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Hummingbird: An Energy-Efficient GPS Receiver for Small Satellites

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Abstract

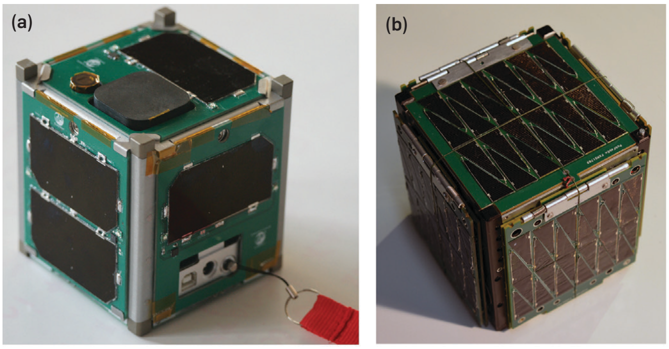
Global positioning system (GPS) is the most widely adopted localization technique for satellites in low earth orbits (LEOs). To enable many state-of-the-art applications on satellites, the exact position of the satellites is necessary. With the increasing demand for small satellites, the need for a low-power GPS for satellites is also increasing. However, building low-power GPS receivers for small satellites poses significant challenges, mainly due to the high speeds (∼7.8 km/s) of satellites and low available energy. While duty cycling the receiver is a possible solution, the high relative Doppler shift among the GPS satellites and the small satellite contributes to an increase in Time to First Fix (TTFF), which negatively impacts energy consumption. Further, if the satellite tumbles, the GPS receiver may not be able to receive signals properly from the GPS satellites, thus leading to an even longer TTFF. In the worst case, the situation may result in no GPS fix due to disorientation of the receiver antenna. In this work, we elucidate the design of a low-cost, low-power GPS receiver for small satellites. We also propose an energy optimization algorithm to improve the TTFF. With the extensive evaluation of our GPS receiver on an operational nanosatellite, we show that up to 96.16% of energy savings can be achieved using our algorithm without significantly compromising (∼10 m) the positioning accuracy.

1. INTRODUCTION

An uptrend in the number of small satellites launched every year since the last decade is clearly seen in a recent survey.[10] Meanwhile, there is also a revolution in miniaturizing the satellites because of operational costs and the possibility to launch a large number of satellites in a single batch.[8] Small satellites provide a range of key advantages over their larger counterparts. Apart from lower deployment and operational costs, they are also robust to schedule variations and launch failures. Most of the small satellites in low earth orbit (LEO) can use commercial-off-the-shelf (COTS) components, thus being highly cost-effective.

Small satellites come in a variety of form factors, from femtosatellites (<0.1 kg mass) to nanosatellites (1–10 kg mass). Among the latter, the so-called *CubeSats*,[19] shown in Figure 1, represent a paradigmatic example of features and limitations. Though CubeSats started as an academic effort,[19] they eventually became a platform for many applications such as remote sensing and Earth observation. The CubeSat standard[19] prescribes the size and provides indicative mass and power figures. CubeSat initiatives are also increasing globally,[22] especially toward deploying massive constellations of distributed CubeSats to achieve global Earth coverage and ubiquitous Internet access through coordinated operations.

Figure 1. (a) Vermont Lunar CubeSat and (b) SkyCube CubeSat.



Mass: 1 kg
Dimension: 10cm × 10cm × 10cm

Mass: 1.3 kg
Dimension: 10cm × 10cm × 11.3 cm

Small satellites represent a formidable mobile computing platform enabling multiple space applications at a fraction of the cost of larger satellites. However, they equally pose a range of interdisciplinary challenges that are to be tackled within severe resource constraints dictated by the size, weight, and available power. The combination of these challenges prompts different communities to push the envelope in the design and realization of a range of functionality—from attitude control to localization.

Accurate positioning is essential for both the small satellite's housekeeping operation and application-level tasks, for example, when coordinating a constellation for radio interferometry[1] or mapping a picture with the exact location on Earth. GPS is the most commonly used technology in space for localization. However, GPS receivers are seen as one of the subsystems constantly consuming a significant portion of the energy in most of the small satellites. This can be even as high as 20% of the power budget in cubesats.[9]

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One of the most common energy conservation techniques proposed for space-borne receivers is duty cycling.[3] This technique is efficient only when the TTFF of the receiver is relatively short. TTFF is 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. Thus, TTFF is one of the major factors that affect the performance of space-borne duty-cycled GPS receivers in terms of energy consumption. Hence, we mainly focus on a specific problem in this work—reducing the TTFF to minimize energy consumption. To this end, we present an algorithm to minimize the energy consumption of the GPS receiver by exploiting the orbital information of the satellite on which the receiver is mounted. Our efforts on this work eventually led to the launch of *Hummingbird*[13]—our space-proven energy-efficient GPS receiver.

Before we dive into our work on the challenges, solutions, and results of *Hummingbird*, we briefly discuss multiple issues involved in designing and building small satellites.

2. CHALLENGES

A big picture of the important challenges in the design, implementation, and deployment of small satellites is graphically depicted in Figure 2. Solving one of these challenges most often entails striking a proper balance with components and solutions of different subsystems, or sacrificing performance on orthogonal system metrics.

Below, we discuss what we argue to be the primary challenges at stake while highlighting their relationship with the overall system design.

2.1. Miniaturization

Access to space is generally expensive, and enormous resources are required, proportional to the size and mass of a satellite. Thus, making space objects as small as possible is inevitable. However, miniaturization brings many issues. As the satellite electronics and physical structure become smaller, the size and number of solar cells used for harvesting energy also reduce leading to less available energy. This directly constraints the overall energy budget, thus affecting the entire operation of the satellite. Additionally, the need for compacting equipment in small spaces leads to issues such as mitigating radiation effects and thermal control, which are generally difficult to address.[18]

Figure 2. Major challenges in realizing small satellites.

2.2. Energy management

While harvested energy reduces due to miniaturization, the power consumption of different modules may not reduce proportionally. An example is the communication subsystem—regardless of the satellite size, transmission power needs to be strictly within the budgeted range while offering optimal throughput. For example, a CubeSat's transmission power is usually capped at 1 W, whereas the maximum harvested power is approximately 2 W. If half of the energy budget is allotted just for communication, then other modules, including thermal control, on-board processing, localization, attitude determination, and control, and sensing equipment must work within the remaining 1 W. As half of the energy budget is allocated just for the communication subsystem, the other subsystems must work within the residual energy. This brings in additional challenges such as strict requirements on the energy budget of individual modules and the run-time power distribution.

2.3. Communication

Access to ground stations is intermittent except when the satellites are in geostationary orbits. Satellites in LEO have approximately 10 min of visibility to ground stations. Large bandwidth is, therefore, necessary to make the most of the short times a satellite can funnel data to the end-users. This can only be achieved by investing large amounts of energy, which is, however, scarce in small satellites as mentioned before. Alternatively, large antennas potentially ameliorate these issues but the size of the antenna is limited because of the structural issues due to the small size of the satellites.

2.4. Dependability

Small satellites are bound to operate in harsh space environments, with temperatures varying from −100°C to 150°C and cosmic radiations harming or causing transient faults in electronics.[2] Large satellites are designed to be highly dependable, using expensive thermal protections and radiation-hardened space-grade components. Small satellites are usually built using COTS components to reduce costs and thus cannot provide the same or similar dependability guarantees. Redundancy is, therefore, a natural choice in the design to ensure dependable operations. However, this inherently clashes with the aforementioned need for miniaturization and energy constraints. Thus, the designing small satellites require a trade-off between redundancy, space-qualified components and the available space and power.

2.5. Coordination

Orbit management is a key requirement in small satellite constellations, wherein the spatial separation between the satellites must be maintained for certain applications, for example, to observe environmental phenomena globally. Energy constraints have an adverse effect on achieving proper coordination among small satellites, as inter-satellite communications consume additional power and orbit management takes up resources for computing, localization, and attitude determination and control. Further, when exchanging data with other small satellites, optical communications, such as lasers,[17] are also reported to be used in space that has less cost, yet the cost of accurate attitude control is high to ensure precise beaming.

2.6. Localization

As described before, performing localization in power-constrained small satellites is a highly challenging task. This challenge is at the core of our work on Hummingbird[13]—our space-proven GPS receiver for small satellites. Through a novel hardware and software co-design, we significantly reduce the TTFF, thus achieving energy-efficient operation, without impacting the positioning accuracy.

This paper looks closely into the issues and our solutions in building a GPS for small satellites. Specifically, we discuss energy optimization and the time to get the fix.

3. FUNDAMENTALS

Before we present the core of our work, we briefly explain the satellite orbital dynamics and the fundamentals of the GPS for civilian use.

3.1. Satellite orbital dynamics

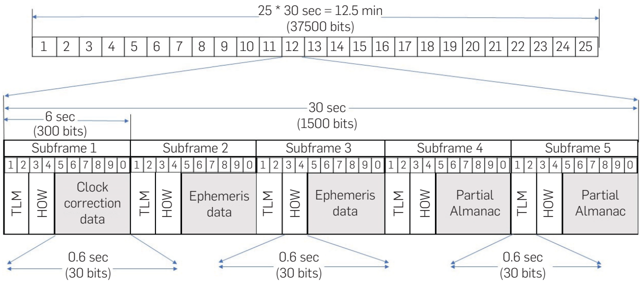
Most of the satellites in LEO form an elliptical orbit with Earth as one of the focal points. With a known ejection time, position, and velocity of a satellite in its orbit, it is possible to deduce the geometry of the satellite orbit. With this geometry, the entire satellite orbit and the position of a satellite in space can be determined at any time.[12]

North American Aerospace Defense Command (NORAD) provides the complete orbital element information along with the Keplerian elements as two-line element (TLE), which is unique to a satellite.[12] 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 estimated using TLE is accurate to 2 km and the position data become stale over a few days.[11]

3.2. Fundamentals of GPS

The GPS constellation consists of 31 active satellites transmitting navigation messages on the same carrier frequency. These navigation satellites are orbiting at an altitude of 20,200 km above Earth. The orbit geometry is such that at least four satellites are visible at any location on the Earth at any instant. 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.

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



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 subframe will be transmitted along with the clock corrections. Subframes 2 and 3 together constitute the *ephemeris* information, which is a set of time-varying parameters that are used to calculate the position and velocity of the corresponding GPS satellite.[a] Subframes 4 and 5 contain a partial *almanac*, which includes coarse information about the state and position of all the GPS satellites.

A receiver has to wait for one subframe (6 s), one navigation frame (30 s), and 25 navigation frames (12.5 min) 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 only for around 4 h.

There are three major phases wherein specific tasks are performed to get a position fix.

(I) Acquisition: The receiver searches for the signals from the visible GPS satellites by correlating the received signal with the pre-saved PRN codes.

(II) Decoding: The receiver locks onto a GPS satellite, and it decodes the received signal to get the information on GPS time, ephemeris, and clock bias.

(III) Positioning: With the help of the decoded data, the 3D position of the receiver is obtained using trilateration.

Typically, the TTFF varies depending on the state of the GPS receiver when starting the positioning process. In situations of a *cold start,* the receiver does not know its last position or time and has no valid ephemeris or almanac data. Typically, this is the case when the receiver is powered down for more than two weeks. A typical cold start TTFF takes at least 12.5 min if the previous almanac is not valid and if it has to be downloaded only from the GPS satellites. In situations of a *warm start*, a valid almanac is present in the memory of the receiver and the current position is within 300 km of the last active position. However, a valid ephemeris data is not present in the memory. A typical warm start is between 35 s and 4 min for TTFF. A receiver starts up in *hot start* mode when warm start conditions are met, and a fix had been established within the last 2 h, and the receiver has valid ephemeris data of at least five satellites.

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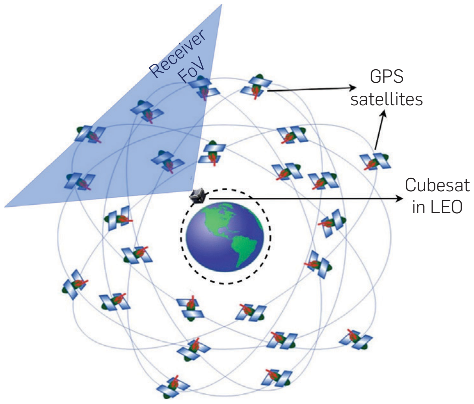
[a] An ephemeris gives the trajectory of space objects i.e., the position (and possibly velocity) over time.

Figure 4. A scenario demonstrating the visibility of GPS satellites for a GPS receiver antenna mounted on a cube satellite in LEO.



A scenario describing the visibility of GPS satellites from a GPS receiver antenna mounted on a CubeSat in LEO is shown in Figure 4. The satellites in LEO move very fast. For example, a CubeSat may travel as fast as 7.8 km/s, that is, faster than a bullet. GPS satellites, in turn, move at about 3.8 km/s. The relative movement of small satellites with respect to GPS magnifies the Doppler effect. The search range due to Doppler effects increases up to ±80 kHz, as opposed to a mere ±10 kHz on Earth, prolonging the TTFF. In small satellites with no attitude control, rapid changes in GPS visibility due to tumbling further compound the problem. GPS receivers are normally duty cycled to save energy, but longer TTFFs play against this, as the GPS receiver must stay on for long.[6]

4. CHALLENGES AND WORKAROUNDS

We list the challenges in designing a low-power GPS receiver for space applications and elucidate our solutions below.

4.1. Challenges

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. Our work, therefore, focuses on developing a low-power GPS subsystem entailing an algorithm that significantly reduces energy consumption by abating the TTFF without sacrificing position accuracy. Several non-trivial challenges need to be addressed to achieve this goal.

- **Visibility of GPS satellites**. The visibility of GPS satellites from small satellites changes rapidly, while the receiver needs to update positions frequently. This would not be an issue if the receiver was continuously actively listening as it can lock to more than four (six to ten usually) GPS satellites as a backup. However, it is tricky in the case of duty cycling the GPS receiver to conserve energy. Each time the receiver is turned on, it will be far away from the previous position and with no information on which GPS satellites to search for, TTFF will eventually be longer.
- **High Doppler shift.** As mentioned earlier, due to the high relative velocity between LEO and GPS satellites, the Doppler search range can be as high as ±80 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 re-acquisition in case the visibility of a GPS satellite is lost after locking. This implies a significant increase in the TTFF that can be as high as 25 min.[11]
- **Performance vs. energy.** The acquisition and decoding of navigation messages must be performed as quickly as possible. A small delay of 10 ms in the processing places the satellite 78 m away when the speed is 7.8 km/s. Hence, the receiver should offer high-performance processing hardware, while being energy-efficient.
- **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 unfavorable when the satellite tumbles. This might lead to a loss of GPS signals. 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 at all, while expending energy.

4.2. Possible workarounds

Some workarounds are possible to address these challenges. However, they require striking compromises through the use of additional devices or losing space.

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 tumbles. However, this implies reduced mounting space for solar cells, thus reducing the energy intake.
2. As an alternative, assisted GPS (A-GPS) where the GPS almanac and ephemeris data can be uploaded to the receiver frequently so that TTFF can be improved. This requires multiple ground stations globally impacting the operational costs.
3. Updated TLE information 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 and is detrimental to the overall cost.
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.[15] The same technique can be applied in space but it requires duty cycling at a higher rate. In LEO, a receiver should activate once every 20 s. This is not energy-efficient.

We present an algorithm, called F^3, wherein the duty cycling period is selected optimally to minimize energy consumption. The algorithm does not impose additional requirements such as multiple antennas or ground stations. To demonstrate these features, we design and deploy a space-qualified GPS receiver called Hummingbird.

5. HUMMINGBIRD IN A NUTSHELL

We design Hummingbird as shown in Figure 5, aiming at a small footprint, low weight, and energy efficiency.

5.1. Hardware

Hummingbird is small (40 mm × 30 mm), weighs just 20 g, and requires 145-mW peak power, which is low compared to the 1 W energy figure of space-grade receivers.[16] It houses a customized low-power GPS front-end supporting GPS L1 frequency (1.54 GHz), a customized Skytraq Venus GPS receiver chip, and an MSP432 microcontroller unit (MCU) featuring an ARM Cortex M4 core. The choice of the GPS chip is dictated by tests we carry out using space-grade simulation tools, which provide evidence that the chip can ensure 10-m (10 cm/s) position (velocity) accuracy in space.[13] The MCU provides sufficient computing power in an energy-efficient fashion to compute the navigation solution and to control the duty cycling of the GPS front end.

The total component costs for Hummingbird do not exceed $200, in contrast to commercial GPS receivers for small satellites that cost approximately $4,000.

5.2. Design of the F^3 algorithm

The F^3 algorithm intelligently duty cycles the GPS chip to reduce TTFF, hence improving energy consumption as a result. The basic idea is as follows: The initial location fix is obtained with a reduced TTFF. Then, the receiver can be duty cycled. When the GPS chip is off, the position and velocity are estimated using TLE of the satellite by the microcontroller. Since continuous TLE propagation is prone to deviations, we correct the error by getting the true position from the GPS intermittently by turning on the GPS chip. The TLE is updated/corrected for the bias for further propagation. The functional flow diagram of F^3 is shown in Figure 6, and the methodology is implemented in two main steps, explained next.

Figure 5. Hummingbird GPS receiver.

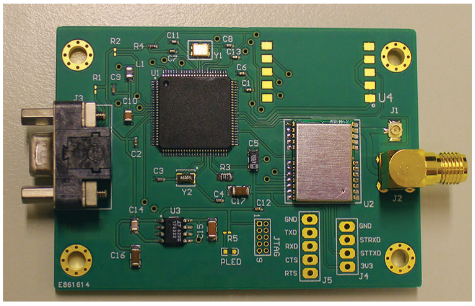
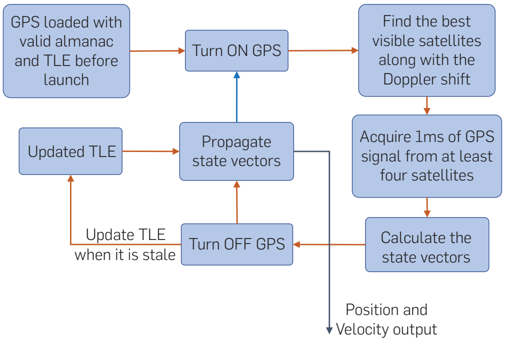


Figure 6. F^3 functional block diagram.



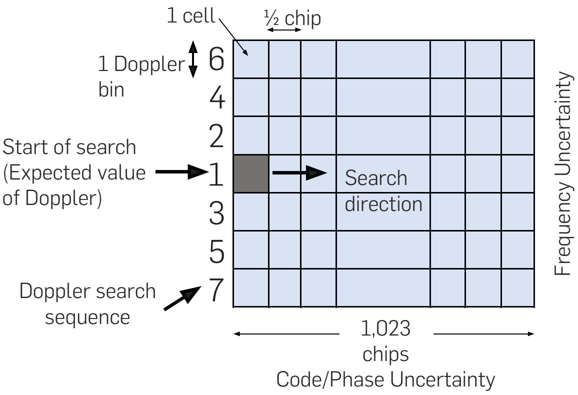
Reducing TTFF. The acquisition phase in GPS localization is a search process. The process includes replication of both code and carrier of the GPS satellites to acquire the signal. Hence, the process is two dimensional: (a) The range dimension is associated with the replica code and the (b) Doppler frequency dimension is associated with the replica carrier. When range and Doppler frequencies are unknown, the resulting search space is large. Because of Doppler effects, TTFF may consequently increase up to 25 min. Most of the components on a GPS receiver operate at peak power during this 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 approximately 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.[21] Figure 7 shows the two-dimensional C/A code search pattern. Each bin also needs to search for a correct PRN code phase. Predicting the Doppler shifts using estimates of the receiver, and the position and velocity of the GPS satellites reduce the dwell time. This is possible only when the approximate receiver position is known or the prior position is within 300 km.[15] There exist many methods to reduce the search space on the frequency axis but the process is two dimensional.[5, 23] We reduce the search space to one dimension.

During the launch, the receiver is loaded with the satellite's TLE, the almanac of GPS constellation, and the ejection time of the satellite. It should be noted that the ejection time of a satellite is known prior to the launch to place the satellite in the defined orbit. The receiver uses this when it

Figure 7. C/A code search pattern.



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 the almanac. The TLE file is comprised of 138 bytes and this can easily be accommodated in the MCU.

During the first cold start, the GPS receiver estimates its position on the orbit using the loaded TLE since the current time is known approximately. 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, that is, single row search space, as the Doppler frequency is known. Hence, the complexity of the TTFF algorithm reduces to $\mathcal{O}(N)$ from $\mathcal{O}(M\,N)$, 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 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.

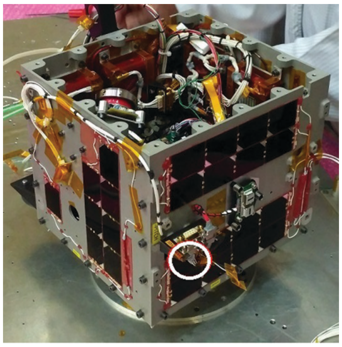
Duty cycling. Lowering the TTFF with F^3 remains compatible with the duty-cycled operation. In Hummingbird, this is also the opportunity to update the information used for reducing the search space over time.

Once a position is computed, the GPS front-end of Hummingbird is turned off. During this time, the MCU propagates the previous position to estimate the next one, thus continuously providing (estimated) position updates to the satellite. We employ NORAD SGP4 orbit propagator to estimate the new position of the receiver depending on the previous position.[7] Notably, the TLE and almanac go stale over days, leading to an increased error in position measurements when used for propagation. Since GPS acquisition gives the true position, we use the position provided by Hummingbird to periodically update TLE information and GPS almanac.

6. HUMMINGBIRD IN SPACE

We mounted Hummingbird onto a nanosatellite, shown in Figure 8, and launch the system into a 520-km orbit. The goal of the mission was remote sensing using experimental high-resolution cameras, while the energy budget of the parent satellite was extremely constrained. Hence, accurate and energy-efficient positioning is the key.

Figure 8. Placement of Hummingbird on the nanosatellite.



In addition to demonstrating our design in space, the launch of Hummingbird is also an opportunity to gather real-world performance measurements. A full-blown performance evaluation partly obtained with accurate simulations is also available in Narayana.[13]

Energy. Figure 9 shows the energy consumption of Hummingbird for 5 h of operation in space using three different configurations: in **S1**, Hummingbird is continuously on and F^3 does not execute; in **S2**, Hummingbird is duty cycled once in 50 min and still F^3 does not execute; in **S3**, Hummingbird operates with the same 50-min duty cycle but uses F^3 for positioning. The 50-min duty cycle is determined to obtain a 10-m positioning accuracy, as dictated by application requirements.

Figure 9 shows the drastic performance improvements obtained by running the complete Hummingbird, including the F^3 algorithm. Using **S2**, even if the GPS chip is duty cycled, longer TTFFs cause the energy consumption to remain high and only about half of **S1** configuration, where Hummingbird is continuously on. In this configuration, we measure TTFF for up to 20 min. The order of magnitude in improvement is obtained by abating the TTFF with F^3, which pushes this figure down to a maximum of 33 s, thus saving 96.16% (92.7%) of the energy of **S1** (**S2**).

Positioning accuracy. Figure 10 shows the in-orbit accuracy of the navigation solution in the aforementioned scenarios. 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 **S1**, the error is within 10 m 99% of the times. However, in **S2** and **S3**, the state vectors

Figure 9. Energy consumption in different configurations, depending on duty cycling and execution of F^3.

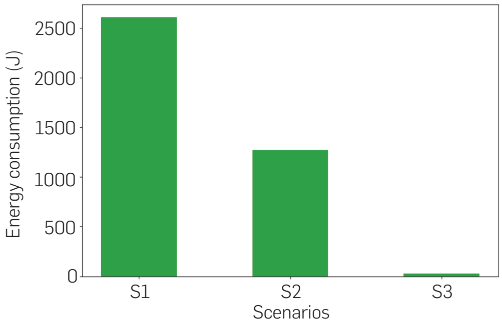
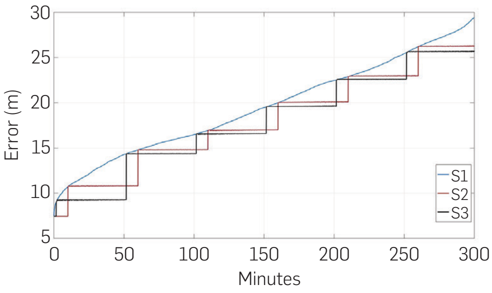


Figure 10. Positioning accuracy.



are propagated after the GPS chip is turned off, and TLE is propagated, so the position error.

It should be noted that, in **S2**, 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 three months after the launch, we observed that the propagation error was within 10 m (99% of the times) when the GPS was duty cycled once in 50 min.

Duty cycling. Generally, the duty cycle settings determine the trade-off between energy consumption and positioning accuracy. If the receiver stays off for short times, better accuracy is obtained at the price of additional energy consumption. However, longer off-periods lead to inaccurate positioning because of cumulative errors in TLE propagation. Hummingbird maintains the positioning error within 10m for duty cycle intervals up to 50 min. A further increase of duty cycle interval leads to a linear increase in error up to 18 m when the interval is 90 min. For the position error measurements, the ground truth of the satellite was provided by the space agency.

Because of the crucial role the TTFF plays in determining the performance of the whole satellite, we further study its behavior as a function of duty cycle interval. We duty cycle Hummingbird every 10–100 min, while in orbit. The TTFFs averaged over ten trials are shown in Figure 11. Further, Figure 12 shows the CDF of TTFF obtained for different duty cycling intervals in orbit. The average TTFF is between 4 s and 10 s. Irrespective of the duty cycle interval, we observe a maximum TTFF of 33 s. This is because, if the receiver is duty cycled with intervals beyond 4 h, the ephemeris becomes stale and must be downloaded again. This takes a maximum of 30 s. Therefore, the TTFF does not solely depend on the duty cycling interval, but also the validity of ephemeris data. The plot in Figure 12 shows that 60% of the time, the TTFF stays within 20 s.

Tumbling. Most of the small satellites are not be equipped with the attitude control systems and they may be tumbling in orbit. One of the important features of Hummingbird is that it can still get a fast fix even when the satellite is tumbling. The TTFF at different tumbling rates is shown in Figure 13. As tested on the nanosatellite when it was tumbling at 34°/s, the maximum tumbling rate observed in the launched nanosatellite, Hummingbird got a position fixed in-orbit but the position ground truth was not reported.

However, simulation tests using GPS simulator proved that Hummingbird supports up to 80°/s tumbling rate while maintaining the position accuracy of 10 m. The accuracy obtained was 15 m when the tumbling rate was around 100°/s. This is significant considering the existing space-based receivers that support only up to 10° 3-axis rotation while the satellites may tumble at a higher rate.

7. OUTLOOK

Access to space is becoming more prevalent irrespective of its cost. Small satellites represent a new breed of mobile computing platform. The unique combination of challenges outlined above, being interdisciplinary nature, offers fertile ground for mobile computing researchers to conceive new solutions, or to revisit existing solutions in a new context. Moreover, the quest for efficiency within extremely limited resources does not forgive unnecessary complexity and eminently demands simple solutions to complex problems.

As the application domains for small satellites evolve, these opportunities grow accordingly. Large-scale constellations of small satellites are envisioned as key enablers for the emerging Space Internet of Things,[14] as a backbone for ubiquitous Internet access,[20] or as a massively distributed remote sensing systems.[4] Still, the body of work on mobile computing remains fundamental to tackle the challenges at stake, even when they are brought to an extreme as in a case where so many competing dimensions are to be considered at once. Hummingbird is one of the examples that showcase some aspects of the above vision, practically. ◼

Figure 11. TTFF at different duty cycling intervals.

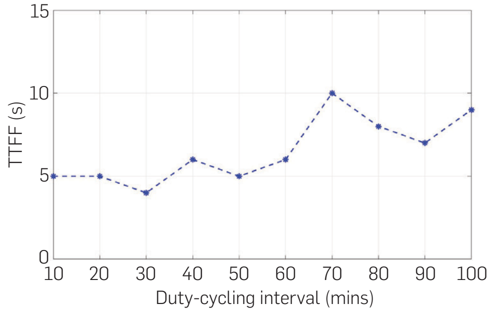


Figure 12. CDF of TTFF for different duty cycling intervals.

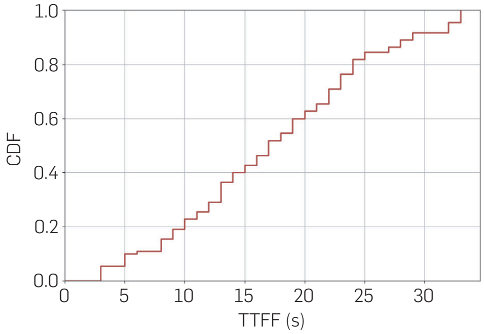
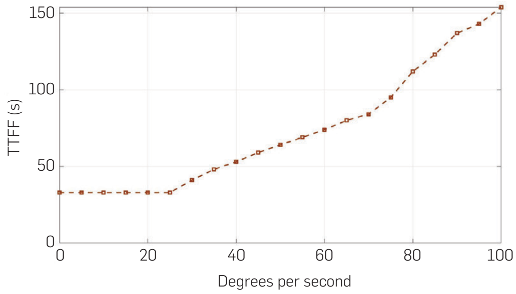


Figure 13. TTFF at different tumbling rates.



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