Three Corner Sat Constellation – New Mexico State University: Communications, LEO Telecommunications Services, Intersatellite Communications, and Ground Stations and Network

S. Horan and B. Anderson
New Mexico State University
Klipsch School of Electrical and Computer Engineering
Box 30001, MSC 3-O
Las Cruces, NM 88003-8001
Phone: (505) 646-3012
E-mail: shoran@nmsu.edu and boanders@nmsu.edu

B. Underhill, A. Friedman, J. Wong, and H. Reed
Arizona State University
Mechanical and Aerospace Engineering
Box 87-6106
Tempe, AZ 85287-6106
Phone: (480) 965-2823
E-mail: brian.underhill@asu.edu, assib@imap1.asu.edu, joyce.wong@asu.edu, and helen.reed@asu.edu

E. Hansen and D. Rodier
University of Colorado, Boulder
Dept. of Engineering and Applied Science
Campus Box 520
Boulder, CO 80309-0520
Phone: (303) 492-3141
E-mail: elaine@rodin.colorado.edu and rodier@colorado.edu

Abstract. The Three Corner Satellite Constellation is part of the AFOSR/DARPA University Nanosatellite program. This project is a joint effort among Arizona State University (ASU), University of Colorado at Boulder (CU), and New Mexico State University (NMSU). The constellation will consist of three identical nanosatellites, that will demonstrate stereo imaging, innovative command and data handling, and formation flying with RF communications and a possibility of cellular phone communications through LEO telecommunications satellites. To achieve mission objectives, the satellites in the constellation and the ground communications network will need to be designed as a cooperative communications and control network that will allow the satellites in the constellation to form a virtual formation. In this paper, we will present the necessary communications and control architecture for the space segment and the ground segment to form this virtual formation that are NMSU's responsibility in the program. Companion papers describe the respective areas of responsibility of the other partners: ASU -- Project Management; Electrical Power System; Structures, Mechanisms, Thermal, and

Radiation; Attitude/Orbit Determination and Control; Micropropulsion experiment; and Integration; CU -- Command & Data Handling, Distributed Operations, Stereoscopic Imaging, Science Operations, and Spacecraft Operations.

Introduction

In this paper, we describe the communications architecture for the Three Corner Sat (3⅄Sat). We will begin by providing a brief overview of the initial opportunity that was presented and which resulted in formation of the 3⅄Sat project. Next, a summary of the 3⅄Sat mission goals will be presented. Based on the mission goals, further details on the initial concepts for the space segment and ground segment communications system will be presented. Challenges to the design and areas of system tradeoff will be presented.

Overview

3⅄Sat is a constellation of satellites to be built by Arizona State University (ASU), University of Colorado at Boulder (CU), and New Mexico State University (NMSU). A proposal requesting Air Force Office of Scientific Research / Defense Advanced Research Projects Agency funding for this project was submitted under the University Nanosatellite Program, a Special Topic of the Broad Agency Announcement on the Air Force Research Lab TechSat 21 Initiative. The TechSat 21 concept 'involves satellites flying in formation that operate cooperatively to perform a surveillance mission'. Five basic areas of research were identified to support this concept, as follows:

- Micro-Propulsion
- Sparse Aperture Radar
- Micro-Electro-Mechanical Systems
- Ionospheric Effects
- Collective Behavior of Intelligent Systems

The University Nanosatellite Program is funding ten university 'research projects centered on the design and demonstration of nanosatellites', defined as sizes from 1 – 10 kg. The awards are 'for universities to design, assemble, and conduct on-orbit experiments for these satellites.'

Mission Objective

The primary mission objective of the 3⅄Sat is to stereo image small (< 250 meter), highly dynamic (< 1 minute) scenes including deep convective towers, atmospheric waves, and sand/dust storms. The result will enable the computation of a range to within 250 meters giving accurate data regarding the shape, thickness and height of the observed phenomena. There are several advantages of using stereo imaging from space over conventional imaging. The first of which is to derive range data which can be substantially more accurate than range data acquired by other more usual means and also cover a much greater area. The three nanosatellites will allow for the use of triangulation. The triangulation can be used to determine accurate range data and three-dimensional images allowing depth maps to be created.

To accomplish the primary mission objective, a "virtual formation" is proposed and will be demonstrated as part of our program. The virtual formation will be a cooperative effort between satellites operating as a network where targeting and data acquisition are accomplished. These results are transmitted to the ground segment and to the other satellites via communications links without the need for strict physical proximity of the satellites. Operation in this mode allows the communication links to carry the command and control data necessary to accomplish the mission regardless of the physical location of the satellites. The locations of the satellites will need to be "in range" and mutually known in order for each to support its portion of the mission, but physical proximity is not a requirement for the formation network. For accurate stereo imaging, the satellites must have a nominal spacing of tens of kilometers between them. With a controlled deployment to achieve this initial spacing, the satellites will remain in range for the lifetime of the mission, which is suggested to be four months. Given this initial spacing and lifetime, propulsive capability is not needed.

Besides the conventional RF communication links, the concept of using existing commercial telecommunications network assets in Low Earth Orbit (LEO) is of considerable interest by the government and private-sector space communities. This capability would allow government and private sector users to consider the ways to transition space-to-ground communications away from closed, proprietary networks to generally available, commercial networks. The baseline design for the 3◭Sat will be to incorporate the use of these LEO telecommunications networks for communications and operational coordination as one of the primary experiments for the constellation. Using the LEO tele-communications network has the definite advantage of providing extended coverage relative to direct-to-ground broadcasts. With the LEO networks, the 3◭Sat constellation members can be contacted regardless of their position relative to the ground station that has predictable visibility outages relative to the ground station. The communications networking influences the design of the Command and Data Handling System (C&DH) which now must be designed as a part of a distributed system. The distributed arrangement allows each satellite to use a Satellite Processor Board that serves as its local controller, data interface, on-board memory, and processor. By proper design and integration of the communications interfaces, the 3◭Sat constellation can be controlled and managed by a processor on any of the three satellites via the communication links.

Sensor Suite

The science mission will be based around imaging of cloud formations from orbit. The primary imaging camera will utilize CMOS active pixel array technology as described by Hansen[1]. There will be two images formed per satellite and the total complement of images from all three satellites in the constellation will be combined in ground processing to form the composite stereo image. The command and telemetry system will need to coordinate image acquisition and transport for all three satellites

Propulsion Experiment

The Arizona State University satellite component of the constellation will need to have command and telemetry support to perform the propulsion experiments planned for that particular satellite as described by Underhill[2]. These are added capabilities over that required for the other two satellites in the constellation.

Spacecraft Management

The command and telemetry system will also need to support the spacecraft management system as described by Hansen[1]. This will include file transfers, command transfers, and spacecraft telemetry functions. The management communications will need to accommodate both direct links between the individual satellites and ground stations but also inter-satellite communications.

Communications Architecture

Current plans call for three means of communication within the 3⅄Sat constellation and ground network: space-to-space, space-to-ground, and a ground-to-ground network as illustrated in Figure 1. In this section, we will outline the initial concepts for these links.

The space-to-space communication link will basically allow the nanosatellites to communicate with one another or allow a user to access one nanosatellite via a different nanosatellite. The design for this link is to use commercially available radio technology to realize this link. Generally, these are not intended as high-bandwidth links but will exchange short, packet-type of communications.

The space-to-ground communications link will be designed to allow a specific nanosatellite to communicate with its respective ground station and vice versa. Each nanosatellite will nominally be controlled from its respective owner university. However, cross-linking will permit one university to access its satellite through another's space-to-ground link.

The ground-to-ground communication link allows the one ground station to communicate with the other ground stations supporting the constellation. This link will enable the first ground station to access a different nanosatellite through that nanosatellite's respective ground station. With the ground- to-ground communication link, each ground station and nanosatellite may act as a node on the Internet.

Initial Communications Requirements Definition

The communications architecture is being described with the following baseline capabilities. The capabilities are expected to evolve as the constellation is better defined and the full capabilities that are required to support all mission phases become better known. The initial specification for the communications system is:

- Provide a Radio Frequency (RF) telemetry downlink at a minimum data rate of 9600 bits per second and command uplink at a minimum data rate of 2400 bits per second with both links having a Bit Error Rate (BER) no worse than 10^{-5}.
- The radio frequency link is to be compatible among all ground stations and all satellites to allow for cross support capabilities.
- Provide an experimental LEO telecommunications bi-directional service with a minimum data rate of 2400 bits per second in each direction and a BER no worse than 10^{-5}.
- Provide cross link capabilities between the satellites up to a link range of 30 km through either a direct radio link or via the experimental LEO telecommunications link.

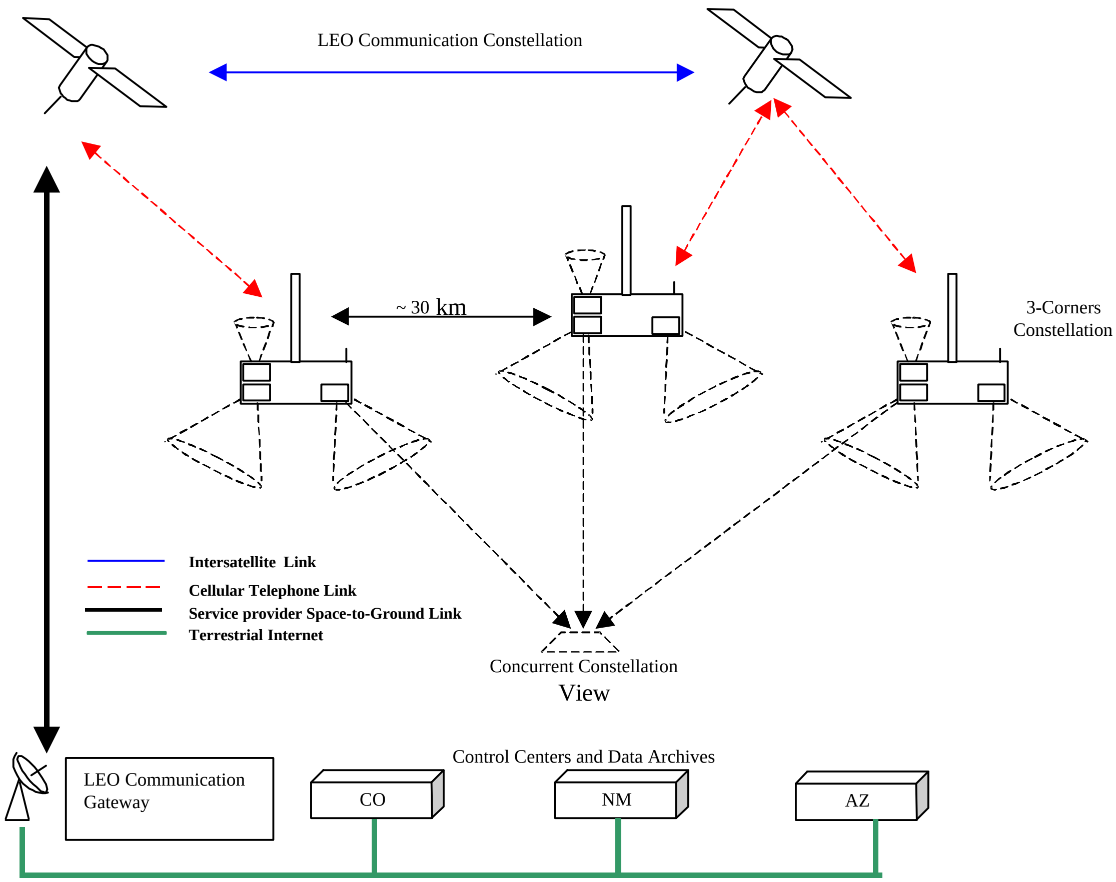

Figure 1 – Communications Architecture for the 3⮝Sat Constellation.

- Provide the means to share processed satellite and administrative data between the member institutions control centers.
- Provide the means whereby each ground station can control every satellite and provide the means whereby each satellite can link to any ground control station to send telemetry to and receive command from any other ground control station.

The RF space-to-ground and ground-to-space communications link ranges will be a function of the constellation orbit. Presently, a shuttle-type orbit at 350 km with a 51° inclination is anticipated as shown in Figure 2. However, a higher, sun-synchronous orbit at 700 km as shown in Figure 3 would be desirable from a science and attitude-control point of view. In the simulations, a 10° elevation angle was assumed for the lower operational limit during a contact. Basic link parameters for both orbit types are listed in Table 1 based on simulations conducted with Satellite Tool Kit[3] for a 30-day simulation period. These parameters will affect link power and data rate design. They will also affect data transport protocol selection. The lower orbit gives a shorter link distance thereby making the link power budget closure easier. However, the sun-synchronous orbit makes data transport easier by allowing for longer contacts. Assuming a 9600-bit-per-second space-to-

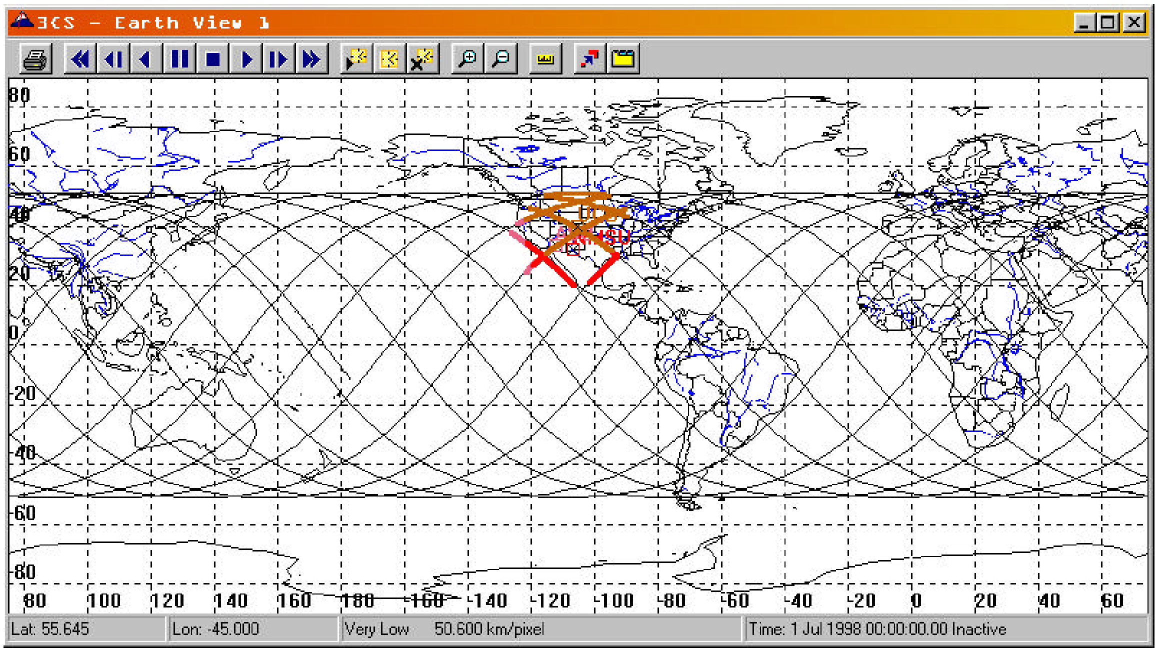

Figure 2 – Simulated 24-hour contacts between a single 3Ʌ Sat in a 350-km, 51° inclination orbit and the three university ground stations. Highlighted portions of the orbit centered around -105° longitude indicate contact periods.

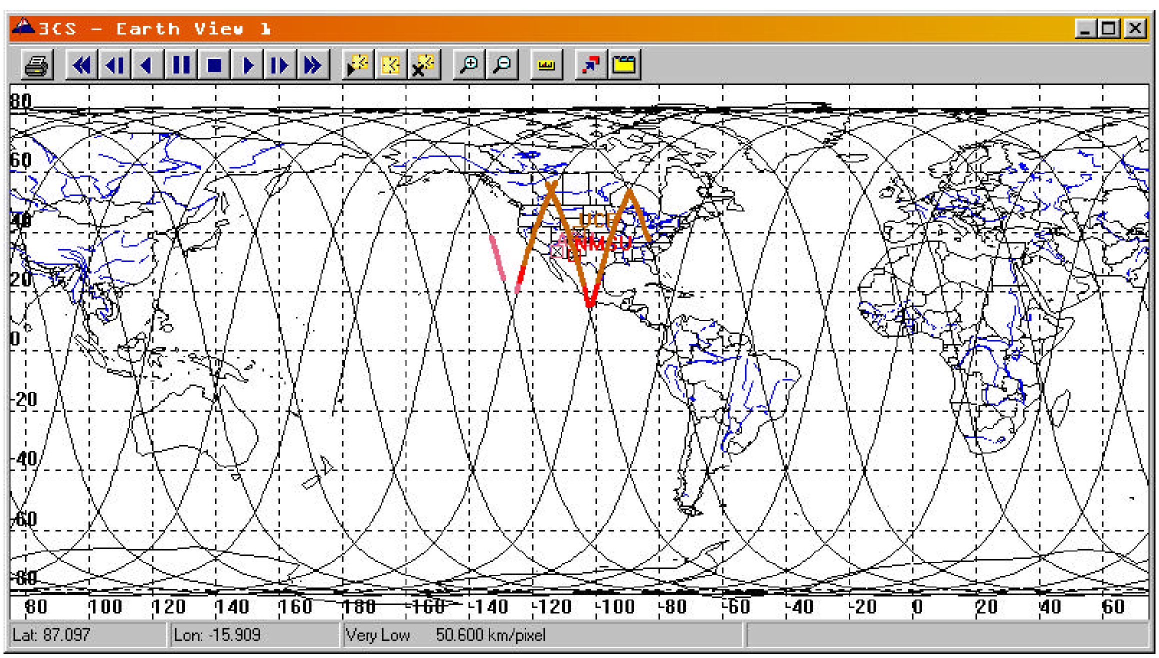

Figure 3 – Simulated 24-hour contacts between a single 3Ʌ Sat in a 700-km, sun-synchronous orbit and the three university ground stations. Highlighted portions of the orbit centered around -105° longitude indicate contact periods.

Table 1. Constellation Link Parameters		
Parameter	**350 km, 51^{o} orbit**	**700 km, sun-synchronous orbit**
Avg. contact duration (sec)	312	448
Min. contact duration (sec)	95	72
Max. contact duration (sec)	398	571
Min. link range (km)	413	705
Max. link range (km)	1485	2178
Avg. link range (km)	1149	1667

ground link data rate as a minimally acceptable data rate, the largest data file that could typically be sent during a single pass would be at most 3 Mb for the 350-km orbit and 4.3 Mb for the 700-km orbit. Because the three university ground stations are in the same geographical region, most passes are visible at all three stations at about the same time for nearly the same duration. Therefore, there will not be much of a chance to experiment with handovers from one ground station to the next to significantly extend the pass duration.

Communications Technology

1. Radio Links

The first means of communication from the ground station to the nanosatellites will be through standard RF technology. There are a variety of frequencies allocated to our specific purpose. The design process now needs to finalize frequency selection driven, in part, by choices in affordable equipment and reasonable antenna sizes for both the space segment and the ground segment. For the ground-to-space RF communication link, we anticipate applying for allocation in the range of 1427-1429 GHz for the earth-to-space link and 1533-1535 GHz for the space-to-earth link. For the space-to-space communication link, we anticipate applying for allocation in either the 400-450 MHz or 900-980 MHz bands. There is only one problem with the RF method of communications, the fact that ground-to-space connectivity can only occur when the nanosatellites are visible to the ground stations. The outages will be predictable but limit the amount of time communication is allowed per orbit. This will be a driver on the available bandwidth in the command and telemetry channels.

2. LEO Telecommunications Services

The concept of using cellular phones to provide the LEO telecommunications service is very promising because it will allow us to use them for the ground-to-space links, the space-to-ground links, and the space-to-space links for the entire constellation. There are two major advantages to using the commercial tele-communications infrastructure for these purposes: visibility and frequency allocations. The nature of the LEO telecommunications networks is that they have high visibility, albeit, for ground-based users only. However, depending upon the relative altitude of the 3⅄Sat constellation and the LEO constellation, there should be relatively frequent access times – more than a single ground station will give. The second advantage of using cellular phones from commercial network communications via LEO satellites is the frequency allocation is already predetermined through the government and the vendor of the commercial network.

There are also several major challenges with the LEO constellation method of communications. At the present time (summer 1999) there are only a few operational, commercial networks through LEO satellites but others are scheduled to come on line over the next few years. Depending on the relative orbits of the nanosatellites and the commercial network, these networks may or may not be a realistic means of communication. If the altitude of the nanosatellites is close to that of the LEO satellites, the amount of time the nanosatellites are within the main beam of the LEO satellites will be relatively small. This small amount of time will not provide a reliable communications method. This would happen, for example, if the 3ᗑSat were in a 700-km orbit and an attempt was made to communicate through Iridium at a slightly higher orbit.

If the nanosatellites can remain visual for a substantial amount of time to provide a reliable communication link, other problems and concerns occur. For our purpose, it is most desirable for the nanosatellites to be positioned in a sun-synchronous or polar orbit. Since the nanosatellites and the LEO satellites will most likely have different orbits and velocities, there will be a significant Doppler. Because of the possibility of a significant Doppler offset, modification of the cellular phone may be required. The design for this possibility is proceeding at NMSU to develop means for real-time Doppler estimation without *a priori* knowledge of the relative Doppler offset. The data rate of the commercial network may be sufficiently lower than expectations. To increase the data rate, multiple cellular phones consuming different channels may be used. Acquisition time to connect to the system takes approximately 5 seconds, so if the connection is lost, reconnecting to the system may be difficult. The cellular phone is the controller for making and requesting handoffs between satellites and beams within one satellite. The rate of the requests and handoffs may be much slower than the rate the nanosatellite is actually passing through the beams or individual satellites of the LEO constellation. Also, attenuators may need to be placed on the output of the cellular phones to avoid interference with other users.

While these problem areas are not trivial, we are proceeding with the design methods to overcome them and make this part of the experiment work. To date, we have been able to obtain technical information from the LEO constellation providers and this type of support will be required to complete the design.

3. Data Formatting

The data formatting for the space-to-ground and ground-to-space links is expected to be compatible with standard computer networking protocols. We are considering a baseline TCP/IP configuration for this formatting. This will allow us to consider each satellite to be a node on the Internet and make cross link communications easier to achieve. This will also maximize the potential for using other existing software in the system design. Additionally, standard operating systems such as Linux or VxWorks, which may be used in the satellite computer operating system, have TCP/IP interfaces as part of their general configuration. Recent experiments by

Horan and Wang[4] transfers using TCP/IP over a PPP serial link in a simulated space channel environment show that file transfers are possible at these data rates if the BER is kept below 10^{-5}. A BER worse than 10^{-5} introduces unacceptable link performance.

4. Ground Segment Communications

Ground segment communications between the control centers at each university will utilize the Internet to provide communications support. This will facilitate having each satellite being considered a node on the Internet as well as each control center. Data and file transfers can then proceed using industry-standard techniques for data routing across the Internet.

Conclusions

3⮙Sat is a student-run project under the AFOSR/DARPA/ University Nanosatellite Program. Three universities are teamed together to build a constellation of three nanosatellites that demonstrates stereo imaging, formation flying, cellular-phone communications, and innovative command and data handling. Launch is expected in late 2001. This paper describes the baseline concepts for the space-segment and ground segment communications architecture that are NMSU's functional areas of responsibility towards meeting the 3⮙Sat mission objectives. The satellite constellation will not permit large communications margins in the space-to-ground links to achieve the required data transport. While using commercial telecommunications links are an exciting new possibility, there are many challenges to overcome to enable the technology to be acceptable to the service providers. The companion papers by Hansen and Underhill provide ASU and CU functional areas of responsibility.

Acknowledgements

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