Integrated Communication Extension Capability (ICE-Cap)

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ABSTRACT

Nanosatellite technology made it possible for universities, commercial industries and government agencies to develop low cost and responsive satellites. However, one of the limitations of this technology is the communications shortfalls. The Navy SPAWAR System Center Pacific (SSC Pacific), with support from the Navy's Program Executive Office for Space Systems (PEOSS), is developing the Integrated Communication Extension Capability (ICE-Cap) satellite, a 3U CubeSat, to demonstrate a cross-link from a CubeSat in Low Earth Orbit (LEO) to a Mobile User Objective System (MUOS) satellite in geosynchronous orbit in order to instantaneously relay information to a terrestrial data network, which will be a solution to the communications shortfalls. The ICE-Cap will also demonstrate the relay of Ultra High Frequency (UHF) Satellite Communication (SATCOM) from the poles using a CubeSat and will mature and miniaturize space vehicle components such as radio, antenna, and other technologies for potential responsive UHF SATCOM missions. The ICE-Cap is scheduled to launch into sun-synchronous, LEO orbit in December 2015. For back-up communication method, there is a dedicated ground station (GS) in San Diego, CA that provides a line-of-sight communication to the satellite. All development and testing is expected to be completed by September 2015 and delivery of the flight-ready unit to the launch provider will take place in October 2015.

BACKGROUND

The MUOS is the Navy's newest narrowband satellite communication system designed for use by the United States military and its allies. MUOS, designed to replace the aging UHF Follow-On (UFO) satellite communications system. MUOS will be able to provide 10 times the data throughput of its predecessor once it is operational.

ICE-Cap is meant to serve as a force enhancer for satellite communication systems. ICE-Cap has been designed to work with the MUOS UHF SATCOM system in order to provide communication and data relay capabilities for those warfighters outside of MUOS' area of responsibility.

An area of particular concern to the ICE-Cap mission is the North Pole. Outside of the MUOS area of operation, the North Pole has become increasingly significant as the sea ice in the region continues to melt and activity in the region starts to increase. Because of its resources, maritime shipping routes, and strategic military importance, the Arctic region is quickly becoming a contested area for the handful of countries that possess territory or operate in that region.

Due to the increase of US political, military, and economic interests, proper and adequate communications capabilities for our country and its allies are essential for sustained operations in the polar region. By leveraging the flexibility and adaptation capabilities of MUOS, and the relatively inexpensive funding requirements associated with nanosatellites such as CubeSats, a cheap and effective solution can be ascertained with the combination of the two. ICE-Cap offers this solution by establishing a communications bridge, connecting the isolated user in the polar region with the MUOS SATCOM system.

The MUOS network allows data connections to secure DoD networks. The operational View (OV-1) for the Wideband Code Division Multiple Access (WCDMA) MUOS Crosslink concept is illustrated in Figure 1.

Today, nanosatellite technology is becoming more popular among various communities including universities, commercial industries, and government agencies. The reasons for the small, standardized nanosatellite form factor are low development cost and responsiveness. However, there are a few limitations that need to be resolved. One of the main issues is the communications shortfalls due to short communication windows and long times between ground station contacts. Most nanosatellites are deployed to Low Earth Orbit and because of that, they are only within the line-of-sight of any given ground station antenna for a few minutes each day. The lack of available line-of-sight opportunities severely limits the capacity of Telemetry, Tracking, and Commanding (TT&C) and payload data transfer availability.

CONCEPT OF OPERATIONS

The Navy's Program Executive Office Space Systems with support from Navy SPAWAR Systems Center Pacific, is developing the ICE-Cap satellite, a technology demonstration CubeSat with three main objectives:

1. Demonstrate a LEO-GEO-Earth cross-link with a CubeSat in low Earth orbit to a MUOS satellite in geosynchronous orbit to instantaneously relay information to a terrestrial data network.

2. Demonstrate a data relay using UHF SATCOM from Polar Regions via CubeSat.

3. Mature and miniaturize radio, antenna, and other technologies for potential responsive UHF SATCOM missions.

The Navy developed MUOS, a communication satellite constellation in geosynchronous orbit, to provide cellular phone equivalent capability from space using WCDMA waveform. The MUOS network allows data connections to secure Department of Defense (DoD) networks, as illustrate in Figure 1.

The ICE-Cap will leverage MUOS WCDMA crosslink capability to achieve on-demand TT&C and payload data retrieval to reduce communications shortfalls. In addition, it can possibly eliminate the need for dedicated ground stations for DoD nanosatellites by communicating through MUOS.

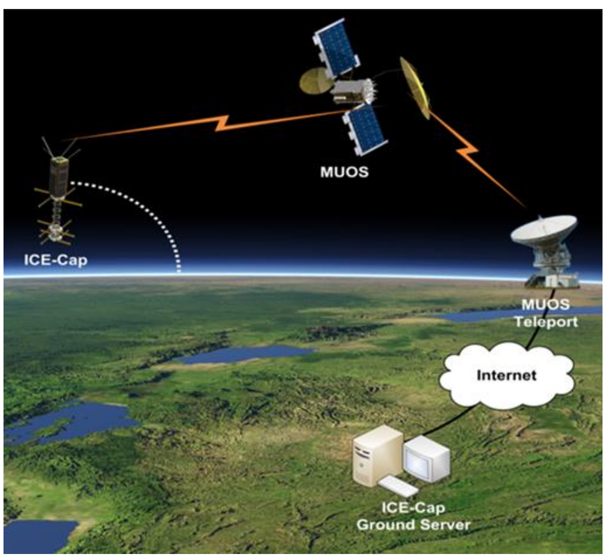

Figure 1: MUOS Crosslink Operational View

The ICE-Cap is scheduled to launch to a sun-synchronous orbit in December 2015. For a back-up communication method, there is a dedicated ground station in San Diego, CA that provides a line-of-sight communication to the satellite. All development and testing is expected to be completed by September 2015 and delivery of the flight-ready unit to the launch provider will take place in October 2015.

Demonstrate UHF SATCOM Relay from the Poles

The ICE-Cap system is to serve as a communications and data relay for mobile users outside of MUOS' operations coverage area, i.e., above 65 degrees North latitude and below 65 degrees South latitude. By setting up a polar, Low Earth Orbit constellation consisting of numerous nanosatellites, a continuous, near real time communications and data relay can be established for the isolated user. The OV-1 for the UHF SATCOM Relay concept is illustrated in Figure 2.

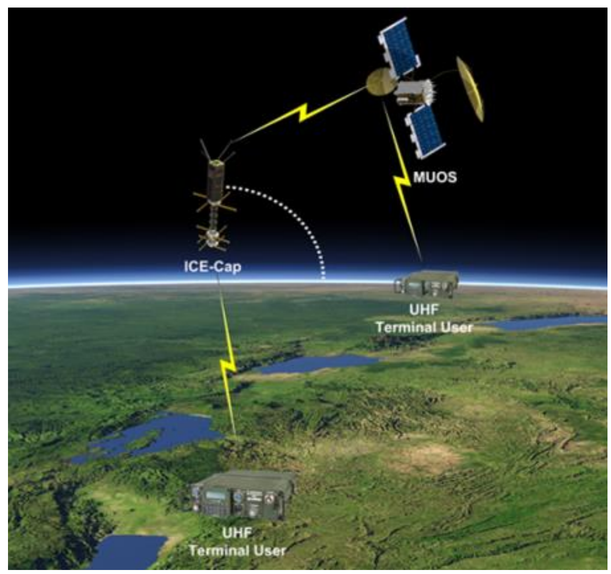

Figure 2: Legacy UHF Relay Operational View

SYSTEM DESCRIPTION

The ICE-Cap project consists of four different Small Business Innovative Research (SBIR) projects, managed by SSC Pacific in support of PEOSS. The table below describes all organizations/companies participating in development and their functions.

Table 1: ICE-Cap Work Breakdown Structure

Function	Organization
Program Management	PEO Space Systems

Function	Organization
System Engineering Support	SSC Pacific
SW Development / Integration	SSC Pacific
Ground Control Development	SSC Pacific
Ground Control Development Support	Naval Postgraduate School
HW Integration	Space Micro, Inc.
Low Gain Antenna Development	Space Micro, Inc.
High Gain Antenna Development	Physical Optics Corp
Radio Development	Vulcan Wireless
Cryptographic Unit Development	Innoflight

Space Vehicle

The ICE-Cap Space Vehicle (SV) is a 3U CubeSat. It measures 10 x 10 x 34 centimeters in the stowed configuration. Launch mass is currently estimated at 5.15 kilograms. Except where noted, the ICE-Cap space vehicle is built in accordance with the CubeSat Design Specification Rev 12 (Ref 1). Rendered depictions are shown in Figure 3.

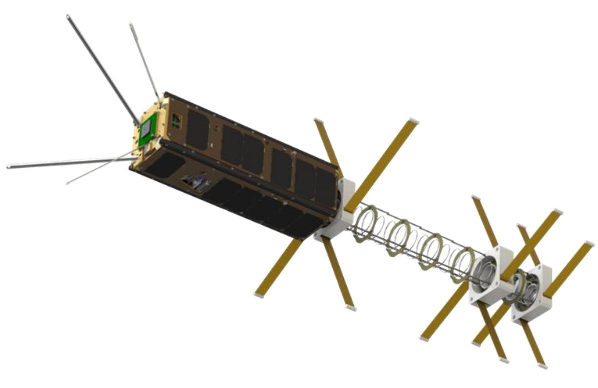

Figure 3: ICE-Cap CubeSat Image with Both Antennas Deployed

The space vehicle includes two software-defined radios (SDR), two deployable antennas, an active attitude determination and control system (ADCS), a flight computer (FC), and an electrical power system (EPS). As in most other nanosatellites, ICE-Cap does not have a propulsion system and is therefore incapable of expending fuel to maintain an orbit. The space vehicle is designed to survive in orbit for approximately one year.

Each of the ICE-Cap subsystems has a level of autonomy sufficient to operate via basic state machine and is only intermittently controlled by the flight computer. The Electrical Power System (EPS) takes power generated by the four solar panels and recharges batteries. EPS also converts the battery power to other voltages necessary for operation. The flight computer accepts ground telecommand, maintains a real time clock, provides high-level coordination and fault monitoring to other subsystems, and initiates operational mission tasks based on a ground-defined schedule. ICE-Cap SV attitude, angle with respect to the surface of the earth, is controlled by the attitude determination and control system (ADCS). The two onboard SDRs are used to command the space vehicle and report health and status data to the ground station. Two SDRs are used because there are two independent communication links - UHF Legacy and WCDMA. Both communication paths will be demonstrated during the on-orbit mission phase. The ICE-Cap SV Interface is shown in Figure 3.

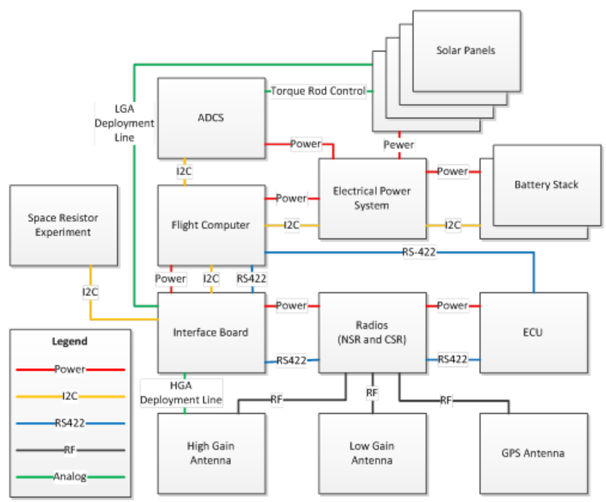

Figure 4: ICE-Cap Interface Architecture

Each subsystem operates based on its internal software and relays telemetry status to the flight computer to be logged (stored) and transferred to ground station. The flight computer, P200K-Lite, collects health and status data and executes the pre-programmed operational schedule and event-triggered task operation. The flight computer responds to real time commands and is able to accept new state machines for time triggered operations. The real time commands are executed immediately. Each command can be used to set a variable, get a telemetry variable, or trigger a branching, but non-looping, state machine. Real time commands can be combined into more complicated structures, called Stored Command Sequences (SCS). Execution of SCS can be triggered from either the real time clock or events interrupt.

Operational Modes- ICE-Cap may operate in four distinct modes: Initialization, Safe, Normal, and Sleep modes, as shown in Figure 5. The operational mode dictates which SCS are executable. Real time commands are executable in every mode. This structure is used to increase software safety, resolve anomalies that occur in the space environment, and protect against potential compromise.

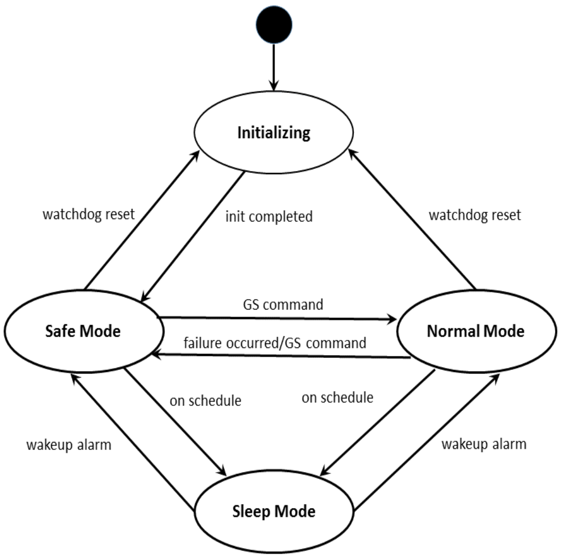

Figure 5: Mode Transfer State Diagram

Initialization Mode- Initialization mode occurs when power is enabled or the watchdog resets the flight computer. A series of Built-In-Tests (BITs) are performed during the boot sequence before the satellite is allowed to proceed to safe mode.

Safe Mode – Safe Mode is the most restrictive in terms of mission execution. Only SCS essential to systems safety are executed and the SV waits for contact from ground. In safe mode, SV broadcasts a short Health and Status beacon every 30 seconds. The remainder of the time, the FC is in the sleep mode while waiting for an interrupt from the radio triggered by an incoming message from ground station. The satellite waits for a connection and command from a GS to go into an operational mode. The satellite enters Safe Mode if severe anomalies are detected during BITs or if nothing is heard from a GS for a period of time (10 days).

Normal Mode – In Normal Mode, the satellite is autonomously executing the mission. The satellite controls pointing, transfers mission data, responds to auxiliary GSs, and transfers basic telemetry. If the satellite receives mission schedules from GSs, it will execute its mission during the scheduled time. If it does not receive schedules from GSs, the satellite performs its predefined missions at a given time.

Sleep Mode – During Sleep Mode, most of the systems are powered off or in low-power mode to conserve power when the satellite completes its normal operational routine. The satellite sets the timer to wake-up for the next scheduled routine. When the timer is off, the satellite goes back to Normal mode.

Software updates to the SV can be uploaded only from the SSC Pacific GS, located in San Diego, CA. Updated software, baselines, and "gold", are stored onboard the satellite. The satellite can revert to a previous baseline if there are problems with an update. The satellite will also revert to gold if it has not communicated with a SSC Pacific GS in at least 15 days. The gold version is stored in a protected memory location, not subject to update or revision. Maintaining the three software versions on SV is designed as a method of automated anomaly resolution in case of software malfunction.

Antenna Deployment Sequence – After launch when the ICE-Cap satellite is initially deployed from the CubeSat dispenser, the ICE-Cap flight software will undergo initialization and will trigger the antenna deployment sequence for both antennas. The antenna deployment sequence state machine monitors for a successful deployment of independent antenna elements and attempts to minimize additional spin caused by deployment. Failure of antenna to deploy may cause serious degradation in communication. Figure 6 shows the antenna deployment sequence block diagram.

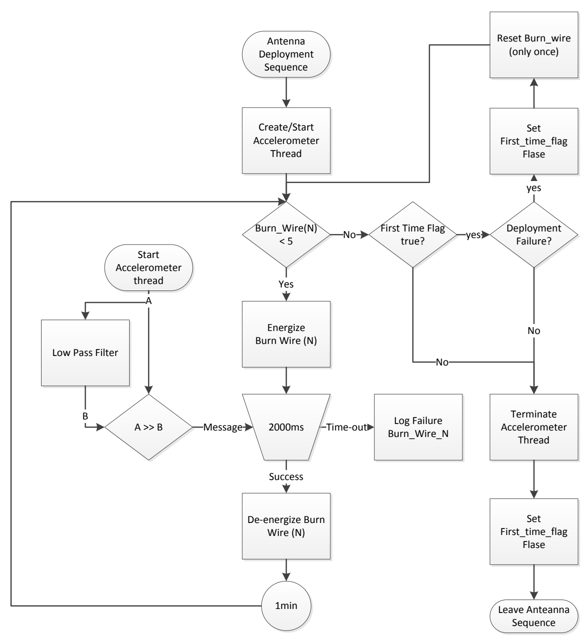

Figure 6: Antenna Deployment Sequence Diagram

Ground Control

The ICE-Cap Ground Station in San Diego, CA will provide capabilities to command and control, retrieve, and analyze satellite data during the on-orbit phase. The

GS software includes a command database, Command Message Generator, Command Scheduler, Telemetry Database, and MUOS Internet Protocol (IP) link. The GS hardware includes the computer workstation and the legacy UHF RF radio with RF front-end. The ground software architecture is shown in Figure 7.

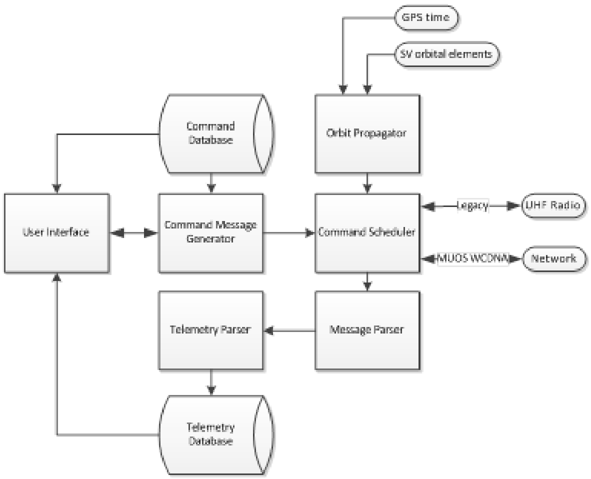

Figure 7: Ground Software Architecture

Command Database – Command database stores the list of commands that the SV is able to execute and acceptable arguments for each of the respective commands. Command database also maintains alarm conditions and statistics of transmitted commands.

Commands Message Generator – Used to create both the RT and SCS messages that will be used to control the space vehicle. The message generator appends the appropriate prefix and postfix to the command as described in the "ICE-Cap Ground to Space ICD" and validates the integrity and accuracy of the message prior to transmission.

Command Scheduler – Maintains a queue of messages that must be transmitted to the SV and controls the flow of messages based on overflight opportunities and the acknowledgement messages that are received from the SV. The orbit propagator provides the line-of-sight opportunity windows.

Telemetry Database – Used to warehouse the downloaded SV health and status telemetry data, and maintain alarm logs and mission data.

The Legacy UHF Radio – The primary method of command and control is via the line of sight 25 kHz Legacy UHF Channel. The commands are generated within the Command Scheduler and are transmitted to the SV via the line-of-sight link through the legacy UHF radio

MUOS IP link – Telecommand over the IP network is accomplished in a similar method as line-of- sight except that after the commands are generated, they are transmitted over IP socket. The command and telemetry link is shown in Figure 1.

Ground-to-Space Protocol

The messages generated in the GS are used to control the satellite and update subsystem software. The messages generated onboard the space vehicle contain command execution status, telemetry, and error readouts. The data transport protocol described below contains a standard header for both uplink and downlink messages.

Message Structure – An ICE-Cap message is a variable binary message that begins with two synchronization bytes, two message number bytes, two payload length bytes, variable payload between the size of 0 to 65,536 bytes, and two checksum bytes. ICE-Cap is able to accommodate a number of message structures. Table 2 shows an example of a Real Time Command message with byte assignments but an incorrect Cyclic Redundancy Check (CRC).

Table 2: Message Structure Format

Category	**Header**			**Message Payload**			
Mnemonic	Start	Message Number	Payload Length	Payload Indicator	Command ID	Argument	CRC
Size [Bytes]	2	2	2	1	2	4	2
Position	0:1	2:3	4:5	6	7:8	9:12	13:14
Example	0x1CEF	0x0003	0x0007	0x02	0x015E	0x001CECA4	0xFFFF

Message Acknowledgement Protocol – The ICE-Cap flight computer must acknowledge (ACK) all received messages immediately. The ground station need not acknowledge received messages. Whenever ICE-Cap SV receives a message, it acknowledges the message by sending a standard ACK message. The payload indicator of the acknowledgement message will consist of (0x01) to indicate acknowledgement. The last four bytes of the ACK message payload are reserved for the return argument from the executed real time command.. Figure 8 shows the flow diagram for generating the ACK/NACK message.

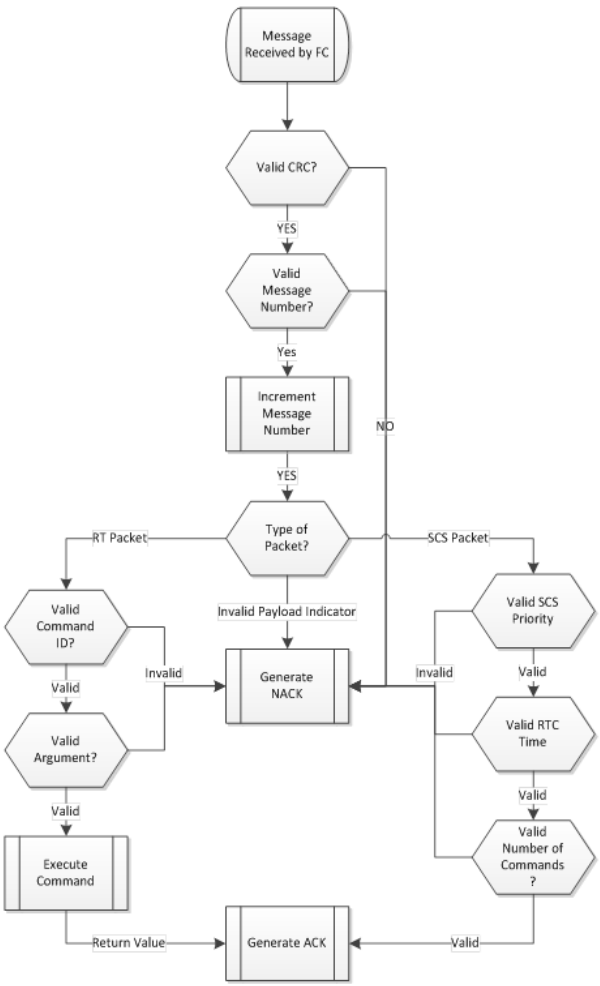

Figure 8: ACK/NACK Generation Logic

Stored Command Sequence Structure – Individual ICE-Cap missions are generally of short duration. When a mission is scheduled to be carried out, a burst of commands must be executed in short proximity. Individual real time commands are combined into sequences to be executed at a default real time (Figure 9).

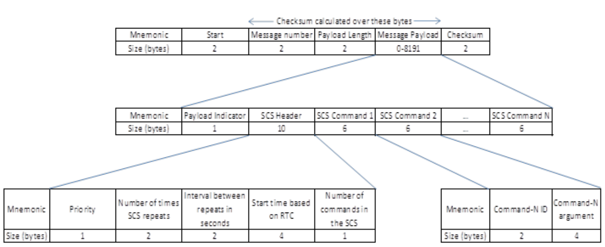

Figure 9: Stored Command Sequence Message Structure

SYSTEM TEST PLAN

The ICE-Cap has three fundamental levels of testing: hardware environmental testing, software testing, and integrated system level day-in-the-life testing. The test sets will be conducted with analysis and any adjustments, if necessary, will be made before the final delivery for the launch.

Hardware Environmental Testing

The integrated ICE-Cap hardware has completed through a series of environmental testing to provide confidence in flight-readiness. The majority of the environmental testing is conducted at the Space Micro facility, the ICE-Cap SV system integrator. The hardware environmental testing includes:

- Vibration Testing – Vibration testing was performed with respect to General Environment Verification Standard (GEVS). Critical subsystems, and high risk components such as the deployable high gain antenna, were tested independently prior to integration.

- Thermal operations – multiple cycles of operations in thermal extremes at operational and safety limits were performed. Some of the testing was conducted at vacuum.

- RF antenna characterization was accomplished at the outdoor antenna range at SSC PAC.

Software Testing

All flight software has undergone developmental, unit, and functional testing conducted by SSC Pacific, Space Systems engineering group.

Static Testing – Code and peer reviews are done by the programmers informally. Code validation software is written by the developers to validate the functions implemented.

Unit Testing – Unit testing is a software verification and validation method in which a programmer tests individual units of source code and verifies expected operation. A unit is defined as the smallest testable part of an application. This could be at the function level, class level, or module level. These types of tests typically deal with verifying that the code correctly handles arguments that pass into the code and verifies error handling for unexpected arguments.

For ICE-Cap Flight Software, unit testing will be a formalized test event utilizing CUnit, a system for writing, administering, and running unit tests in C language, a general-purpose programming language. Unit tests will be generated, executed, and reported as part of the standard reports submitted to the project team. Unit tests are designed, implemented, and reviewed before code is implemented. Additionally, unit tests are added, refined, or updated as code changes, environment changes, or software defects identify gaps or inconsistencies.

Unit tests are the foundation for code implementation and determine when the code is complete. Code is not considered complete until all defined unit tests pass. This is considered white box testing and is typically done on an uncontrolled development workstation. All unit tests will be developed, reviewed, and approved as a team (peer team review). Unit tests are coded with the purpose of maximizing value-added code coverage using C and added to the CUnit framework. CUnit tests are executed as part of the build process. Full unit test metrics including volume, pass/fail, and coverage are reported at each review meeting.

Integration Testing – Integration testing is a software verification and validation method in which an entire application or system is built and verified for expected operation. All software components, modules (including third party applications), and dependencies of the system are built and verified that all pieces of the system function as expected when combined. This testing activity requires complete, passing unit tests as an input and prepares the software for full functional and system validation. It is the transition activity out of individual workspaces and into the semi-controlled continuous integration server.

For the ICE-Cap Flight Software project, integration testing was conducted at least weekly. Each day all code was checked into Subversion (SVN). The tester extracted the latest source code from SVN, compiled all components, and if compilation was successful, generated all necessary build files. The build then was deployed, all integration test cases were executed, and results distributed to the team. If any of the integration tests failed, the build was then labeled as "Bad" and the team worked to resolve the issue in preparation for the next build. The team decided the frequency of integration testing due to the repetitive nature of the build and test. Ideally, all builds and integration tests must be automated.

Functional Testing – Functional testing is a software verification and validation activity in which software functions and requirements are validated. Functional testing ensures that each requirement is met and that software operations and algorithms function as defined by the software requirements. A "good" build as defined by the integration testing phase above and a successful deployment is required as the input into this process.

System Testing – System testing focuses on the complete flow from creation through completion. These test cases serve to mimic user functionality. They are less concerned with specific functionality and more focused on transitions between states, components, modules, features, and supporting applications. System test cases will be manually generated and executed. Once manual execution is successful and all defects have been resolved, the test cases can be automated. System test case automation is done by running a defined scenario for one or multiple days.

LAUNCH AND ON-ORBIT OPERATION

At launch, the ICE-Cap Payload is stowed in the CubeSat Dispenser attached to the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Ring. While stowed in the CubeSat Dispenser, there is no power to the ICE-Cap Payload. Power systems are inhibited by the deployment switch while stowed in the deployment pack. After the ICE-Cap is deployed from the QuadPack dispenser, the ICE-Cap flight software operational timer is set for 30 minutes, after which the antenna deployment and the checkout begin.

Once safe launch and deployment occurs, ICE-Cap will begin the on-orbit checkout. The four monopoles of the low gain antennas will be deployed individually by activating four burn wires with an interval of 30 seconds per antenna. Once the low gain antenna is deployed successfully, the FC will send a command to deploy the High Gain antenna. Once the flight computer verifies both antennas are successfully deployed, the legacy radio will begin to transmit periodic beacon messages and wait to receive a command from the ground. At the same time, the Attitude Determination and Control System (ADCS) will begin to de-tumble the satellite and point the high gain antenna towards the earth.

After successful link establishment from the SV to GS, ICE-Cap will proceed with mode transition and start scheduling missions. Once the GS verifies all systems are functioning as expected, the GS will begin the on-orbit technical demonstration. In order to participate in the technical demonstration, participants need Military UHF SATCOM RF front-end equipment (tracking antenna preferred) and a computer with an appropriate SW suite that can be requested through SSC Pacific.

ACKNOWLEDGMENTS

- U.S Army Space and Missile Defense Command (SMDC) for providing the Operational Nanosatellite Effect (ONE) satellite for this effort.
- Air Force Research Laboratory for collaboration and contract oversight on the cryptographic unit.

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