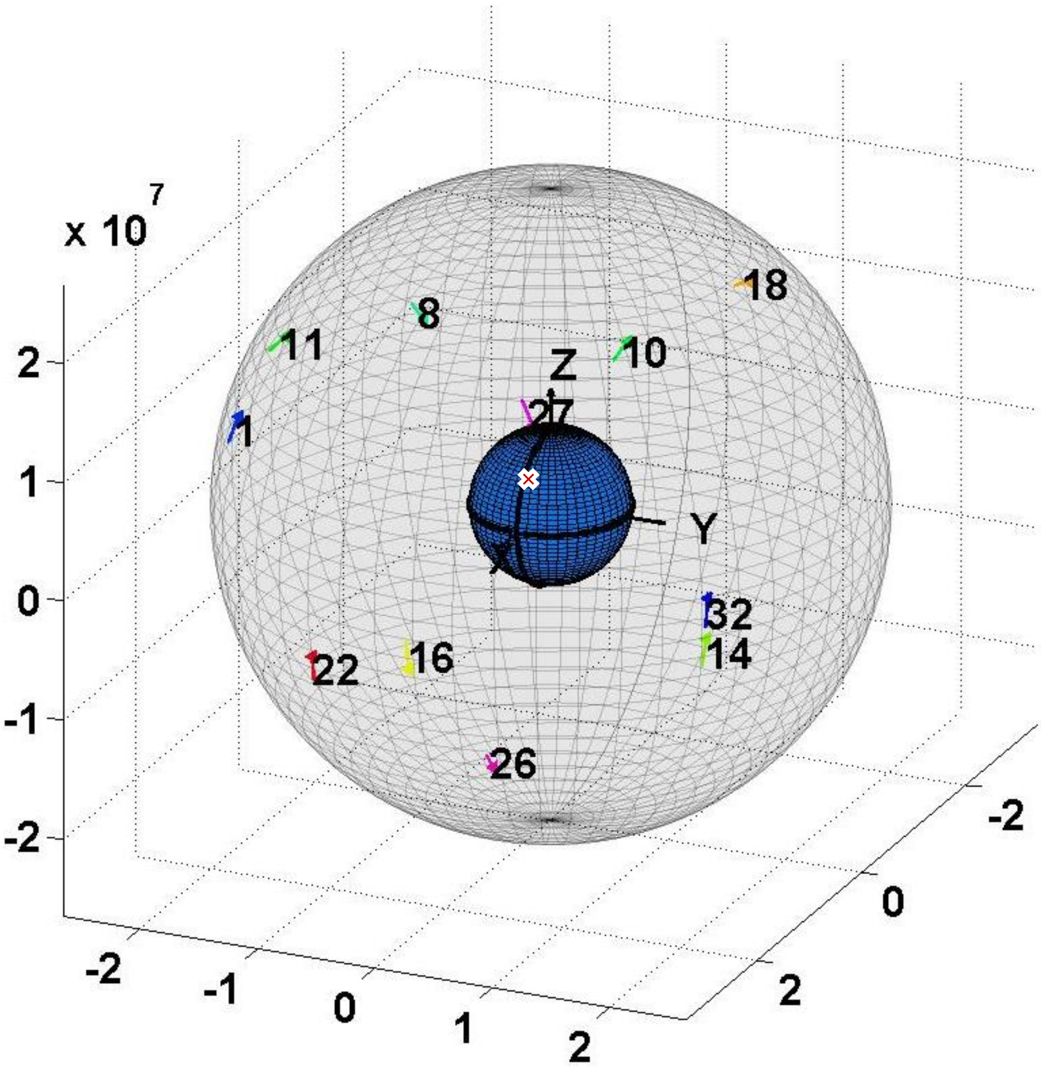


Figure 11: Visible healthy satellites' paths tracked along test 1, approximately 10 min

6.2.1.4 Pseudorange Estimation

Pseudorange measurements are essential if DGPS corrections (the common method) wants to be computed. As mentioned before, the available GPS receivers do not allow to output raw data, so pseudoranges cannot be obtained as GPS output parameter and must indirectly recomputed. That estimation can be performed if the active satellites' positions, navigation final solution and Range Residuals are known.

Range Residuals is the parameter that relates the original measured pseudoranges with the ranges between Space Vehicles and the navigation solution. It is a key parameter for those correction methods that require information about the initial pseudoranges used to compute the navigation solution. Range Residuals are defined, [16], as shown in equation (6.29)

$$Range\ Residuals = Calculated\ Range - Estimated\ Range \qquad (6.29)$$

Understanding calculated range as the initial pseudorange before any correction and estimated range as the range between the final solution and the satellite.

Equation (6.30) illustrates pseudoranges between satellite *k* and receiver *i* computation.

Geometric Range: $$\rho_i^k = \sqrt{(X_k - X_i)^2 + (Y_k - Y_i)^2 + (Z_k - Z_i)^2} \qquad (6.30)$$

Pseudorange: $$P_i^k = \rho_i^k + RR_i^k \qquad (6.31)$$

Where *P* stands for pseudorange, *ρ* for geometric range of the final navigation solution and *RR* for Range Residuals.

Figure 12 illustrates this concept.

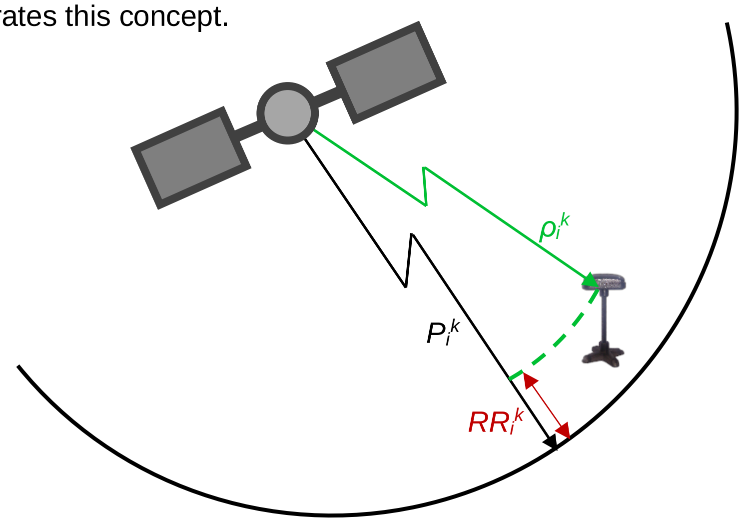


Figure 12: Range Residual, pseudorange and geometric range relationship

It is important to note that, geometric ranges and pseudoranges are measures of the distance travelled by the signal, and the effect of the Earth's rotation needs to be considered.

This effect is accounted by correcting the Space Vehicle position at the arrival time as follows:

Earth's rotation rate: $\dot{\omega}_e = 7.292115147\ rad/s$ (6.32)

Travel time: $\Delta t = \frac{\rho^k_{i\_uncorrected}}{c}$ (6.33)

Earth's rotated angle: $\Delta\theta_e = \dot{\omega}_e \cdot \Delta t$ (6.34)

Correcting SV position:

$$\begin{bmatrix} X_k \\ Y_k \\ Z_k \end{bmatrix} = \begin{bmatrix} \cos(\Delta\theta_e) & \sin(\Delta\theta_e) & 0 \\ -\sin(\Delta\theta_e) & \cos(\Delta\theta_e) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_{k\_unc} \\ Y_{k\_unc} \\ Z_{k\_unc} \end{bmatrix} \quad (6.35)$$

6.2.2 Overall view of the procedure

Before corrections could be applied, data must be previously collected, stored, decoded and processed. Figure 13 illustrates the overall procedure.

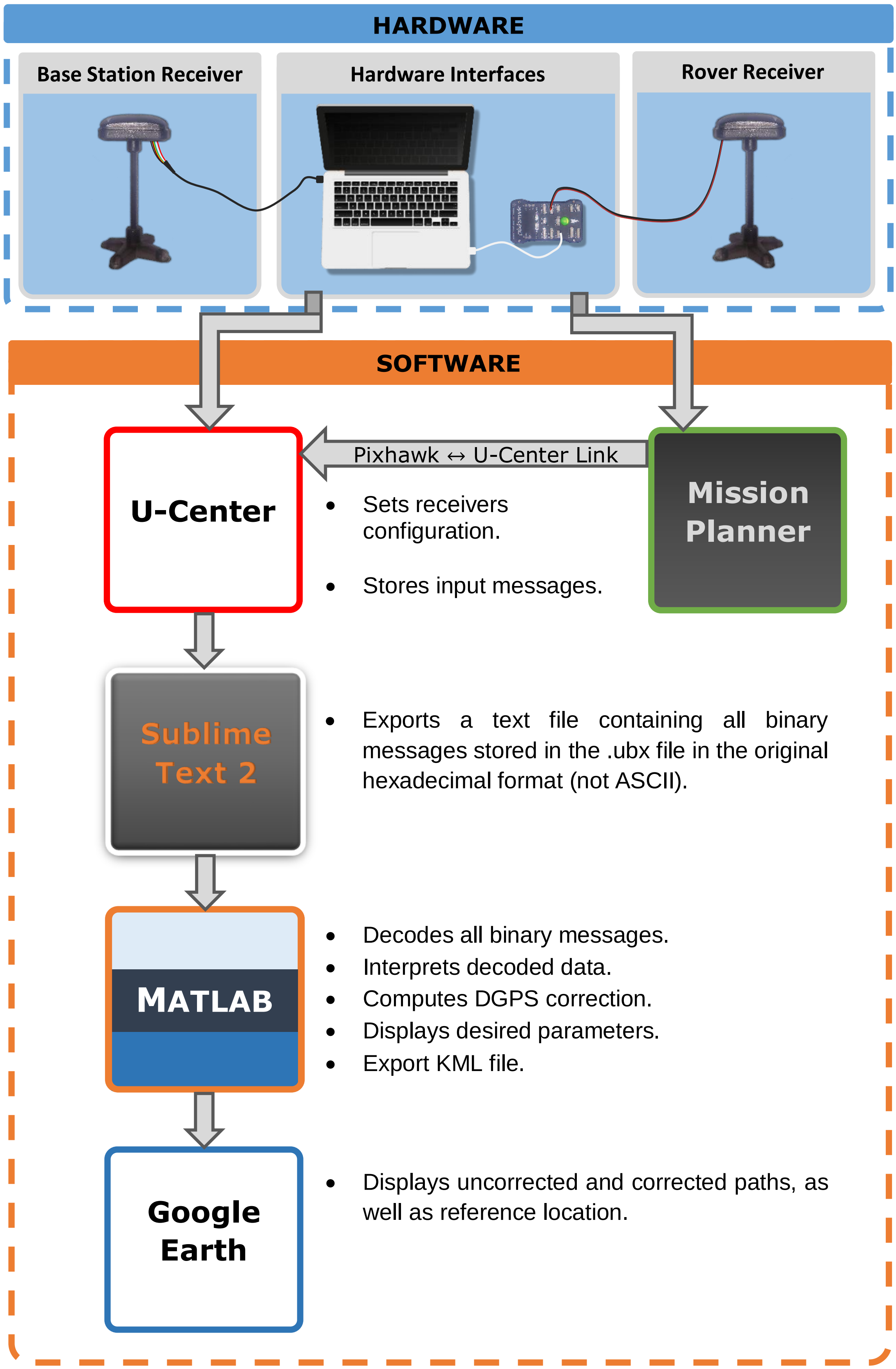


Figure 13: Overall scheme of the procedure

Note that, in figure 13 both receivers are connected, directly or indirectly, to the same laptop. This is done when measures taken at the same location want to be compared, which is the simplest test and the one taken as example. Section 7.2 exposes more configurations.

7. Hardware and connections

In this section are detailed the main features of the GPS receivers, as well as the elements that allow them to communicate with the laptop.

All hardware components involving this project are:

- GPS receiver (x2)
- APM 2.5 Flight Control Cable DF13 6 Position Connector (x2).
- *Pixhawk Autopilot*
- Standard USB to micro USB cable
- USB to TTL-232R Serial cable
- Laptop (x1 or x2)

Where the most important components (GPS receivers, *Pixhawk* and one of the APM 2.5 Flight Control Cable DF13 6 Position Connector) have been granted by the Aerospace Department of ESEIAAT (UPC).

7.1 GPS receivers

The procedure followed to achieve the goal of the project, begins by acquiring pseudoranges measurements and computing navigation solution (depending on the correction method it is enough with the first process[10]). Both tasks are carried out by the GPS receivers, whose good performances[11] are essential for the success of the project.

The model of GPS receiver used in this project is the same for both, rover and base station, and it is the *3DR U-Blox GPS with Compass Kit,* which is based on *U-Blox NEO-7N* GPS module and it is supplied by *3D Robotics*. This model integrates the so-

[10] Recall that pseudoranges are not transmitted to the user and must be estimated.
[11] Understood as having good electronics, strong against interferences and internal noise, with low hardware delay, good sensitivity, etc.

mentioned *U-Blox NEO-7N* GPS module with the *Taoglas GPS patch 1575 MHz antenna* and the *HMC5883L* digital compass.

The components integrating the whole module are presented[12] below:

Main features of U-Blox NEO-7N			
Receiver type	GPS L1 C/A		
	GLONASS L1 FDMA		
Supply	2.7 V – 3.6 V		
	17 mA at 3V (5mA Power Save Mode)		
Interfaces	UART		
	USB		
	SPI		
	DDC (I^2C)		
Features	Programmable (Flash)		
	Data logging		
	Additional SAW		
	Additional LNA		
	RTC crystal		
	Temperature Compensated Crystal Oscillator		
	Active antenna/LNA supply (Opcional or requires external components) (Posar per referència)		
	Active antenna/LNA control		
	Unavailable Raw data output		
Performance	Navigation update Rate	Up to 10Hz	
	Tracking and Navigation Sensitivity	-162 dBm	
	Accuracy	2.5m	
	Acquisition	Cold starts	29 s
		Aided starts	5 s
		Reacquisition	1 s

Table 6: Main features of U-Blox NEO-7N module, more information can be found in [7]

12 *HMC5883L* digital compass is not presented such it is not used for this project's purpose.

Main Features of the *Taoglas GPS patch 1575 MHz antenna*	
Frequency Groups	UHF (1 ~ 2 GHz)
Frequency (Centre/Band)	1575 MHz
Antenna Type	Ceramic Patch
Number of Bands	1
Return Loss	10dB
Gain	1.55 dBi[13]
Height	4 mm
Applications	GPS

Table 7: Main features of the Taoglas GPS patch 1575 MHz antenna, information obtained from [18]

The whole module is protected by a case that has a mast to improve GPS performance and presents the following specifications and features:

Features and Specifications of 3DR U-Blox GPS with Compass Kit
✓ *U-Blox NEO-7N* module ✓ 5 Hz update rate ✓ 25 x 25 x 4 mm ceramic patch antenna (*Taoglas GPS patch 1575 MHz)* ✓ LNA and SAW filter ✓ Rechargeable 3V lithium backup battery ✓ Low noise 3.3V regulator ✓ I2C EEPROM for configuration storage ✓ Power and fix indicator LEDs ✓ Protective case ✓ APM compatible 6-pin DF13 connector ✓ Exposed RX, TX, 5V and GND pad ✓ 38 x 38 x 8.5 mm total size, 16.8 grams.

Table 8: Features and specifications of 3DR U-Blox GPS with compass kit [6]

[13] dBi mean that the gain is refererd to an isotropic radiator, which it has been takes as 0 dB.

Figure 14 illustrates the GPS receiver and its pinout.

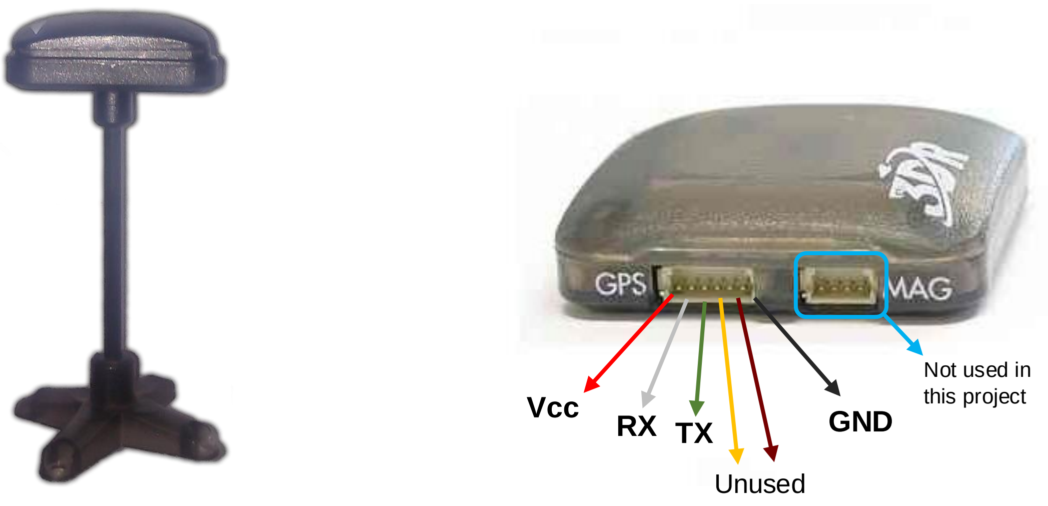


Figure 14: Available GPS receiver, own image and edited picture from https://3drobotics.zendesk.com/hc/en-us

7.2 Connections Schematics

Driving data from the GPS receivers to the laptop, is equally important than collecting data. There are 2 lines that do that, one for the rover and one the base station, and, even though both connect the receivers with the laptop, each one presents its own particularities.

Before detailing them, recall that, in figure 13, only 1 laptop is used and both receivers are connected to it. As previously said, this configuration allows to compare measures taken at the reference location, which is the basic experiment to test DGPS performances, but it is limited to this purpose.

In order to allow measurements far from the reference location, a second laptop where the connections are the same with respect the first case, is required.

Finally, the process to perform inflight corrections, for the last tests and the final debugged DGPS corrections, consists in 2 stages: inflight measurements, where the GPS receiver is connected to the *Pixhawk*; and DGPS correcting process, where the flight data is transferred to the computer through the *Pixhawk* like in the previous configurations.

Figure 15 illustrates these configurations.

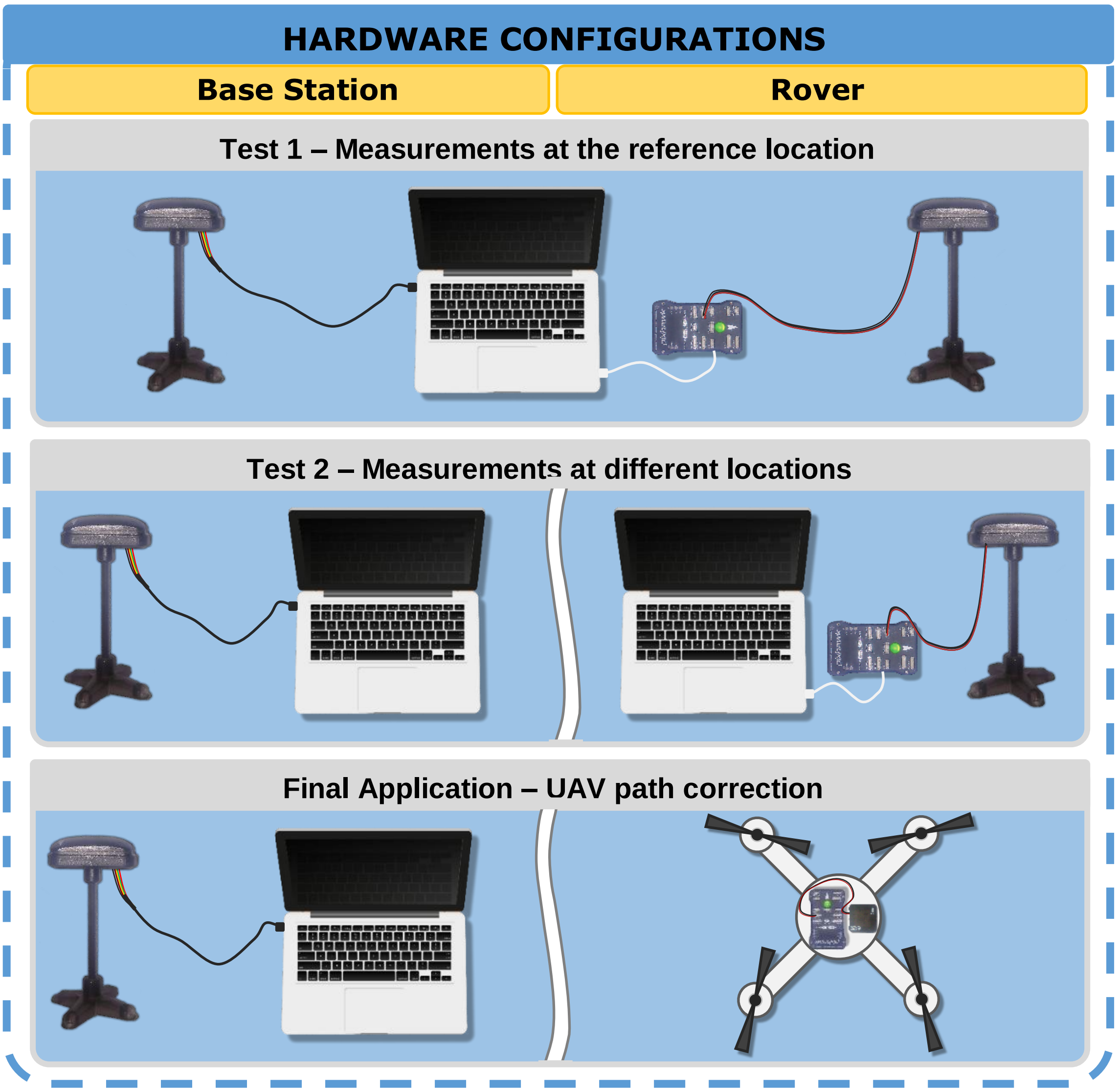


Figure 15: Possible configurations of the hardware components

7.2.1 Rover

The GPS receiver acting as rover, is connected to the laptop by a two-stage link. First, it is connected to the *Pixhawk*, whatever the configuration, through the APM 2.5 Flight Control Cable DF13 6 Position Connector provided by *3D Robotics* as part of the GPS+compass *Pixhawk* kit[14].

Figure 16: Pixhawk, micro USB and APM 2.5 Flight Control Cable DF13 6 Position Connector, images from https://pixhawk.org, http://mikrokopter.altigator.com/ and http://reciclatecnologia.com/.

And second, simultaneously or after the flight (depending on the configuration), the *Pixhawk* is connected to the laptop by a Standard USB to micro USB cable as shown in

The first and second configurations, use *Pixhawk* as a passthrough as it is explained in section 8.1.

[14] The kit just provides one so the other unit has to be bought.

7.2.2 Base Station

Base station GPS receiver is able to communicate with the laptop by a single-stage connection using a USB to TTL-232R Serial cable (3.3V) plus a DF13 header, which has been cut out from one of the APM 2.5 Flight Control Cable DF13 6 Position Connector.

The joint is made as shows figure 17.

Figure 17: USB to TTL-232R serial cable to DF13 6-pin joint

TTL-232R + DF13 6-pin joint Colour Code			
Name	**Symbol**	**DF13 Colour**	**TTL Colour**
Power Supply	Vcc – 3.3V	**Red**	**Red**
Transmitter	TX	**White**	**Orange**
Receiver	RX	**Green**	**Yellow**
Unused		**Yellow**	**Green**
Unused		**Brown**	**Brown**
Ground	GND	**Black**	**Black**

Table 9: TTL-232R and DF13 6-pin joint colour code

There reasons why base station and rover connections are different and they are not both connected through *Pixhawks* or TTL-232R Serial cables are exposed next.

The first case is not possible because the localhost cannot attend multiple requests at the same time. Furthermore, it is enough waste of resources using once a so capable device such as *Pixhawk* just as a passthrough.

Upon the second case, as previously said, to make this last cable, 2 components are required, a USB to TTL-232R Serial cable and a APM 2.5 Flight Control Cable DF13 6 Position Connector. This means time and money, so it has been arrived to an optimal solution.

8. Software

In the whole project four different software have been required in three different steps to reach the final solution and one more to visualize it. Each of them explained below.

8.1 Mission Planner

Mission Planner is an open-source ground station application for planes, copters or rovers using a compatible flight controllers such as *ArduPilot, Multiwii or Pixhawk.* It is capable of monitoring telemetry in real time, analyse flight data after flying, plan autonomous missions or arm the aircraft.

None of that functionalities have been used in this project but another very important one.
As previously said, *Mission Planner* can interact with the *Pixhawk* autopilot, where the rover GPS receiver is connected to. So it allows to read stored GPS data for computing corrections, if the flight configuration is set, or, in lack of a pair of FTDI cables, it acts as a link between rover GPS receiver and U-C*enter* for the ground-based configurations.
This is possible due to *Mission Planner* allows to create an exclusive passthrough for the GPS at localhost port 500, where *U-Center* has access to.

8.2 U-Center

U-Center is a software developed by *U-Blox* used as interface of *U-Blox* GNSS receivers. It allows to monitor receivers' performance in reals time, as well as to set up their desired configuration and store the data got from the receivers.
It is able to display all messages that receivers are allowed to send but **it is not possible to work with the input data**. This fact adds value to the implemented code.

8.2.1 Messages and Protocols

U-Center can read and understand data coming from receiver coded in two protocols, NMEA and UBX. Combining the information obtained from some key messages coded in these protocols, it has been possible to implement this project. Understanding messages' structure is crucial in the decoding process. Next, are introduced receivers' protocols and those messages that have been used or had any utility at some point. However, each message's structure must be perfectly known such it can be decoded, the full description of these messages is detailed in annex D and can be also found in [19].

8.2.1.1 NMEA

NMEA protocol is the specification within GPS receiver communication is defined. It was developed by the National Marine Electronics Association (NMEA) to define the interface between marine electronic equipment [16].

NMEA format it is defined by lines of data called sentences that contains totally self-contained information. Each sentence begin with dollar symbol '$' and ends with an asterisk '*' followed by two checksum hexadecimal numbers. Message information is ASCII coded text contained between those characters in a single line. It begins with a pair of letters that identifies the GNSS type followed by three more specifying the message class. The content fields sent by each message is separated by commas until the checksum and it cannot be longer than 80 visible characters plus the line terminators.

NMEA sentences general structure it is shown in figure 18.

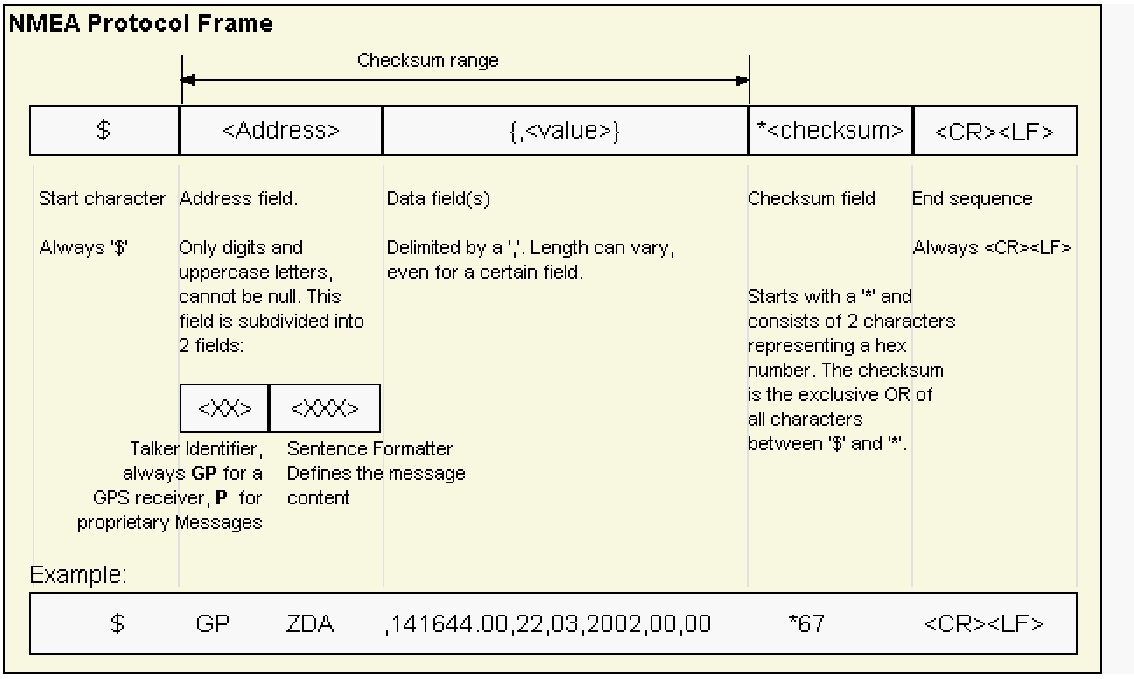


Figure 18: NMEA Protocol frame, as specified in [17]

A part from standard sentences, NMEA allows to define your proprietary sentences that can be used by an individual company. For instance it could be used PUBX as NMEA proprietary sentences of *U-Blox*., but it has not been necessary.

8.2.1.2 UBX

UBX is a *U-Blox* proprietary GNSS protocol used to transmit receiver data to a computer. It uses 8-bit data and it is checksum protected.

All UBX messages start with 2 synchronization bytes (B5 62) identifying UBX protocol followed by class and ID specification. Payload length is variable and determined by the own message through a 2-byte length field next to ID byte.

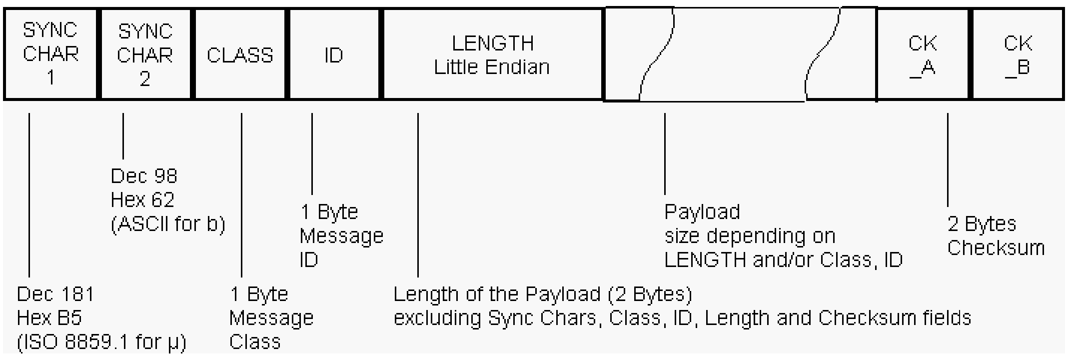


Figure 19: UBX frame structure, defined in [17]

8.2.2 Decoded messages

Those messages considered useful will be decoded by the implemented code. Obviously its structure must be entirely identified.

Decoded messages description	
Message	**Description**
NMEA procotol	
GGA	Global Positioning System fix data
GRS	GNSS Range Residuals
GSA	GNSS DOP and Active Satellites
TXT	Text transmission
UBX protocol	
AID-EPH	Aiding Ephemeris Data for a SV
AID-HUI	GPS Health, UTC and ionosphere parameters
NAV-DOP	Dilution Of Precision
NAV-POSECEF	Position Solution in ECEF
NAV-POSLLH	Geodetic Position Solution
NAV-SOL	Navigation Solution Information

Table 10: Decoded messages description

8.3 Sublime Text

Sublime Text is a free cross-platform source code editor. It has not been used for its main purpose which is to write code but to open *U-Blox Log Files* (.ubx), which contains binary data of all messages from the receiver, in the original hexadecimal format and export this data into a text file. Other applications such as *NotePad* or *Matlab* translate messages into ASCII code, losing information.

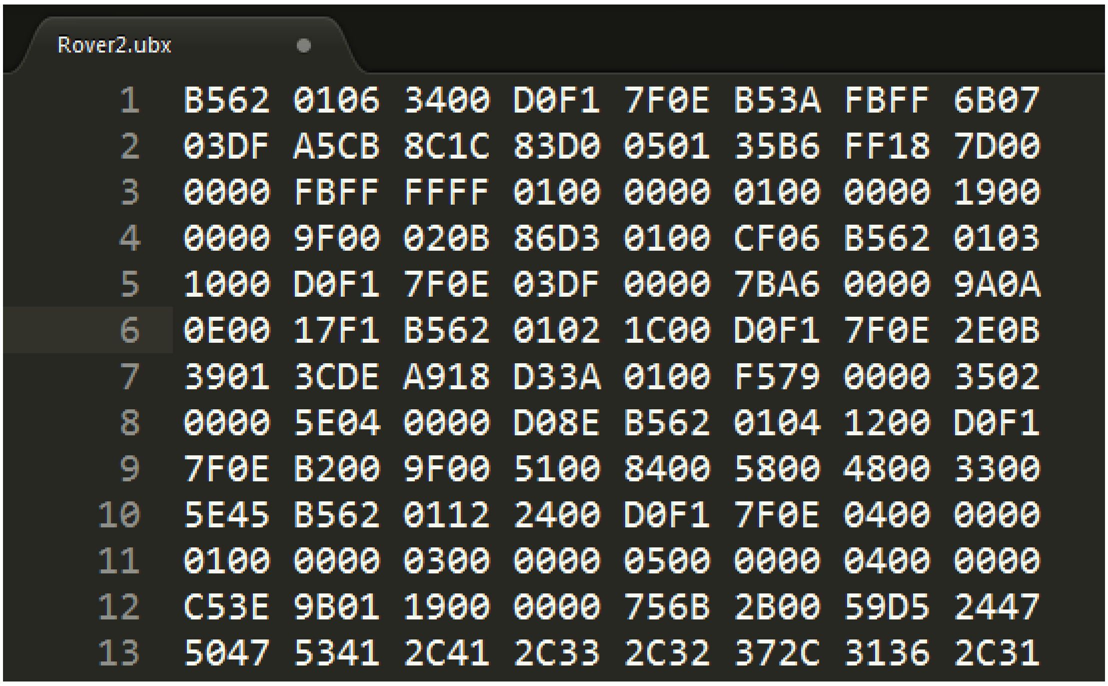


Figure 20: Sublime text screenshot showing the firsts 13 lines (of 77756) of binary data file about to be exported

8.4 Implemented MATLAB Code

In this section, it is presented the implemented code based on *MATLAB* that performs all the tasks previously exposed. The code **reads** and **decodes the input text files**, rover and base station, according to protocols' guidelines exposed in 8.2.1 and annex D. From the decoded binary data the information is extracted and processed. All the date is properly classified in structures and the user has access to all received and processed data. Along this **preparation stage** data is verified, satellites are tracked, timings are unified, and so on. Then the selected correcting method is applied and position recomputed (if pseudorange domain corrections are demanded), according to section 6.2.1. After all, results are plotted, saved and into a KML file.

Even though this task has consumed the major part of the time, only the most important functions are presented through flowcharts in order to keep an adequate extension of the report and the interest of the reader. All functions, except graphs and post-processing, and the main structures, used to store and deal with the decoded data, are detailed in annexes E and F respectively.

This has been the largest and more complex task, not only because of the code implementation but the extensive **validation process** that has been submitted.

8.4.1 Flowcharts

Note that, the flowcharts have been simplified, otherwise it would result excessively large and unclear.[15]

Also, it has been drawn as parallel processes some tasks that could be performed at the same time if enough computers work together. In the current code version this is not contemplated.

[15] For instance, the code has some tools to prevent user mistakes and internal errors that are not shown in the flowcharts.

8.4.1.1 Overall view of the algorithm

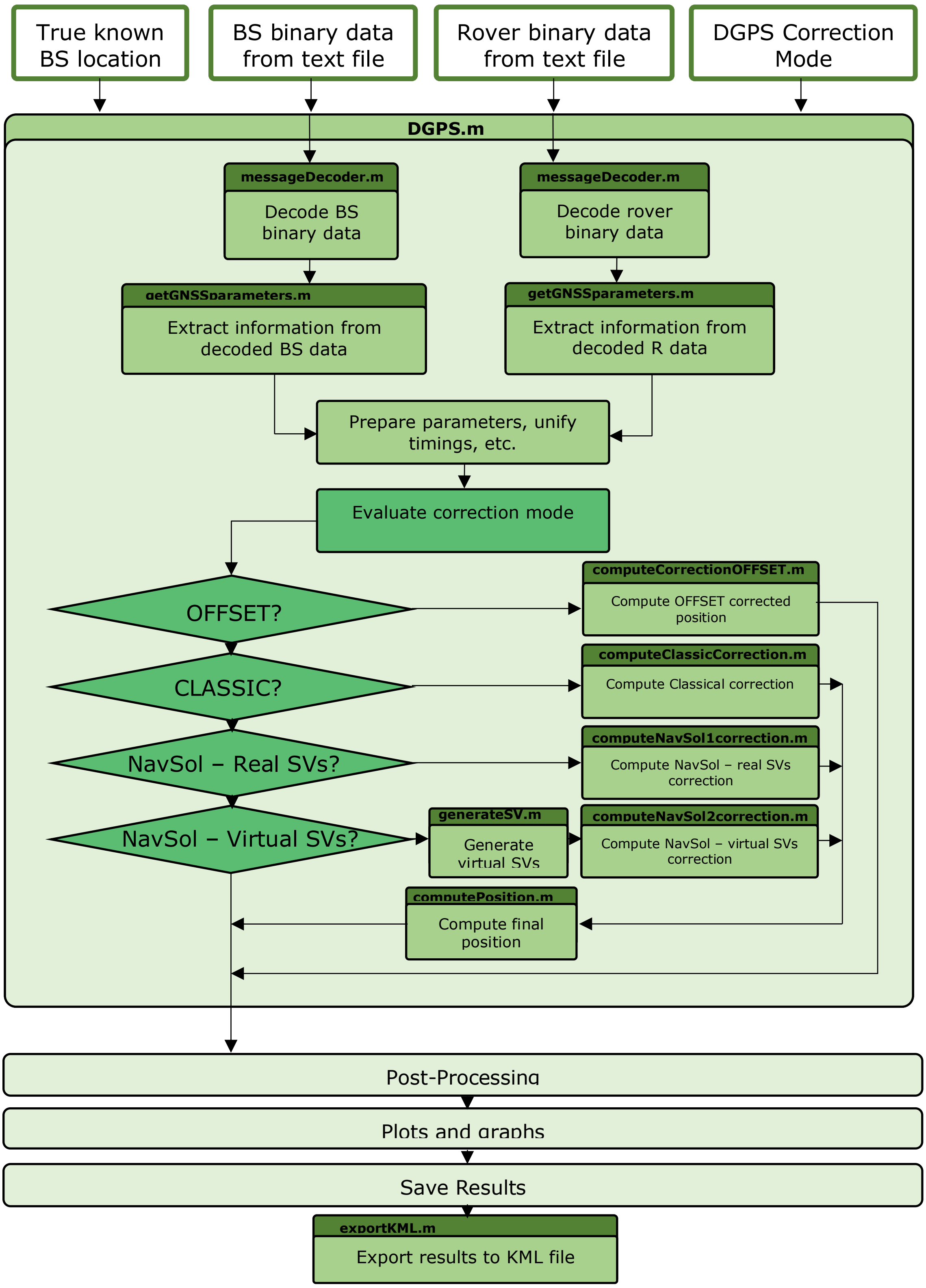


Figure 21: Flowchart of DGPS.m

8.4.1.2 Message Decoder

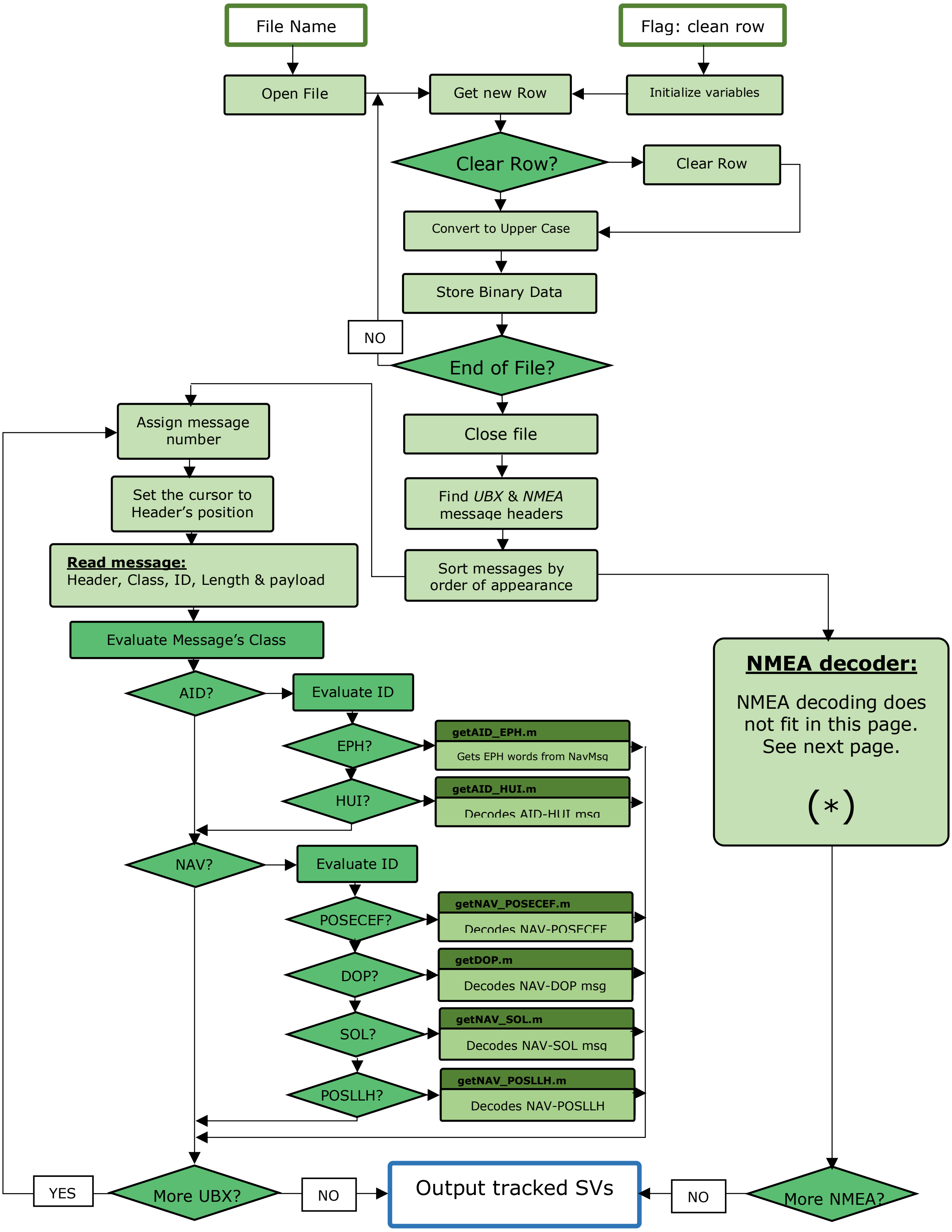


Figure 22: Flowchart of messageDecoder.m

(*) NMEA Decoder

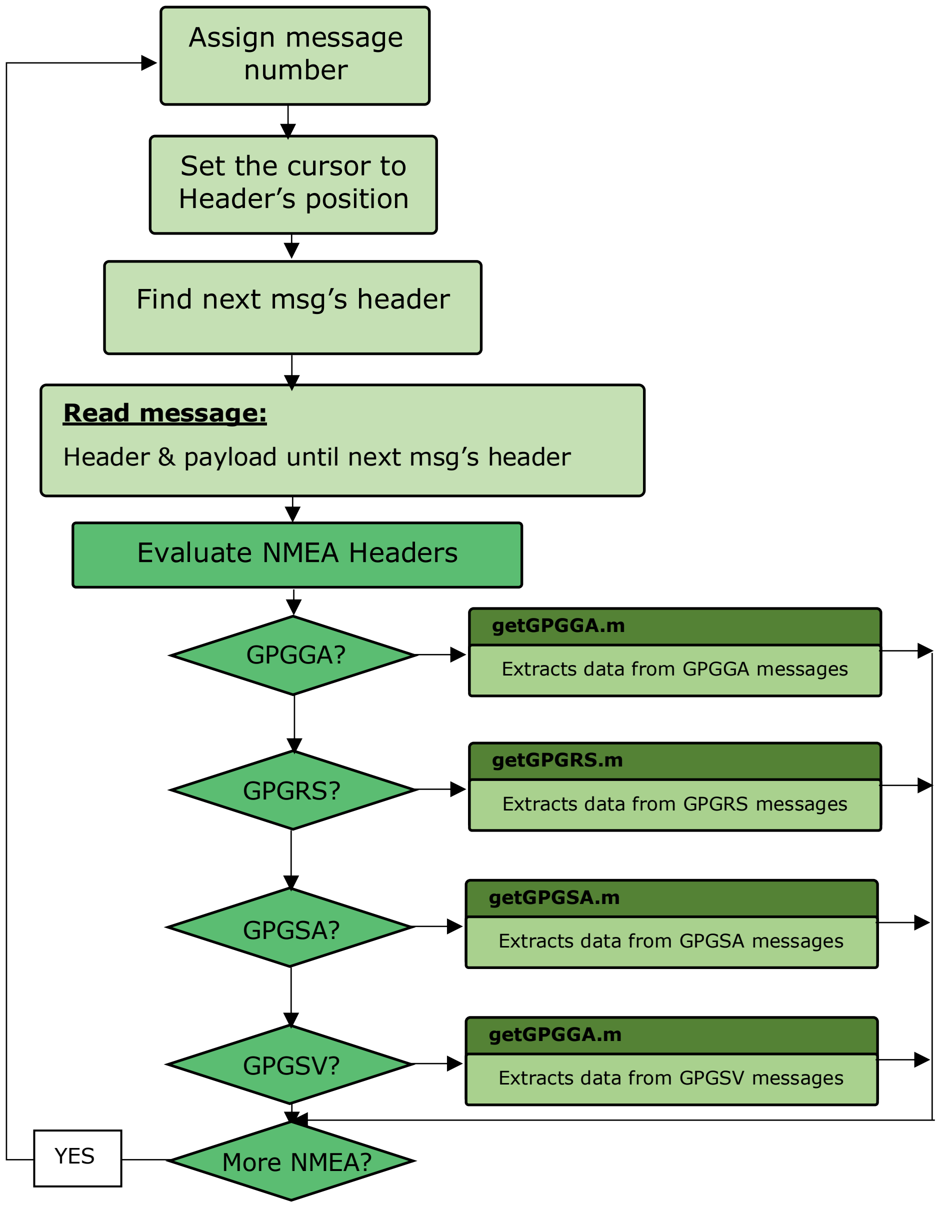


Figure 23: NMEA decoder, attachment to flowchart of messageDecoder.m

8.4.1.3 Get GNSS parameters

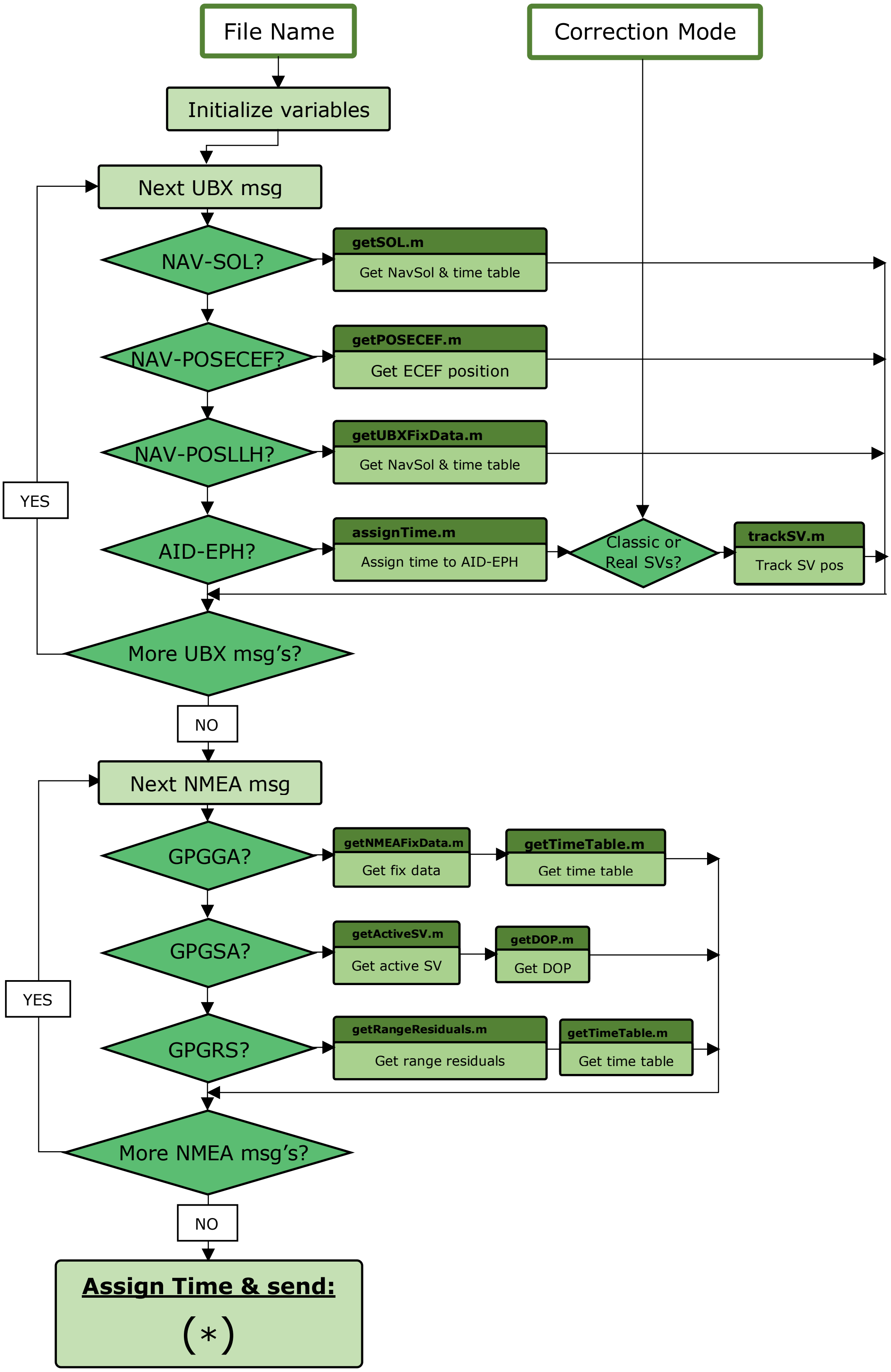


Figure 24: Flowchart of getGNSSparameters.m

(∗) Assign Time and send

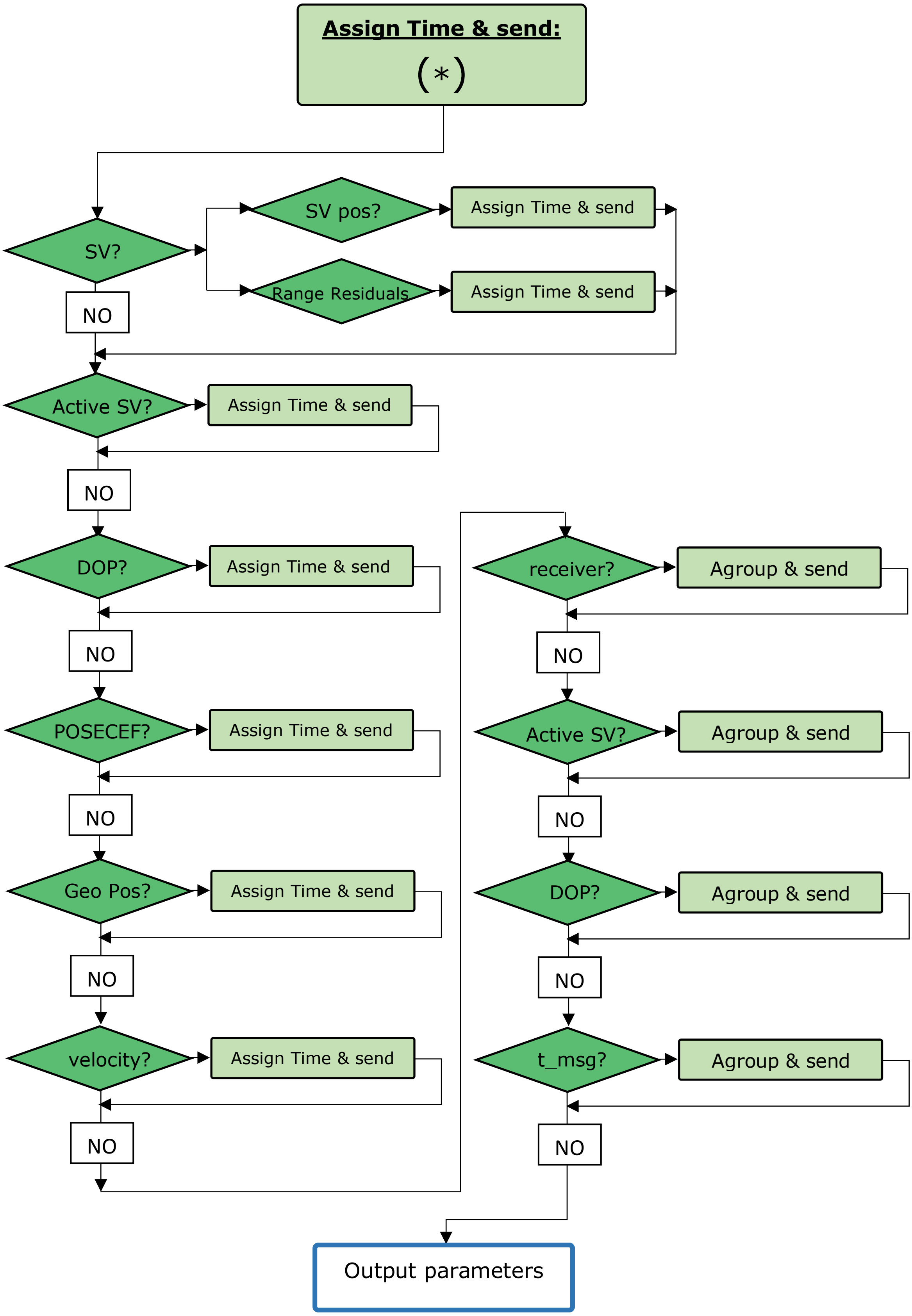


Figure 25: Time assignment and sending attachment to flowchart of getGNSSparameters.m

8.4.1.3.1 Track Space Vehicles

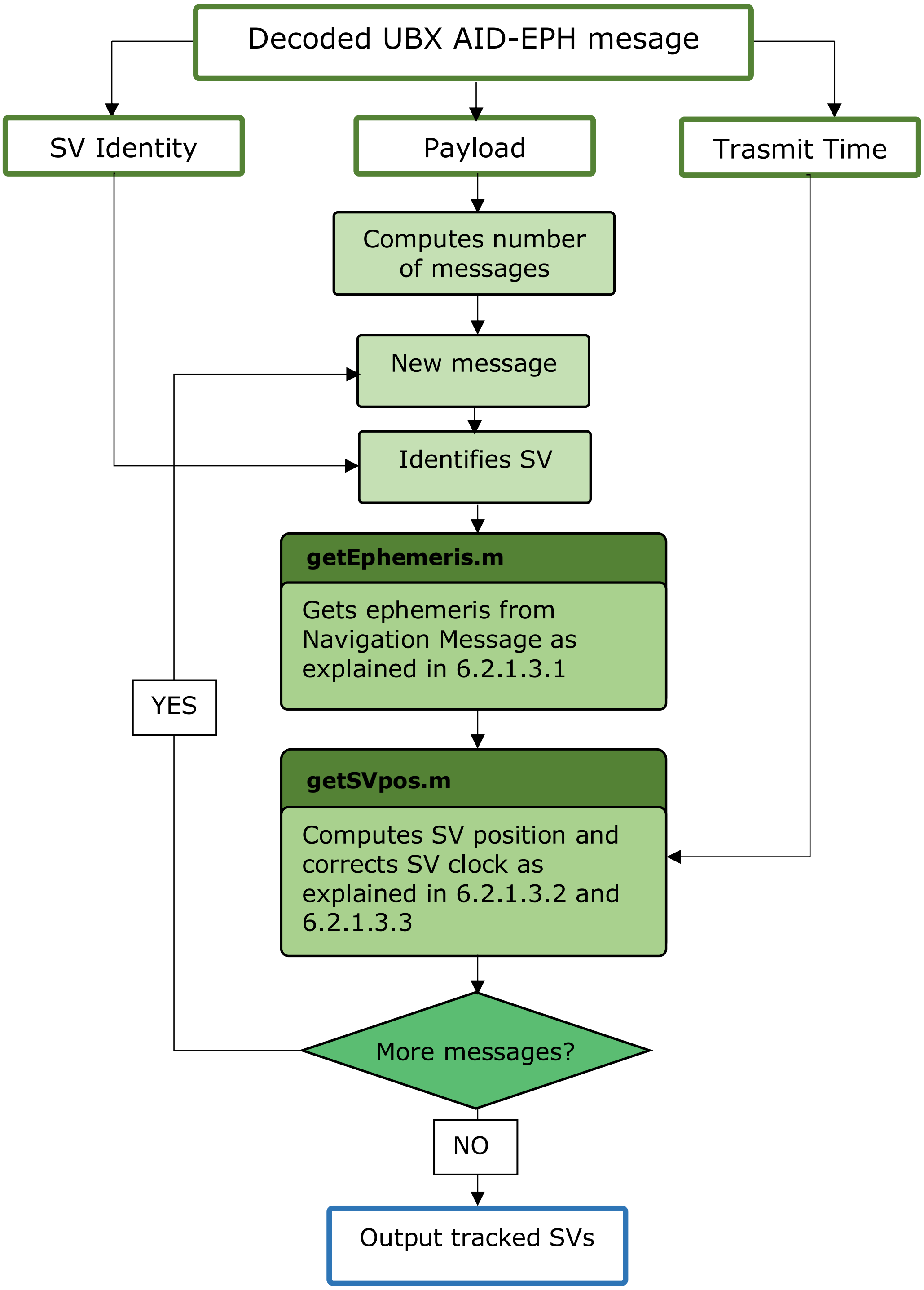


Figure 26: Flowchart of trackSV.m

8.4.1.4 Time Coordination

Each message is received in different moments and provide information of different instants. However, it is necessary to perform corrections to coordinate those parameters such as rover, base station and Space Vehicle position, active satellites, ionosphere information, etc.

To do that, it has been taken as a reference base station *UBX NAV-SOL* messages, because provide accurate TOW, and the other parameters have been linearly interpolated to fit base station navigation solution time. The unification has been performed in the correction rank, this is the interval of time when all the parameters required to compute and apply the corrections provide valid information.

The routine implemented works as follows:

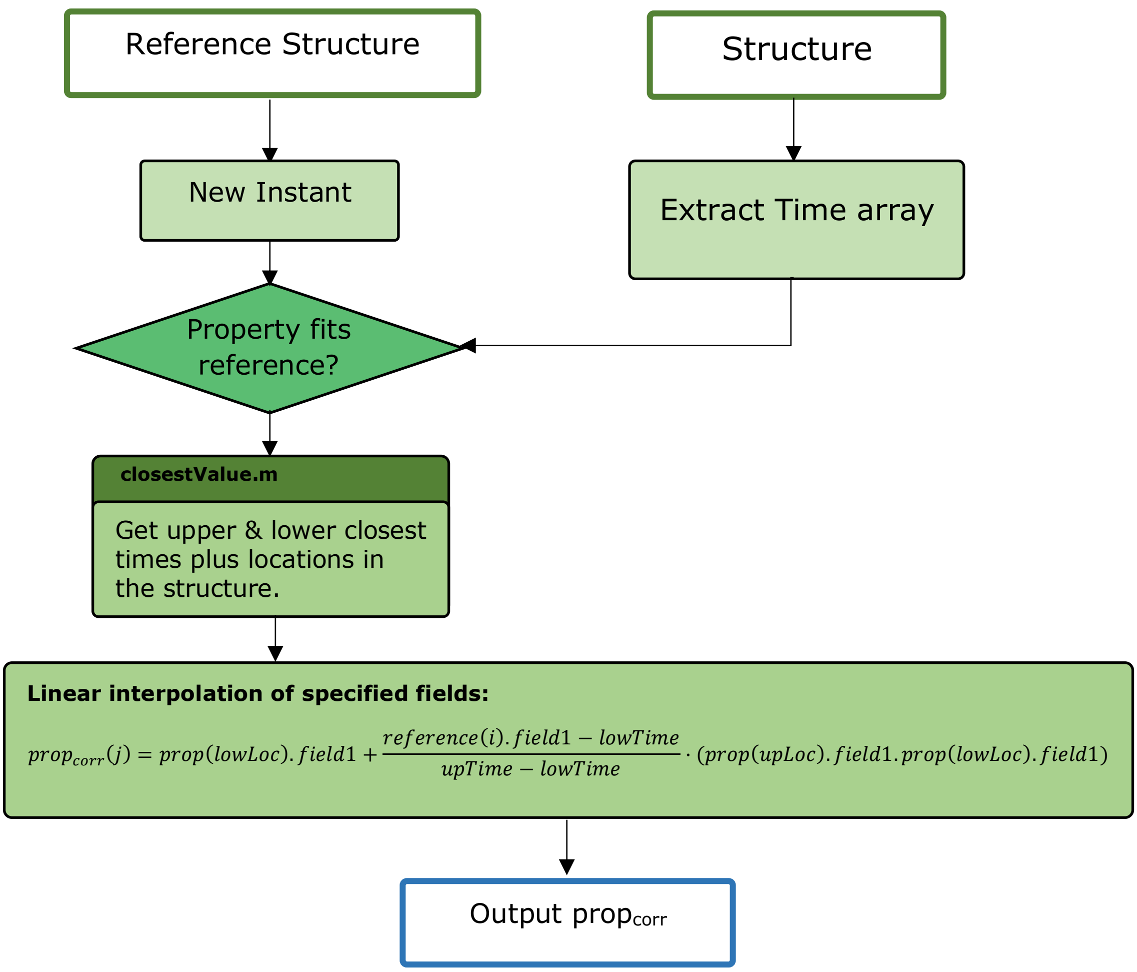


Figure 27: Flowchart of time coordination

8.4.1.5 Compute DGPS corrections

8.4.1.5.1 OFFSET Correction

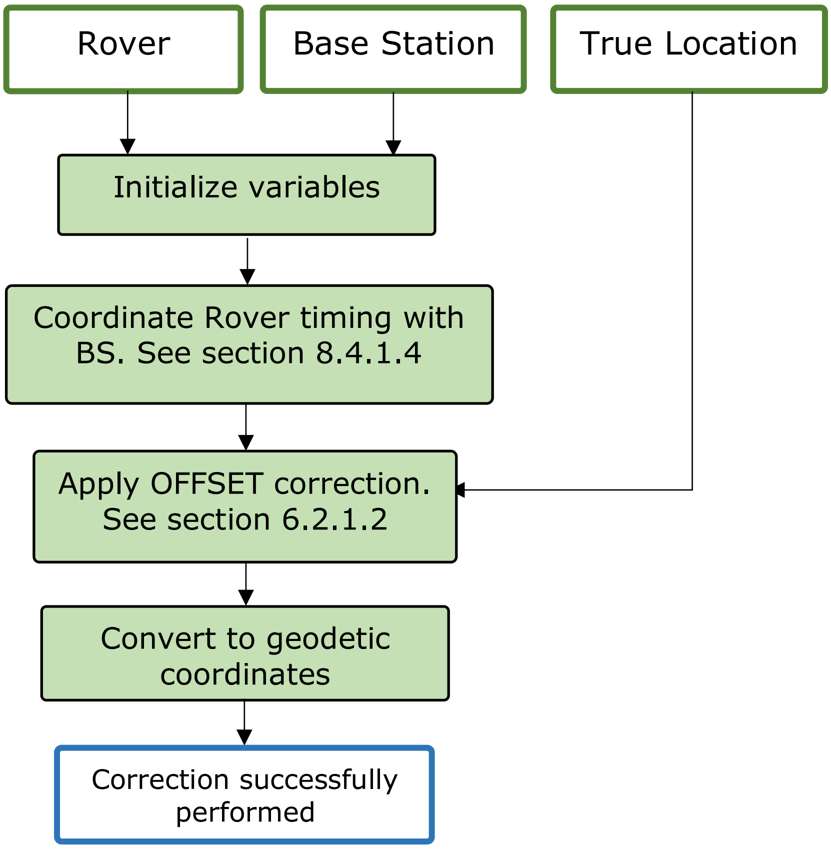


Figure 28: Flowchart of computeCorrectionOFFSET.m

8.4.1.5.2 COMMON DGPS Correction

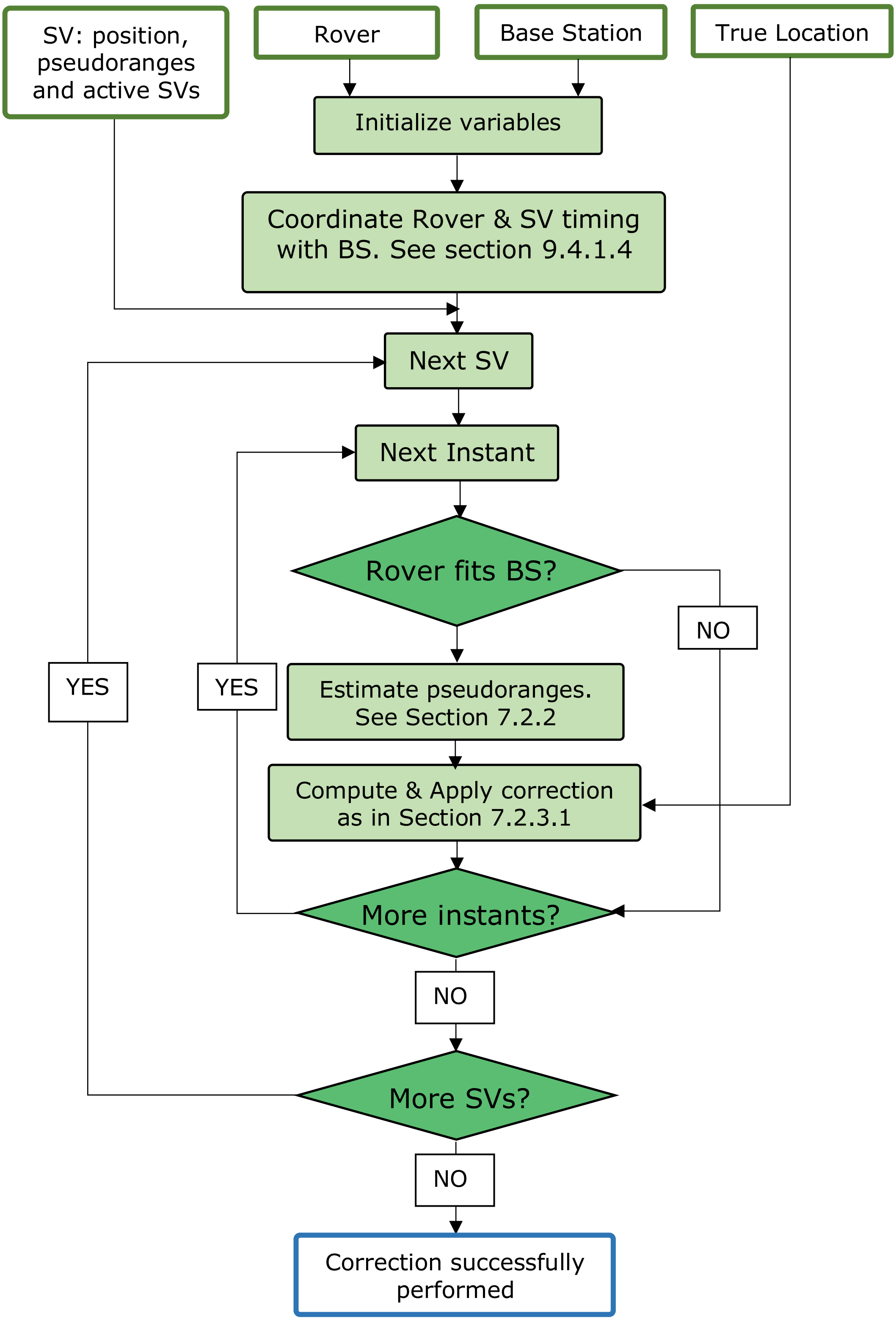


Figure 29: Flowchart of computeCorrectionCOMMON.m

8.4.1.5.3 Navigation Solution Correction – Real SVs

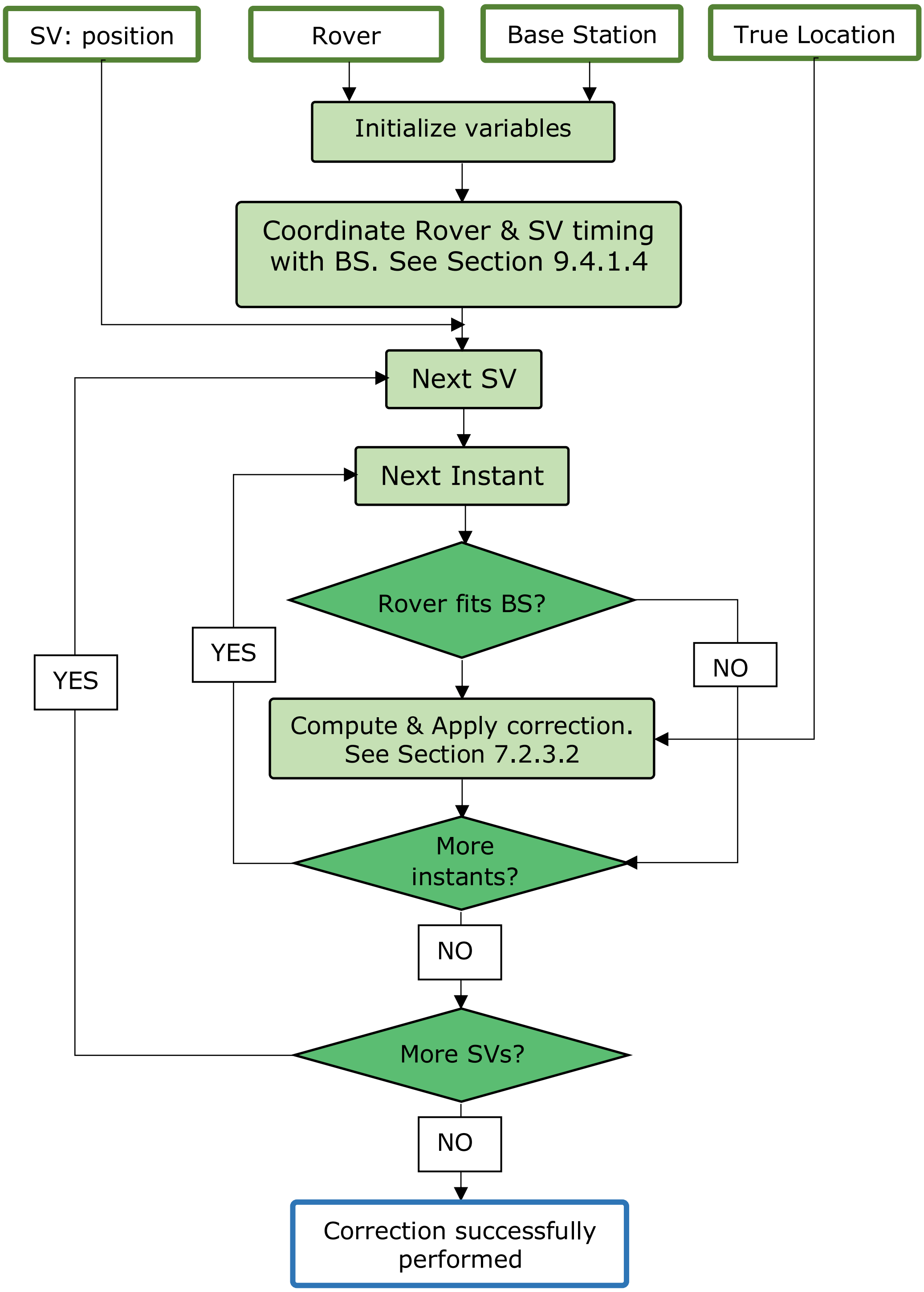


Figure 30: Flowchart of computeCorrectionReal.m

8.4.1.5.4 Navigation Solution Correction – Virtual SVs

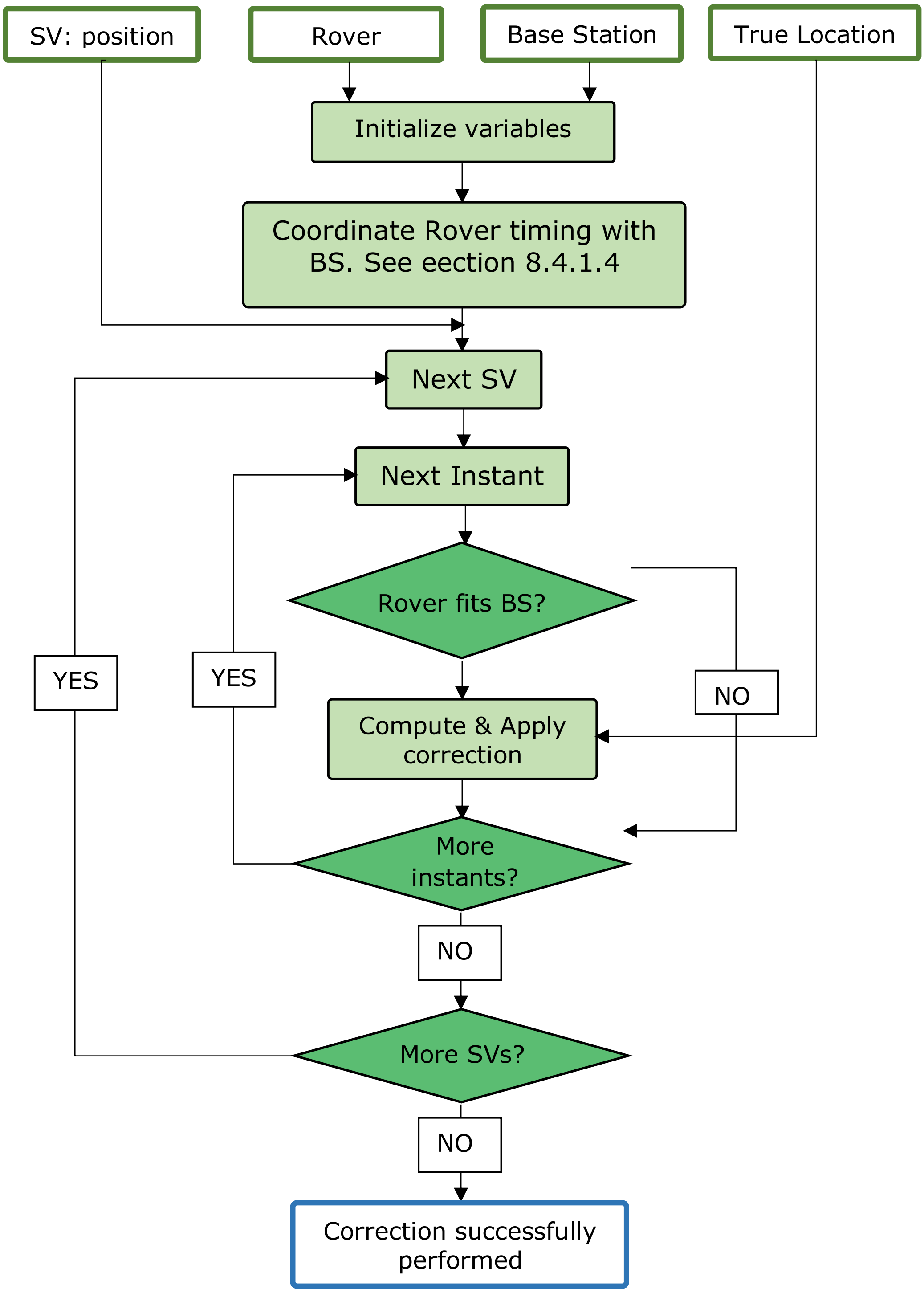


Figure 31: Flowchart of computeCorrectionVirtual.m

8.4.1.6 Compute Position

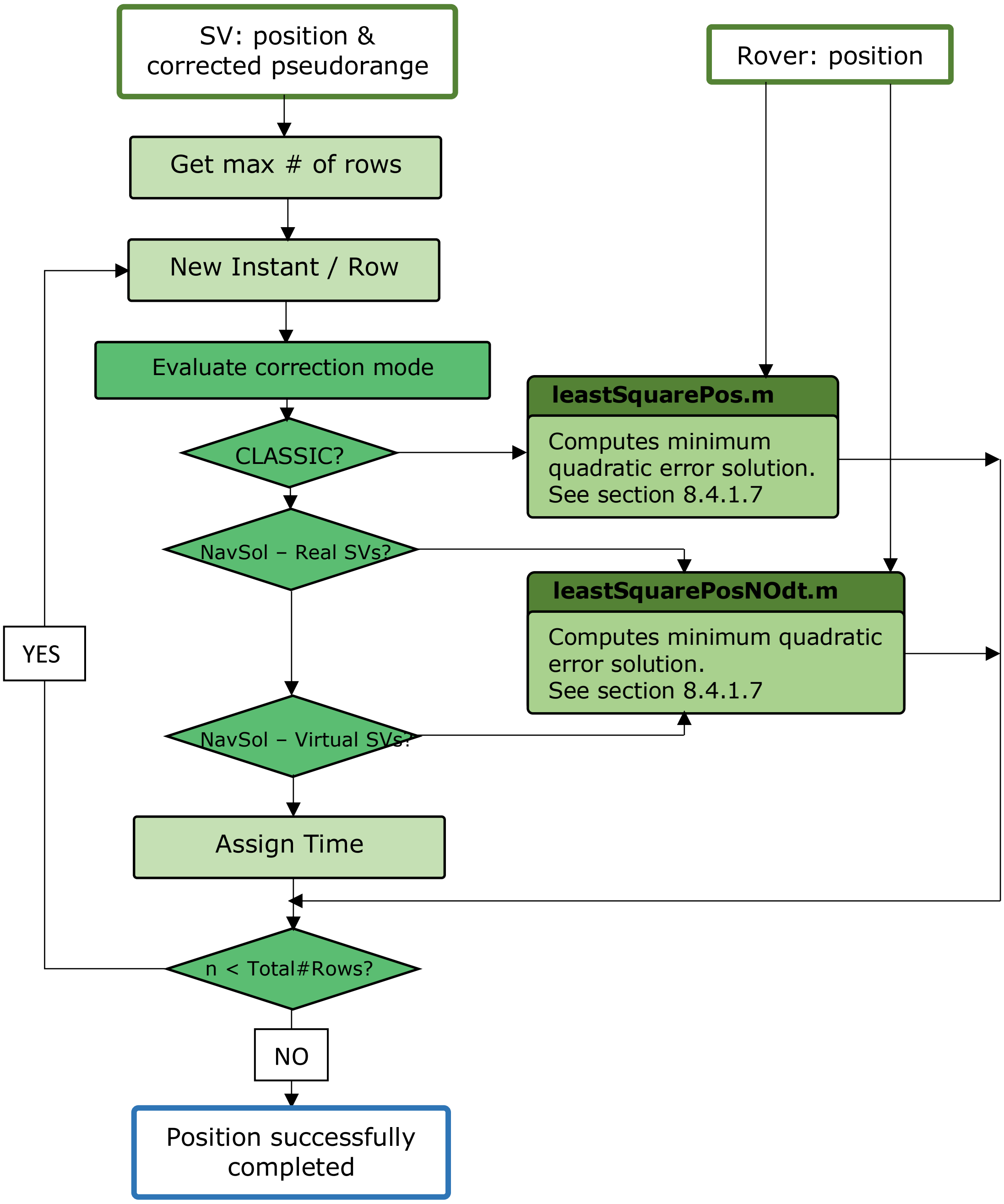


Figure 32: Flowchart of computePosition.m

8.4.1.7 Least Squares Method

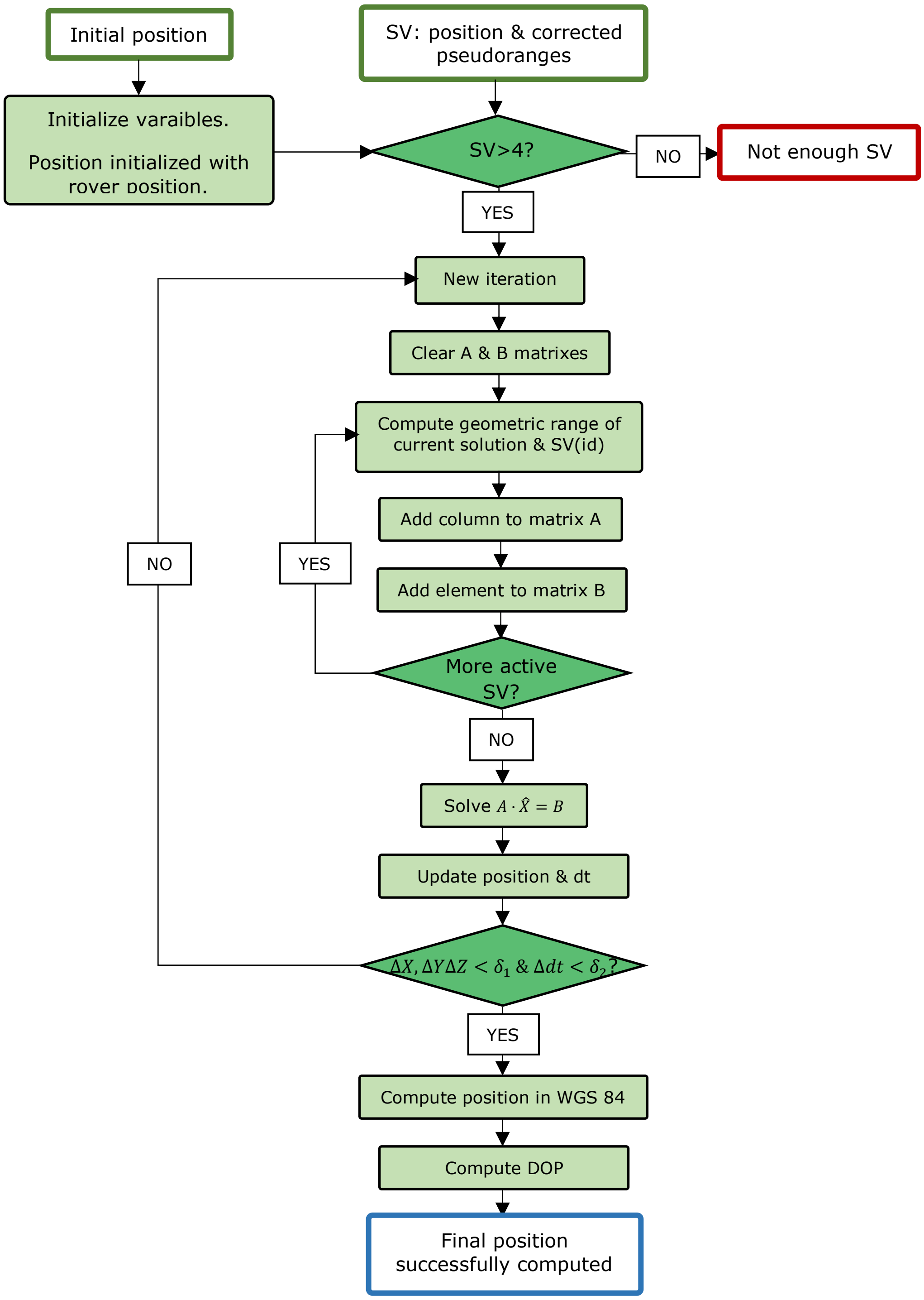


Figure 33: Flowchart of leastSquaresPos.m

8.5 Google Earth

Thanks to this powerful tool, it is not required an expensive cartographic equipment to get the reference coordinates, since *Google Earth* allows the user to get the geographic coordinates of the reference location, as well as, once the results have been obtained and exported, it allows to visualize the corrected and uncorrected 3D paths on the map, so it is easy to check the effectivity of each method.

Google Earth's 3D map is obtained by the superimposition of images from satellite imagery, aerial photography and geographic information. Of course, it has a limited accuracy and the obtained coordinates for the given coordinates may differ from their true values and the solution given by the GPS receiver.

Actually this fact does not matter, due to the correction methods overcome this error. Since measurements are corrected based on the reference position, and it is taken from *Google Earth,* all coordinates get referred to this, that at the end are exported this 3D map again.

9. Results

Once the methodologies has been introduced, described and implemented, it is time to test them.

9.1 Test design

Before proceeding to perform the field work, it is necessary to design the experiment. The **location**, **duration** and **receivers' configuration** have been considered.

9.1.1 Selection of Location

A very relevant factor to consider while designing the experiments, it's the location where they are going to be performed. It is important to highlight two aspects that need to be taken into account while selecting it.

The first one is that the experimentation needs to be developed into an open area with the minimum obstacles. Ensuring this, the effect of multipath reflections and shadowing will be minimized, as well as a good satellite coverture is warranted. This consideration does not compromises the fidelity of the test with the real application since agrees with the desired flight environment.

The other element to consider is that in order to get an accurate reference, as it is got from *Google Earth*, the selected environment should have a recognizable reference element.

The selected location for testing satisfies both requirements, it is spotted in the middle of a wide avenue surrounded by much separated low buildings without any near disturbing obstacle. The exact situation is between *Sant Feliu de Llobregat* and *Sant Joan Despí*, in front of the sports complex *Ciutat Esportiva Joan Gamper*, where a given post has been taken as reference.

The coordinates of the reference location are:

Reference Location – Geodetic coordinates	
Latitude	41º 22' 42.84'' N
Longitude	2º 3' 5.62'' E
Altitude above MSL	35 m
Geoid Height	49.505 m

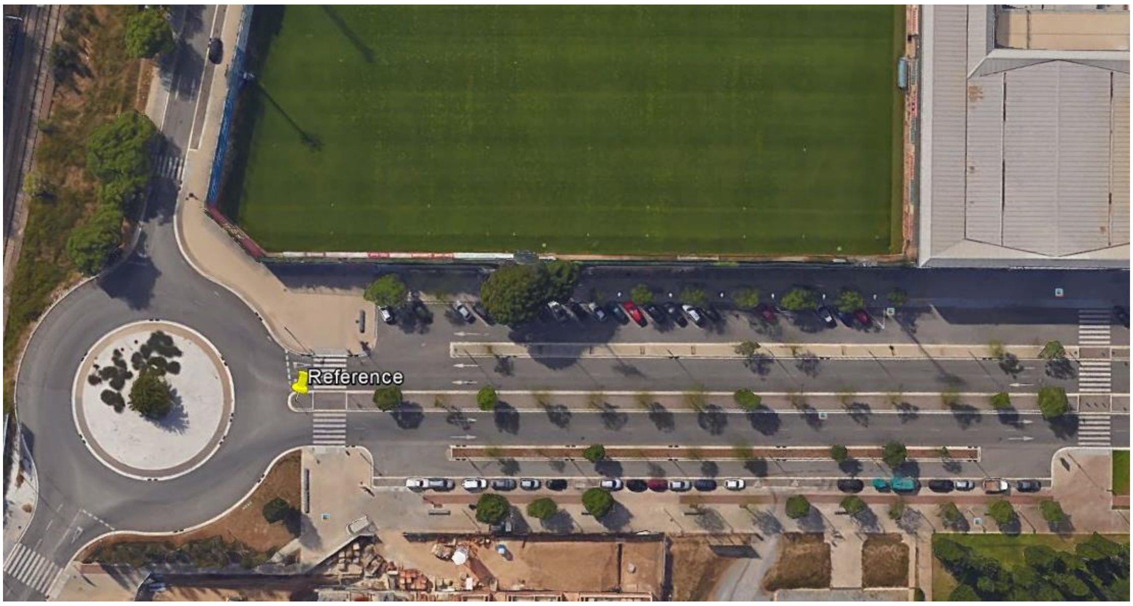


Figure 34: Aerial view of *Avinguda de l'Onze de Setembre*, *Sant Joan Despí*. Image taken from *Google Earth*

The avenue has a longitude of 600m full of possible references, so it is also a good scene to test the relation of the method's effectivity and distance.

9.1.2 Length

Upon the extension of the tests, it has to be taken enough measures to make it representative of the methodology's performance. The duration of all tests has been around 10 min, since is the approximate autonomy of a UAV.

9.1.3 Message configuration

Before proceeding to start the test, each GPS receiver needs to be configure it using *U-Center.* In the configuration process has to be defined the baud rate, the output protocols, the output messages, and so on.

The requested messages depend on the correction mode that is going to be used. If the program ignored the messages that are not required for the current correction method.

In the next table are presented the requested messages and other configuration parameters needed by each correction mode.

<table>
<tr><th colspan="5">Required Messages for each Correction Mode[16]</th></tr>
<tr><th rowspan="2">Correction Mode</th><th colspan="2">Base Station</th><th colspan="2">Rover</th></tr>
<tr><th>UBX</th><th>NMEA</th><th>UBX</th><th>NMEA</th></tr>
<tr><td>Offset</td><td rowspan="2">NAV-SOL</td><td rowspan="2">(GPTXT)</td><td rowspan="2">NAV-SOL
(NAV-DOP)</td><td rowspan="2">(GPTXT)</td></tr>
<tr><td>Navigation Solution – Virtual Space Vehicles</td></tr>
<tr><td>Common DGPS</td><td rowspan="3">AID-EPH
NAV-SOL
(NAV-POSLLH)</td><td rowspan="3">GPGRS
GPGSA
(GPTXT)</td><td rowspan="3">NAV-SOL
(NAV-DOP)</td><td rowspan="3">GPGRS
GPGSA
(GPTXT)</td></tr>
<tr><td>Navigation Solution – Real Space Vehicles</td></tr>
<tr><td>All Modes</td></tr>
</table>

Table 11: Require messages for each correction mode

The baud rate needs to be set according to the enabled messages, especially if the navigation message is demanded by enabling *UBX AID-EPH* messages, and the rate of messages specified. If the baud rate needs to be raised an error message appears advertising it if *NMEA GPTXT* messages are enabled. The baud rate in the several tests ranges between 9'600 and 115'200, a typical value is 38'400.

This configurations are stored in text files and can be easily loaded as shown in annex G.

[16] Messages in parenthesis are not required but recommended.

9.2 Tests

9.2.1 Test 1: static at reference location

The first test that is performed is the simplest one. Both receivers, rover and base station, are placed at reference location all along the test.

As both receivers are at reference location, it is expected that pseudoranges of rover and base station suffer the same atmospheric delay and even the same multipath error. Passing this test is a requisite to continue through the next level.

First, it is plotted the distance between the corrected and uncorrected rover's paths (with different correction methods) to the reference point.

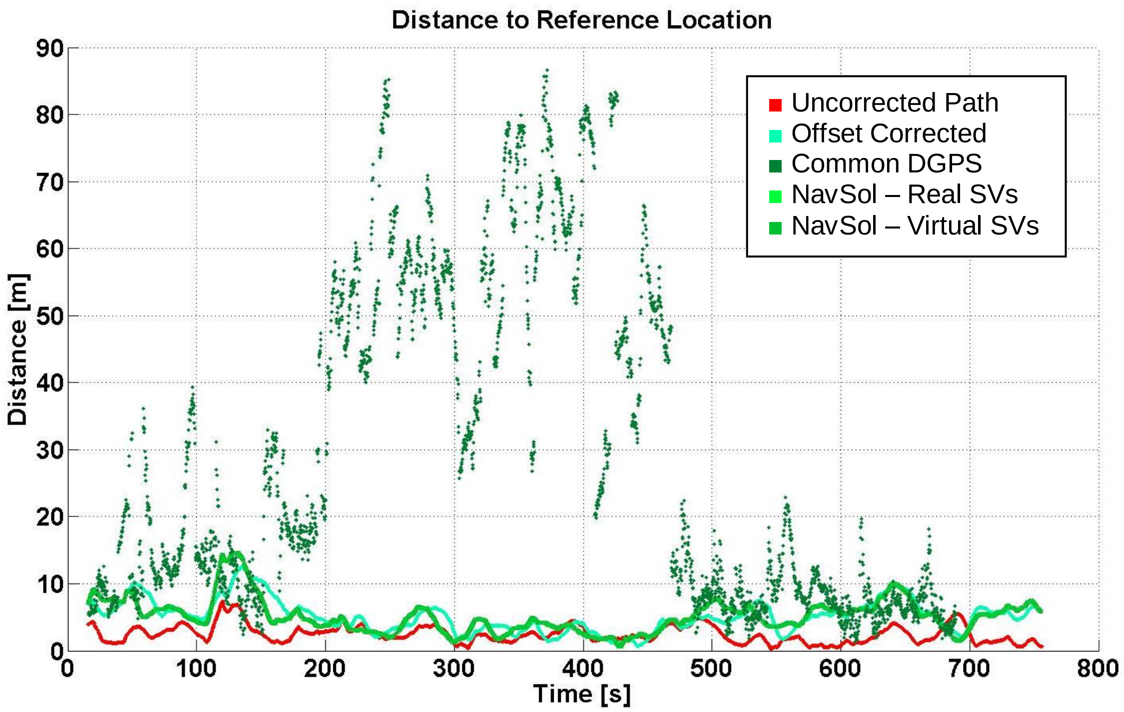


Figure 35: Test 1. Distance from each solution to reference location

At first glance, it can be easily seen in figure 35, that common DGPS correction methodology gives awful results spoiling the original navigation solution given by the receiver. The other methods are not so catastrophic but don't improve single-GPS's performance. It can also be seen that both techniques based on navigation solution fit perfectly, this is due to real satellites provide good coverture along this test. Virtual satellites are especially useful when few healthy Space Vehicles are visible.

Each methods' corrected paths are shown below. They are represented by 2D-plot of the path contained in the plane tangential to the Earth's surface at the reference location, and a screenshot of the 3D-path on *Google Earth.*

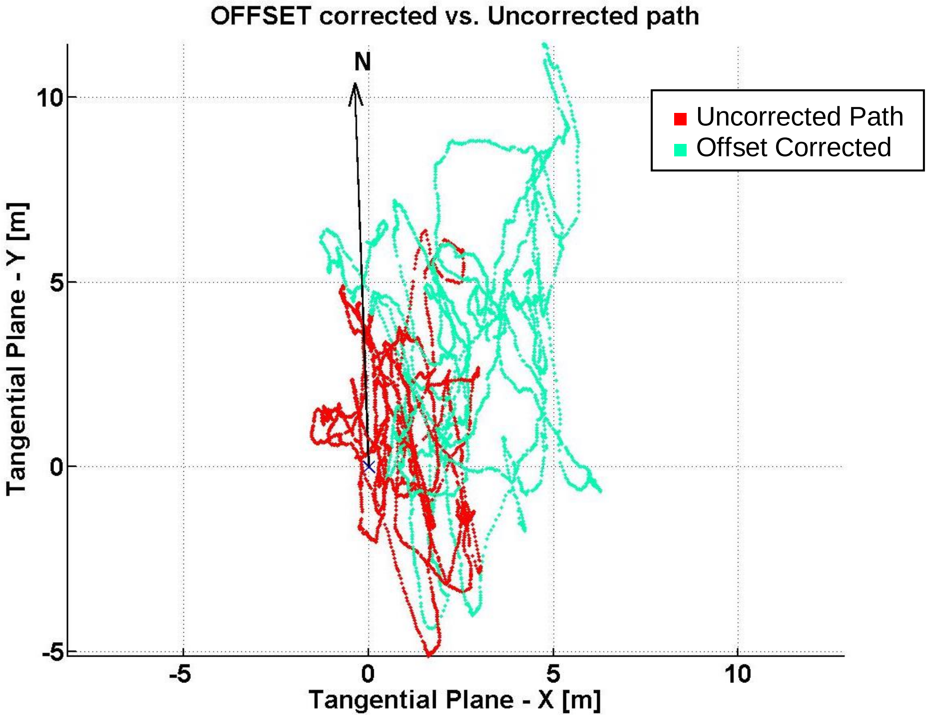


Figure 36. Test 1. OFFSET corrected path vs. uncorrected path, horizontal path and 3D path plotted on *Google Earth*

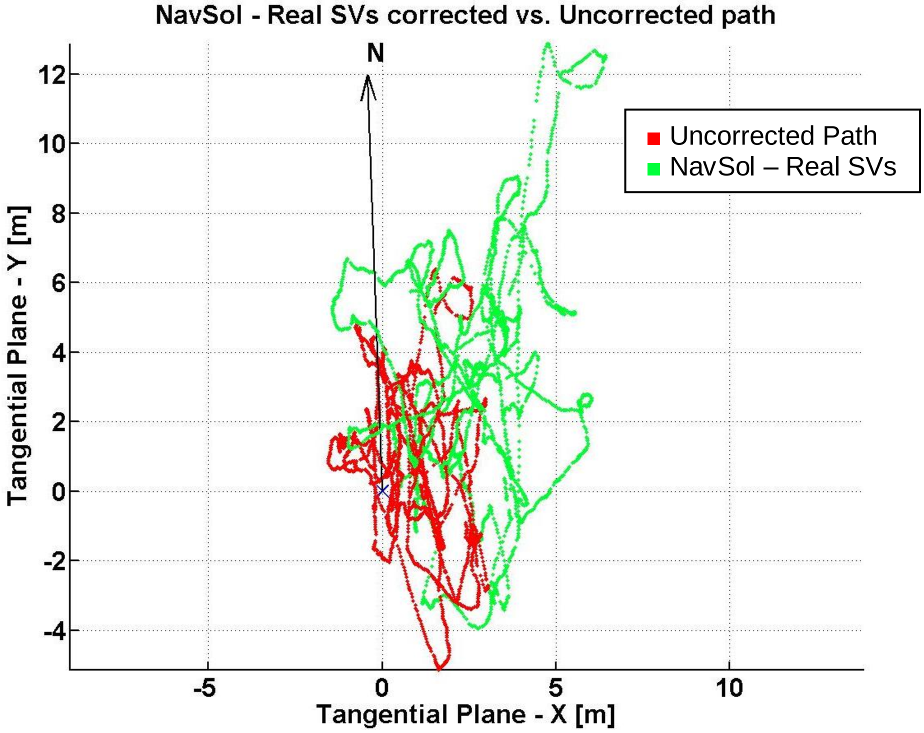


Figure 37: Test 1. NavSol - Real SVs corrected path vs. uncorrected path, horizontal path and 3D path plotted on Google Earth

Virtual Space Vehicles' distribution	
Description	Spherical distribution
Centre	Reference location
Radius	1000 m
No. of satellites	36

Table 12: Test 1. NavSol - Virtual SVs distribution description

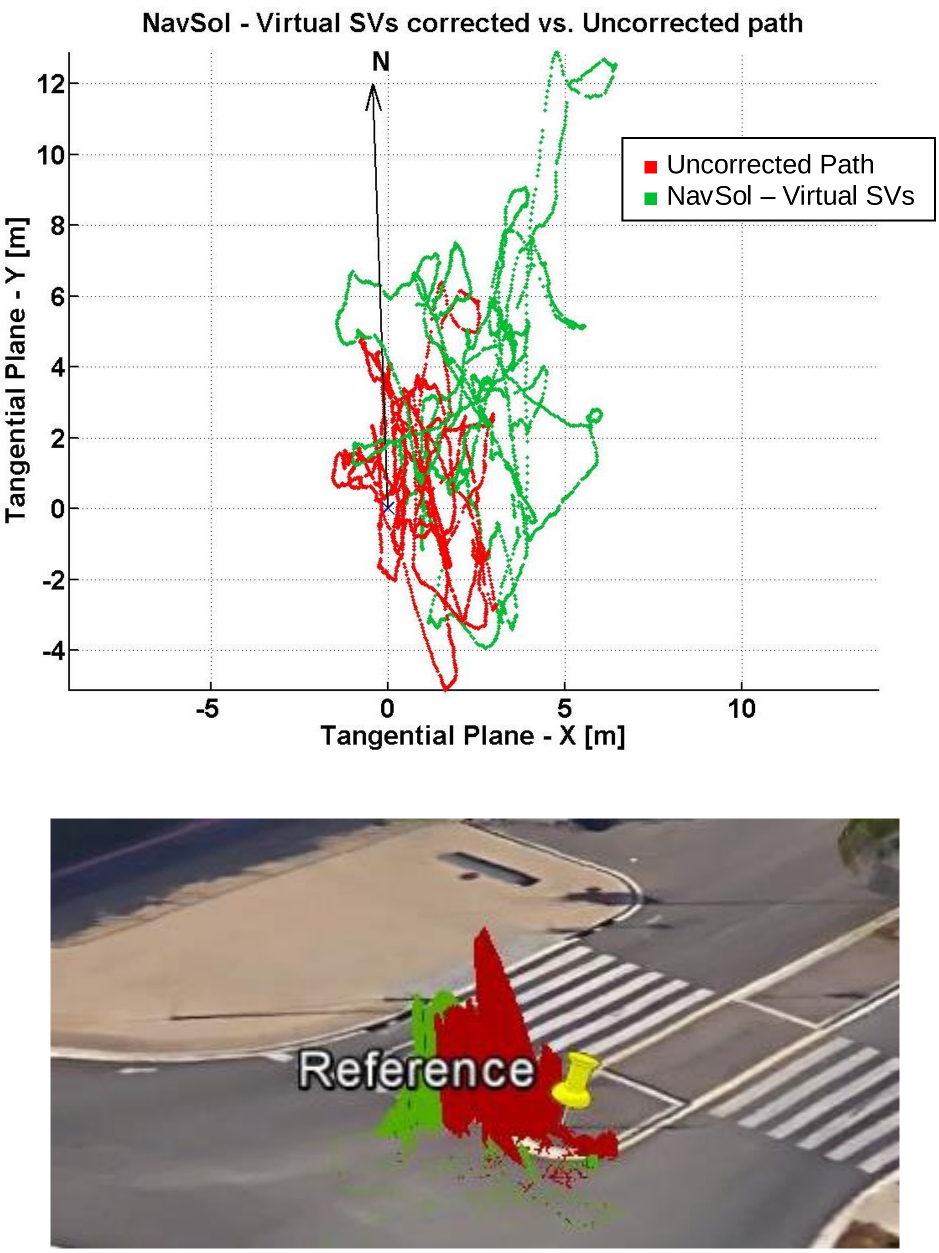


Figure 38: Test 1. NavSol - Virtual SVs corrected path vs. uncorrected path, horizontal path and 3D path plotted on Google Earth

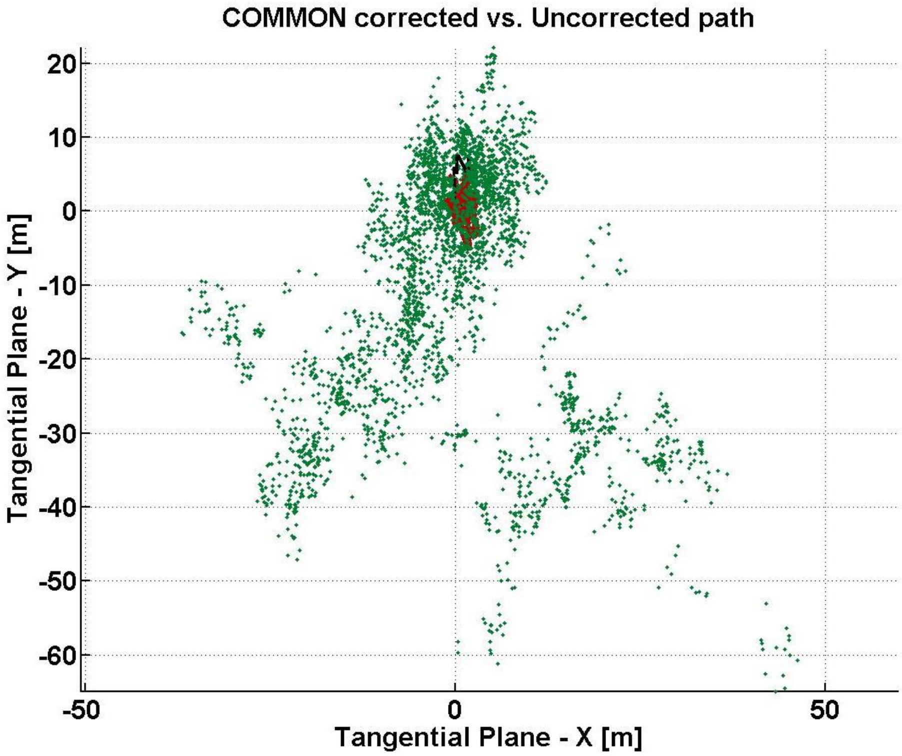


Figure 39: Test 1. COMMON corrected path vs. uncorrected path, horizontal path and 3D path plotted on Google Earth

The results of this first test, plotted in figures from 35 to 39, are not good. The corrected paths are not better than the uncorrected but sometimes worse or horrible like in the latter figure where common DGPS correction results are plotted. To find the reason, let's compare both uncorrected receivers' navigation solution.

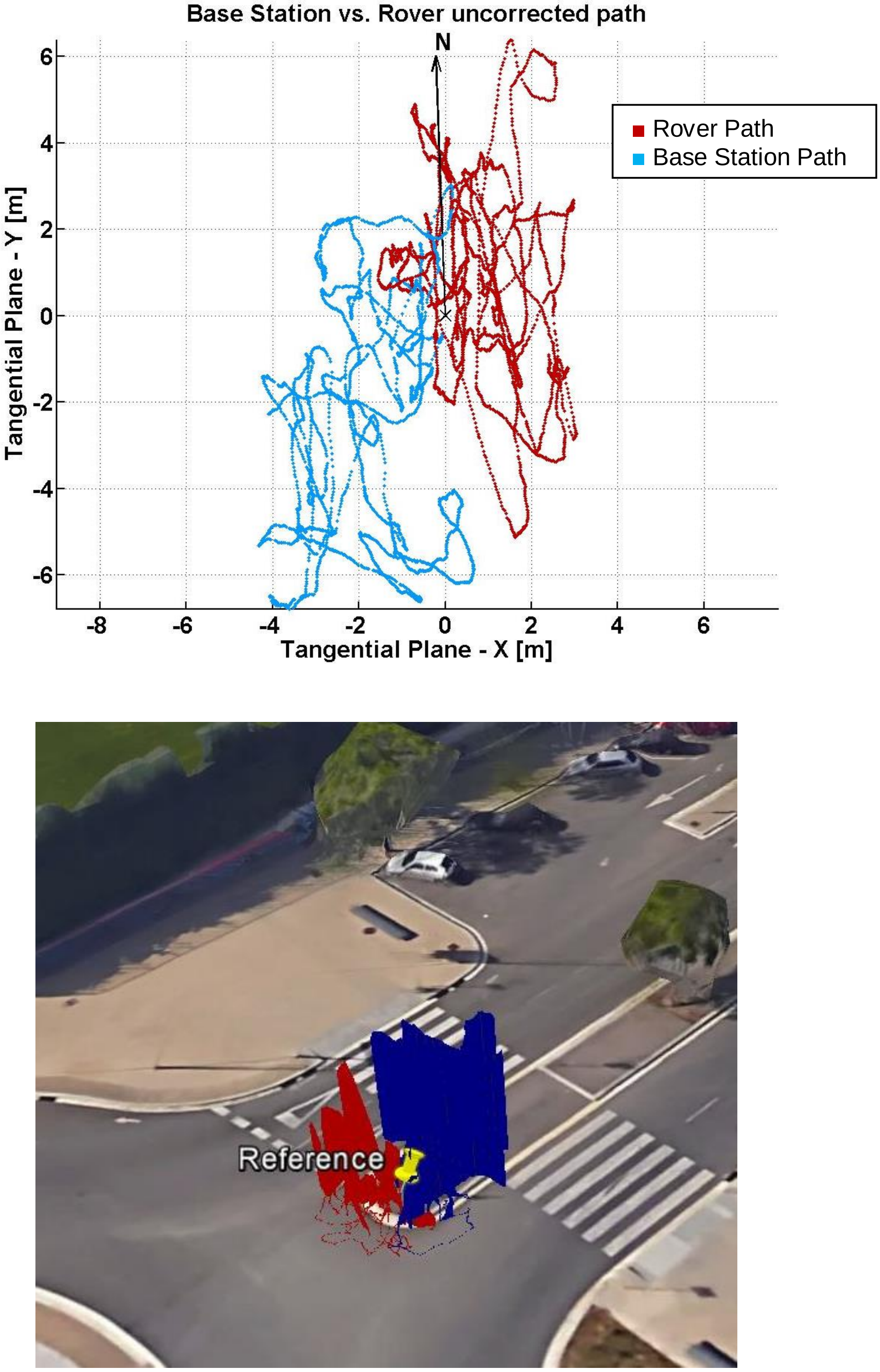


Figure 40: Test 1. Base Station uncorrected path vs. Rover uncorrected path, horizontal path and 3D path plotted on Google Earth

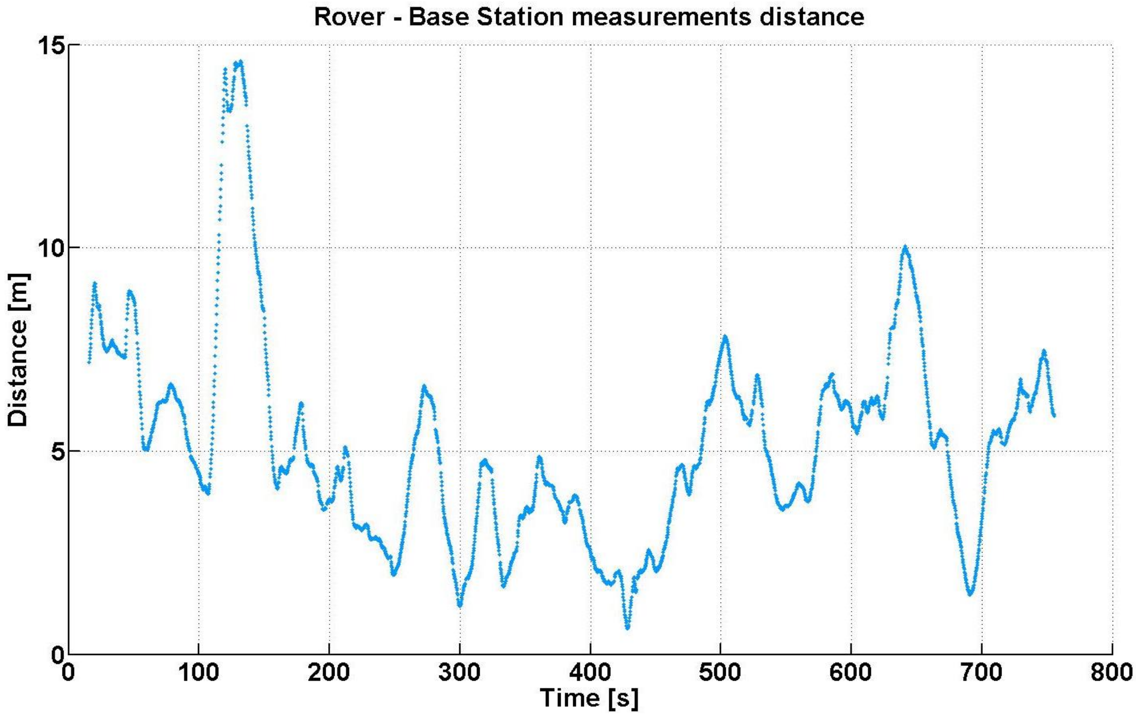


Figure 41: Test 1. Distance between uncorrected rover and base station paths

Figure 40 and 41 show that both receivers' measurements differ noticeably even when placed at the same location, so **the initial assumption of DGPS corrections is not accomplished**.

In order to analyse the results in more detail and find why the assumed premise is not valid, first recall error sources classification:

GPS sources of error	
Common errors	**Non-common errors**
✓ Ephemerides errors ✓ Satellites' clock errors ✓ Atmospheric: tropospheric and ionospheric delays.	✓ Receiver's clock error × Multipath × Noise and interference × Hardware delays

Table 13: GPS sources of error

In table 13, all the errors marked with a check mark have been already corrected by models, correction parameters or solved as part of the solution. Furthermore, the common sources of error are corrected by the DGPS methods, which remove the residual error of the mentioned corrections.

This was the initial hypothesis, after this test, it has been revealed the relative weight of the errors that affect our measurements. The non-common errors, **multipath error**, **hardware delays** and **noise** and **interferences;** are so much important than the common errors: **residual errors** of **ephemerides errors**, **satellites' clock errors**, **receiver's clock error** and **atmospheric delay**s. For this reason, since corrections tries to correct a highly corrections do not improve rover receiver's positioning but they slightly deteriorate it.

Just as a point, multipath errors probably are not as much relevant in this case as hardware or noise errors, since it has been selected a proper environment[17].

Once this has been clarified, the origin of the horrible results given by common DGPS corrections can be identified. As has been recently said, GPS receivers correct several of the errors' sources before computing navigation solution, however this methodology do not take advantage of this fact as the rest of methodologies, which try to improve these corrections, but to overcome errors' sources[18] by comparing base station and rovers' pseudoranges.

Figures 43 illustrates rover's navigation solution without many corrections.

[17] Recall that multipath phenomena always occurs but its effects are corrected, what is problematic and it has been avoided by selecting a proper location is multipath plus shadowing.
[18] Receiver and satellites' clock errors have been already corrected.

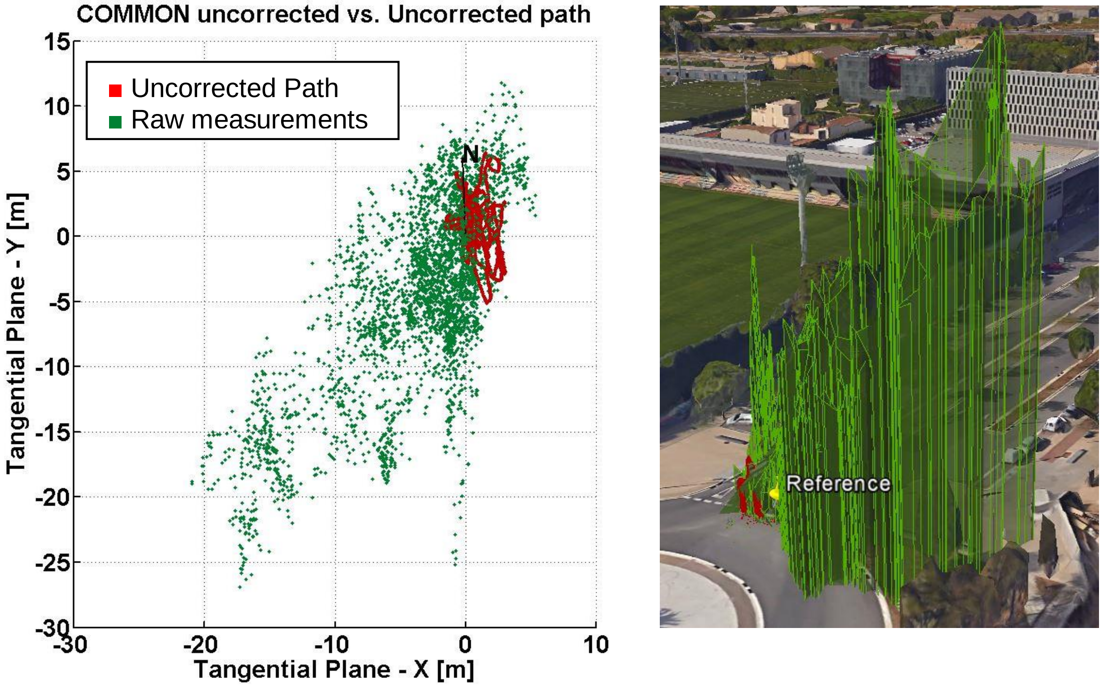


Figure 42: Test 1. Absolutely uncorrected measurements solutin vs. rover final solution

As can be seen, navigation solution without modelling the atmosphere or correcting ephemerides' errors is substantially worse, therefore as the post-processing correction method is not valid, since the main hypothesis is not satisfied, results cannot be satisfactory.

In order to sustain this, Position Dilution Of Precision (PDOP) comparison is plotted. The lower this value, the higher the methods' confidence in their results.

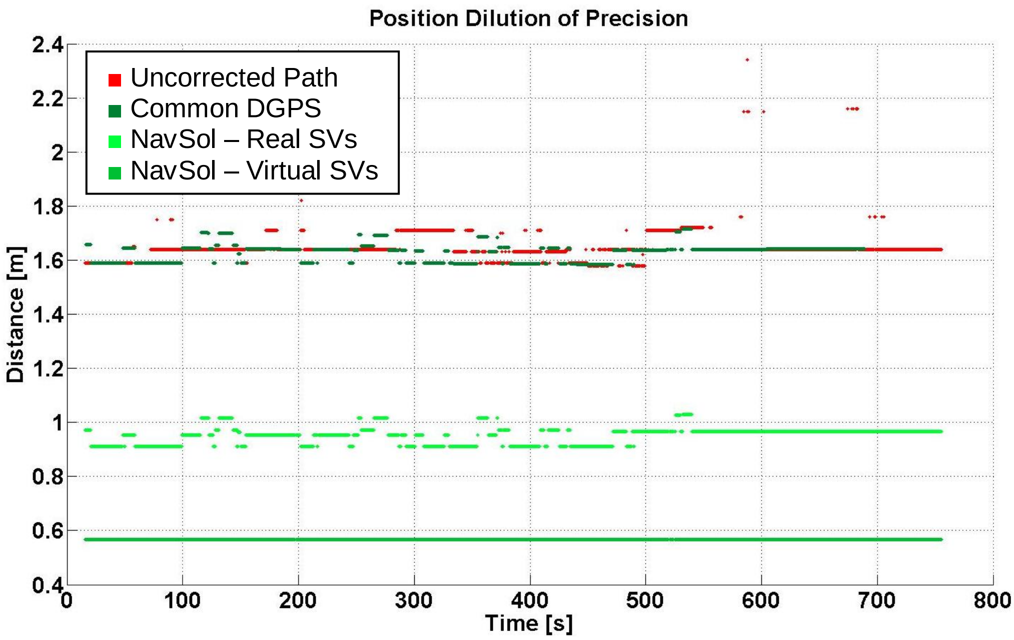


Figure 43: Test 1. Position DIlution of Precision (PDOP) comparison

As it is shown in figure 44, common DGPS corrections maintain the original dilution of precision meanwhile navigation solution methods reduce it. The advantage of using virtual satellites is that dilution can be reduced until almost reach zero by adding more Space Vehicles or modifying the geometry.

The same idea is hold by Range Residuals, but segregated into each satellite.

9.2.2 Test 2: static at different locations

Even though the results obtained from the basic test are not satisfactory, a similar test is performed but this time GPS receivers are statically placed at known locations separated 322 m. Good results are not expected but to see if they get markedly worse by the effect of distance. If they do, the incapacity of the methods to correct atmosphere delays would be revealed.

Figure 44: Test 2 receivers' locations

Again, the distance between corrected paths and its known location is plotted.

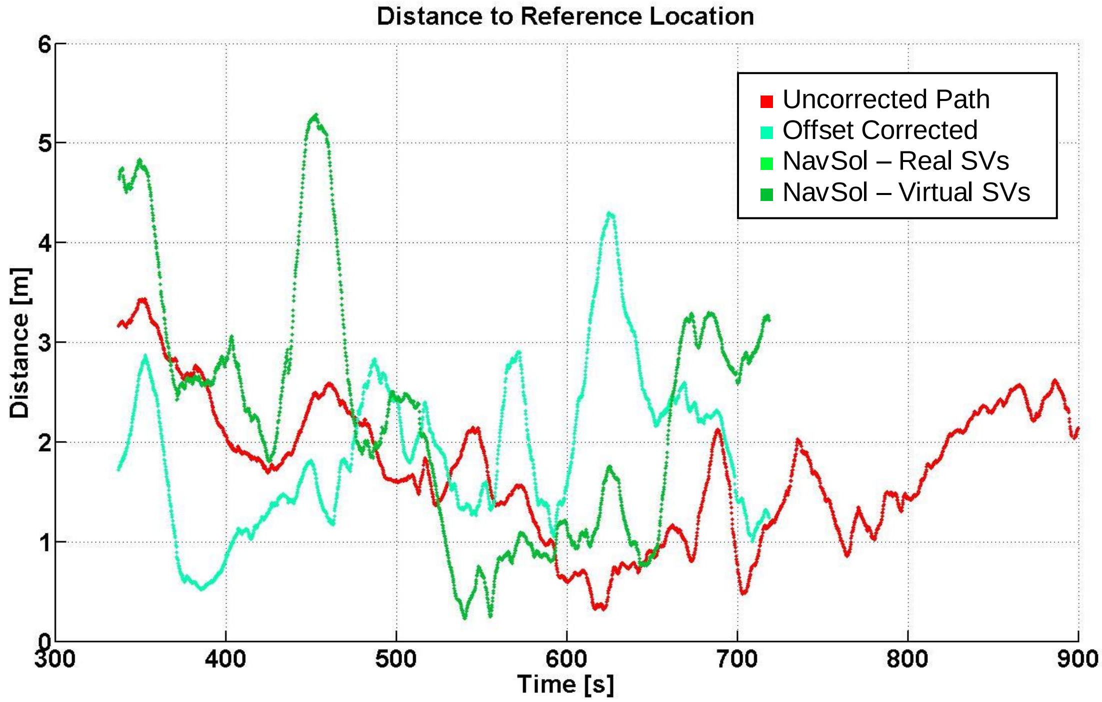


Figure 45: Test 2. Distance from each solution to rover's known location

In figure 46 has been plotted a comparison of the distance of the solution given by each method to the known true location. Figure 47 recalls test 1 results without classic DGPS corrections for a clearer comprehension.

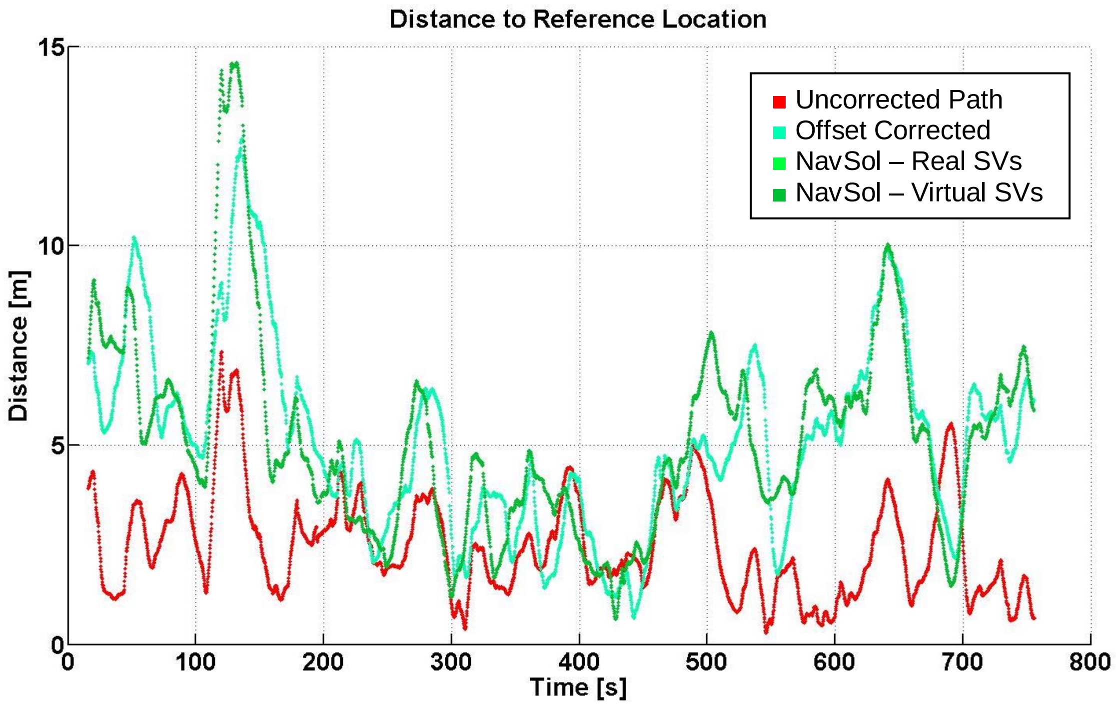


Figure 46: Test 1. Distance to each solution to reference location

This time results are slightly better as can beconfirmed in figures 48 and 49. However, it is not appreciated a significantly improvement of the original measurements. This enhancement is attributed to a higher similiraty between base station and rover receivers' errors due.

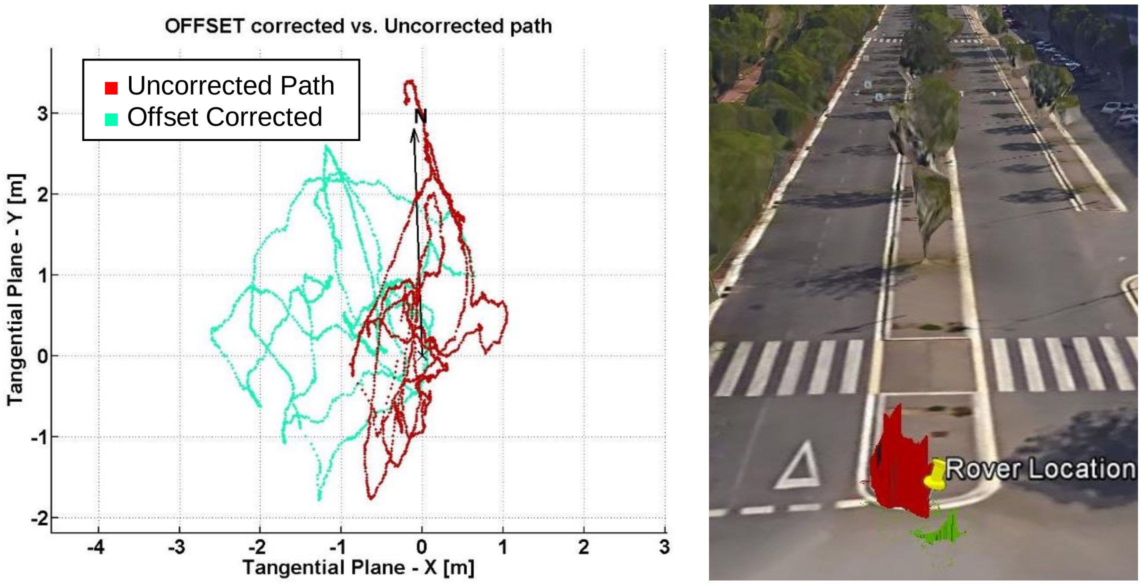


Figure 47: Test 2. OFFSET corrected path vs. uncorrected path, horizontal path and 3D path plotted on Google Earth

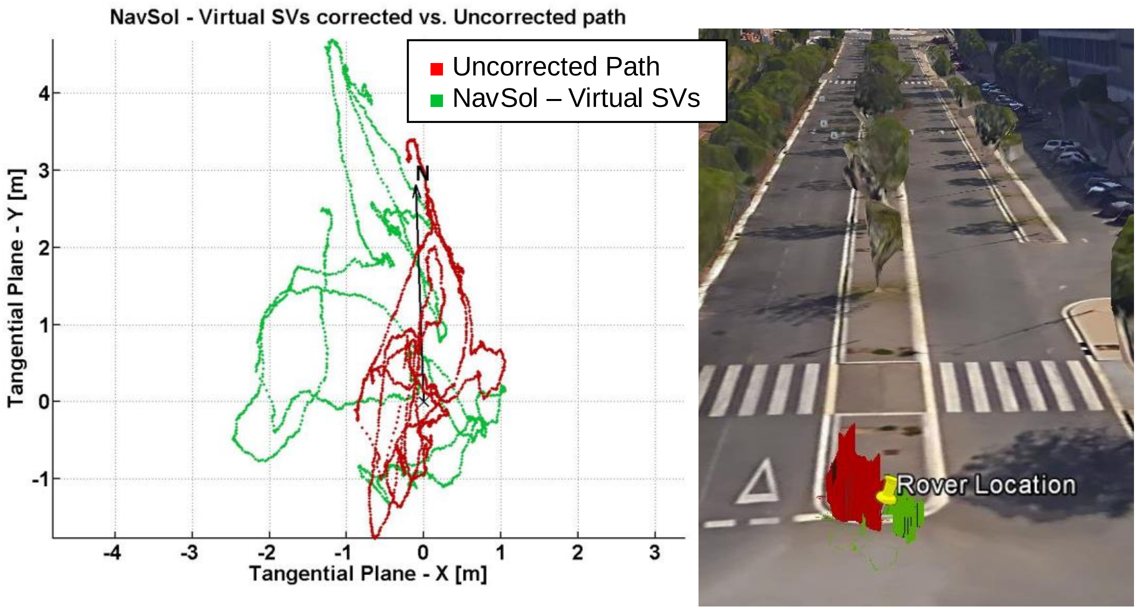


Figure 48: Test 2. NavSol - Virtual SVs corrected path vs. uncorrected path, horizontal path and 3D path plotted on Google Earth

Nonetheless, it has to be note that **altitude is highly corrected**. Since it is the hardest coordinate to estimate, due to the poor satellite spreading along this coordinate (most of the Space Vehicles are eclipsed by the Earth), GPS receivers tend to calculate a higher altitude than the real value, giving to the correction methods a chance to improve positioning.

10. Environmental Impact

The **direct environmental impact** of the implementation of this project almost zero, since no CO_2 emissions have been produced and the only power consumption has been the basic to supply energy to the computer.

As the majority of the applications, it has an **indirect environmental impact** associated and several factors has to be considered. In this case, it must be accounted that pollution is emitted when the devices (PC, *Pixhawk*, GPS receivers and cables) are transported from the manufacturer to the buyer, as well the contamination produced in the fabrication process and the fact that, the electronic components are not easy to be discomposed by the nature if they are improperly discarded. Luckily, it is in our hands to avoid that.

Once the methodology presented in this projected could be applied to real UAVs applications, it would also be associated to the power consumption required to fly, which would be usually electric.

However, it has also a positive effect, such as this affordable GPS enhancement allows to improve the performance of a lot of civil applications based on UAVs most of them focused on avoiding forest fires, high-precision agriculture, control and protection of the fauna, and more of them that involve the conservation of the environment.

11. Future planning and scheduling

In this section it is proposed a planning and scheduling for the future lines of investigation that precede this study.

In order to achieve a centimetre-level precision, as specified in the requirements, it is necessary the upgrade the receivers to a dual-frequency (L1 and L2) capable receivers, using carrier-phase measurements and applying radio interferometry technique. Also GPS receivers should be able to output raw data.

Once this is accomplished, it might be studied the possibility of implementing a real-time application.

These goals are split in the tasks described below, which have been scheduled between the time lapse going from 1st September 2016 to 31st January 2017.

1. **Purchase of new GPS receivers**: extensive research of the market possibilities and acquire the best option considering the demanded specifications and the limited resources.

2. **Adapt code the new receivers**: the implemented code needs to be updated considering new receivers.
   - **2.1. Decode new messages:** decode new according to the protocols.
   - **2.2. Modify to work with carrier-phase measurements:** adapt the program to work with carrier-phase measurements.
   - **2.3. Validate the code:** as in the present study, the code is extensively validated to ensure that it is free of errors.
   - **2.4. Test the resulting program:** the resulting validated program has to be tested.

3. **Analyse of the results:** analyse and compare new precision, Dilution Of Precision and so on.

4. **Implement methodology in real-time:** implement the correction methodology as a real-time corrections.

4.1. Select and purchase communication link: study the necessities and the market offer in order to choose the best components for the current purpose. Then buy them**.**

4.2. Optimize the code: optimize to reduce the computational cost and speed up the methodology.

4.3. Select and acquire rover's microprocessor: it is necessary in order to apply DGPS corrections and compute position an auxiliary microprocessor with enough computational power.

11.1 Proposed schedule for future work

Name of the task	**Work**	September	Octuber	November	December	January
Purchase of the new GPS receivers	15d					
Adapt code to new receivers	**54d**					
Decode new messages	10d					
Modify to work with carrier-phase measurements	30d					
Validate the code	30d					
Test the resulting program	10d					
Analyse the results	15d					
Implement methodology in real-time	**50d**					
Select and purchase communication link	30d					
Optimize the code	20d					
Select and acquire rover's microprocessor	30d					
Validate real-time application	20d					

12. Conclusions

It is clear that the main goal of the project has not been reached, since a reliable post-processing correction methodology is not achieved, or at least none of them could be validated for the set conditions.

However, the origin of the problem has been identified. Tests have failed because the initial hypothesis of Differential GPS corrections is not satisfied, since both receivers' errors differ more than expected even when placed at the reference location. This is due to atmospheric residual errors are lower and receiver electronics' errors higher, for the available receivers, than we had anticipated.

Furthermore, it has been implemented a program that works as a good environment for dealing with GPS data. Allowing the user to monitor and work with data, since a bunch of post-processing functions are given and user's implemented functions can be easily incorporated. Also, navigation solution computation is externalised and can be performed on the computer, enabling the possibility to introduce any desired modification such as changing position's computation process, atmospheric models, adding corrections, etc.

Additionally, the code is able to overcome the problem of the disabled raw data by estimating pseudoranges and computing satellites' paths. Obviously, it is also ready to apply DGPS corrections when a suitable scenario is given.

The other requirement, referred to the cost of the whole project, it has been clearly satisfied. The total budget ascends to 27407.22€ (see BUDGET document) accounting the personnel cost, but considering giving the software as free-license, a user that already owns a computer with MATLAB and a UAV using *Pixhawk,* which is for instance the case of the Aerospace Department of ESEIAAT (UPC), could implement these system for 224.61€ including both GPS receivers. Which it is far from the thousands of euros that costs a professional equipment.

Finally, just remark that it has been a continuous learning process full of difficulties that have been overcome, such as to communicate with receivers, decode input messages, estimate disabled raw data and a lot of unexpected troubles; and even a correction method has been proposed.

That is why, despite of the unsuccessful results, I can feel proud of the job done.

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