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Emergency Locator Signal Detection and Geolocation Small Satellite Constellation Feasibility Study

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ABSTRACT

Aircraft Emergency Locator Transmitters (ELTs) are vital in helping search and rescue (SAR) teams in locating downed aircraft. Currently there are two types of ELTs available; one transmits at 121.5 MHz and the other at 406 MHz. The transmitters operating at 121.5 MHz have since been abandoned by satellite tracking systems even though these beacons are still available for non-commercial aviation use. Space based receiver decommissioning of 121.5 MHz systems was largely due to an inefficiency of the Very High Frequency (VHF) transmitter beacons; which have a 97% false alarm rate and only provide aircraft location within approximately 20 km of the transmitter. 406 MHz ELTs replaced the old VHF system but many do not broadcast GPS location data. While the Federal Aviation Administration (FAA) mandates all commercial air traffic use the 406 MHz transmitters, many privately owned aircraft still utilize 121.5 MHz and non-GPS 406 MHz ELTs. Small satellites have the capability of providing global coverage for a geolocation SAR constellation due to their low-cost and easily duplicated platform. This study assesses several identifying factors and risks regarding the implementation of such a small satellite SAR system that supports ELTs. Results from this study show that the need for an emergency locator signal detection and geolocation constellation can be seen as a low-cost solution to the current need for a 121.5 MHz and 406 MHz ELT detection system.

BACKGROUND AND OBJECTIVES

The current search and rescue satellite system, known as Cospas-Sarsat, provides support for not only aircraft ELTs but Emergency Position-Indicating Radio Beacons (EPIRB) for maritime distress as well as Personal Locator Beacons (PLB). Legacy hardware for each of the three beacons formerly operated at 121.5 MHz and has since moved to the new frequency of 406 MHz. All Cospas-Sarsat satellites' on-board receivers for the 121.5 MHz frequency were turned off in February of 2009, discontinuing any further support of older beacons from a space-based platform. This system still provides support for all three types of beacons operating at 406 MHz and was used as an initial baseline in this study.[1]

Cospas-Sarsat consists of both geostationary and polar orbiting spacecraft, designated LEOSAR and GEOSAR. NOAAs Polar Orbiting Environment Satellites (POES) make up most of the LEOSAR portion and are most relevant to this study. Both LEOSAR and GEOSAR systems combine with local user terminals to allow Cospas-Sarsat to be able to provide global coverage for all three types of ultra high frequency (UHF) emergency transmitters operating at 406 MHz.[2]

A shortfall of this system is that the satellite segment contains large and very expensive spacecraft. Because of this cost gap, LEOSAR can only provide coverage based on the limited number of satellites in orbit. If replacement satellites are needed they will have to be much lower cost while still providing the same functionality. A lower cost also enables more satellites to be placed in orbit. Subsequently increasing global coverage and revisit times, allowing SAR teams a quicker response while not solely relying on the GEOSAR portion of Cospas-Sarsat; the CubeSat platform is ideal in fulfilling these criteria.

In terms ELTs, it is estimated that over 170,000 aircraft around the world still operate older 121.5 MHz beacons. This causes an increase in the time it takes SAR and civil air patrol teams to respond to an aircraft emergency involving older beacons; further showing a need for legacy transmitter support.[1]

The objectives of this study are to first ensure need for a small satellite constellation supporting legacy 121.5 MHz as well as non-GPS capable 406 MHz emergency beacons. This is a key mission risk as the legacy beacons may be completely replaced when newer beacons become cheaper, more readily available, and include GPS information by design. Next, an initial receiver concept will be discussed as well as a CubeSat bus that will support this receiver payload. Because of the constellation nature of this mission the bus must also be able to be mass produced at an inexpensive rate. Each satellite will need to be constructed in a quick time frame for maximum mission applicability towards both frequencies. Finally, this study will look at the constellation orbital parameters best suited for fulfilling current mission requirements.

REQUIREMENTS

This concept study shall utilize and adhere to the performance requirements for a Detection and Geolocation Satellite Constellation (DGSC), stated below: [3]

- The DGSC coverage region shall be defined as the surface of the Earth between 70° N latitude to 70° S latitude.
- The DGSC shall detect 121.5 MHz, 0.1 W and 406 MHz, 5 W ELT signals originating in the coverage region.
- The DGSC shall estimate beacon position within 1 km and communicate this data to local user terminals within 15 minutes of signal detection.
- The DGSC shall provide a revisit period within 60 minutes to all points inside the coverage region.
- The average mission duration of each DGSC satellite shall be 12 months.
- The design life of each DGSC satellite shall be 18 months.

Additionally, each DGSC satellite must meet CubeSat specifications and de-orbit 25 years after the 18 month lifetime as designated by US National Policy.

MISSION RISKS

Mission risks include those that could limit the feasibility of the success from a mission standpoint. Using already developed resources from an existing CubeSat program will greatly drive down any mission development risks. However, some risks still exist; the paragraphs below describe the impact that each risk has on the mission and schedule as well as a proposed mitigation to prevent the risks from affecting the program.

Mission Applicability

The greatest risk to this mission is the diminished demand for VHF locator beacons. Since consumers are now purchasing the 406 MHz ELTs instead of the 121.5 MHz beacons, the 121.5 MHz ELTs may be considered to be obsolete and could potentially be phased out by all users. Although it is mandatory for commercial and Department of Defense aircraft to switch to the 406 MHz frequency, many private aircraft are also switching to this new frequency, as it is supported unlike the 121.5 MHz.

Like the analog to digital television broadcasting switch that occurred in June 2009, it is expected that the switch from the analog 121.5 MHz ELT to the digital 406 MHz ELT will occur in the future where the analog frequency will no longer be utilized. Because of such a risk, the time to prepare the spacecraft with dual payload capability may be insufficient. It has been proposed by the Federal Communication Commission (FCC) to outlaw the use of 121.5 MHz emergency beacons. Although they have been unsuccessful, and have currently dropped the proposed ban, the question still remains as to how long the monitoring of 121.5 MHz beacons will be useful.[4]

Currently, there are not enough 406 MHz beacons available to fill the equipment gap if all aircraft were mandated to switch to the new frequency.[5] Therefore, it is irrational to assume ban of the 121.5 MHz ELTs as this would ground several thousand aircraft. Furthermore, even though this frequency is no longer supported by Cospas-Sarsat (or an alternative space based system). Other organizations, such as the Civil Air Patrol, continue to monitor this frequency indicating that there is still a need to monitor ELTs at 121.5 MHz. This further supports a need to monitor both frequencies.

Even though the 121.5 MHz analog frequency will eventually be phased out completely, in comparison to the analog to digital television conversion, even after the discontinuation was approved it took over 2.5 years past the intended deadline for actual phase out to occur.[6] A similar setback may be expected in any ELT switchover.

To ultimately determine if the inclusion of the 121.5 MHz frequency is feasible, a study should be performed to forecast the usage rates of each frequency in the near and long term.

Software

Existing software may be available or in development to use for ground stations and normal subsystem operations aboard the spacecraft bus. Issues could arise when porting prior software to a new platform since the original hardware drivers may have been updated over time and may cause new bugs in the pre-existing state. If issues were to arise with the use of software in this way, it may cause setbacks to an already advanced schedule. Early porting of these drivers may help reduce the schedule impact as issues will be determined in advance and personnel can provide attention early in the programs development. Software for the receiver payload must be created and tested early on as the algorithms used for direction-of-arrival estimation will need to be defined.

Spacecraft Components

Commercial-off-the-shelf (COTS) components may not be able to withstand the space environments. Many COTS electrical components do not have space radiation performance data available causing early failures or intermittent disruptions, resulting in a loss of mission data. The use of radiation tolerant electronic components may help to reduce the loss of electrical failure due to component characteristic changes or degradation. Considering these issues when designing or purchasing flight COTS systems will help to reduce this risk.

Bus

Using the standardized CubeSat bus places certain restrictions onto the spacecraft. The size is limited to 10 cm × 10 cm × 30 cm with a maximum mass of 4.0 kg. Due to these limitations, it is necessary to keep size and mass restrictions in consideration. A mass budget will need to be developed with estimates of each subsystem mass, along with the assigned margins depending on system maturity. Also, the volume within the spacecraft needs to be closely monitored as systems are developed. This is most easily be performed using a solid modeling tool, where accurate 3D electronic models of each subsystem will be pieced together before, during, and after assembly of the spacecraft.

The power system design for the spacecraft is also limited by the form factor with the amount of power the spacecraft can produce as well as the amount that can be stored aboard the spacecraft. The power consumption for each system will be tracked, with margin, to ensure that the spacecraft could survive for the mission life duration.

MANAGEMENT RISKS

Management risks are those that could limit the success of the satellite mission from a program management standpoint. There are standard management risks which are associated with this mission including: scheduling, cost, and the management of subcontractors. The most important risks to this mission are ability to manage the costs associated with the spacecraft development and to ensure a quick delivery date.

A quick development of each spacecraft is essential to the overall mission timeline. To accomplish this, the use of commercial parts is necessary to reduce development time of the overall satellite bus. Components are available for purchase from several vendors nationally and internationally alike. These COTS parts should be utilized as frequently as possible to keep the cost low. Management must coordinate with these vendors to ensure an on-time delivery of each component.

RECEIVER PAYLOAD

The receivers proposed for the 121.5 MHz and 406 MHz frequencies are superheterodyne convertors with Digital Signal Processing (DSP) demodulation. This will permit the use of low cost analog radio electronics and still achieve the narrow noise bandwidths and usable link margins needed. Another advantage to making the radio partly software defined is that the personality and performance may be modified with DSP software updates, allowing for improvements over the mission lifetime.

Link analysis was done for both frequencies using STK and an AMSAT link budget Excel sheet developed by Jan King.[7] Each link budget method assumed an 800 km circular orbit with a 70° inclination and a 5° minimum elevation angle at the ground transmitter. These orbital parameters, specifically the altitude, were used to assume worst case link quality.

Geolocation is determined by using a synthetic linear array technique with a direction-of-arrival (DOA) algorithm. The synthetic linear array is essentially an antenna array created by combining the velocity measurement from an onboard GPS receiver with a Fast Fourier Transform (FFT) of the retrieved distress signal. While the satellite passes over the beacon multiple FFTs are processed, creating the synthetic array. From this array a bearing angle can be obtained, enabling a line of bearing to the distressed target to be output to local user terminals. Hence, a single pass from one satellite will output this line of bearing estimate for the broadcasting ELT. Location is achieved by the three or more passes from multiple satellites in the constellation. The more passes reduces the amount of error in the location estimation.

The nature of the signal processing method used to form the array results in an equivalent noise bandwidth that is much smaller than the radios intermediate frequency (IF) bandwidth. This is paramount to achieve a usable link budget as is outlined below.

121.5 MHZ RECEIVER

The 121.5 MHz beacon signal uses A3X modulation; this consists of an amplitude-modulated carrier with audio frequencies sweeping from 1600 Hz to 300 Hz.[8] The sweep is referred to as a "chirp" and is illustrated with Figure 1 below.

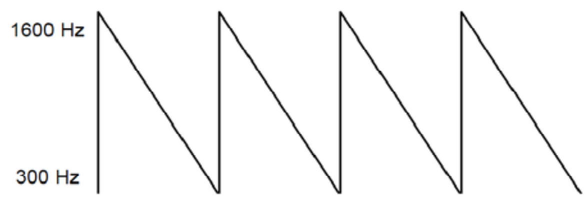

Figure 1: 121.5 MHz ELT Chirp

Bearing determination for 121.5 MHz relies on the ability to recover the chirp signal. Therefore the easiest way to correlate bearing determination to signal quality is the signal-to-noise ratio (S/N). This ratio is defined by the receiver's bandwidth (R_{BW}) using the equation below.

$$S/N = P_{s(dBW)} - K + 10\log(T_{sc}) + 10\log(R_{BW})$$

Where $P_{s(dBW)}$ is the signal power at the receiver input terminal, T_{sc} is spacecraft noise temperature, and K is Boltzmann's constant, also expressed in dBW (-228.6 dBW/K/Hz).[7]

The receiver bandwidth was used in both 121.5 MHz and 406 MHz link calculations and is traced out using Figure 2, the linear receiver noise model; each bandwidth stage is discussed in the following paragraphs.[9]

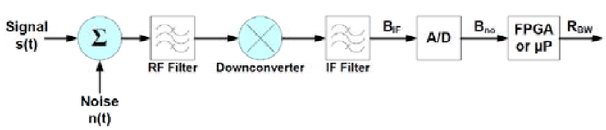

Figure 2: Receiver Noise Model

First, the minimum intermediate frequency bandwidth (B_{IF}) can be calculated (shown below) by finding the carrier frequency stability and adding it to the highest modulation frequency, this calculation assumes an oscillator stability of ~50ppm.

$$B_{IF} = 2 \cdot (121.5\ \text{MHz})(50\ \mu s) + 2 \cdot (1.6\ \text{KHz})$$

$$B_{IF} \approx 15\ \text{KHz}$$

Since the receiver uses DSP demodulation an analog-to-digital converter (A/D) will provide information for the next bandwidth stage. The output of the A/D, receiver noise bandwidth (B_{no}), can be calculated by simply taking twice the maximum audio frequency of 1.6 kHz, yielding 3.2 kHz. As the maximum audio frequency is mainly determined by the chosen A/D, this value may be subject to change based on the part specification, though 1.6 kHz is well within current technology limits for this design.

After the digital signal comes out of the A/D it will go through an FFT as part of the DOA processing. This processing will be accomplished through the use of a Field Programmable Gate Array (FPGA) or microprocessor. This type of signal processing will also decrease the equivalent receiver noise bandwidth (B_{no}) to the resolution bandwidth of the FFT (B_{res}) in the digital domain. The final receiver bandwidth (R_{BW}) can finally be found by applying the following equation.

$$R_{BW} = \frac{f_{sample}}{N} B_{res} = B_{no} = \frac{f_{sample}}{N}$$

f_{sample} represents the sample frequency and N is the total number of FFT points. Instead of calculating these values this study used the conservative estimate of 500 Hz for the receiver bandwidth. f_{sample} and N will need to be defined based on future testing, likely resulting in a R_{BW} that is than this estimate. A representative diagram of each bandwidth stage is shown in Figure 3. In all 121.5 MHz link calculations a receiver bandwidth of 500 Hz was used.

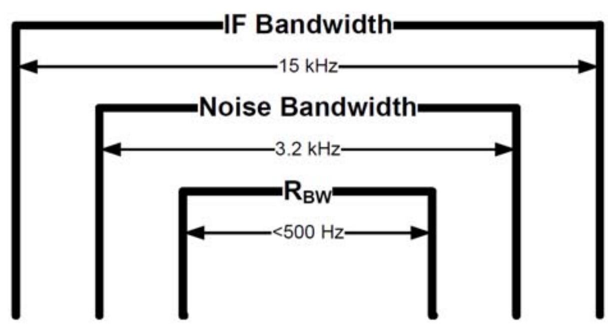

Figure 3: Receiver Bandwidth's

Figure 4 shows a diagram of the proposed 121.5 MHz receiver architecture. It may consist of a mostly COTS receiver, depending on current CubeSat transceiver specifications. This receiver will piggyback on an existing VHF half-wave dipole antenna used for command telemetry. Such a configuration allows the receiver's antenna to be modeled as a half-wave dipole with a beam-width of 60°. This beam-width will be used as the satellite ground footprint input for the constellation optimization section.

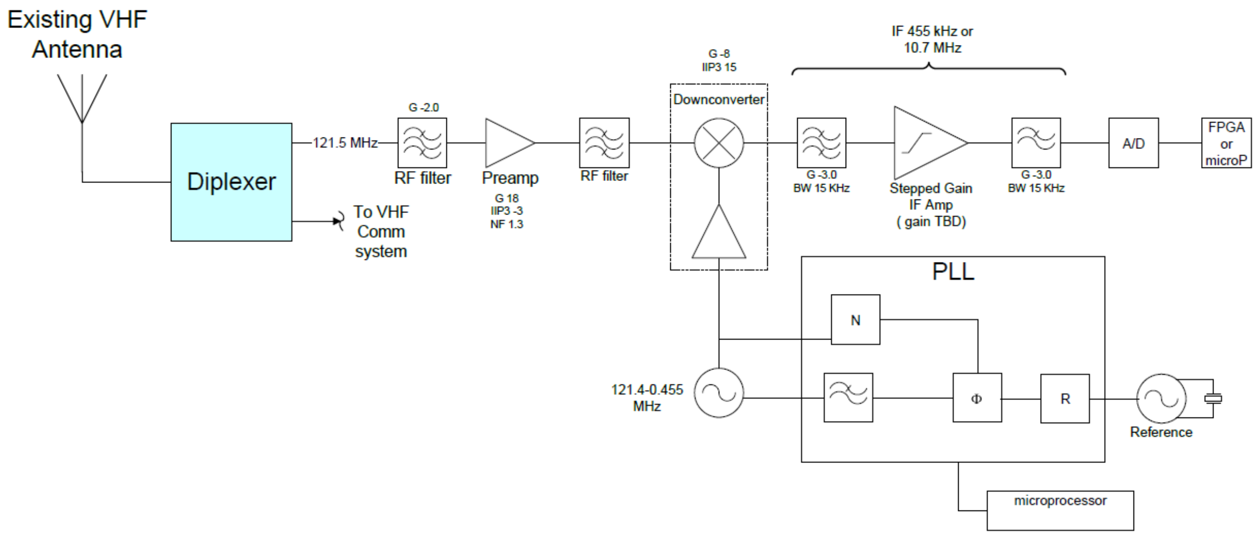

Figure 4: 121.5 MHz Receiver Architecture

A diplexer facilitates the piggyback, allowing the satellite to receive command / control signals and emergency beacon transmissions on the same antenna. From the diplexer the beacon signal passes through an off-the-shelf receiver architecture until after the IF section where the signal enters an A/D and the rest of the radio is specifically software defined. A key component being the FPGA or microprocessor, this provides chirp post processing, enabling the decrease in receiver bandwidth and DOA estimation.

121.5 MHz Link Analysis

Since the frequency chirp is an analog based signal and the FFT signal processing will produce a pulse dependant on signal quality alone. The best way to characterize the 121.5 MHz link is with the S/N method.

Table 1 shows the power seen at the receiver, gain-to-noise-temperature (G/T), and the S/N as calculated by each link tool. Both calculation methods model the ground ELT as having an isotropic antenna with a power out of 0.1 W. This analysis shows that a stable link can be achieved with a receiver noise bandwidth of 500 Hz.

Table 1: Link Budget Results, 121.5 MHz Receiver

Parameter	AMSAT Link Calculator	STK
Received Power	-152 dBW	-155 dBW
G/T	-26.3 dB/K	-24.0 dB/K
S/N	21 dB	20 dB

406 MHZ RECEIVER

The 406 MHz ELTs utilize a Bi-Phase-L type modulation transmitting for 500 ms every 50 seconds. A simple block convertor may be added to the 121.5 MHz hardware (Figure 4) and the DSP code modified to process the 406 MHz signal. This makes design considerations for this receiver slightly simpler.

Bandwidth calculations for the 406 MHz signal are slightly different since the transmitted signal uses BPSK modulation. The modulation bandwidth (B_m) is the wanted input to the link budget and is found using the spectral efficiency factor (η) for BPSK which is 0.5 bps / Hz.[9] Solving for Hz in the equation below, the modulation bandwidth is simply twice the maximum bit data rate (R) of the 406 MHz ELT, which is 404 bps.[10]

$$\eta = \frac{1}{2} = \frac{R\ (bps)}{B_m\ (Hz)}$$

$$B_m = 2R = 2 \cdot 404 = 808\ Hz$$

Thus 808 Hz is the minimum noise bandwidth of the processed signal as input to the A/D. Also needed for the 406 MHz link calculations is the receiver IF bandwidth. For this BPSK signal the minimum receiver noise bandwidth is the modulation bandwidth plus the transmitter stability of current ELT beacons, which is ±5 kHz.[10]

Since signal processing stage of the 406 MHz receiver will also use a FPGA or microprocessor, it is possible to reuse the 121.5 MHz receiver with the addition of a Block Converter to mix down the 406 MHz signal to 121.5 MHz. This design, shown in Figure 5, may again incorporate a diplexer to reduce the number of antennas needed to a maximum of two half-wave dipoles.

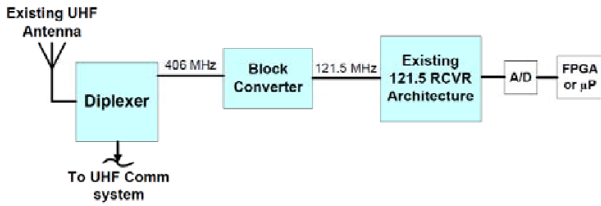

Figure 5: 406 MHz Receiver Architecture

406 MHz Link Analysis

Link calculations for the 406 MHz receiver still utilize the S/N method even though the 406 MHz signal is Bi-phase-L modulation with a five year oscillator stability of ±5 kHz, uplink side. This is because by applying similar FFT processing to 406 MHz transmissions the signal recovery becomes more reliant on a relationship between the signal strength and the noise floor. Both calculation methods in Table 2 model the ground ELT as having an isotropic antenna with a power out of 5 W.

Table 2: Link Budget Results, 406 MHz Receiver

Parameter	AMSAT Link Calculator	STK
Received Power	-150 dBW	-147 dBW
G/T	-23.4 dB/K	-23.0 dB/K
S/N	25 dB	25 dB

SPACECRAFT CONFIGURATION

The basic spacecraft configuration will consist of primary functional subsystems to support the spacecraft; including the structure, power, communications, and attitude control. Due to the need for rapid manufacturing, it is suggested that the components be purchased from COTS vendors rather that developed in house, unless necessary. The development of these subsystems allows for the basic operation of the spacecraft while supporting the payload in its operational and standby states. This section describes the details and function of each subsystem, as well as a CubeSat configuration COTS solution to each of these subsystems.

Structure

The structure determines the overall size of the spacecraft being suggested. Using a common satellite platform, the payload and bus components can fit into a typical 3U CubeSat configuration form factor. The spacecraft will be a chromate converted 6061-T6 or 7075 aluminum and hard anodized for protection against corrosion. The volume within the spacecraft can be divided into two sections; approximately 2U available for the spacecraft bus, and at most 1U available for the payload. There are several alternatives to purchase a COTS structure commercially from Innovative Solutions in Space (ISIS) and Pumpkin, Inc. These companies have readily available 3U CubeSat structures in multiple configurations. All configurations are in compliance with the CubeSat Design Specification.[11]

Attitude Control

There are two options for an attitude control subsystem, active and passive. Utilizing one over the other will be determined through payload requirement development and a pointing budget. An active attitude determination and control system (ADACS) provides the spacecraft with far greater pointing accuracy than the passive attitude control system (ACS). Both the ADACS and ACS have flight heritage within the CubeSat community. Another consideration is the need for a GPS aboard this spacecraft as this will also drive pointing requirements and attitude control selection.

If an ADACS was chosen, it would be a 3-axis stabilized system ensuring that the spacecraft's GPS and payload antenna were pointed in the correct direction with a low margin of error. A commercial ADACS currently supporting 3-axis stabilization is available from Maryland Aerospace. The MAI-100 is a hermetically sealed enclosure that occupies approximately 0.8U of space within the CubeSat. This is the largest single component within the proposed spacecraft configuration. It provides pointing accuracy within ±1° utilizing a magnetometer and sun sensor for determination and a set of miniature reaction wheels along with torque coils for actuation and control. The MAI-100 also comes with a fully programmed flight computer and custom algorithms for accurate pointing and determination. However, custom controlling software will need to be developed based on pointing requirements and satellite orbit.

The passive ACS option would include the use of permanent magnets along the Earth's magnetic field for stabilization of the spacecraft. Although this system is less accurate, it's simplicity and ease of development could make it a better choice for a less complex spacecraft. Based on preliminary analysis, a passive system would be appropriate for the payload design given.

Global Positioning System

The GPS will give an accurate reading of each satellite's positioning. This is essential information to ensure that the spacecraft can calculate a bearing line for the distress signal. A NovAtel OEMV-1 GPS receiver is one such system that provides accurate positioning for the spacecraft based on inputs from the current U.S. GPS constellation which operates at an altitude of 20200 km. These parameters allow an onboard GPS receiver to acquire a signal from a number of GPS satellites within its field of view.[12]

Communications

The communications subsystem is essential to the uplink and downlink between the spacecraft, ground control, and local emergency responder terminals. This system will include a radio receiver and transmitter as well as an appropriate antenna system. This radio will need to have the capability of operating concurrently with the separate receiver payload and will likely share the same antenna. It is common in CubeSat missions to utilize the amateur radio bands for telemetry, control, and data downlink. This may help with the overall effectiveness of the system since radio amateurs around the world, many of which are affiliated with emergency SAR teams, would also be able to receive the emergency geolocation data.

The AstroDev Helium-100 (He-100) Radio is an FSK/GMSK transceiver that will work sufficiently for communication with the spacecraft. It operates on a TX frequency of 120-150 MHz or 400-450 MHz and a RX frequency of 400-450 MHz or 120-150 MHz. It is compatible with standard amateur radio ground station communication at 1200 bps, 9600 bps, or higher. With the use of this transceiver, the HAM community is able to track and receive beacon data from the spacecraft. By distributing a piece of ground decoding software, they will gain the ability to also help lead the efforts to track emergency distress signals. During mission concept development it must be verified that this radio or other that would be used can interface with the current Cospas-Sarsat ground infrastructure

Command and Data Handling

The flight computer will need to distribute information and commands throughout the spacecraft. A command and data handling (C&DH) board that would be acceptable for use is the FM430 board provided by Pumpkin, Inc. This board includes a PIC24 microprocessor, which allows for faster inter-subsystem communication as directed by ground control.[12] Due to this speed in processing, data points can be handled and translated quickly, therefore saving time and power aboard the spacecraft. This processor may also be used for the FFT calculation of ELT signals received at the payload this may be done instead of using a separate FPGA or microprocessor on the payload itself. Data storage is also available on this processor board through an expandable SD card memory slot. All data points monitored aboard the spacecraft as well as the data generated by the payload will need to be made available to the ground station upon command.

Flight Software

Flight software will need to be developed primarily in house for all subsystems. With the exception of the ADACS software provided with the MAI-100, software will ensure full system performance and compatibility. Flight and test software will be the most time consuming aspect of the spacecraft design since several drivers will need to be written for each subsystem and interfaced with one another. Ground software will also need to be written to be utilized with the transmitted data and beacons from the spacecraft reporting on the status of the signals generated by the payload. Space and ground based aspects will need to be tied into the existing Cospas-Sarsat architecture.

Power

One of the most limiting aspects of the spacecraft is the power consumption versus the onboard power generated. The power system of each satellite needs to be able to generate adequate power through the solar arrays and distribute it throughout the spacecraft. In addition, the power system will be required to safely manage the charge and discharge of a set of lithium batteries to enable each spacecraft to operate in both sunlight and eclipse. This subsystem will primarily consist of a set of solar arrays located on each side of the spacecraft or a deployable panel if a 3-axis stabilization solution is required.

Based on the power systems commercially available several are likely to be able to perform the necessary requirements needed to support the selected subsystems and easily integrate with selected batteries and solar arrays. A power budget will need to be calculated with the final determination of total power needs in order to effectively select and develop the power system for each DGSC satellite.

Thermal

For thermal control, the spacecraft will predominately utilize a passive system incorporating Kapton strip heaters as needed. The structure will be hard anodized in a color that will best dissipate heat for orbit considerations. The receiver payload will receive data only from distress signals. Since it is in receive only, there is less heat generated from the payload compared to the communications systems, which needs to send and receive data.

CONSTELLATION OPTIMIZATION

The goal of the proposed detection and geolocation satellite constellation is to provide location estimation within 1 km between -70° and 70° latitude. As required, each satellite element shall have a 60 minute revisit time with respect to any ELT broadcasting in the coverage area. STK was used as the primary tool to perform this analysis and the ground area "seen" by each satellites receiver (coverage footprint) was the metric used to better define the number of satellites and orbits needed to fulfill these requirements.

Method

From the Receiver Study it was concluded that each satellite's antenna could be modeled as a half-wave dipole with a beam-width of 60°. Based on this result, each receiver's coverage footprint was created from a conical sensor with a solid-angle of 60°.

First, a coverage grid of approximately 4400 points was created in STK, each grid point defining the centroid of a cell with an average area of approximately 100,000 km^2. This grid was then bounded between -70° and 70° latitude before inputting satellite constellation parameters. A visual concept of this grid is shown in the Figure 6 (left) on the following page. Figure 6 (right) depicts the coverage footprint and how access times are calculated using the centroid of each cell and not the cell boundaries. Model accuracy can be increased by increasing the number of grid points with a trade-off of longer computation time.

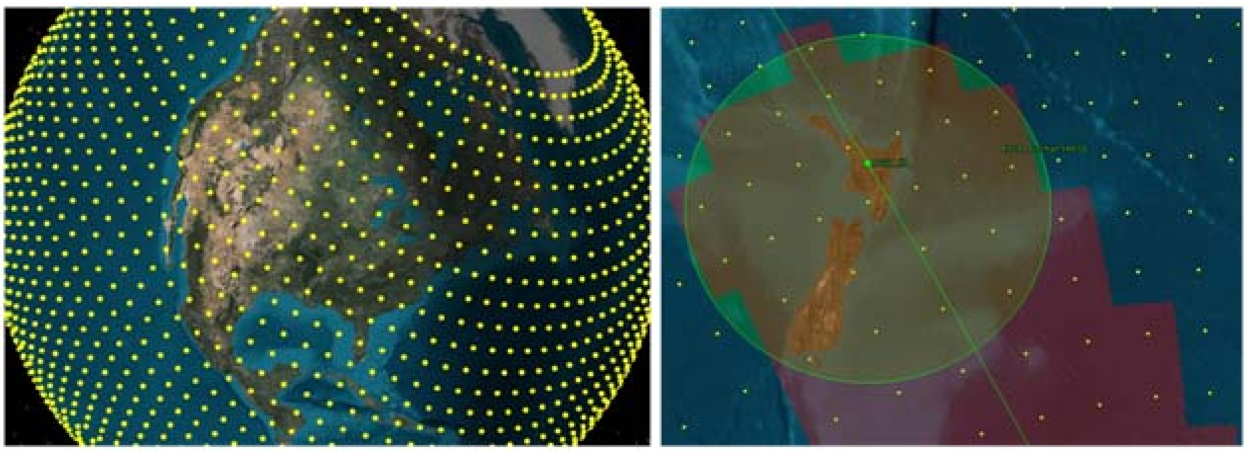

Figure 6: Global Grid and Centroid Accesses

Each satellite constellation was created using the Walker method at altitudes of 500 km and 800 km. These altitudes were chosen based on the performance of both the link and coverage footprint, which have an inverse relationship: as altitude decreases link margin increases and the coverage footprint area on the surface of the Earth decreases

The Walker method was used to create test constellations as it has been applied in the creation of current operational telecommunication and GPS satellite constellations.[13] The three equations, shown below, were used in STK to automatically create an optimal Walker constellation based on user defined input parameters.

$$t = s \cdot p$$

$$i = t/p/f$$

$$T = f \cdot \frac{360}{t}$$

$\boldsymbol{t}$: Total number of satellites
$\boldsymbol{s}$: Number of satellites in each orbital plane
$\boldsymbol{p}$: Number of equally spaced orbital planes
$\boldsymbol{i}$: Plane inclination
$\boldsymbol{f}$: Inter-plane separation (integer value)*
$\boldsymbol{T}$: True anomaly in degrees

$\boldsymbol{p}$, $\boldsymbol{s}$, $\boldsymbol{f}$, and $\boldsymbol{i}$ were input into STK based on observations of the orbital parameters in the existing Cospas-Sarsat satellite constellation. After setting the user-defined inputs STK calculates $\boldsymbol{T}$ and populates the model with the needed satellites.

The four constellations, shown in Table 3, were first evaluated to assess revisit time on a global scale. Chosen altitudes were based on best and worst case (link quality and coverage footprint).

Table 3: Constellation Evaluations

* Inter-plane separation is the relative spacing between satellites in adjacent planes. This is an integer value that must range from 0 to $\boldsymbol{p}$ – 1 for each orbit to have the same angular relationship to the next. An increase in $\boldsymbol{f}$ will increase angle or phase difference between adjacent planes.[13]

Parameters	Sun Sync, 98° Inclination		Circular, 70° Inclination	
Number of Planes	12	6	12	6
Satellites per Plane	2	2	2	2
Inter-plane Separation	1	1	1	1
Altitude	500 km	800 km	500 km	800 km

For each constellation, the revisit time was estimated using a metric known as average gap duration. This is a conservative metric that was computed by STK and is defined as the average duration of the coverage gaps found at each grid point. It is calculated using random sampling and represented by a weighted average. The equation used is shown below, where scenario length is that of one day.

$$\frac{\sum(GapDuration)^2}{ScenarioLength}$$

Results

First, average gap duration was used to analyze the difference between the different orbits in Table 3. Figure 7 and Figure 8 are the results of this test. Grid point failures, shown in red, portray that the circular orbit is superior to sun-synch at 800 km as the sun-synchronous has more grid points that fail the 60 minute revisit time requirement. These plots also show that the 800 km circular orbit with 12 satellites still fails the 60 minute revisit time requirement at some points on the equator.

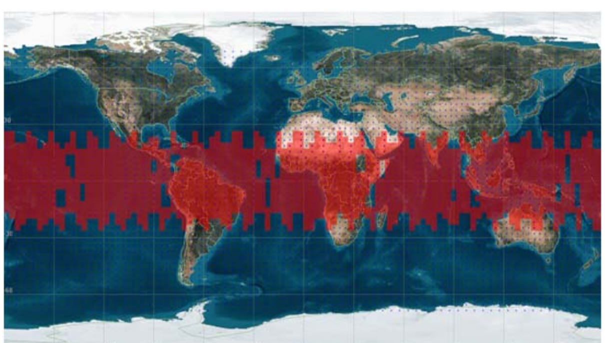

Figure 7: Points that fail the 60 minute revisit time under the average gap duration calculation, 98° sun-synchronous orbit at 800 km.

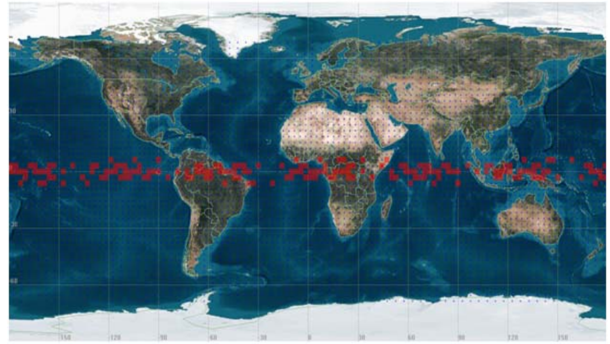

Figure 8: Points that fail the 60 minute revisit time under the average gap duration calculation, 70° circular orbit at 800 km.

Based on the results in Figure 7 and Figure 8 the circular orbit was chosen as an initial baseline, the number of satellites needed in the constellation per orbital altitude was next evaluated, again using the Walker method for constellation creation. To simplify this initial model, both the number of satellites per plane and inter-plane separation were held constant at two and one, as displayed in Table 3. Orbital altitude was varied from 900 km to 500 km at 50 km increments and the number of planes was increased at two per 50 km in altitude decrease.

Figure 9 shows the resulting plot of the number of satellites vs. maximum gap duration during a period of one day. Note that the altitude decreases (900 km to 500 km) in the positive x-direction and the 60 minute revisit time failure line (red).

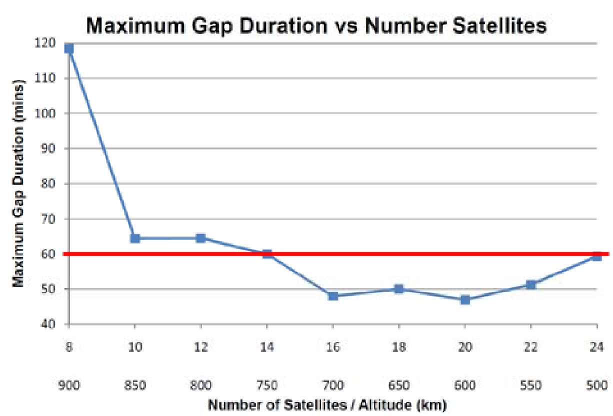

Figure 9: Maximum gap duration (max revisit time) vs. the number of satellites at varying altitudes.

Analysis of this plot shows that the number of the satellites in the constellation have a greater impact on revisit time than the orbital altitude. Additionally, altitudes ranging from 550 km to 700 km are shown to be ideal using this method of constellation optimization. However, two variables were set constant and no models were run using satellites at higher altitudes, showing that more work is needed in this area.

Since many CubeSat launch opportunities currently rely on having a range of orbits they can operate in; the ideal altitude region shown by Figure 9 (550 km to 700 km) provides some evidence to support a constellation such as this being able to still meet mission requirements even if its satellite elements are at varied altitudes. However, this is just a preliminary observation and more work is needed to confirm this, including constellation models with satellites at different altitudes.

These initial constellation results were based on a 60 minute revisit time for a single satellite. As stated in the receiver payload section, to achieve accurate location detection, within one kilometer, three or more passes are needed. This means that the total number satellites in the constellation may need to increase by a factor of three, or more from initial estimates. To better define this constellation more work is needed in understanding the dynamics of a three-pass minimum requirement.

CONCLUSIONS

The objectives of this study were to assess the risks associated with a small satellite constellation able to detect signals and determine geolocation of older aircraft emergency locator transmitters. As well as ascertaining the feasibility of implementing such a constellation.

The major mission risk involved in the implementation of this constellation included the needs assessment for future tracking of 121.5 MHz ELTs due to the limited and decreasing users of this frequency. It was assumed that eventually this frequency will be phased out to allow for a digital only ELT (406 MHz), but that time frame has yet to be determined since the number of 406 MHz ELTs available would not be able to replace the 121.5 MHz ELTs currently in use. Therefore, it was concluded that the need for dual payload to monitor both 406 MHz and 121.5 MHz was necessary.

A receiver study showed that with the signal gain provided by DSP methods using an FPGA or microprocessor, a solid link can be achieved for both 406 MHz and 121.5 MHz ELTs. Initial receiver designs are relatively simple but more research is required. The resolution bandwidth provided by the signal processing also needs to be further defined, this requires a better definition of components in the processing stage such as the sample rate of the FFT on the 121.5 MHz signal.

Conclusions from the receiver study also show that it is able to be supported by a CubeSat bus. This ensures that satellites in the constellation will be of low cost and easily duplicated. Furthermore, since the proposed payload will be relatively small, it may be able to fit future 3U CubeSat missions, as space allows.

Regarding the coverage analysis, initial results show that such a constellation may be feasible and that a circular orbit should be preferred over that of sun-synchronous. However, more detailed work needs to be done, this includes: the addition of the existing Cospas-Sarsat ground infrastructure into the model to simulate total system response time and the incorporation of the three-pass minimum requirement needed for location determination.

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