The Design of the Communication and Telemetry System Used by the Ionospheric Observation Nanosatellite Formation Mission

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Abstract

This document describes the approach taken by the Ionospheric Observation Nanosatellite Formation (ION-F) communication team in designing and developing a ground communication system, space communication system, and amateur communication system for three satellites in the ION-F constellation. It outlines the mission objectives, the system requirements, the theory of operation, hardware, software, communication protocols; including equipment specifications and other major aspects of the system. An important feature of the communication system is the extensive use of commercial off the shelf (COTS) components, which has lowered cost and shortened development time. This system will be adopted by all three universities.

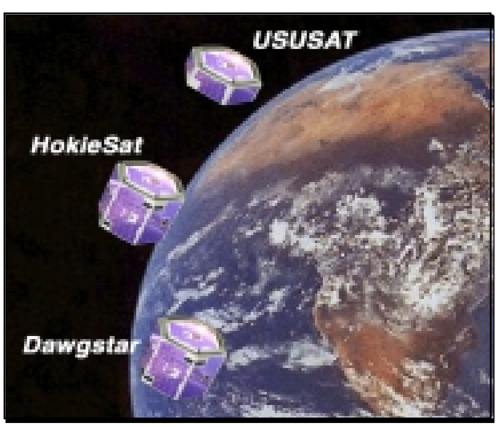


Figure 1: ION-F Formation

Key words: satellite, space communication, nanosatellite, ionosphere, space systems, inter-satellite communications, telemetry, ground station, uplink, downlink, crosslink, satellite antenna, transmitter, receiver, transceiver, beacon, amateur radio, Ham radio, GPS, terminal node controller, TNC, real-time data, link budget, PCM page.

1 INTRODUCTION

The ION-F mission consists of a constellation of three small satellites each weighing about 15 kgs. They are being constructed by Utah State University (USU), Virginia Polytechnic Institute (VT), and University of Washington (UW) students. USU's satellite is called 'USUSAT', VT's satellite is called 'HOKIESAT', and UW's satellite is called 'DAWGSTAR'. ION-F is sponsored by the AFSOR/DARPA University Nanosatellite Program, the United States Air Force Space Test Program, National Aeronautics and Space Administration (NASA), and industry. ION-F will be the first multi-satellite mission to make systematic middle and low-latitude ionospheric electron density measurements. The three nanosatellites will be released at a 370 km altitude on a 51 degree inclined orbit and they will be sharing a joint set of frequencies for the uplink, downlink, and crosslink communication channels. The frequencies will be used in a round robin fashion. Two

Figure 2: Ground Station Coverage

ground stations located at USU and VT will be jointly operating and servicing the three satellites. These locations were chosen primarily to facilitate easy student access, lower program costs, and above all, provide excellent coverage over the United States. In order to successfully coordinate the three satellites, Internet based ground stations are being developed. This will allow coordination of experiments by the three universities as well as individual satellite control and data dissemination.

Overall Mission Objectives

1. Investigate a distributed multisatellite space system for space science using cutting- edge technology.
2. Demonstrate formation flying and management.
3. Demonstrate inter-satellite communication through the use of crosslinks.
4. Demonstrate Internet based control of a multi-satellite mission.

The communication and telemetry system's mission is to command, control, and relay all telemetry, tracking, and science data among co-ordinated ground stations and satellites in the ION-F constellation with minimal error.

2 SYSTEM REQUIREMENTS

The ION-F program is a student managed, designed, built, and operated project scheduled for launch in 2002-2003 aboard the space shuttle. This is a joint effort of three universities with a goal to perform creative low-cost science, telemetry, and communication experiments. These experiments serve as a testbed for future developments and applications in the expanding field of satellite technology. The USU communication team has made remarkable progress since its inception in March, 1999. Satellite communication systems have been thoroughly researched to arrive at an advanced understanding of the field and several preliminary trade studies have been performed. It was decided early on to apply for the use of government allocated frequencies. The frequencies chosen after thoroughly reading the Federal Communication Commission (FCC) [1] regulations, the IRIG[1], and the NTIA[2] standards are 450 MHz for the uplink and 2.2 GHz for the downlink. These standards provided rules, regulations, and guidelines for frequency selection. The necessary military DD1494 Frequency Allocation Request forms were filled out to get the frequencies allocated for the ION-F mission. Simultaneously, telemetry and command systems were researched to understand how the communication system fits into this aspect of satellite operations. A survey of twenty-one small satellites and university satellite communication systems was conducted. A link analysis has been performed to understand the uplink, downlink, and, crosslink. Following the preliminary research, the on-board communication system architecture and interfaces with the command and data handling system (C&DH) were defined.[3] Hardware has been selected and preliminary failure analysis has been performed. Several formal trade studies have been performed using satellite tool kit (STK), STS Plus, UI-View, DosAPRS, qy4, and advanced design system (ADS), after which plausible values for the link budget have been obtained. This budget has become one of the major driving forces for design decisions along with low cost, mass, volume, power, thermal, and radiation constraints.

Link Budget

The link budget is a group of formulas that depict definite relationships between the various system parameters such as transmitted, received, and noise power; antenna gain/loss; free-space loss to the $\frac{E_b}{N_o}$ (energy per bit to noise power spectral density) at the detector input of the receiver [2]. Evaluating these formulas provides a quantitative insight into the communication system performance. The link budget for the ION-F project is shown in table 1.

The following requirements are the end result of extensive analysis and link budget computations:

1. The ground station transmitter should be able to transmit at 450 MHz at a baud rate of both 1200 and 9600. It should have a power output of at least 10W.
2. The ground station transmitting antenna system should provide a gain of at least 23.5 dB while the receiving antenna system on the ground must possess a gain of at least 36 dB. Both systems must be able to be rotated so that they can track the satellite at any point 5 degrees above the horizon with a pointing accuracy of 5 degrees for the uplink and 1 degree for the downlink.
3. The on-board antennas must have a gain of at least 0 dB and an acceptable radiation pattern. These antennas must have low mass, occupy optimum space, and ensure 75% communication irrespective of the orientation of the spacecraft.
4. The spacecraft transmitter and receiver should be able to withstand the space environment and

[1] http://www.herley.com/Herley-Metraplex/www/irigpcm.htm#A3

[2] http://www.ntia.doc.gov/osmhome/redbook/redbook.html

[3] http://www.aa.washington.edu/research/nanosat/docs/docs.shtml

comply with the mass, power, and thermal requirements. The on-board transmitter must have a power output of at least 1W while the receiver must have a sensitivity of 0.35μV.

5. The ground station receiver should be able to receive a 2.2 GHz pulse code modulation (PCM) signal at a baud rate of 115.2 Kbps.

3 SYSTEM LAYOUT

General Overview

The ION-F communication system can be broadly classified into three segments (see figure 4):

1. Ground Communication System(GCS)
2. Spacecraft Communication System(SCS)
3. Amateur/Public Communication System(PCS)

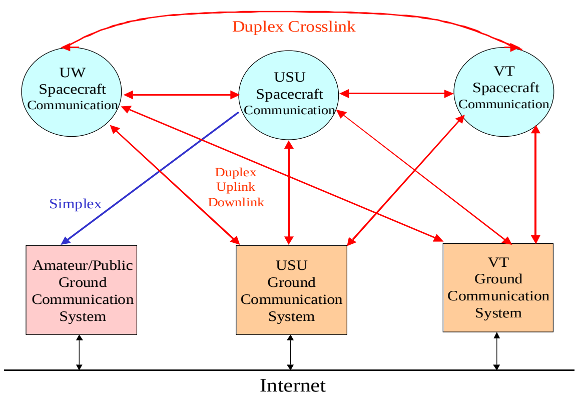


Figure 4: ION-F Communication System

The spacecraft communication system designed by USU will be flown aboard the three satellites. This communication system will also include a GPS receiver and a crosslink radio which will facilitate inter-satellite communication and will be a source of GPS information. This is supplied by Goddard Space Flight Center (GSFC) and built by Applied Physics Laboratory (APL). This is an experiment carried out by NASA. This is apart from the uplink and downlink communication, which involves communication between the ground station and individual satellites. With the help of a special space-based terminal node controller (TNC), ground commands can be directed towards each satellite without any major interference even though all three satellites share the same frequency. A unique feature of the USU communication system is that an autonomous GPS/telemetry beacon module will be flown on the USUSAT, which will provide location and health status of the USUSAT. Experimental ground stations are being set up at USU, VT, and five thousand other amateur radio sites around the world. These will closely observe, monitor, and control the satellites with the help of simple and robust ground commands. The mission will last anywhere from 6 to 18 months.

4 THEORY OF OPERATION

The ION-F communication system consists of one simplex and two full duplex links.

1. The simplex link - The GPS/telemetry beacon.
2. Duplex 1 - The uplink and the downlink.
3. Duplex 2 - The crosslink.

The GPS/telemetry beacon simplex link will use a non return to zero - inverted (NRZ-I) data format at 1200 baud audio frequency shift keying (AFSK). The modulation that will be used is simple binary frequency shift keying (FSK) [3] with NRZ-I data format on the uplink and non return to zero - level (NRZ-L) data format on the downlink. The crosslink uses spread spectrum techniques. Due to Doppler shifts, adjustments in frequency will be made at the ground stations.

4.1 Ground Communication System

The basic operation of the ground communication system (figure 5) is as follows:

As an example, a subsystem operator wishes to send a command to the spacecraft to determine the internal temperature of a particular spacecraft in the ION-F constellation. The operator requests this information

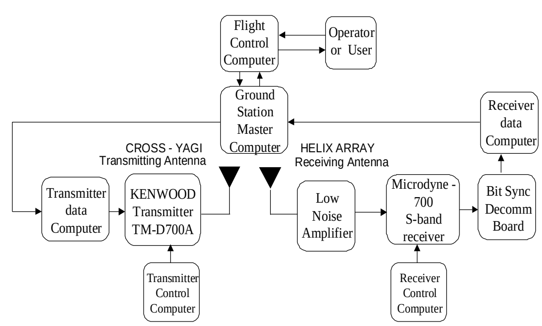


Figure 5: Ground Communication System

directly through his computer or through the flight control computer. The flight control computer then relays the information by the way of Internet, or local area network (LAN) to one of the two ground station master computers. The information is next passed to the transmitter data computer, which forwards it to the ground station transmitter, the Kenwood TMD-700A (refer to figure 6), at 9600 baud. The ground station

Figure 6: The Ground Station Transmitter

transmitter has a built-in modem/TNC, which modulates the incoming data onto a 450 MHz carrier and transmits it at 10-35W using the AX.25 protocol at 1200 baud. The modulation employed is binary FSK [4] and the data is transmitted using the NRZ-I format. The modulated signal at 1200 baud is then passed to the ground station transmitting antenna. This antenna array consists of four cross yagis (see figure 7). They

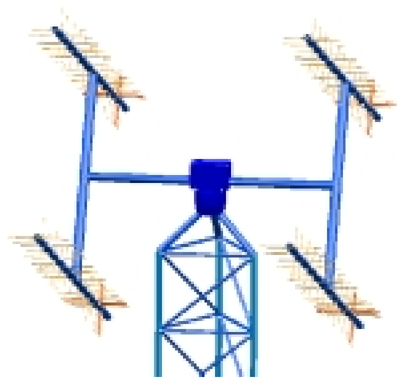


Figure 7: The Ground Station Uplink Antenna Array

are mounted on a rotor system and a 40 foot tower. This antenna array will track the satellites from 0-360 degrees in azimuth and 0-90 degrees in elevation (with 1 degree pointing accuracy) using the antenna control computer. The transmitting antenna array radiates the signal into space. The spacecraft communication system, along with the flight computer, will process the received request and send an appropriate response. The response received from the spacecraft is picked up by an antenna array of nine helixes (see figure 8), which has a gain of 36 dB. The helixes are mounted on a rotor system atop another 40 foot tower. The antenna array has a pointing accuracy of 1 degree. The signal from the helixes is amplified by a low noise amplifier (LNA) having a gain of 43 dB. It is then received by a Microdyne-700, S-band receiver[4] (see figure 9). This amplifies and demodulates the signal. Next, the bit

[4] http://www.microdynecti.com/Products/1600_700.htm

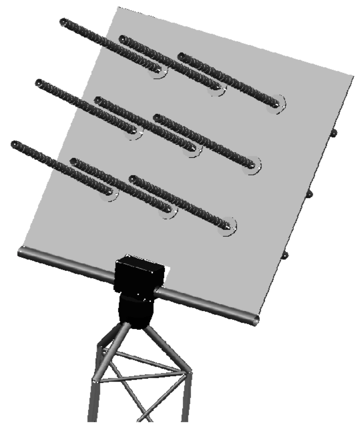


Figure 8: The Ground Station Downlink Antenna Array

sync decomm board unrandomizes the data and separates the real-time data from the other stored data. The data obtained enters the receiver data computer and is forwarded to the ground station master computer. From here it is sent to the flight control computer by means of the Internet. Thus the subsystem operator obtains the spacecraft internal temperature.

Figure 9: The Ground Station Receiver

To be able to command and control the satellites, it is important to know the position and velocity vectors as well as the spacecraft health status. The USUSAT will furnish this information to thousands of ground stations around the world via an autonomous GPS/telemetry beacon module flown aboard the satellite. In order to support this mission objective, USU has a J-pole antenna (refer to figure 10) at the ground station. The information for the J-pole antenna design is available on the Internet[5]. This omni-directional J-pole antenna will receive GPS/telemetry data and feed it, via a coaxial cable, to a Kenwood TMD-700A receiver, which is tuned to 144.39 MHz. The receiver is controlled by an automatic position reporting system (APRS)[6] computer, which flashes the GPS/telemetry

[5] http://www.packetradio.com/j-poles-unlimited.html
[6](R) registered to Bob Bruninga

information on the Internet, thus sharing it with users around the world.

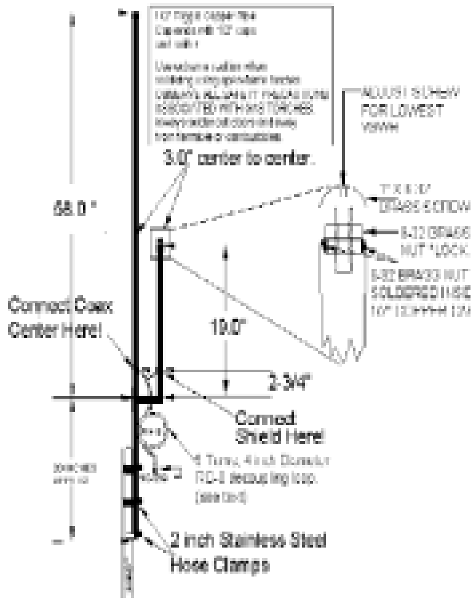


Figure 10: The Ground Station Receiving Antenna for the GPS/Telemetry Beacon

4.2 Spacecraft Communication System

Referring to figure 11 and to the previous example concerning the command requesting the internal temperature of the spacecraft, the signal arrives at a 450 MHz patch antenna on the USUSAT (Table 2) or to the nine inch loop antenna on the HOKIESAT or the DAWGSTAR. The signal obtained from the antenna is

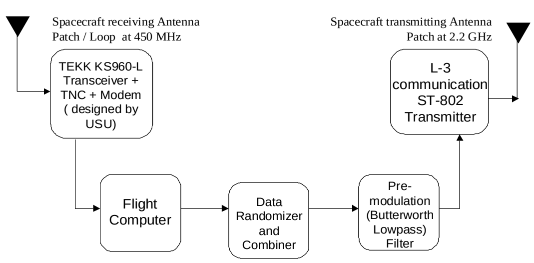
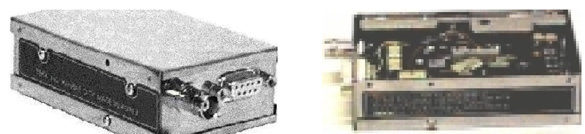


Figure 11: Spacecraft Communication System

received by a UHF TEKK-KS960L transceiver, which is modified by USU to meet the communication and space requirements. One transceiver (as shown in figure 12) will be modified and employed on each of the three spacecrafts. They are dual heterodyne FM receivers with RF channeling capability fixed on a single frequency at 450 MHz. The TEKK has two IF filters and hence two IF frequencies: the first being 21.4 MHz and the second being 455 kHz. They have RF selectivity of 70 dB and a sensitivity of -116 dBm. The thermal noise power is -153 dBm. The signal is amplified and demodulated by means of a modem/TNC. The TNC performs the cyclic redundancy check (CRC) and decodes the the AX.25 packets into an ASCII string which is then passed to the flight computer. The received ASCII



Modifications for space application
– conformal coating
– replace all electrolytic capacitors with tantalum
– epoxy/seal tuning coils (space grade sealant)
– replace variable components with fixed values
– replace BNC with SMA connector
– new Housing
– added Connectors

Figure 12: The spacecraft Transceiver - TEKK

string contains information for addressing a particular satellite as well as the command that requests the satellite internal temperature (or any other command.) The flight computer acts on the received request and checks the respective temperature sensor. The response from the flight computer enters the telemetry board in the command and data handling subsystem. This information is then passed on to an Actel field programmable gate array (FPGA), which combines real-time data with the stored data. A randomizer then converts it to a sequence of NRZ-L data. The data is next fed

Downlink Spacecraft Transmitter

L3 Comm. model ST-802 S/L

Frequency	- 2.2 - 2.3 GHz
Power Output	- 2 W
Voltage	- 28 ± 4 V
Current Drain	- 0.8 A Max
Dimensions	- 2” x 3” x 0.80”
Mass	- 200 g
Connectors	- SMA

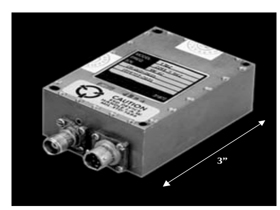


Figure 13: The spacecraft transmitter - ST802

through a pre-mod filter, which is a low-pass third order Butterworth filter. This filter converts the digital signal to analog and band limits the signal. The data then goes to the ST-802 transmitter (see figure 13) via a co-axial cable. One transmitter will be employed on each of the three spacecrafts. It is an FM transmitter with a tuning range of 2200MHz to 2400MHz. The transmitter amplifies the data stream and passes it on to the downlink 2.2 GHz patch antenna. There will be three patch antennas (figure 14) at 2.2 GHz (specs are given in table 2) on the spacecraft so that 75% communication is ensured independent of the orientation of the spacecraft. A zero degree power splitter, which is

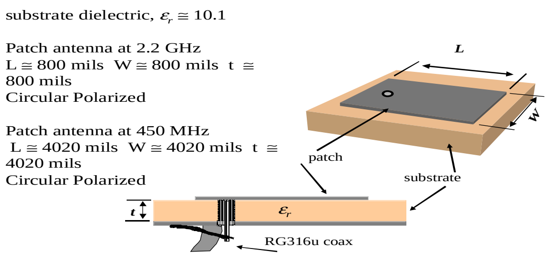


Figure 14: The Patch Antenna

a reciprocal passive device, will be used to accept one input signal and deliver multiple output signals with specific phase and amplitude characteristics.

4.3 Amateur/Public Communication System

The amateur communication system is an integral part of this communication system (refer to figure 15.) It consists of the following:

- An autonomous GPS/telemetry beacon aboard the spacecraft
- A six inch directional discontinuity ring radiator (DDRR) [5] aboard the spacecraft
- The ground station at Utah State University
- Individually owned amateur radio stations around the world
- The Internet

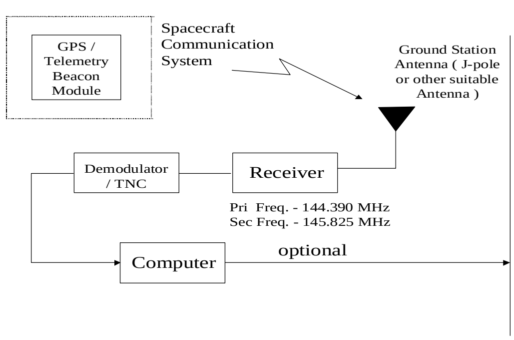


Figure 15: Amateur/Public Communication System

The beacon module (figure 16) consists of:

- A VHF Hamtronics transmitter TA-51
- A beacon controller which has a PIC 16C76 microcontroller and a 93C66 serial electrically erasable programmable read only memory (EEPROM) with the associated software
- A power controller

The beacon has five analog and eight digital channels for obtaining the satellite health status, science data, position, and velocity vector information. The complete module weighs 500 gms and operates at 12V DC drawing 550 ma max in the transmit mode. The beacon

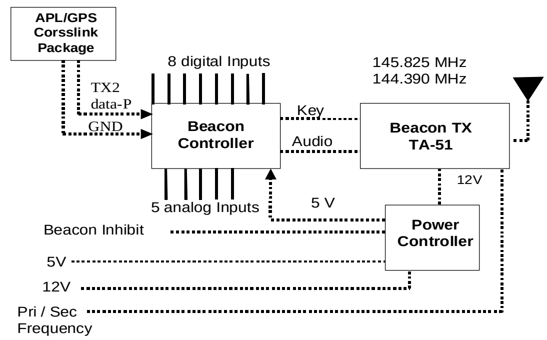


Figure 16: Beacon Module

will transmit NRZ-I [3] data using AX.25 protocol at 1200 baud audio frequency shift keying (AFSK). This module is independent of the flight computer. If the flight computer fails, the beacon continues its mission of providing data. The beacon module can be used by anyone worldwide; especially by children, helping them learn more about physics, mathematics, communication and space sciences. No form of license is required. Ground station requirements for outreach programs are very simple and as follows:

1. A VHF receiver or scanner capable of receiving 145.825 MHz or 144.390 MHz. The receiver should have a sensitivity of 0.35µV.

2. A suitable receiving antenna, which can be as simple as a piece of wire, a half-wave dipole, or a copper J-pole antenna.

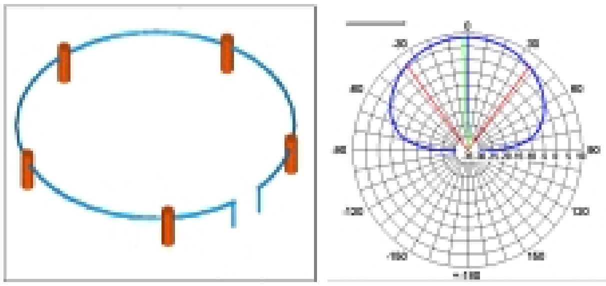
3. A demodulator designed for 1200 - 2200 Hz. A sound card could be used.

4. Any computer, but a Personal Computer is recommended.

5. Software packages that can be used are: WinAPRS, DosAPRS, UI-View, MacAPRS, Linux, and PalmAPRS.

6. Internet access is optional.

The on-board transmitting antenna for the beacon is a six inch DDRR loop at 145 MHz as shown in figure 17. USU's ground station will be using a J-pole antenna tuned to the same frequency.



Gain - 8.5 dB

Beamwidth - 80 degrees

Figure 17: A Loop Antenna for the GPS/Telemetry Beacon

5 COMMUNICATION PROTOCOLS

Different communication protocols are used between different interfaces in the communication link. The TCPIP protocol is used between the ground station and the ground station support equipment. The AX.25[7] and the APRS (R)[8] protocol are used for communication between the satellite uplink and the ground station equipment. The following is an example implementation of the AX.25 protocol. The packet structure is shown in figure 18.

Flag 01111110	Address 112 / 560 Bits	Control 8 bits	PID 8 Bits	Info. N * 8 Bits	FCS 16 Bits	Flag 01111110

•Each field is made up of an integral number of octets/bytes and serves a specific function.

• FCS -- Frame Check Sequence

• PID -- Protocol Identifier field

Figure 18: AX.25 Information Frame Construction

The pulse code modulation (PCM) page is used for the downlink [6] as shown in figure 3 in the appendix. There are 80 words in a frame and each major frame consists of 256 minor frames as per the IRIG-standard maximum major frame length [7]. The minor frame is composed of 128 bytes. Every tenth word comprises real-time data. The amount of data that can be downloaded depends upon how long the satellite is in view of the ground station. Using STK and other simulators, it is estimated that the satellite will make 6-8 passes a day. The amount of data that can be collected at 1000 bps will be 10.8 Mbytes per day. Using STK simulations, the average access time per day, per satellite is twenty three mintues. The downlink rate for the stored data is 105.6 Kbps (downlink rate for all data, minus downlink rate for real time data.) The time required to downlink the stored data is approximately fourteen minutes (stored data, divided by downlink rate) per day. This shows that all of the collected data can be downlinked during each twenty-four hour period. There is a surplus of nine minutes per day for downloading other information under ideal conditions. The communication between the GPS cross-link and the beacon is through the National Marine Electronics Association (NMEA)[9] protocol. The following three NMEA sentences: GPGGA, GPGSV, GPRMC, will be acquired. These sentences contain the direction, speed, and position of the USUSAT. The beacon can handle the NMEA sentences at 4800 baud (asynchronous) with only one start bit, eight data bits, and one stop bit. These sentences will arrive at the telemetry beacon at a rate which is less than two minutes, but greater than two seconds. The TNC and the flight computer communicate using the asynchronous RS232-C (ASCII) protocol.

6 SOFTWARE

6.1 Spacecraft Software

The software aboard the sapcecraft, consists of a number of modules integrated together, which is operated under the VX-Works operating system. Main functions of the software are categorized as follows:

1. The entire software is going to employ object-oriented programming which facilitates ease of operation, maintenance, remote sharing among universities, and code update.

2. Modular interaction will be encouraged through built-in VX-works messaging queues, which ensure task priority and prevents conflicting operations.

3. All commands and messages will have a source address, destination address, actual data, priority values, and parameters.

The flight software is designed around a simple looping task manager and a set of executable modules that perform the necessary functions. After power on and initialization, the main loop will be executed by the task manager. The task manager, regardless of what main tasks are executed, will perform a set of maintenance operations every cycle. These operations include time tagged command processing, memory management, etc. Some housekeeping routines can collect information about the status and health of the system

[7] http://www.tapr.org/tapr/html/Fax25.html

[8] http://www.tapr.org/tapr/html/Faprswg.htmlis

[9] http://www4.coastalnet.com/nmea/0183.htm

for both real time display and long term storage. Portions of the housekeeping data suite can be collected every loop cycle and assembled in a housekeeping memory segment. The receiver will be on at all times listening for commands, parameters, and code changes from the ground. The downlink process will be initiated when the command to start the downlink is received by the satellite. The parameters of the downlink command will tell the satellite what data to send (by indicating which PCM page to start the downlink) and how much data to send (by indicating how many pages to send.) If the telemetry buffer is emptied and there is no real-time data, the donwnlink will stop. If a corrupted command is received the satellite will request (via real-time data stream) that the corrupted packet be resent.

6.2 Ground Station Software

There are several pieces of equipment at the ground stations, which are software controlled. The antenna subsystem is software controlled by means of an antenna control computer using WISP. The Kenwood radios will be software controlled with the help of a proprietory Kenwood software program. WinAPRS and DosAPRS along with UI-View will be responsible for linking the information from the GPS/telemetry beacon to the Internet. The data computers can run Windows Hyperterminal to obtain data to and from the Kenwood and the decomm board. Paket 6.2 and Baycomm 6.1 are similar to Hyperterminal, which works with AX.25 packet formats. Writing additional software for the ground station and integrating it to the Internet is planned. Some of the features of the software are:

- Station monitoring and control
- Uplinking data or commands
- Downlinking data
- Data storage, archiving, and processing

7 SUMMARY

The communication design, architecture, and interfaces required for this system have been defined, and they meet all system requirements. Prototype testing is nearing completion and the final flight hardware will be ready for integration testing by the end of September 2001. The adoption of COTS components for the ION-F mission has significantly boosted the mission development process. The COTS have potential to make such missions enticing to a wide variety of satellite development groups as this greatly lowers the effort involved in system research, design, development, and cost.

8 ACKNOWLEDGEMENTS

The AirForce Office of Scientific Research (AFOSR) and the Defence Advanced Research Projects Agency (DARPA) need to be commended for their relentless support. Appreciation is extended to the Air Force Research Laboratory (AFRL) for their excellent program management. Thanks also to the National Aeronautics and Space Administration (NASA) for support of this endeavor. Gratitude to Dr. Charles M. Swenson, advisor, who has not only guided the research, but also demonstrated active interest and concern for the students. Thank you to all of the members on the ION-F team for their outstanding effort and dedication in supporting the ION-F mission.

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USUSAT MODE 1 Telemetry

Revision Date 03/20/2001

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SYNC	SYNC	SFID	SC1	SC2	XLN	SCI	SCI	SCI	RT	SCI	SCI	SCI	SCI	SCI	SCI	SCI	SCI	SCI	RT

20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
SCI	SCI	SCI	SCI	SCI	SCI	SCI	SCI	SCI	RT	SCI	SCI	SCI	SCI	SCI	SCI	SCI	SCI	SCI	RT

40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
IMG	PFPh	PFPl	PFPh	PFPl	PFPh	PFPl	PFPh	PFPl	RT	IMG	PFPh	PFPl	PFPh	PFPl	PFPh	PFPl	PFPh	PFPl	RT

60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79
PSPH	PFPh	PFPl	PFPh	PFPl	PFPh	PFPl	PFPh	PFPl	RT	PSPL	PFPh	PFPl	PFPh	PFPl	PFPh	PFPl	PFPh	PFPl	RT

SYNC WORD = (1110 1011 1001 0000) binary or EB90 hex

SFID WORD = (M S6 S5 S4 S3 S2 S1 S0) binary

Sx = Subframe Id Count roll over every 80 seconds

M = Mode-0 or Mode-1 Select for PCM page

SCI	**GPS Scintillation Science Data**
PFPh	**Science Data**
RT	**Real Time Data**
IMG	**Image Data**
PSPH	**Plasma Sweep Probe Data**

Figure 3: PCM Page Layout

Table 1: Link Budget Analysis

Link Analysis	-	-	-	Downlink	Uplink
– Constants –	Symbol	Units	Source	Value	Value
Speed of Light	c	m	Input	2.99E+08	2.99E+08
Boltzmann Constant	k	J/K	Input	1.38E-23	1.38E-23
Design Element	Symbol	Units	Source	Link	Link
Link Frequency	f	GHz	Input	2.245	0.45
Transmitter Power	P	Watts	Input	2.000	10.000
Transmitter Power	P	dBW	Cal	3.010	10.000
– Transmitter –	-	-	-	-	-
Antenna Gain	Gt	dB	Input	1.67	23.96
Antenna Transmitter Losses	Ltx	dB	Input	-0.5	-0.5
Antenna Beamwidth	Theta_t	Deg	Input	100.00	11.67
Antenna Misalignment	Alphabet	Deg	Input	80	5
Alignment Loss	Lt	dB	Cal	-7.68	-2.204
Equi_Iso_ Radiated Power	EIRP	dBW	Cal	-3.5	31.26
– Losses –	-	-	-	-	-
Propagation Path Length	S	Km	Input	1775.6	1775.6
Space Loss	L_s	dB	Cal	-164.46	-150.5
Atmospheric loss	L_a	dB	Input	-0.3	-1
Polarization Loss	L_p	dB	Input	-3	-3
Fade Margin	L_f	dB	Input	-0.05	-0.2
Total Losses	L	dB	Cal	-167.81	-154.7
– Receiver –	-	-	-	-	-
Antenna Gain	Gr	dB	Input	36.00	-6.00
Antenna Receiver Loss	Lrx	dB	Input	-0.5	-0.5
Antenna Beamwidth	Theta_r	Deg	Input	3.4	180.0
Antenna Misalignment	Alpha_r	Deg	Input	1	45
Alignment Loss	Lr	dB	Cal	-1.04	-0.75
Total Receiver Loss	G	dB	Cal	34.46	-7.25
Sky (Antenna) Noise Temp	Ta	K	Input	50	300
Receiver Temperature	Tr	K	Input	64.0	371.0
System Noise Temperature	T	K	Cal	114.0	671.0
System Noise Temperature	T	dB	Cal	20.6	28.3
Receiver Merit	G/T	DB(1/K)	Cal	13.89	-35.52
– Powers –	-	-	-	-	-
Power Flux Density	phi	dB(W/m^2)	Cal	-139.48	-104.72
Carrier Power Received	C	dBW	Cal	-136.85	-130.69
Noise Spectral Density	No	dB(W/Hz)	Cal	-208.03	-200.33
Carrier to Noise Density	C/No	dB(Hz)	Cal	71.18	69.64
– Rates –	-	-	-	-	-
Data Rate	R	Bps	Input	115.2E+3	1.2E+3
Eb/No	Eb/No	dB	Cal	20.569	38.85
Bit Error Rate	BER		Input	1.00E-05	1.00E-05
Required Eb/No	REb/No	dB	Input	12.4	12.4
Implementation Loss	dB		Input	3	3
– Margin –	dB		Cal	5.17	23.48

Table 2: Antenna Specifications for the 450 MHz and 2.2 GHz Patch Antennas

Antenna Type	Patch Antenna at 450 MHz	Patch Antenna at 2.2-2.29 GHz
Antenna Dimensions (H × W × L)	4020mils × 4020mils × 4020mils	800mils × 800mils × 800mils
Mass(including Delrin panel & fasteners)	Less than 65 g	Less than 20 g
Antenna gain	4-5dB	4dB-5.3dB
Antenna Beamwidth	90-100 deg	90-100 deg
Antenna Bandwidth	2.5 - 8.5 MHz	17.5 - 26.5 MHz
Antenna Polarization	Circular	Circular
Attachment to Satellite	Screw holes, Epoxy, Adhesive	Screw holes, Epoxy, Adhesive