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THE USE OF SATELLITES IN NON-GEOSTATIONARY ORBITS FOR UNLOADING GEOSTATIONARY COMMUNICATIONS SATELLITE TRAFFIC PEAKS

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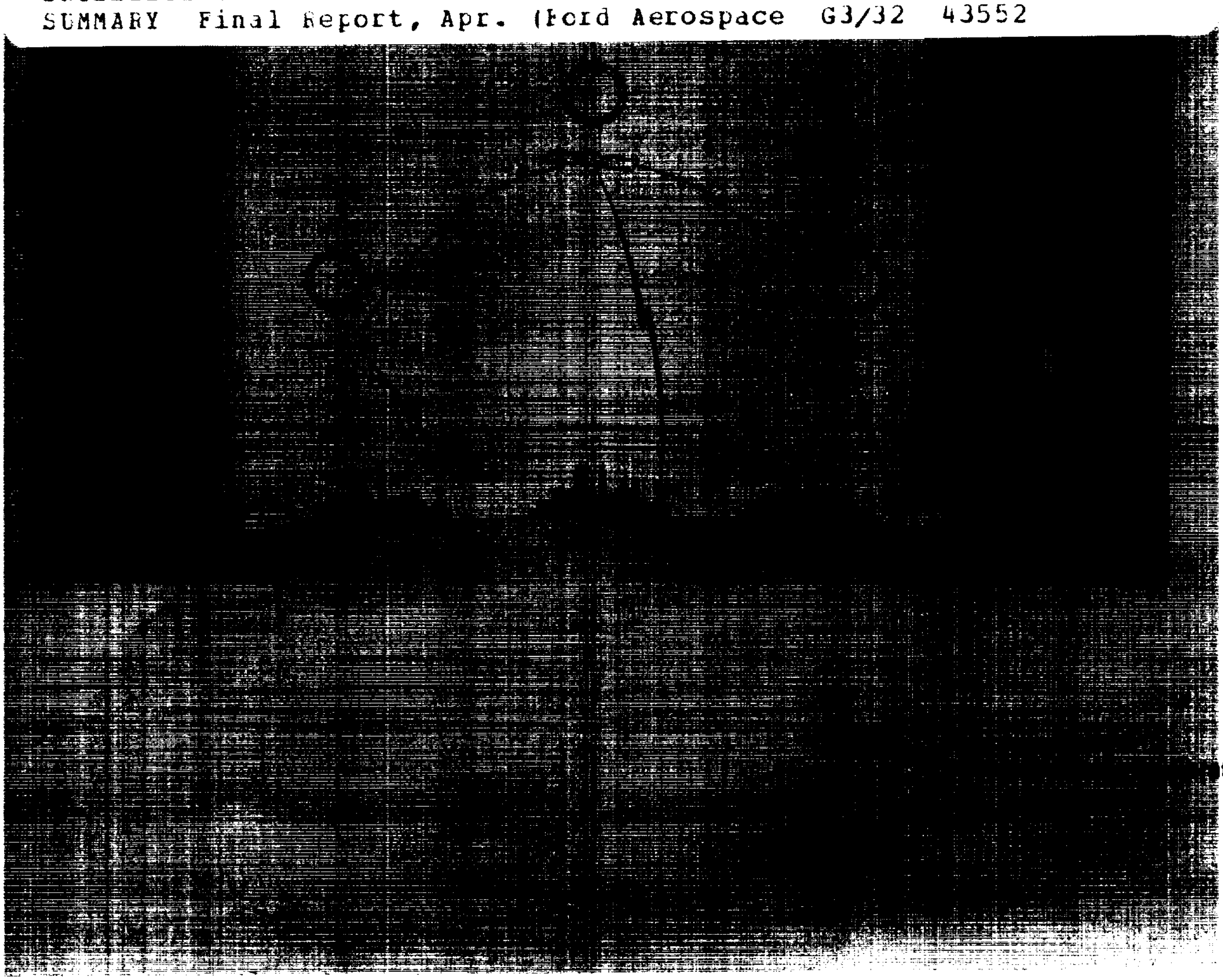

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16. Abstract

The part of the geostationary (GEO) orbital arc used for United States domestic fixed, communications service is rapidly becoming filled with satellites. One of the factors currently limiting its utilization is that communications satellites must be designed to have sufficient capacity to handle peak traffic leads, and thus are under utilized most of the time. A solution is to use satellites in suitable non-geostationary orbits to unload the traffic peaks.

Three different designs for a non-geostationary orbit communications satellite system are presented for the 1995 time frame. The economic performance is analyzed and compared with geostationary satellites for two classes of service, trunking and customer premise service. The result is that the larger payload of the non-geostationary satellite offsets the burdens of increased complexity and worse radiation environment to give improved economic performance. Depending on ground terminal configuration, the improved economic performance of the space segment may be offset by increased ground terminal expenses.

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Volume I:

EXECUTIVE SUMMARY

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EXECUTIVE SUMMARY

1 Introduction

The part of the geostationary orbit (GEO) arc used for United States domestic fixed communications service is rapidly becoming filled with satellites. One of the factors currently limiting its utilization is that communications satellites must be designed to have sufficient capacity to handle peak traffic loads, and thus are underutilized most of the time.

A potential solution is to use satellites in suitable non-geostationary orbits to unload the traffic peaks. This approach may enable a significant increase in the effective utilization of the geostationary satellites. However, the cost of implementing the non-GEO orbit satellites must be less than the gain from increased utilization of the GEO satellites.

The overall objective of this study program is to assess the application, economic benefits, and technology and system implications of satellites in non-GEO orbits for off-loading peak traffic from GEO communications satellites.

The study is organized into four technical tasks which are described in turn.

1. Concepts Development
2. System Definition
3. Economic Comparisons
4. Technology Requirements Definition

1.1 Task 1 – Concepts Development

A GEO-only concept and three alternative non-GEO concepts are developed for each of two representative systems.

1. A satellite system such as RCA Americom's Satcom system which provides a mix of fixed services (voice, video, data) and is *trunking service* orientated.
2. A satellite system such as Satellite Business Systems which provides voice, data, and videoconferencing services business services directly to and from *customers' premises.*

The system concepts are developed on the basis of the technology state-of-the-art at the end of 1990 with the satellites of each system becoming operational in the 1994 to 1997 time frame. The concepts are developed and compared on the basis of a system of satellites addressing an appropriate portion of the year 2000 traffic. A design life of 12 years is assumed for all satellites.

1.2 Task 2 – Systems Definition

For each of the system concepts developed in Task 1, the configurations of the satellites and earth terminals are defined and described.

The differences between non-GEO and GEO satellites are specifically addressed, including the following items:

- Degradation of solar array panels by Van Allen belt radiation
- Orbital drag at perigee
- Delta V required to achieve orbit

1.3 Task 3 – Economic Comparisons

An economic comparison between the GEO system and the GEO plus non-GEO systems defined in Task 2 is performed. The economic assessment includes the following items:

- An estimate of the recurring and non-recurring costs.
- A life cycle cost analysis for each system.

The economic assessment is based on the Financial Model for commercial communications satellite systems developed by Ford Aerospace and Coopers and Lybrand under NASA/LeRC contract number NAS3-24253, *Communications Satellite Systems Operations with the Space Station.*

1.4 Task 4 – Technology Requirements

The enabling or critical technology required to implement the systems defined in Tasks 1 and 2 is identified and described.

2 Traffic Model

2.1 NASA Traffic Model

The projected satellite traffic for CONUS in the year 2000 is derived from the data developed on NASA/LeRC contract NAS3-24235, *Communication Platform Payload Definition (CPPD) Study.*

The baseline traffic model gives the U.S. domestic fixed-service satellite addressable traffic distribution by category and by location but does not contain information about distribution of traffic by time of day. With the exception of video broadcasting, satellite addressable traffic is defined to be between parties separated by at least 640 km (400 mi).

The following information is used from the NASA traffic model:

- Peak traffic breakdown by category:
  - Voice trunking
  - Voice customer premise service (CPS)
  - Data trunking
  - Data CPS
  - Video conferencing trunking
  - Video conferencing CPS
  - Broadcast video
- The peak traffic distribution by location in the four time zones:
  - Intra-zone traffic (within same zone)
  - Inter-zone traffic (between zones)

The traffic forecast for United States domestic fixed satellite demand in the year 2000 is summarized in Table S-1 by category of service. Table S-2 shows the peak traffic distribution by time zone in units of Gb/s and percentage of total peak traffic. The total traffic is 208.6 Gb/s which is the total in Table S-1 minus the 4.6 Gb/s of broadcast video which is independent of the time of day. The intra-zone traffic (over 640 km within the same time zone) refers to two-way (full voice) circuits while the inter-zone values are for half circuits.

As shown in Table S-2, the traffic in and between the Eastern (E) and Central (C) time zones is 70% of the total traffic. The East intrazone traffic itself accounts for 25% of the peak traffic. The East and Central traffic will be the focus for unloading of peaks.

2.2 Traffic Model Results

The total CONUS satellite-addressable traffic is composed of traffic components from the four time zones, appropriately combined to account for the progressive one hour shift in local time across the time zones. The study assumes that the same time-of-day behavior (in local time) is applicable to each individual time zone.

The total of the intra and inter-zone peak traffic in Gb/s is given in Figure S-1 for one hour time periods during the day. A scale of Gb/s and Eastern time is used. The peaks of the total traffic are typically 2/3 inter-zone traffic and 1/3 intra-zone traffic. Note that the peak traffic of 161 Gb/s is significantly less than the 208 Gb/s of Table S-1 (213 Gb/s minus 4.6 Gb/s broadcast video). This is due to the application of time-of-day analysis to the peak traffic.

The traffic model of Figure S-1 shows a rise in activity over the business day for the ten hours from 0830 to 1830 (6:30 pm). There are two peak traffic periods; one around 1100 in the morning and the other around 1630 in the afternoon.

The total traffic plot suggests two possible non-GEO satellite coverages.

1. A single coverage from around 9 am to 5 pm ET (8 hr duration) could offload half of the 160 Gb/s total.

Category	Traffic Quantity	Units
Trunking Service:		
– Voice	6,814,000	HVC
– Data	3,178	Mb/s
– Videoconference	7,786	channels
CPS Service:		
– Voice	35,000	HVC
– Data	23,767	Mb/s
– Videoconference	439	channels
Broadcast Video	158	channels

Category	Mb/s	%
Trunking Service		
– Voice	163,536	76.71
– Data	3,178	1.50
– Video confer.	16,351	7.67
CPS Service		
– Voice	840	.39
– Data	23,767	11.15
– Video confer.	922	.43
Broadcast Video	4,582	2.15
Totals	213,176	100.00

Table S–1: Peak Traffic Forecast for 2000

Time Zone	Peak Traffic (Gb/s)				
To / From	E	C	M	P	Total
E	52.4	38.4	5.0	10.2	106.1
C	38.4	18.3	4.0	7.6	68.2
M	5.0	4.0	.5	2.1	11.7
P	10.2	7.6	2.1	2.8	22.6

Time Zone	Peak Traffic (%)				
To / From	E	C	M	P	Total
E	25.1	18.4	2.4	4.9	50.9
C	18.4	8.8	1.9	3.6	32.7
M	2.4	1.9	.3	1.0	5.6
P	4.9	3.6	1.0	1.3	10.8

Table S–2: Traffic Distribution by Time Zone

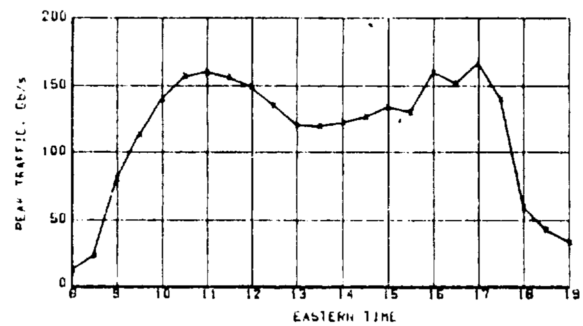

Figure S–1: Total CONUS Traffic

2. A two peak coverage, with peaks of 3.5 hr duration separated by 4 hr, could offload about 25% of the 160 Gb/s total.

After analysis of candidate non-geostationary orbits, the best match of possible orbits and traffic will be made.

2.3 Traffic Analysis Conclusions

Although there is considerable debate about the magnitude of the satellite-addressable traffic in the year 2000, it is the time of day distribution of traffic that is important for this study. Variation in the total amount of traffic is expected to scale directly to variation in the amount of potential non-geostationary traffic.

The double peak form of the total CONUS traffic as shown in Figure S-1 is typical of the expected traffic. The majority of this traffic lies in the Eastern and Central time zones. The feasibility of a satellite or system of satellites supplying 8 or 9 hours continuous coverage, or two 4 hour coverages separated by 4 hours, is investigated next.

3 Analysis of Orbits

3.1 General Requirements

To off-load the daily peaks in geostationary communications traffic, the candidate satellite orbit should meet the following requirements:

- The satellite is in the correct position to service the daily traffic peaks:
  - The satellite (or other constellation member) is visible at the same time each day for the required period of time.
  - The satellite is above 10° elevation for the the traffic which it is servicing.
  - The satellite remains above 10° elevation for the region of CONUS being serviced for at least two hours each day.
- The non-GEO satellites do not physically or electrically interfere with existing satellites.
- The system costs are as low as possible.

The following two orbits are selected for use in offloading daily traffic peaks.

- Apogee at Constant time-of-day Equatorial (ACE) orbit
- Sun-synchronous Twelve-hour EquaTorial (STET) orbit

3.2 ACE Orbit

ACE orbit is the abbreviation for Apogee at Constant time-of-day Equatorial orbit. The ACE orbit is sun-synchronous and highly eccentric, with the satellite completing five revolutions per day. The satellite depends upon a continuing perturbation of its orbit to overfly the same area of the earth at the same time each day. A 4.8 hour orbital period enables a single satellite to be used for both the morning traffic peak and on the next orbit Table S-3 summarizes the parameters of the orbit.

A satellite in the ACE orbit has five apogee crossings each day, with each crossing occurring above a particular point on the equator. These points are separated by one-fifth the circumference of the earth or 72° of longitude and remain fixed throughout the year. Good coverage for CONUS peak times is afforded by a satellite in an ACE orbit which reaches apogee above 48° W and 120° W at 11:50 am and 4:37 pm eastern time respectively. Table S-4 gives the coverage

Parameter	Value	Unit
Period	4.79	h
Semi-major axis	14,445	km
Eccentricity	.49	
Inclination	0.0	°
Perigee radius	7,410	km
Perigee altitude	1,030	km
Apogee radius	21,480	km
Apogee altitude	15,100	km
Nodal regression	-.986	°/day
Apsidal rotation	1.972	°/day

Table S-3: ACE Orbit Parameters

times and duration (satellite above 10° elevation angle) for the first and second apogees of this ACE orbit for nine CONUS cities.

The ACE orbit satellite is in continuous motion with respect to any ground terminal. The satellite never approaches the zenith. The slant range and one-way signal propagation delay vary with time.

3.3 STET Orbit

A satellite in the Sun-synchronous Twelve-hour Equatorial Orbit (STET) depends only on the specific value of its orbital period to bring it into view of its service region at the same time each day. The orbit is circular and does not depend on perturbations to enable the satellite to carry out its mission. Furthermore, the path of the satellite across the sky is the same each day, greatly simplifying tracking. Table S-5 summarizes the STET orbital parameters.

Table S-6 displays the times for which a STET satellite could be used to provide coverage for seven CONUS cities. Simultaneous coverage of all cities is only provided from 9:29 am to 2:13 pm EST, a period of 4 hr 44 min. The STET satellite moves from west to east and remains about 3.5° away from the geostationary arc as viewed from Miami.

City	1st Apogee 48° W Coverage Hours (ET) Begin	End	Duration
San Francisco	0945	1032	.76
Los Angeles	0944	1053	1.15
Denver	0950	1138	1.79
Dallas	0948	1222	2.56
Omaha	0853	1109	2.27
Chicago	0956	1232	2.61
Miami	0951	1301	3.17
New York City	1000	1300	3.00
Boston	1002	1301	2.98

City	2nd Apogee 120° W Coverage Hours (ET) Begin	End	Duration
San Francisco	1458	1814	3.26
Los Angeles	1459	1818	3.33
Denver	1514	1823	3.15
Dallas	1518	1830	3.20
Omaha	1426	1726	3.00
Chicago	1540	1829	2.80
Miami	1539	1838	2.98
New York City	1613	1834	2.33
Boston	1627	1833	2.10

Table S-4: ACE Orbit Coverages

Parameter	Value	Unit
Period	12	h
Eccentricity	0	
Inclination	0.0	°
Radius	26,590	km
Altitude	20,210	km

Table S-5: STET Orbit Parameters

City	Coverage Hours (ET) Begin	End	Duration
Los Angeles	0715	1413	8.14
Dallas	0740	1542	8.21
Omaha	0757	1529	7.71
Chicago	0830	1602	7.68
Miami	0833	1655	8.48
New York City	0915	1700	7.76
Boston	0929	1706	7.63

Table S-6: STET Orbit Coverages

4 Deloading Peak Traffic

The basic restriction in providing deloading capacity is the time the satellite is visible to the potential users. Traffic analysis gives a requirement of from 7 to 10 hours continuous coverage, depending on coverage area and amount of deload desired.

Deloading with a single non-GEO satellite is severely constrained by the visibility coverage that the single satellite provides for different time zones. Both STET and ACE orbits do not provide enough continuous coverage (i.e. 10 to 12 hours) over the entire CONUS to arbitrarily deload any desired amount of traffic. Thus *traffic deloading will be restricted to a portion of the total CONUS traffic, the 70% situated in the Eastern and Central time zones.*

The deloading capacity of a single and multiple.satellites at approximately the same orbital locations is summarized for the STET and ACE orbits in Table S-7. Total deloading is around 10% to 12% of the peak capacity of 208.5 Gb/s.

One non-GEO satellite location cannot provide full CONUS deloading. However, two satellites (with sufficient capacity) in the STET orbit can deload 35% to 44% of the peak traffic. However, the economics of having two non-GEO satellites do the work of one GEO satellite may not be attractive.

The conclusion is that one non-GEO satellite, in STET or ACE orbit, can provide substantial deloading of Eastern and Central intra-zone traf-

Satellite	Peak Traffic Deload (Gb/s) East. Intra	Cent. Intra	E↔C Inter	Total CONUS
One STET	1.3	9.6	20.9	0.0
One ACE	1.0	10.8	25.8	0.0
Two STET				72.0
Two ACE				0.0
Five ACE				148.0

Table S–7: Peak Traffic Deloading Performance

fic and E↔C inter-zone traffic. System concepts for these cases will be developed and defined, and the economics of the resulting non-GEO satellites analyzed.

5 Forecast of 1990 Technology

An assessment is made of the expected state-of-the-art status of communications satellite systems and operations for U. S. domestic FSS systems based on the 1990 technology level. The assessment considers each of the seven communications satellite subsystems. The anticipated technology developments for each subsystem are summarized along with the anticipated technical benefits.

The bottom line is that satellites will have a significant improvement in payload capacity, perhaps by 50%, which will allow a reduction in transponder lease cost.

6 System Concepts

The following potential differences between GEO and non-GEO satellite systems are discussed before non-GEO satellite systems are defined.

1. Antenna coverage
2. Attitude control
3. Battery versus solar array capacity
4. Launch vehicle capacity
5. Orbital drag at perigee
6. Radiation environment effects

6.1 Antenna Coverage

Comparison of plots of required antenna coverage for the non-GEO ACE and STET orbits with that of the GEO orbit satellite shows the following.

- The lower altitude non-GEO satellites have a wider antenna coverage angle than a GEO satellite. The resultant antenna has lower gain and a smaller diameter.

- As the STET and ACE satellites change orbital position, the size and shape of the coverage area changes. This suggests a more complex reconfigurable antenna may be required.

6.2 Attitude Control

The rising and setting of the satellite requires that the pointing direction of the satellite antenna be continuously changed during times of coverage. This is true regardless of the reference frame to which the satellite is fixed, even with gravity gradient stabilization. In addition, the antenna may be pointed to minimize the composite coverage pattern envelope. The range of pitch motion required for each coverage region pass is 25° for the STET and 37° for the ACE orbit satellite.

Since both the STET and ACE satellites are closer to the earth, an earth sensor with a wider field of view is needed. There is no mass change for the STET orbit, but the ACE orbit requires a panoramic earth sensor with a 1 kg mass increase.

For spin stabilized satellites, attitude control simply requires that the antenna platform is despun at a different rate for the STET satellite. For the ACE satellite there is a slightly varying despin rate with additional control electronics required to change the despin rate.

The proposed solution for the 3-axis satellite is to use a reaction wheel to provide small increments of attitude control for the satellite. The estimated impact is 4 kg mass and 15 W electric power.

6.3 Battery Versus Solar Array Size

Since there is no requirement for communications during solar eclipse for the non-GEO satellite, the battery capacity can be reduced to the level of the satellite "housekeeping power" which is typically 15% of full power. Approximately 85% of the GEO satellite battery mass can be saved by the non-GEO satellites.

A better approach is to reduce solar cell area by increasing battery capacity. This is possible since the non-GEO satellite provides communications for only 8 hr a day, and the worst case eclipse scenario results in sunlight on the solar arrays 22 hr per 24 hr.

Solar array area can also be reduced by use of higher efficiency GaAs solar cells. However, the 21% GaAs efficiency (versus 12% Si) is offset by its greater thickness, density, and cost. GaAs is projected to be used only where there are limits on available area for solar cells.

6.4 Launch Vehicle Capacity

Table S-8 compares launch vehicle performance of different launch vehicles for the GEO, STET, and ACE orbits. The STS (Shuttle) and Atlas Centaur launch from ETR (Eastern Test Range or Cape Canaveral) and the Ariane from Kourou. The mass in kilograms that can be placed into orbit is tabulated for the beginning of life (BOL) satellite (includes station keeping fuel and attitude control fuel) and for the dry or end of life satellite.

Also tabulated is the ratio of non-GEO to GEO mass placed into orbit. Depending on launch vehicle and launch site, the STET orbit can be reached by a satellite with 1% to 39% more mass and the ACE orbit with 63% to 181% more mass. The mass savings are due to the lower delta Vee required to launch to these orbits and the savings in stationkeeping fuel. The GEO orbit requires enough stationkeeping fuel to supply a velocity increment of 600 m/s, the STET 380 m/s, and the ACE orbit satellite a nominal 100 m/s.

The increase in launch capacity is so great for the ACE satellite that use of a considerably smaller perigee stage is possible. The result is a reduction in STS launch cost and upper stage cost.

6.5 Orbital Drag at Perigee

Satellites in orbits low enough to encounter the top of the earth's atmosphere experience drag forces which cause their orbits to decay with time. The minimum altitude of the STET orbit is 20,210 km and the ACE orbit is 1,030 km. For 12 year satellite lifetimes, even considering a disturbed atmosphere during a solar maximum, negligible drag force is experienced. No fuel expenditure is required to maintain the satellite orbit.

6.6 Radiation Effects

The radiation environment and its impact on the satellite is analyzed. For satellites using 1990 technology, the STET orbit requires the equivalent of 100 mils aluminum additional shielding around sensitive electronic piece parts in addition to the use of harder parts. The ACE orbit requires no additional shielding.

For the solar array, the effect of protons must be added to that of electrons, with the result that there is considerable impact on the ACE orbit but not very much on the STET orbit satellites. The ACE and STET orbit satellites require 85% and 15% more area respectively compared to the equivalent GEO satellite. The ACE satellite also requires thicker cover glass on the solar array.

6.7 Summary of Impacts

The impact of these differences on the satellite is reflected in mass changes which are directly related to costs. Table S-9 summarizes the impacts on the satellite system.

7 System Definition

The following satellite system concepts are defined.

1. Trunking System Concepts:
   - Baseline GEO system

	Mass Placed in Orbit (kg)					
	GEO		STET		ACE	
Launch Vehicle/Site	BOL	Dry	BOL	Dry	BOL	Dry
STS/PAM D, ETR	560	445	690	585	990	945
(Mass ratio: non-geo/geo)			1.23	1.33	1.77	2.11
STS/PAM D2, ETR	1,020	811	1,260	1,087	1,820	1,742
(Mass ratio: non-geo/geo)			1.24	1.33	1.79	2.13
STS/TOS, ETR	1,170	932	1,510	1,306	2,210	2,118
(Mass ratio: non-geo/geo)			1.29	1.39	1.89	2.25
Atlas Centaur, ETR	1,310	1,046	1,320	1,140	2,140	2,051
(Mass ratio: non-geo/geo)			1.01	1.09	1.63	1.95
Ariane 2, Kourou	1,020	811	1,300	1,122	2,400	2,302
(Mass ratio: non-geo/geo)			1.27	1.38	2.35	2.81

Table S–8: Launch Vehicle Performance for GEO, STET, and ACE Orbit Satellites

- STET satellite system
- ACE satellite systems:
  Increased payload
  Reduced size launch vehicle

2. Customer Premise Service Concepts:
   - Baseline GEO system
   - STET satellite system
   - ACE satellite systems:
     Increased payload
     Reduced size launch vehicle

Table S-10 summarizes the definitions of the four types of trunking systems, and Table S-11 summarizes the definitions of the four types of CPS systems.

7.1 Trunking Satellite Systems

The baseline trunking satellite design is a spin stabilized satellite of 560 kg beginning-of-life (BOL) mass, C-band payload, and STS/PAM D launch. The use of 1990 technology gives mass and power savings that allow higher power transponders and greater redundancy to meet the 12 year lifetime than on the original HS-376 bus on Galaxy 4.

For both the STET and ACE orbit satellite designs, an increase in payload mass is possible because of reduced station-keeping fuel requirements and increased launch capability for satellites in this orbit (see Table S-8). The payload is increased to the limit that is launchable using the STS/PAM D combination. The alternate ACE design concept, called the ACE*, keeps the same payload mass as the GEO concept but uses a smaller perigee motor.

All trunking satellite designs are spin stabilized. The main design drivers of the non-GEO designs compared to the GEO design are as follows:

- Larger mass can be launched into orbit.
- "Smart" antenna systems are required to follow changes in coverage region size and shape.
- Solar array size is doubled for ACE orbit on account of radiation environment. This is particularly difficult for spinner satellites which already require 2.5 times more solar

Component	Impact on Satellite System	
	STET Orbit	ACE Orbit
Antenna:	Closer to earth implies smaller antenna.	ditto
	Variable coverage region shape implies:	ditto
	– less gain, potential interference;	
	– need for reconfigurable antenna	Reconfigurable antenna required.
	Small efficient beams imply larger antenna.	ditto
Attitude control:	More mass for reaction wheels (3-axis).	ditto
	Additional attitude control fuel (3-axis).	ditto
		More mass for earth sensor.
Power:	Battery mass can be reduced by 85%.	ditto
	Alternately, solar array area can be reduced 50% and battery capacity increased.	ditto
	Radiation environment requires 15% increase in solar cell area.	85% increase solar cells.
	More power for attitude control (3-axis).	ditto
	More power for reconfigurable antenna.	ditto
Propulsion:	Smaller apogee motor.	ditto
		Possible integral upper stage.
Structure:	Larger satellite needs more structure mass.	ditto
		Electronics radiation shielding.
Launch Vehicle:	+33% dry mass into orbit for same vehicle.	110% more dry mass into orbit.
	Or smaller perigee and apogee motors and less STS fuel and volume.	ditto
Earth terminal:	Position tracking capability.	ditto
	Polarization vector tracking capability.	ditto

Table S–9: Impact of Non-GEO Orbits on STET and ACE Satellite Systems

Parameter	GEO	STET	ACE	ACE*
Baseline satellite type:	HS-376	–	–	–
Design life (yr)	12	12	12	12
BOL mass (kg)	560	690	990	560
Payload mass (kg)	100	160	260	124
– Antenna (kg)	20	60	80	44
– Transponder (kg)	80	100	180	80
EOL power (W)	830	520	800	465
Stabilization	spin	spin	spin	spin
Frequency	C-band	C-band	C-band	C-band
Number of transponders	24	30	48	24
Transponder bandwidth (MHz)	36	36	36	36
Transponder power (W)	9	9	9	9
Antenna coverages:	2	3	4	2
EIRP, half CONUS (dBW)	38	38	38	38
Launch vehicle(s):	Ariane 4 STS/PAM D	Ariane 4 STS/PAM D	Ariane 4 STS/PAM D	Ariane 4 STS/Star 37
Satellite Cost ($M, 1986)	39.3	48.6	73.4	44.2

Table S–10: Summary of Trunking Satellite Characteristics

	GEO	STET	ACE	ACE*
Baseline satellite type:	Satcom K2	–	–	–
Design life (yr)	12	12	12	12
BOL mass (kg)	1,020	1,260	1,820	990
Payload mass (kg)	277	379	549	282
– Antenna (kg)	29	49	53	34
– Transponder (kg)	248	330	496	248
EOL power (W)	2,900	3,800	3,000	1,600
Stabilization	3-axis	3-axis	3-axis	3-axis
Frequency	Ku-band	Ku-band	Ku-band	Ku-band
Number of transponders	24	32	48	24
Trans. bandwidth (MHz)	54	54	54	54
Transponder power (W)	50	50	50	50
Antenna coverages:	3	4	6	3
EIRP, half CONUS (dBW)	49	49	49	49
Launch vehicle(s):	Ariane 4 STS/PAM D2	Ariane 4 STS/PAM D2	Ariane 4 STS/PAM D2	Ariane 4 STS/PAM D
Satellite Cost ($M, 1986)	53.7	66.5	94.5	59.6

Table S–11: Summary of CPS Satellite Characteristics cell area than a 3-axis satellite due to their geometry.

- Solar array size can be reduced at the expense of increased battery mass on account of the low communications duty cycle (8 hr per 24 hr).

For the STET satellite, the number of transponders increases slightly and it is expected that economic performance will be about the same as the GEO satellite.

For the ACE satellite, the number of transponders is doubled and a significant performance improvement is expected. However, the power subsystem becomes large and requires use of GaAs solar cells on account of the limited solar cell area on the spinner satellite.

The ACE* satellite is relatively simple in that it keeps the same number of transponders as the GEO satellite, but uses a smaller perigee motor. Considering the small mass penalty of the ACE orbit, its economic performance should be very similar to the GEO satellite.

7.2 CPS Satellite Systems

All CPS designs are 3-axis satellites. The main design drivers of the non-GEO designs compared to the GEO design are as follows:

- Larger mass can be launched into orbit.
- "Smart" antenna systems are required to follow changes in coverage region size and shape.
- Solar array size is doubled for ACE orbit on account of radiation environment.
- Solar array size can be reduced at the expense of increased battery mass on account of the low communications duty cycle (8 hr per 24 hr).

For the STET satellite, the number of transponders increases and it is expected that performance will improve slightly due to economies of scale.

For the ACE satellite, the number of transponders is doubled and a significant performance improvement is expected. However, the power subsystem becomes large and is dominated by 264 kg of NaS batteries. There are also two 90-element reconfigurable antennas.

The ACE* satellite is relatively simple in that it keeps the same number of transponders as the GEO satellite, but uses a smaller perigee motor. Considering the small mass penalty of the ACE orbit, its economic performance should be very similar to the GEO satellite.

7.3 Discussion

7.3.1 STET Versus GEO Satellites

From the standpoint of satellite design, the penalties associated with the STET orbit (more complex antenna, radiation shielding) are balanced by the increased payload which allows more transponders. Thus while satellite cost increases, satellite revenues also increase. Thus economic performance should be similar to the GEO design if the STET transponders can be sold for a similar price to the GEO transponders.

7.3.2 ACE Versus GEO Satellites

The penalties associated with the ACE orbit (more complex antenna, doubling of power subsystem mass) are considerable, but are more than offset by a doubling in payload mass. There is a large potential for increased satellite economic performance.

7.3.3 Spinner Versus 3-Axis Satellites

Generally speaking, the spinner satellite design has a cost advantage over the 3-axis design for smaller satellites. However, for the ACE orbit, the spinner design must be of low power due to the double effects of the radiation environment and the spinner geometry. Thus the spinner design is not suited for ACE orbit CPS applications.

7.3.4 Trunking Versus CPS Satellites

The non-GEO orbits appear to be more suitable for trunking applications (than for CPS) due to the fewer number of ground stations and the fact that larger ground stations are likely to have a tracking capability.

For CPS applications that are uplink power limited, there is potential for the non-GEO satellites to have better EIRP than GEO satellites due to decreased space loss. However, the antenna system has to be designed to subdivide the coverage area into smaller pieces.

8 Economic Comparison

The economic assessment is based on the Financial Model for commercial communications satellite systems developed by Ford Aerospace and Coopers and Lybrand under NASA/LeRC contract number NAS3-24253, *Communications Satellite Systems Operations with the Space Station.*

8.1 Methodology

The methodology used to compare economic performance of GEO and non-GEO satellite systems is as follows.

- Start with 1985 GEO satellite designs
- Predict end-of-1990 technology
- Evolve 1985 GEO satellites to 1994 launch date designs
  - These are the "baseline" GEO trunking and CPS designs described in Section VII.
- Use the Financial Model to calculate the baseline satellite system initial rate-of-return (DTRR).
- Adjust the baseline transponder price until the rate of return equals 18%.
  - The results are basic transponder prices of $1.65 M/yr (C-band, 9 W, 36 MHz) and $2.14 M/yr (Ku-band, 50 W, 54 MHz).
- Modify the baseline GEO satellite designs as per the system definitions of Section VII.

Satellite Design	Capital Cost, $M	
	Trunking	CPS
GEO	81.47	116.58
STET	94.41	134.49
ACE	127.24	172.65
ACE*	88.05	110.12

Table S-12: Capital Expenditures

Satellite Design	Rate of Return, %	
	Trunking	CPS
GEO	18.00	18.00
STET	18.13	19.43
ACE	20.47	20.98
ACE*	17.79	18.42

Table S-13: Rate of Return (DTRR)

  - The results are the STET and ACE non-GEO designs for trunking and CPS applications.
- Use the Financial Model to determine economic performance of the non-GEO satellite designs:
  - Rates of return for non-GEO designs.
  - Non-GEO transponder prices which give 18% rate of return.

Table S-12 compares the total capital expenditures in 1986 dollars for the different satellite designs. Capital expenditures are for one satellite and include satellite cost, STS launch cost, perigee stage cost, launch support cost, mission operations, and launch insurance at 20%.

Table S-13 gives the dual terminal rate-of-return (DTRR) for the six satellite types that are analyzed, based on a fixed transponder price of $1.65 M yearly lease fee for C-band (9 W, 36 MHz) and $2.14 M for Ku-band (50 W, 54 MHz) transponders.

Table S-14 turns the question around and gives the transponder price corresponding to an 18% rate-of-return (DTRR) for the eight satellite types that are analyzed. This is perhaps

Satellite Design	Transponder Price ($M/yr)	
	Trunking	CPS
GEO	1.65	2.14
STET	1.63	1.84
ACE	1.27	1.56
ACE*	1.69	2.05

Table S–14: Transponder Prices (18% Return)

more reasonable since in an open market, the non-GEO transponders would be expected to sell at a discount from their GEO counterparts.

8.2 Economic Performance

8.2.1 Summary of Payloads

Table S-15 summarizes the transponder payloads on the different satellite designs. Note that the same types of transponders are used on the different trunking and CPS designs respectively. The assumed lease fee per transponder-year is based on an 18% rate-of-return as given in Table S-14.

8.2.2 Capital Expenditures

The capital expenditures for the three trunking systems (baseline GEO, STET, and ACE) are detailed in Table S-16, and the three CPS systems are given in Table S-17. The considerable variation in satellite costs among the GEO, STET, and ACE designs is simply related to the number of transponders in the payload. There is variation in STS launch costs based on length and mass of the satellite plus perigee stage. The mission operations become more expensive for shorter period orbits due to the necessity to only make orbital adjustments while the satellite is in view of the control station; (i.e. more time is required for mission operations). Launch insurance is calculated at 20%.

8.2.3 Rates of Return

The Financial Model considers expenditures and revenues to calculate rate of return (DTRR) on investment. The results are given in Table S-13. It is evident that a better rate of return is obtained with the non-GEO compared to the baseline GEO satellite. This is primarily due to the use of the greater payload to generate additional revenues and the consequent economies of scale of larger payload satellites.

It is evident from comparison of the GEO and ACE* designs (same payload) that there is little intrinsic difference in economic performance between orbits. The savings in launch costs are balanced by the costs of the ACE orbit (i.e. complex antenna and oversize solar arrays). In addition there are further ground terminal costs for the non-GEO satellite systems which have not yet been considered.

8.2.4 Transponder Prices

Table S-14 indicates the potential transponder prices for the GEO and non-GEO orbit satellite designs. The tabulated transponder lease fees are adjusted to give the operator a uniform 18% dual terminal rate of return (DTRR).

Although the tabulated prices for the ACE* trunking and CPS designs and the STET trunking design are competitive with the baseline GEO transponder prices, there probably must be an incentive (i.e. lower prices) to use these designs. This is particularly true since additional costs for a tracking ground terminal have not yet been considered. However if the GEO arc is full, there is no penalty (other than a tracking ground terminal) for use of these non-GEO designs and they may be acceptable.

More interesting are the STET CPS concept which has a 14% price reduction and the trunking and CPS ACE designs which have 23% and 27% transponder price reductions respectively. These reductions may be enough to make a carrier prefer the non-GEO system.

8.2.5 Ground Terminal Costs

The consideration of ground terminal costs is approached by considering how much additional expense is required to build and maintain a new ground terminal that can track the non-GEO designs. Since the satellite motion is the same ev-

Satellite System			Transponders			
System	Orbit	Freq. Band	Number	Power (W)	Bandwidth (MHz)	Lease Fee ($ M/yr)
Trunking	GEO	C	24	9	36	1.65
	STET	C	30	9	36	1.63
	ACE	C	48	9	36	1.27
	ACE*	C	24	9	36	1.69
CPS	GEO	Ku	24	50	54	2.14
	STET	Ku	32	50	54	1.84
	ACE	Ku	48	50	54	1.56
	ACE*	Ku	24	50	54	2.05

Table S–15: Transponder Payloads for Different Satellite Designs

Capital Expenditure	Cost in $ M, (1986)			
	GEO	STET	ACE	ACE*
Satellite cost	39.30	48.60	73.40	44.20
STS launch cost	16.01	22.46	22.46	15.93
Perigee cost	6.20	6.20	6.20	3.00
Launch support cost	1.63	1.63	1.63	1.63
Mission operations	2.56	3.20	3.80	3.80
Launch insurance	15.77	18.27	24.63	16.46
Total	81.47	94.41	127.24	85.05

Table S–16: Capital Expenditures for Trunking Satellites

Capital Expenditure	Cost in $ M, (1986)			
	GEO	STET	ACE	ACE*
Satellite cost	53.70	66.50	94.50	59.60
STS launch cost	25.43	26.43	28.41	17.58
Perigee cost	10.70	10.70	10.70	6.20
Launch support cost	1.63	1.63	1.63	1.63
Mission operations	2.56	3.20	3.80	3.80
Launch insurance	22.56	26.03	33.41	21.31
Total	116.58	134.49	172.65	110.12

Table S–17: Capital Expenditures for CPS Satellites ery day, a programmed track capability is adequate.

For a trunking system scenario where two large (11 m) ground terminals fully utilize two transponders, the conclusion is that the increased cost of tracking has a negligible effect ($0.03 M/yr) over the 12 year system lifetime. (However, other considerations such as siting will certainly make the GEO transponder the preferred choice unless there are some financial incentives for non-GEO transponder use.)

The situation is quite different for CPS systems where many thousands of very small aperture terminals (VSATs) may share one transponder. Analysis shows that the additional ground terminal cost plus maintenance is equivalent to a $0.32 M/yr transponder lease fee. For this scenario the conclusion is that the non-GEO transponder price should be $0.32 M/yr less than the comparable GEO transponder price in order to allow for additional ground terminal expenses. This analysis is sensitive to the relative costs of the ground and space segments of the system.

8.3 Economic Analysis Conclusions

Conclusions of the economic analysis are as follows.

- Non-GEO satellites are competitive with GEO satellites.
- The STET orbit used for CPS service allows a 14% transponder price reduction.
- The ACE orbit allows about 25% transponder price reduction for both trunking and CPS service.
- The ground system impact of tracking the non-GEO satellite is not significant economically for the trunking system, but can require a 15% lower transponder price for the CPS VSAT system in order to compensate for the user's increased ground terminal costs.

9 Technology Requirements

Any enabling or critical technology required to implement the systems concepts is identified. In particular, technology shortfalls are given from the state-of-the-art expected to be achieved by the end of 1990 in the following areas.

- Antennas with reconfigurability
- Intersatellite links
- Solar cells resistant to radiation
- VSATs with tracking

In addition the following regulatory question should be pursued.

- Non-GEO interference requirements

9.1 Reconfigurable Antennas

The technology of MMIC phased arrays should be pursued at C-band and Ku-band in order to reduce the penalty associated with reconfigurable antenna systems.

The changing coverage region area and shape with time (as viewed from non-GEO orbit) require use of reconfigurable satellite antenna designs to control antenna losses and potential interference with ground terminals. The projected 1990 technology is ferrite-in-waveguide variable phase shifters, variable power dividers, and switching circulators. This technology has a substantial mass, volume, power, and cost penalty for multiple element antennas.

9.2 Intersatellite Links

The development of light weight intersatellite links (ISLs) should be pursued, both at 60 GHz and light wavelength. Projected 1990 technology ISLs are too heavy to be economically incorporated in a satellite system unless they are specifically required by the mission.

Non-GEO systems in particular, with their limited coverage times, could be greatly enhanced by a feasible ISL. The problem with 60 GHz ISLs is their limited RF power and low efficiency. Optical ISLs are even heavier than 60 GHz ISLs.

9.3 Solar Cells

Satellites in certain non-GEO orbits such as the ACE orbit suffer a heavy penalty in solar array mass due to the adverse radiation environment and the susceptibility of silicon solar cells to degradation.

Development of GaAs solar cells to be more competitive with the price of silicon cells would be a great help for satellites in these non-GEO orbits. Development of GaAs should concentrate on weight and cost reduction, and not just maximum efficiency.

9.4 Tracking VSATs

A requirement of non-GEO orbit satellites is that the ground terminal be capable of tracking. Very small aperture terminals (VSATs) of 1.2 m and 1.8 m size need to have developed an innovative tracking mechanism that is low cost in large quantities and requires little maintenance.

This may be a technology development that occurs naturally by industry as the requirement for VSATs and tracking grows. However, it should not be overlooked as it does impact system economic performance as the cost of the ground segment grows relative to the satellite.

9.5 Non-GEO Interference

The following two interference issues should be pursued.

- Regulations regarding interference among non-GEO and GEO systems.
- Interference of nonGEO-to-nonGEO ISLs with GEO-to-GEO ISLs.

Non-GEO satellites can interfere with earth stations in equatorial countries if the non-GEO satellite antenna pattern is not carefully controlled. Conversely, GEO ground stations may interfere with non-GEO satellites if the non-GEO ground antenna pattern is sloppy out of the equatorial plane.

The other issue is that of non-GEO ISLs sweeping across the GEO arc and potentially interfering with GEO ISLs.

10 Conclusions

A summary and discussion of the study conclusions and recommendations follows.

10.1 Addressable Traffic

The satellite-addressable traffic has a double peak coinciding with the local business day (see Figure S-1, p. S-3). The majority of CONUS traffic lies in the Eastern and Central time zones. Satellites coverages of 8 hour continuous or two 3 hour separated by 5 hours are desirable.

10.2 Suitable Non-GEO Orbits

Two suitable non-GEO orbits are proposed.

- ACE (Apogee at Constant time-of-day Equatorial) orbit
- STET (Sun-synchronous Twelve-hour EquaTorial) orbit

The ACE orbit is a new orbit (patent applied for by Ford Aerospace) devised for the purpose of this study and which may be of use to NASA for other programs such as the *Voice of America* Broadcast Satellite.

These orbits are sun-synchronous to match the traffic throughout the year and require less energy to launch into orbit and less station-keeping fuel than comparable GEO satellites.

Both these orbits lie in the equatorial plane and thus are only usable by higher latitude geographical locations such as CONUS sites. They can not be used for equatorial region communications since satellites in these orbits pass directly below the GEO arc satellites. The ACE orbit is separated from the GEO arc by $> 5.6°$, and the STET orbit by a constant $3.5°$ for an observer in Miami. The separation is greater at higher latitudes.

10.3 System Concepts

The limited coverage time of the STET and ACE orbits make a single satellite suitable for half CONUS coverage only. The high traffic Eastern/Central time zone region is selected for coverage. The expense of an intersatellite link between satellites to extend the coverage area or time is not judged to be economical. However, the use of ground terminals with dual feeds would offer operational advantages.

10.4 Non-GEO Satellite Designs

Six non-GEO satellite designs are summarized in Tables S-10 and S-11 (page S-10), for both ACE and STET orbits and for trunking and CPS applications. Both 3-axis and spin stabilized satellite designs are used.

The main design drivers of the non-GEO designs compared to the GEO are as follows.

- Larger mass can be launched into orbit.
  - 33% more dry mass for STET orbit.
  - 110% more dry mass for ACE orbit.
- "Smart" antenna systems are required to follow changes in coverage region size and shape as the satellite changes position.
- Solar array size increases on account of radiation environment. This is particularly difficult for a spinner satellite which already requires 2.5 times more solar cell area than a 3-axis satellite due to geometry.
  - Area increases 15% for STET orbit.
  - Area increases 85% and mass doubles for ACE orbit.
- Solar array area can be reduced 50% at the expense of increased battery mass on account of the low communications duty cycle (8 hr per 24 hr).

10.5 Economic Analysis

Conclusions of the economic analysis are as follows.

- Non-GEO satellites are competitive with GEO satellites.
- The STET orbit used for CPS service allows a 14% transponder price reduction.
- The ACE orbit allows about 25% transponder price reduction for both trunking and CPS service (Table S-14).
- The ground system impact of tracking the non-GEO satellite is not significant economically for the trunking system but can require a 15% lower transponder price for the CPS VSAT system in order to compensate for increased ground terminal costs.

10.6 Reconfigurable Antennas

The changing coverage region area and shape with time (as viewed from non-GEO orbit) require use of reconfigurable satellite antenna designs to control antenna losses and potential interference with ground terminals. The technology of MMIC phased arrays should be pursued at C-band and Ku-band in order to reduce the penalty associated with reconfigurable antenna systems.

10.7 Radiation Impact

The non-GEO radiation environment poses a severe penalty on two areas of the satellite.

- Shielding of electronics
- Solar cells

Fortunately, radiation-hard technology is an increasing concern and the technology forecast for hardness of 1990 piece parts mitigates the more severe (than GEO) radiation environment. However, the equivalent of an additional 100 mil Al is required for the STET orbit satellite. (The ACE orbit satellite does not need additional shielding.)

For the silicon solar cells used for GEO orbit, an increase of 15% cell area is required for STET orbit satellites to compensate for the increased radiation degradation. The situation in worse in ACE orbit, requiring 85% additional cell area in addition to 5 times (17 kg/kW) the cell cover glass mass. Thus GaAs cells with their greater radiation hardness may be attractive for ACE orbit satellites.

10.8 ACE Versus STET Orbit

The relative advantages and disadvantages of the ACE and STET orbits for non-GEO communications satellites are summarized below. (The

+'s indicate an advantage and the –'s a disadvantage.)

ACE

+ Much less launch fuel
+ Much less station-keeping fuel
+ Smaller size antenna
- More complex antenna
- Short (< 3 hr) coverage time
- Non-uniform motion across the sky
- Radiation impact on solar cells

STET

+ Longer continuous coverage (up to 8 hr) than the ACE orbit
+ Uniform motion across sky
- Large antenna size
- Radiation impact on electronics

10.9 Tracking Earth Terminals

The requirement for tracking the STET or ACE orbit satellite may impose a heavy burden for the small earth terminal. (Larger earth terminals already have two-axis tracking and slew capabilities.) However, with projected VSAT markets in the 10,000's of terminals per application, private business is likely to act to minimize tracking VSAT costs.

10.10 Interference Issues

A potentially difficult issue is the interaction of GEO and non-GEO satellites with regards to interference. Fortunately, the STET and ACE satellites lie 15,000 to 20,000 km below the GEO satellites and the potential for satellite-to-satellite interference is slight unless intersatellite links (ISLs) are in use.

However, the potential for radiating non-GEO satellites to interfere with receiving earth terminals is great due to their changing position in the sky with time and the fact that for equatorial sites, the non-GEO satellites lie directly in front of the GEO satellites. Careful control of the non-GEO radiation pattern is required to keep sidelobes out of the equatorial regions.

Another issue is the interference of GEO ground terminal transmissions with non-GEO satellites. Since the FCC requirements for earth antenna sidelobes are more stringent in the equatorial plane (where 2° and 1° satellite spacing in proposed) than perpendicular to the plane, there is significant potential for small GEO ground terminals to interfere with the non-GEO satellite (particularly STET).

Although non-GEO to non-GEO ISLs are not used for the systems of this study, ISLs could be of major value in extending coverage times. However, the non-GEO ISL would sweep along the GEO arc and potentially interfere with GEO-to-GEO ISLs. Regulations need to be developed to protect GEO users while still allowing the possibility of non-GEO to non-GEO ISLs.