SSC18-II-06

Making the Invisible Visible: Precision RF-Emitter Geolocation from Space by the HawkEye 360 Pathfinder Mission

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ABSTRACT

To be launched in Q4 2018, the HawkEye 360 (HE360) Pathfinder mission will validate key enabling technologies and operational methods necessary to provide unprecedented analysis of wireless signals for commercial and government applications using small satellites. Applications range from logistics monitoring and tracking of aircraft, ships, and ground transportation, to emergency response and other data analytics and services. The mission will nominally consist of three Pathfinder satellites, operated in formation, to demonstrate and validate an initial operational capability. Following the Pathfinder demonstration a constellation with more than 18 satellites will be deployed.

HE360 has contracted Deep Space Industries (DSI) and major subcontractor Space Flight Laboratory (SFL) to design and manufacture the spacecraft platform for the Pathfinder demonstration mission. In addition to being a world leader in low-cost high-performance small spacecraft, SFL is a pioneer in low-cost precision spacecraft formation flight, a key enabling technology for HE360 mission. DSI, a world leader in state-of-the-art launch safe propulsion systems, is providing the Comet™ water-fueled resisto-jet propulsion system for the mission.

This paper describes the HawkEye 360 Pathfinder mission, with a focus on the core enabling platform and payload technologies.

INTRODUCTION

HawkEye 360 (HE360) has developed an innovative combination of classical and novel geolocation algorithms that will enable precise space borne geolocation of terrestrial and aerial radio frequency (RF) emitters related to a broad array of business enterprises. In late 2018, the HE360 Pathfinder mission, a formation-flying cluster of three microsatellites, will launch to demonstrate the commercial capability of HE360's high-precision RF geolocation technology. The spacecraft will be placed into a Sun synchronous orbit (SSO) at a 575km altitude and a local time of descending node (LTDN) of 10:30am.

Each of the three spacecraft will be identical and their primary payload is a Software Defined Radio (SDR) and custom RF front end, along with band-specific antennas. The frequency agile payload will enable reception of many different types of signals, covering various RF segments spanning VHF through Ku-band, which will then be geolocated by applying signal processing to the combined received data of all three spacecraft. The three spacecraft, each with its own propulsion system, will establish a relatively wide-baseline, geometrically diverse formation and continue to maintain the relative position formation for the duration of the nominal three year mission.

The Pathfinder mission serves to demonstrate the practicality of the geolocation mission and paves the way for a future commercial constellation. Initially, an eighteen satellite constellation (arranged as six clusters of three) is envisioned for commercial, global service. However, the final constellation size and geometry will depend on market factors including the results of the Pathfinder mission.

HE360 selected Deep Space Industries (DSI) and major subcontractor Space Flight Laboratory (SFL) to design the platform for the Pathfinder mission. DSI is the prime contractor, and the manufacturer of a novel water-fueled electro-thermal propulsion system which will fly on each spacecraft. SFL is responsible for the design and manufacturing all three spacecraft platforms. SFL's versatile flight-proven 15kg Next-generation Earth Monitoring and Observation (NEMO) microsatellite bus was selected for the mission. In addition to being a world leader in providing low-cost high-performance small spacecraft, SFL was selected for this mission as it is a pioneer in low-cost precision spacecraft formation flight, a key enabling technology for HE360 mission. SFL has developed compact, low-cost formation flying technology at a maturity and cost that no other small satellite developer can credibly offer at present. This precise formation control was demonstrated on-orbit by SFL in the highly successful CanX-4/CanX-5 mission in 2014[1]. With 18 successful spacecraft missions on-orbit, SFL's solutions have demonstrated high reliability and high availability products, which can be depended upon for a wide array of commercial applications. By leveraging SFL's successful spacecraft platforms and formation flying technology, along with DSI's pioneering innovations and next-generation propulsion systems, the mission will deliver unparalleled performance in smaller, affordable satellites.

THE MISSION

Clearly understanding the world around us is becoming more important than ever. Many of the big problems we face as a society require solutions that contextualize the world around us. This applies directly to the RF domain. HawkEye 360 is capitalizing on the explosive growth of RF signals and their application to tracking assets. Opportunities and applications that arise from this high-precision radio frequency mapping and analytics technology are enormous and appeal to a broad array of business enterprises and government users. The mission is filling a void by bringing a level of visualization to a domain that has historically only been understood by governments. For example, the ability to locate and characterize RF signals across many bands from space will allow regulators, telecommunications companies and broadcasters to monitor spectrum usage and to identify areas of interference. In the field of transportation, RF signals transmitted from the air, ground or sea could be precisely monitored. The system may also be used to expedite search and rescue operations by quickly pinpointing activated emergency beacons.

RF geolocation as it pertains to this mission means the identification of a terrestrial signal emitter's location through signal processing and analysis of the received signal at one or more remote observation platforms. In this case, the observation platforms are the three HE360 spacecraft in the Pathfinder cluster. Hereafter the spacecraft will be referred to as "Hawks" and individually as Hawk-A through Hawk-C.

As an example of the utility of the technology which will be made available by this mission, consider an AIS detection case. There are 21 different types of Automatic Identification System (AIS) messages, many of which include the maritime vessel's location provided by the vessel's GPS receiver. Many existing satellites decode or receive this information and use the embedded geolocation data for commercial or national purposes.

Unfortunately, it has been demonstrated that AIS data is not universally reliable. It is fairly easy for individuals, such as pirates or illegally operating fishing fleets to "spoof" their AIS emissions, effectively changing the GPS positions they report to make it look as if they are somewhere other than where they actually are or simply changing their identifier. Furthermore, bad actors with less technical capability frequently turn off their AIS transceivers - "going dark" and disappearing from port and satellite AIS data feeds while engaging in criminal activities. HE360 will demonstrate that independent geolocation of AIS and other signals is possible without having to trust potentially false data in the transmissions. In the event that an AIS transmitter is disabled, other well-known signals commonly transmitted by ships can be substituted to maintain position knowledge of an emitter when traditional AIS-receiving satellites would lose contact.

The three Hawks will fly in formation, with co-visibility of a large number of terrestrial emitters at any one time. Pairs of satellites or the entire trio may intercept the same transmission when the transmission originates from the common footprint of the intercepting satellites. The satellites will synchronize clocks using GPS receivers, and these same GPS receivers will stabilize the phase locked loops (PLLs) governing tuning frequency in the satellites' digitizing RF tuner payload.

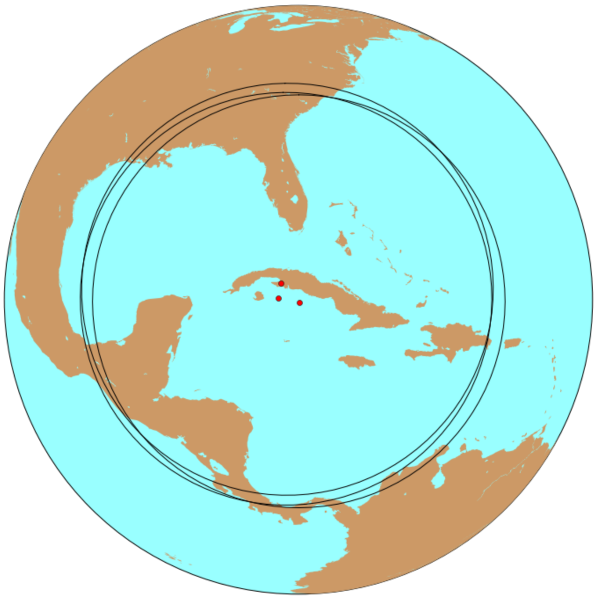

Figure 1: Local horizon footprints of the three spacecraft in formation

Signals will arrive at the three receivers at separate times corresponding to different slant ranges between the satellite and the emitter. Signals will arrive at different apparent center frequencies corresponding to velocity components in the direction of the signal's path of travel from the transmitter to the receiver (Doppler effects). Comparing time-of-arrival (TOA) and frequency-of-arrival (FOA) measurements between pairs of receivers serves as a basis for discovering the position of the transmitter using multi-lateration. GPS receivers provide precise estimates for the position and velocity of the receivers, furnishing the remainder of the information required for multi-lateration.

THE PAYLOAD

Each spacecraft will have an identical payload, consisting of two high-level components: i) A SDR comprised of an embedded processor and FPGA resource, and a baseband signal processor, and ii) a custom-RF front-end with antennas, as illustrated in Figure 2.

The SDR flown on the Pathfinder satellites is comprised of an embedded processor system and three baseband processors. The baseband processor is built around the Analog Devices 9361 product. This is a highly integrated RF transceiver that combines high-speed ADCs and DACs, RF amplifiers, filtering, switching and more on a single chip. The transceiver product is capable of tuning from 70 MHz to 6 GHz, with an instantaneous bandwidth of up to 56 MHz. The 9361 has two receive chains and two transmit chains. Although the device has transmit capability, it is not intended to be used for the receive-only Pathfinder mission. The payload supports three 9361s so that up to three receive channels can be processed simultaneously and on separate frequencies. Although the 9361 has two receive channels, they are tuned via a common local oscillator (LO), which limits the tuning range of one channel to within the instantaneous bandwidth of the other. The embedded processor system is based on the Xilinx Zynq 7045 SOC, which combines a dual-core ARM processor with a Kintex FPGA. The two devices are very tightly integrated on a single chip, which facilitates easy cross-domain switching between the processor and FPGA. This is advantageous for signal processing applications.

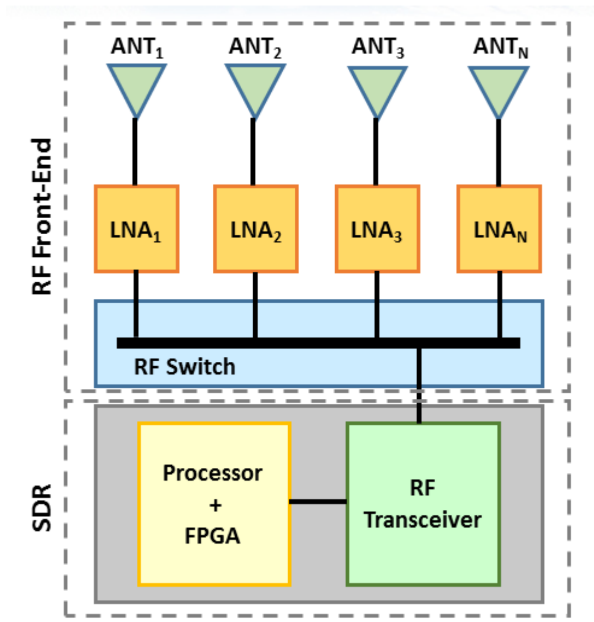

Figure 2: Payload simplified block diagram

The HE360 designed custom-RF front end connects to the baseband processors and provides a number of unique, switchable RF paths and antennas to support a range of bands and frequencies of interest. Each switchable path has custom filters, low noise amplifiers (LNA) and even attenuators tailored to a specific band. A low noise block down-converter (LNB) is included to extend the SDR's frequency range up to Ku-band (~18 GHz). A range of antennas, including quarter-wave dipoles, patches, and wide-band button and horn antennas support the full frequency range, from VHF to Ku-band.

The processor system takes advantage of open-source signal processing software and firmware to maximally mimic desktop SDR products. This allowed ground development to proceed agnostic of the final space hardware and foster adoption of a "fly as you try" philosophy. For the software side, GNURadio was be used. GNURadio is "a free and open-source toolkit for software radio." It is widely used in small space projects for ground software processing and may have been used on previous spacecraft in similar embedded environments.

In operation, the payload can be commanded to tune the baseband processor to a center frequency and stream samples at a given sample rate. Nominally, the baseband processor will produce complex (quadrature) samples. The RF front end will also be configured based on the signal of interest. Samples will be conditioned to some extent in the FPGA, including filtering and balancing associated with the ADCs. HawkEye, however, will maximize on-board processing wherever doing so contributes to the bottom line in terms of the product delivered[2]. Constraints inherent to the mission in terms of downlinking and crosslinking data motivate reducing full-take RF to meta-data surrounding that RF. To accomplish this reduction, user-defined signal processing chains optimized for the embedded platform are implemented.

The payload had gained considerable in-field aerial test experience in parallel with development, building confidence prior to the actual launch of the Pathfinder mission. Indeed, the SDR payloads and receiving antennas were fitted onto three rented aircraft, flown in diverse formations over live RF emitters (including maritime vessels and commercial maritime radar, amongst other targets), yielding RF signal detection and geolocation with unprecedented accuracy.

THE PLATFORM

The HE360 Pathfinder mission employs SFL's versatile flight proven NEMO platform. This state-of-the-art microsatellite bus has been employed by a wide range of commercial and government users, and depended upon in applications and business models which would only allow for a high-performance high-reliability yet affordable platform. Indeed, the NEMO bus has been selected by the Norwegian government for the NORSAT-1, -2, and -3 satellites (scientific, maritime AIS, VDES, and radar applications), the Indian government for NEMO-AM (aerosol monitoring), and GHGSat Inc. for the GHGSat Constellation (greenhouse gas emissions monitoring). The platform supports a full suite of heritage SFL subsystem hardware. The NEMO platform is configurable, with many design aspects tailorable, if needed. The NEMO-platform itself builds upon the extensive heritage gained from SFL's widely used Generic Nanosatellite Bus (GNB). By leveraging heritage designs and experiences gained through many cumulative years of on-orbit operation, the cost, schedule, and risk associated with the Pathfinder mission was significantly reduced.

The HE360 Pathfinder platform is essentially a 20x20x44 cm form factor with an additional ~7 cm high 'mezzanine', with a launch wet mass of 13.4kg. Similar to spacecraft designed to the CubeSat standard, four launch rails interface with the separation system and guide the spacecraft during ejection from SFL's XPOD separation system. An external view of the Pathfinder spacecraft is found in Figure 3. The bus structure is predominantly lightweight magnesium, with careful arrangement of structural components to provide high mechanical margins. The structural concept of the spacecraft is a dual tray based design, as shown in Figure 4. Most of the platform avionics are clustered towards the +Y end of the spacecraft. This allows for integration and harness design ease, and offers considerable payload accommodation volume.

Figure 3: Artistic Rendering of the HE360 Pathfinder Platform

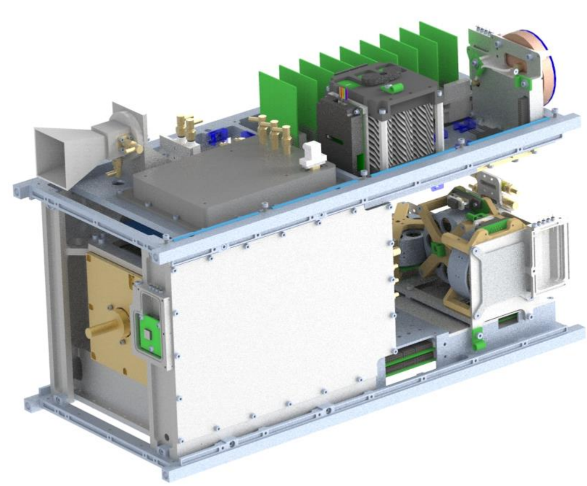

Figure 4: HE360 Pathfinder Internal Layout

As the spacecraft carries a sensitive RF payload, electromagnetic interference (EMI) mitigation was an important consideration in design. The spacecraft was segregated into three distinct RF zones: i) the payloads isolated within their enclosures, ii) the balance of the platform, and iii) the environment external to the spacecraft. The zones were setup by creating boundaries, essentially Faraday cages, which would significantly attenuate noise. This was accomplished by:

- The use of RC-filtered connectors, sized to reject signals above a design cut-off frequency,
- The use of conductive gaskets to ensure DC and RF seals across all interfaces of the faraday cages,
- Strict aperture control, to significantly attenuate RF noise, but yet still comply with spacecraft venting requirements. This is particularly important for the spacecraft exterior, as strict aperture control was enforced to prevent transmission of noise which may otherwise be picked up by the payload receive antennas.

The Pathfinder spacecraft employs a single-string design that results in a compact, low mass spacecraft. The power architecture is based on SFL's modular power system (MPS), which generates power from the body mounted high-efficiency triple-junction solar arrays, and uses a 12V lithium ion battery for energy storage. A solar array and battery regulator (SABR) unit within the MPS provides peak power tracking functionality to optimize power generation. The MPS also provides power conditioning to generate 3.3V and 5V regulated buses in addition to the unregulated 12V bus, as well as load switching and protection against off-nominal voltage and current events.

The command and data handling architecture is centred on two SFL-designed on-board computers (OBCs), which interface to the uplink and downlink radios and all other spacecraft hardware. One OBC is nominally designated as the house keeping computer (HKC), and is responsible for telemetry collection, routing packets to and from the radios, payload operations, and execution of time tagged commands. The second OBC is designated as the attitude determination and control computer (ADCC) and is responsible for polling attitude determination sensors, running the estimation and control algorithms, and commanding actuators. Both computers are cross-connected to all on-board hardware, providing a level of redundancy. In this configuration, either computer can take on the tasks of the other if required.

Primary telemetry and command is provided in S-band and UHF respectively. A SFL UHF receiver is used to provide the uplink channel at a fixed 4kbit/sec data rate. A variable data rate SFL S-band transmitter, which can operate between 32kbit/sec and 2048kbit/sec (scaled on-the-fly), in either BPSK or QPSK modulation and 0.5 rate convolutional encoding, is used on the downlink. The platform is also equipped with dedicated high-data rate payload links: uplink in S-band, downlink in X-band and cross-link to other satellites in S-band. The X-Band transmitter is capable of 3 – 50 Mbps usable data rate. The transmitter uses Offset Quadrature Phase Shift Keying (OQPSK) and a ½ rate convolutional encoding Forward Error Correction (FEC) scheme. A high-rate S-band uplink is implemented within the payload SDR itself, with a LNA positioned between the radio and the body-mounted patch antenna. A SFL S-Band inter-satellite link, although not required for the mission, is integrated to demonstrate the capability to perform the geolocation calculations entirely on orbit. In this scenario, information must be exchanged between the satellites so that all measurements reside on a single spacecraft where the geolocation problem can be solved.

The attitude determination and control subsystem employs six sun sensors, a three-axis magnetometer, and a three-axis rate sensor for attitude determination. Attitude control is achieved through three vacuum core magnetorquers and three reaction wheels. Orbit position and velocity measurements are sampled by a L1/L2 GPS receiver and active antenna. Several modes of attitude control are available including de-tumble (for initial stabilization after kick-off from the launch vehicle), inertial pointing, nadir tracking, align-constrain, and ground target tracking. This system allows for 2σ pointing accuracy with only 2.1o and 4.2o error in sunlight and eclipse respectively.

DSI is providing a novel electro-thermal propulsion system that uses liquid water as the working fluid, significantly reducing integration and launch risks relative to other market options of similar performance. The unit has a qualified specific impulse (Isp) of 182 seconds, giving it exceptional performance with comparison to a typical cold-gas system. Conversely, while it has a lower Isp than newly available low-power electric propulsion systems, the higher thrust means that DSI's system can be used quasi-impulsively. This reduces the time required for maneuvers. Electric propulsion systems also typically utilize high voltage power supplies or RF-amplifiers that produce wide-band RF noise, which is detrimental to the RF payload. The propulsion system on Pathfinder has a ΔV of 96 m/s, though, the system features an easily expandable propellant tank, allowing for simple propellant volume tailoring. The water propellant needs to stay liquid at all times. The thermal design of the spacecraft passively maintains the propellant in a liquid state, but auxiliary heaters are positioned to augment this in an emergency.

THE FORMATION

SFL has a strong history in the development and implementation of technologies and algorithms aimed towards operational formation flying missions. The CanX-4 and CanX-5 spacecraft were the first nanosatellites to demonstrate autonomous formation reconfiguration and control with a control error of less than one metre[1]. This was enabled by a real-time relative navigation algorithm based on carrier-phase differential GPS techniques, which was shown to have a typical RMS error of better than 10 cm [4]. In addition, the drift recovery and station keeping (DRASTK) software was developed and used successfully to design and implement a guidance trajectory for rendezvous following initial spacecraft separation from the launch vehicle, and to maintain a coarse along-track separation in a passively safe relative configuration by appropriately phasing in-plane and out-of-plane motions[3]. It is with this proven track-record of success in applied formation guidance and navigation that SFL is uniquely positioned to implement these techniques operationally for the HE360 Pathfinder mission.

The baseline orbit for the Pathfinder mission is a circular Sun-synchronous orbit with an altitude of 575 km and a local time of descending node of 10:30. In the target formation, the three spacecraft are equally spaced along-track by 125 km. The middle spacecraft has its right ascension of the ascending node (RAAN) adjusted such that it has a 20 km peak-to-peak out-of-plane oscillatory motion, whose maxima are achieved at the equator. For a RAAN-offset orbit, the formation becomes co-linear at the maximum and minimum sub-latitudes of the cluster, which occurs near the northern and southern polar regions. The reduced geolocation precision in the polar regions is tolerable since the human population and activity in this region is limited. Also, the payload data will be downloaded to X-band earth stations in this region frequently. No inclination difference is desired, due to the large cost in maintaining this formation owing to the required RAAN corrections. This formation provides a good balance between ground target viewing geometry for geolocation of RF signals, and fuel cost of formation initialization and maintenance. The quasi-nonsingular mean orbital element set from [6] is adopted in this work for several reasons. First, this parameterization results in an intuitive geometric representation of the formation design variables given its relationship to the solutions of the Hill-Clohessy-Wiltshire equations of relative motion. Second, the equations of relative motion are significantly simplified, so formation guidance and control tasks can be moved onboard more easily. Finally, the use of orbital elements easily lends itself to analysis of "mean" or averaged relative motion, such that short-period and long-period oscillations are ignored and only linear drift in the formation is controlled. The quasi-nonsingular elements cannot be used in equatorial orbits, but this is not considered a detriment since such orbits are not beneficial to HE360 from a ground-coverage perspective.

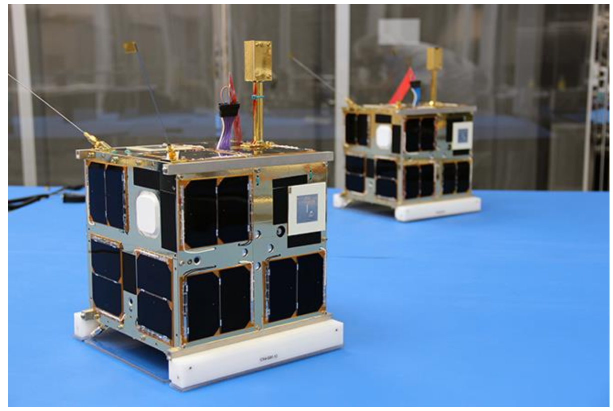

Figure 5: The CanX-4 and CanX-5 spacecraft, which successfully demonstrated in orbit precise, controlled formation flight at the nanosatellite scale in 2014

The required formation control is 5 km (1σ), which must also be tolerant to 1 week ground station outages. The guidance, navigation, and control strategies selected can be implemented on-board the spacecraft, however at present control maneuvers are to be computed on the ground and uploaded to each spacecraft given the relatively coarse formation-keeping requirement. This strategy removes the complexity and risk in implementing autonomous relative navigation and control where it is not warranted. The target mission duration is two years, with a stretch goal of three years. Over this time, only two of the three spacecraft shall be actively controlled. From a power perspective, the spacecraft are constrained to applying orbit control maneuvers at least 45 minutes apart.

Conceptually the formation control strategy is broken down into two phases: formation initialization, and station keeping. Following a two-week commissioning period for the spacecraft systems, the initialization phase is expected to last approximately six weeks. During initialization two of the three spacecraft are maneuvered into the target formation – exactly which two depends on the initial relative configuration upon separation from the launch vehicle. It is expected that all three spacecraft will be deployed approximately five minutes apart from SFL's XPOD separation system, each at a velocity of roughly 1.8 m/s in an uncontrolled direction relative to the local orbital frame. Given the GPS telemetry from each spacecraft, a guidance plan can be simulated for each permutation of controlled spacecraft. The spacecraft pair leading to minimum fuel consumption will be selected as the controlled spacecraft going forward. The total initialization phase is broken down into sub-intervals (ΔTinit), during which roughly 85% of orbits are allotted for control, while 15% are reserved as maneuver-free periods for the purpose of orbit determination used as input for the next initialization window.

The guidance law during formation initialization is based on [6], where the fuel-optimal reconfiguration from some initial state to a final desired state is framed as a problem of minimizing the net total change in the differential mean orbital elements. This is possible since incremental changes in the orbital elements can be equated to impulsive thrust maneuvers (i.e., instantaneous changes in velocity). The guidance plan generates a set of waypoints in differential mean orbital element space from the current time to the desired initialization time in ΔTinit intervals. The waypoint at the start of the next sub-interval is used as the target during the current control period.

The set of control maneuvers during each initialization sub-interval is computed using the method of Roscoe et al., which exploits a duality between the continuous and discrete time optimal formation reconfiguration problem in order to iteratively solve for a set of maneuver locations and magnitudes that result in a minimum-fuel maneuver plan to reach the target waypoint at the target time[5]. This control strategy is augmented to enforce a minimum time-spacing between maneuvers, and to prevent maneuvers from being planned inside configurable "no thrust" windows, which are specified by operators as a set of intervals.

The station keeping guidance law is designed to keep the spacecraft within a designated control window while keeping the spacecraft passively safe using the eccentricity/inclination vector separation concept[7]. The station keeping phase is conceptualized as a long period of no control (the drift period; approximately 1 week), followed by a short window within which the control maneuvers occur (the control period; approximately 4 orbits). The strategy is motivated by [8], whereby during each control window the active spacecraft targets a specific differential semi-major axis which will cause a drift from one side of the control window to the other. Likewise, the relative eccentricity vector is adjusted such that it will be parallel with the relative inclination vector half-way through the drift period, which maximizes safety during the drift period. The relative inclination vector is simply readjusted to its target value during each control period, since there is no drift desired here. The long drift period is allowable because control maneuvers are expected to be infrequent, owing to the fact that all spacecraft will mirror their attitudes thus minimizing the impact of differential drag on the formation. A side-benefit of this strategy is maximizing the time spent performing payload observations.

The formation control simulations are performed with the aid of Systems Tool Kit (STK). The orbit model includes an EGM2008 gravity model of degree and order 30, third-body perturbations due to the Sun and moon, solar radiation pressure, and atmospheric drag with a Jacchia-Roberts atmospheric density model. Thrusts are modeled as impulsive with a mean error of zero and a standard deviation of 5%. A thrust timing error with standard deviation 10 seconds is applied as well. Thrust minimum impulsive bit and saturation effects are also accounted for, as well as attitude control errors with standard deviation of 2 degrees. Guidance and control calculations are performed with an "error" differential orbital element state, whereby the true states are corrupted with a Gaussian noise whose mean and standard deviation are provided in Table 1.

In the initialization simulation, the spacecraft are assumed to begin in the aforementioned baseline orbit, after which they separate from the launch vehicle at a relative velocity of 1.7 m/s. One is deployed along the velocity vector, the second along the orbit normal vector, and the third towards anti-velocity. The spacecraft are allowed to drift with no control for 2 weeks, after which there are 6 weeks allowed for formation initialization. The desired relative orbital elements are given in Table 2, where the values provided are relative to Hawk-B which is assumed to be at the formation center and is uncontrolled. The results of the initialization simulation are provided in Figure 6, which shows the relative trajectory of Hawk-A with respect to Hawk-B during the initialization period. The initial plan and the actual trajectory match fairly well for the along-track separation and out-of-plane oscillation, but there appears to be a large offset in the relative eccentricity vector. This indicates that the relative eccentricity vector model does not capture the true dynamics adequately at the global scale. In a practical sense, this is not an issue because the global trajectory is recomputed after each initialization sub-interval effectively closing the loop. The ΔV required for this initialization is 5.43 m/s. This value is heavily dependent on the initial separation dynamics, as well as the total initialization period – longer periods lead to greater fuel savings, as the natural drift due to J2 can be leveraged to aide in adjusting the in-track offset and RAAN.

The results of a station-keeping simulation are shown in Figure 6. After achieving the target orbit, the spacecraft are in their maintained within the desired control bounds using only four maneuvers every week. The departures from the reference orbit seen in Figure 7 are due to mismatches between the true and modeled relative motion in the simulation, as well as relative position determination errors, thrust timing and magnitude errors, and attitude pointing errors modeled in the simulation. In spite of the modeled errors and non-idealities, the station-keeping method employed is capable of maintaining the spacecraft within the desired control window. The set of maneuvers over the two-year period is given in Figure 8. The fuel consumption throughout the mission is regular, showing that a steady-state of control has been achieved. Overall, the spacecraft use about 2.2 m/s per year of operations to maintain the formation, yielding propellant margins in excess of 80%.

Table 1: Navigation error applied to differential mean orbital element states in formation simulations.

	δa [m]	$\delta\lambda$ [rad]	δe_x [−]	δe_y [−]	δi_x [rad]	δi_y [rad]
Mean	3	-7×10^{-7}	-6.78×10^{-9}	-5.93×10^{-9}	-6.5×10^{-9}	-1.13×10^{-8}
Stdev.	1	1.82×10^{-8}	5.88×10^{-7}	5.934×10^{-7}	1.35×10^{-8}	1.95×10^{-8}

Table 2: Target differential mean orbital elements for initialization relative to Hawk-B.

	δa [m]	$\delta\lambda$ [rad]	δe_x [−]	δe_y [−]	δi_x [rad]	δi_y [rad]
Hawk-A	0	0.018	0	0	0	1.44×10^{-3}
Hawk-C	0	-0.018	0	0	0	1.44×10^{-3}

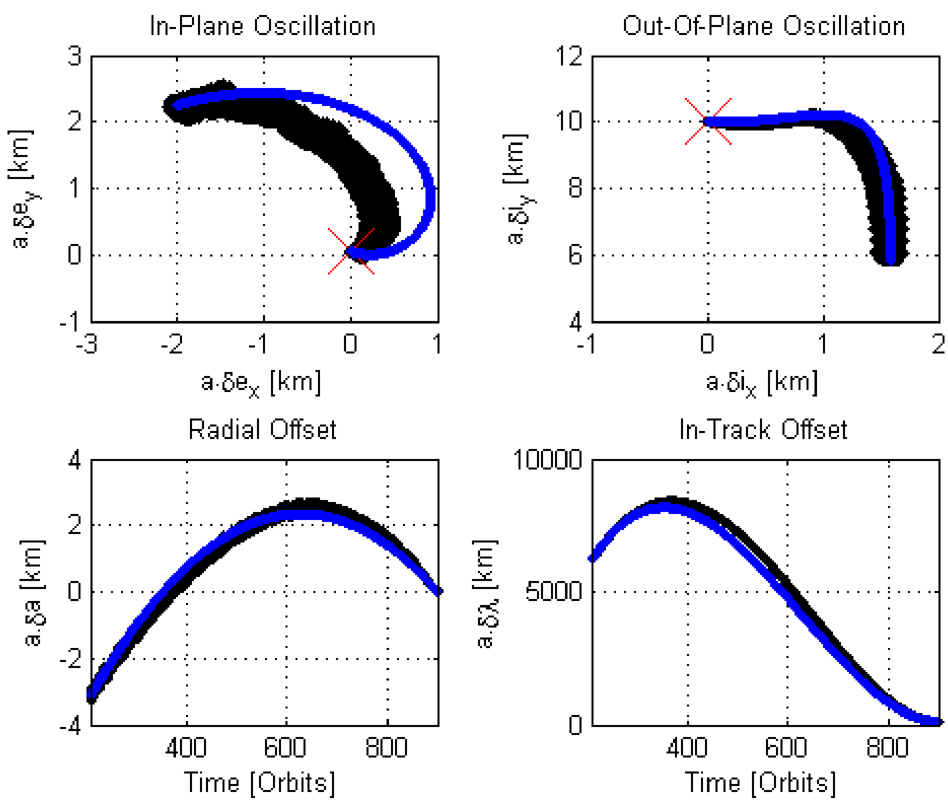

Figure 6: Initialization trajectory in differential mean orbital element space (blue is the initial plan, black is the actual trajectory, and the red X marks the final desired state).

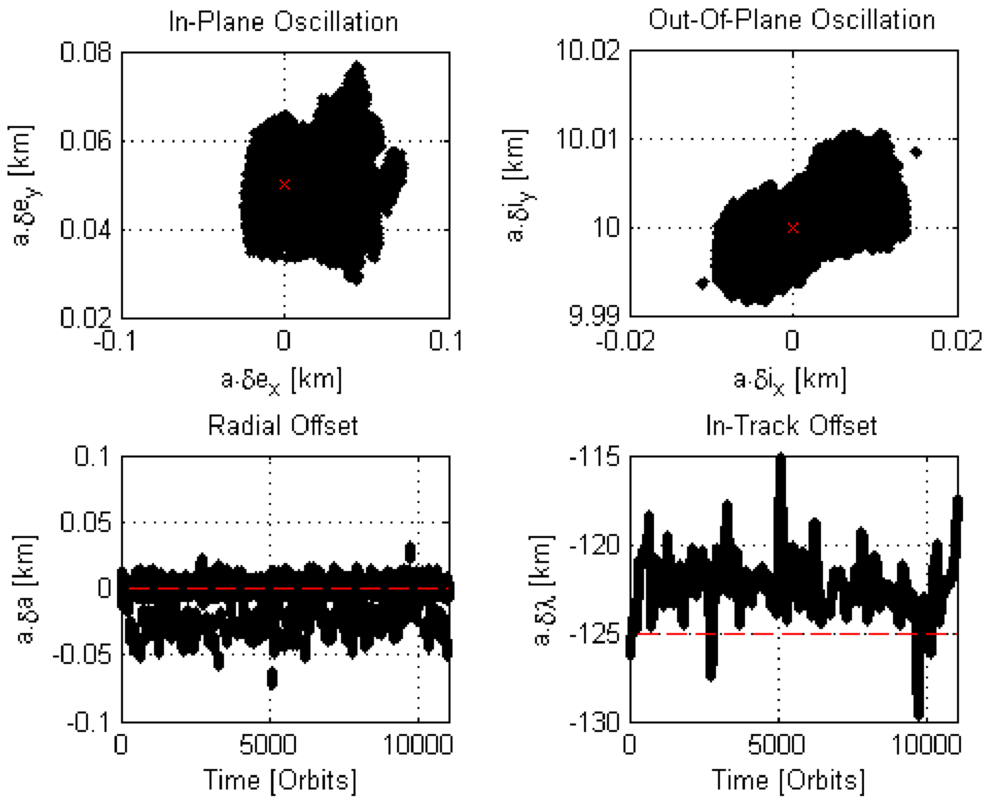

Figure 7: Station-keeping results for 2 years of operation.

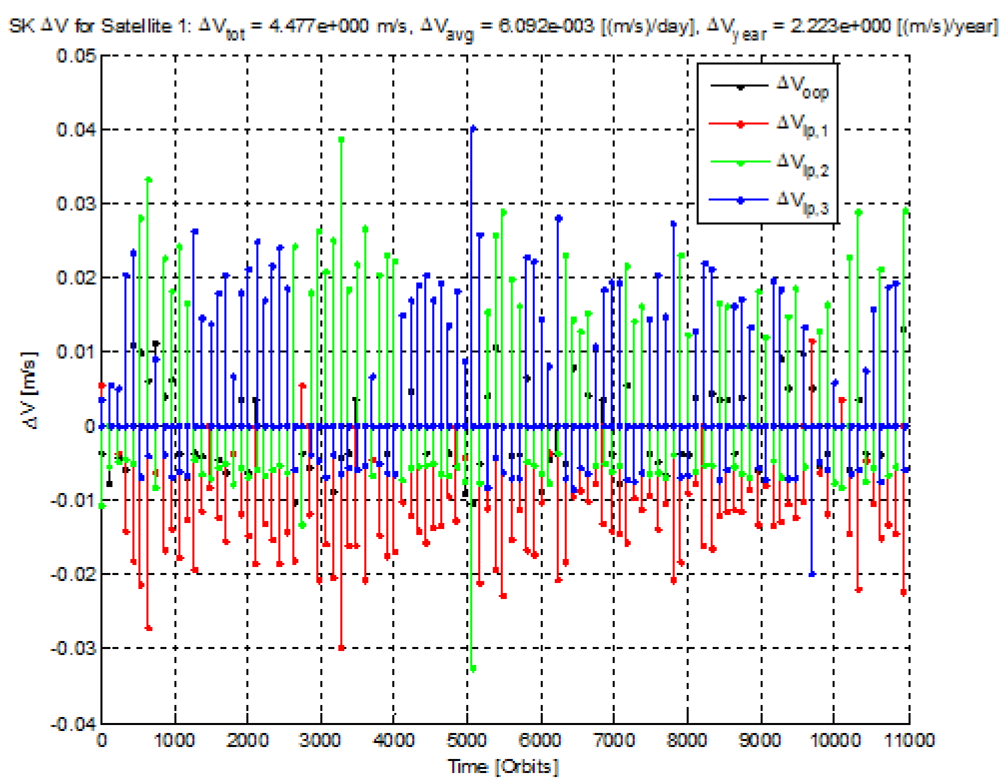

Figure 8: Fuel consumption over 2 year station-keeping period.

THE FUTURE

At the time of writing, all three Hawks are in final flight integration and environmental test. The payloads have been fully flight integrated, tested at the spacecraft system-level, and ready for flight. In the coming months, the spacecraft will be subject to electromagnetic compatibility (EMC), vibration, and thermal vacuum (TVAC) test before being shipped to the launch integration facility in early August 2018, for a launch in October 2018.

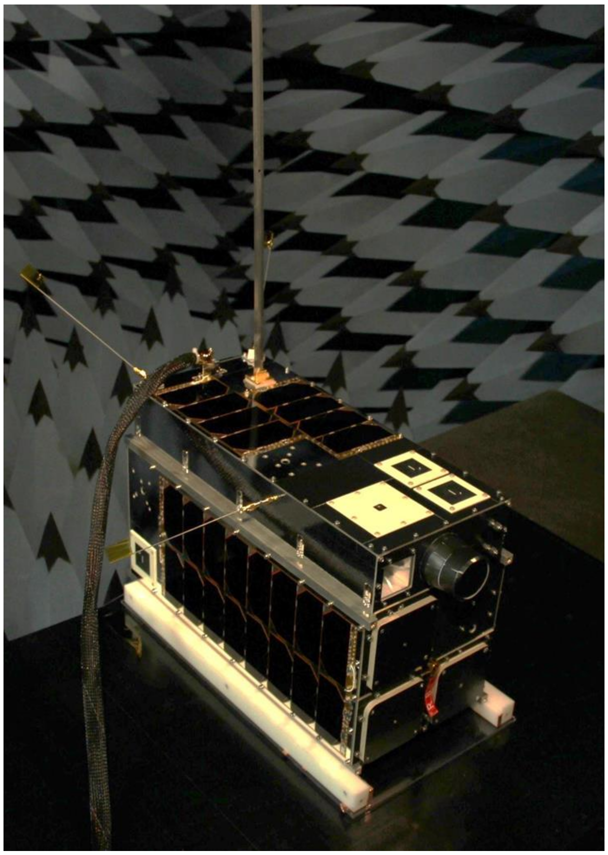

Figure 9: A HE360 Pathfinder satellite in EMC test

The ground segment is currently under development and test. The network will involve UHF/S-band telemetry and command stations located at the Virginia headquarters of HawkEye 360, however, the mission will largely be operated out of northern latitude KSAT S-band/X-band stations.

Following the successful demonstration of the Pathfinder mission, HE360 plans to deploy a commercial constellation of similar clusters of spacecraft. This constellation would provide similar geolocation services on a global scale with high revisit rates. HE360 has modeled constellations with as many as eighteen spacecraft (six clusters of three Hawks) for specific studies, but the actual constellation size and geometry will depend on requirements that stem from the results of the Pathfinder mission. Figure 8 shows one example constellation. The clusters are in 650 km circular orbits and divided into three planes: 97°, 44°, and 63.5° (chosen for this example because of their common availability in cluster launches). Two clusters are distributed per plane, with the clusters separated by 180°. It is evident that even with a simple constellation design, global revisit rates are quite high, especially in those latitudes most commonly populated.

Finally, the Pathfinder mission is a successful example of well-co-ordinated execution on a multi-organization project. Often, missions being developed within multi-part groups tend to face financial and schedule burdens of bureaucracy, logistics, documentation and communication restrictions. This partnership was built for success at the outset as each organization was able to focus on the core competencies each brought to the table, allowing for the rapid development and fiscally responsible approaches synonymous with the microspace design philosophy.

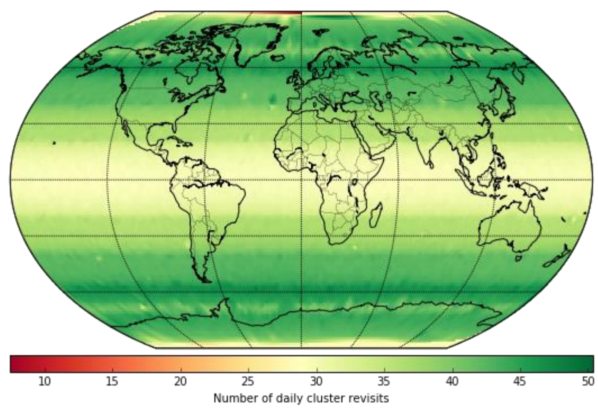

Figure 10: Example 18 Satellite Constellation Revisit

ACKNOWLEDGEMENTS

The authors of would like to thank the teams of engineers, managers and support personnel at the offices of HawkEye 360, Deep Space Industries, and Space Flight Laboratory who devoted their time and passion in enabling this project to take shape.

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