Hummingbird: Energy Efficient GPS Receiver for Small Satellites

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ABSTRACT

Global Positioning System is a widely adopted localization technique. With the increasing demand for small satellites, the need for a low-power GPS for satellites is also increasing. To enable many state-of-the-art applications, the exact position of the satellites is necessary. However, building low-power GPS receivers which operate in low earth orbit pose significant challenges. This is mainly due to the high speed (~7.8 km/s) of small satellites. While duty-cycling the receiver is a possible solution, the high relative Doppler shift between the GPS satellites and the small satellite contributes to the increase in Time To First Fix (TTFF), thus increasing the energy consumption. Further, if the GPS receiver is tumbling along with the small satellite on which it is mounted, longer TTFF may lead to no GPS fix due to disorientation of the receiver antenna. In this paper, we elucidate the design of a low-cost, low-power GPS receiver for small satellite applications. We also propose an energy optimization algorithm called $F^3$to improve the TTFF which is the main contributor to the energy consumption during cold start. With simulations and in-orbit evaluation from a launched nanosatellite with our μGPS and high-end GPS simulators, we show that up to 96.16% of energy savings (consuming only ~ $\frac{1}{25}$th energy compared to the state of the art) can be achieved using our algorithm without compromising much (~10 m) on the navigation accuracy. The TTFF achieved is at most 33 s.

CCS CONCEPTS

• **Theory of computation → Mathematical optimization**; • **Hardware → Sensor applications and deployments**.

KEYWORDS

GPS, GNSS, Time to First Fix, TTFF, satellite, positioning, attitude, navigation

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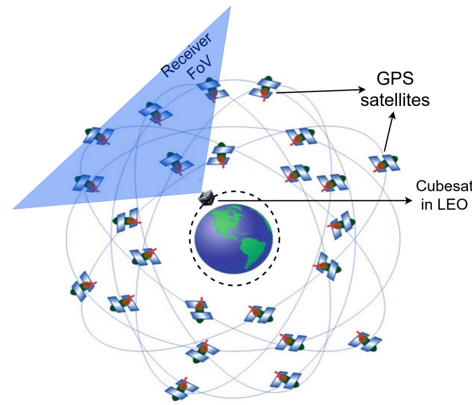

Figure 1: A scenario demonstrating the visibility of GPS satellites for a GPS receiver antenna mounted on a cubesatellite in LEO

1 INTRODUCTION

Location information is an important aspect of many terrestrial applications as well as space applications including for satellites and the applications offered by them. Global Positioning System (GPS) is a widely accepted technique for satellites to identify their locations in the Low Earth Orbits (LEO) and Medium Earth Orbits (MEO). Positioning helps in various satellite applications such as surveillance, mapping, estimating sea levels and areas of forest and lakes. Advanced applications such as finding the levels of ice on glaciers and movement of pollutants also need exact positioning. Indeed, the satellite also needs to know its position for its orbit correction and navigation. With the rise in demand for small satellites over the past decade, the need for low-cost, low-energy space-borne GPS receivers is also increasing. While big satellites typically do not have any constraints on energy consumption (as they have big deployable solar panels) for GPS subsystem, this is not the case in miniaturized satellites. Most of the small satellites such as nano, cube, pico and femtosatellites are severely powered-constrained (because of their restricted solar panel size), and the GPS receivers are seen as one of the subsystems constantly consuming significant portion of the energy, even as high as up to 20% of the power budget in cubesats [4, 15]. Even though there are many GPS receivers readily available, most of them are optimized for terrestrial applications and they may not be energy-aware to employ on small satellites or would not even be functional when it comes to space applications.

One of the most common energy conservation techniques proposed for space-borne receivers is duty-cycling [5]. Here, the receiver is turned ON until a position fix (ability to calculate the position with reasonable accuracy) is acquired and then it is turned OFF for a specified duration to save energy. This technique is efficient only when the Time To First Fix (TTFF) of the receiver is relatively short *i.e.,* the time taken by the receiver to get locked to at least four GPS satellites, acquire signals and navigation data, and obtain the position fix. On the account of duty cycling, if the receiver takes more time to get a position fix (or TTFF) every time it is turned ON, then there may not be any significant minimization in energy consumption. However, attaining a short TTFF in space-borne receivers can be tricky unlike in terrestrial systems where cell tower data can be used to achieve a faster fix [2, 24]. During TTFF, most of the energy is consumed for searching the GPS satellites and acquiring the signals [1]. Unless the local time and information about the GPS constellation are known a priori, the receiver, to get the first fix, has to search for the visible GPS satellites, estimate the Doppler shifts in signals of the satellites, and correlate the pseudo-random noise (PRN) codes that are unique to each GPS satellite.

Majority of the acquisition time is spent on searching for a GPS satellite's PRN code in the presence of the Doppler shift and time to read the navigation data [1]. The high Doppler shifts in the GPS signals are due to the high orbital velocities (around 7.8 km/s at 500 km altitude) of the GPS receivers mounted on satellites and the GPS satellites (around 3.9 km/s). While the general GPS receivers are designed to consider the Doppler shift of around ±10 kHz on Earth, the receiver on a satellite in LEO can experience Doppler shifts up to ±80 kHz. This impacts the TTFF significantly as the receiver has to blindly search for the visible GPS satellites that is within the Field of View (FoV) of the receiver (Figure 1). Additionally, when there is no prior information on the GPS constellation and time, the acquisition search takes place for all the satellite in the entire Doppler range during correlation even if the satellite is not visible at that moment. Therefore, the TTFF for a receiver in space can go as high as 25 minutes, and in such cases, even duty-cycling may not be beneficial [13].

Once the receiver locks to a GPS satellite, the almanac (coarse information on the position of GPS satellites at a given time) and ephemeris (precise location of the GPS satellites) can be downloaded, which takes 12.5 minutes and 30 s, respectively. Most of the small satellites, such as nanosats, cubesats and femtosatllites may not be equipped with attitude control systems – which are commonly present in big satellites – leading to tumbling (spinning) on all three axes, including the GPS receiver and antenna. While it is beneficial to keep the energy consumption low in satellites with or without attitude controls, it is extremely important to lock onto the GPS satellite as quickly as possible and download the ephemeris and almanac when the receiver antenna is disoriented (rotating). This is a kind of a challenging *catch-22* situation, wherein the approximate GPS location and time is required by the receiver to get a faster fix but cannot be obtained without having a position fix. Furthermore, energy-saving must not be at the cost of position accuracy. Missions involving payloads such as cameras may need high position accuracy.

Due to the high orbital velocities, a duty-cycled GPS receiver usually has to lock on to a new set of GPS satellites each time it wakes up. Thus, TTFF is one of the major factors that affect the performance of space-borne GPS receivers in terms of energy consumption. Hence, we mainly focus on a specific problem - reducing TTFF to minimize energy consumption. In this paper, we present an algorithm to minimize the energy consumption of the GPS receiver

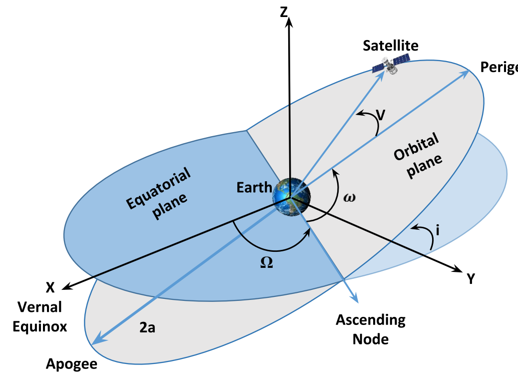

Figure 2: Satellite orbital dynamics

by exploiting the orbital information that is included at the launch time to achieve a faster fix. To demonstrate this, we also focus on designing and developing a low-power GPS receiver (employing an off the shelf GPS chip) for satellite applications. To this end, we design a space qualified, low-power GPS receiver subsystem, called μGPS, that is energy-efficient[1]. The novelty of this work mainly lies in the design of low-cost, low-power miniaturized GPS receiver - μGPS. While TTFF is a major factor that affects the energy consumption of duty-cycled space-borne receivers, we mainly concentrate on significantly improving the TTFF by proposing an energy-aware algorithm. Furthermore, we propose an algorithm, Fast Fix and Forward/Propagate (F^3), that minimizes the time and energy to get the first fix. We reduce the TTFF significantly by readily estimating the visible satellites and the Doppler frequencies for the respective satellites, thereby reducing the frequency search space for PRN codes. Once the Doppler frequency is located and the signal is being received, our receiver requires a maximum of 33 s to achieve the position accuracy of ~8 m (95% of the time). With in-orbit evaluation from a launched camera based remote-sensing nanosatellite 'NANOSAT', we show that up to 96.16 % of energy savings can be achieved using our algorithm without compromising much on the position accuracy 99 % of the time.

To estimate the Doppler Shift, the GPS receiver is updated with the latest GPS almanac and the receiver's Two-Line Element (TLE)[2] data just before the launch. This helps F^3 to switch off the GPS front-end radio on the receiver and keep only the microcontroller running to propagate the previous position and GPS time using the TLE data. This enables to duty-cycle the receiver efficiently; the GPS front-end is turned ON only a few times per orbit to calibrate its position and clock drifts. μGPShas been realized and was launched recently in two nanosatellites. The receivers are successfully operating in orbit as intended. Specifically, our contributions are of several folds:

1. We design a low-power miniaturized GPS receiver subsystem called μGPS for space applications and present the in-orbit results.
2. We present a complete solution to minimize the energy for space-borne GPS receivers considerably.

[1] Analogy of the hummingbird is used in the title to highlight that our solution is *small*, *fast* and *energy efficient* as the bird

[2] Two Line Elements is a file containing the orbital information of a satellite using which its location in space at any instant can be estimated.

(3) We make use of a COTS GPS chip (where raw data is available) to keep the design low-cost rather than designing a proprietary GPS module. Thus, our solution could be used in almost all situations.
(4) With in-orbit data from a launched nanosatellite with our μGPS, we demonstrate that our proposed algorithm, F^3, performs well even when the satellite is tumbling and the GPS antenna is disoriented.
(5) The TTFF with μGPS and F^3 is only a few seconds more than the time required to download ephemeris from one GPS satellite, hence it is extremely fast.

The rest of the paper is organized as follows. In §2, we provide the satellite orbital dynamics and fundamentals of the GPS. We list the challenges and motivations posed to design a low-cost and low-power GPS receiver for space-borne applications in §3. The design of the μGPSis presented in §4, and the proposed algorithm F^3 is explained in §5. We evaluate the performance of μGPSin §6, and in §7, we list the related state-of-the-art in the literature. Finally, we conclude in §8.

2 FUNDAMENTALS OF SATELLITE ORBITAL DYNAMICS AND GPS

Before we present our energy minimization technique and algorithm to reduce TTFF, we briefly explain the satellite orbital dynamics and the fundamentals of the GPS system for civilian use.

2.1 Satellite Orbital Dynamics

Most of the satellites in Low Earth Orbits (LEO) form an elliptical orbit with Earth as one of the focal points. The geometry of such an elliptical orbit is shown in Figure 2. The entire satellite orbit and the position of a satellite in space at any time can be determined using the six *Keplerian orbital parameters*:

(1) *Semi-major axis (a)* of the elliptical orbit.
(2) *Eccentricity (e)* of the ellipse.
(3) *Inclination (i)* is the angle between the orbital and equatorial planes;
(4) *Argument of perigee (ω)* is the angle between the perigee and ascending node vectors.
(5) *Right ascension of ascending node (Ω)* is the angle between the vernal equinox and the ascending node vectors. This angle is thus measured along the equatorial plane.
(6) *Mean anomaly (ν)* is the angle between the perigee and the satellite's current position vectors.

More details on the relation between these elements can be found in [16]. North American Aerospace Defense Command (NORAD) provides the complete orbital element information along with the Keplerian elements as Two-line Element (TLE), that is unique to a satellite. Using TLE, anyone can track the satellite, and the TLE is available for public use. NORAD updates it once in a day or two. The position is estimated using TLE is accurate to 2 km and the position data become stale over a few days [13].

2.2 Fundamentals of the GPS

The GPS constellation consists of 31 active satellites transmitting navigation messages on the same carrier frequency. The satellites

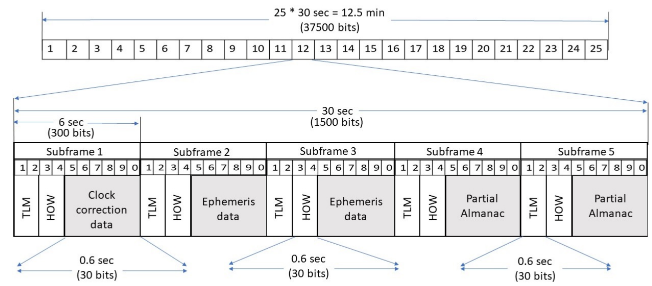

Figure 3: Data frame format of signal from a GPS satellite

are orbiting at an altitude of 20200 km above the Earth. The orbit geometry is such that at least four satellites are visible at any location on the Earth at all the times. All the satellites transmit GPS data in the same frequency band using Code Division Multiple Access (CDMA). Each satellite has a unique pseudo-random noise (PRN) code which is used to identify the satellite. The navigation message (actual data) is transmitted at 50 bps. There are three bands – L1, L2 and L5. The codes used for the L1 band (1.575 GHz) Coarse Acquisition (C/A - for civilian use) are 1023 bits long and are transmitted every 1 ms. As shown in Figure 3, a single navigation message frame consists of five sub-frames, transmitted every 30 s. Each sub-frame is transmitted every 6 s. All the sub-frames consist of the time at which the next sub-frame will be transmitted along with the clock corrections. Subframes 2 and 3 together constitute the *ephemeris*[3] information, which is a set of time-varying parameters that are used to calculate the position and velocity of the corresponding GPS satellite. Subframes 4 and 5 contain partial almanac, which has coarse information about the state and position of all the GPS satellites. The receiver has to wait for one subframe (6 s), one navigation frame (30 s), and 25 navigation frames (12.5 minutes) to download the GPS time, ephemeris and almanac, respectively. While the almanac is valid for around 2 months after which the accuracy of the data becomes poor, the ephemeris is valid for around 4 hours only.

There are three major steps performed to get a position fix:

(1) **Acquisition:** First, the receiver has to search for the signals from the visible GPS satellites. Even though all the GPS satellites transmit in the same frequency, there may be Doppler shift and the receiver has to lock to that received signal frequency. This search is done by correlating the received signal with the pre-saved PRN codes of GPS satellites. If the received signal matches the PRN code of a satellite, then the receiver is said to be locked onto that satellite. To get a 3-dimensional (3D) fix, it is necessary for the receiver to get locked onto at least four GPS satellites.
(2) **Decoding:** Once the receiver locks to a GPS satellite, it decodes the received signal to get the information on GPS time, ephemeris, clock bias, etc. are obtained.
(3) **Positioning:** With the help of the decoded data, the 3D position of the receiver is obtained using trilateration.

A scenario demonstrating the visibility of GPS satellites for a GPS receiver antenna mounted on a cubesat in LEO is shown in Figure 1.

[3] An ephemeris gives the trajectory of space objects *i.e.*, the position (and possibly velocity) over time.

The time taken by the receiver to startup, acquire satellite signals, receive navigation data and calculate its current position for the first time after the receiver is turned ON is called *Time To First Fix* (TTFF). Typically, the TTFF is classified into three different start types based on the data already stored in the GPS receiver.

Cold start. The receiver does not know its last position or time, and it has no valid ephemeris or almanac data. Typically, this is performed whenever the receiver has been powered down for more than two weeks. A typical cold start will take at least 12.5 minutes – without considering any software optimization – when almanac stored in the memory is not valid. Even when there is a valid almanac, the receiver can take more than 5 minutes to get position fix, which is typical [9].

Warm start. In this case, a valid almanac is present in the receiver's memory and the current position is within 300 km from the last active position. However, ephemeris is not present in memory. A typical warm start takes between 35 s to 4 minutes.

Hot start. A receiver starts up in this mode when warm start conditions are met and a fix had been established within the last two hours. The receiver has a valid ephemeris data for at least five satellites.

The ephemeris data contains precise corrections to the almanac data and is required for accurate positioning. It is continuously updated and thus the ephemeris data within a deactivated GPS receiver will become stale after ~4 hours. We point the readers to [6, 25] for more information on the GPS theory. With this foundation we now provide motivation for this work and also we try to provide the problems in detail in the sequel.

3 CHALLENGES AND WORKAROUND

As discussed earlier the positioning of small satellites is a challenge because of many constraints. We list the challenges encountered in designing a low-power GPS receiver for space applications and the possible directions towards solutions, in this section.

3.1 Challenges

Using GPS is the easiest method for satellites in LEO orbit to keep track of their current position. Given that the satellites are being miniaturized, their power budgets are also being reduced correspondingly. Nanosatellites and cubesats can dissipate as low as 1 W, while femtosatellites have even lower power budget of approximately 200 mW [20]. If 140 mW is the average power spent on the GPS receiver in these small satellites, there is hardly any power left for other subsystems to operate (more so in femtosatellites), and hence they may fail in their mission. Furthermore, the current state-of-the-art receivers may not work when a satellite is tumbling at high rates (~10°/s). As GPS is one of the most power-consuming subsystems in small satellites, it is highly desirable to reduce its energy consumption.

Duty-cycling the GPS receiver operation is a common method to reduce energy consumption. Generally, due to the high orbital velocity of the satellites, the GPS receivers need to find a new fix each time they wake up. This technique is power hungry and inadequate if the TTFF is high. This paper, therefore, focuses on developing a low-power GPS subsystem and an algorithm that significantly reduces the energy consumption without sacrificing the position accuracy.

There are several non-trivial challenges that need to be addressed in order to realize μGPSand the F^3 algorithm. Further, nanosatellite applications make it much harder. We list them briefly here.

- **Visibility of GPS Satellites.** On terrestrial GPS receivers, there is a possibility of getting the same GPS satellite or the same constellation even after 4 hours. However, satellites in LEO revolve around the Earth in just 90 minutes (at approx. 500 km altitude). Hence, the visibility of GPS satellites changes rapidly, while the receiver needs to update itself for new acquisitions more frequently. This would not be an issue when the receiver is continuously ON as it can get locked to more than four (six to ten usually) GPS satellites as a backup in case if it had lost track. However, it is tricky in case of duty cycling to conserve energy. The receiver, when turned ON each time, will be far away from the previous position and it has no idea of which satellites it should search for resulting in longer TTFF.
- **High Doppler shift.** A satellite in LEO travels at a velocity as high as 7.8 km/s at approx. 500 km orbit. The GPS satellites themselves travel at 3.8 km/s. Due to the high relative velocity between them, the Doppler search range can be as high as ±80 kHz compared to that on Earth (±10 kHz). Alongside, the rate of change of the Doppler offset is also significant. This increases the receiver frequency search range during initial signal acquisition and reacquisition in case GPS satellite is lost after locking. This implies an increase in the TTFF significantly and that can be as high as 25 minutes [13]. Hence, reducing TTFF is a challenging task for space-borne GPS receivers.
- **Higher performance at low-power.** The acquisition and decoding of the navigation message must be performed as quickly as possible. A small delay of 10 ms in the algorithm points the satellite 78 m away when the speed is 7.8 km/s. Hence, the receiver should contain high-performance hardware while it has to be of low-power.
- **Attitude control**: When the satellite attitude is uncontrollable, which is usually the case in small low-power satellites, the receiver antenna orientation with respect to the GPS constellation may be unfavourable when the satellite is tumbling (spinning). This leads to a loss of GPS signal resulting in the search for GPS satellites multiple times. In some cases, the receiver may not be able to get the complete almanac, ephemeris and clock corrections from any of the GPS satellites due to the antenna disorientation. This leads to no fix, and also draining the battery on account of signal acquisition.

3.2 A Possible Workaround

All the above challenges can be addressed using workarounds. However, they require some compromise through the use of additional devices, or losing space. We list them below.

(1) Multiple antennas can be mounted all around the satellite so that the signals from all the visible GPS satellites can be acquired and locked continuously even if the satellite is tumbling. However, this comes at a cost of sacrificing the mounting space for solar cells as the small satellites, such as cube-, pico-sats, are covered by body-mounted solar cells to harvest maximum energy.

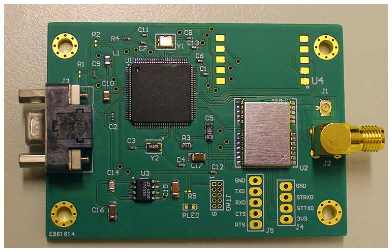

Figure 4: μGPSReceiver

(2) As an alternative to Assisted GPS (A-GPS), the GPS almanac and ephemeris data can be uploaded to the receiver from multiple ground stations on Earth so that TTFF can be improved. This requires additional ground stations that are not cost-effective.
(3) Updated TLE can be uploaded to the satellite from the ground stations continuously for propagating the position in orbit when the receiver is OFF. Again this requires multiple ground stations.
(4) In terrestrial applications, it is possible to get a faster fix (~2 s TTFF) if the position of the receiver does not change more than 300 km [18]. The same technique can be applied in space but it requires duty cycling at a higher rate (in LEO, a receiver has to be duty-cycled once every 20 s approximately). This may not be energy efficient.

In this work, we try to address all the aforementioned challenges. We present an algorithm that does not need any additional requirements such as multiple antennas or ground stations. Further, the duty cycling period is selected optimally to minimize energy consumption while designing a space-borne GPS receiver. To demonstrate these, we design and deploy a space-qualified GPS receiver with these algorithms. To the best of our knowledge, we are the first to provide such a complete solution and also test it in stringent conditions by launching our module into LEO.

4 DESIGN OF μGPSRECEIVER

Designing a GPS receiver for space applications is a challenging task. Unlike GPS receivers for terrestrial use, the μGPSon a satellite has to sustain the harsh environmental specifications of space – extreme temperatures, vibration during launch, vacuum and radiation. All the components used should be reliable as there is no chance of repair after launch. Furthermore, the software must also be of high-reliability albeit the mission fails. Considering these requirements, the following design goals were set as requirements.

G1 The dimension should be as small as possible however it must withstand vibrations and it should be robust. Based on the structural requirements and the mounting, our μGPSreceiver has the dimension 40 mm × 30 mm × 2 mm. The mass is 50 g including a U.FL antenna connector. The available power budget is 150 mW. It should be noted that the power budget provided here is similar to/lower than the generic commercial miniaturized GNSS receivers for small satellite applications [11, 22, 23]. Typically, the power budget for a cubesat is around 1 W, and GPS subsystem consumes 10% to 20% of the total available power [12, 20, 21].

G2 An in-orbit accuracy of 30 m (with a minimum of 99.7 percentile) for the position and velocity of 30cm/s (99.7 percentile) is sought.

G3 The navigation solutions must be sent to the On-Board Computer (OBC) at 1 Hz in a custom format.

G4 The GPS should provide clock synchronization to the satellite's main OBC since GPS fix could provide an exact clock.

The μGPS, that we developed for the NANOSAT[4] is shown in Figure 4. The receiver weighs 20 g. The maximum power consumption of the receiver is 145 mW, which is within the limit imposed by the structures team (**G1**). The receiver houses a *customized* low-power GPS chip with frontend - Venus series from Skytraq, supporting GPS L1 frequency (1.54 GHz). It provides the navigation solution in NMEA format [17] as a standard, like any other commercial consumer and space grade GPS receivers. The chip also provides raw GPS data such as ephemeris, GPS time, pseudo-range, clock corrections and other required data to estimate the position. The On-Board Computer (OBC) has no computational power to parse these data and execute the algorithm. Hence, the receiver also includes a low-power ARM microcontroller, MSP432 on which the navigation solution is computed, and to power duty-cycle the GPS front-end. Before the launch, the GPS chip was subjected to emulation by sophisticated equipment that completely mimics the dynamics of space and GPS satellites. The observed accuracy by the chip was 10 m (at 99 percentile) for the position and 10cm/s (at 99 percentile) velocity, catering to **G2**. The reasons for selecting the aforementioned GPS chip are its low-power operation, accuracy, and most importantly the availability of raw data. The microcontroller sends the navigation solution to the OBC at 1 Hz (**G3**).

Since the OBC clock drifts 2 s per day, an important requirement of the μGPS is to provide real-time clock synchronization to the OBC periodically. The receiver sends the Pulse Per Second (PPS) signal on one of its GPIO pins to the OBC. PPS is the time at which the GPS front-end receives signals from GPS satellites and obtains the position fix (the time taken for processing the signals and executing positioning algorithm is compensated). Since the time synchronization has to be in microsecond accuracy, the delay in communication between the OBC and the receiver is also included in the algorithm. The GPS receiver also corrects its clock periodically meeting the goal **G4**. The receiver supports both SMA based active and passive GPS antenna and we chose Tallysman 2410W because of its robustness to sustain in the harsh space environment.

During the duty-cycling, when the GPS chip is OFF, the power reduces to ~6 mW, wherein only the microcontroller is active. The overall component cost of the receiver was ~\$200 (commercial GPS sub-systems for small satellites cost around \$3000-\$4000). The receiver has passed all the environment tests such as reliability, thermal, vacuum, vibration and radiation adhering to space systems requirements. We execute our proposed algorithm Fast Fix and Forward (F^3) on the microcontroller to reduce the energy consumption.

5 DESIGN OF THE F^3 ALGORITHM

The basic idea behind the Fast Fix and Forward (F^3) is to duty-cycle the GPS chip to minimize energy consumption. To reduce energy consumption, we mainly target improving the TTFF of the receiver

[4]The actual name of the satellite is not mentioned to maintain anonymity. Because of the launch opportunity, we designed this receiver for a nanosatellite, though it can also be used in a cube or pico satellite.

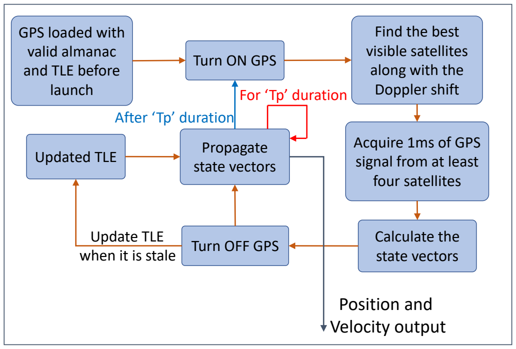

Figure 5: Functional block diagram of the F^3 algorithm

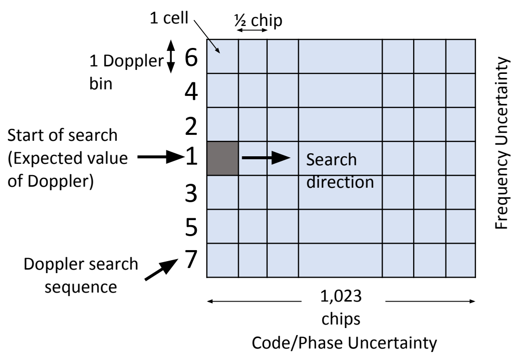

Figure 6: C/A code search pattern

since it consumes a significant amount of energy, especially in acquisition mode. The basic idea is as follows: When the GPS chip is OFF, the state vectors (position and velocity) are propagated using TLE of the satellite. Since continuous TLE propagation is prone to deviations, we correct the error by getting the true position from the GPS intermittently. Then, the TLE is updated/corrected for the bias for further propagation. The functional diagram of our algorithm is shown in Figure 5 and the methodology is implemented in five main steps explicated below.

5.1 Reducing the Time To First Fix (TTFF)

GPS signal acquisition is a search process. This process requires replication of both the code and the carrier of the GPS satellites to acquire the signal. Hence, the process is two dimensional – the range dimension is associated with the replica code and the Doppler dimension is associated with the replica carrier. To perform the search, the receivers utilize the tracking loops such as Phase Locked Loop (PLL) and Delay Locked Loop (DLL). When the code phase and the Doppler frequencies of signals are unknown, the corresponding search space is large. Thus the expected search time increases and it can go as high as 25 minutes because of the high Doppler shift range of received signals in satellite orbits as mentioned earlier, contributing to the TTFF. Therefore, we try to reduce the searching time.

The initial C/A code search usually involves replicating all 1023 C/A code phase (1 ms signal = 1023 chips) states in the range dimension. The code phase is typically searched in increments of 0.5 chip. Each code phase search increment is a code bin. Each Doppler bin is roughly $2/(3T)$ Hz, where T is the search dwell time (the longer the dwell time, the smaller the Doppler bin). The combination of one code bin and one Doppler bin is a cell. In a typical receiver, the default bandwidth of the search bin is set at 250 Hz [24]. Figure 6 shows the two dimensional C/A code search pattern. Each bin also needs to search for a correct PRN code phase. This search period is called the dwell time. Predicting the Doppler shifts (using estimates of receiver and GPS satellites' position and velocity) reduces this dwell time. This is possible only when the approximate receiver position is known or the prior position is within 300 km [18]. There are many methods proposed to reduce the search space in frequency axes but the process is always two dimensional [6, 25]. In our proposed method, we reduce the search space to one dimension.

During the launch, the receiver is loaded with the parent satellite's TLE, the almanac of GPS constellation and the ejection time of the satellite[5]. The receiver uses this when it is turned ON for the first time. Note that the almanac does not cause any storage overhead as all the GPS chips reserve onboard storage space for almanac. However, TLE file is comprised of 138 characters (138 bytes) and this can easily be accommodated in the microcontroller. On the first cold start of the GPS receiver, it estimates its position on the orbit using the loaded TLE as the approximate current time is known. Using the almanac, the best visible GPS satellites at that position are calculated and their Doppler frequencies are estimated. Now, the two-dimensional search space converges to one dimension i.e., single row search space, as the Doppler frequency is known. Hence the complexity of the TTFF algorithm reduces to $O(N)$ from $O(MN)$, where M is the number of Doppler bins and N is the number of chips. However, the reduction in code/phase uncertainty is not possible unless the accurate ephemeris is known. Now, it is necessary to show that the estimated Doppler frequency is within 250 Hz due to the Doppler bin size, and the search stays within a single bin for different code phases.

Error bounds. Even though the tracking frequency is identified now, there is a possibility that the almanac and TLE used for calculation may not be accurate. It has been shown that the TLE provided by NORAD is accurate to a few meters and deviates as high as ±2 km on continuous propagation for days [13]. The almanac will remain valid for around two months and accurate enough to get ±3 km accuracy on the day of launch of the receiver [10]. Hence, the estimated position has a combined maximum error of 10 km. However, the maximum error from almanac can go up to 50 km if it is two months old [10].

The estimated satellite ejection time and the actual time is assumed to be accurate to ±5 s, else the satellite orbit will change. Therefore, the estimated position of the GPS satellite by the receiver may have deviated by 78 km in ±5 s with the assumption that velocity of the receiver is 7.8 km/s. Hence, the maximum possible error in estimated position = *Error from TLE + Error from almanac + Error from ejection time* = 4 + 6 + 78 = 88 km. For ease of calculations later we round this on the higher side to 100 km.

[5]Ejection time of a satellite is known prior to the launch to place the satellite in the defined orbit.

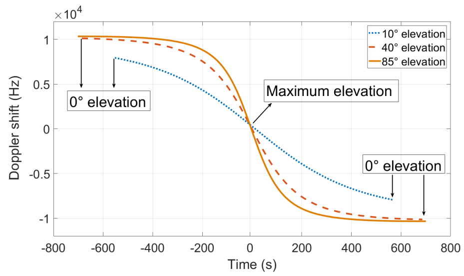

Figure 7: Doppler shift observed for different elevation between the observer and a satellite at 500 km

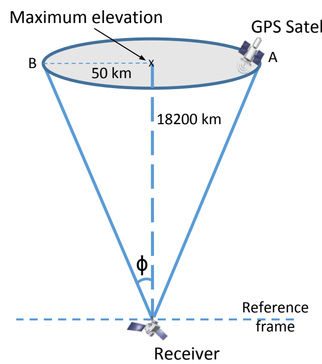

Figure 8: A scenario where estimation of a GPS satellite's position is off by the maximum possible error distance.

The Doppler frequency f observed by the receiver is given by,

$$f = \left(1 + \frac{\Delta V Cos\theta}{c}\right) f_o, \quad (1)$$

where ΔV is the relative velocity between the receiver and the GPS satellite, θ is the angle between them along the velocity vector, c is the velocity of light, and f_o is the transmitted signal frequency. For GPS L1, f_o = 1.575 GHz.

Figure 7 shows the Doppler frequency observed for different elevation (angles) between the observer and a satellite at 500 km, travelling at 7.8 km/s. We observe from the plot that the Doppler frequency is zero when the elevation is maximum, i.e., 90°. The same also holds when we substitute $\theta = 90$ in Eq. (1). Additionally, when the elevation approaches its maximum, the slope of the curve also reaches its extreme. This indicates that the rate of Doppler shift is more around the maximum elevation, so as the estimated Doppler frequency using error-prone TLE and almanac. Let us consider the scenario where a GPS satellite is visible to the receiver as depicted in Figure 8. Let the relative velocity ΔV, be $|(3.8 + 7.8)|$ km/s, which is the maximum possible. The receiver is at the vertex of the cone and the GPS satellite is anywhere on the circumference of the plane surface, let us say Position A. The rate of Doppler shift is maximum when the GPS satellite moves along the diameter of the circle, crossing the maximum elevation point, and then touching the circumference of the circle at, say, Position B. As per our consideration, the maximum possible error in the estimated position of the GPS satellite is 100 km. Hence, the radius of the circle is 50 km. Considering the LEO orbit that extends up to 2000 km above the earth, the altitude of the cone is the difference between, the altitude of the GPS satellite and altitude of the receiver in LEO, which is, 18,200 (20,200 - 2000). Note that, as the distance between the GPS satellite and the receiver decreases, the Doppler rate increases. Hence, we consider the farthest possible LEO orbit. Now, we have the angle between the slant range and the altitude vector, $\phi = 0.158°$.

The maximum error in the Doppler frequency= ± (Doppler shift at Position A - Doppler shift at maximum elevation point).

Substituting $\Delta V = 11.6$ km/s, $\theta = 90 - \phi = 89.842$, $c = 3\text{x}10^8$ m/s and $f_o = 1.575$ GHz in Eq. (1), we get the maximum Doppler Shift of approximately ±170 Hz, which is less than ±250 Hz – the frequency search bin size of the receiver. Therefore, with the maximum position error of 100 km in estimating the position of a GPS satellite, it is possible to reduce the satellite search space to one dimension, thus improving the TTFF. Since modern receiver chips contain multiple channels, the search can be done in parallel to speed up and also to identify multiple satellites as fast as possible. At the end of search, at least four GPS satellites must be locked to get the position fix.

5.2 Time synchronization

At this stage, it should be noted that the receiver clock is not synchronized to that of the GPS satellites even though a minimum of four satellites is found. Therefore, it is necessary to download at least one navigation frame from these satellites, which includes ephemeris and GPS time. This takes around 30 s as explained in Section 2.2, after which the GPS receiver is synchronized with the GPS time. In the case of tumbling satellites, the GPS signals are intermittent thus it may take longer duration – the number of packets received depends on the FoV of the receiver antenna, tumbling speed and orientation. Packets received partially are stitched to get a complete frame. It should be noted that the GPS time can be downloaded in just 6 s if the tumbling speed (degrees/second) is $\frac{1}{6}^{\text{th}}$ of the Antenna FoV and is oriented perpendicular to the direction of the incoming signal. In literature, we find methods to estimate the position just by using the Doppler measurements but they are not worthy for satellite applications because of the long TTFF issues [18]. However, with our improved TTFF methodology, the same algorithms can be used for tumbling satellites when there is no possibility of downloading ephemeris. We do not explain this in detail as it is out of the scope of this paper but we show the results in §6. Because of the quick lock to the GPS satellites, coarse estimation of the position is possible even when they are tumbling at high speeds or on satellites where the power is too low to turn ON the receiver for 30 s.

5.3 Duty Cycling the Receiver

Once we have the ephemeris downloaded and the receiver clock is synchronized, the position of the receiver and measurement error are calculated using classic algorithms such as least square error method or Kalman filter. Indeed, the position accuracy can be improved with a custom designed state estimation algorithm but this is out of the scope of this work as we mainly concentrate on minimizing the energy consumption without jeopardizing the position accuracy much. Further, $F^3$is independent of the estimation/tracking algorithm employed. For more details on the position estimation algorithms, we point the interested readers to [6, 25]. As mentioned earlier, we duty cycle the receiver to conserve energy. The receiver is ON for a short duration just to synchronize the GPS time and to correct the clock offsets of the receiver. When the GPS front-end is OFF, the microcontroller on the receiver propagates the previous position using TLE. Let us formulate our energy minimization problem as follows.

Our main objective is to minimize the consumed energy $E_c = n(T_{ON} \mathrm{x} P_G + P_M(T_{ON} + T_{OFF}))$ where T_{ON} is the total time for which both GPS chip and microcontroller are ON. T_{OFF} is the time during which only the microcontroller is ON, n is the number of times the GPS chip is duty-cycled, P_G and P_M are the power consumption of the GPS chip and the microcontroller, respectively. However, the duty cycling period depends on the following three conditions.

(1) *Available energy.* The receiver cannot consume more energy than the available energy, E_A, at any moment.
(2) *Propagation time.* The receiver cannot propagate the TLE for more than T_P s – starting from the time at which GPS chip is turned OFF – to stay within the error limits of propagation and to maintain the navigation accuracy. Hence, the GPS chip has to be turned ON after every T_P s for error correction. Through T_P, we consider the GPS accuracy error in our optimization problem.
(3) *Navigating duration.*: The GPS chip has to be ON for at least T_{ON} duration so that the position fix can be obtained.

If T_{TTFF} is the time taken by the receiver for the first fix, T_{nav} is the time taken to compute navigation solutions, our energy minimization problem can be formulated as Linear Programming model as given below,

$$\textbf{Minimize } E_c = n(T_{ON} \mathrm{x} P_G + P_M(T_{ON} + T_{OFF})) \textbf{ s.t.}$$

$$E_c \leq E_A \tag{2}$$

$$T_{OFF} \leq T_P \tag{3}$$

$$T_{ON} = T_{TTFF} + T_{nav} \tag{4}$$

$$\text{and } T_{OFF} \geq 0; T_{TTFF}, T_{nav}, E_c, n, P_G, P_M > 0. \tag{5}$$

Since we have already optimized T_{ON} with our proposed algorithm, it is clear from the above equations that, to minimize E_c, n should be minimized as the rest of the parameters are constant for a particular receiver. However, it is also true that E_c has a trade-off with T_P. If the state vectors can be propagated using TLE for a longer duration (higher T_P) while maintaining the accuracy within the threshold (as per the requirement), then T_{OFF} increases. Thus, n can be reduced and the chip can be turned OFF for longer duration in a considered period.

5.4 Updating TLE and Almanac

The TLE and almanac go stale over days, leading to increasing error in position measurements when used for propagation. Since GPS gives the true position (depends on the accuracy of the navigation algorithm though), we use the position provided by the GPS receiver to update the TLE and GPS almanac.

The solution provided by the GPS navigation algorithm will be in Earth Centered Earth Fix frame (ECEF) and the TLE is in True Equator Mean Equinox (TEME) frame that is the subset of Earth Centred Intertial (ECI) frame [6, 25]. ECI coordinate frames have their origins at the centre of mass of Earth and are called inertial, in contrast to the ECEF frames, which rotate in inertial space in order to remain fixed with respect to Earth's surface. The relation between the ECEF and ECI frame can be given using the rotation matrix as,

$$P_{ECEF} = \begin{bmatrix} cos(\omega_g) & sin(\omega_g) & 0 \\ -sin(\omega_g) & cos(\omega_g) & 0 \\ 0 & 0 & 1 \end{bmatrix} P_{ECI}, \tag{6}$$

where ω_g is the rate of Earth's rotation.

We use NORAD SGP4 function to update the TLE from the estimated position and velocity. SGP4 is a well known and widely used technique in Aerospace industry to estimate the position of the satellite at any given instant [8, 16]. However, we do not restrict ourselves to use only the SGP4 since there are numerous methods to update TLE. Moreover, the TLE propagation accuracy affects the duty-cycling period as explained in §5.3. The elements of TLE and almanac are in the format,

$$y_i = f_i(a, e, i, \Omega, \omega, \nu, B^*) \qquad i \in \{1, ..., 7\}, \tag{7}$$

where y_i is the i^{th} state estimate, B^* is the ballistic coefficient used in SGP4 propagator and the rest are the orbital elements as explained in [8].

Once we have the position in ECI format, the TLE and partial almanac (update details only for the satellites whose ephemeris have been downloaded) are updated using the relations between the estimated state vectors and orbital elements as described in [6, 25].

5.5 Propagation using TLE

When the GPS chip is off, the microcontroller propagates the state vector using TLE. We use NORAD SGP4 orbit propagator to estimate the next position depending on the prior position. This is the inverse operation of the calculations performed in §5.4. Usage of stale TLE leads to an erroneous propagation compromising the position accuracy. Since we update the TLE periodically as mentioned earlier, the error in propagation is corrected.

6 EVALUATION

We evaluated the performance of our GPS receiver and the proposed technique by means of long duration simulation as well as real-time test in the LEO orbit. The evaluation setup for both cases is as follows.

6.1 Evaluation Setup

6.1.1 Simulation. We used Spirent G6700 simulator (Spirent is one of the top companies that offers GPS simulators with satellite orbit simulation) to test the performance of our GPS receiver. The simulator is capable of providing a coherent simulated signal from GPS satellite constellation. It especially considers the LEO scenario by adjusting the Doppler frequencies and satellite visibilities for the set receiver orbit. It also incorporates atmospheric effects and errors in the simulated signal so that the receiver will experience the same effect as that in the orbit. The simulator provides RF

Figure 9: Placement of the μGPSreceiver in NANOSAT

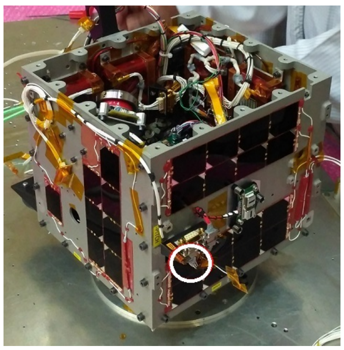

Figure 10: Antenna placement on NANOSAT

output over an antenna. In this simulation process, even though the receiver is stationary, it experienced a high relative Doppler shift and high velocity as if it is in the orbit. The maximum Doppler shift considered in simulations is ±80 kHz, as explained in Section 3.1 and Section 5.1.

For simulation, the receiver orbit was considered to be 520 km, same as that of the NANOSAT. Mbed LPC1768 microcontroller was used as OBC of the NANOSAT to record data and clock synchronization from the GPS receiver and to validate the results. The TLE[6] of the receiver orbit and the latest GPS almanac were given as input to the simulator and also stored on the receiver microcontroller. The simulator was also updated with the latest Ionospheric error models.

6.1.2 In-orbit evaluation. The receiver was fixed on the NANOSAT and was launched at an altitude of 520 km. The receiver was attached on one of the side panels inside the satellite as shown in Figure 9. The antenna was placed in such a way that it points deep space. The antenna placement is shown in Figure 10. The data from the receiver is recorded by the OBC and sent to the ground station whenever there was visibility

For both simulation and in-orbit evaluation, we set the following values to the parameters described in Section 5.3, unless mentioned otherwise.

We set T_{ON} = 33 s as the complete TTFF and navigation algorithm execution including TLE, almanac update was performed within 32.8 s. The continuous power of 150 mW was available from the NANOSAT. The TLE propagation error was within the threshold of 30 m position and 0.3 m/s velocity at 3σ level as per the

[6] This was provided by the space organization responsible for NANOSAT

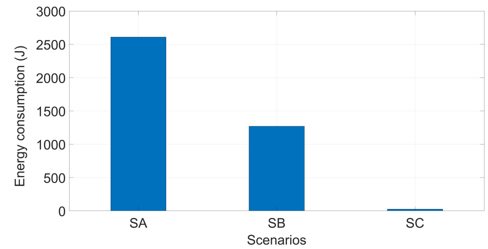

Figure 11: Energy consumption on different scenarios

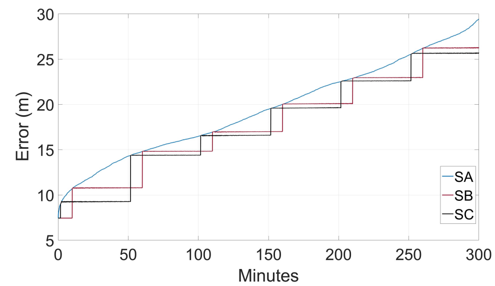

Figure 12: Accuracy of the solution

requirement when $T_P \leq 300$ minutes. Note that, as T_P increases, T_{OFF} increases, thus maximizing the energy savings.

6.2 Simulation and In-orbit results

With our experiments, we study the impact of the proposed algorithm on various factors as follows.

6.2.1 Energy consumption. To evaluate the energy savings of the receiver 'in-orbit', we consider three scenarios.

Scenario A (SA): The receiver is continuously ON. Here, there is no requirement of the propagation of orbit since continuous GPS fix is available. Our algorithm is not executed in this case.

Scenario B (SB): The receiver is duty-cycled once in 50 minutes (to get an accuracy of 10 m) and our TTFF algorithm is not used. During duty-cycling, when the GPS chip is OFF, the microcontroller is continuously ON, propagating the state vectors.

Scenario C (SC): The receiver is duty-cycled once in 50 minutes but with improved TTFF (using our algorithm).

The performance of one of the best available commercial spaceborne GPS chip from Skytraq, the state-of-the-art methodology, and our F^3 algorithm are evaluated in the above three scenarios respectively.

The energy consumption of the receiver in the above three scenarios for 5 hours are shown in Figure 11. The total power consumption of the receiver was ~145 mW, wherein the microcontroller consumed ~6 mW and the GPS chip consumed ~139 mW power. It is evident from the plots that our F^3 algorithm saves energy significantly. In SA, the receiver is continuously ON, consuming maximum energy. In SB, even though the GPS chip was duty-cycled, it was a cold start for it every time it is turned ON. The TTFF went as high as 20 minutes. In SC, the maximum TTFF was 33 s, thus saving 96.16% compared to that in SA, and 92.7% to that of SB.

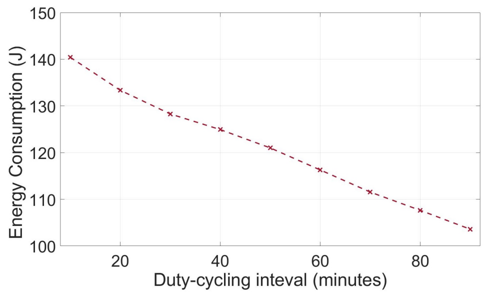

Figure 13: Impact of duty-cycling interval on energy consumption

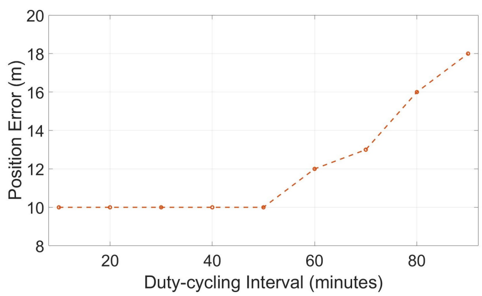

Figure 14: Impact of duty-cycling interval on position error

6.2.2 Accuracy. Figure 12 shows the accuracy of the navigation solution in the aforementioned scenarios, tested in-orbit. Since velocity is the function of position, we show the error only in Z direction (along with altitude) as it was the maximum in all the cases. In SA, the error is within 10 m (99%) always. However, in SB and SC, the state vectors are propagated after the GPS chip is turned OFF, and TLE is propagated, so the position error. It should be noted that, in SB, the receiver continues to propagate for a few minutes even after the GPS chip is ON as the fix has not happened yet. We observe from the plots that TLE propagation also propagates the error from the GPS solution. In the first 3 months after launch we observed that the propagation error was within 10 m (99%) when the GPS was duty cycled once within 50 minutes.

6.2.3 Duty cycling. We evaluate the impact of duty cycling time on energy consumption using simulator. The receiver was turned on at different intervals from 10 s to 90 minutes for 300 minutes. The results are shown in Figure 13. We observe from the plots that as the GPS chip is turned ON less and less, the energy consumption decreases almost linearly. When it is duty-cycled every 90 minutes[7], the energy consumption was at the minimum.
Since the position accuracy is dependent on the TLE propagation duration T_p, the duty-cycling duration also impacts on the accuracy. The position error for different turn ON intervals of the receiver is shown in Figure 14. We observe in the figure that the error is within 10 m for turn ON intervals until 50 minutes. Further increase in the interval leads to more error because of incremental error from TLE propagation. Hence, even though the energy consumption decreases as the duty-cycling interval is increased, this comes at a cost of sacrificing the position accuracy.

[7]GPS receiver turned on every 90 minutes and once fix is done, it is turned OFF.

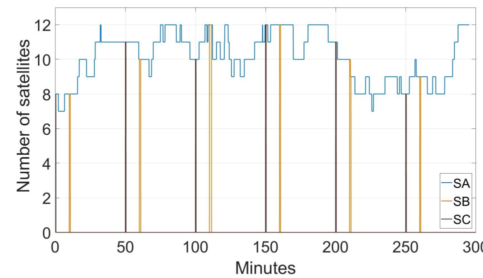

Figure 15: Visibility of GPS satellites

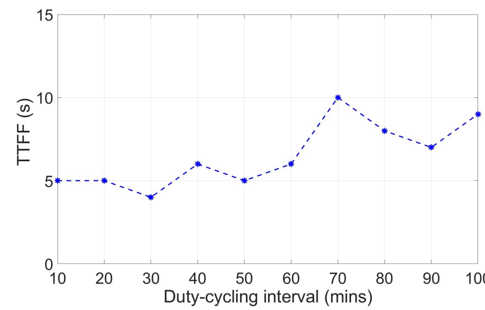

Figure 16: TTFF at different duty-cycling intervals

6.2.4 Satellite Visibility. We also evaluate our F^3 algorithm for visibility of GPS satellites using a simulator to asses the performance of the TTFF. Figure 15 shows the results in all scenarios. In SA, more than four GPS satellites are visible always as there is a continuous fix. In SB, the TTFF was around 10 minutes. Even the visibility of the satellite was more than four during acquisition phase, there was no fix. We do not know the exact reason as the solution is being calculated by the commercial chip and the algorithm is unknown. In SC, the receiver gets fix to the visible satellites at a faster rate due to improved TTFF.

6.2.5 TTFF vs Duty cycling. To evaluate the trade-off between TTFF and the duty cycling interval, the receiver was duty cycled at different intervals between 10 and 100 minutes in-orbit. The TTFFs averaged over 10 trials are shown in Figure 16, and the CDF of TTFF obtained for all the duty-cycling intervals is shown in Figure 17. As we observe in Figure 16, the average TTFF for any of the duty-cycling intervals is between 4 s to 10 s. However, irrespective of the duty-cycle period, the maximum TTFF observed during evaluation was 33 s. This is because the ephemeris downloaded from all the GPS satellites is valid for four hours. If the receiver is duty cycled within four hours, it does not have to download ephemeris again (which takes 30 s to complete the task). However, the receiver may need to download information related to GPS time and clock drifts that can take a few seconds depending on the sub-frame being sent from respective GPS satellites. As seen in Figure 17, the maximum TTFF was 33 s (cold start) and the minimum (hot/warm start) was 3 s. This latency is acceptable for any of the satellite missions (so the mission of NANOSAT) when the receiver has to download the ephemeris directly from the GPS satellites. As per the CDF plot, 60 % of the times, the TTFF was within 20 s. Therefore, the TTFF

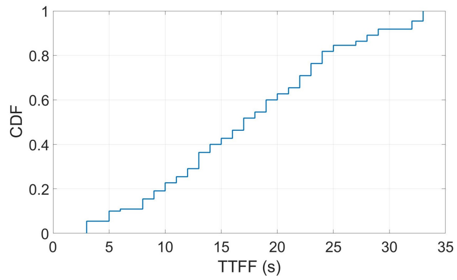

Figure 17: CDF of TTFF for different duty-cycling intervals

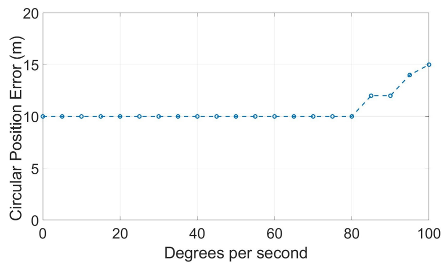

Figure 18: Circular position error at different tumbling rates

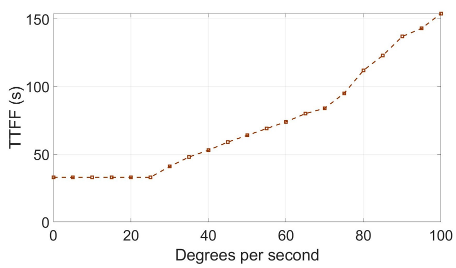

Figure 19: TTFF at different tumbling rates

does not solely depend on the duty cycling interval, but also on the validity of the ephemeral data.

6.3 Tumbling

The receiver antenna was mounted on the satellite body during the simulation and rotated to emulate the tumbling scenario. F^3 was implemented on the receiver to get a faster fix. We measured Circular position error (difference in position as estimated by the receiver and the true position provided by the simulator) and the TTFF at different tumbling rates. The results were shown in Figure 18 and Figure 19 respectively.

Observing Figure 18, when the rate was less than 80°/s, the receiver was able to download the ephemeris in 33 s and get the position accuracy of 10 m. The accuracy obtained was 15 m when the rotation rate was around 100°/s. This is considerable against the case where no fix is obtained without F^3 algorithm when it was tumbling at the rate of 10°/s and higher. As the tumbling rate increases after a certain extent (80°/s in our case), there will be carrier phase error introduced in the received signal. Hence, position error increases.

The TTFF at different tumbling rates is shown in Figure 19. Until 25°/s, the TTFF was 33 s as the receiver could get locked to the visible satellites quickly. Beyond this rate, the receiver loses track of the visible satellites or receives only partial signal (as explained before, 6 s is required to receive one subframe from a GPS satellite) because of tumbling. Hence, the receiver spends more time in acquisition mode to get locked to the visible/possible GPS satellites.

Table 1: Comparison between the performance of different state-of-the-art GPS receivers

	Chen et al.	Aalto	Aurora	CAN-X2	μGPS
Power	0.143 W	0.16 W	1.1 W	1.6 W	0.145 W
Position Accuracy	12 m	100 m	30 m	20 m	10 m (99%)
Energy savings	22.7%	–	–	–	96.16%

6.4 Comparison

We compare the performance of different state-of-the-art GPS receivers. Chen et al. [4], Aalto [12], Aurora [21], CAN-X2 [9] and μGPSare space-borne receivers that are considered for comparison the results are depicted in Table 1. It is clear from the table that μGPS, when employed with F^3algorithm, saves considerable energy, providing a decent position accuracy. Most of these state-of-the-art works do not report their acquisition and tracking algorithms. While Chen et al. use rudimentary least square method to estimate the position, in μGPS, we use adaptive Kalman filter to estimate the position and velocity [25].

7 RELATED WORK

We list some of the relevant and important works – not necessarily space-borne – related to energy minimization and improving TTFF for GPS receivers.

For terrestrial applications. Patil et al. propose two methods to reduce the TTFF for smartphones by avoiding the download of the ephemeris data, thus reducing the energy consumption of the receiver [19]. The first method bypasses the need for downloading the ephemeris and the second method enhances the rate at which ephemeris is downloaded using Assisted GPS (A-GPS). An energy-efficient GPS acquisition technique with sparse-GPS is proposed by Misra et al. [15]. They present a new computing framework for GPS acquisition via sparse approximation. They show that the energy consumption can be reduced 5-10 times than a standalone GPS, with a median positioning accuracy of 40 m. Liu et al. design a cloud-offloaded GPS (CO-GPS) solution that allows a sensing device such as a mobile phone to duty-cycle its GPS receiver and log just a few milliseconds of raw GPS signal for post-processing. The position information is extracted later on a back-end server [14]. A novel multi-step algorithm for low-energy positioning using GPS is proposed by Orn et al. [18]. With a prototype receiver, they demonstrate that the position can be computed using only two milliseconds of GPS raw data. The system includes a GPS receiver that collects the raw GPS data, and a server that utilizes Doppler navigation and coarse time navigation to estimate the positions.

Recently, Chen et al. established an energy model for a standard GPS receiver architecture to analyze the impact of key software parameters on the GPS energy consumption [4]. Their findings show that the energy consumption increases as more GPS satellites are tracked. Their approach is to track only a subset of the visible satellites that are just enough to produce equally accurate positions. They also present a method called *SatProbe* allowing low energy and fast indoor/outdoor detection based on raw GPS processing [3]. Bissing et al. propose a new method to shorten the TTFF by exploiting the shape of the likelihood function in collective detection of satellites, thus minimizing the energy on constrained situations like continuous position tracking on small wearable devices.

These works either require a centralized server or assisted GPS (internet/cell tower) to speedup the TTFF. This is not practical in the case of space applications.

For space applications. Leung et al. implement a signal acquisition aiding concept based on an analytical orbit model, which regularly calculates the approximate position and velocity of the receiver [13]. They use data from the satellite orbit model to improve TTFF when there is a temporary loss in the fix. Power saving in small satellite GPS receivers by duty-cycling the receiver is investigated by Hartmann [7]. The author also attempts to combine orbital propagation along with duty-cycling. Anghileri et al. present a concept aiming at improving the TTFF performance of navigation receivers by defining a set of clock and ephemeris data (CED) with reduced size [1]. This newly defined message types could be added into the transmission schemes of today's and future GNSS satellites to reduce the TTFF. There are other state-of-the-art receivers that have been tested successfully in the orbit but they are not energy-aware to suit small satellite requirements even if they employ duty-cycling [9, 12, 21]. In these works, duty-cycling is performed in a traditional way by turning ON the receiver whenever the position error exceeds a fixed threshold. However, they do not concentrate on the TTFF, thereby spending energy by retaining the receiver ON until a fix is obtained. With such methods, duty-cycling may not be even beneficial to reduce energy consumption when the TTFF is longer. On the contrary, our algorithm improves the TTFF as well as duty-cycles the receiver, thus achieving energy minimization.

Filling the gap. In most of the aforementioned methods, even though a small portion of the received GPS signals is used for estimating the position, the post-processing is done outside of the receiver. Additionally, all the state-of-the-art techniques is analogous to A-GPS, where the ephemeris, almanac, clock corrections and other navigation parameters are acquired through a secondary channel (e.g., GPRS). However, in the case of a space-borne GPS receiver, these details are completely unknown unless they are uploaded from ground stations frequently. Though propagating TLE to estimate the position is a known technique, it requires updating the new TLE to the satellite from the ground station more often (e.g., once in a day) and the satellite may not be equipped with telecommand capabilities in some cases. Hence, none of the above work can be directly used for a low-power receiver in space. Further, the existing energy saving techniques such as duty-cycling for space-borne GPS receivers may not be beneficial if TTFF is huge. To this end, we propose an energy-aware algorithm to reduce the TTFF significantly so that the duty-cycling technique is more efficient. To evaluate our algorithm, we design a low-cost, energy aware GPS receiver for space-borne applications.

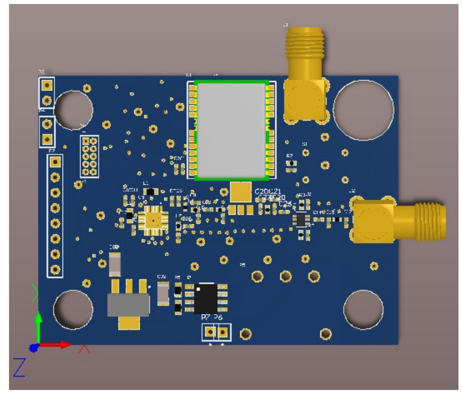

Figure 20: New version of μGPS, yet to be tested in space

There are plenty of works done on GPS algorithms in the context of TTFF, energy savings, accuracy, etc., for terrestrial applications. Most of the solutions require Assisted GPS (AGPS) that requires an Internet connection. However, this cannot be adapted for space applications. In the existing space-borne GPS receivers: (i) none of them provides TTFF of 33 s which we have achieved, especially when the satellite is tumbling and duty-cycled; (ii) there is no facility to execute our own algorithms on the receiver; (iii) most of them are not low-cost; and (iv) in terms of algorithm, the state-of-the-art include duty cycling the receiver. When the receiver is OFF, TLE is used to estimate the position and velocity based on the previous measurement. However, when the receiver is turned ON again, it enters acquisition mode and takes time, thus more energy is spent to get TTFF. Our algorithm gets the TTFF at the earliest, thereby saving energy.

8 CONCLUSION

In this work, we presented the overall design of a low-power, low-cost GPS receiver for space-borne applications. We provided the nuances of GPS technology and its applicability in space, covering the constraints and requirements. Specifically, we showed how TTFF can significantly contribute to the energy consumption of the GPS receivers and in turn the small satellite on which it is mounted. We explained the orbit dynamics that increase TTFF. Since higher amount of energy is consumed during TTFF, we proposed an energy aware algorithm called F^3that decreases the TTFF in spite of higher relative Doppler shift in low earth orbits. Further, the F^3reduces the complexity of the traditional GPS navigation algorithm so that it could be used in other scenarios. We tested our GPS receiver in in-orbit experiments by mounting it on a nanosatellite that was launched recently. We have evaluated the performance of F^3, and we observed TTFF being at most 33 s. We showed that up to 96.16% of energy savings can be achieved compared to the current state of the art. We have also designed a new version of μGPSthat weighs only 8 g and has the dimension of 20 mm × 20 mm × 2 mm, whose 3D diagram is shown in Figure 20. $F^3$is implemented on this receiver and is ready to be launched in the next three months so that the hardware can be tested in space.

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