ENGINEERING NOTICE

ENGINEERING NOTICE		**SHEET** 1 OF 1	**EN NUMBER** 403
SPECIAL INSTRUCTIONS / NOTES:			**WBS** 31114
DOCUMENT / MEDIA NUMBER	**DOCUMENT / MEDIA TITLE**	**DOC TYPE**	**REVIEW SIGNATURES**
UN2-RPT-31114-403, Rev.a	3 Corner Satellite Communications Link Estimates	RPT	ORIGINATOR / DATE
			REA C/ DISCIPLINE / DATE
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DOCUMENT TYPES:

- SPEC - Requirements/Specification
- DWG - Drawing
- PL - Parts List
- RPT - Report
- PLN - Plan
- PROC - Procedure, Instruction
- MAN - Manual
- REC - Record
- POL - Policy

Three Corner Sat

3 Corner Satellite Communications Link Estimates

UN2-RPT-31114-403, Rev.a

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Prepared for:
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Approvals:

Originator	Date	I & T Manager	Date
REA	Date	Safety	Date
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Revision Log

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1. Scope

1.1. Identification

This document applies to the Three Corner Sat (3CS) project, a joint project undertaken by Arizona State University, University of Colorado at Boulder, and New Mexico State University. This project is part of the University Nanosatellite Program sponsored by the Air Force Office of Scientific Research (AFOSR) and the Defense Advanced Research Projects Agency (DARPA).

3CS is teamed with the ION-F project aboard the second Shuttle launch of the University Nanosatellite Program. This joint payload is named the University Nanosat-2 (Nanosat-2) payload.

1.2. Document Maintenance

This document was developed and is maintained by the program participants at New Mexico State University as part of the overall 3 Corner Satellite in the University Nanosatellite program. While this document does not fall under the strict program Configuration Management structure, it is part of the project documentation. No changes or updates should be made without the cooperation of the author and/or maintainer at New Mexico State University.

1.3. System Overview

The main objective of the 3CS mission is the successful demonstration of the following technologies and approaches:

- Imaging
- Virtual formation flying
- Intersatellite Communications
- Distributed & Automated Operations
- Modular, Generic Nanosatellite Design
- Micropropulsion Experiment - Validate MEMS Heater Chip for FMMR
- Student Education

1.4. Document Overview

This report covers the expected radio link performance for the 3 Corner Satellite (3CS) constellation that is part of the University Nanosatellite program. Concerns that need to be addressed as part of the link design include:

1. Power margins for the forward and return links
2. Access times for the VHF/UHF and S-Band systems
3. Expected data throughput at the design data rates
4. Pointing limits and tracking rates.

The design power margin at this point needs to be at least 3dB to call a link closed. Given the unknowns in the system, a realistic link power margin is 10 dB at this point in the system development. Access times are computed using the Satellite Tool Kit (STK) simulation software. The simulations are run for a 30-day period to given an indication of expected performance. Because the constellation launch mode is not yet known, we look at orbits that range from 325 to 500 km altitude and 28.5º to 51.7º orbital inclination. The baseline case is an orbital altitude of 350 km and 36º orbital inclination.

1.5. Definitions, Acronyms, and Abbreviations

Acronym	**Name**
3CS	Three Corner Sat
ADC	Analog to Digital Converter
AFRL	Air Force Research Laboratory
AOCS	Attitude and Orbit Determination and Control Subsystem
AODC	Attitude/Orbit Determinations and Control
APRS	Automatic Position Reporting System
ASU	Arizona State University
C&DH	Command and Data Handling
CDR	Critical Design Review
CMOS	Complimentary Metal Oxide Semiconductor
COMM	Communications Subsystem
COTS	Commercial off the Shelf
CPR	Customer Payload Requirements
CPU	Central Processing Unit
CU	University of Colorado at Boulder
DSES	Deep Space Exploration Society

Acronym	Name
DSP	Digital Signal Processor
EEPROM	Electrically Erasable Programmable Read Only Memory
EEDS	End to End Data Subsystem (C&DH)
EPS	Electric Power Subsystem
FCP	Fracture Control Plan
FEA	Finite Element Analysis
FEM	Finite Element Method
FM	Frequency Modulation
FMMR	Free Molecule Micro Resistojet
FSDP	Flight Safety Data Package
FSK	Frequency Shift Key
GaAs	Gallium Arsenide
GMSK	Gaussian Minimum Shift Key
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HH	Hitchhiker
I	Current
ICB	Imaging Control Board
IMG	Imaging
IR	Infrared
JSC	Johnson Space Center
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LR	Latching Relay
MCDL	Master Control Document List
MDP	Maximum Design Pressure

Acronym	**Name**
MEMS	Micro-Electro-Mechanical Systems
MOP	Maximum Operating Pressure
MSDS	Multiple Satellite Deployment System
MUX	Multiplexer
NASA	National Aeronautics and Space Administration
NiCd	Nickel Cadmium
NMEA	National Marine Electronics Association
NMSU	New Mexico State University
NSTS	National Space Transportation System
OEM	Original Equipment Manufacturer
O/S	Operating System
P	Power
PIC	Programmable Integrated Controller
PLB	Payload Bay
PPF	Payload Processing Facility
PROP	Propulsion Subsystem
PSDU	Propellant Storage and Delivery Unit
PSRP	Payload Safety Review Panel
PWM	Pulse Width Modulation
RFDW	Request For Deviation
RTD	Resistance Temperature Device
RTE	Realtime Engine
RF	Radio Frequency
SA	Solar Arrays
SCC	Stress Corrosion Cracking
S/C	Space Craft

Acronym	Name
SCL	System Control Language
SHCS	Socket Head Cap Screw
SHELS	Shuttle Hitchhiker Ejection Launch System
SMA	Shape Memory Alloy
SMTR	Structures, Mechanisms, Thermal and Radiation
SPAM	Size Power And Mass
STK	Satellite Tool Kit
SVP	Structural Verification Plan
SSS	Stack Separation System
STRUCMECH	Structures and Mechanisms Subsystem
UHF	Ultra High Frequency
V	Voltage
VHF	Very High Frequency
WDT	Watch Dog Timer

1.6. Referenced Documents

List all documents that are referred to in this document. DO NOT state where the files are stored, as this changes from time-to-time and you won't want to re-release your document each time. An example follows:

Contact other team members or the Project Leader for the location of these documents and for instructions of how to access them (project website and MCDL).
NASA Reference Documents
Safety Policy and Requirements for Payloads Using the Space Transportation System, NSTS 1700.7B, NASA/JSC, July 28, 1999.
Payload Verification Requirements, Space Shuttle Program, NSTS 14046D, NASA/JSC, July 1997.
Controlled Project Documents
Program Management Plan (PMP)
System Development Plan (SDP)

2. Link Options

2.1. Introduction

This report covers the expected radio link performance for the 3 Corner Satellite (3CS) constellation that is part of the University Nanosatellite program. Concerns that need to be addressed as part of the link design include:

1. Power margins for the forward and return links
2. Access times for the VHF/UHF and S-Band systems
3. Expected data throughput at the design data rates
4. Pointing limits and tracking rates.

The design power margin at this point needs to be at least 3dB to call a link closed. Given the unknowns in the system, a realistic link power margin is 10 dB at this point in the system development. Access times are computed using the Satellite Tool Kit (STK) simulation software. The simulations are run for a 30-day period to given an indication of expected performance. Because the constellation launch mode is not yet known, we look at orbits that range from 325 to 500 km altitude and 28.5º to 51.7º orbital inclination. The baseline case is an orbital altitude of 350 km and 36º orbital inclination.

From the orbital access, we look at data throughput. The expected data throughput for the VHF/UHF links is limited to 9600 bps at most. The S-Band link is assumed to support a data rate of 100,000 bps. Pointing and tracking limits are computed using STK for the expected 60-foot dish at the Deep Space Exploration Society (DSES) location in Colorado near the CU Boulder campus.

2.2. Orbital Analysis

The results from several Satellite Tool Kit simulations are presented along with the link budget analysis to estimate the performance of the 3 Corner Satellite constellation members while on orbit. For each link, four possibilities are considered: 325 km, 28.5º inclination; 500 km, 28.5º inclination; 325 km, 51.7º inclination; 500 km, 51.7º inclination. These will be compared with the mission baseline of 350 km, 36º inclination to give the full range of variation. To complete the link budget analysis, we need to maximum distance between the ground stations and the satellites. To compute performance, we look at the minimum, maximum, and average contact time. We divide the analysis into VHF/UHF links and S-Band links.

2.2.1. VHF/UHF Contacts

2.2.1.1. Case 1: 325 km/28.5º

The first case to be examined is the "worst case" orbital condition of 325 km altitude and 28.5º inclination angle.

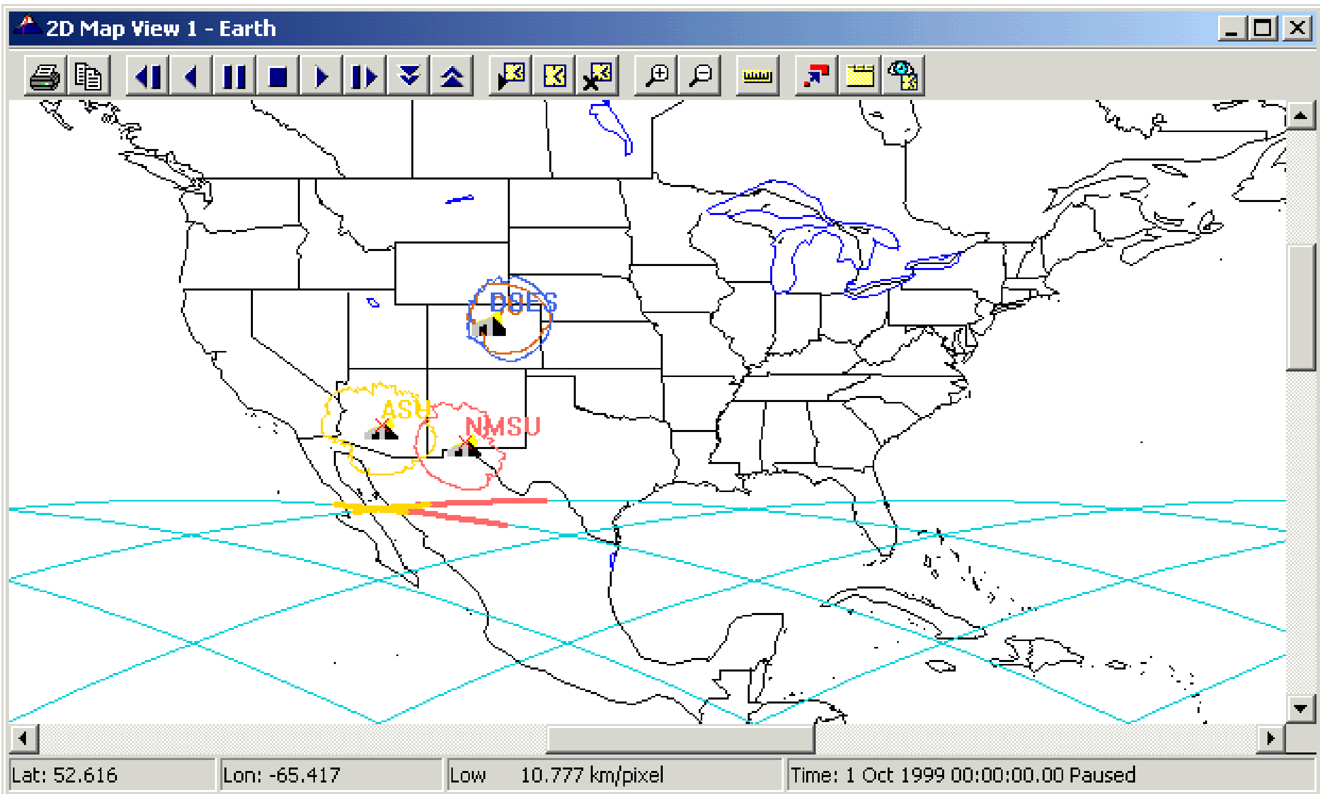

Figure 2-1 – Case 1: 325-km altitude, 28.5º inclination orbit

Conservative Assumptions:

a. VHF/UHF antenna has a 120º HPBW (STK cone angle of 60º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-1 – Conservative Access Summary for Orbital Case 1

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	724.03	0.219	1.611	1.351	1.2
CU	no access opportunities				0.0
NMSU	721.07	0.063	2.307	1.791	2.0

Best-case Contact Assumptions:

a. VHF/UHF antenna has a 150º HPBW (STK cone angle of 75º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-2 – Best Case Access Summary for Orbital Case 1

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	1594.08	0.297	6.848	5.861	4.1
CU	1588.89	0.720	3.787	2.882	2.4
NMSU	1591.66	2.498	7.040	5.907	4.6

Forward 450 MHz Link			Units				
Transmitter (Tx)							
1	Tx Power, Pt	44.8	dBm		Assume:	30	Watts
2	Tx Component Line Losses, Ltl	3.0	dB		roof line losses		
3	Tx Antenna Gain (Peak), Gt	17.3	dBi		KLM 435-40CX		
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	58.1	dBm				
Propagation							
	Transmission Frequency, f	450.0	MHz				
	Link Range, R	725.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	142.7	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	142.7	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	0.0	dBi				
12	Rx Polarization Loss, Lrpol	1.0	dB				
13	Rx Pointing Loss, Lrp	0.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	1.0	dB				
16	Rx Implementation Losses, Lri	1.0	dB				
17	Received effective carrier power	-87.6	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	38.4	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	41.5	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	14.2	dB		Assume BER=0.000001		
25	Margin (24-25-26)	24.3	dB				

Figure 2-2 – Forward link budget at 725 km maximum link range.

Forward 450 MHz Link			**Units**				
Transmitter (Tx)							
1	Tx Power, Pt	44.8	dBm		Assume:	30	Watts
2	Tx Component Line Losses, Ltl	3.0	dB		roof line losses		
3	Tx Antenna Gain (Peak), Gt	17.3	dBi		KLM 435-40CX		
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	58.1	dBm				
Propagation							
	Transmission Frequency, f	450.0	MHz				
	Link Range, R	1600.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	149.6	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	149.6	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	0.0	dBi				
12	Rx Polarization Loss, Lrpol	1.0	dB				
13	Rx Pointing Loss, Lrp	0.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	1.0	dB				
16	Rx Implementation Losses, Lri	1.0	dB				
17	Received effective carrier power	-94.5	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	31.5	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	34.7	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	14.2	dB		Assume BER=0.000001		
25	Margin (24-25-26)	17.5	dB				

Figure 2-3 – Forward link budget at 1600 km maximum link range.

Return 137 MHz Link			Units				
Transmitter (Tx)							
1	Tx Power, Pt	27.0	dBm		Assume:	0.5	Watts
2	Tx Component Line Losses, Ltl	1.0	dB		(low power mode)		
3	Tx Antenna Gain (Peak), Gt	0.0	dBi				
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	25.0	dBm				
Propagation							
	Transmission Frequency, f	137.0	MHz				
	Link Range, R	725.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	132.4	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	132.4	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	15.1	dBi		KLM 2M-22C		
12	Rx Polarization Loss, Lrpol	3.0	dB				
13	Rx Pointing Loss, Lrp	1.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	3.0	dB		roof cable loss		
16	Rx Implementation Losses, Lri	3.0	dB				
17	Received effective carrier power	-102.3	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	23.7	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	26.9	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	13.4	dB		Assume BER=0.00001		
25	Margin (24-25-26)	10.5	dB				

Figure 2-4 – Return link budget at 725 km maximum link range.

Return 137 MHz Link			**Units**				
Transmitter (Tx)							
1	Tx Power, Pt	27.0	dBm		Assume:	0.5	Watts
2	Tx Component Line Losses, Ltl	1.0	dB		(low power mode)		
3	Tx Antenna Gain (Peak), Gt	0.0	dBi				
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	25.0	dBm				
Propagation							
	Transmission Frequency, f	137.0	MHz				
	Link Range, R	1600.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	139.3	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	139.3	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	15.1	dBi		KLM 2M-22C		
12	Rx Polarization Loss, Lrpol	3.0	dB				
13	Rx Pointing Loss, Lrp	1.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	3.0	dB		roof cable loss		
16	Rx Implementation Losses, Lri	3.0	dB				
17	Received effective carrier power	-109.1	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	16.8	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	20.0	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	13.4	dB		Assume BER=0.00001		
25	Margin (24-25-26)	3.6	dB				

Figure 2-5 – Return link budget at 1600 km maximum link distance.

2.2.1.2. Case 2: 325 km/51.7º

The second case to be examined is the lower orbital altitude of 325 km but with the high inclination angle of the ISS at 51.7º.

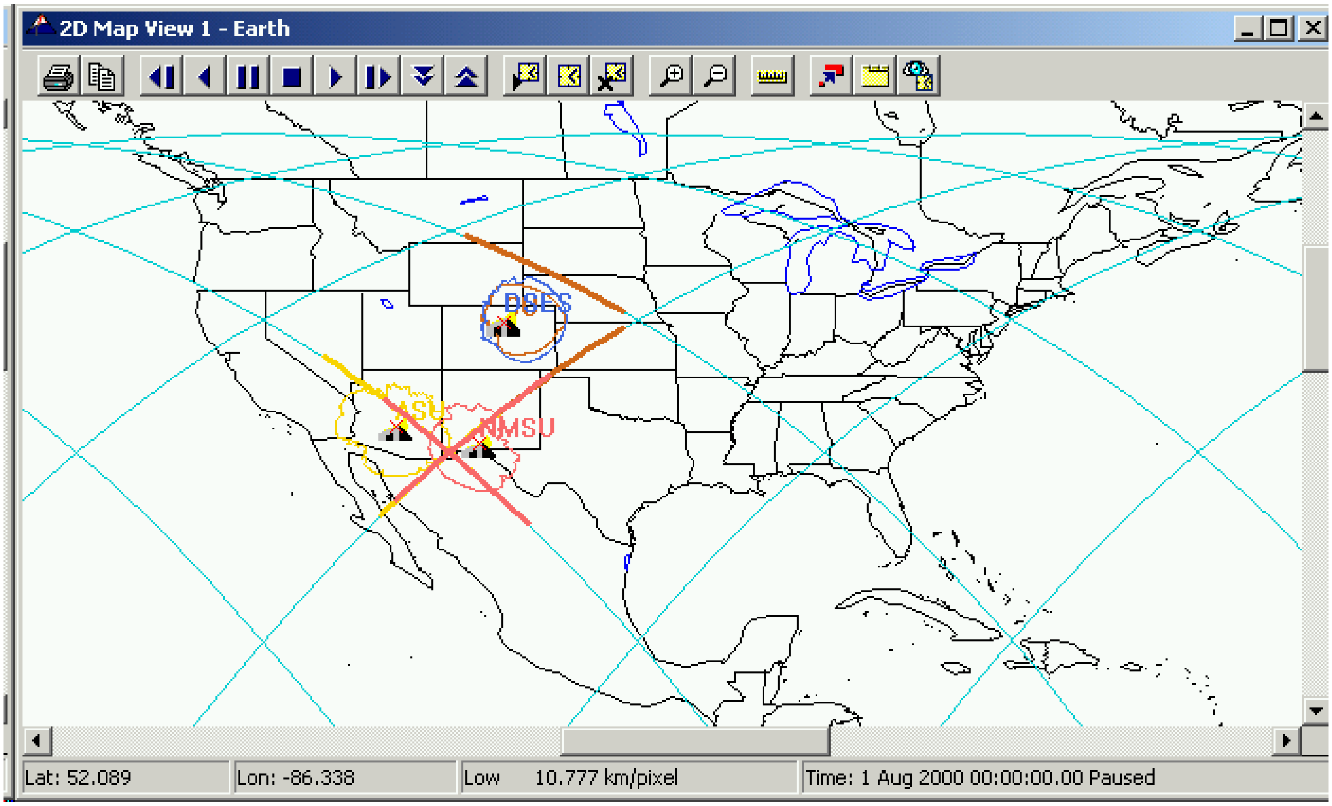

Figure 2-6 – Case 2: 325-km altitude; 51.7º inclination orbit.

<u>Conservative Assumptions:</u>

a. VHF/UHF antenna has a 120º HPBW (STK cone angle of 60º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-3 – Conservative Access Summary for Orbital Case 2					
Ground Station	**Max. Range (km)**	**Minimum (min)**	**Maximum (min)**	**Avg (min)**	**Contacts/ Day**
ASU	724.04	0.600	2.970	2.278	1.7
CU	726.60	0.364	2.981	2.287	2.2
NMSU	721.08	0.703	2.956	2.331	1.6

Best-case Contact Assumptions:

a. VHF/UHF antenna has a 150º HPBW (STK cone angle of 75º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-4 – Best Case Access Summary for Orbital Case 2

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	1612.73	1.021	7.226	5.602	4.4
CU	1615.18	0.056	7.243	5.481	6.3
NMSU	1608.77	0.182	7.209	5.511	4.3

2.2.1.3. Case 3: 500 km/28.5º

The third case to be examined is the higher orbital altitude of 500 km but with the lower inclination angle of 28.5º.

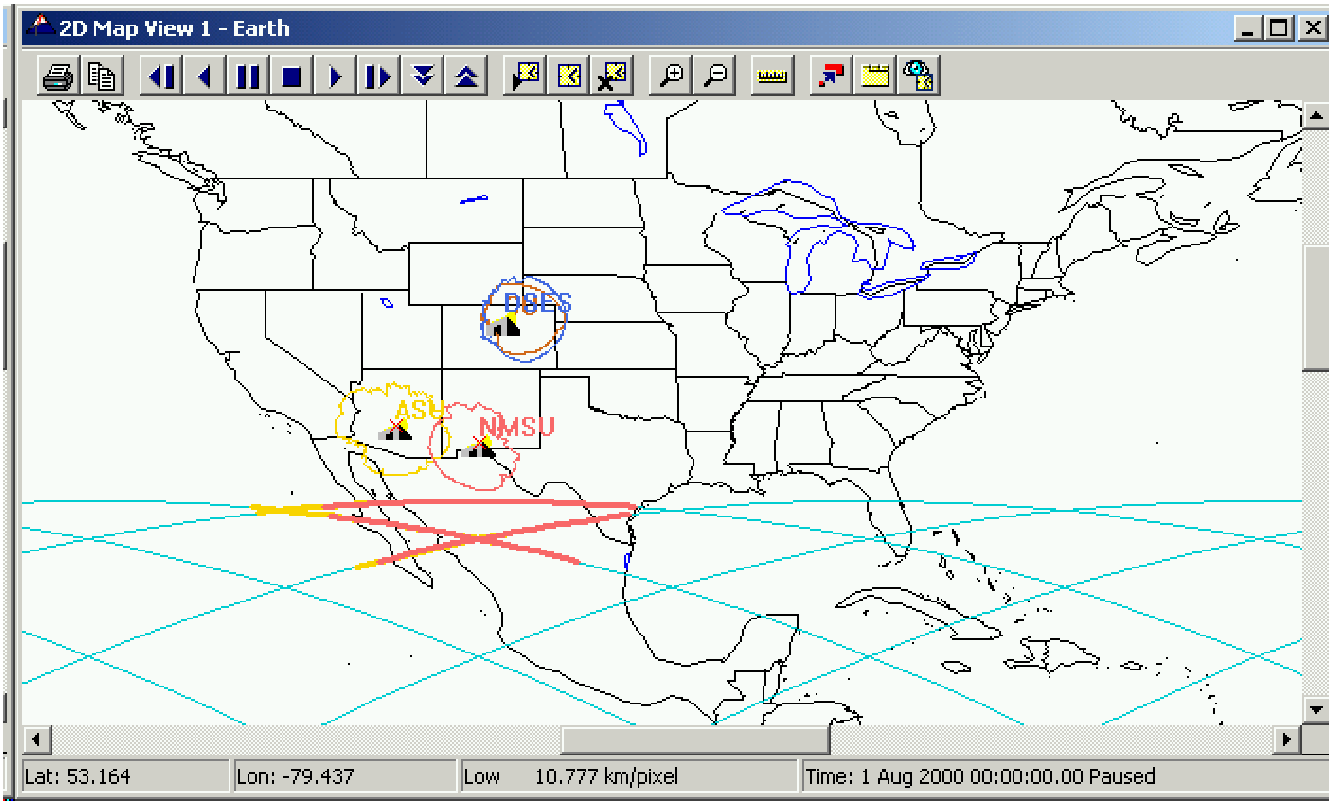

Figure 2-7 – Case 3: 500-km altitude; 28.5º inclination orbit.

<u>Conservative Assumptions:</u>

a. VHF/UHF antenna has a 120º HPBW (STK cone angle of 60º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-5 – Conservative Access Summary for Orbital Case 3

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	1176.02	0.700	4.380	3.552	2.9
CU	no accesses opportunities				0.0
NMSU	1172.59	0.867	4.689	3.813	3.2

Best-case Contact Assumptions:

a. VHF/UHF antenna has a 150º HPBW (STK cone angle of 75º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-6 – Best Case Access Summary for Orbital Case 1					
Ground Station	**Max. Range (km)**	**Minimum (min)**	**Maximum (min)**	**Avg (min)**	**Contacts/ Day**
ASU	2090.34	1.403	9.427	7.872	5.0
CU	2086.15	0.190	7.217	5.298	3.7
NMSU	2088.35	1.192	9.575	7.941	5.3

Forward 450 MHz Link			**Units**				
Transmitter (Tx)							
1	Tx Power, Pt	44.8	dBm		Assume:	30	Watts
2	Tx Component Line Losses, Ltl	3.0	dB		roof line losses		
3	Tx Antenna Gain (Peak), Gt	17.3	dBi		KLM 435-40CX		
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	58.1	dBm				
Propagation							
	Transmission Frequency, f	450.0	MHz				
	Link Range, R	1200.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	147.1	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	147.1	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	0.0	dBi				
12	Rx Polarization Loss, Lrpol	1.0	dB				
13	Rx Pointing Loss, Lrp	0.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	1.0	dB				
16	Rx Implementation Losses, Lri	1.0	dB				
17	Received effective carrier power	-92.0	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	34.0	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	37.2	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	14.2	dB		Assume BER=0.000001		
25	Margin (24-25-26)	20.0	dB				

Figure 2-8 – Forward link budget at 1200 km maximum link range.

Forward 450 MHz Link			Units				
Transmitter (Tx)							
1	Tx Power, Pt	44.8	dBm		Assume:	30	Watts
2	Tx Component Line Losses, Ltl	3.0	dB		roof line losses		
3	Tx Antenna Gain (Peak), Gt	17.3	dBi		KLM 435-40CX		
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	58.1	dBm				
Propagation							
	Transmission Frequency, f	450.0	MHz				
	Link Range, R	2100.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	152.0	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	152.0	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	0.0	dBi				
12	Rx Polarization Loss, Lrpol	1.0	dB				
13	Rx Pointing Loss, Lrp	0.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	1.0	dB				
16	Rx Implementation Losses, Lri	1.0	dB				
17	Received effective carrier power	-96.8	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	29.1	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	32.3	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	14.2	dB		Assume BER=0.000001		
25	Margin (24-25-26)	15.1	dB				

Figure 2-9 – Forward link budget at 2100 km maximum link range.

Return 137 MHz Link			Units				
Transmitter (Tx)							
1	Tx Power, Pt	27.0	dBm		Assume:	0.5	Watts
2	Tx Component Line Losses, Ltl	1.0	dB		(low power mode)		
3	Tx Antenna Gain (Peak), Gt	0.0	dBi				
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	25.0	dBm				
Propagation							
	Transmission Frequency, f	137.0	MHz				
	Link Range, R	1200.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	136.8	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	136.8	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	15.1	dBi		KLM 2M-22C		
12	Rx Polarization Loss, Lrpol	3.0	dB				
13	Rx Pointing Loss, Lrp	1.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	3.0	dB		roof cable loss		
16	Rx Implementation Losses, Lri	3.0	dB				
17	Received effective carrier power	-106.6	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	19.3	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	22.5	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	13.4	dB		Assume BER=0.00001		
25	Margin (24-25-26)	6.1	dB				

Figure 2-10 – Return link budget at 1200 km maximum link range.

Return 137 MHz Link			Units				
Transmitter (Tx)							
1	Tx Power, Pt	27.0	dBm		Assume:	0.5	Watts
2	Tx Component Line Losses, Ltl	1.0	dB		(low power mode)		
3	Tx Antenna Gain (Peak), Gt	0.0	dBi				
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	25.0	dBm				
Propagation							
	Transmission Frequency, f	137.0	MHz				
	Link Range, R	2100.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	141.6	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	141.6	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	15.1	dBi		KLM 2M-22C		
12	Rx Polarization Loss, Lrpol	3.0	dB				
13	Rx Pointing Loss, Lrp	1.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	3.0	dB		roof cable loss		
16	Rx Implementation Losses, Lri	3.0	dB				
17	Received effective carrier power	-111.5	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	14.5	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	17.7	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	13.4	dB		Assume BER=0.00001		
25	Margin (24-25-26)	1.3	dB				

Figure 2-11 – Return link budget at 2100 km maximum link range.

2.2.1.4. Case 4: 500 km/51.7º

The fourth case to be examined is the higher orbital altitude of 500 km but with the high inclination angle of the ISS at 51.7º.

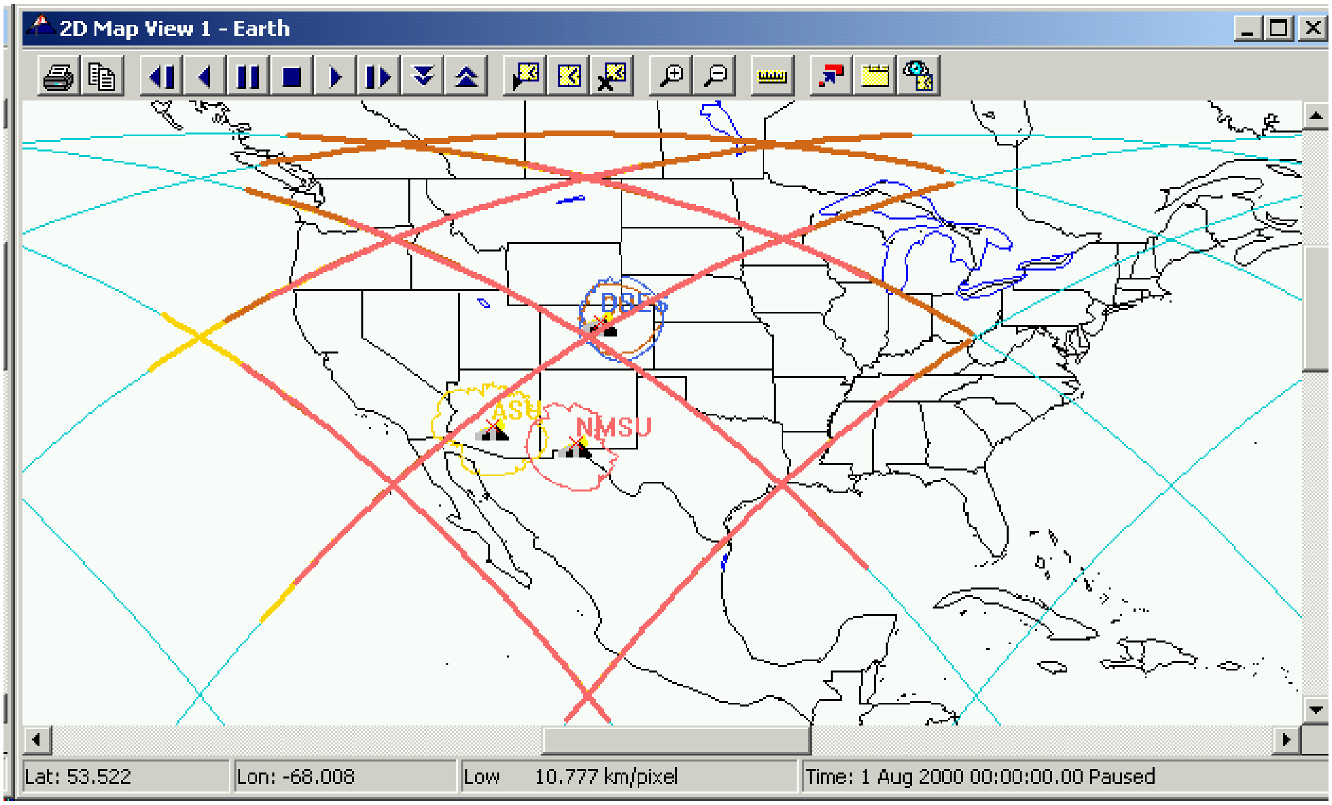

Figure 2-12 – Case 4: 500-km altitude; 51.7º inclination orbit.

<u>Conservative Assumptions:</u>

a. VHF/UHF antenna has a 120º HPBW (STK cone angle of 60º)
b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-7 – Conservative Access Summary for Orbital Case 1					
Ground Station	**Max. Range (km)**	**Minimum (min)**	**Maximum (min)**	**Avg (min)**	**Contacts/ Day**
ASU	1176.03	0.696	5.005	3.822	2.8
CU	1179.01	0.267	5.050	3.921	3.4
NMSU	1172.59	0.390	4.833	3.578	2.8

Best-case Contact Assumptions:

a. VHF/UHF antenna has a 150º HPBW (STK cone angle of 75º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-8 – Best Case Access Summary for Orbital Case 1					
Ground Station	**Max. Range (km)**	**Minimum (min)**	**Maximum (min)**	**Avg (min)**	**Contacts/ Day**
ASU	2108.45	4.049	9.655	7.534	6.0
CU	2108.06	0.064	9.644	7.331	7.1
NMSU	2105.28	2.717	9.574	7.263	6.0

2.2.1.5. Case 5 - Baseline: 350 km/36º

The last case to be examined is the mission baseline orbital altitude of 350 km with an orbital inclination angle of 36º.

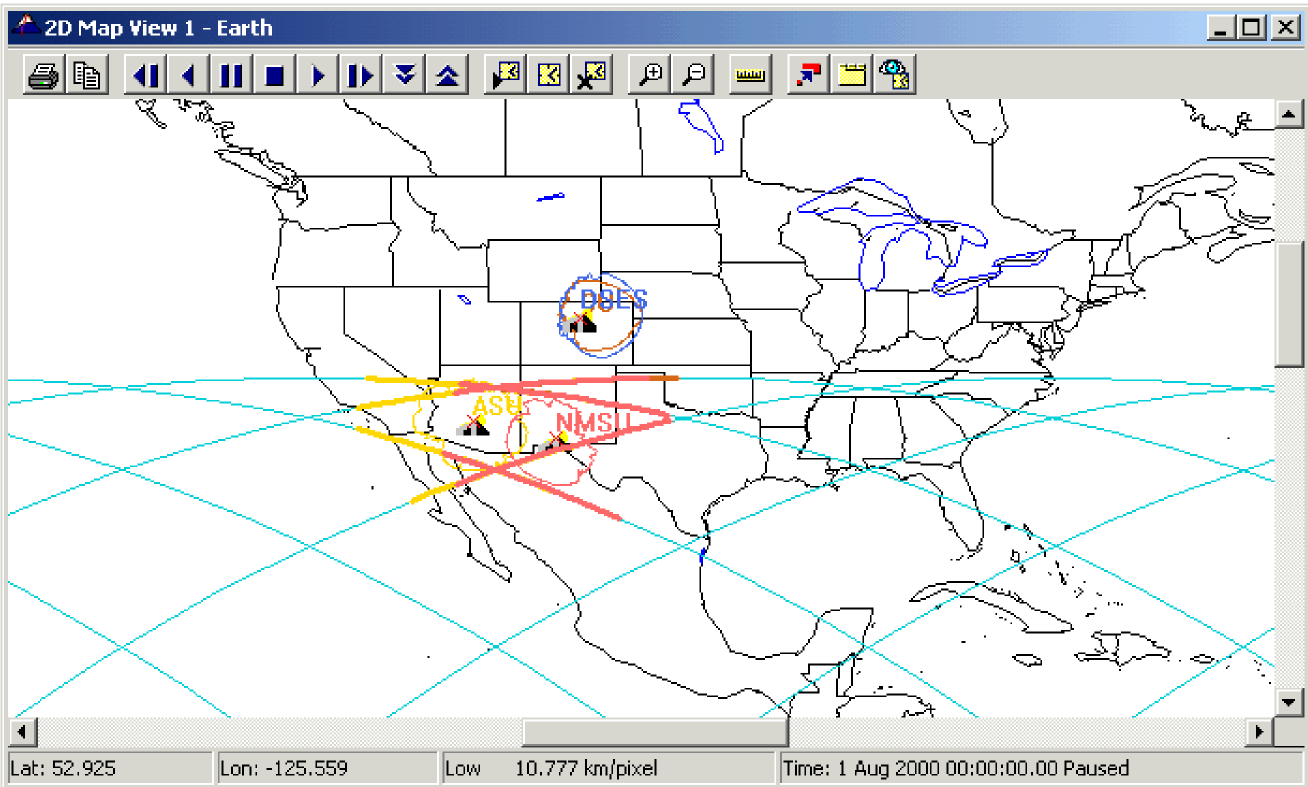

Figure 2-13 – Baseline mission design: 350-km altitude; 36º inclination orbit.

<u>Conservative Assumptions:</u>

a. VHF/UHF antenna has a 120º HPBW (STK cone angle of 60º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-9 – Conservative Access Summary for Orbital Case 1

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	784.90	0.482	3.278	2.895	3.8
CU	787.52	0.411	2.573	2.065	2.0
NMSU	781.89	0.347	3.265	2.784	4.1

Best-case Contact Assumptions:

a. VHF/UHF antenna has a 150º HPBW (STK cone angle of 75º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-10 – Best Case Access Summary for Orbital Case 1					
Ground Station	**Max. Range (km)**	**Minimum (min)**	**Maximum (min)**	**Avg (min)**	**Contacts/ Day**
ASU	1678.77	0.695	7.687	6.786	5.5
CU	1675.07	0.349	7.274	5.659	4.5
NMSU	1676.20	0.495	7.670	6.794	5.6

Forward 450 MHz Link			Units				
Transmitter (Tx)							
1	Tx Power, Pt	44.8	dBm		Assume:	30	Watts
2	Tx Component Line Losses, Ltl	3.0	dB		roof line losses		
3	Tx Antenna Gain (Peak), Gt	17.3	dBi		KLM 435-40CX		
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	58.1	dBm				
Propagation							
	Transmission Frequency, f	450.0	MHz				
	Link Range, R	800.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	143.6	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	143.6	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	0.0	dBi				
12	Rx Polarization Loss, Lrpol	1.0	dB				
13	Rx Pointing Loss, Lrp	0.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	1.0	dB				
16	Rx Implementation Losses, Lri	1.0	dB				
17	Received effective carrier power	-88.5	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	37.5	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	40.7	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	14.2	dB		Assume BER=0.000001		
25	Margin (24-25-26)	23.5	dB				

Figure 2-14 – Forward link budget at 800 km maximum link range.

Forward 450 MHz Link			**Units**				
Transmitter (Tx)							
1	Tx Power, Pt	44.8	dBm		Assume:	30	Watts
2	Tx Component Line Losses, Ltl	3.0	dB		roof line losses		
3	Tx Antenna Gain (Peak), Gt	17.3	dBi		KLM 435-40CX		
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	58.1	dBm				
Propagation							
	Transmission Frequency, f	450.0	MHz				
	Link Range, R	1700.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	150.1	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	150.1	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	0.0	dBi				
12	Rx Polarization Loss, Lrpol	1.0	dB				
13	Rx Pointing Loss, Lrp	0.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	1.0	dB				
16	Rx Implementation Losses, Lri	1.0	dB				
17	Received effective carrier power	-95.0	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	31.0	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	34.1	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	14.2	dB		Assume BER=0.000001		
25	Margin (24-25-26)	16.9	dB				

Figure 2-15 – Forward link budget at 1700 km maximum link range.

Return 137 MHz Link			Units				
Transmitter (Tx)							
1	Tx Power, Pt	27.0	dBm		Assume:	0.5	Watts
2	Tx Component Line Losses, Ltl	1.0	dB		(low power mode)		
3	Tx Antenna Gain (Peak), Gt	0.0	dBi				
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	25.0	dBm				
Propagation							
	Transmission Frequency, f	137.0	MHz				
	Link Range, R	800.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	133.2	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	133.2	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	15.1	dBi		KLM 2M-22C		
12	Rx Polarization Loss, Lrpol	3.0	dB				
13	Rx Pointing Loss, Lrp	1.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	3.0	dB		roof cable loss		
16	Rx Implementation Losses, Lri	3.0	dB				
17	Received effective carrier power	-103.1	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	22.9	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	26.0	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	13.4	dB		Assume BER=0.00001		
25	Margin (24-25-26)	9.6	dB				

Figure 2-16 – Return link budget at 800 km maximum link range.

Return 137 MHz Link			**Units**				
Transmitter (Tx)							
1	Tx Power, Pt	27.0	dBm		Assume:	0.5	Watts
2	Tx Component Line Losses, Ltl	1.0	dB		(low power mode)		
3	Tx Antenna Gain (Peak), Gt	0.0	dBi				
4	Tx Pointing Loss, Ltp	1.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	25.0	dBm				
Propagation							
	Transmission Frequency, f	137.0	MHz				
	Link Range, R	1700.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	139.8	dB				
8	Atmospheric Absorption, Lpa	0.0	dB				
9	Precipitation Absorption, Lpp	0.0	dB				
10	Total Propagation Loss (7+8+9)	139.8	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	15.1	dBi		KLM 2M-22C		
12	Rx Polarization Loss, Lrpol	3.0	dB				
13	Rx Pointing Loss, Lrp	1.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	3.0	dB		roof cable loss		
16	Rx Implementation Losses, Lri	3.0	dB				
17	Received effective carrier power	-109.7	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	43.0	dBHz		Assume:	20000	Hz
20	Rx Noise Figure, NF	5.0	dB				
21	Effective Noise Power (18+19+20)	-126.0	dBm				
Result							
22	Available CNR (17-21)	16.3	dB				
23	Data Rate	39.8	dBHz		Assume	9600	bps
24	Available Eb/No (22+19-23)	19.5	dB				
25	Implementation Losses	3.0	dB				
26	Required Eb/No	13.4	dB		Assume BER=0.00001		
25	Margin (24-25-26)	3.1	dB				

Figure 2-17 – Return link budget at 1700 km maximum link range.

2.2.2. S-Band Link Contacts

2.2.2.1. Case 1: 325 km/28.5º

The first case to be examined is the “worst case” orbital condition of 325 km altitude and 28.5º inclination angle.

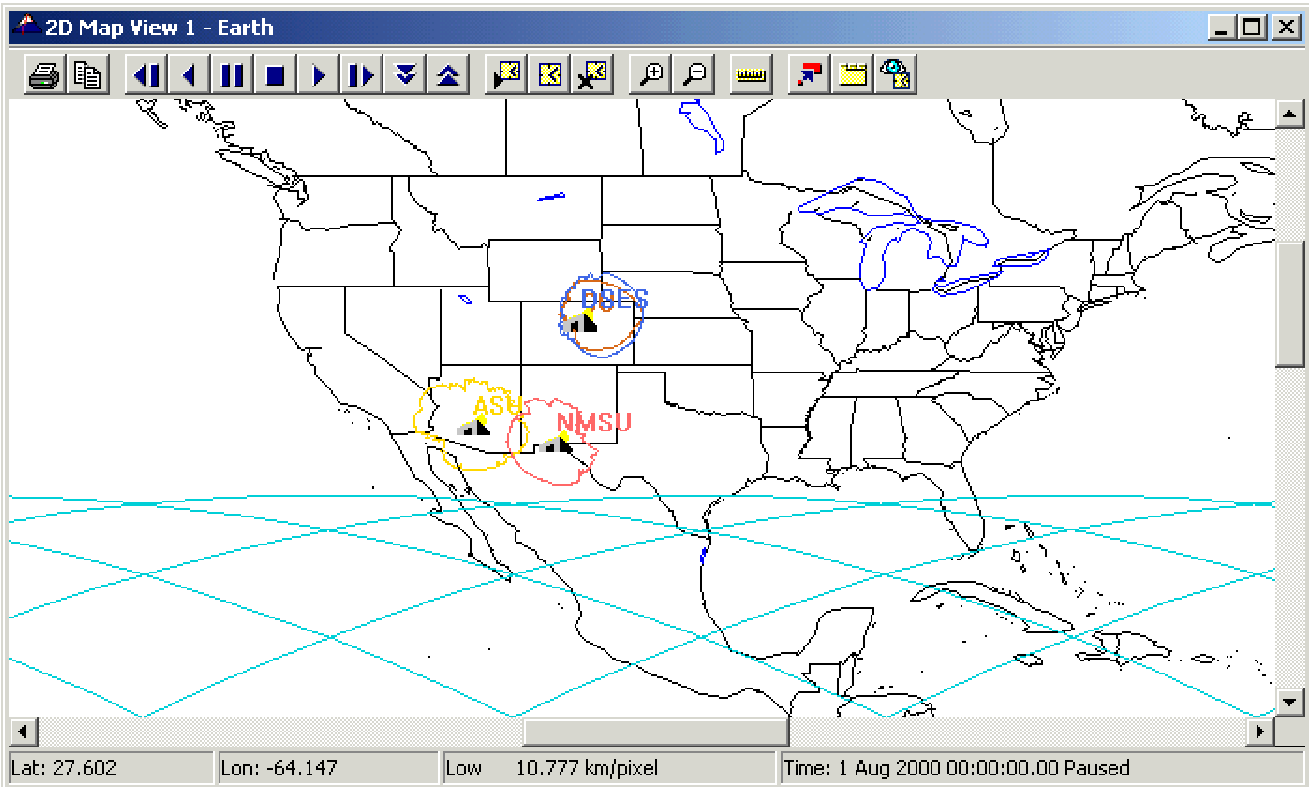

Figure 2-18 – Case 1: 325-km altitude; 28.5º inclination orbit.

Conservative Assumptions:

a. VHF/UHF antenna has a 60º HPBW (STK cone angle of 30º)

b. minimum elevation angle is 5º but modified by terrain masking effects

<table>
<tr><th colspan="6">Table 2-11 – Conservative Access Summary for Orbital Case 1</th></tr>
<tr><th>Ground Station</th><th>Max. Range (km)</th><th>Minimum (min)</th><th>Maximum (min)</th><th>Avg (min)</th><th>Contacts/ Day</th></tr>
<tr><td>ASU</td><td colspan="4" rowspan="4">no access opportunities</td><td>0.0</td></tr>
<tr><td>CU</td><td>0.0</td></tr>
<tr><td>DSES</td><td>0.0</td></tr>
<tr><td>NMSU</td><td>0.0</td></tr>
</table>

Best-case Contact Assumptions:

a. VHF/UHF antenna has a 120º HPBW (STK cone angle of 60º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-12 – Best Case Access Summary for Orbital Case 1

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	724.03	0.219	1.611	1.351	1.2
CU	no access opportunities				0.0
DSES					0.0
NMSU	721.07	0.063	2.307	1.791	2.0

Return S-Band Link			**Units**				
Transmitter (Tx)							
1	Tx Power, Pt	28.0	dBm		Assume:	0.631	Watts
2	Tx Component Line Losses, Ltl	3.0	dB				
3	Tx Antenna Gain (Peak), Gt	5.0	dBi				
4	Tx Pointing Loss, Ltp	3.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	27.0	dBm				
Propagation							
	Transmission Frequency, f	2200.0	MHz				
	Link Range, R	750.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	156.8	dB				
8	Atmospheric Absorption, Lpa	0.5	dB				
9	Precipitation Absorption, Lpp	0.5	dB				
10	Total Propagation Loss (7+8+9)	157.8	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	10.0	dB		Assume	Helical	
12	Rx Polarization Loss, Lrpol	1.0	dB				
13	Rx Pointing Loss, Lrp	3.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	3.0	dB				
16	Rx Implementation Losses, Lri	3.0	dB				
17	Received effective carrier power	-130.8	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	32.6	dBHz		Assume:	1800	Hz
20	Rx Noise Figure, NF	3.0	dB				
21	Effective Noise Power (18+19+20)	-138.4	dBm				
Result							
22	Available CNR (17-21)	7.6	dB				
23	Data Rate	30.8	dBHz		Assume	1200	bps
24	Available Eb/No (22+19-23)	9.4	dB				
25	Implementation Losses	2.0	dB				
26	Required Eb/No	13.4	dB		Assume BER=0.00001		
25	Margin (24-25-26)	-6.0	dB				

Figure 2-19 – Return link over a 750-km maximum range to a university-class ground station.

Return S-Band Link			**Units**				
Transmitter (Tx)							
1	Tx Power, Pt	28.0	dBm		Assume:	0.631	Watts
2	Tx Component Line Losses, Ltl	3.0	dB				
3	Tx Antenna Gain (Peak), Gt	5.0	dBi				
4	Tx Pointing Loss, Ltp	3.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	27.0	dBm				
Propagation							
	Transmission Frequency, f	2200.0	MHz				
	Link Range, R	750.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	156.8	dB				
8	Atmospheric Absorption, Lpa	0.5	dB				
9	Precipitation Absorption, Lpp	0.5	dB				
10	Total Propagation Loss (7+8+9)	157.8	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	45.0	dB		Assume	60-foot dish	
12	Rx Polarization Loss, Lrpol	1.0	dB				
13	Rx Pointing Loss, Lrp	3.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	3.0	dB				
16	Rx Implementation Losses, Lri	3.0	dB				
17	Received effective carrier power	-95.8	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	51.8	dBHz		Assume:	150000	Hz
20	Rx Noise Figure, NF	3.0	dB				
21	Effective Noise Power (18+19+20)	-119.2	dBm				
Result							
22	Available CNR (17-21)	23.4	dB				
23	Data Rate	50.0	dBHz		Assume	100000	bps
24	Available Eb/No (22+19-23)	25.2	dB				
25	Implementation Losses	2.0	dB				
26	Required Eb/No	13.4	dB		Assume BER=0.00001		
25	Margin (24-25-26)	9.8	dB				

Figure 2-20 – Return link over a 750 km maximum range to a 60-foot dish.

2.2.2.2. Case 2: 325 km/51.7º

The second case to be examined is the lower orbital altitude of 325 km but with the high inclination angle of the ISS at 51.7º.

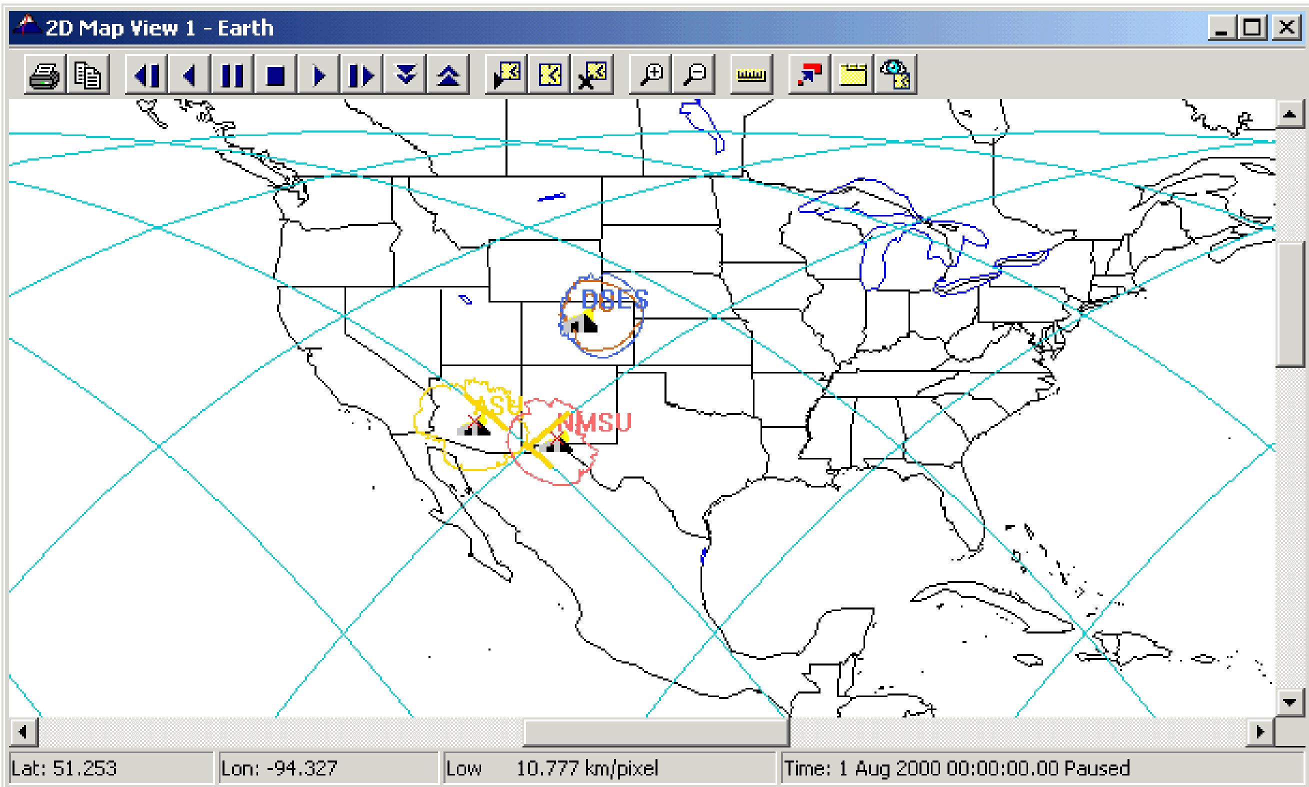

Figure 2-21 – Case 1: 325-km altitude; 51.7º inclination orbit

<u>Conservative Assumptions:</u>

a. VHF/UHF antenna has a 60º HPBW (STK cone angle of 30º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-13 – Conservative Access Summary for Orbital Case 2

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	385.68	0.261	0.912	0.728	0.5
CU	386.92	0.183	0.914	0.738	0.63
DSES	386.98	0.522	0.915	0.774	0.60
NMSU	384.24	0.256	0.905	0.706	0.53

Best-case Contact Assumptions:

a. VHF/UHF antenna has a 120º HPBW (STK cone angle of 60º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-14 – Best Case Access Summary for Orbital Case 2

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	724.04	0.60	2.970	2.278	1.7
CU	726.60	0.364	2.981	2.287	2.2
DSES	726.73	0.375	2.982	2.329	2.1
NMSU	721.08	0.703	2.956	2.331	1.6

Return S-Band Link			**Units**				
Transmitter (Tx)							
1	Tx Power, Pt	28.0	dBm		Assume:	0.631	Watts
2	Tx Component Line Losses, Ltl	3.0	dB				
3	Tx Antenna Gain (Peak), Gt	5.0	dBi				
4	Tx Pointing Loss, Ltp	3.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	27.0	dBm				
Propagation							
	Transmission Frequency, f	2200.0	MHz				
	Link Range, R	400.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	151.3	dB				
8	Atmospheric Absorption, Lpa	0.5	dB				
9	Precipitation Absorption, Lpp	0.5	dB				
10	Total Propagation Loss (7+8+9)	152.3	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	10.0	dB		Assume	helical	
12	Rx Polarization Loss, Lrpol	1.0	dB				
13	Rx Pointing Loss, Lrp	3.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	3.0	dB				
16	Rx Implementation Losses, Lri	3.0	dB				
17	Received effective carrier power	-125.3	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	32.6	dBHz		Assume:	1800	Hz
20	Rx Noise Figure, NF	3.0	dB				
21	Effective Noise Power (18+19+20)	-138.4	dBm				
Result							
22	Available CNR (17-21)	13.1	dB				
23	Data Rate	30.8	dBHz		Assume	1200	bps
24	Available Eb/No (22+19-23)	14.8	dB				
25	Implementation Losses	2.0	dB				
26	Required Eb/No	13.4	dB		Assume BER=0.00001		
25	Margin (24-25-26)	-0.6	dB				

Figure 2-22 – Return link over a 400 km maximum range to a university ground station.

2.2.2.3. Case 3: 500 km/28.5º

The third case to be examined is the higher orbital altitude of 500 km but with the lower inclination angle of 28.5º.

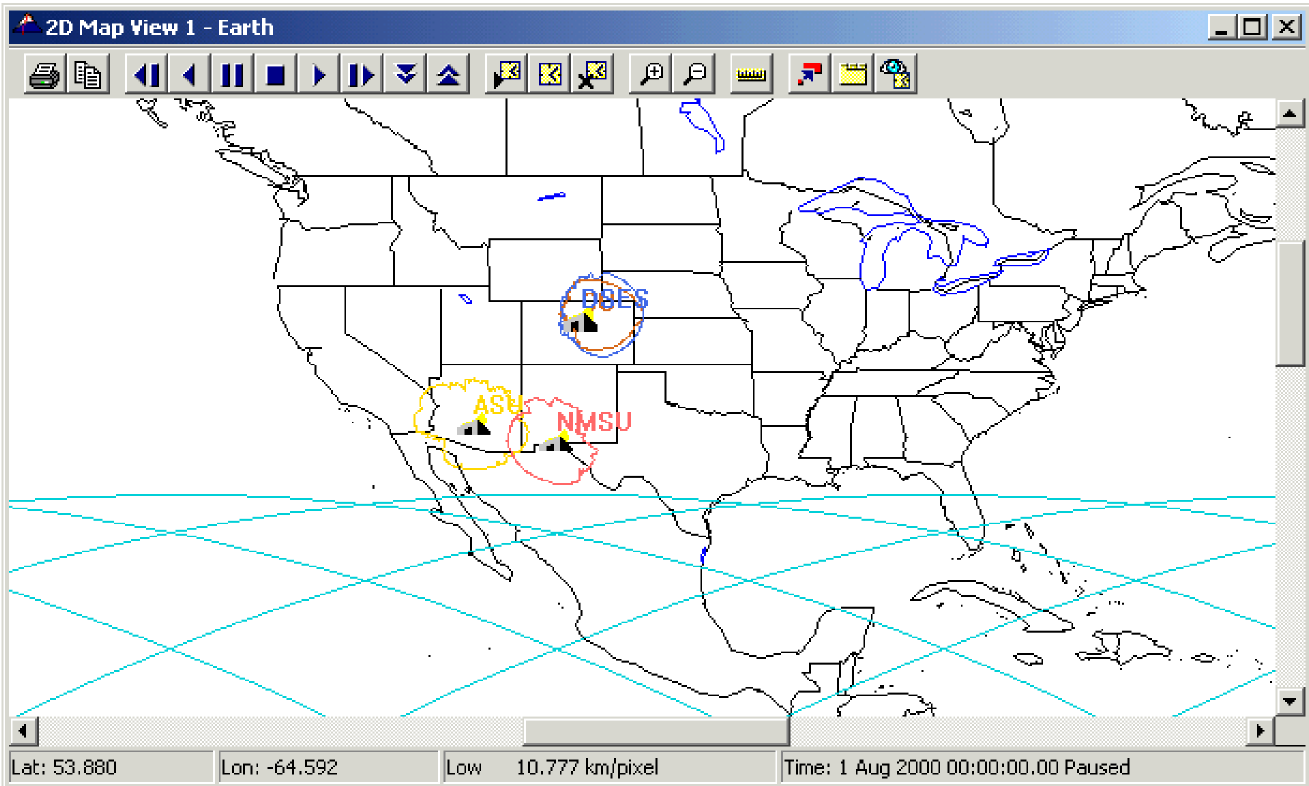

Figure 2-23 – Case 1: 500-km altitude; 28.5º inclination orbit

<u>Conservative Assumptions:</u>

a. VHF/UHF antenna has a 60º HPBW (STK cone angle of 30º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-15 – Conservative Access Summary for Orbital Case 3

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	no access opportunities				0.0
CU					0.0
DSES					0.0
NMSU					0.0

Best-case Contact Assumptions:

a. VHF/UHF antenna has a 120º HPBW (STK cone angle of 60º)
b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-16 – Best Case Access Summary for Orbital Case 3					
Ground Station	**Max. Range (km)**	**Minimum (min)**	**Maximum (min)**	**Avg (min)**	**Contacts/ Day**
ASU	1176.02	0.700	4.380	3.552	2.9
CU	no access opportunities				
DSES					
NMSU	1172.59	0.867	4.689	3.813	3.2

Return S-Band Link			**Units**				
Transmitter (Tx)							
1	Tx Power, Pt	28.0	dBm		Assume:	0.631	Watts
2	Tx Component Line Losses, Ltl	3.0	dB				
3	Tx Antenna Gain (Peak), Gt	5.0	dBi				
4	Tx Pointing Loss, Ltp	3.0	dB				
5	Tx Radome Loss, Ltr	0.0	dB				
6	EIRP (1-2+3-4-5)	27.0	dBm				
Propagation							
	Transmission Frequency, f	2200.0	MHz				
	Link Range, R	1200.0	km		Maximum		
	Propagation Factor, n	1.0					
7	Free Space Loss, Ls	160.9	dB				
8	Atmospheric Absorption, Lpa	0.5	dB				
9	Precipitation Absorption, Lpp	0.5	dB				
10	Total Propagation Loss (7+8+9)	161.9	dB				
Receiver (Rx)							
11	Rx Antenna Gain (Peak), Gr	45.0	dB		Assume	60-foot dish	
12	Rx Polarization Loss, Lrpol	1.0	dB				
13	Rx Pointing Loss, Lrp	3.0	dB				
14	Rx Radome Loss, Lrr	0.0	dB				
15	Rx Component Line Losses, Lrl	3.0	dB				
16	Rx Implementation Losses, Lri	3.0	dB				
17	Received effective carrier power	-99.9	dBm				
	(6-10+11-12-13-14-15-16)						
Noise							
18	Standard Thermal Noise, kT	-174.0	dBm/Hz				
19	Rx Noise Bandwidth, W	51.8	dBHz		Assume:	150000	Hz
20	Rx Noise Figure, NF	3.0	dB				
21	Effective Noise Power (18+19+20)	-119.2	dBm				
Result							
22	Available CNR (17-21)	19.3	dB				
23	Data Rate	50.0	dBHz		Assume	100000	bps
24	Available Eb/No (22+19-23)	21.1	dB				
25	Implementation Losses	2.0	dB				
26	Required Eb/No	13.4	dB		Assume BER=0.00001		
25	Margin (24-25-26)	5.7	dB				

Figure 2-24 – Return link over a 1200 km maximum range to a 60-foot dish.

2.2.2.4. Case 4: 500 km/51.7º

The fourth case to be examined is the higher orbital altitude of 500 km but with the high inclination angle of the ISS at 51.7º.

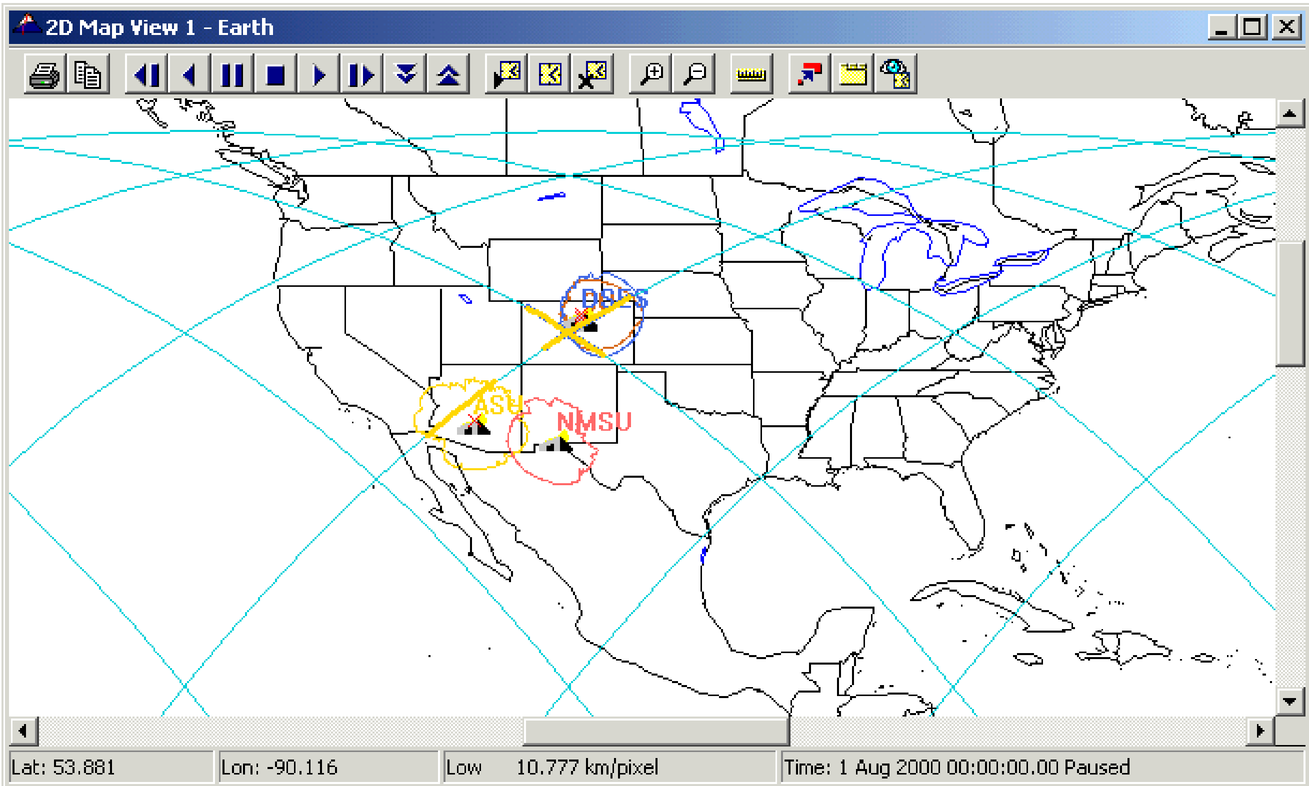

Figure 2-25 – Case 1: 500-km altitude; 51.7º inclination orbit

Conservative Assumptions:

a. VHF/UHF antenna has a 60º HPBW (STK cone angle of 30º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-17 – Conservative Access Summary for Orbital Case 4

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	592.34	0.358	1.335	0.988	0.5
CU	593.59	0.194	1.462	1.174	1.6
DSES	593.65	0.071	1.462	1.179	1.5
NMSU	590.88	0.097	0.425	0.261	0.07

Best-case Contact Assumptions:

a. VHF/UHF antenna has a 120º HPBW (STK cone angle of 60º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-18 – Best Case Access Summary for Orbital Case 4

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	1176.03	0.696	5.005	3.822	2.8
CU	1179.01	0.267	5.050	3.921	3.4
DSES	1179.15	0.118	5.051	3.881	3.5
NMSU	1172.59	0.390	4.833	3.578	2.8

2.2.2.5. Case 5 - Baseline: 350 km/36º

The last case to be examined is the mission baseline orbital altitude of 350 km with an orbital inclination angle of 36º.

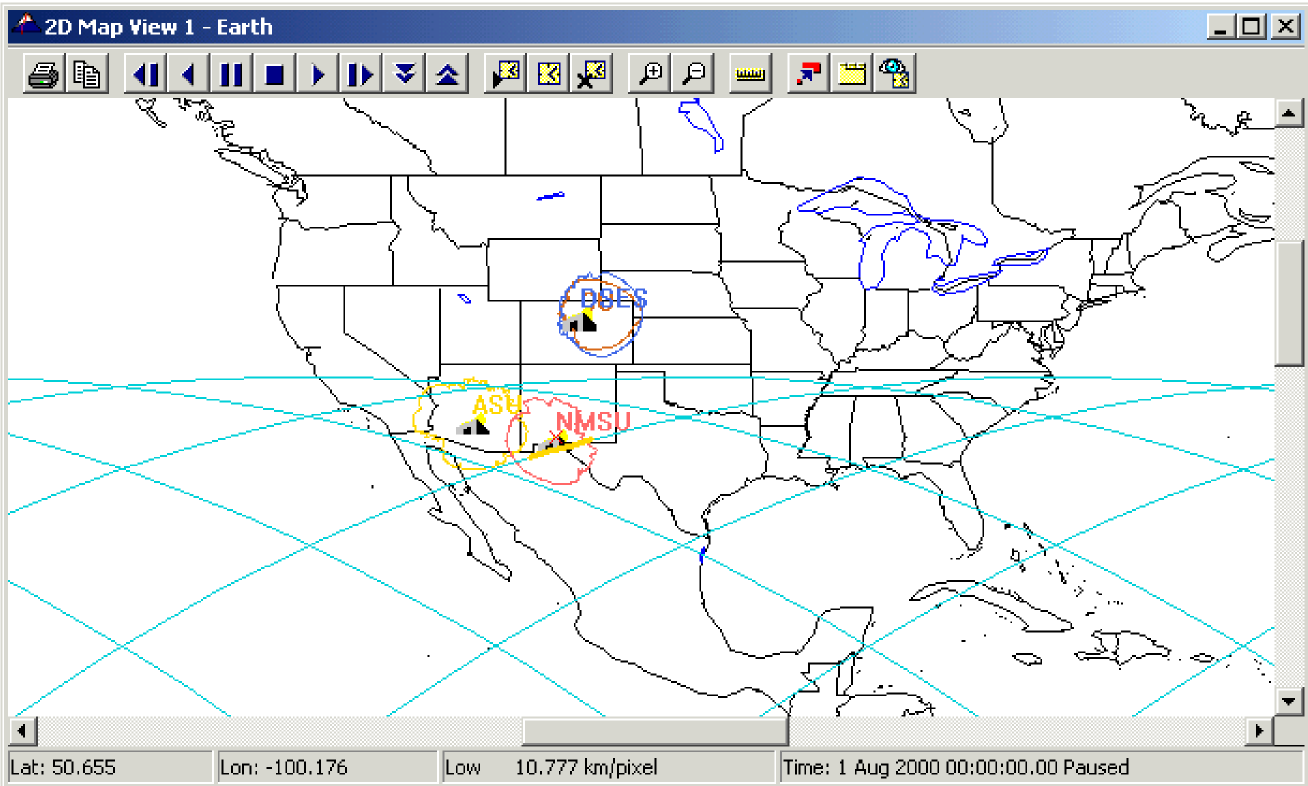

Figure 2-26 – Baseline mission design: 350-km altitude; 36º inclination orbit.

<u>Conservative Assumptions:</u>

a. VHF/UHF antenna has a 60º HPBW (STK cone angle of 30º)

b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-19 – Conservative Access Summary for Orbital Case 5

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	415.08	0.122	0.999	0.767	1.5
CU	no access opportunities				0.0
DSES					0.0
NMSU	413.64	0.053	0.995	0.785	1.2

Best-case Contact Assumptions:

a. VHF/UHF antenna has a 120º HPBW (STK cone angle of 60º)
b. minimum elevation angle is 5º but modified by terrain masking effects

Table 2-20 – Best Case Access Summary for Orbital Case 5

Ground Station	Max. Range (km)	Minimum (min)	Maximum (min)	Avg (min)	Contacts/ Day
ASU	784.90	0.482	3.278	2.895	3.8
CU	787.52	0.411	2.573	2.065	2.0
DSES	787.64	0.632	2.513	2.049	1.9
NMSU	781.89	0.347	3.265	2.784	4.1

3. Estimated Throughput

In this section, we examine the expected throughput that can be achieved. In this examination, we will look at the maximum throughput that can be expected on the link. In practice, lesser amounts can be expected due to protocol inefficiencies, transmission gaps, link establishment, etc. The exact value will depend upon the protocol scheme used.

3.1. VHF/UHF Links

The first set of links to be examined are the VHF/UHF links. The data will be grouped in the same manner as the orbital analysis.

3.1.1. Case 1: 325 km, 28.5º

In this case, limited access is possible. The following table illustrates the maximum expected data throughput. For comparison a 75% efficiency is used to allow for protocol effects. The access times are based on Tables 1 and 2 while the data rate is based upon Figures 2 through 5.

Table 3-1 – Data Throughput for Orbital Case 1

Access Time/ Pass	Passes/ Day	Data Rate	Daily Maximum Throughput	75% Efficiency
1.5 min	1.5	9600 bps	162,000 byte	121,500 byte
2.8 min	2.4	9600 bps	483,840 byte	362,880 byte
5.8 min	4.25	9600 bps	1,774,800 byte	1,331,100 byte

The 450 MHz and 137 MHz links are both closed with these parameters. However, the 137 MHz link does not have the desired 10 dB margin but only a 3.6 dB margin at the maximum link distance. That may still be acceptable.

3.1.2. Case 2: 325 km, 51.7º

This orbital inclination allows all ground stations to directly view the 3CS constellation members at various times throughout the day. The access times are based on Tables 3 and 4 while the data rates are based upon Figures 2 through 5 since the overall link distances did not change from Case 1.

Table 3-2 – Data Throughput for Orbital Case 2				
Access Time/ Pass	**Passes/ Day**	**Data Rate**	**Daily Maximum Throughput**	**75% Efficiency**
2.2 min	2.0	9600 bps	316,800 byte	237,600 byte
5.5 min	4.4	9600 bps	1,742,400 byte	1,306,800 byte
5.5 min	6.3	9600 bps	2,494,800 byte	1,871,100 byte

The 6.3 passes per day is for the CU ground station alone while 4.4 passes per day is for the ASU and NMSU ground stations. This is mostly a latitude effect due to CU being at a latitude near the inclination of the satellite while ASU and NMSU are nearly 10º further south.

3.1.3. Case 3: 500 km, 28.5º

In this case, limited access is possible. The following table illustrates the maximum expected data throughput. For comparison a 75% efficiency is used to allow for protocol effects. The access times are based on Tables 1 and 2 while the data rate is based upon Figures 2 through 5.

Table 3-3 – Data Throughput for Orbital Case 3				
Access Time/ Pass	**Passes/ Day**	**Data Rate**	**Daily Maximum Throughput**	**75% Efficiency**
1.5 min	1.5	9600 bps	162,000 byte	121,500 byte
2.8 min	2.4	9600 bps	483,840 byte	362,880 byte
5.8 min	4.25	9600 bps	1,774,800 byte	1,331,100 byte

The 450 MHz and 137 MHz links are both closed with these parameters. However, the 137 MHz link does not have the desired 10 dB margin but only a 3.6 dB margin at the maximum link distance. That may still be acceptable.

3.1.4. Case 4: 500 km, 51.7º

In this case, limited access is possible. The following table illustrates the maximum expected data throughput. For comparison a 75% efficiency is used to allow for protocol effects. The access times are based on Tables 1 and 2 while the data rate is based upon Figures 2 through 5.

Table 3-4 – Data Throughput for Orbital Case 4				
Access Time/ Pass	**Passes/ Day**	**Data Rate**	**Daily Maximum Throughput**	**75% Efficiency**
1.5 min	1.5	9600 bps	162,000 byte	121,500 byte
2.8 min	2.4	9600 bps	483,840 byte	362,880 byte
5.8 min	4.25	9600 bps	1,774,800 byte	1,331,100 byte

The 450 MHz and 137 MHz links are both closed with these parameters. However, the 137 MHz link does not have the desired 10 dB margin but only a 3.6 dB margin at the maximum link distance. That may still be acceptable.

3.1.5. Case 5: 350 km, 36º

In this case, limited access is possible. The following table illustrates the maximum expected data throughput. For comparison a 75% efficiency is used to allow for protocol effects. The access times are based on Tables 1 and 2 while the data rate is based upon Figures 2 through 5.

Table 3-5 – Data Throughput for Orbital Case 5				
Access Time/ Pass	**Passes/ Day**	**Data Rate**	**Daily Maximum Throughput**	**75% Efficiency**
1.5 min	1.5	9600 bps	162,000 byte	121,500 byte
2.8 min	2.4	9600 bps	483,840 byte	362,880 byte
5.8 min	4.25	9600 bps	1,774,800 byte	1,331,100 byte

The 450 MHz and 137 MHz links are both closed with these parameters. However, the 137 MHz link does not have the desired 10 dB margin but only a 3.6 dB margin at the maximum link distance. That may still be acceptable.

3.2. S-Band Links

3.2.1. Case 1: 325 km, 28.5º

This case is very problematical for S-band access from the nominal 3CS ground station locations. From Table 11, we see that if the link margin does not allow any more than a 30-degree off-boresight pointing, there will be no S-band accesses possible. From Table 12, if the system can accommodate 60-degree off-boresight pointing, then limited access times are available from ASU and NMSU only.

Table 3-6 – Data Throughput for Orbital Case 1				
Access Time/ Pass	**Passes/ Day**	**Data Rate**	**Daily Maximum Throughput**	**75% Efficiency**
1.5 min	1.5	100000 bps	1,687,500 byte	1,265,625 byte

The university-class ground station would require that the data rate be dropped to at most 1200 bps. The link would still need another 6 dB in the power budget to close the link to this class of ground station. The 60-foot dish will close the link but the DSES site in Colorado would not have any passes visible.

3.2.2. Case 2: 325 km, 51.7º

In this case, limited access is possible. The following table illustrates the maximum expected data throughput. For comparison a 75% efficiency is used to allow for protocol effects. The access times are based on Tables 1 and 2 while the data rate is based upon Figures 2 through 5.

Table 3-7 – Data Throughput for Orbital Case 2				
Access Time/ Pass	**Passes/ Day**	**Data Rate**	**Daily Maximum Throughput**	**75% Efficiency**
0.75 min	0.5	1200 bps	3,375 byte	2,531 byte
0.75 min	0.5	100000 bps	281,250 byte	210,938 byte
2.3 min	2.0	100000 bps	3,450,000 byte	2,587,500 byte

The 450 MHz and 137 MHz links are both closed with these parameters. However, the 137 MHz link does not have the desired 10 dB margin but only a 3.6 dB margin at the maximum link distance. That may still be acceptable.

3.2.3. Case 3: 500 km, 28.5º

In this case, limited access is possible. The following table illustrates the maximum expected data throughput. For comparison a 75% efficiency is used to allow for protocol effects. The access times are based on Tables 1 and 2 while the data rate is based upon Figures 2 through 5.

Table 3-8 – Data Throughput for Orbital Case 3				
Access Time/ Pass	**Passes/ Day**	**Data Rate**	**Daily Maximum Throughput**	**75% Efficiency**
1.5 min	1.5	9600 bps	162,000 byte	121,500 byte
2.8 min	2.4	9600 bps	483,840 byte	362,880 byte
5.8 min	4.25	9600 bps	1,774,800 byte	1,331,100 byte

The 450 MHz and 137 MHz links are both closed with these parameters. However, the 137 MHz link does not have the desired 10 dB margin but only a 3.6 dB margin at the maximum link distance. That may still be acceptable.

3.2.4. Case 4: 500 km, 51.7º

In this case, limited access is possible. The following table illustrates the maximum expected data throughput. For comparison a 75% efficiency is used to allow for protocol effects. The access times are based on Tables 1 and 2 while the data rate is based upon Figures 2 through 5.

Table 3-9 – Data Throughput for Orbital Case 4				
Access Time/ Pass	**Passes/ Day**	**Data Rate**	**Daily Maximum Throughput**	**75% Efficiency**
1.5 min	1.5	9600 bps	162,000 byte	121,500 byte
2.8 min	2.4	9600 bps	483,840 byte	362,880 byte
5.8 min	4.25	9600 bps	1,774,800 byte	1,331,100 byte

The 450 MHz and 137 MHz links are both closed with these parameters. However, the 137 MHz link does not have the desired 10 dB margin but only a 3.6 dB margin at the maximum link distance. That may still be acceptable.

3.2.5. Case 5: 350 km, 36º

In this case, limited access is possible. The following table illustrates the maximum expected data throughput. For comparison a 75% efficiency is used to allow for protocol effects. The access times are based on Tables 1 and 2 while the data rate is based upon Figures 2 through 5.

Table 3-10 – Data Throughput for Orbital Case 5				
Access Time/ Pass	**Passes/ Day**	**Data Rate**	**Daily Maximum Throughput**	**75% Efficiency**
1.5 min	1.5	9600 bps	162,000 byte	121,500 byte
2.8 min	2.4	9600 bps	483,840 byte	362,880 byte
5.8 min	4.25	9600 bps	1,774,800 byte	1,331,100 byte

The 450 MHz and 137 MHz links are both closed with these parameters. However, the 137 MHz link does not have the desired 10 dB margin but only a 3.6 dB margin at the maximum link distance. That may still be acceptable.

4. Angles and Rates

The largest concern for the communications links is with the use of the DSES 60-foot dish and the limits on its tracking and pointing. Using the simulation analysis from STK, we look at the expected angles and rates for the DSES site and an S-band link. For the simulations, we used the 350-km orbital altitude at 51° inclination.

The azimuth and elevation angles over a simulated one-month simulation duration are given in Figure 27. Here, we see that the highest elevation angle that is reached is 70°. This addresses the concern of the DSES management for the satellite passes going through the local zenith pointing angle. Most of the time, the pointing will not exceed the 50° - 60° elevation pointing angle. Azimuth pointing angles cover the full range.

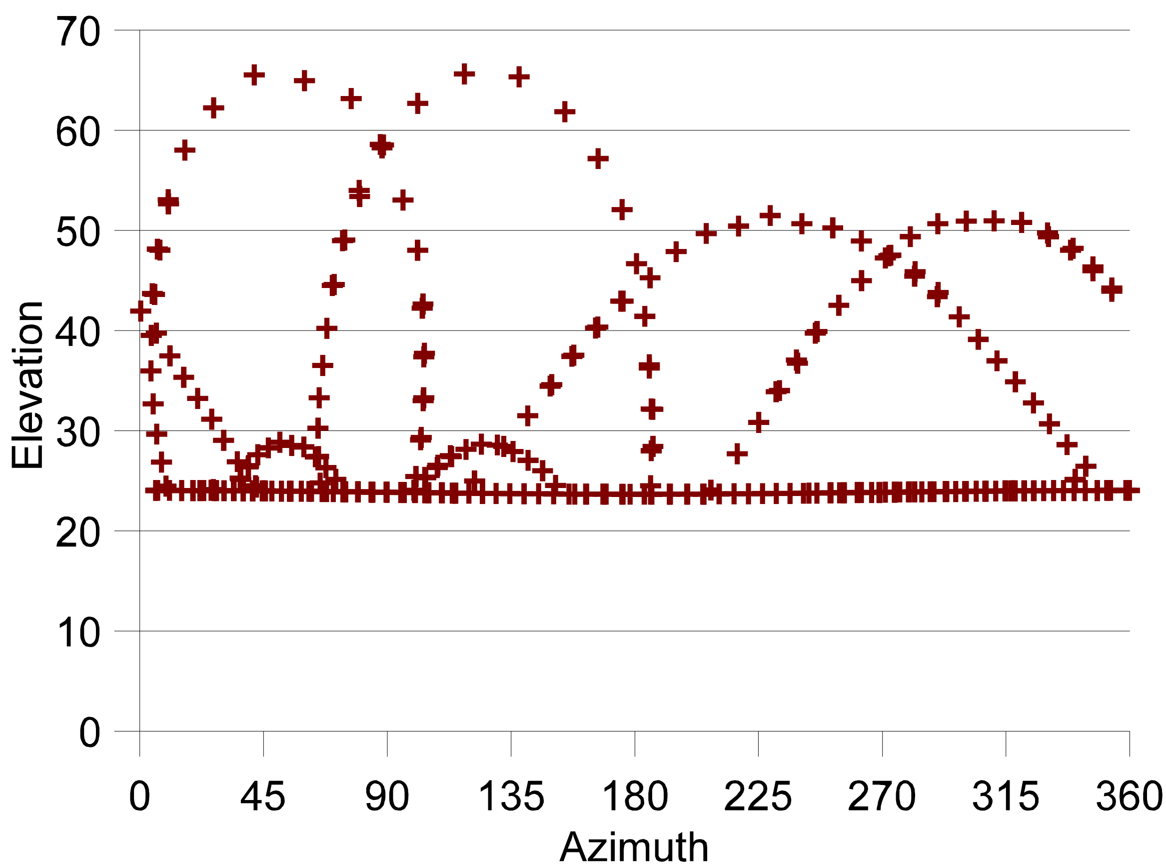

Figure 4-1 – Azimuth and elevation angles for pointing to a 3 Corner Satellite constellation member from the DSES site.

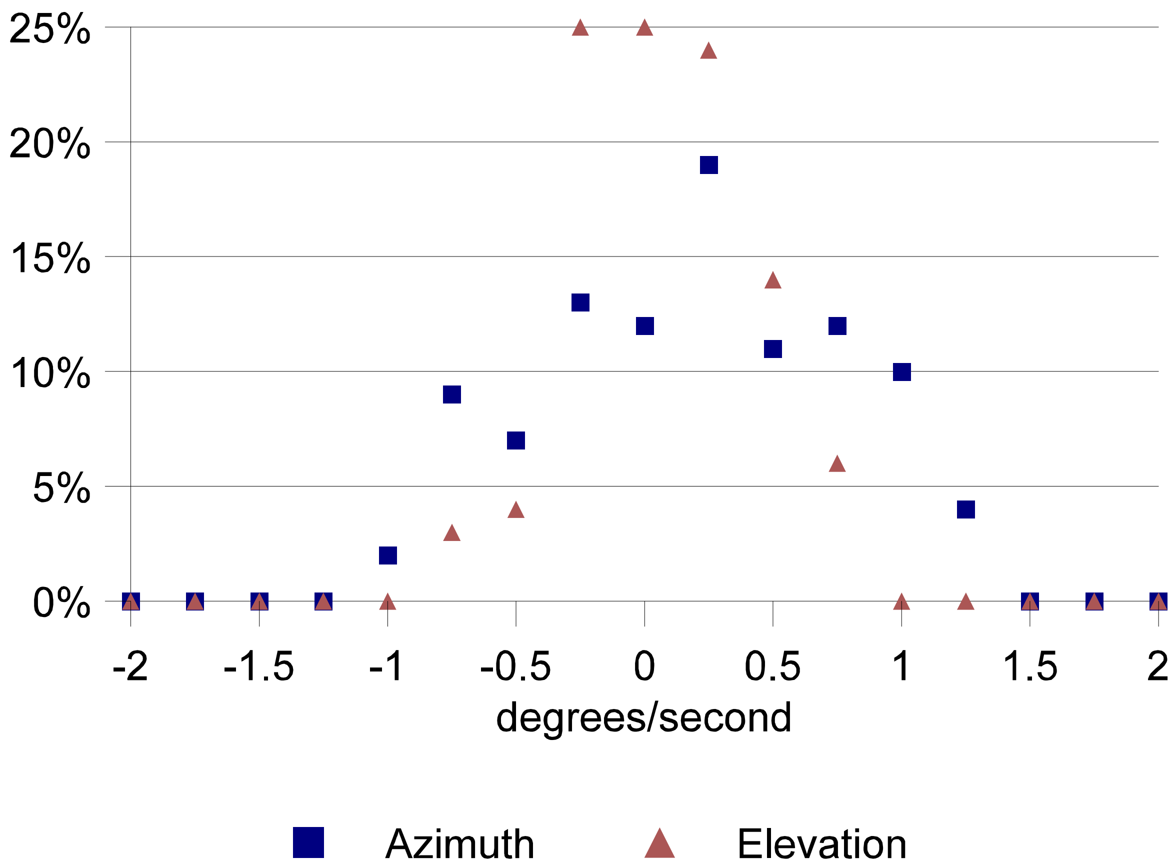

Figure 4-2 – Histogram of azimuth and elevation angle rates for the DSES site.

The STK simulations show that the largest tracking rates are approximately 1.25 degrees per second in magnitude. However, these large rates are encountered only 5% of the time at the most. The majority of the tracking rates are below 0.5 degrees/second in magnitude.

5. Conclusions and Recommendations

Based upon the analysis, we make the following conclusions:

1. The "worst case link" (325 km, 28.5º) can still be useful at VHF/UHF frequencies but only the ASU and NMSU ground stations would have sufficient access time for command uplinks to be attempted. The S-Band link could be maintained to a 60-foot dish but not a university-class ground station.
2. The 51.7º inclination orbits provide VHF/UHF and S-Band access to all member universities and the DSES site. The higher orbital altitudes give a bit longer access times but this may be offset by the lower link power margins. Generally, we would expect ~ 1.3 MB per day throughput at 9600 bps is possible from the constellation.
3. The S-Band links at 51.7º inclination are expected to have approximately 2.5 MB per day throughput. However, this may be an underestimate because the S-Band patch has not been fully characterized and the 60-foot dish performance has been conservatively estimated. It is hoped that this throughput is an underestimate of the actual performance exhibited by the actual components.
4. The angular tracking rates for the 60-foot dish seem to be limited to +/- 1.25 degrees/second at most with tracking through the local zenith being a low-probability event.

Our recommendations for the communications links are as follows:

1. If we end up with the "worst case link," command operations should be moved to NMSU or ASU as the prime and maybe have CU as the backup or experimental link. There would be no need to run S-band return link operations unless a 60-foot class dish antenna were available at ASU or NMSU. The alternative would be to contract with a commercial concern such as Universal Space Network to obtain the S-band ground station option.
2. We need better characterization of the S-Band link to better assess the performance of both the satellite and the ground antenna.

Reminder: these results are based on a single satellite at a time. If time sharing between constellation members individually and with the ION-F constellation as well is required, these data volumes will be reduced.

Appendix A.

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