NAVITEC 2018

5-7 December 2018
ESA/ESTEC, Noordwijk, The Netherlands

PERFORMANCE ANALYSIS OF LOW-POWER GNSS POSITIONING IN IOT

Vicente Lucas-Sabola[(1)], Gonzalo Seco-Granados[(1)], José A. López-Salcedo[(1)], José A. García-Molina[(2)]

[(1)] Dept. Telecommunications and Systems Engineering – IEEC-CERES, Universitat Autònoma de Barcelona (UAB)
Campus de la UAB, Bellaterra, Spain
Email: {vicente.lucas, gonzalo.seco, jose.salcedo}@uab.es

[(2)] European Space Agengy - European Space Research Technology Centre (ESA-ESTEC)
Keplerlaan 1, Noordwijk, The Netherlands
Email: jose.antonio.garcia.molina@esa.int

INTRODUCTION

During the recent years we have witnessed the advent of internet of things (IoT), whose main goal is to connect physical objects (e.g., urban furniture, wearables, assets, etc.) within a wireless low-end sensor network for data sensing, data gathering, computation and communication [1]. Then, the collected data from a sensor network is used for different purposes such as efficient resource management, big data analytics, or health monitoring, among others. Due to the exponential growth of the number of deployed IoT sensors, they are designed as low-cost and low-power solutions [2]. Low power consumption allows increasing the span between maintenance of a sensor, hence reducing the overall costs of deploying an IoT sensor network.

Apart from the sensed or gathered data, context-aware information plays a key role in order to achieve an intelligent IoT system, being location information crucial for this purpose [3]. Among the myriad of positioning technologies available for IoT, global navigation satellite systems (GNSSs) is a widespread solution thanks to its global coverage and free of charge provision of signals [4]. The drawback of employing a GNSS module or receiver to obtain the position, velocity and time (PVT) solution is the cost and power consumption, typically being one the most power hungry devices of the whole sensor, thus significantly reducing the battery life [5]. Furthermore, the accuracy and availability of the GNSS service is disrupted in typical IoT environments such as indoor or urban scenarios, therefore requiring of complementary solutions and advanced signal processing techniques to fulfill a minimum quality of service [6], clashing with the limited computational resources an IoT sensor have.

Together with the use of novel semiconductor technologies, mass market (MM) GNSS vendors are tackling the power consumption quandary with the use of assisted-GNSS (A-GNSS) services and duty cycle operation modes. The former reduces the time-to-first-fix (TTFF) of a GNSS receiver by providing an estimate of the code-delay and frequency offset of the available satellites, thus decreasing the search space [7]. The latter, diminishes the average power consumption of a GNSS module as most components are shut down (i.e., sleep) between position fixes. Nonetheless, duty cycle configurations have been shown to degrade the accuracy of the PVT solution, being worse for longer sleep states [8]-[9]. Similarly, different techniques are applied to reduce the power consumption of the GNSS receiver while computing the PVT solution (e.g., selecting the optimum geometry with a subset of the visible satellites). On the other hand, innovative solutions to reduce the power consumption of IoT sensors for positioning include the use of a cloud-based GNSS receiver. In this approach, the PVT solution is computed at a cloud server by means of a GNSS software receiver, thus offloading the computational tasks from the sensor [10]-[11].

The contribution of this paper is twofold. First, an analysis of the techniques applied by state-of-the-art GNSS receivers to tackle the power consumption and computing capacity constraints of IoT GNSS positioning is performed. Second, an assessment of the performance of a cloud-based snapshot GNSS receiver and a MM GNSS receiver configured with different operation and starting modes (i.e., cold and hot) in a representative light-indoor environment is carried out.

ANALYSIS OF LOW-POWER GNSS RECEIVERS

Despite the fact that there exists a wide range of technologies for IoT positioning such as low power wide area (LPWA), cellular or ultra-wide band (UWB) among others, GNSS still is the most widely used due to its higher accuracy and pervasiveness. Low-power consumption plays a key role to enable longer battery life, increase the number of deployed low-cost sensors and reducing the operational cost of the network. To keep the power consumption and cost to a minimum, designers have been forced to limit the computational power of sensors. Nevertheless, GNSS receivers are high-power devices, hence colliding with the power-consumption burden of IoT positioning. In this section we discuss the solutions of novel GNSS receivers in order to fulfill the stringent requirements of IoT (i.e., low-cost, low-power and reduced computational resources).

Mass Market GNSS Receivers

From a high-level perspective, a standard MM GNSS receiver is divided in four modules: front-end, acquisition, tracking and navigation. The front-end mode is in charge of receiving the satellite signals with a GNSS band antenna and performing the signal conditioning (i.e., pre-filtering, pre-amplification, baseband conversion, and analog-to-digital conversion). After the front-end, the acquisition module correlates the received signal with a local replica and carries out a frequency and code-delay search for detecting the presence of a satellite signal. The obtained coarse estimation of the frequency and code-delay for a detected satellite is then fed to the tracking module, whose goal is to accurately estimate these signal parameters (code and carrier tracking). Finally, at the navigation module the data of the GNSS signal is demodulated and fed into a positioning algorithm to compute the PVT solution (e.g., least-square, Kalman filter). During these steps, generic MM GNSS receivers may apply techniques whose main goal is to decrease the power consumption, such as reducing the amount of satellite signals to be processed, using A-GNSS data or by implementing duty cycling.

Efficient Processing Load

During the acquisition stage, the received signal is correlated with the local replica generated at the GNSS receiver in order to detect if a satellite signal is present. This process is performed in parallel through different correlation channels, one for each of the satellite signals to be searched. MM GNSS receivers offer multi-constellation (e.g., GPS, Galileo, GLONASS), thus considerably increasing the number of satellite signals to be correlated in contrast with single-constellation (i.e., x4) in order to achieve a higher availability. Furthermore, novel MM GNSS receivers are including multi-frequency positioning (e.g., L1/E1, L5/E5), which will increase the accuracy of the PVT solution from meters up to centimeters [12]. Nonetheless, the use of a larger amount of correlator channels at the acquisition stage causes an increase of consumption, and a balance between processing load and power consumption has to be carried out.

A straightforward way to reduce the amount of correlator channels to be used at acquisition stage and hence the power consumption is working with a single-constellation instead of multi-constellation in exchange of lower performance (e.g., availability and accuracy). On the other hand, there are techniques for reducing the amount of correlator channels to be employed by selecting a subset from all the visible satellites, and whose minimum performance is equal to traditional approaches in which all satellites are used. In a satellite selection technique, an optimal satellite geometry is used in order to minimize the geometric dilution of precision (GDOP) [13], which multiplied by the ranging accuracy gives the positioning accuracy of a GNSS receiver. The GDOP is defined as follows [14]:

$$\mathrm{GDOP} = \sqrt{\mathrm{trace}((\mathrm{H}^T\mathrm{H})^{-1})}, \tag{1}$$

where $\mathbf{H}$ is the geometry matrix containing the receiver-satellite geometry and whose size depends on the number of visible satellites.

In GNSS, the least-squares solution is traditionally used to calculate the position and clock error (additional unknowns are included in multi-constellation positioning)

$$\boldsymbol{x} = (\mathrm{H}^T\mathrm{H})^{-1}\mathrm{H}^T\boldsymbol{y}, \tag{2}$$

where $\boldsymbol{x}$ is the vector including position offset of the true and estimated coordinates of the receiver, the offset between the receiver and the GNSS time $\boldsymbol{x} = [\delta x, \delta y, \delta z, c\delta t]$, and $\boldsymbol{y}$ the corrected pseudorange measurement vector after linearization. Nonetheless, the computational complexity of matrix inversion involves an increase of power

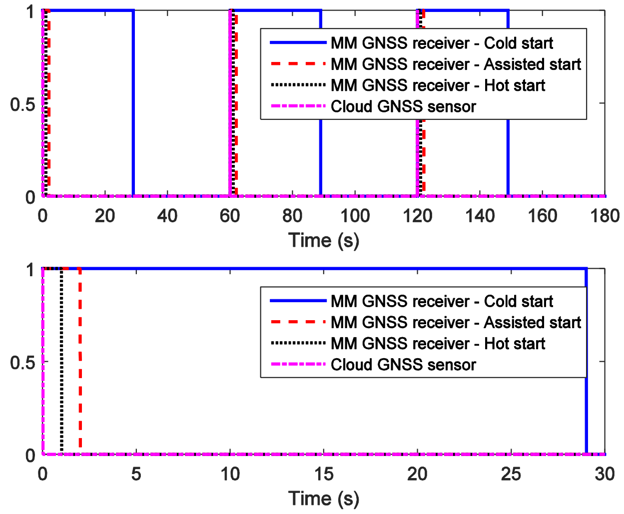

Fig. 1. Required minimum active time to obtain a position fix for a MM GNSS receiver with different starts [16] and a cloud-based GNSS sensor

consumption during the computation of the navigation solution, particularly if multi-constellation is used. A satellite selection algorithm allows shortening the size of $\mathbf{H}$, thus decreasing the computational load of the acquisition and navigation module. Other solutions such as the Bancroft method or Kalman filters do also use the geometry matrix to obtain the navigation solution, thus benefit from decreasing the size of $\mathbf{H}$.

A-GNSS

A key parameter of GNSS receivers is the TTFF, which is the time since they receive the GNSS signals until they provide the first PVT solution, available at the acquisition module output. This key parameter defines the amount of time the IoT sensor must be active until obtaining a position fix and switching off until the next fix. The TTFF of a GNSS receiver depends on the amount of prior information it includes from previous fixes at startup: code-delay and frequency shift of a given satellite, broadcast time, and ephemeris. In this sense, the startup of a GNSS receiver is defined as cold (~30 seconds) whenever it does not hold any prior information and hot (~1 second) whenever previous estimates and navigation data are used for the current start [7]. A previous estimate of the code-delay and frequency shift allows reducing the search space of a satellite at acquisition stage, whereas holding the broadcast time and ephemeris from previous fixes allows reducing the amount of signal to be received and processed. For instance, to decode the navigation message of a GPS L1 C/A signal a GNSS receiver requires a minimum of 30 seconds of signal, which may be even larger in harsh environment due to the lack of signal quality and availability during the reception of the signal. A TTFF of a minimum of 30 seconds is prohibitive in low-power positioning, as IoT sensors are expected to be active only during a couple of seconds before switching off to sleep mode until the next fix.

To reduce the TTFF, current GNSS receivers download A-GNSS data, which includes a list of the visible satellites given an approximate location and time, a coarse estimate of the code-delay and frequency shift of each satellite, and the navigation message of the signal of interest (i.e., RINEX navigation file message). The advantage of using A-GNSS data is threefold. First, it avoids the need of decoding the navigation message of the signal, thus only requiring a couple of seconds of signal. Second, a reduction of the code-delay and frequency shift search space of the satellites is achieved. Third, it restricts the amount of satellites to be searched to only those that are visible, thus leveraging the amount of correlator channels to be used at the acquisition module and decreasing the size of geometry matrix $\mathbf{H}$ used during the PVT computation.

Duty Cycle Operation Modes

In conventional GNSS-based positioning approaches, the receiver is enabled during the whole time (i.e., continuous mode), first searching for all satellites and decoding the navigation message at the acquisition stage and then switching

Fig. 2. MM GNSS antenna placed in a light-indoor scenario

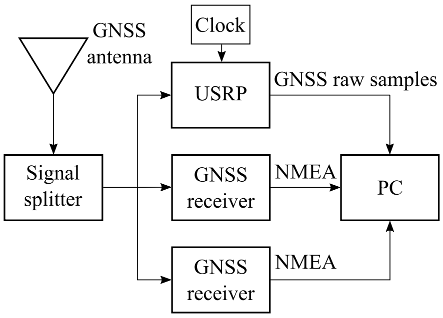

Fig. 3. Experimental setup of the laboratory

to tracking state, where the required power consumption is much lower, and just providing a position fix every update period. A simple way of reducing the average power consumption of a GNSS receiver is shutting down the components when they are not required, the so-called duty cycling. This solution suits with the operation mode of an IoT positioning sensor, as they are only activated during a couple of seconds until computing the position fix and then they go back to sleep mode, where the power consumption of the components is substantially lower (i.e. µA).

Current GNSS receivers offer a wide configurability in terms of operation mode, and the acquisition and tracking times can be limited to decrease the power consumption [15]. In this sense, the tracking stage can be configured to 0 seconds, thus changing the behavior of the GNSS receiver similar to a snapshot-based approach. The goal is to be active until just obtaining a first position fix from the acquisition module output. Nevertheless, such solution has an impact in the performance of the GNSS receiver, due to their acquisition stage is not designed to give fine code-delay and frequency shift estimates and no tracking is implemented, thus working with coarser measurements.

Cloud-based GNSS Receivers

The computational and power consumption burden presented by MM GNSS receivers for IoT positioning can be tackled transferring the computational load to a cloud server. In this context, the IoT sensor would only need to include an antenna and a radio-frequency (RF) front-end to receive the GNSS signal and implement the signal conditioning, to finally transfer the GNSS raw samples to the cloud through a communication module. Therefore, no GNSS receiver is required, and hence the IoT sensor is get rid of one of the most power hungry components [5].

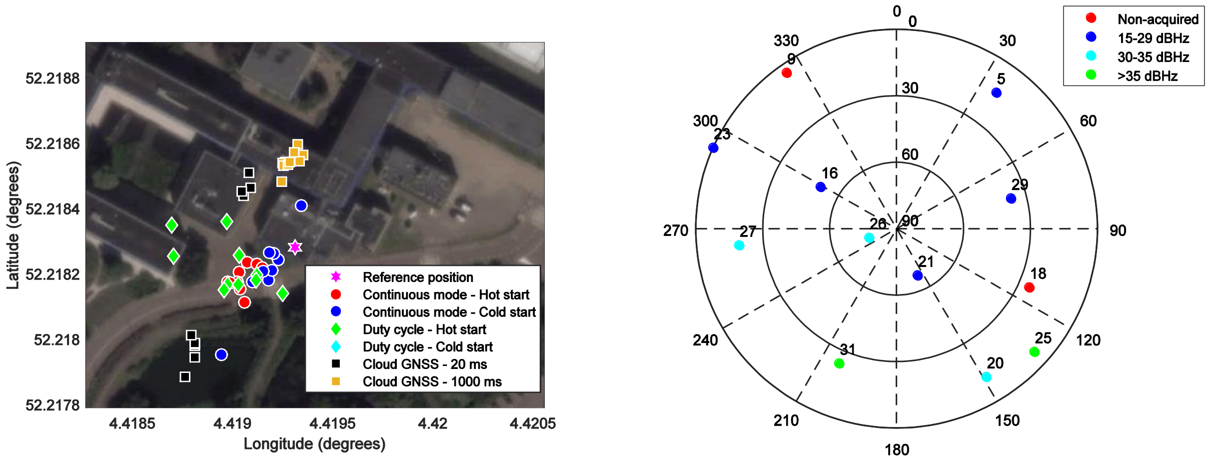

Fig. 4. (left) Obtained PVT solution of the MM GNSS and the cloud GNSS receiver, (right) sky plot of the visible satellites during the test

Table 1. Mean accuracy error and availability results

Receiver	Operation mode	Start	H2D mean error (m)	Availability (%)
MM GNSS	Continuous	Hot	20.1	100
MM GNSS	Continuous	Cold	15.5	90
MM GNSS	Duty cycle	Hot	25.5	100
MM GNSS	Duty cycle	Cold	-	0
Cloud-based	Snapshot	-	39.5	100
Cloud-based	Snapshot	-	29	100

Then, a snapshot-based software GNSS receiver is in charge of reading, decoding and processing the GNSS raw samples to provide a position fix. In a snapshot receiver no tracking is performed and an advanced acquisition is carried out instead. The output of this acquisition stage directly gives the fine code-delay and frequency shift of the satellite, in contrast with conventional approaches where such parameters are obtained at tracking. In addition, the connectivity of the cloud allows downloading the RINEX navigation files from GNSS data centers (GDC), thus no navigation message needs to be decoded. Thanks to this, the amount of signal to be received and then transferred to the cloud servers is limited to a few milliseconds (i.e., a minimum of 1 ms for GPS L1 C/A and 4 ms for Galileo E1-C), hence reducing the active time of an IoT sensor from typically seconds to milliseconds (Fig. 1). The amount of signal to be received and transferred depends on the environment the IoT sensor is working and the sensitivity of the GNSS receiver. In this sense, larger signal lengths are required in harsh environments to be able to detect satellites with lower carrier-to-noise ratio (C/N_0) [6].

The use of a cloud-based approach has been demonstrated to be more energy efficient than conventional approaches (including a GNSS receiver), up to one order of magnitude and up to 2.5 orders of magnitude in contrast with hot and cold starts, respectively [17]. Furthermore, the collection of GNSS raw data from different sensors distributed in a geographic area can be exploited for the implementation of innovative techniques and applications, such as cooperative positioning or interference detection, with the goal of improving the availability and accuracy of the PVT solution [11].

PERFORMANCE EVALUATION

Experimental Setup

In this work we aim to obtain the PVT performance of two MM GNSS receivers configured for low-power positioning and a cloud-based GNSS receiver in a representative IoT environment (i.e., light-indoor) and with real signal (Fig. 2). The test consists in the implementation of 1 position fix per minute during 10 minutes with cold and hot starts for the MM GNSS receivers and different signal lengths for the cloud GNSS receiver (i.e., 20 and 1000 ms).

The experimental setup of the laboratory is depicted in Fig. 3. First, a MM GNSS antenna is placed next to a window of the European Space Research Technology Centre (ESTEC) GNSS laboratory. A signal splitter is then used to feed two MM GNSS receivers (i.e., u-blox M8Ts) whose output is a national marine electronics associations (NMEA) file including the PVT solution. One MM GNSS receiver has been configured to work in continuous mode, and the other with a duty cycle operation mode, the tracking time fixed to 0 seconds. Then, the GNSS receivers are switched to active mode once per minute to obtain a position fix, to finally off to sleep mode, imitating the behavior of an IoT sensor. Both receivers have been configured for single-constellation positioning, thus replicating the workflow of low-cost and low-power GNSS receiver for IoT positioning. On the other hand, a USRP N210 with a bandwidth of 10 MHz is used as a cloud GNSS sensor prototype and whose output is the GNSS raw samples file of integers.

Performance Results

In Fig. 4 (left) are depicted the obtained position fixes for each of the test cases. First, there is an accuracy degradation of the MM GNSS receiver (hot start) whenever the duty cycle operation mode is used instead of the continuous mode (Table 1), something expected as the receiver does not implement any tracking of the GNSS signals. However, when the receivers are configured with cold start, duty cycle operation modes significantly disrupts the performance, up to the limit of not being able to provide any position fix during the 10 minutes of the test, whereas the obtained availability with continuous mode is 90%.

On the other hand, the cloud-based GNSS receiver offers an availability of 100% for both signal lengths of 20 and 1000 ms. Nevertheless, the obtained accuracy with 20 ms of signals is larger than the obtained by MM GNSS receivers. This is mainly due to the low C/N_0 of the visible satellites (Fig. 4) of the light-indoor scenario test. By increasing the signal length, the software GNSS receiver is able to detect and acquire satellites with lower C/N_0, and hence a much finer accuracy is obtained due to the GDOP improvement, but slightly worse than the obtained with the MM GNSS receivers. Again, this is expected as the cloud-based solution uses a snapshot-based GNSS receiver, and a finer acquisition is implemented instead of tracking the signal during a larger amount of time.

CONCLUSIONS

In this work we have briefly analyzed the approaches of state-of-the-art MM GNSS receivers to carry out low-power positioning, mainly focusing for IoT applications, where the computational resources, energy and cost of sensors are highly restricted. Then, we have evaluated the performance of MM GNSS receivers configured in low-power mode and a cloud-based GNSS approach in a light-indoor scenario with real signal.

The availability and accuracy performance of current MM GNSS receiver in harsh scenarios is jeopardized when duty cycle operation modes are used. Hence, there is a balance between active time and performance. On the other hand, performing a cold or hot start not only has an impact at power consumption and TTFF, but also at PVT level as shown by the obtained test results. In this sense, the positioning availability in cold start may involve a denial of service in harsh environments. It is for this reason that the use of A-GNSS data becomes mandatory in IoT low-power positioning for reducing power consumption and increasing the availability of the service.

Finally, the use of a cloud-based GNSS receiver has been proposed to tackle the power consumption and computational load burden of IoT positioning sensors and evaluated under the same experimental setup than the MM GNSS receivers. The obtained results confirms the cloud GNSS receiver as a valid option for IoT positioning due to its high availability as only a few milliseconds of signal are required instead of seconds, which in harsh environments might not be able to be captured due to the signal disruption. Even though the accuracy of the PVT solution is slightly worse than with MM GNSS receivers, the reader should bear in mind that the cloud-based GNSS receiver works with a snapshot approach and with short signal lengths, and hence requires of less energy per position fix. Still, the use of a cloud-based approach may be interesting for IoT applications with relaxed requirements in terms of PVT.

ACKNOWLEDGMENT

The views presented in this article represent solely the opinion of the authors and not necessarily the view of European Space Agency (ESA). This work was partly supported by ESA under contract No. 4000119070/16/NL/GLC and by the Spanish Government under grant TEC2017-89925-R.

REFERENCES

[1] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, “Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications,” *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2347-2376, 2015.

[2] S. Seneviratne, Y. Hu, T. Nguyen, G. Lan, S. Khalifa, K. Thilakarathna, M. Hassan, and A. Seneviratne, “A Survey of Wearable Devices and Challenges,” *IEEE Communications Surveys & Tutorials*, vol. 19, no. 4, pp. 2573-2620, 2017.

[3] C. Perera, A. Zaslavsky, P. Christen, and D. Georgakopoulos, “Context Aware Computing for the Internet of Things: A Survey,” *IEEE Communications Surveys & Tutorials*, vol. 16, no. 1, pp. 414-454, 2014.

[4] R. C. Shit, S. Sharma, D. Puthal, and A. Y. Zomaya, “Location of Things (LoT): A Review and Taxonomy of Sensors Localization in IoT Infrastructure,” *IEEE Communications Surveys & Tutorials,* vol. 20, no. 3, pp. 2028-2061, 2018.

[5] P. Zhang, C. M. Sadler, S. A. Lyon, and M. Martonosi, “Hardware Design Experiences in ZebraNet,” in *Proceedings of the 2nd International conference on Embedded networked Sensor Systems.* ACM, 2004, pp. 227-238.

[6] G. Seco-Granados, J. López-Salcedo, D. Jiménez-Baños, and G. López-Risueño, “Challenges in Indoor Global Navigation Satellite Systems: Unveiling its core features in signal processing,” *IEEE Signal Processing Magazine*, vol. 29, no. 2, pp. 108-131, March 2012.

[7] F. Van Diggelen, *A-GPS: Assisted GPS, GNSS, and SBAS.* Artech House, 2009.

[8] u-blox, “Portables: The challenge of low power and good GNSS performance,” White Paper, Aug. 2017.

[9] N. Linty, L. L. Presti, F. Dovis, and P. Crosta, “Performance analysis of duty-cycle power saving techniques in GNSS mass-market receivers,” in *Proc. IEEE/ION PLANS*, Monterey, CA, USA, May 2018, pp. 1096-1104.

[10] J. Liu, B. Priyantha, T. Hart, H. S. Ramos, A. A. F. Loureiro, and Q. Wang, “Energy Efficient GPS Sensing with Cloud Offloading,” in *Proc. of the 10th ACM Conference on Embedded Network Sensor Systems*, Nov. 2012, pp. 85-98.

[11] V. Lucas-Sabola, G. Seco-Granados, J. A. López-Salcedo, J. A. García-Molina, and M. Crisci, “Cloud GNSS receivers: New advanced applications made possible,” in *Proc. ICL-GNSS*, Barcelona, Spain. Jun. 2016, pp. 1-6.

[12] R. Warnan, and L. Van de Vyvere, “Positioning with Single and Dual Frequency Smartphones Running Android 7 or Later”, in *Proc. ION GNSS+*, Sep. 26, 2018.

[13] M. Zhang, and J. Zhang, "A fast satellite selection algorithm: beyond four satellites." *IEEE Journal of Selected Topics in Signal Processing*, 3.5 (2009): 740-747.

[14] Kaplan, Elliott, and Christopher Hegarty. *Understanding GPS: principles and applications*. Artech house, 2005.

[15] u-blox, “Power Management: Considerations for u-blox 7 and M8 GNSS receivers,” Application Note, 20 Feb. 2014.

[16] u-blox, “MAX-M8: u-blox M8 concurrent GNSS modules,” Data Sheet, 15. Aug. 2016.

[17] V. Lucas-Sabola, G. Seco-Granados, J. A. López-Salcedo, J. A. García-Molina, and M. Crisci, “Efficiency Analysis of Cloud GNSS Signal Processing for IoT Applications ,” in *Proc. ION GNSS+*, Sep. 2017.