A Hummingbird IN SPACE: An energy-efficient GPS receiver for small satellites

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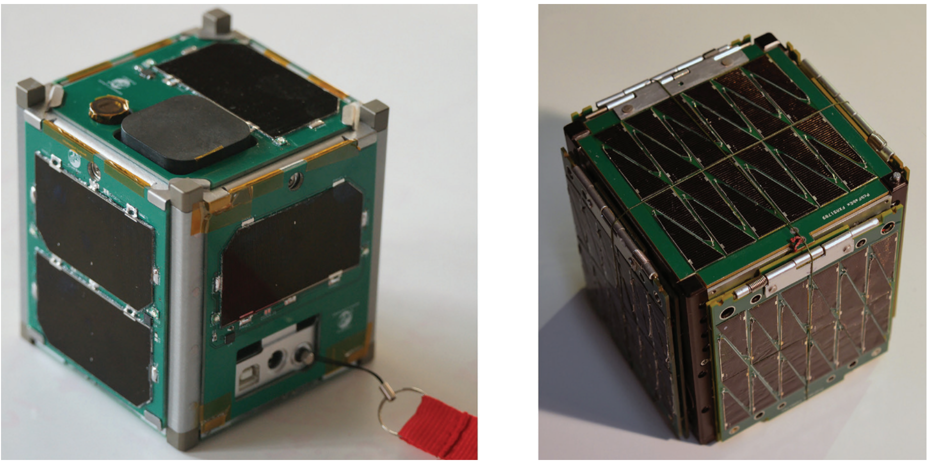
Two distinct trends are apparent in the design and planning of satellite missions. Until the late 1990s, multibillion-dollar space programs centered on large satellites, such as Envisat [1], promised to provide a common platform to support a variety of co-located sensing equipment. A reduction in cost was expected, as several instruments shared a single bus and a single launch. These benefits did not materialize due to the rise of a plethora of engineering and scheduling problems: electromagnetic incompatibilities between diverse technologies; instruments inducing vibrations on the platform that affect other equipment; and deployment-ready instruments waiting for other equipment in earlier development stages. As a reaction to these issues, the second trend where programs based on single-instrument satellites of much smaller sizes and mass began to emerge, eventually leading to the deployment of space devices that nowadays we call small satellites [11].

Small satellites provide a range of key advantages over their larger counterparts. They resolve most of the aforementioned issues while being robust to schedule variations and launch failures, and also cost-effective due to the use of Commercial Off The Shelf (COTS) components. They come in a variety of form factors, from femtosatellites (<0.1 Kg mass) to nanosatellites (1 Kg to 10 Kg mass). Among the latter, so-called *CubeSats* [9], shown in Figure 1, represent a paradigmatic example of their features and limitations. Though CubeSats started as an academic effort [9], they eventually became a platform for Earth observation too. The related standard prescribes the size, mass, and power figures. CubeSat initiatives are spreading globally [12], especially towards deploying massively distributed CubeSat constellations able to achieve global Earth coverage and ubiquitous Internet access through a coordinated operation. Typical configurations include 16bit or 32-bit Microcontroller Units (MCUs), memory, thermal management, and energy harvesting, communication support, and a sensing payload.



(a) **Mass: 1 kg**
Dimension: 10cm x 10cm x 10cm

(b) **Mass: 1.3 kg**
Dimension: 10cm x 10cm x 11.3 cm

FIGURE 1. (a) Vermont Lunar CubeSat [9] (b) SkyCube CubeSat [8].

Small satellites represent a formidable mobile computing platform enabling large-scale space applications at a fraction of the cost of larger satellites, but equally present a range of inter-disciplinary challenges that are to be tackled within severe resource constraints dictated by size, weight, and available power. The combination of these challenges prompts different communities to push the envelope in the design and concrete realization of a range of functionality, from attitude control to localization. In the following, we discuss a brief account of such challenges and later dive into our work on the satellite positioning problem. Our efforts in the latter area eventually led to the launch of *Hummingbird* [6]: our space-proven energy-efficient GPS receiver.

CHALLENGES

Example challenges arising in the design, implementation, and deployment of small satellites are graphically depicted in Figure 2. Solving one of these challenges most often entails striking proper trade-offs with solutions addressing different issues, or sacrificing performance on orthogonal system metrics. A key example is energy management. On a small satellite, energy is harvested using solar panels. The amount of harvested energy is therefore limited by its size and efficiency. Consuming energy for one task, e.g., remote sensing, means limiting other operations, such as on-board processing. As the energy envelope is limited, different functionality competes to obtain their share of the scarce resources.

Next, we discuss what we argue to be the primary challenges at stake while highlighting their relations.

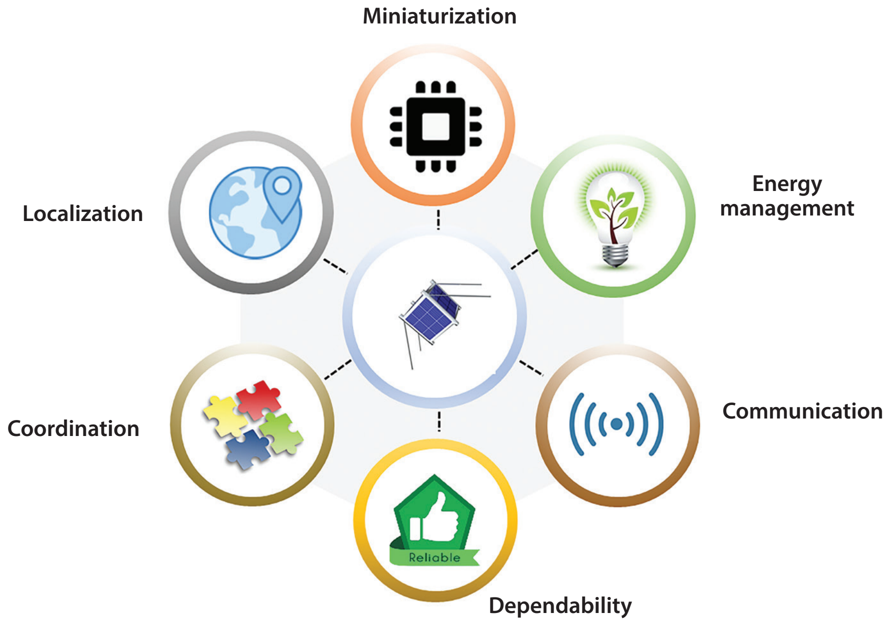


FIGURE 2. Major challenges in realizing small satellites.

Miniaturization. Apart from the switch in design approach discussed earlier, access to space is generally expensive, and enormous resources are required. Making space objects as small as possible is thus inevitable. However, miniaturization presents its own issues.

As the satellite electronics and physical structure become smaller, the size and number of solar cells used for harvesting energy are also reduced. This directly asserts constraints on generated power and the overall energy figures, affecting the entire satellite operation. Additionally, the need for compacting equipment in small spaces leads to issues of radiation mitigation and thermal control, which are generally expensive or difficult to address [13].

Energy management. While harvested energy reduces due to miniaturization, the power consumption of the different modules may not reduce proportionally.

An example is the communication subsystem: regardless of the satellite size, transmission power settings may need to fulfill strict requirements to ensure range and bandwidth. For example, a CubeSat's transmission power is usually set to 1W, 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 without performance degradation. This imposes severe requirements on both the energy figures of individual modules and on the run-time distribution of available power.

Communication. Relaying data to the ground or exchanging information among small satellites is vital in most application scenarios. The two communication means, however, expose sharply different requirements compounded by the different communication technology used in small satellites, ranging from RF to optical communications [12].

Access to ground stations is intermittent. Large bandwidth is, therefore, necessary to make the most of the short times the small satellite can funnel data to the end-users. This can only be achieved by investing large amounts of energy, which is however scarce as per the discussion above. With RF technology, large antennas potentially ameliorate these issues, yet their size is limited by the satellite's physical structures. When exchanging data with other small satellites, on the other hand, optical communications, such lasers [12], are also reported to be operational in space, yet at the cost of accurate attitude control to ensure precise beaming to the destination.

Dependability. Small satellites are bound to operate in harsh space environments, with temperatures varying from -100 °C to 150 °C and cosmic radiations harming elementary data operations, such as memory reads/writes, causing transient faults [3].

Large satellites are designed to be highly dependable, using expensive thermal protections, radiation-hardened space-grade components, and highly reliable storage hardware, such as Error Coding and Correction memories. Small satellites are usually built using COTS components to reduce costs, which provide nowhere near the same or similar dependability guarantees. Redundancy is therefore elected to the chosen design approach to ensure dependable operation. However, this inherently clashes with the aforementioned need for miniaturization and energy constraints.

Coordination. Orbit management is a key requirement in small satellite constellations, wherein the spatial separation between the satellites must be maintained so that certain application requirements are continuously fulfilled, for example, to achieve global coverage of environmental phenomena on the ground.

Moreover, individual small satellites in a constellation must be accurately time-synchronized for inter-satellite communication, for example, when using time-triggered communication patterns [11].

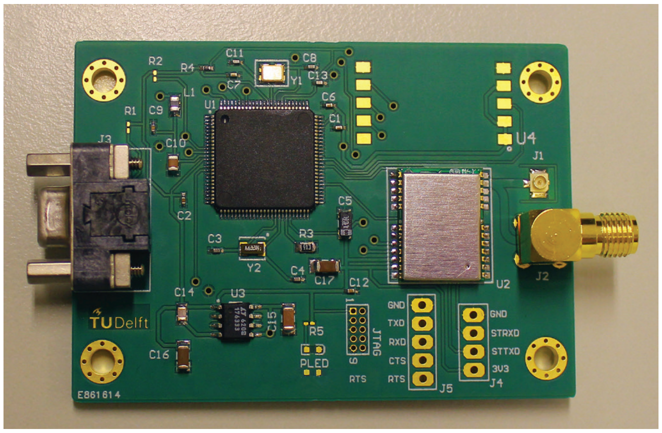


FIGURE 3. Hummingbird GPS receiver.

AS THE APPLICATION DOMAINS FOR SMALL SATELLITES EVOLVE, THESE OPPORTUNITIES GROW ACCORDINGLY

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.

Localization. Accurate positioning is essential for both the small satellite's own operation and for application-level tasks, e.g., when coordinating a constellation for radio interferometry [2].

GPS localization is the elective positioning technique in space. However, small satellites move fast. For example, a CubeSat in low Earth orbit (LEO) 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 compared to GPS ones magnifies Doppler effects. The search range due to Doppler effects increases up to ±80 KHz, as opposed to a mere ±10 KHz on Earth, prolonging the Time To First Fix (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, eventually.

The latter challenge is at the core of our work on Hummingbird [6]: our space-proven GPS receiver for small satellites. Through a novel hardware/software co-design, we significantly reduce the TTFF, thus achieving energy-efficient operation, without impacting positioning accuracy.

HUMMINGBIRD IN A NUTSHELL

We design our GPS receiver Hummingbird, shown in Figure 2, aiming for a small footprint, limited weight, and energy efficiency.

Hardware. Hummingbird is small (40 x 30 mm), weighs just 20 g, and absorbs 145 mW at the peak, which is low compared to the 1 W energy figure of space-grade receivers [10]. 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 10m (10cm/s) position (velocity) accuracy in a space settings [4]. 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.

Total component costs for Hummingbird do not exceed $200, in contrast to commercial GPS receivers for small satellites that cost around $4000.

Reducing TTFF. GPS positioning is a search process. It requires replication of both code and 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 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 minutes. Most of the energy-hungry components on a GPS receiver operate at peak power during this time.

We aim to lower the TTFF to improve energy efficiency. We do so by turning the two-dimensional search process into a single-dimensional one. Figure 4 shows the steps we take in Fast Fix and Forward (F^3): the positioning algorithm we run on Hummingbird. Before the launch, we load Hummingbird with three bits of information: i) the parent satellite's Two Line Element (TLE), that is, a file containing parameters useful to approximate the position of the satellite at any instant after launch, ii) the almanac of GPS constellation at the time of launch, which includes coarse-grained information on the GPS constellation, and iii) the ejection time of the satellite into the orbit. Hummingbird uses this information every time it is turned on. Using the current time, the TLE, and the almanac, we calculate the GPS satellites we expect to be visible at a certain position and estimate their Doppler frequencies. The two-dimensional search space converges to one dimension, as the Doppler frequencies to search through are now fixed.

Next, we download at least one navigation frame from each visible satellite, which includes ephemeris and GPS time, enabling accurate positioning and time synchronization respectively. This takes at most 30 s based on the length of GPS navigation frames and data rates. In the presence of rapid changes of GPS visibility, e.g., due to tumbling, partially received packers are stitched together until we obtain a complete frame. Once the receiver clock is synchronized, positioning occurs using classic algorithms, such as the least square error method or Kalman filters.

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

Once a position is computed, the GPS

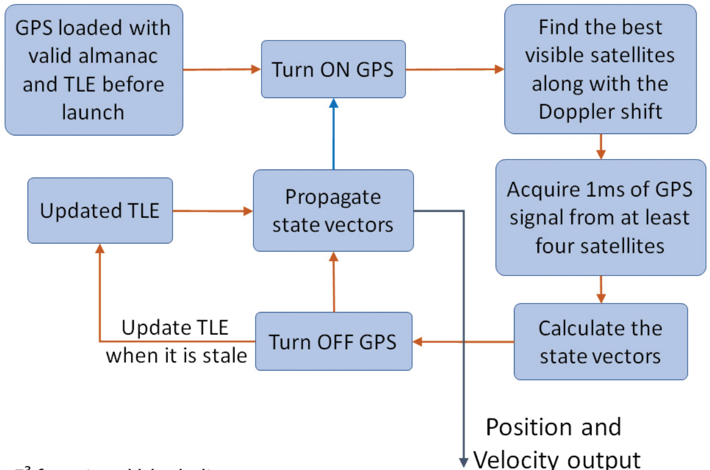


FIGURE 4. F^3 functional block diagram.

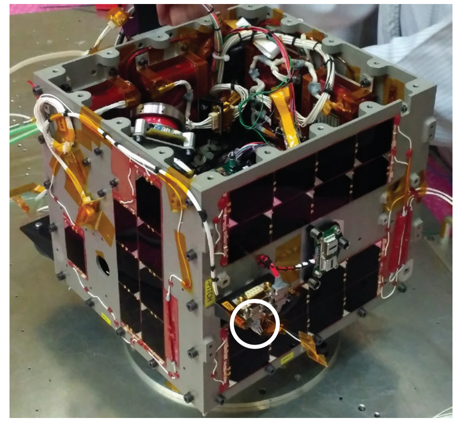


FIGURE 5. Placement of Hummingbird on the nanosatellite.

front-end of Hummingbird turns off. During this time, the MCU propagates the previous position to estimate the next one, thus continuously providing (estimated) position updates to the small satellite. We employ the NORAD SGP4 orbit propagator to estimate the new position of the receiver depending on the previous ones [5]. Moreover, the TLE and almanac go stale over days, leading to the 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 the TLE and GPS almanac.

FLYING HUMMINGBIRD

We fix Hummingbird onto a nanosatellite, as shown in Figure 5, and launch the system into a 520 km orbit. The goal of the mission is remote sensing using experimental high-resolution cameras, while the energy budget of the parent satellite is extremely constrained. Hence, accurate and energy-efficient positioning is key.

In addition to demonstrating our design into actual space operation, the launch is an opportunity to gather real-world performance measurements. A full-blown performance evaluation, partly obtained with accurate simulations, is also available [6].

Energy. Figure 6 shows the energy consumption of Hummingbird for five hours 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 minutes and still F^3 does not execute; in **S3**, Hummingbird operates with the same 50 minute duty-cycle but uses F^3 for positioning. The 50 minute duty-cycle is determined to obtain a 10 m positioning accuracy, as dictated by application requirements.

The plot in Figure 6 shows the drastic performance improvements obtained by running the complete Hummingbird, including the F^3 algorithm. Using **S2**, even though the GPS chip is duty-cycled, longer TTFFs cause the energy consumption to remain significant and only about half of configuration **S1**, where Hummingbird is continuously on. In this configuration, we measure TTFF for up to 20 minutes. The order of magnitude 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)**.

Duty cycling. Generally, the duty-cycle settings determine the trade-off 5 between energy consumption and position 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

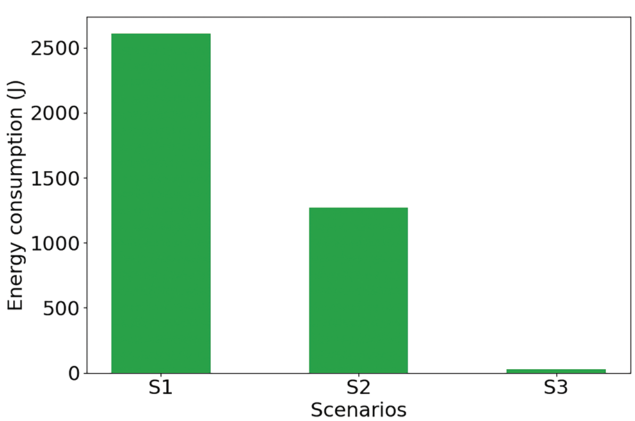


FIGURE 6. Energy consumption in different configurations, depending on duty-cycling and execution of F^3.

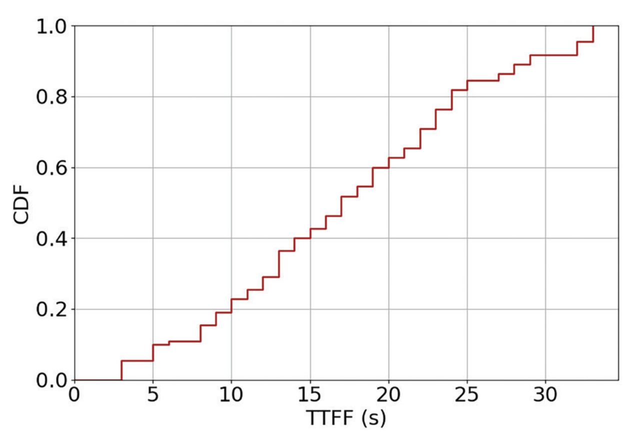


FIGURE 7. CDF of TTFF for different duty-cycling intervals.

positioning because of cumulative errors on TLE propagation. Hummingbird maintains the positioning error within 10 m for duty-cycle intervals up to 50 minutes. A further increase of duty-cycle interval leads to a linear increase in error to 18 m when the interval is 90 minutes. For the position error measurements, the ground truth position of the satellite is provided by the space agency.

Because of the crucial role the TTFF plays in determining the overall performance, we further study its quantitative behavior as a function of duty-cycle interval. We duty-cycle Hummingbird every 10 to 100 minutes, while in orbit. Figure 7 shows the CDF of TTFF obtained for different duty-cycling intervals in orbit. The average TTFF is between 4s to 10s. Irrespective of the duty-cycle interval, we observe a maximum TTFF of 33s. This is because, if the receiver is duty-cycled with intervals beyond 4 hours, the ephemeris becomes stale and must be downloaded from the GPS satellites again. This takes a maximum of 30 s, in principle. The plot in Figure 7 shows that 60% of the time, the TTFF stays within 20 s.

Tumbling. Most of the small satellites may not be equipped with 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. As tested on the nanosatellite when it was tumbling at 34°/s[1], Hummingbird got a position fix in-orbit while 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 rotation rate was around 100°/s. This is still considerable against the existing space-based receivers that support only up to 10° 3-axis rotation while the satellites may tumble at a higher rate.

OUTLOOK

Small satellites represent a new breed of mobile computing platform, one that pushes us "beyond the cloud(s)." The unique combination of challenges outlined above, along with their inter-disciplinary 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 [7], as a backbone for ubiquitous Internet access [15], 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. ■

[1] This was the maximum tumbling rate observed in the launched nanosatellite.

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