Geolocation of RF Emitters with a Formation-Flying Cluster of Three Microsatellites

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ABSTRACT

In 2017, the HawkEye 360 Pathfinder mission will demonstrate the capability to perform high-precision RF geolocation using a formation-flying cluster of microsatellites. HE360 has developed an innovative combination of classical and novel geolocation algorithms that will enable precise geolocation of RF emitters related to a broad array of business enterprises. These algorithms are robust to errors in self-reported geolocation data such as those commonly seen in maritime radio service systems like the Automatic Identification System (AIS). Each spacecraft in the Pathfinder cluster will host a primary payload consisting of a Software Defined Radio (SDR) capable of covering various RF segments spanning VHF through Ku-Band. The spacecraft will leverage formation-flying techniques and propulsion technology demonstrated on earlier cubesat missions to maintain a loose, long-term, geometrically diverse formation where all three spacecraft have co-visibility of the signal of interest. This paper describes the challenges associated with the demanding requirements of this Pathfinder mission, the technology and architectural approach that enable it, and the value of independent geolocation services to commercial, governmental and humanitarian concerns. Furthermore, a future mission consisting of an expanded constellation of similar clusters will be explored.

INTRODUCTION

Over the past decade, a number of RF-sensing, commercial Low Earth Orbit (LEO) satellite systems have been developed and deployed. RF-sensing missions are distinct from electro-optical systems in that they frequently can sense a larger swath width of the Earth at any one time, subject to frequency and ground emitter RF power constraints. Two commercially successful examples are the use of maritime Automatic Identification System (AIS) data to track ships and the more recent application of GPS Occultation to derive meteorological information.

Satellite systems that focus on these signals and others rely on payloads that are essentially RF receivers of one type or another. These payloads often exert relatively modest requirements on the host spacecraft relative to other missions. Building on the success of these early pioneers, a new class of RF-sensing missions is proposed that takes advantage of multiple RF-sensing spacecraft, working in concert to geolocate ground based emitters using both documented and novel signal processing techniques.

HawkEye 360 Pathfinder Mission Overview

HawkEye 360 (HE360) is a new space startup based in Herndon, VA. Although satellites will be a key resource in HE360’s business plan, the focus of the company will be on signal processing and data analytics. In late 2017, HE360 will launch a cluster of three microsatellites to a Sun Synchronous Orbit (SSO) between 550 and 650 km. 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.

Each of the three spacecraft will be identical and their primary payload is a Software Defined Radio (SDR) and custom Radio Frequency (RF) front end, along with band-specific antennas. The frequency agile payload will enable reception of many different types of signals, which will then be geolocated by applying signal processing to the combined received data of all three spacecraft.

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 (six cluster) constellation 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.

Project Background

HawkEye 360 was founded in September 2015 with Allied Minds as the seed investor in the company.
Located in Herndon, Virginia, HawkEye 360 is developing an end-to-end architecture for detecting, geolocate and analyze RF spectrum. Analytic reports, fused with Multi-INT sources, can be used to monitor transportation, detect distress alerts, assist with emergencies and much more. HE360 will provide maritime domain awareness, establish a spectrum inventory, and develop insight into global usage of wireless signals, addressing needs of commercial and government customers worldwide.

Recently, HE360 selected Deep Space Industries (DSI) as the prime contractor, with UTIAS Space Flight Laboratory (SFL) acting as a subcontractor providing the majority of the spacecraft components. DSI will also provide a novel electro-thermal propulsion system that uses liquid water as the working fluid.

Leading up to the Pathfinder mission, several terrestrial and airborne demonstrations are scheduled over the coming year. These demonstrations, including UAV and light aircraft-based tests will demonstrate the Pathfinder payload and geolocation algorithms in realistic environments. These demonstrations will be discussed further.

Market Potential

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. The market applications span both government and commercial domains and seek to augment our understanding of human behaviors as well as assist in accidents and emergencies. We are filling a void by bringing this level of visualization to a domain that has historically only been understood by governments. Key markets include:

- Transportation and activity tracking
- Emergency response
- Interference detection and geolocation
- Spectrum Management

GEOLOCATION

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-1 through Hawk-3.

Representative Signal

Although the cluster will be able to geolocate emitters using many different types of signals and frequencies, a representative example serves to demonstrate the concept. AIS will serve as an example signal. It has been described in many other papers before [13], so a brief summary will suffice.

AIS is a maritime port navigation and information system. AIS transceivers are mandated for use on commercial ships over 300 gross tons and are widely used on smaller vessels as well. AIS is transmitted on two VHF channels, at 161.975 MHz and 162.025 MHz, using Gaussian Minimum Shift Keying (GMSK) modulation at a baud rate of 9600 bits per second and a 0.4 bandwidth time product (BT). The transmissions are locally coordinated using Self-Organized Time Division Multiplex Access (SOTDMA). The rate of transmission from each ship depends on a number of factors, including its velocity and activity, but transmissions typically occur frequently enough that a low earth orbiting satellite can receive multiple transmissions from a single ship on a pass.

There are 21 different types of AIS messages, many of which include the ship’s location, which is provided by the ship’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 “spoil” 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, those 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.

This paper 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 or other platforms can be substituted to maintain position knowledge of an emitter when traditional AIS-receiving satellites would lose contact. A number of geolocation techniques will be explored. Some of them are standard algorithms and others are proprietary techniques developed by HE360.
Time and Frequency of Arrival

The three Hawks fly in formation, with co-visibility of a large number of terrestrial emitters at any one time i.e. their ground footprints will overlap to great extent. 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. We assume the payloads can synchronize tuning frequency precisely via calibration techniques specific to the payloads and the RF environment.

![Figure 1: Hawk 3-Ball Cluster Footprints Overlap](image)

Signals arriving at the three receivers will arrive at separate times corresponding to separate slant ranges between the satellite and the emitter. Signals will arrive at separate apparent center frequencies corresponding to separate velocity components in the direction of the signal’s path of travel between the satellite and 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 multilateration. GPS receivers provide precise estimates for the position and velocity of the receivers, furnishing the remainder of the information required for multilateration.

Let \( \mathbf{u} \) be a vector variable representing the position of a (fixed) transmitter (where we assume the familiar ECEF coordinate system). For \( i \in \{1, 2, 3\} \), the slant range between \( \mathbf{u} \) and \( s_i \), the position of the \( i^{th} \) receiver, is

\[
r_e^i = s_i - \mathbf{u} = \sqrt{(s_i - \mathbf{u})^t (s_i - \mathbf{u})}.
\]  

(1.1)

We arrive at the time-difference-of-arrival (TDOA) equation:

\[
\tau_{i,j} = \frac{1}{c} (r_e^i - r_e^j)
\]

\[
= \frac{1}{c} \left( \sqrt{(s_i - \mathbf{u})^t (s_i - \mathbf{u})} - \sqrt{(s_j - \mathbf{u})^t (s_j - \mathbf{u})} \right)
\]

(1.2)

where \( \tau_{i,j} \) is the difference in time of arrival for a single pulse between receivers \( i \) and \( j \), and \( c \) is the speed of light.

Let \( \mathbf{s}_i \) be the velocity of satellite \( i \). Our interest is the instantaneous time-rate-of-change in \( r_e^i \), denoted \( \dot{r}_e^i \), where we consider position components from equation 1.1 as functions of time. Taking the derivative yields

\[
\dot{r}_e^i = \frac{(s_i - \mathbf{u}) (s_i)^t}{r_e^i}.
\]

(1.3)

The perceived change in frequency from the transmitted frequency \( f_e \) owing to the component of \( \dot{\mathbf{s}}_i \) along the signal’s path of travel between \( \mathbf{u} \) and \( s_i \) is \( (f_e/c) \ast \dot{r}_e^i \). The frequency-difference-of-arrival (FDOA) equation follows:

\[
\tau_{i,j} = \frac{f_e}{c} (r_e^i - r_e^j)
\]

\[
= \frac{f_e}{c} \left( \frac{(s_i - \mathbf{u}) (s_i)^t - (s_j - \mathbf{u}) (s_j)^t}{r_e^i} \right)
\]

(1.4)

Putting TDOA and FDOA to Work

Equations 1.2 and 1.4 provide a framework for one method (the bog-standard method?) to calculate geolocation estimates from available data. Suppose each of three satellites intercepts a single pulse. If we can combine information from each satellite at some point in the processing chain, we can apply digital signal processing techniques (generally CAFs or matched filters) to estimate the TOA \( \tau_i \) for \( i \in \{1, 2, 3\} \). Separately, we estimate the FOA \( \dot{\tau}_i \) for \( i \in \{1, 2, 3\} \). Consulting GPS readings and ephemera, we can estimate \( s_i(\tau_i) \) and \( \dot{s}_i(\tau_i) \), the position and velocity, respectively, of satellite \( i \) at time \( \tau_i \). We want an estimate for \( \mathbf{u} \). We can compose four independent equations in three unknown variables \( (x_e, y_e, z_e) \) using equations 1.2 and 1.4:

\[
\tau_i - \tau_3 = \frac{1}{c} \left( \sqrt{(r_s(\tau_i) - \mathbf{u})^t (r_s(\tau_i) - \mathbf{u})} - \sqrt{(r_s(\tau_3) - \mathbf{u})^t (r_s(\tau_3) - \mathbf{u})} \right)
\]

\[
\tau_i - \tau_3 = \frac{f_e}{c} \left( \frac{(s_i(\tau_i) - \mathbf{u}) (s_i(\tau_i))^t - (s_3(\tau_3) - \mathbf{u}) (s_3(\tau_3))^t}{r_e^i} \right)
\]

(2.1)
for \( k \in \{2, 3\} \). We have one more piece of information: our emitter lies on the surface of the Earth, so
\[
u = R_u ,
\]
(2.2)
where \( R_u \) is the radius of Earth at point \( u \). Although certain combinations of these equations can be linearized to produce exact candidate solutions given (noisy) estimated inputs ([7] offers a method using TDOA information alone), equations 2.1 form a non-linear, over-determined system. The astute reader will notice a two-receiver scenario together with equation 2.2 leads to a critically-determined system for the position of a fixed emitter on the surface of the earth. The system being over-determined in the three receiver case leads to sharper geolocation results, or, seen another way, greater certainty in geolocation estimation per unit revisit-time. If we complicate the scenario by allowing the emitter to move on the surface of the earth, then equation 2.2 yields a system in four variables, two each for position and velocity, and this new system is critically-determined with three receivers. Removing the assumption in equation 2.2 (generally, we refer to such emitters as “aircraft” and assume, simultaneously, that such emitters are not fixed) further complicates the model and leaves us with an under-determined system absent multiple pulses to analyze. These scenarios go beyond the scope of this paper, but certainly not beyond the scope of the Pathfinder mission.

Solving system 2.1 optimally with respect to computational constraints involves using an assortment of estimators, combinations of which may change depending on the nature and cause of the noise present in the equation inputs. One general approach to assess the potential to resolve geolocation estimates accurately, to examine the effects of certain engineering decisions on available resolution, and, indeed, to inform the composition of estimators for these equations themselves involves studying the Cramer-Rao Lower Bound (CRLB) for this (and similar or derived) systems. In [6], the authors characterize CRLBs succinctly: “The CRLB is the lowest possible variance an unbiased linear estimator can achieve.”

Following [6] and [12], we assume maximum-likelihood estimators for equations 2.1, allowing us to decompose our CRLB as
\[
J := [H^T \xi^{-1} H]^{-1}
\]
(2.3)
where \( H \) and \( \xi \) take the following definitions.

\[
H := \begin{bmatrix}
\frac{\partial \tau_1}{\partial u} & \frac{\partial \tau_2}{\partial u} \\
\frac{\partial \tau_1}{\partial u} & \frac{\partial \tau_3}{\partial u}
\end{bmatrix}, \quad \text{and} \quad \xi := \begin{bmatrix}
\tau_1 \\
\tau_2 \\
\tau_3
\end{bmatrix}.
\]

The operator \( \text{Cov}() \) denotes finding the covariance matrix. Evaluating at any point \( u = (x_e, y_e, z_e) \), \( H_{(x_e, y_e, z_e)} \) is a \( 4 \times 3 \) matrix, and \( \xi \) is \( 4 \times 4 \). The CRLB, then, cleanly decomposes HawkEye’s engineering challenges: to achieve a favorable geometry for geolocation when, or for which regions, those geolocation estimates matter most and to push covariance values in \( \xi \) low enough to achieve good results when the geometry is favorable. We discuss deriving values for the entries of \( \xi \) (and the engineering challenges those values present) in section 3. Our orbit propagation simulations address challenges related to geometry.

For the remainder of this section, we outline how to manipulate \( J \) to derive meaningful accuracy estimates. \( J_{(x_e, y_e, z_e)} \) is a three-dimensional covariance ellipsoid for the system 2.1, so the square roots of the eigenvalues for \( J_{(x_e, y_e, z_e)} \) give the magnitudes of the axes for the one-sigma ellipsoid of the three-dimensional probability density function describing the precision of geolocation estimates for an emitter at point \( (x_e, y_e, z_e) \). Up to this point, we have not leveraged equation 2.2. To do so, we project \( J \) into the tangent plane to Earth at point \( (x_e, y_e, z_e) \). The figures presented assume a simple oblate spheroid model for the surface of the Earth with major axis \( a = 6378137.0 \text{m} \) and minor axis \( b = 6356752.314245 \text{m} \), so the equation for Earth’s surface is
\[
g = \frac{x^2}{a^2} + \frac{y^2}{a^2} + \frac{z^2}{b^2} - 1 = 0.
\]
(2.4)
The unit normal vector to the surface at \( (x_e, y_e, z_e) \) is
\[
\hat{e} := \nabla g_{(x_e, y_e, z_e)},
\]
(2.5)
where \( \nabla \) is the gradient operator. We define
\[
P := I_n - \hat{e} \hat{e}^T
\]
where \( I_n \) is the \( n \times n \) identity matrix. We state the following without proof:
\begin{enumerate}
\item \( P \hat{e} = 0 \), and
\item \( P d = d \) if and only if \( \hat{e} d^T = 0 \).
\end{enumerate}
Decomposing three-space \( V \) into orthogonal complements, \( V_\perp \oplus V_\perp^\perp \), if we write...
then it follows
\[ \mathbf{P} \mathbf{J}_{\{x, y, z\}} \mathbf{v}' = \mathbf{v}' (J_{\{x, y, z\}} \mathbf{v}) ' \mathbf{P} \]
Combining the above, we conclude
\[ \mathbf{P} \mathbf{J}_{\{x, y, z\}} \mathbf{P}\]
has three eigenvalues: one eigenvalue equal to 0 with corresponding eigenvector \( \mathbf{v}' \) and two more eigenvalues equal to the covariance axes of the projection into the tangent plane at \((x_e, y_e, z_e)\) of the original covariance matrix \( \mathbf{J}_{\{x, y, z\}} \). Denoting these two covariance axes as \( \text{eig}_1 \) and \( \text{eig}_2 \), we estimate the circular error probable (CEP) as
\[ \frac{3}{4} \sqrt{ \text{eig}_1 (\mathbf{J}_{\{x, y, z\}})^2 + \text{eig}_2 (\mathbf{J}_{\{x, y, z\}})^2} \]

**Examining the Covariance Matrix \( \xi \)**

Examining the Covariance Matrix Nothing in our derivation for CRLB estimates from section 2 speaks to characterizing noise in our readings. The decomposition in equation 2.3 allows us to build that characterization into an analysis of the matrix \( \xi \) (which is fortunate since \( \xi \) is the only component of the total CRLB estimate we have not yet addressed). To begin the process of building \( \xi \) appropriately for our mission, we first consult [12]. This work offers straightforward calculations for the standard deviation in TOA and FOA (\( \sigma_{T, \text{Stein}} \) and \( \sigma_{F, \text{Stein}} \), respectively) owing to information-theoretic bounds. We denote excess bandwidth for our target signal by \( b_e \), and symbol rate by \( b \) (so that the RF bandwidth is \((1 + b_e) b \)). By \( \gamma \) we mean the effective signal to noise ratio (SNR) in the noise bandwidth \( B \) measured at the receiver. If we assume a noiseless matched filter, effective SNR is \( 2 \gamma \), where \( \gamma \) is the SNR in the noise bandwidth \( B \) at the receiver. (For the purposes of Stein’s equations, we may use any value \( B \geq (1 + b_e) b \) provided \( \gamma \) accurately measures SNR in \( B \).) We assume matched filter processing to determine TOA and FOA values, and we use \( T \) to mean the integration time of the matched filter.

\[ \sigma_{T, \text{Stein}} = \frac{\sqrt{3}}{(1 + b_e) b \pi T} \sqrt{B T \gamma} \]
\[ \sigma_{F, \text{Stein}} = \frac{\sqrt{3}}{\pi T} \sqrt{B T \gamma} \]

(We do follow Stein’s simplifying assumption that the receiver shapes its spectrum rectangularly.)

The standard deviation values \( \sigma_{T, \text{Stein}} \) and \( \sigma_{F, \text{Stein}} \) are lower bounds, and many factors may contribute to variance in TOA and FOA estimation beyond purely information-theoretic ones. GPS product literature will give estimations under various assumptions for RMS time error and short-term error clock stability. For our calculations, having not chosen specific hardware for GPS-governed RF reception hardware at this juncture, we use the figures \( \text{err}_{t, \text{clk}} = 20\text{ns} \) and \( \text{err}_{t, \text{clk}} = 5\text{Hz} \) at 10GHz, respectively, having plucked those terms from an informal product survey. Separately, error in GPS readings for position and velocity contribute to error in our position estimates, and we can capture those errors as contributors to offsets in TOA and FOA. Reading-to-reading error in position and velocity is highly correlated to reading-to-reading time and frequency stability error, and, in theory, it is possible to estimate satellite position and velocity more precisely than reading-to-reading GPS estimation allows, clauding the responsible course of action for incorporating these error terms. We leave atmospheric and implementation-specific noise off the table for discussion, noting it, too, can be error in our estimates. Rolling these errors into one catch-all term for each of our TOA and FOA estimates, and asserting this term is independent of the Stein noise factors, we state

\[ \sigma_{T, \text{Stein}} = \sqrt{\sigma_T^2 + \sigma_{\text{err}, \text{clk}}^2} \] \[ \sigma_{F, \text{Stein}} = \sqrt{\sigma_F^2 + \sigma_{\text{err}, \text{clk}}^2} \]

Roughly, this approximation attempts to account for clock error and position/velocity error as uncorrelated terms (and it accounts for nothing else). It’s worth reflecting on this decomposition before moving on to the construction of \( \xi \), as the HawkEye mission will include efforts to reduce both components in an effort to squeeze our system for geolocation accuracy. The Stein component expresses information-theoretic limits, and ultimately, the bandwidths, center frequencies, and signal durations within the purview of combinations of the HawkEye receivers (however that purview is defined in terms of SNR drop off as slant ranges vary across the shared footprints of the receivers) will impose limits to the mission’s resolving power. Achieving or approaching the stated limits by maximizing usable integration time and SNR in matched-filter processing, especially in the context of smallsat-domain STWAP (both for onboard processing and downlink/crosslink throughput) is not straightforward. Both in terms of DSP implementation and RF front-end engineering, the mission will involve
making trade-offs and pushing the edge of the possible in DSP processing with software. Similarly, the Pathfinder mission will require focused analysis on error terms in the TOA and FOA estimates not owing to Stein. We will measure and leverage correlations in error terms contributing to $\sigma_{\text{TOA},i}$ and $\sigma_{\text{TOA},j}$ driving out systematic error and containing implementation error. Understanding and reducing terms contributing to $\sigma_{\text{TOA}}$ and $\sigma_{\text{FOA}}$ gives us the only power we have to improve our product, since $\xi$, and, ultimately, the system's CRLB values depend entirely on these numbers.

We ascribe TOA and FOA estimates to each satellite individually: $\sigma_{\text{TOA},i}$ and $\sigma_{\text{FOA},i}$ for $i \in \{1, 2, 3\}$. Deriving $\tau_{\text{DOD}}$ and $\tau_{\text{FDOA}}$ from TOA and FOA estimates is additive, and we assume error terms $\sigma_{\text{TOA},i}$ and $\sigma_{\text{FOA},i}$ are uncorrelated when $i \neq j$. The standard deviation in TDOA and FDOA between any two satellites is thus

$$\sigma_{\text{TDOA}} = \sqrt{2 \sigma_{\text{TDOA}}^2}, \quad \text{and} \quad \sigma_{\text{FDOA}} = \sqrt{2 \sigma_{\text{FDOA}}^2} \quad (3.5)$$

On the other hand, $\tau_{1,2}$ and $\tau_{1,3}$ share noise from a receiver (half of the total noise contribution) in common, so

$$T_{\text{cov}} = \begin{bmatrix} \tau_{1,2} \\ \tau_{1,3} \end{bmatrix} = \begin{bmatrix} \sigma_{\text{TDOA}}^2 & \sigma_{\text{TDOA}}^2 \\ \sigma_{\text{TOA}}^2 & \sigma_{\text{TDOA}}^2 \end{bmatrix}. \quad (3.6)$$

Similarly,

$$F_{\text{cov}} = \begin{bmatrix} \tau_{1,2} \\ \tau_{1,3} \end{bmatrix} = \begin{bmatrix} \sigma_{\text{FDOA}}^2 & \sigma_{\text{FDOA}}^2 \\ \sigma_{\text{FOA}}^2 & \sigma_{\text{FDOA}}^2 \end{bmatrix}. \quad (3.7)$$

To complete our construction of $\xi$, we assume (along with [6] and others) that FDOA and TDOA measurements from the same pulse are uncorrelated:

$$\xi = \begin{bmatrix} T_{\text{cov}} & 0 \\ 0 & F_{\text{cov}} \end{bmatrix}. \quad (3.8)$$

**Blind Coherent Integration**

Blind Coherent Integration (BCI) is a proprietary algorithm developed by HE360. BCI is capable of generating significant processing gain, which enables geolocation of emitters with impressive accuracy. BCI is particularly effective for signals whose Signal to Noise Ratio (SNR) is too low to be processed using traditional TDOA and FDOA techniques.

**MODELING AND SIMULATION**

**Link Budgets**

A number of Signals of Interest (SOIs) are evaluated to determine their viability in aiding geolocation from the Hawk cluster. The cluster payloads will nominally be capable of receiving frequencies between 70 MHz and 6 GHz. The upper end may be extended to 15 or 18 GHz through the use of one or more Low Noise Block down-converters (LNB).

The SOIs are very diverse in nature: with different bandwidths, RF power, baud rates, modulation schemes, Forward Error Correction (FEC) codes, etc. Not all terrestrial signals will be viable for the Pathfinder mission. RF link budgets for various SOIs will determine their individual viability. The metric for viability is generally SNR. To collocate a specific SOI, the received SNR must exceed a threshold. The threshold SNR will be frequency dependent and will also depend on the payload antenna being used. As will be shown, the SNR is also very important to the geolocation error.

<table>
<thead>
<tr>
<th>Table 1: AIS Summary Link Budget</th>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
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<tr>
<td>Orbit Altitude</td>
</tr>
<tr>
<td>Slant Range (e=1°)</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Emitter Transmit Power</td>
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<tr>
<td>Transmit Gain (+ Losses)</td>
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<td>Free Space Loss</td>
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<td>Receiver Noise Figure</td>
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<td>Receiver Noise Bandwidth</td>
</tr>
<tr>
<td>Data Rate</td>
</tr>
<tr>
<td>Received Power</td>
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<tr>
<td>SNR (C/N0)</td>
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**Simulations**

Several dynamic simulations were developed which include Hawks in various candidate formation geometries. An orbit propagator is utilized to model the spacecraft movement. Terrestrial RF emitters of various types are also modeled. Candidate geolocation algorithms are evaluated using the received signals at each simulated Hawk. Simulations are developed in Python and make use of other open-source numerical libraries including NumPy and SciPy. The individual geolocation algorithm simulations are further described in the subsequent sections.

**Sources of Error**

Several error sources are modeled in the simulations. Thermal noise is a significant source of error. This is modeled by Seymour Stein’s equations. The Stein
errors include a time error and frequency error term, both measured as 1-sigma standard deviations. The time error is nominally measured in nanoseconds (ns) and the frequency error in hertz (Hz). These errors effectively impair our ability to accurately measure the Time of Arrival (TOA) of a signal and are a major contribution to our final geolocation accuracy capability.

Another source of error will come from the spacecraft GPS receivers, which will measure the state vectors of the Hawks continuously during payload operations. These state vectors are important to the TDOA and FDOA calculations since the relative range and range rates between the Hawks and emitter are fundamental to many algorithms. This GPS error component will likely be less than 10 m and 1 cm/sec or around 20 ns. It is clear that Stein’s error dominates GPS error for the example SOI.

There are additional sources of error that will contribute to the final accuracy of geolocation solutions. Some errors may be measured empirically and other must be modeled. Atmospheric errors, including tropospheric and ionospheric errors can be modeled and corrected for to some extent. Further corrections may be possible by using information from known emitters on the ground.

**TDOA and FDOA Simulations**

TDOA and FDOA measurements are simulated based on the relative range and range rate between the Hawks and the emitter. Applicable error sources are applied to the measurements. The final noised measurements are applied to the TDOA, FDOA or combined TDOA/FDOA geolocation algorithms and a geolocation estimate is derived. The estimate is compared to the known emitter location to determine the residual error.

Monte Carlo simulations repeating the above simulation for thousands of random targets and random times demonstrates the range of precision available over relative cluster to target geometries and formation geometries. This is demonstrated more succinctly using CRLB Maps in a subsequent section.

**ORBIT**

The HE360 Pathfinder cluster is targeting a Sun Synchronous Orbit. Actual beta angle is not important to the mission (though certain angles would be more or less favorable for the power budget). SSOs represent the majority of secondary launch opportunities and the polar nature of the orbit provides for frequent download opportunities at polar earth stations.

The orbits should be nearly circular and altitudes between 550 km and 650 km are ideal. At lower altitudes than 550 km, the mission lifetime begins to suffer from atmospheric drag. For this reason, at this time, HE360 is not considering ISS deployment opportunities, though we understand that new orbit-raising opportunities are being developed. Altitudes above 650 km are not desirable for a number of reasons, foremost among them being the increased difficulty in meeting the 25 year de-orbit criteria.

The orbits should, in general, be J2-invariant so as to minimize the delta-v budget for formation maintenance. This will be discussed in more detail in the subsequent sections.

**FORMATIONS**

There are multiple formations of Hawks being evaluated for performance relative to our geolocation algorithms. Some initial options are described here.

**Non-Coplanar Oscillator**

The Non-Coplanar Oscillator (NCO) formation is defined by all three Hawks in circular orbits, with two of them being co-planar and the third with an offset plane. The third Hawk’s offset plane can be accomplished with either a change in inclination or RAAN. If the change is effected with RAAN, then the orbits can be J2-invariant, which is desirable. J2-invariant orbits are designed such that perturbations due to the non-spherical nature of the Earth are minimized. These controlled-perturbation orbits will not drift apart, reducing the cost of formation control.

An example delta-v budget for a simple NCO formation is provided in Table 1. This formation is based on a 40 km baseline, with a 1 km offset to the cross-track vehicle.

<table>
<thead>
<tr>
<th>Source</th>
<th>Drift Recovery</th>
<th>Initialization</th>
<th>Maintenance</th>
<th>ΔV Required</th>
<th>ΔV Available</th>
<th>Margin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawk-1</td>
<td>5.00</td>
<td>1.68</td>
<td>28.08</td>
<td>34.76</td>
<td>100</td>
<td>65%</td>
</tr>
<tr>
<td>Hawk-2</td>
<td>5.00</td>
<td>1.68</td>
<td>22.23</td>
<td>28.91</td>
<td>100</td>
<td>71%</td>
</tr>
<tr>
<td>Hawk-3</td>
<td>5.00</td>
<td>0.00</td>
<td>0.00</td>
<td>5.00</td>
<td>100</td>
<td>95%</td>
</tr>
</tbody>
</table>

**Natural Motion Circumnavigation**

Natural Motion Circumnavigation (NMC) is a more complex formation where all three Hawks are in...
Projected Circular Orbits (PCO) around a 4th Virtual Satellite (VS) in the center. The advantage of this formation is that the Hawks never form a co-linear geometry. By phasing the Hawks carefully, the formation can maintain optimum geometric diversity across the whole orbit, which positively affects the geolocation accuracy of the formation.

**Co-Planar**

A co-planar formation is one where all three Hawks are in the same plane, but phase separated within that plane by offsets in true anomaly. This is the most inexpensive formation in terms of delta-v, but the worst in terms of geometric diversity.

**TDOA / FDOA Impacts**

Although it has been noted that an all-co-planar satellite formation is undesired, this is primarily for a TDOA-only solution. If however, FDOA information is used in the geolocation algorithm, then the combination of TDOA and FDOA information yields a good solution, even in the event of a momentary co-linear geometry. This is because as the third Hawk crosses between the two others, briefly becoming co-linear, there still remains some (maximal, actually) velocity diversity between the Hawks, which contributes to an FDOA solution.

Therefore, both inclination and RAAN-offset formations should perform nearly identically across all latitudes. However, the J2-invariant property of the RAAN-offset formation still makes it the preferred formation. NMC is likely superior to all formations with respect to geolocation error, but again has the disadvantage of requiring more delta-v overall.

**CRLB Maps**

CRLB maps are created to show the effect of formation geometry on theoretical geolocation accuracy for a formation. For the figures below, an NCO formation with a 250 km baseline and 10 km cross-track offset for Hawk-3 is assumed. The emitter is an AIS beacon and one pulse is presumed during the pass. SNR varies according to the slant range from the Hawks to the emitter locations. The CRLB surface for the cluster when over the equator is shown in Figure 2 and over the North Pole in Figure 3. Figure 4 depicts an equatorial pass, but with 9 AIS bursts assumed. One may observe that by incorporating multiple bursts, the CRLB is lowered dramatically (an order of magnitude in this case), significantly improving the chances of a high-precision geolocation for the emitter.
SPACECRAFT

HE360 is primarily a signal processing and analytics company rather than a space company; so to a large extent, the spacecraft itself is being outsourced. DSI and SFL are providing the spacecraft components and services.

Figure 5: NEMO-15 Bus

Spacecraft Bus

The Pathfinder spacecraft are based on SFL’s NEMO-15 bus. This bus does not conform to a standard cubesat form factor and therefore is most accurately described as a microsatellite. However, the available volume in the bus can be approximated at 20 liters or 20U. The spacecraft mass can be much greater than a cubesat of similar size, but for the Pathfinder mission, it will be less than 15 kg.

The NEMO-15 bus is also being used by several other teams, including GHGSat-D, NEMO-AM, and NORSATS 1 and 2.

Communications

Command and control of the spacecraft will be accomplished using a UHF low-rate uplink and an S-Band downlink.

Payload data is downloaded from the spacecraft at either S-Band or X-Band. The S-Band transmitter is provided by SFL and is based on a heritage design flown numerous times. It has a controllable rate from 32 kbps to 2 Mbps. The X-Band transmitter is a Syrlinks EWC27 system capable of 3 – 50 Mbps usable data rate. The Syrlinks transmitter uses Offset Quadrature Phase Shift Keying (OQPSK) and a ½ rate convolutional encoding Forward Error Correction (FEC) scheme.

The majority of payload data can be downloaded at lower rates and with parabolic dish sizes around 3.7m with positive link margin. Occasional use of the higher bandwidth options may require a larger dish.

A low-rate S-Band inter-satellite link is also available. Although it is not required for the mission, it may be used 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 of the spacecrafts’ measurements reside on a single spacecraft where the geolocation algorithm can be solved.

Propulsion

DSI is providing an electro-thermal propulsion system that uses liquid water as the working fluid. The unit has an estimated $I_{sp}$ of 200 seconds, giving it exceptional performance with comparison to a typical cold-gas system. Conversely, while it has a lower $I_{sp}$ than newly available low-power electric propulsion systems, the higher thrust means that DSI’s system can be used 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 our RF payload.
The propulsion system has an easily expandable propellant tank, allowing up to 100 m/s of delta-v in the available volume. 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 available to augment this in an emergency.

**SDR PAYLOAD**

Each spacecraft will have an identical SDR payload. The payload is a custom-implementation of a Commercial Off-The-Shelf (COTS) SDR used commonly for terrestrial use. The SDR consists of three high-level components: An embedded processor and FPGA resource, a baseband signal processor, and a custom-RF front-end with antennas.

The baseband processor will be built around the Analog Devices 9361 or 9364 products. These are highly integrated RF transceivers that combine high-speed ADCs and DACs, RF amplifiers, filtering, switching and more on a single chip. The 9361 has two receive chains and two transmit chains, while the 9364 provides a single receive and transmit chain pair. The transceiver products are capable of tuning from 70 MHz to 6 GHz, with an instantaneous bandwidth of up to 56 MHz.

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.

The custom-RF front end connects to the baseband processor and provides a number of unique, switchable RF paths and antennas to support a range of bands and frequencies of interest. A range of antennas, including quarter-wave dipoles, patches and even a wide-band horn are envisioned to support the full frequency range. The processor system will take advantage of open-source signal processing software and firmware to maximally mimic desktop SDR products. This will allow 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 will be used. GNURadio is “a free and open-source toolkit for software radio.” In operation, the payload can be commanded to tune the baseband processor to a center frequency and stream samples at a given sample rate. In normal use, 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.

Initially, we will implement most of these processes in software, using GNURadio. GNURadio software and surrounding packages feature several technologies enabling accelerated performance on ARM-based processing systems. A number of the most common DSP routines for signal processing and datatype manipulation already have aligned, vectorized GNURadio implementations using NEON instructions through the VOLK (Vector Optimized Library of Kernels) libraries used by GNURadio processing blocks. However,

Typically, the result of a GNURadio or FPGA signal processing chain will return to the embedded processor or to some form of onboard memory.

**LAUNCH**

At the time of this writing, HE360 is considering multiple launch opportunities for a late 2017 launch, targeting SSOs between 500 and 600 km. All three Hawks will be launched together and deployed as close together as possible. Although unlikely, an extra cross-track boost for the third vehicle would be welcome to reduce the Hawk’s own necessary plane change maneuver.

**GROUND SEGMENT**

**Ground Stations**

The Pathfinder mission will utilize commercial earth station services. At the time of this writing, HE360 was in the process of evaluating a number of providers. Nominal payload operations should be supported by the commonly available 3.7m dishes that make up the recent small satellite earth station offerings.
The authors also have considerable experience in building and maintaining a global SDR-based earth station network. It is likely that at some point, HE360-owned antenna sites will be deployed – the first of which will be at the company headquarters in Herndon, VA.

**Signal Processing**

While some signal processing will be performed onboard the Hawks, other processing algorithms and geolocation techniques, especially those using data from combinations of receivers, will require implementations for ground processing. Ground-based processing solutions will leverage a wealth of convenient scientific code packages more suited to the cloud environment than an embedded processor. GNURadio applications port well to multiprocessor environments and even clusters of shared memory multiprocessor systems, moving data across system boundaries with the help of software such as ZeroMQ. Other tasks, including much of the geolocation work, will rely on NumPy, SciPy and a universe of available routines and algorithms in Python. The BCI algorithm, in particular, may have outsize computational requirements necessitating implementation on GPU. HawkEye will look to access GPU hardware through TensorFlow, Theano and other preexisting tools.

**Analytics**

Although data collection and processing bring HawkEye into the smallsat business sector, the company’s overall mission rests, at least in part, on deriving value from that data. HawkEye has begun building an analytics component founded on three bases. All three of these bases grow out of advances in the internet economy.

First, many companies participating in this economy have open-sourced powerful tools to digest, manipulate, and mine in real time increasingly vast volumes of data. HawkEye has built an analytic pipeline from software projects such as Kafka, Storm (with StreamParse) and MongoDB. We have emphasized stream processing for low-latency analytics: many of the harder and more rewarding problems we aim to tackle involve time-sensitive geolocation estimates and RF survey activities. HawkEye is not unique in using and understanding these data-analytic tools, and, in many ways, that’s the point. HawkEye understands many of the customers for its data and data-analytic products will not be just data producers or just data processors or just data consumers. Most customers in the data economy will play roles in all three categories, and interacting with those customers will require interfacing with their systems at arbitrary points along the data-production pipeline. By sticking to well-documented, widely used and widely available software pipeline tools, HawkEye aims to make it easier for our system to interface with other, perhaps similar, systems, creating a more valuable whole.

To consider flexibly combining data pipelines leads to the second of three bases for the HawkEye analytics component: data (and the information we derive from data) rarely provides value absent other data. HawkEye has built and continues to build its systems expecting to perform data fusion and to feed other systems performing data fusion. In the narrow sense, HawkEye ascribes value to its RF data sources insomuch as those data sources can augment partners’ (Synthetic Aperture Radar (SAR) and imaging) data collection systems. An RF geolocation service may not extract every detail of value from an observable scenario, but it may help point another system more precisely at an observable scenario of value. In the wider sense, HawkEye expects to combine its RF data with other sources (scraped web data, photographs, radar images and analytics produced by customers and partners) to derive value.

Deriving value from data fusion will mean leveraging machine learning, the third of three bases for the HawkEye analytic component. Machine learning software such as OpenCV, TensorFlow and Intel’s PNL have become increasingly capable and accessible, while applications such as self-driving cars and DeepDream have energized academia and tech industry participants to produce more people capable of using those software packages. Although a surprisingly narrow array of machine learning techniques can sometimes apply to a surprisingly diverse set of problems, HawkEye makes no claims concerning the development of single algorithms suitable to all geospatial data problems generically. Nor does HawkEye intend to plumb the depths of just one machine learning technique, applying it to all problems equally. HawkEye will single out specific problems of interest, develop expertise in the conditions causing those problems, and make realistic assessments concerning machine learning approaches to automating solutions.

**CONSTELLATION**

Following the successful demonstration of the Pathfinder mission, HE360 intends 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.

![Figure 8: Example 18 Satellite Constellation Revisit Rate Map](image)

A number of lower cost dedicated launch vehicles such as Rocket Lab USA’s Electron will be available within a few years. Such launch opportunities afford the possibility to further tailor orbit selection, making it possible to better target the constellation to a region of interest at a reasonable cost.

TERRESTRIAL DEMONSTRATIONS

Leading up to the Pathfinder mission, which will launch no earlier than Q3 2017, HE360 will demonstrate early versions of the payload, signal processing and geolocation algorithms with a number of ground and aerial tests.

FUTURE WORK

Further study of the sources of geolocation error and their estimation is one area where significant future work is planned. It is understood that there are several additional error components that are not incorporated in the current simulations. These include: emitter motion and atmospheric delays.

The link models include some basic information about the antenna patterns of the emitter and the receivers, but future work will model these antenna patterns more robustly. This will serve to provide more realism in geolocation simulations and to better derive requirements for payload antennas.

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