2021 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
AUTONOMY, ARTIFICIAL INTELLIGENCE & ROBOTICS TECHNICAL SESSION
AUGUST 10-12, 2021 - NOVI, MICHIGAN

Sequential Satellite Lock (GPS-SL)

Alberto Lacaze, Ray Wilhelm, Anne Schneider, Tanner Ray

Robotic Research, LLC
Clarksburg, Maryland

ABSTRACT

This paper presents a new concept in GNSS navigation: Sequential Lock GPS (GPS-SL). The new concept and prototype provide a variety of advantages for robustness, solution maintenance, and jamming resistance. Under normal circumstances, GNSS receivers need to receive signals from four satellites simultaneously to get a fix on position and the receiver time bias. If three or less satellites are visible given the occlusions provided by the environment, or because someone/something is intentionally or unintentionally jamming the space, no benefit is provided to the navigation solution. In other words, four or more simultaneous satellites give you a fix, three or less simultaneous satellites usually do not contribute (with some caveats) at all.

1. INTRODUCTION

The paper presents a new GPS receiver algorithm that can compute a positioning solution without seeing four satellites simultaneously, and under some conditions with less than four satellites. The advantages are numerous, including the capabilities to benefit from partial views of the sky and jamming resistance. This new algorithm can even compute a positioning solution with three, two and even one satellite in certain conditions.

Perhaps most importantly in the GPS-SL paradigm, a single satellite per epoch can contribute to the solution. In other words, a previous position fix can be updated using a single pseudorange. This is not usually the case for most Global Navigation Satellite System, (GNSS) receivers in the market.

The presented solution uses a combination of GPS inertial, and odometry sensors. One of the big advantages of the approach is that it does not require any changes to the GNSS signals and infrastructure or receiver hardware. The prototype system has similar SWAP-C to current units available on the market.

This paper presents a preliminary study of the drift of the solution over time and how the new paradigm affects Army Ground Vehicle autonomy programs (e.g., Leader Follower, RCV and SMET), as they are likely to encounter occlusions, jamming, spoofing and other GPS challenged environments. The paper will showcase the advantages of this new technology for Leader Follower applications in GPS challenged environments and show preliminary test results in relevant environments.

The paper will go over some of the theoretical framework and present results of the first prototype system. Measured drift rates versus predicted drift, and predicted performance will be compared with actual drift performance of our prototype system.

We expect that this technology will be utilized in a variety of applications, not only in the ground Army applications, but also maritime, Air Force and other parts of the DoD and perhaps for commercial endeavors.

This work is partially funded by C5ISR in conjunction with SOCOM.

Robotic Research LLC is a developer of PNT and autonomy solutions, and we have significant expertise in the development manufacturing and deployment of autonomous systems both for DoD and commercial customers.

2. The need for a robust GPS solution

GPS is used ubiquitously in commercial and military applications. Arguably, it is one of the top inventions and infrastructure accomplishments of the 20th century. How it is utilized today far surpasses the original applications for which it was designed.

On the other hand, GPS is not perfect and some of the problems become self-evident for certain applications. Case in point: autonomous vehicles (AVs). Many challenges of AVs are highly publicized, such as pedestrian prediction and detection. However, accurate localization is one of the pillars of autonomy. Without accurate localization the problem of autonomously driving and avoiding obstacles becomes harder and, in some cases, impossible using current technology. There are several different components of a localization system: odometry, inertial, vision, and usually GNSS. Each has its challenges given the scenario and mission. GPS is no exception.

GNSS assumes that a direct line of sight is available between the satellites and the receiver. The frequencies used for these transmissions are high enough that they do not penetrate most obscurants. Specifically, they do not penetrate dense foliage, walls, or buildings. Therefore, an autonomous system driving in a forested environment or city environment is subject to many occlusions. These occlusions stop the receiver from collecting the information from those satellites, and therefore, the solution is compromised.

The accuracy of the GNSS solution depends on a variety of factors, but one important aspect is the number of satellites in view and the relative position of those satellites in the field of view of the observer. As a rule of thumb, satellites closer to the horizon improve accuracies in the Northing and Easting, while satellites overhead contribute to the minimization of errors in the altitude.

Forested environments are notoriously challenging. Several studies have been made showing the degradation of GPS reception as a function of the density of the vegetation [1].

As the number of satellites received goes down, the solution can degrade. In traditional receivers, the minimum number of satellites needed is four. In other word, four simultaneous satellites must be visible to the receiver to get a reading. These four measurements solve for the unknowns in the PNT solution (position and time).

Figure 1 shows a vehicle traversing a forested environment. This data was collected with one of Robotic Research’s autonomous shuttles operating at Hamburg Castle in Germany. Depending on the amount of foliage, the number of available satellites changes significantly. In many areas, the number of satellites in view goes below the four required to get a fix using traditional GPS in those locations. Therefore, as the vehicle traverses those areas, the localization solution is only relying on inertial and visual odometry.

Technology patented under patent #63/146,493

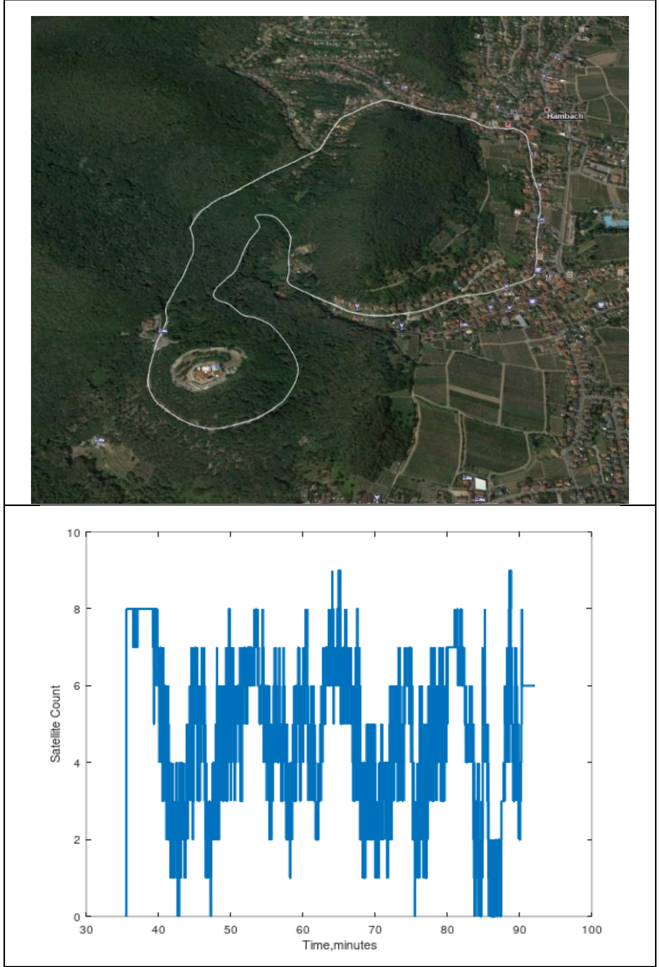

Figure 1. Autonomous shuttle traversing a route in a forested area in Hambach Castle, Germany. The number of GPS satellites in view is plotted showing that approximately half of the trajectory does not have the four satellites required to get a lock.

In the case of this shuttle, the autonomous vehicle has already recorded landmarks in the area that allows it to still maintain accurate localization. However, in other applications, such as convoying (Leader Follower), the vehicles may be seeing the terrain for the first time and will not have the advantage of having geo-registered landmarks.

The plot shows that for this operating environment, approximately half of the trajectory falls below the four required satellites, and therefore in those areas the localization error accumulated will be directly proportional to the error in inertial dead reckoning.

Sequential GPS acquisition allows the vehicle to benefit from the GNSS constellations even when the satellite numbers fall below four. In other words, sequential acquisition allows the system to benefit from every satellite in the chart.

In the next sections we will present how this is achieved.

3. Sequential GPS Method

3.1. Background and Theory

GPS positioning is based upon the method of trilateration, which computes the unknown position of the object of interest by measuring distances to other points with known positions [2]. GPS pseudoranges are computed by measuring the time of flight (ToF) of the signal from the satellite to the receiver. The standard GPS pseudorange equation is

$$\rho_{\{k,i+1\}} = \sqrt{\{(x_k - x_u)^2 + (y_k - y_u)^2 + (z_k - z_u)^2\}} + b_u$$

where $\rho_{k,i+1}$ is the pseudorange of the kth satellite at time t_{i+1}, $\{x_k, y_k, z_k\}$ is the known satellite positions, $\{x_u, y_u, z_u\}$ is the unknown receiver (user) position, and b_u is the receiver clock bias. A GPS position solution requires at least four pseudoranges from four different satellites. A system of four or more equations (if there are more than four satellites in view) are formed. These equations are linearized and the four unknowns $\{x_u, y_u, z_u, b_u\}$ solved for at each point in time. A drawback of this method is, unless an advanced GPS technique is used (e.g., tightly coupled GPS/INS or vector tracking), no useful information is produced when there are less than four satellites in view. Robotic Research has improved upon this by using incomplete GPS information (i.e., less than four satellites in view) with a relative navigation solution and a Chip-Scale Atomic Clock (CSAC).

Robotic Research first investigated the feasibility of using GPS pseudoranges at different points in time for a single user in order to compute their position. An example of this would be if a vehicle receives four GPS pseudoranges from different satellites at different moments in time (Figure 2).

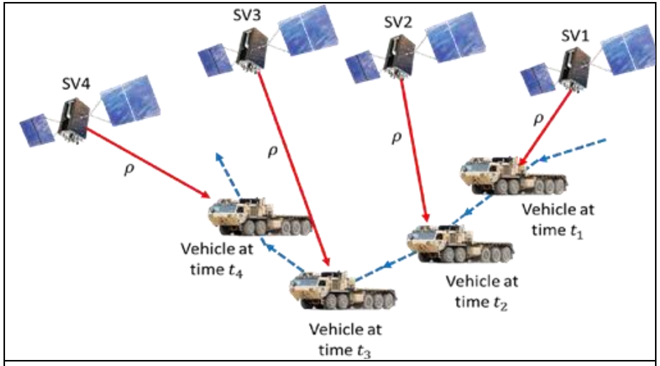

Figure 2: Sequential GPS

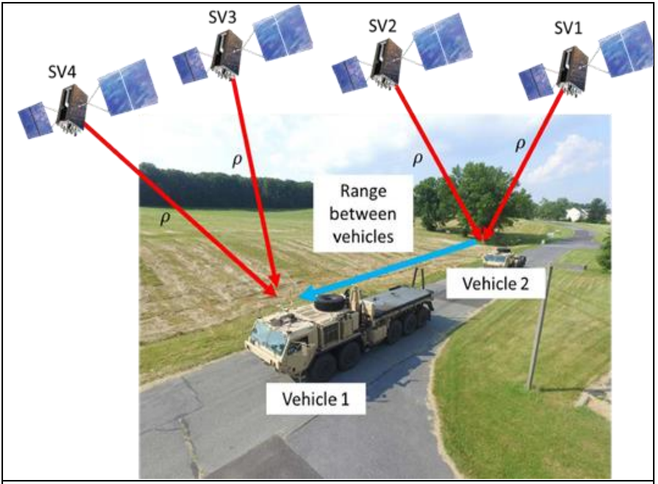

Figure 3: Collaborative Sequential GPS

A standard GPS receiver receives the satellite signals from different satellites ‘simultaneously’ in time. In reality, these measurements are separated by tens to hundreds of nanoseconds which is then mitigated by the receiver [3]. This new method can combine measurements that are received more than one second apart. Robotic Research has named this technique ‘sequential lock GPS’ (GPS-SL). The system concept requires a CSAC and a vehicle’s onboard relative navigation solution, as the system is most likely in motion in between GPS measurements.

A relative navigation solution (i.e., dead-reckoning solution) estimates the change in position of the body of interest and the new position by adding the change in position to the previously known position. These systems use sensors mounted on the body of interest to estimate the relative position and not the absolute position. To think of this more intuitively, a relative navigation system knows that you have just traveled from point A to point B, but you do not know where point A and B are on the Earth. An example of this idea is illustrated in Figure 4, below. The red path is an absolute navigation solution in which the location on the Earth is known whereas the blue path is a relative navigation solution. The path that the user has traveled is known, but it is not known where that path is on the Earth. For a ground vehicle the relative navigation solution would be an INS that includes an IMU and wheel odometry via wheel encoders.

Additionally, sensors like barometers, magnetometers, LIDARs, cameras, could also be used. This system concept is not limited to just ground vehicles but could also be used with a dismounted warfighter, UAVs, fixed wing aircraft, and ships.

For the sequential GPS method, the pseudorange equations need to be modified to account for the user position not being the same for pseudorange measurements at different points in time. This is done by adding three additional terms that account for the changes in position from the user’s first position. The modified pseudorange equation is

$$\rho_{\{k,i+1\}} = \sqrt{\left\{\begin{array}{l} \left\{\left(x_k - x_u - \delta x^{\{e\}}_{\{u,i+1\}}\right)\right\}^{\{2\}} \\ + \left\{\left(y_k - y_u - \delta y^{\{e\}}_{\{u,i+1\}}\right)\right\}^{\{2\}} \\ + \left\{\left(z_k - z_u - \delta z^{\{e\}}_{\{u,i+1\}}\right)\right\}^{\{2\}} \end{array}\right\}} + b_u \tag{10}$$

where $\{\delta x^e_{u,i+1}, \delta y^e_{u,i+1}, \delta z^e_{u,i+1}\}$ is the change in relative position from the first user position to the current user position at time t_{i+1}. Note that these terms are in the ECEF frame which is denoted by the superscript e.

Although this paper showcases the advantages of a single GPS-SL receiver, the solution can be extended to solve for multiple vehicle positions using data from multiple receivers at multiple moments in time. This technique is what we refer to as collaborative GPS-SL which is illustrated in Figure 3. This system would be able to provide absolute positioning information to an entire convoy in a GPS denied environment. The measurements from just a single vehicle or multiple vehicles can be used to accomplish this. This method would require each vehicle to have a relative navigation solution and a way to compute the relative distance between convoy vehicles. This is currently performed by using existing ranging nodes that utilize Ultra-Wide-Band (UWB) technology. The following section will discuss the testing and results of the GPS-SL method.

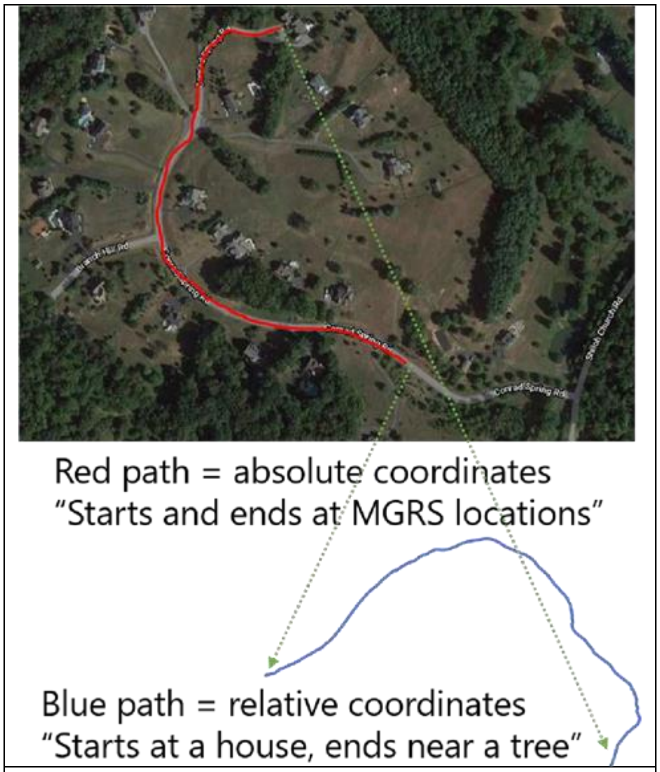

Figure 4. Relative Versus an Absolute Navigation System

3.1.1 Testing and Evaluation

Robotic Research first performed a data collection with a General Dynamics SMET MUTT vehicle shown in Figure 5. This vehicle has onboard it a RR-N-140 navigation system which provided the relative navigation solution needed. The test equipment can be seen in Figure 6 and Figure 7. The vehicle was driven around the Robotic Research COMSAT facility campus several times for approximately 1 hour in duration.

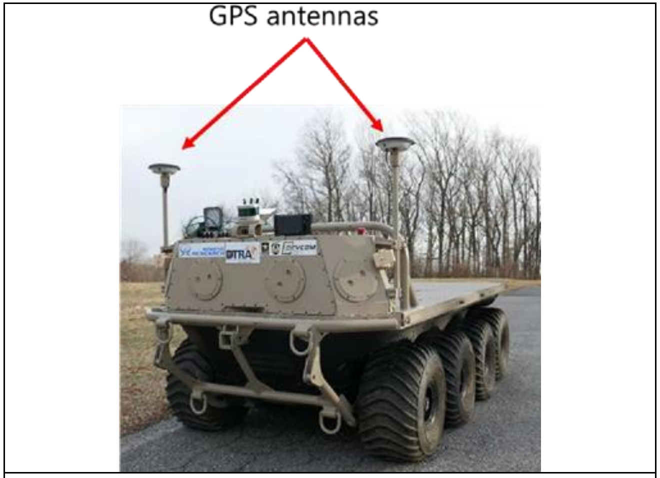

Figure 5. General Dynamics SMET MUTT Vehicle

Figure 6. MUTT Vehicle with Test Equipment

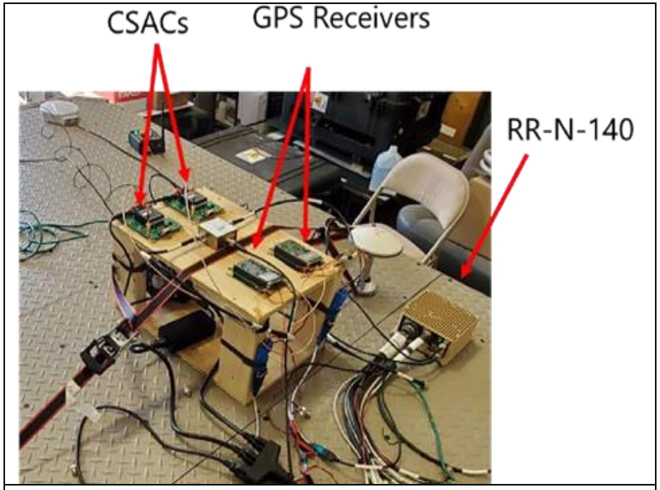

Figure 7. Test Equipment

The sequential GPS algorithm was run on the experimental data taken around the COMSAT facility. In order to simulate a challenging GPS environment, most of the GPS measurements were not used. The algorithm was run in the following manner illustrated by Figure 8 and described in the steps below. Note that this approach is arbitrary in nature and just used a proof of concept. In future work, the time period between measurements will be increased to test the robustness of the algorithm.

1. Receiver clock bias and position initialized with a good estimate.
2. For 1.5 sec, do accept any pseudorange measurements from any satellites.
3. For 1.5 sec, accept pseudoranges from a single satellite. Apply pseudoranges to algorithm.
4. Iterate to the next satellite number and go to step 2.

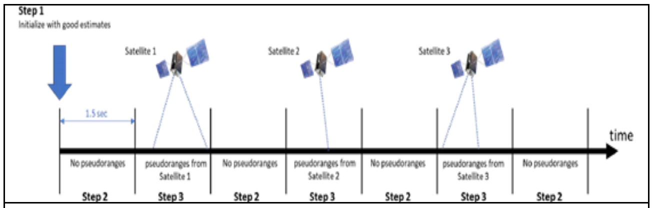

Figure 8. Sequential GPS Steps

Over the hour-long period, 29,000 pseudorange measurements were taken. In Figure 9, the red (absolute path) uses all measurements for its solution. With the sequential GPS method (blue), the algorithm only uses 246 pseudorange measurements.

The relative solution (green) is initialized to the correct heading but then never receives any more GPS pseudoranges. This solution is computed exclusively with inertial and wheel odometry measurements. Additional error is added to the relative navigation solution via scale factor and yaw drift for testing purposes only. The 2D error is computed for the relative navigation solution and the sequential GPS solution in Figure 10. With the sequential GPS (blue), we see a maximum of around 8 meters error, even with a degraded relative solution. With the relative solution (green), the error increases as a function of time. Extra error is added to the solution, compared with what would be seen with the RR-N-140. Spikes in error for the Sequential GPS requires more analysis. We suspect its due to poor GPS satellite geometry because the algorithm does not choose the optimal satellite at any point in time.

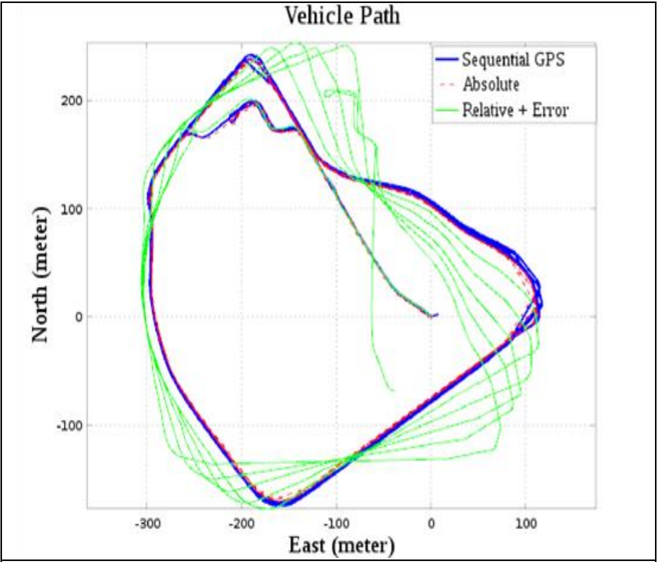

Figure 9. Vehicle Path

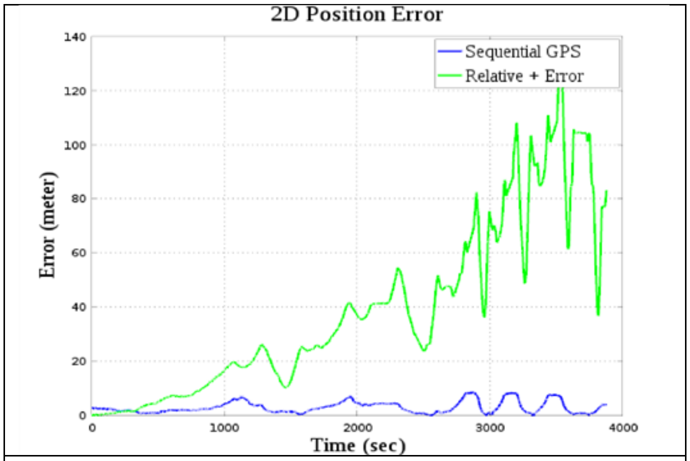

Figure 10. 2D Position Error

Our preliminary results show that with the integration of a CSAC into our navigation solution, the error added by time drift over a period of time is approximately 10 meters. In other words, if the time between the first satellite and the last satellite seen (four in total) to complete the four necessary for lock is one hour, the error added by the clock drift of GPS-SL is approximately 10m CEP.

4. Implications to the Leader Follower Program of Record (POR) and RCV.

There is little doubt that autonomous vehicles will be deployed by the DoD. There is also no doubt that the reliance on GPS will be challenged either by our adversaries or by the environment.

The system presented here provides a new mechanism for alleviating this problem. Sequential GPS acquisition provides several advantages for these programs:

- Initial acquisition of a position fix using a single satellite measurement per epoch at separate points in time to increase the receiver robustness in a GPS challenged environments.
- Incorporation of pseudoranges into the filters when less than 4 satellites are in view can provide corrections to the relative solution that significantly improve the navigation solutions.

- Significant advantages for GPS jamming and spoofing.
- Ready for implementation on vehicle systems.
- Incorporation of GPS solutions into the filters when less than 4 satellites are in view.
- Providing localization to a convoy where different vehicles can benefit from satellites acquired by their peers.

Ensuring accurate PNT data is essential to the U.S. Army and other military groups. It enables them to perform their various warfighting tasks and roles to complete their mission, thus this has become a high priority of DoD.

The overwhelming advantages of sequential GPS over traditional GPS acquisition for DoD applications is an important change to the PORs moving forward. Robotic Research is already incorporating the changes into future revisions of our navigation unit suites and plans to start the process of upgrading older units to accomplish this new technique.

1. RFERENCES

[1] William Wright, Development of a GPS Forest Signal Absorption Coefficient Index, Department of Geography and Environmental Engineering, United States Military Academy, West Point, NY 10996, USA. 2018

[2] G. Blewitt, “Basics of the gps technique: observation equations,” Geodetic applications of GPS, pp. 10–54, 1997.

[3] Kaplan, Elliott, and Christopher Hegarty. "Understanding GPS/GNSS: Principles and Applications." (2017).