University of Colorado Boulder
Department of Aerospace Engineering Sciences
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Project Design Document (PDD)

Deep-space Orbital Telecommunications (DOTCOM)

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Approvals

Role	Name	Affiliation	Approved	Date
Customer	Benjamin Kragt	GA-EMS Satellite Systems Engineer	Benjamin Kragt	Digitally signed by Benjamin Kragt Date: 2020.09.14 16:27:33 -06'00'
Customer	Tommy Romano	GA-EMS Director of Engineering	TOmmy Romano	9.14.20
Course Coordinator	Jelliffe Jackson	CU/AES		

Project Customers

Benjamin Kragt Benjamin.Kragt@ga.com 720-255-0900	Tommy Romano Tommy.Romano@ga.com 720-545-0874

Team Members

Tristan Liu tristan.liu@colorado.edu 703-963-3109	Hunter Rohlman huro6781@colorado.edu 720-353-0471
Jennifer Gurtler jegu5171@colorado.edu 720-454-7668	Douglas Brough dobr2274@colorado.edu 303-656-5890
Buck Guthrie jagu2282@colorado.edu 303-726-4187	Caelan Maitland cama2924@colorado.edu 612-819-5460
N. Sebastian Damm nida5622@colorado.edu 805-807-7975	Conner Lewis cole8123@colorado.edu 720-243-9029
Forrest Jordan fojo3298@colorado.edu 970-237-0994	Sam Taylor sata5601@colorado.edu 303-883-8722

1. Problem Statement

With three Mars missions taking off this summer and the planned Lunar Gateway and Artemis projects set to launch in 2024, Lunar and Martian exploration has reached an operational tempo not seen since the 1960's. As the Lunar and Martian space becomes increasingly crowded, there is a growing need for reliable and high data rate communication between the Earth, Moon and Mars. The aim of this project is to create an architecture and mission concept to address this need through the use of RF and laser communication technology. The scope of the DOTCOM project includes command and control, collection and relaying of data, and ultimately supporting human exploration around Lunar and Martian orbit and on the surface through the design of satellite constellations. The project will develop the mission concept and architecture in an efficient, reliable, scalable and cost effective way to meet the needs and enable technological advancement for Lunar and Martian applications. While providing the high level mission architecture, the DOTCOM group will also focus on creating a simulation of this network that will be scalable to the overall mission objective. This increased communication capability will allow scientists and engineers to expand their capabilities in orbit and on the surface of these objects. The increasing usage of martian and Lunar space could outpace the current communication capabilities provided in part by NASA's Deep Space Network. Through the use of RF and Laser communication technology, this project aims to address the need for reliable and high data rate communications between the Earth, Moon and Mars.

2. Previous Work

A. General Atomics

General Atomics (GA) is a defense and technology company started in 1955. GA has and continues to develop technologies for energy systems, unmanned aircraft systems, and commercial products. One of the most recent developments out of GA is their Airborne Laser Communication System (ALCoS). This laser system is currently in testing and in February 2020, GA tested the ALCoS from an observatory in the Canary Islands and successfully closed a link with Tesat-Spacecom's (TESAT) Laser Communication Terminal 135 (LCT 135) on the Geo-synchronous Earth Orbit (GEO) satellite Alphastat [8]. ALCoS is the first step in delivering Low Probability of Intercept (LPI) and Low Probability of Detect (LPD).

B. European Data Relay Satellite System

In the past twenty years there has been a large increase in the number of satellites and space missions in lunar and Martian space. With the advancement in technology and deep space communications, and the help of private and government funded space programs, there are more satellites in space than ever before. As the aerospace industry grows, there is an ever growing need for reliable and high data rate communications between the ground and satellites as well as inter-satellite communication. Right now there are satellites in low Earth Orbit that receive data for a number of tasks including but not limited to: Precise and long-term weather forecasting, High-precision climate modeling, Ecosystem monitoring, city and transport planning, and support in the event of a disaster [2]. Conventional radio transmission allows for a certain window where data can be relayed from the ground station to the satellite or vice versa. This transmission window only allows for a certain amount of data to be transmitted due to the limitation of the transmission speed. However, the European Space Agency has been developing the European Data Relay Satellite System (EDRS) also known as Europe's space data highway to solve this problem. The EDRS is a constellation of geostationary communications satellites that will communicate with a relay satellite, located at 36,000 km above Earth, that is in permanent radio contact with the ground stations. The relay satellite will link to the Low Earth Orbit constellation via high-performance laser communication.

In late January, 2016 the European Space Agency (ESA) launched the European Data Relay Systems first laser terminal, EDRS-A. The satellite was initially positioned around 36,000 km over the equator and eventually found its final geostationary orbit, positioned at 9 degrees E over Europe. EDRS is one of the largest telecom programs taken on by ESA. The ESA partnered with Airbus Defense and Space and the DLR German Space Administration to aid in operating the service and to fund the development of the laser terminal, respectively. The EDRS will be able to relay user data almost in real time at a rate of 1.8 Gbit/s. The first step is to have two relay satellites (EDRS-A and B) over Europe and then two additional satellites over Asia and America to complete EDRS and ensure real-time data transmission anywhere in the world.[2]

C. Network Protocols

NASA space networks, such as the Near Earth Network (NEN)[1] and Deep Space Network (DSN)[6], have historically operated on a strategy that is very labor intensive. The NEN employs modified Internet Protocol (IP) that rely on continuous data connections and relatively short round trip data times. To engineer around the limitations posed by these IP protocols, direct human management is required. Data transfer is often managed and scheduled manually by a communications team so that data is sent only while a spacecraft has access to a network connection. In addition, a failed data transfer often requires a manual resend by the ground team. This communication strategy becomes risky, labor intensive, and cost limiting as network sizes increase [3]. These restrictions have lead to the development of new network protocols that address IP's limitations.

Delay tolerant networking (DTN) is a network protocol strategy that routs data over networks where permanent end-to-end connections may not be available. DTN is also effective in environments with large round trip data latency. Space communications are often characterized by a lack of instantaneous end-to-end paths, and are prime candidates to run DTN protocols. DTN is based on a store and forward philosophy. Data is sent in small bundles, which can be stored in various nodes of the network and then forwarded on once a connection to the next node has been established [4]. The Deep Impact Network Experiment (DINET) run by NASA in 2008 was designed to elevate DTN protocols to a technology readiness level 8 (TRL 8). A technology with a TRL 8 is a 'flight qualified' technology [7]. To further advance DTN technology, NASA has created the Interplanetary Overlay Network (ION). ION is an implementation of DTN bundle protocol that NASA has designed specifically to operate in a spaceflight network [3].

3. Specific Objectives

The DOTCOM project will develop and test a network architecture capable of transmitting, receiving, storing, and handling simultaneous and non-simultaneous communications with multiple ground based nodes, with a node being any device capable of utilizing the network architecture. The capabilities of the network will be scalable to long range communications between surface based instruments and orbiting satellites.

Table 1 below details the levels of success for the project. Level 1 outlines the minimum operational capacity of the network. Level 2 begins to incorporate the desires of General Atomic and displays the network's proficiency. Level 3 and 4 are an ideal scenario with the network architecture displaying its full capabilities with the applicable hardware and fully satisfy the customers requirements.

Level	Software	Hardware/Electronics	Testing
1	Network is capable of transmitting, receiving, storing, and handling non-simultaneous communications between nodes.	Simple network hardware implemented in order to support software goal of handling non-simultaneous ground-based communications.	Run communications network on each node and test communications capability between stationary nodes.
2	Less than 1 second delay on data relay. Can Command ground vehicles.	Hardware solution receives scalable range architecture in order to facilitate expansion to larger systems.	Test command capability of network through use of TBD vehicle.
3	Network will receive, process, and transmit simultaneous communications to/from 2 nodes and store & forward to/from 2 nodes. 500 Mbps bandwidth.	Basic (2+) simultaneous connectivity lanes implemented. Hardware throughput high enough for light-time +1 sec relay to 2+ nodes.	Test and sort simultaneous communication to/from TBD nodes with specific command order and command destination.
4	Capable of handling simultaneous communications to/from 25 and store & forward to/from 50 nodes. 5 Gbps bandwidth.	Hardware throughput is expanded in order to support long range (TBD) comms with TBD simultaneous connectivity lanes.	Long range test conducted at TBD rancge to further analyze scalability of network architecture.

Table 1 Project DOTCOM Levels of Success

4. High Level Functional Requirements

4.1 Functional Requirement

The high level functional requirements of project DOTCOM are tabulated below. These functional requirements will be tested and verified through a scalable project model and simulation method.

1	Communication architecture must be capable of collecting and linking simultaneous and non-simultaneous communications data between the Earth, Moon, and Mars.
2	Satellite constellations around Moon and Mars must be able to provide communication and vehicle control capabilities on their surfaces and in their orbits.
3	Communication network must ensure safety of and be collaborative with existing and future communications infrastructure.

Requirement 1 addresses our need to design a network architecture that allows for communication links between the Earth, Moon, and Mars. The architecture must be able to provide real-time relay of data between mission segments on all three planetary bodies. This architecture shall link Earth-based commands to the Lunar and Martian environments, on or within 1000 km of their surfaces. Additionally, General Atomics asks for communications data transfer rates between the planetary bodies to meet a certain standard. Martian-Lunar communications must meet a threshold rate of 50 Mbps, with an objective rate of 500 Mbps, and Lunar-Earth communications must meet a threshold of 500 Mbps, with an objective rate of 5 Gbps.

Requirement 2 encompasses a number of design requirements in regards to surface and orbital coverage. In order to make communication viable between each planetary body, there must exist satellite constellations that can provide >99% global surface telecommunications coverage of the Lunar and Martian surface, with continuous telecom availability for >99% of Lunar and Martian surfaces and orbits. In addition to providing coverage to a number of Lunar and Martian locations in orbit and on the surface, this network architecture must also be capable of providing communications support for vehicles in orbits and on surfaces.

Requirement 3 refers to the adaptability of this project and its desired future uses and applications. General Atomics is a satellite and space systems company, and they require this project be compatible with a number of other existing and future communications projects. As a company contracted by NASA and the US government, they require the DOTCOM architecture to be compatible with existing NASA architecture, as well as provide support for Lunar Gateway communication signals and government and/or commercial communications infrastructure. It must also not interfere with the operational capabilities of the Lunar Gateway in any way. In order to ensure safety, the mission must comply with FTC and ITU regulations and take no more than 20 launches to achieve operational capacity. GA-EMS's expectations are that a project of this magnitude can be scaled such that it reaches 50% operational capability by 2030 and 100% operational capability by 2035. Designing launch protocol that would send up these satellite constellations is outside the scope of this project.

4.2. Concept Of Operations (CONOPS)

This mission is expected to have four primary steps of operation.

1. A signal originates from a ground station on Earth with the intent to communicate with a unit on Mars. The signal contains both the actual communication as well as network protocols to identify the specific destination of the signal.

2. The signal is sent first to a centralized orbital platform, the structure of which is to be determined. There, the signal is interpreted based on the signal's destination, and attitude control of the orbital platform shall be performed as necessary.

3. The signal is relayed to the satellite constellation in Martian orbit. After further interpretation, the signal may be distributed amongst the constellation to ensure that the signal can be transmitted to its destination promptly.

4. The signal is transmitted to its destination, which may be a unit on the Martian surface or in orbit. This system shall be equipped to handle multiple transmissions at once, with the goal of 10 surface units and 15 orbital units using simultaneous communication, and 20 surface units and 30 orbital units using non-simultaneous store and forward communication.

This system shall be capable of working in reverse to allow for return signals, as well as have a comparable architecture in lunar orbit. The communication system to be designed, built, and tested in this project considers a narrower scope, and shall fulfill the role of the system described in step 4. Illustrations of the broad and narrow-scoped portions of this mission are shown in Figures 1 and 2.

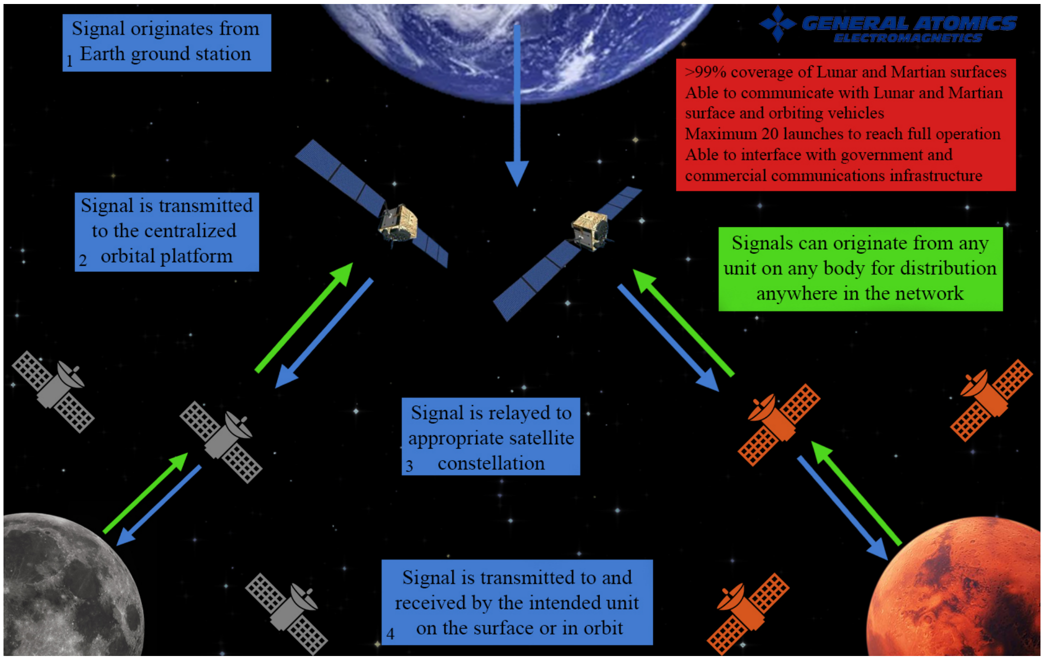

Fig. 1 High-level concept of operations for the communications network. The design, build, and test portion of this project will focus on step 4.

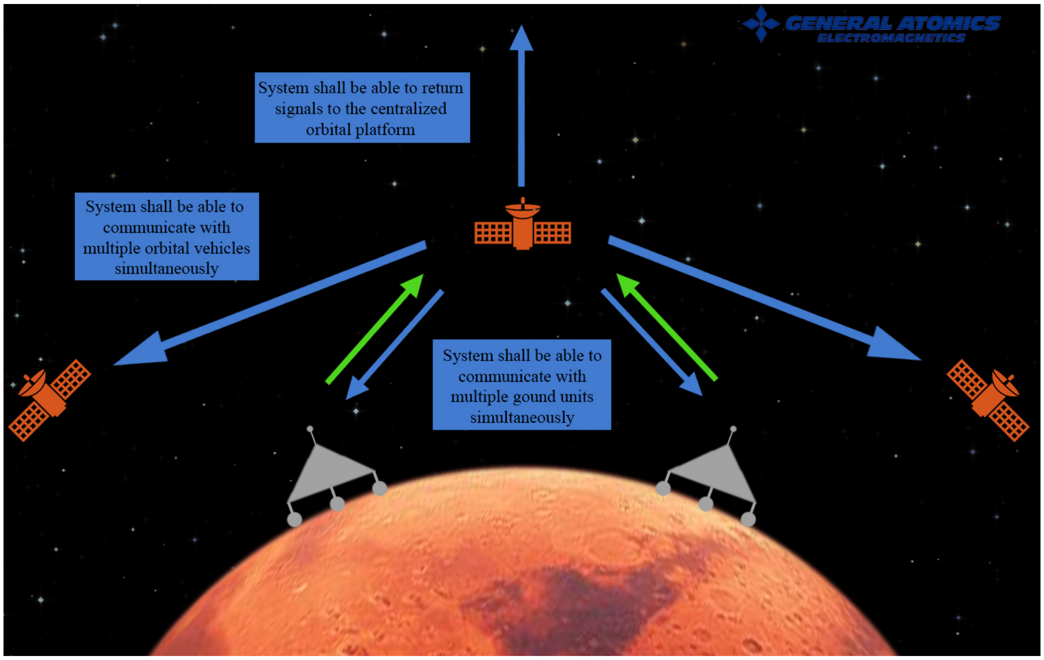

Fig. 2 Narrow-scope concept of operations for the communications system to be developed for the project

5. Critical Project Elements

5.1 Network Protocol

This project will be focused on the transmit/receive the signal on the surface or in orbit. The communication network will be the signal transmit/receive to one of the satellite in orbit then it transmits/receives the signal to the satellite constellation or vehicles on surface. The network is required to transmit the signal to the constellation or vehicle from Earth ground station, and the ground station also willing to receive the signal from the constellation or vehicle.

5.2 Communication Software

The software onboard this mission is critical to its successful operation. The software will interpret incoming signals, including the ultimate destination of a signal, as well as provide control to the satellite in order to assure the signal reaches said destination. This software shall be constrained by established communication protocols, which it must be capable of adhering to in order to interface with existing communication systems.

5.3 Communication Hardware/Electronic

The critical part of this mission is transiting data for a long range communication in simultaneous and non-simultaneous. The electronic supports the software to operate the satellite communication system. The communication hardware will receive the command from the communication software then transmit/receive the signal either to the constellation or the vehicles.

5.4 Satellite Constellation Architecture

The physical structure of the satellite constellation must be designed in such a way that successfully supports the communication hardware and allows it to be used properly. This includes both the hardware design of the satellites as well as their orbital design. The satellite hardware will provide power to the communication hardware, and its attitude control will provide pointing direction as necessary. Meanwhile, the orbital design of the constellation will distribute the communication hardware to allow it to carry out its objectives, including transmitting signals anywhere in the network, providing near total surface coverage of the Moon and Mars, and allowing communications to be consistently available. The constellation architecture is constrained by a maximum of 20 launches, after which it must be fully operational. This portion of the mission will only be designed theoretically, and will not be built or tested.

5.5 Testing

The function of the communications software may be tested using contrived signal inputs, with the software being assessed against the desired outputs appropriate for the contrived signal. The communications hardware will be tested on Earth under controlled conditions. Tests will be run to assess the ability of the hardware to transmit/receive signals as designed. Additional tests will be run to assess the entire system's ability to process multiple signals at once as well as store signals for future transmission.

6. Team Skills, Interests, and Resources

Team Member	CPE Interested In	Relevant Skills/Interests	Resources
Douglas Brough	5.3,5.4,5.5	Electronics, Prototyping, Testing, Dynamics, Controls	TF for ASEN 3300, Access to AERO Building, Arduino, SDR, Contact with Senior Project Advisor for Electrical/Computer Engineering
Hunter Rohlman	5.1,5.2 5.3, 5.5	Software, Electronics, Prototyping, Hardware	
N. Sebastian Damm	5.1, 5.3,5.4,5.5	Electronics, Hardware, Dynamics, Prototyping	Access to ITLL EC and EFC, Arduino Kit, HD3D Printers
Jennifer Gurtler	5.1, 5.2, 5.3, 5.5	Software, Hardware, Prototyping, Testing	Arduino
Caelan Maitland	5.2, 5.3, 5.4, 5.5	Electronics, Hardware Prototyping, Testing	Access to AERO Building, Arduino
Conner Lewis	5.3, 5.4, 5.5	Electronics, Orbital Mission Design, Hardware Construction/Testing	Access to AERO Building
Buck Guthrie	5.1, 5.2, 5.3, 5.5	Software, Electronics, Prototype Design and Testing,	Access to ITLL, Know a Subject Matter Expert (SME) works on RF and satellite communications
Tristan Liu	5.2, 5.3, 5.4	Software, Electronics, Prototyping and Design, Link Budgets, Dynamics and Controls	Access to AERO Building, contacts that work on Starlink
Sam Taylor	5.1, 5.3, 5.4	Electronics, Link Budget, Design	Work for Voyager Space Holdings w/ contacts to Altius Space Machines
Forrest Jordan	**5.1**, 5.2, 5.3, **5.4**, 5.5	Spacecraft Dynamics and Control, Software, Hardware, Systems Integration	Access to a wood-shop and C4C meeting space. Contact with a Ball Aerospace risk assessment manager and systems engineer

7. References

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