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The SAMSON Project – Cluster Flight and Geolocation with Three Autonomous Nano-satellites

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ABSTRACT

Satellite Mission for Swarming and Geolocation (SAMSON) is a new satellite mission initiated and led by the Technion – Israel Institute of Technology and supported by Israeli space industries and other partners. SAMSON shall include three inter-communicating nano-satellites, based on the Cubesat standard. The mission is planned for at least one year, and has two goals: (1) demonstrate long-term autonomous cluster flight of multiple satellites and (2) geolocate a cooperative radiating electromagnetic source on Earth. Additional payloads may include a micro Pulsed Plasma Thruster and a new space processor. The configuration of each satellite is a 6U Cubesat, comprising of an electric power system with deployable solar panels, communication system, on-board data handling system, attitude control system and a cold-gas propulsion system for orbit and cluster-keeping. The SAMSON mission commenced in early 2012 and is planned to be launched in 2015. All three satellites shall be launched with the same inclination and semi-major axis into a near-circular orbit. In orbit, they shall separate to form a cluster with inter-satellite relative distances ranging from 100 m to 250 km. One satellite shall be designated as "leader", and the rest would serve as "followers". The leader shall station-keep to control the nominal mean orbital elements, while the followers shall only perform relative orbital element corrections to satisfy the relative distance constraints. During the course of the mission, the cluster shall also perform geolocation experiments, using signals received from known locations on Earth. SAMSON will serve as a platform for academic research and hands-on engineering education. It will also contribute to the advancement of Search and Rescue mission technologies.

INTRODUCTION

The SAMSON project is an innovative satellite mission led by the Distributed Space Systems Lab (DSSL) and the Asher Space Research Institute (ASRI) at the Technion. It includes the first-ever nano-satellite trio, and has two main goals: (1) demonstrate long-term autonomous cluster flight of multiple satellites and (2) geolocate a radiating electromagnetic terrestrial source based on time difference of arrival (TDOA) and/or frequency difference of arrival (FDOA).

SAMSON consists of the space segment, ground segment, user segment and launch segment, as shown in Figure 1. The space segment consists of 3 nano-satellites. These satellites form a cluster and perform autonomous cluster flight. When the satellites have access to user(s) on the ground, they receive the signals transmitted by the User Ground Emitter (UGE) at a predefined designated frequency and code. Each satellite computes data required for the geolocation, which is downloaded to the ground station, located at the Technion. In addition to receiving data, the ground station will perform the functions of command transmission and telemetry reception to / from the satellites.

The received data from all satellites will be transferred to the Geolocation Mission Operations Center (GMOC). Using geolocation algorithms, the GMOC will compute the location of the UGEs and display them graphically to the operators.

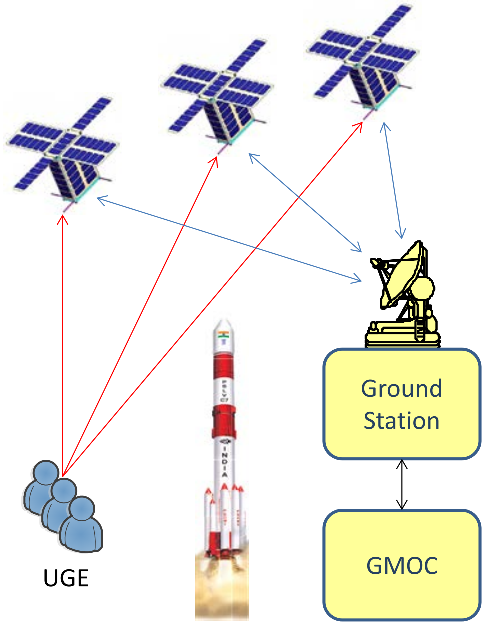


Figure 1 – Samson project configuration

The three satellites will be launched together to form a cluster (see Figure 2) with relative distances ranging from 100 m for the closest two to 250 km for the farthest two. The satellites will perform relative orbital element corrections to satisfy the relative distance constraints based on GPS measurements.

The actual orbit of the satellite cluster shall be determined by the availability of a suitable launch. However, the orbit is planned to be a circular LEO, with the minimum perigee and maximum apogee altitudes ranging from 500 to 800 km, respectively.

BACKGROUND

The first Israeli university satellite, Gurwin-TechSAT-2, was successfully launched in 1998 and operated more than twelve years in orbit. Gurwin-TechSAT-2 was designed and built at ASRI.

Following the heritage of Gurwin-TechSat-2, a number of student projects in the field of space systems have been initiated. Student design projects are a complementary tool for space education in the Faculty of Aerospace Engineering at the Technion. In the last two years, a satellite project named CAESAR was successfully performed by students and partially inspired the SAMSON mission.

The CAESAR project [1] addressed the need for search and rescue in oceanic environments, which presents numerous risks. Due to the nature and size of the oceanic environment, the process of sending out a distress call and accurately locating a person in distress is somewhat problematic since no cellular coverage is available, and even in places where cellular coverage is available, using a cellular phone may not be easy for a person in distress.

Figure 2 – Samson mission concept (drawing by M. Rubanovitch)

Between hundreds to thousands of sea-related accidents occur every year, depending on the geographical area, sea conditions and the type and condition of the watercraft. The main requirements are to identify and locate a user in distress, within 15 minutes, with an accuracy of 1 km.

The need is traditionally fulfilled by the COSPAS-SARSAT system, but it requires the use of bulky and costly Personal Locator Beacons (PLBs). CAESAR was targeted to use affordable 3U Cubesats, using Time Difference of Arrival (TDOA) geolocation techniques. The user segment should be an inexpensive transmitter, enclosed in a simple bracelet worn by the person.

A complete constellation was designed [1], to cover the globe. The constellation is distributed in 6 planes, with 4 satellites couples per plane. Orbits are circular, 700 km altitude, 45° inclination. This constellation adheres to a 15 minute revisit time between 60° north to south latitudes.

In order to optimize the number of spacecraft needed, only two satellites were used in an in-plane formation [1]. TDOA measurements were taken one at a time, so for each subsequent user transmission pulse, the two satellites were in a different position in orbit. To validate the mission algorithms, a test was conducted in DSSL [2]. This laboratory carries out research on satellite formation flying, disaggregated space architectures and other aspects of distributed space systems. Two robotic satellite models were placed in a formation floating on an air-bearing table. An ultrasonic transmitter simulated the user-transmitted pulses. The geolocation algorithms were converted to the sonic medium by proper scaling and were executed by the laboratory computer, as shown in Figure 3.

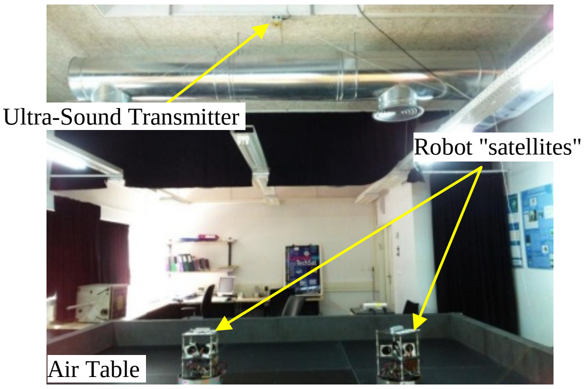


Figure 3 – CAESAR test in DSSL

Test results validated the algorithms and reassured the applicability of a two-satellite cluster for TDOA geolocation.

The CAESAR satellite design was based on a standard 3U Cubesat bus, employing common electronics modules. A propulsion subsystem was designed, to comply with the required Δv of about 10 m/s. It is a cold gas propulsion system, using nitrogen as the propellant. A fuel tank was designed, along with two thrusters and the accompanying valves. CAESAR satellite is shown in Figure 4 [1].

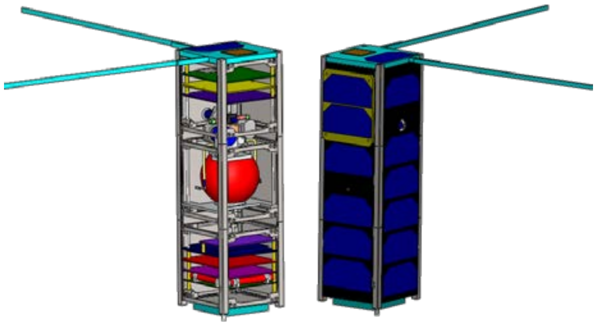


Figure 4 – The CAESAR student satellite

The preliminary design of CAESAR led to the current SAMSON project, which will demonstrate the key technologies and the capability to perform real geolocation for search and rescue.

SAMSON CLUSTER FLIGHT MISSION

Without control forces, two initially close satellites – a chief and a deputy – will rapidly drift apart due to differential accelerations. It is thus imperative to identify orbits on which the satellites remain within some pre-specified relative distance for a relatively long interval of time. These orbits can considerably reduce the propellant mass required for orbit maintenance and render the entire mission much more cost-effective. In the unperturbed two-body problem, such orbits can be simply designed by imposing energy matching. However, when perturbations are present, other conditions for mitigating the relative drift must be found.

The SAMSON project includes cluster establishment and cluster-keeping methods for long-term cluster flight. To that end, new methods for generating relative initial states guaranteeing distance-bounded relative motion are being developed. Using an astrodynamical design model comprised of zonal harmonics and a time-independent drag force, analytical upper and lower bounds on the distance between satellites are found.

To maintain cluster flight for the entire mission lifetime, SAMSON will be using cluster-keeping algorithms aimed at minimizing fuel consumption. These algorithms determine bi-impulsive maneuvers that enable the satellites to attain relative states satisfying both maximal and minimal distance-keeping constraints, while tracking a desired reference orbit.

SAMSON GEOLOCATION MISSION

The geolocation mission will be performed by all three satellites in the cluster. There are many techniques to geolocate an object via electromagnetic measurements. The "user" to be located is a simple transmitting device with known codes. The satellites fly in a cluster, which is ideal for this mission. Since the inter-satellite distance in the cluster is bounded, each satellite will receive the terrestrial signal to be located. The satellites have different locations and velocities, so they receive the signals at a slightly different time and frequency, due to different propagation times and Doppler shifts. Electromagnetic geolocation techniques exploit these physical phenomena to perform localization. As part of the SAMSON mission, various geolocation algorithms will be investigated.

The TDOA Method

TDOA geolocation principles translate each TDOA measurement to a hyperbolic equation where the two measuring satellites locations are parameters and the ECEF coordinates of the user are the unknown variables:

$$\Delta t_{21} = \frac{1}{c}\|s_2 - u\| - \frac{1}{c}\|s_1 - u\|$$

Here, c is the speed of light, and

$$\left\|\overline{s}_i - u\right\| = \sqrt{\left(X_i - X\right)^2 + \left(Y_i - Y\right)^2 + \left(Z_i - Z\right)^2}$$

The variable Δt_{21} represents the TDOA between the arrival at satellite 2 and satellite 1, s_1, s_2 represent the locations of the two satellites participating in the TDOA, and *u* represents the user location.

Thus, the TDOA measurement represents a hyperboloid on which the user must be located. With three participating satellites, two TDOA measurements can be computed. The two hyperboloids can be intersected to obtain a small number of candidates for the actual location.

Ho and Chan [3] added the assumption that the user's altitude above the Earth's surface is known, and thus were able to add another equation. They demonstrated that given the altitude assumption and 2 TDOA measurements of a single pulse collected by a 3 satellite formation, an analytic algebraic solution of the location can be obtained by finding the roots of a 4th order polynomial.

In practice, the TDOA measurements are not precise and include errors. Therefore, multiple measurements are required in order to generate an over-determined set of equation, from which the user's location can be estimated using least-squares techniques. Such techniques are highly dependent on a good initial "guess". The method of Ho and Chan can be used to generate such an initial point for the least-squares calculation.

The FDOA Method

Another technique to locate an unknown emitter location is using Frequency Difference of Arrival (FDOA). In this method, we measure the received frequency of the signal at the satellites, along with the satellite speed and location. Taking advantage of the Doppler Effect, we can calculate the emitter location.

The user signal will arrive to each satellite with the following frequency (FOA – Frequency Of Arrival):

$$f_i = f_0\left(1 + \frac{1}{c}\frac{\left(s_i - u\right)\cdot v_i}{\left\|s_i - u\right\|}\right)$$

where f_i is the received frequency on satellite *i*, f_0 is the emitter signal frequency, c is speed of light and v_i is the velocity of satellite *i*.

Hence, the FDOA between satellite 2 and satellite 1 (as mentioned above, our “reference” satellite) will be:

$$f_{21} = f_2 - f_1 = \frac{f_0}{c}\left(\frac{\left(s_2 - u\right)\cdot v_2}{\left\|s_2 - u\right\|} - \frac{\left(s_1 - u\right)\cdot v_1}{\left\|s_1 - u\right\|}\right)$$

Three satellites generate two FDOA measurements. Each measurement describes a surface on which the user may be located. Intersecting the two measurements provides a set of possible locations for the user. Similar to geolocation using TDOA measurements, multiple measurements form an over-determined set of equations that can be solved using various techniques, such as least-squares.

Estimation Algorithm

The two types of measurements, TDOA and FDOA, can be combined to further improve the geolocation accuracy. Aggregating measurements from several positions along the satellites' orbits, we obtain an over-determined set of measurements. There are multiple methods to estimate the position from the measurements. After considering several alternatives, a batch post processing using the least squares method [4] was selected. This selection is due to the method's simplicity, speed, and performance.

The geolocation itself will be performed in the GMOC. It will be possible to select the geolocation algorithm to be used (e.g., TDOA only, or combined TDOA/FDOA mode.).

Geolocation Payload

The basic (default) method used for the geolocation in SAMSON will be TDOA. However, the satellite payload will employ also frequency measurements, to enable usage of both TDOA and FDOA methods. The addition of FDOA measurements is expected to greatly improve the geolocation accuracy.

Since one of the main contributing factors to the geolocation computation accuracy is the satellite time synchronization, a rubidium atomic clock is considered to be employed in each payload. A GPS receiver will synchronize it to GPS time. The overall TDOA measurement error is expected to be below 100 nsec.

In case of FDOA measurements, the geolocation payload will measure frequency with an expected accuracy of about 0.5 Hz.

Geolocation Mission Experiments

In order to test and validate SAMSON geolocation mission, several experiments shall be performed. A UGE with a known location will transmit signals, which the three SAMSON satellites will receive and process.

The ground station will process the downloaded signals and compute the UGE location.

The tests shall check the performance of geolocation for different geometries of the satellites in the formation and different UGE locations relative to the satellites' ground track. Also, the tests shall check the performance achieved using either TDOA or combined TDOA/FDOA methods. Furthermore, the tests will check the performance with different parameters of the UGE transmissions.

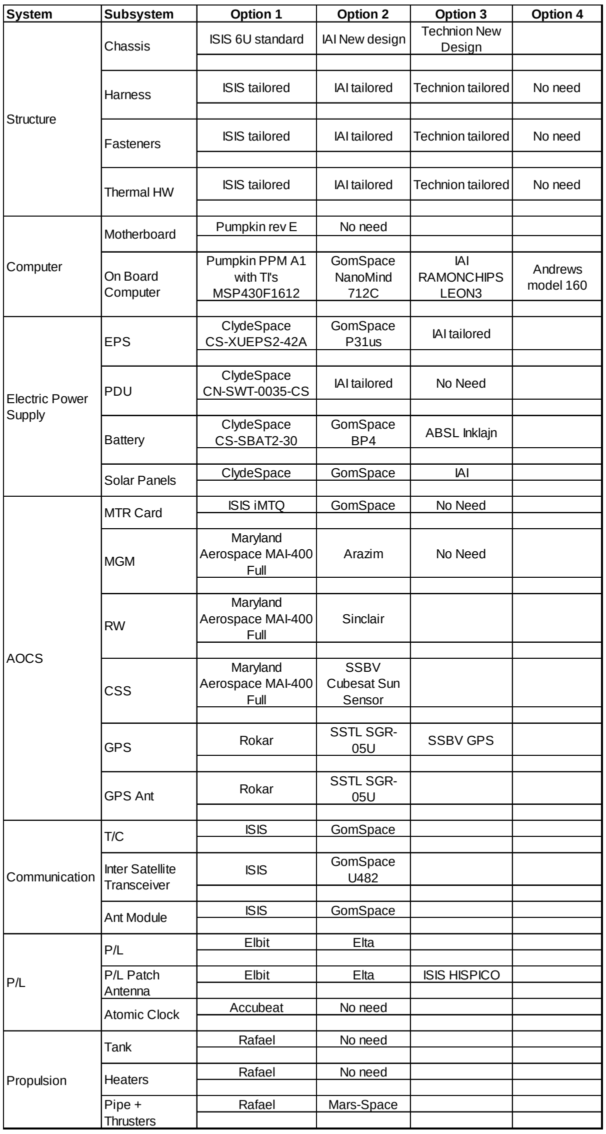
DESIGN CONSIDERATIONS

The task of designing the satellites was approached based on experience gained from previous Israeli space missions such as AMOS-2, AMOS-3, VENµS, and InKlajn-1, and from space system engineering methodology for Integrated Conceptual Design Method (ICDM) developed in [6]. Nevertheless, the challenge of designing, building, testing, and launching three nano-satellites in a timeframe of three years led to a tailored design approach based on COTS hardware that was available during the design phase. In order to have an unbiased design concept, two tables were built, one for the potential hardware at a subsystem level and the other for the selection criteria, providing the score for each solution. This approach is a modification to the classic morphological table, tailored to space systems engineering. Instead of using a set of defining questions we used subsystems and components, and instead of using technological solutions we used specific hardware providers. It was already successfully demonstrated [7] in design of space systems components.

Importance: 5 - most important 1 - least important
Go-No-Go: Yes/No
Criteria
Commonality with other satellites developed in Israel
Complexity
Components traceability
Cubesat commonality
Heritage
Integration effort
Integration experience in Israel
Knowledge and engineering assistance availability in Israel
NRE
Number of known failures in tests/vacuum/missions
Overall Mass
Power consumption
Radiation tolerance
Software related efforts
Testability
Time of delivery
Unit Cost
Units sold

Figure 5 - Stakeholders Requirements criteria

The table in Figure 5 was used to set the importance of selection criteria. These criteria were generated by the project management and main stakeholders. They consist of both performance and programmatic characteristics. After setting the criteria, an alternatives morphological table was defined, as shown in Figure 6, consisting of all relevant components that were considered to be part of the design. This table will serve to select the actual subsystems and components for the design.



System	Subsystem	Option 1	Option 2	Option 3	Option 4
Structure	Chassis	ISIS 6U standard	IAI New design	Technion New Design	
	Harness	ISIS tailored	IAI tailored	Technion tailored	No need
	Fasteners	ISIS tailored	IAI tailored	Technion tailored	No need
	Thermal HW	ISIS tailored	IAI tailored	Technion tailored	No need
Computer	Motherboard	Pumpkin rev E	No need		
	On Board Computer	Pumpkin PPM A1 with TI's MSP430F1612	GomSpace NanoMind 712C	IAI RAMONCHIPS LEON3	Andrews model 160
Electric Power Supply	EPS	ClydeSpace CS-XUEPS2-42A	GomSpace P31us	IAI tailored	
	PDU	ClydeSpace CN-SWT-0035-CS	IAI tailored	No Need	
	Battery	ClydeSpace CS-SBAT2-30	GomSpace BP4	ABSL Inklajn	
	Solar Panels	ClydeSpace	GomSpace	IAI	
AOCS	MTR Card	ISIS iMTQ	GomSpace	No Need	
	MGM	Maryland Aerospace MAI-400 Full	Arazim	No Need	
	RW	Maryland Aerospace MAI-400 Full	Sinclair		
	CSS	Maryland Aerospace MAI-400 Full	SSBV Cubesat Sun Sensor		
	GPS	Rokar	SSTL SGR-05U	SSBV GPS	
	GPS Ant	Rokar	SSTL SGR-05U		
Communication	T/C	ISIS	GomSpace		
	Inter Satellite Transceiver	ISIS	GomSpace U482		
	Ant Module	ISIS	GomSpace		
P/L	P/L	Elbit	Elta		
	P/L Patch Antenna	Elbit	Elta	ISIS HISPICO	
	Atomic Clock	Accubeat	No need		
Propulsion	Tank	Rafael	No need		
	Heaters	Rafael	No need		
	Pipe + Thrusters	Rafael	Mars-Space		

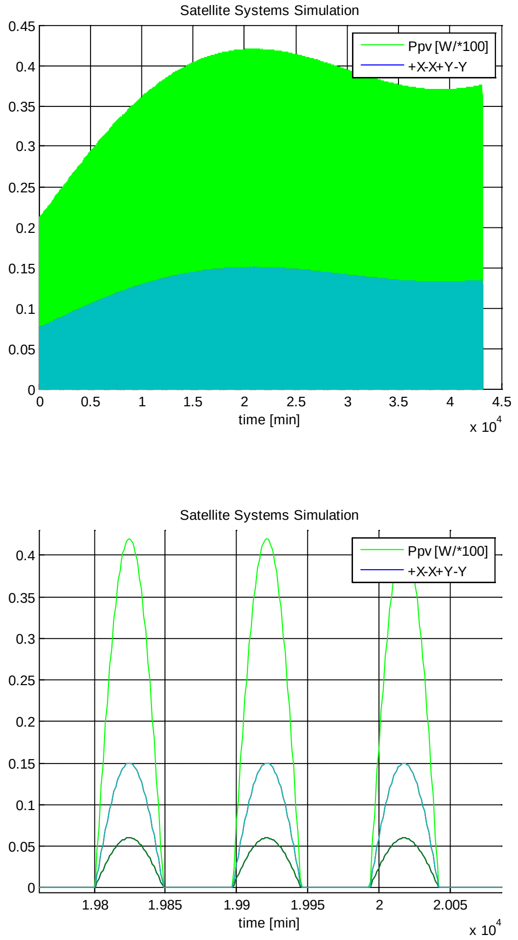
Figure 6 - COTS Morphological Table

SYSTEM DESCRIPTION

SAMSON will consist of three nano-satellites, and a ground station which includes the Geolocation Mission Operations Center (GMOC). Each nano-satellite will consist of a structure with external dimensions of

100x226x340.5 mm (hereafter called 6U, or six-pack). These structures are fabricated from aluminum alloys (such as 7075). Along with the 6U nano-satellites, storage and launch containers will be used for the 6Us; these are called 6-POD and provide mechanical restraints for the nano-satellite as well as a remotely-operated door release and a spring-actuated push-out mechanism for the 6U nano-satellite.

Although single Cubesats were launched and operated a number of times, in many instances as student satellites, multiple-unit Cubesats have rarely been launched. For examples, one 3U Cubesat (10x10x30 cm) was Delfi-C3 launched in 2008. GeneSat-1 is another 3U Cubesat launched in 2006 by NASA. QuakeSat, another 3U Cubesat, was launched in 2003. To date, and to the best of our knowledge, no 6U Cubesat has been launched. The Cubesat constellation concept was extensively discussed by Munteanu [8] in 2009.



(a)

(b)

Figure 7 – Power produced by the solar panels during one month (a) and three revolutions (b)

Each SAMSON nano-satellite will be equipped with four deployable solar panels, two 30x20 cm and two 30x10 cm. Together, these four panels will produce at least 30W when illuminated (see Figure 7), charging two Li-ion battery packs. Thermal control will be performed at the satellite level.

Each satellite will contain one GPS receiver and antenna, one UHF Nano COM half-duplex transceiver (432-438 MHz, radio amateur band) for inter-satellite communication, one VHF uplink/UHF downlink transponder for command and control, and one S-Band receiver for geolocation. Communication with the ground station will be performed via deployable dipole UHF and VHF antennas mounted on each satellite. The choice of the UHF band for telemetry and VHF for command and control was taken to simplify constellation control. The ground control station will broadcast commands to the constellation. All three satellites will have the same command receiving frequency in the VHF band; Separate spacecraft ID enable issuing commands also to a specific satellite. Each satellite will have different telemetry transmitter frequencies at least 1 MHz apart to allow separate data streams from each satellite. The architecture of broadcast for uplink and point-to-point for downlink was chosen not only in order to simplify constellation control but also to simplify frequency registration, as the registration of downlink data streams is easier than that of uplink data streams. The use of amateur radio frequencies for telemetry will allow using the radio amateur network in case of a "lost-in-space" situation.

Attitude control on each satellite, which will be nadir-pointing during most of the mission, will be performed using a miniature 3-Axis reaction wheel package which also includes magnetorquers, magnetometers, Earth sensors, and Sun sensors, as well as a fully programmed ADACS computer. We expect that the accuracy in knowing the orientation of each nano-satellite, from which the direction of the line of sight of the geolocation receiving antenna will be determined, will be better than 0.5 degrees (0.1 degrees desired). To assist recovery in a “lost-in-space” condition, three additional sun sensors will be installed in each satellite. Discharging the momenta of the reaction wheels will be done with the magnetorquers.

We stress that the scheme described here is only one of the possibilities; these will be studied and the most suitable one will be selected following the preliminary and critical design phase of the mission.

Nominal operation includes nadir pointing during orbital night and day and daytime Sun-pointing to charge the batteries whenever necessary. Uplink and downlink telemetry will take place whenever the satellites would be viewing a ground station, but preferably during the orbital day. This is also where the momentum discharge of the reaction wheels will be scheduled.

Inter-satellite communication is needed for autonomous formation and constellation flying. Each SAMSON satellite will be equipped with an onboard GPS that provides position (expected accuracy is better than 10 meters 3σ error) and velocity (better than 0.15 m/sec 3σ error). The inter-satellite communication link enables each satellite to have full knowledge of the other two satellites and thus to use an onboard algorithm to perform cluster-keeping operations. Since the geolocation requires angular separation to provide better accuracies, the cluster will autonomously keep distances of no less than 100 meters and no more than 250 kilometers, which includes cross-track separation through differential node locations

The choice for the propulsion system is limited to Cubesat sizes. We are considering designing a cold gas system, using a non-toxic propellant, adhering to launch requirements. The propellant options are Nitrogen (N_2), which is widely used in such systems, or Butane (C_4H_{10}), which can be less pressurized. The thrusters will be placed on the sides of the satellite body, supplying at least 20 mN of thrust.

End-of-mission

The mission will end when the nano-satellites will drift too far apart to provide an overlapping field of view (FOV) to allow geolocation, or when their payloads will fail. We envisage an extended mode of operation when two functioning nano-satellites could still provide useful geolocation data.

Drag simulations using the 1U Cubesat form factor show that the lifetime in orbit is approximately one month for a 300-km altitude and 12 years for 600-km [8]. The SAMSON satellites that will cease valuable scientific operation will be oriented to maintain the deployable solar panels to the ram direction. This enhancement of the ram cross-section by a factor of 20 in comparison with a 1U Cubesat, together with the low earth orbit, will fasten their re-entry cleaning the orbit of non-functional satellites.

TESTING CONCEPT

It is common to think that the size of the satellite also dictates the amount and the depth of testing needed. Hence, when dealing with nano-satellites, it is expected that the tests will be minimal.

Since the actual launch vehicle is yet to be determined, we adopted the general environmental test requirements approach as presented in GSFC-STD-7000 [5], Chapter 2.

The chart in Figure 8 demonstrates the AIT (Assembly, Integration and Testing) method that will be implemented for SAMSON. This methodology envisages simultaneous actions for all three satellites, which will be treated with the same approach, with two exceptions for the environmental test campaign. During the dynamic mechanical tests and thermal vacuum tests, one of the satellites will be considered Proto-Flight Model (PFM), while the other two will be considered Flight Models (FM). For the dynamic mechanical testing this means that one of the satellites will be exposed to qualification levels but at one third of the duration, and the other two will be exposed to acceptance test levels.

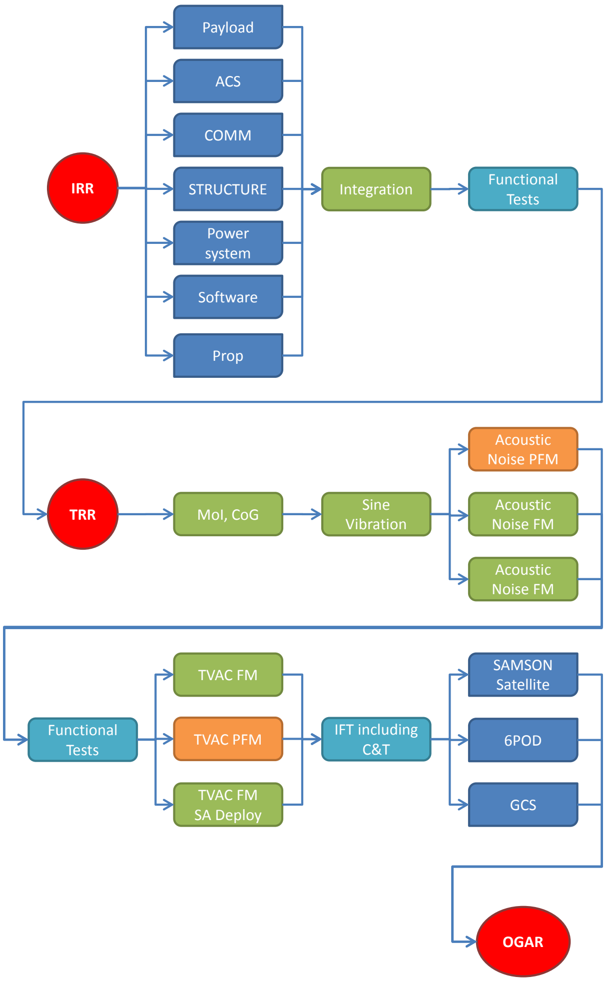


Figure 8: AIT flow for SAMSON

LAUNCH

General orbital requirements for SAMSON are simple: any circular orbit at altitudes between 500 km and 800 km (allowing moderate link budget and minimum drag) and inclination of above 35 degrees (allowing reception of the signals at the ground station at the Technion, Haifa).

Since SAMSON includes three nanosatellites with unique mission requirements expressed by the difference in the ascending node $|\Omega_1 - \Omega_{2,3}| > 0.2^o$ (at least one of the three needs to be apart cross-track from the other two to achieve better geometries for geolocation), a launcher with a maneuvering upper stage (e.g. FREGAT, BLOK, and DRAGON) is desired.

We propose to use the A-train concept developed for the Earth-observing constellation of Aqua, CloudSat, CALYPSO, and Aura but adapted for nano-satellites, and using a single launch to orbit all nanosatellite as secondary payloads. Within this concept, each nanosatellite will be released from the launcher at a different time and with a small Δv so as to enter a slightly different orbit than that of the launcher. This ensures that the nanosatellite of the swarm will be in the same orbit.

SUMMARY

A preliminary design methodology for the first-ever nano-satellite cluster flight mission was presented. Aspects related to the systems engineering aspects, as well as the launch strategy, orbit design and bus design, were presented. This mission embodies high-end research goals as well as educational goals.

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