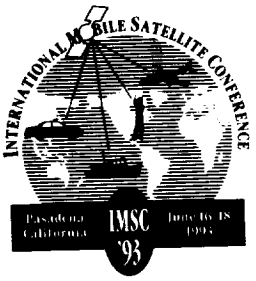

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Mobile SatCom: Communications for People on the Move

Addendum to the Proceedings of the Third

International Mobile Satellite Conference IMSC '93

June 16-18, 1993
Pasadena, California

Co-Sponsored by
The National Aeronautics and Space Administration/
Jet Propulsion Laboratory
and
The Department of Communications, Canada/
Communications Research Centre

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JPL Publication 93-009 *Addendum*

Contents

Abstract

Satellite-based mobile communications systems provide voice and data communications to users over a vast geographic area. The users may communicate via mobile or hand-held terminals, which may also provide access to terrestrial cellular communications services. While the first and second International Mobile Satellite Conferences (Pasadena, 1988 and Ottawa, 1990) mostly concentrated on technical advances, this Third IMSC also focuses on the increasing worldwide commercial activities in Mobile Satellite Services. Because of the large service areas provided by such systems — up to and including global coverage — it is important to consider political and regulatory issues in addition to technical and user requirements issues.

The official Proceedings included approximately 100 papers presented in 11 sessions: the direct broadcast of audio programming from satellites; spacecraft technology; regulatory and policy considerations; hybrid networks for personal and mobile applications; advanced system concepts and analysis; user requirements and applications; current and planned systems; propagation; mobile terminal technology; modulation, coding and multiple access; and mobile antenna technology. This *Addendum* contains papers that were presented at the Conference but arrived too late to be included in the Proceedings, which was distributed at the Conference. In addition, this document contains the final attendee list for the Conference.

This publication was prepared at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Final List of Attendees
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June 16–18, 1993, Pasadena, California, U.S.A.

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Utilizing a TDRS Satellite for Direct Broadcast Satellite-Radio Propagation Experiments and Demonstrations

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ABSTRACT

The NASA/VOA Direct Broadcast Satellite - Radio (DBS-R) Program will be using a NASA Tracking Data Relay Satellite (TDRS) satellite at 62° West longitude to conduct live satellite S-band propagation experiments and demonstrations of satellite sound broadcasting over the next two years (1993-1994) (See Figure 1). The NASA/VOA DBS-R program has applied intensive effort to garner domestic and international support for the DBS-R concept. An S-band DBS-R allocation was achieved for Region 2 at WARC-92 held in Spain. With this allocation, the DBS-R program now needs to conduct S-band propagation experiments and systems demonstrations that will assist in the development of planning approaches for the use of Broadcast Satellite Service (Sound) frequency bands prior to the planning conference called for by WARC-92. These activities will also support receiver concept development applied to qualities ranging from AM to Monophonic FM, Stereophonic FM, Monophonic CD, and Stereophonic CD quality.

INTRODUCTION

The Direct Broadcast Satellite - Radio (DBS-R) Program is a joint effort between The National Aeronautics and Space Administration (NASA) and the United States Information Agency/Voice of America (USIA/VOA). In May, 1990, an interagency agreement established a detailed, multi-year technical effort with joint management and funding by both agencies. The agreement established a program designed to provide service and technology definition and development contributing to commercial implementation of a direct-to-listener satellite sound broadcasting service, thereby benefiting the U.S. satellite communications industry. NASA's Lewis Research Center (LeRC) was assigned program management responsibilities within NASA for the effort, while specific task areas were carried out by LeRC and the Jet Propulsion Laboratory (JPL). LeRC and JPL efforts for the DBS-R Program are conducted under the auspices of NASA's Office of Advanced Concepts and Technology [1].

A DBS-R service has been under discussion domestically since at least 1967, and internationally since at least 1971. Evolution of digital and mobile satellite communications technologies has enhanced the potential quality and availability of a DBS-R service well beyond original expectations. By its nature, a DBS-R satellite system can be very flexible in its antenna coverage area-from approximately 100,000 square mile coverage area using a 1° spot beam to 1,000,000 square mile coverage area using a 3° spot beam-depending upon the desired broadcast area to be reached with the necessary power flux density [2].

DBS-R will also be able to offer audio signals with various levels of sound quality-ranging from robust AM quality, through monophonic FM quality, stereophonic FM quality, monophonic CD quality and stereophonic CD quality. DBS-R digital audio signals will be able to reach a variety of radio receiver types (fixed, portable, and mobile) in various environments (indoor/outdoor, rural, urban, and suburban). Studies have shown that DBS-R systems can provide an economical cost per broadcast-channel-hour for wide-area coverage [2]. As the potential quality and availability of a direct-to-listener satellite radio service have evolved, so has recognition of the desirability of such a service. As a consequence, the 1992 World Administrative Radio Conference (WARC) established new frequency allocations for the Broadcast Satellite Service (BSS) (Sound).

DBS-R offers listeners and service originators many benefits not previously available in the audio broadcast medium. Satellites can broadcast on a single channel to a national, regional, or continental audience. Wider coverage presents new opportunities for audience access to a variety of types of programming. Such programming might include educational, cultural, national, or target audience-oriented broadcasts which may not be economically attractive to offer in any other way. Commercial radio broadcasting has not seen a more dramatic possibility for change since the introduction of FM stereo broadcasting.

THE DBS-R PROGRAM

The DBS-R Program is managed within the Communications Systems Branch of the Space Electronics Division at NASA's Lewis Research Center (LeRC), and the Voice of America's Office of Engineering. Two specific areas of the DBS-R program that need significant effort and study are propagation at S-band and targeted demonstrations.

1992 WORLD ADMINISTRATIVE RADIO CONFERENCE ACTIVITIES

The International Telecommunications Union, an organization within the United Nations, convenes periodic Administrative Radio Conferences to construct agreements among member nations on the use of radio frequency spectrum. The World Administrative Radio Conference for dealing with Frequency Allocations in certain parts of the Spectrum, was held February 3 - March 2, 1992, to consider frequency allocations for the Broadcast Satellite Service (Sound) in the 500-3000 MHz portion of the spectrum [3 and 4].

NASA and VOA made extensive contributions to the U.S. Conference preparations conducted by the Department of State, the Federal Communications Commissions (FCC) and the National Telecommunications and Information Administration (NTIA), particularly by providing numerous U.S. inputs on the subject of the BSS (Sound) to the International Radio Consultative Committee (CCIR).

WARC-92 established multiple frequency allocations for the BSS (Sound), within which DBS-R systems may be implemented. These allocations vary by nation (See Exhibit 1). The U.S. will use the 2310-2360 MHz band. The band 1452-1492 MHz was allocated to this service for a majority of nations throughout the world. However, in some nations, this allocation is secondary to other existing allocations until the year 2007. The band 2535-2655 MHz was allocated to BSS (Sound) for a number of nations in Eastern Europe, Commonwealth of Independent States, and Asia. The WARC also recommended that a future WARC be held prior to 1998, in order to plan the use of frequency bands allocated to the BSS (Sound) service (Ref. 3&4).

PROPAGATION STUDIES AND MEASUREMENTS

NASA conducts propagation research through JPL with investigative support currently performed by the University of Texas-Austin. Prior to WARC-92, the University of Texas-Austin conducted extensive propagation studies relevant to DBS-R in the frequency range 800 MHz to 1800 MHz.

The goal of these studies was to provide propagation data models to the United States WARC-92 Delegation and disburse the data to other countries that were interested in DBS-R. Additionally, the data was made available to satellite system engineers to assist in the design of DBS-R systems.

The research has shown that attenuation varies depending on the environment the receiver is in.

Indoors

During this phase of the propagation studies representative types of buildings were studied to determine what effect they had on the simulated satellite signal(s). These studies indicated that receivers located indoors in a building could experience impaired reception depending upon location. By moving the receiver or antenna only tens of centimeters the reception quality would improve from impaired to acceptable or better. More importantly, this research demonstrated that direct indoor reception of a digital audio signal transmitted by satellite is feasible with receiver antenna gain.

Outdoors/Mobile

During this phase of the propagation study representative measurements were made under varying environmental conditions from a sunny clear day to cloudy, rainy, and foggy days. Locations varied from the desert environment of Texas, to the mountains and seacoast of the pacific northwest to the middle west (St Louis, MO) and east coast (Connecticut and Washington, D.C.). The research indicated that outdoor mobile reception of a DBS-R satellite service was feasible.

Results of these studies contributed significantly to characterizing the indoor/outdoor/ mobile DBS-R reception environment and have formed the basis for several U.S. contributions to the CCIR, CITEL and other such organizations.

Our link budget calculation and experiments indicate that a relatively high powered satellite would be required. Ideally, the satellite should have at least an EIRP of 50 to 60 dBW which will allow sufficient link margins.

Propagation Studies Post WARC-92.

WARC-92 concluded with the United States

Allocation for DBS-R at S-band (2310-2360 MHz). The allocation is in the process of being approved by the Federal Communications Commission. It is necessary that new propagation studies be conducted at S-band. The specific purpose of studies would be to develop the propagation characteristics for S-band.

NASA currently has available, on a scheduled basis a TDRS satellite located at 62° West longitude (see Figure 1). Currently, the satellite in this "spare" position is the latest TDRS launched by NASA in mid January 1993. From this location elevation angles range from 10° for the extreme northwest corner of CONUS to better than 40° for southeast CONUS (See Figure 2). The TDRS satellite provides single-access service to low-earth orbiting spacecraft at both S-band and Ku-band via two steerable 4.9 meter antennas. (It also provides S-band multiple access service via an S-band helical phased array.) The two S-band single access (SSA) forward links (one per 4.9 m antenna) are normally used to transmit command data from the ground to LEO spacecraft at rates up to 300 kbps. The plan is that one of these forward links be used to serve as a satellite downlink to a DBS-R receiver in the 2020.435-2123.315 MHz frequency band which is near the 2310-2360 MHz DAB allocation. (These are the 3-dB band edges. In this range, the TDRS SSA forward link carrier frequency is user selectable over the 2030.435-2113.315 MHz region with a 20 MHz maximum allowable channel bandwidth which is limited by the forward processor hardware onboard the TDRS). Utilizing the TDRS in this fashion will provide a peak transmit EIRP of 46.5 dBW (26W S-band TWT transmitting through a 4.9 meter, 42% efficiency antenna with 4.4 dB line loss). This is nearly 63 times the EIRP of the INMARSAT's MARECS-B satellite used in the initial L-band experiments with an EIRP of 28.6 dBw. With TDRS, link margins for indoor portable reception of DBS-R are estimated to range from 10.77 dB (for reception of 192 kbps CD-quality audio at 20° elevation) to 18.95 dB (for reception of 32 kbps AM quality audio at 40° elevation) (See Tables 2-4). This assumes an indoor receiver with a G/T of -14.7 dB/K and 10^{-4} BER performance using QPSK modulation with rate 1/2, K=7 convolutional coding. For mobile reception using an omni-directional antenna with a receiver G/T of -19 dB/K, link margins range from 4.47 dB (reception of 192 kbps at 20° elevation) to 12.65 dB (reception of 32 kbps at 40° elevation) (See Tables 5-7). These margins are substantially larger than those of the earlier experiments.

It is NASA's intention to utilize the TDRS capabilities, in conjunction with the ongoing propagation studies at JPL and the University of Texas, to better understand the S-band propagation characteristics. While the results will not be at the authorized DBS-R allocation frequencies extrapolation of the data can be made to accurately reflect the signal characteristics at the U.S. authorization and the upper S-band (2535-2655 MHz) allocation. Recognizing these facts we are currently in the process of developing a very extensive S-band propagation study.

Lewis Research Center in coordination with JPL has developed an initial TDRS S-Band propagation measurement plan that will address the following: (1) all or most of the issues that were addressed in the initial propagation plan and discussed earlier in this paper; (2) using as much of the existing equipment from the previous L-band experiments but shifting to the new S-band capability will allow us to accomplish most of the items in 1 plus the following: (a) mobile measurements of amplitude and phase in urban, suburban, and rural environments, and (b) probe spatial signal structure in buildings, in vehicles, behind trees, with linear positioner; and (3) using an airplane-campaign tested delay-spread receiver and new S-band front-end.

FUTURE DEMONSTRATIONS

It is the intention of NASA and the VOA to conduct various demonstrations during the period 1993 through 1994. The purpose of these demonstrations would be to demonstrate DBS-R receiver technology, to evaluate propagation and multipath effects and to educate observers regarding the capabilities of a DBS-R service. Satellite demonstrations of a DBS-R type service will help significantly in the development of planning approaches for the use of BSS (Sound) frequency bands prior to the future planning conference.

The first of these demonstrations is in conjunction with the Electronic Industries Association (EIA), Consumer Electronics Group, Digital Audio Radio Subcommittee which "will organize and initiate a fair and impartial analysis, testing and standards - setting program to determine which DAR technical system will best serve the consumer electronics industry and consumers." The EIA is planning to have demonstrations and testing of proponent systems in the July through December 1993 timeframe. This time schedule is paced by the fact that the CCIR plans to make its recommendations in 1994.

Additional demonstrations will be planned around significant events which will have positive influence for DBS-R. At this point details concerning where and when such demonstrations should be conducted are still being evaluated.

CONCLUSIONS

The relatively high downlink EIRP of TDRS's Single Access S-band beam (46.3 dBW) is quite sufficient for our proposed propagation experiments and demonstrations for most if not all of our DBS-R concepts and innovations that have been or will be identified by the NASA/VOA DBS-R program team as critical for viable commercialization of this new and dynamic service.

ACKNOWLEDGEMENT

The author would like to extend a special thanks to the following individuals for their help and assistance. Mr. Faramaz Davarian and Mr. Nasser Golshan of JPL, and Mr. Rodney L. Spence of LeRC.

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Table 1. DBS-R Broadcast of 192 kbps Stereo CD Quality Digital Audio Channel using TDRS 4.9-meter SSA Antenna (Ku-band feederlink is via 18.3-meter (60') terminal at White Sands,NM; portable receiver with 13 dBi gain)

GENERAL SYSTEM PARAMETERS	
Satellite Altitude (km)	35784.00 (GEO S/C Altitude)
Uplink Frequency (GHz)	14.70 (K-band Uplink to TDRS SGL Antenna)
Downlink Frequency (GHz)	2.05 (S-band Forward Link from TDRS SSA Antenna)
Required Value of Eb/No (dB)	3.30 (10-4 BER using QPSK and R=1/2,K=7 Conv. Coding)
Information Bit Rate (bps) per Channel	192000 (Stereo CD Quality Digital Audio)
TRANSMIT TERMINAL PARAMETERS	
Antenna Diameter (m)	18.30 (60 foot White Sands Ground Terminal)
Transmit Antenna Efficiency	0.50
HPA Xmit Power/Channel (after backoff	5.00
Xmit Feed Loss (dB)	-2.00
Elevation Angle to Satellite (deg)	40.00 (TDRS Satellite located at 62 deg W)
Antenna Gain (dBi)	65.99
Antenna HPBW (deg)	0.08
Transmit Terminal Peak EIRP (dBW)	70.98
SATELLITE PARAMETERS	
Uplink Antenna Diameter (m)	2.00 (TDRS 2-meter SGL Antenna)
Uplink Antenna Efficiency	0.42
Uplink System Noise Temp (K)	4000.00
Uplink Antenna HPBW (deg)	0.72
Uplink Antenna Gain (dBi)	46.01
Satellite Receive G/T (dB/K)	9.99
Downlink Antenna Diameter (m)	4.90 (TDRS 4.9-meter S-band Single Access Antenna)
Downlink Antenna Efficiency	0.42
Xponder Power/Channel (after backoff) (	26.00 (26 W S-band TWT)
Downlink Antenna Feed Loss (dB)	-4.40
Downlink Antenna HPBW (deg)	2.12
Downlink Antenna Gain (dBi)	36.68
Satellite Transmit Peak EIRP (dBW)	46.43
RECEIVE TERMINAL PARAMETERS	
Antenna Diameter (m)	0.30 (S-band indoor table-top portable receiver)
Receive Antenna Efficiency	0.50
System Noise Temp (K)	625.00
Elevation Angle to Satellite (deg)	40.00
Antenna Gain (dBi)	13.31
Antenna HPBW (deg)	28.04
Receive Terminal G/T (dB/K)	-14.65

LINK PARAMETER	UPLINK numeric	UPLINK dB	dB	DOWNLINK numeric	DOWNLINK dB	dB
Transmit Power/Channel (W)	5.00	6.99		26.0000	14.15	
Xmit Line Loss (dB)		-2.00			-4.40	
Xmit Ant Diameter (m)	18.30			4.90		
Xmit Ant Efficiency	0.50			0.42		
Xmit Ant Gain		65.99			36.68	
Peak Xmit EIRP (dBW)			70.98			46.43
Slant Range (km)	37778.30			37778.30		
Free-Space Path Loss (dB)			-207.34			-190.23
Atmospheric Loss (dB)			-0.50			-0.25
Rain Loss (dB) (99.9% availability)			-1.40			-0.05
Xmit Ant Pointing Loss (dB)			-0.10			-0.50
Recv Ant Pointing Loss (dB)			-0.50			-0.05
Other Losses (EOC,Pol,Inserter) (dB)			0.00			-3.00
Power Flux-Density (dBW/m^2)		-93.46			-116.41	
Recv Ant Diameter (m)	2.00			0.30		
Recv Ant Efficiency	0.42			0.50		
Recv Ant Gain		46.01			13.31	
Total System Noise Temp (K)	4000.00	36.02		625.00	27.96	
Recv G/T (dB/K)			9.99			-14.65
Boltzmann Constant (dBW/K-Hz)			-228.60			-228.60
Information Data Rate/Channel (bps)	192000		52.83	192000		52.83
Up/Down Link Eb/N0 (dB)			46.89			13.47
Overall Eb/N0 (dB)	13.47					
MODEM Implementation Loss (dB)	-2.00					
Required Eb/N0 (dB)	3.30					
Link Margin (dB)	8.17					

TABLE 2. DBS-R LINK BUDGETS FOR INDOOR PORTABLE RECEPTION USING TDRS S-BAND DOWNLINK (SATELLITE ELEVATION ANGLE OF 40°, RECEIVER G/T OF -14.7 dB/K)

DIGITAL AUDIO QUALITY	AM	MONO-FM	STEREO FM	NEAR-CD	ALMOST CDCD-QUALITY	
DIGITAL AUDIO BIT RATE (kbps)	32.00	48.00	96.00	128.00	160.00	192.00
TDRS S-band SA Downlink Freq (GHz)	2.05	2.05	2.05	2.05	2.05	2.05
TDRS S-band SA Antenna Diameter (m)	4.90	4.90	4.90	4.90	4.90	4.90
TDRS S-band SA Antenna Efficiency	0.42	0.42	0.42	0.42	0.42	0.42
TDRS S-band SA Antenna HPBW (deg)	2.12	2.12	2.12	2.12	2.12	2.12
TDRS S-band SA Downlink Power (W)	26.00	26.00	26.00	26.00	26.00	26.00
TDRS S-band SA Downlink Power (dBW)	14.15	14.15	14.15	14.15	14.15	14.15
TDRS S-band SA Downlink Ant Gain (dBi)	36.68	36.68	36.68	36.68	36.68	36.68
TDRS S-band SA Downlink Feed Loss (dB)	-4.40	-4.40	-4.40	-4.40	-4.40	-4.40
TDRS S-band SA Downlink EIRP (dBW)	46.43	46.43	46.43	46.43	46.43	46.43
Satellite Elevation Angle (deg)	40.00	40.00	40.00	40.00	40.00	40.00
Slant Range (km)	37778.30	37778.30	37778.30	37778.30	37778.30	37778.30
Free-Space Path Loss (dB)	-190.23	-190.23	-190.23	-190.23	-190.23	-190.23
Atmospheric Losses (dB)	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
Rain Attenuation (50 mm/hr rain rate)	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Pointing Loss (dB)	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50
G/T of Indoor Portable Recvr (dB/K)	-14.70	-14.70	-14.70	-14.70	-14.70	-14.70
Boltzmann Constant (dBW/K-Hz)	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60
Received C/No (dB-Hz)	69.30	69.30	69.30	69.30	69.30	69.30
Data Rate (dB-bps)	45.05	46.81	49.82	51.07	52.04	52.83
Available Downlink Eb/No (dB)	24.25	22.49	19.48	18.23	17.26	16.47
Theoretical Eb/No for 10-4 BER (dB) (QPSK with R=1/2,K=7 Conv. Coding)	3.30	3.30	3.30	3.30	3.30	3.30
Receiver Implementation Loss (dB)	1.50	1.50	1.50	1.50	1.50	1.50
Interference Degradation (dB)	0.50	0.50	0.50	0.50	0.50	0.50
Total Receiver Eb/No Requirement (dB)	5.30	5.30	5.30	5.30	5.30	5.30
Link Margin (dB) at beam center (dB)	18.95	17.19	14.18	12.93	11.96	11.17
Link Margin at 3-dB edge of coverage	15.95	14.19	11.18	9.93	8.96	8.17

COMMENTS:
INDOOR TABLE-TOP CD-QUALITY RECEPTION WILL BE FEASIBLE IN MOST SINGLE FAMILY HOUSES
INDOOR TABLE-TOP FM-QUALITY RECEPTION WILL BE FEASIBLE IN MOST BUILDINGS

TABLE 3. DBS-R LINK BUDGETS FOR INDOOR PORTABLE RECEPTION USING TDRS S-BAND DOWNLINK
(SATELLITE ELEVATION ANGLE OF 30°, RECEIVER G/T OF -14.7 dB/K)

DIGITAL AUDIO QUALITY	AM	MONO-FM	STEREO FM	NEAR-CD	ALMOST CDCD-QUALITY	
DIGITAL AUDIO BIT RATE (kbps)	32.00	48.00	96.00	128.00	160.00	192.00
TDRS S-band SA Downlink Freq (GHz)	2.05	2.05	2.05	2.05	2.05	2.05
TDRS S-band SA Antenna Diameter (m)	4.90	4.90	4.90	4.90	4.90	4.90
TDRS S-band SA Antenna Efficiency	0.42	0.42	0.42	0.42	0.42	0.42
TDRS S-band SA Antenna HPBW (deg)	2.12	2.12	2.12	2.12	2.12	2.12
TDRS S-band SA Downlink Power (W)	26.00	26.00	26.00	26.00	26.00	26.00
TDRS S-band SA Downlink Power (dBW)	14.15	14.15	14.15	14.15	14.15	14.15
TDRS S-band SA Downlink Ant Gain (dBi)	36.68	36.68	36.68	36.68	36.68	36.68
TDRS S-band SA Downlink Feed Loss (dB)	-4.40	-4.40	-4.40	-4.40	-4.40	-4.40
TDRS S-band SA Downlink EIRP (dBW)	46.43	46.43	46.43	46.43	46.43	46.43
Satellite Elevation Angle (deg)	30.00	30.00	30.00	30.00	30.00	30.00
Slant Range (km)	38609.69	38609.69	38609.69	38609.69	38609.69	38609.69
Free-Space Path Loss (dB)	-190.42	-190.42	-190.42	-190.42	-190.42	-190.42
Atmospheric Losses (dB)	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
Rain Attenuation (50 mm/hr rain rate)	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Pointing Loss (dB)	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50
G/T of Indoor Portable Recvr (dB/K)	-14.70	-14.70	-14.70	-14.70	-14.70	-14.70
Boltzmann Constant (dBW/K-Hz)	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60
Received C/No (dB-Hz)	69.11	69.11	69.11	69.11	69.11	69.11
Data Rate (dB-bps)	45.05	46.81	49.82	51.07	52.04	52.83
Available Downlink Eb/No (dB)	24.06	22.30	19.29	18.04	17.07	16.28
Theoretical Eb/No for 10-4 BER (dB) (QPSK with R=1/2,K=7 Conv. Coding)	3.30	3.30	3.30	3.30	3.30	3.30
Receiver Implementation Loss (dB)	1.50	1.50	1.50	1.50	1.50	1.50
Interference Degradation (dB)	0.50	0.50	0.50	0.50	0.50	0.50
Total Receiver Eb/No Requirement (dB)	5.30	5.30	5.30	5.30	5.30	5.30
Link Margin (dB) at beam center (dB)	18.76	17.00	13.99	12.74	11.77	10.98
Link Margin at 3-dB edge of coverage	15.76	14.00	10.99	9.74	8.77	7.98

COMMENTS:
INDOOR TABLE-TOP CD-QUALITY RECEPTION WILL BE FEASIBLE IN MOST SINGLE FAMILY HOUSES
INDOOR TABLE-TOP FM-QUALITY RECEPTION WILL BE FEASIBLE IN MOST BUILDINGS

TABLE 4. DBS-R LINK BUDGETS FOR INDOOR PORTABLE RECEPTION USING TDRS S-BAND DOWNLINK
(SATELLITE ELEVATION ANGLE OF 20°, RECEIVER G/T OF -14.7 dB/K)

DIGITAL AUDIO QUALITY	AM	MONO-FM	STEREO FM	NEAR-CD	ALMOST CDCD-QUALITY	
DIGITAL AUDIO BIT RATE (kbps)	32.00	48.00	96.00	128.00	160.00	192.00
TDRS S-band SA Downlink Freq (GHz)	2.05	2.05	2.05	2.05	2.05	2.05
TDRS S-band SA Antenna Diameter (m)	4.90	4.90	4.90	4.90	4.90	4.90
TDRS S-band SA Antenna Efficiency	0.42	0.42	0.42	0.42	0.42	0.42
TDRS S-band SA Antenna HPBW (deg)	2.12	2.12	2.12	2.12	2.12	2.12
TDRS S-band SA Downlink Power (W)	26.00	26.00	26.00	26.00	26.00	26.00
TDRS S-band SA Downlink Power (dBW)	14.15	14.15	14.15	14.15	14.15	14.15
TDRS S-band SA Downlink Ant Gain (dBi)	36.68	36.68	36.68	36.68	36.68	36.68
TDRS S-band SA Downlink Feed Loss (dB)	-4.40	-4.40	-4.40	-4.40	-4.40	-4.40
TDRS S-band SA Downlink EIRP (dBW)	46.43	46.43	46.43	46.43	46.43	46.43
Satellite Elevation Angle (deg)	20.00	20.00	20.00	20.00	20.00	20.00
Slant Range (km)	39552.52	39552.52	39552.52	39552.52	39552.52	39552.52
Free-Space Path Loss (dB)	-190.63	-190.63	-190.63	-190.63	-190.63	-190.63
Atmospheric Losses (dB)	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
Rain Attenuation (50 mm/hr rain rate)	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Pointing Loss (dB)	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50
G/T of Indoor Portable Recvr (dB/K)	-14.70	-14.70	-14.70	-14.70	-14.70	-14.70
Boltzmann Constant (dBW/K-Hz)	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60
Received C/No (dB-Hz)	68.90	68.90	68.90	68.90	68.90	68.90
Data Rate (dB-bps)	45.05	46.81	49.82	51.07	52.04	52.83
Available Downlink Eb/No (dB)	23.85	22.09	19.08	17.83	16.86	16.07
Theoretical Eb/No for 10-4 BER (dB) (QPSK with R=1/2,K=7 Conv. Coding)	3.30	3.30	3.30	3.30	3.30	3.30
Receiver Implementation Loss (dB)	1.50	1.50	1.50	1.50	1.50	1.50
Interference Degradation (dB)	0.50	0.50	0.50	0.50	0.50	0.50
Total Receiver Eb/No Requirement (dB)	5.30	5.30	5.30	5.30	5.30	5.30
Link Margin (dB) at beam center (dB)	18.55	16.79	13.78	12.53	11.56	10.77
Link Margin at 3-dB edge of coverage	15.55	13.79	10.78	9.53	8.56	7.77

COMMENTS:
INDOOR TABLE-TOP CD-QUALITY RECEPTION WILL BE FEASIBLE IN MOST SINGLE FAMILY HOUSES
INDOOR TABLE-TOP FM-QUALITY RECEPTION WILL BE FEASIBLE IN MOST BUILDINGS

TABLE 5. DBS-R LINK BUDGETS FOR MOBILE RECEPTION USING TDRS S-BAND DOWNLINK
(SATELLITE ELEVATION ANGLE OF 40°, MOBILE RECEIVER G/T OF -19.0 dB/K)

DIGITAL AUDIO QUALITY	AM	MONO-FM	STEREO FM	NEAR-CD	ALMOST CDCD-QUALITY	
DIGITAL AUDIO BIT RATE (kbps)	32.00	48.00	96.00	128.00	160.00	192.00
TDRS S-band SA Downlink Freq (GHz)	2.05	2.05	2.05	2.05	2.05	2.05
TDRS S-band SA Antenna Diameter (m)	4.90	4.90	4.90	4.90	4.90	4.90
TDRS S-band SA Antenna Efficiency	0.42	0.42	0.42	0.42	0.42	0.42
TDRS S-band SA Antenna HPBW (deg)	2.12	2.12	2.12	2.12	2.12	2.12
TDRS S-band SA Downlink Power (W)	26.00	26.00	26.00	26.00	26.00	26.00
TDRS S-band SA Downlink Power (dBW)	14.15	14.15	14.15	14.15	14.15	14.15
TDRS S-band SA Downlink Ant Gain (dBi)	36.68	36.68	36.68	36.68	36.68	36.68
TDRS S-band SA Downlink Feed Loss (dB)	-4.40	-4.40	-4.40	-4.40	-4.40	-4.40
TDRS S-band SA Downlink EIRP (dBW)	46.43	46.43	46.43	46.43	46.43	46.43
Satellite Elevation Angle (deg)	40.00	40.00	40.00	40.00	40.00	40.00
Slant Range (km)	37778.30	37778.30	37778.30	37778.30	37778.30	37778.30
Free-Space Path Loss (dB)	-190.23	-190.23	-190.23	-190.23	-190.23	-190.23
Atmospheric Losses (dB)	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
Rain Attenuation (50 mm/hr rain rate)	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Pointing Loss (dB)	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50
G/T of Mobile Recvr (dB/K)	-19.00	-19.00	-19.00	-19.00	-19.00	-19.00
Boltzmann Constant (dBW/K-Hz)	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60
Received C/No (dB-Hz)	65.00	65.00	65.00	65.00	65.00	65.00
Data Rate (dB-bps)	45.05	46.81	49.82	51.07	52.04	52.83
Available Downlink Eb/No (dB)	19.95	18.19	15.18	13.93	12.96	12.17
Theoretical Eb/No for 10-4 BER (dB) (QPSK with R=1/2,K=7 Conv. Coding)	3.30	3.30	3.30	3.30	3.30	3.30
Mobile Channel Fade Loss (dB)	2.00	2.00	2.00	2.00	2.00	2.00
Receiver Implementation Loss (dB)	1.50	1.50	1.50	1.50	1.50	1.50
Interference Degradation (dB)	0.50	0.50	0.50	0.50	0.50	0.50
Total Receiver Eb/No Requirement (dB)	7.30	7.30	7.30	7.30	7.30	7.30
Link Margin (dB) at beam center (dB)	12.65	10.89	7.88	6.63	5.66	4.87
Link Margin at 3-dB edge of coverage	9.65	7.89	4.88	3.63	2.66	1.87

TABLE 6. DBS-R LINK BUDGETS FOR MOBILE RECEPTION USING TDRS S-BAND DOWNLINK
(SATELLITE ELEVATION ANGLE OF 30°, MOBILE RECEIVER G/T OF -19.0 dB/K)

DIGITAL AUDIO QUALITY	AM	MONO-FM	STEREO FM	NEAR-CD	ALMOST CDCD-QUALITY	
DIGITAL AUDIO BIT RATE (kbps)	32.00	48.00	96.00	128.00	160.00	192.00
TDRS S-band SA Downlink Freq (GHz)	2.05	2.05	2.05	2.05	2.05	2.05
TDRS S-band SA Antenna Diameter (m)	4.90	4.90	4.90	4.90	4.90	4.90
TDRS S-band SA Antenna Efficiency	0.42	0.42	0.42	0.42	0.42	0.42
TDRS S-band SA Antenna HPBW (deg)	2.12	2.12	2.12	2.12	2.12	2.12
TDRS S-band SA Downlink Power (W)	26.00	26.00	26.00	26.00	26.00	26.00
TDRS S-band SA Downlink Power (dBW)	14.15	14.15	14.15	14.15	14.15	14.15
TDRS S-band SA Downlink Ant Gain (dBi)	36.68	36.68	36.68	36.68	36.68	36.68
TDRS S-band SA Downlink Feed Loss (dB)	-4.40	-4.40	-4.40	-4.40	-4.40	-4.40
TDRS S-band SA Downlink EIRP (dBW)	46.43	46.43	46.43	46.43	46.43	46.43
Satellite Elevation Angle (deg)	30.00	30.00	30.00	30.00	30.00	30.00
Slant Range (km)	38609.69	38609.69	38609.69	38609.69	38609.69	38609.69
Free-Space Path Loss (dB)	-190.42	-190.42	-190.42	-190.42	-190.42	-190.42
Atmospheric Losses (dB)	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
Rain Attenuation (50 mm/hr rain rate)	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Pointing Loss (dB)	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50
G/T of Mobile Recvr (dB/K)	-19.00	-19.00	-19.00	-19.00	-19.00	-19.00
Boltzmann Constant (dBW/K-Hz)	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60
Received C/No (dB-Hz)	64.81	64.81	64.81	64.81	64.81	64.81
Data Rate (dB-bps)	45.05	46.81	49.82	51.07	52.04	52.83
Available Downlink Eb/No (dB)	19.76	18.00	14.99	13.74	12.77	11.98
Theoretical Eb/No for 10-4 BER (dB) (QPSK with R=1/2,K=7 Conv. Coding)	3.30	3.30	3.30	3.30	3.30	3.30
Mobile Channel Fade Loss (dB)	2.00	2.00	2.00	2.00	2.00	2.00
Receiver Implementation Loss (dB)	1.50	1.50	1.50	1.50	1.50	1.50
Interference Degradation (dB)	0.50	0.50	0.50	0.50	0.50	0.50
Total Receiver Eb/No Requirement (dB)	7.30	7.30	7.30	7.30	7.30	7.30
Link Margin (dB) at beam center (dB)	12.46	10.70	7.69	6.44	5.47	4.68
Link Margin at 3-dB edge of coverage	9.46	7.70	4.69	3.44	2.47	1.68

TABLE 7. DBS-R LINK BUDGETS FOR MOBILE RECEPTION USING TDRS S-BAND DOWNLINK
(SATELLITE ELEVATION ANGLE OF 20°, MOBILE RECEIVER G/T OF -19.0 dB/K)

DIGITAL AUDIO QUALITY	AM	MONO-FM	STEREO FM	NEAR-CD	ALMOST CD	CD-QUALITY
DIGITAL AUDIO BIT RATE (kbps)	32.00	48.00	96.00	128.00	160.00	192.00
TDRS S-band SA Downlink Freq (GHz)	2.05	2.05	2.05	2.05	2.05	2.05
TDRS S-band SA Antenna Diameter (m)	4.90	4.90	4.90	4.90	4.90	4.90
TDRS S-band SA Antenna Efficiency	0.42	0.42	0.42	0.42	0.42	0.42
TDRS S-band SA Antenna HPBW (deg)	2.12	2.12	2.12	2.12	2.12	2.12
TDRS S-band SA Downlink Power (W)	26.00	26.00	26.00	26.00	26.00	26.00
TDRS S-band SA Downlink Power (dBW)	14.15	14.15	14.15	14.15	14.15	14.15
TDRS S-band SA Downlink Ant Gain (dBi)	36.68	36.68	36.68	36.68	36.68	36.68
TDRS S-band SA Downlink Feed Loss (dB)	-4.40	-4.40	-4.40	-4.40	-4.40	-4.40
TDRS S-band SA Downlink EIRP (dBW)	46.43	46.43	46.43	46.43	46.43	46.43
Satellite Elevation Angle (deg)	20.00	20.00	20.00	20.00	20.00	20.00
Slant Range (km)	39552.52	39552.52	39552.52	39552.52	39552.52	39552.52
Free-Space Path Loss (dB)	-190.63	-190.63	-190.63	-190.63	-190.63	-190.63
Atmospheric Losses (dB)	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
Rain Attenuation (50 mm/hr rain rate)	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
Pointing Loss (dB)	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50
G/T of Mobile Recvr (dB/K)	-19.00	-19.00	-19.00	-19.00	-19.00	-19.00
Boltzmann Constant (dBW/K-Hz)	-228.60	-228.60	-228.60	-228.60	-228.60	-228.60
Received C/No (dB-Hz)	64.60	64.60	64.60	64.60	64.60	64.60
Data Rate (dB-bps)	45.05	46.81	49.82	51.07	52.04	52.83
Available Downlink Eb/No (dB)	19.55	17.79	14.78	13.53	12.56	11.77
Theoretical Eb/No for 10-4 BER (dB) (QPSK with R=1/2,K=7 Conv. Coding)	3.30	3.30	3.30	3.30	3.30	3.30
Mobile Channel Fade Loss (dB)	2.00	2.00	2.00	2.00	2.00	2.00
Receiver Implementation Loss (dB)	1.50	1.50	1.50	1.50	1.50	1.50
Interference Degradation (dB)	0.50	0.50	0.50	0.50	0.50	0.50
Total Receiver Eb/No Requirement (dB)	7.30	7.30	7.30	7.30	7.30	7.30
Link Margin (dB) at beam center (dB)	12.25	10.49	7.48	6.23	5.26	4.47
Link Margin at 3-dB edge of coverage	9.25	7.49	4.48	3.23	2.26	1.47

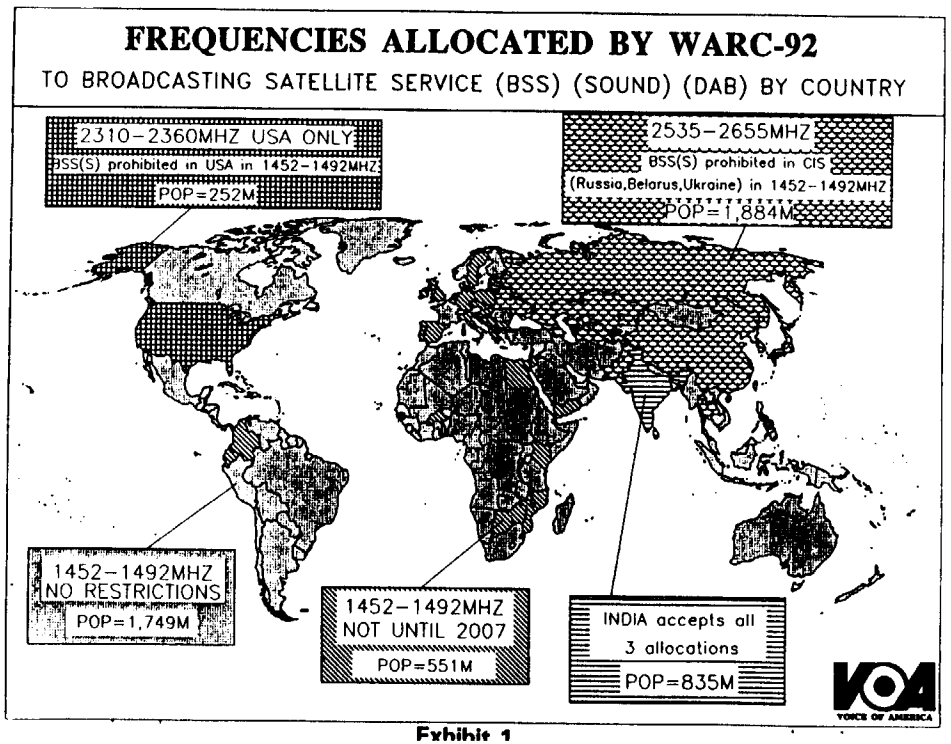

Exhibit 1

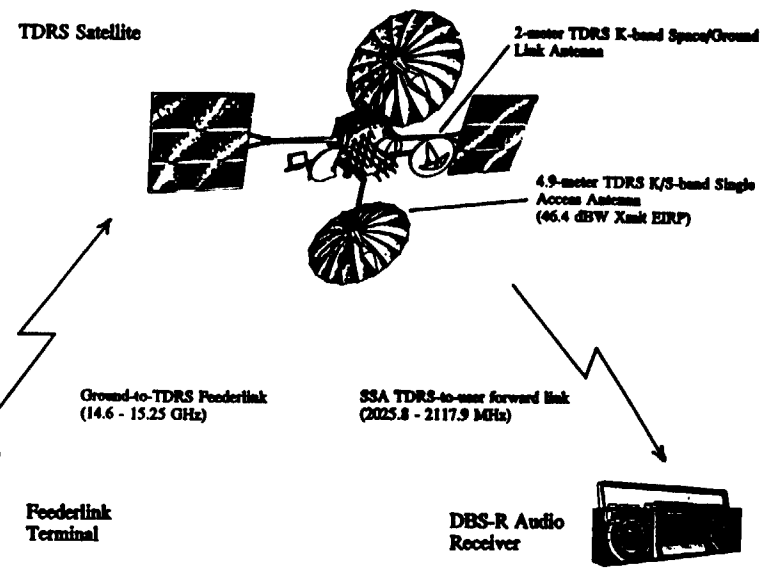

Figure 1. Schematic of DBS-R/TDRS Demonstration

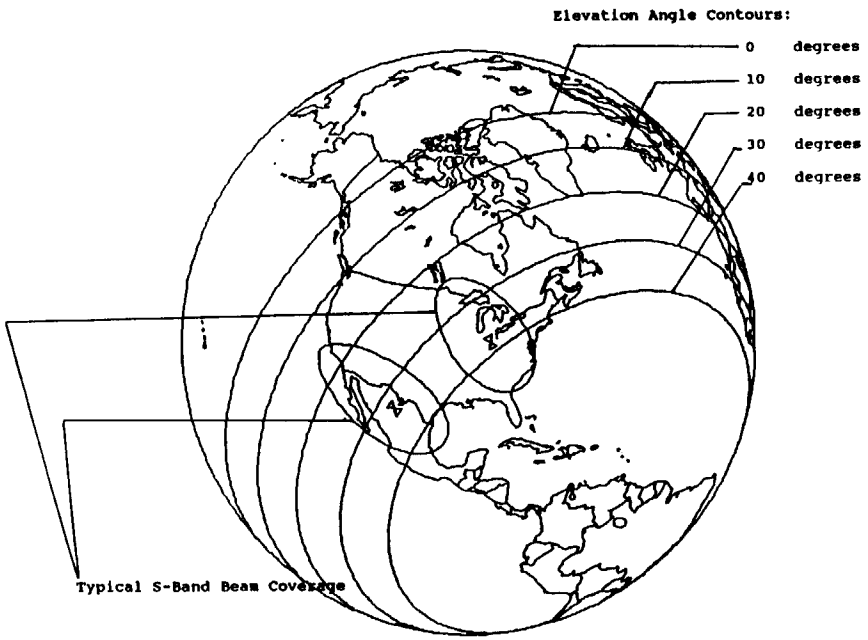

Figure 2. TDRS-1 Elevation Angle Contours From North America
(Satellite at 62° West Longitude)

ADAPTIVE BEAMFORMING IN A CDMA MOBILE SATELLITE COMMUNICATIONS SYSTEM

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1 INTRODUCTION

Over the next few years, Mobile Satellite Communications systems will experience a rapid evolution towards providing Global Personal Communication services to hand-held terminals. To meet the challenge, a number of innovative satellite systems have been recently proposed. In terms of payload technology, the use of advanced on-board digital processing techniques is currently being investigated in order to enhance the satellite performance. The functions to be implemented on board include digital beamforming, multiplexing and demultiplexing, signal regeneration and switching.

Code-Division Multiple-Access (CDMA) stands out as a strong contender for the choice of multiple access scheme in these future mobile communication systems [1]. This is due to a variety of reasons such as the excellent performance in multipath environments, high scope for frequency reuse and graceful degradation near saturation. However, the capacity of CDMA is limited by the self-inteference between the transmissions of the different users in the network. Moreover, the disparity between the received power levels gives rise to the near-far problem, this is, weak signals are severely degraded by the transmissions from other users.

In this paper, the use of time-reference adaptive digital beamforming on board the satellite is proposed as a means to overcome the problems associated with CDMA. This technique enables a high number of independently steered beams to be generated from a single phased array antenna, which automatically track the desired user signal and null the unwanted interference sources. Since CDMA is interference limited, the interference protection provided by the antenna converts directly and linearly into an increase in capacity. Furthermore, the proposed concept allows the near-far effect to be mitigated without requiring a tight coordination of the users in terms of power control.

A payload architecture will be presented that illustrates the practical implementation of this concept. This digital payload architecture shows that with the advent of high performance CMOS digital processing, the on-board implementation of complex DSP techniques –in particular digital beamforming– has become possible, being most attractive for Mobile Satellite Communications.

This paper was first presented at the ERA Conference "DSP-The enabling technology for communications". Amsterdam, 9–10 March 1993.

2 THE COMMUNICATIONS SYSTEM MODEL

Let us consider a communications system in which M mobile users are communicating with a fixed Hub station through a satellite. An *On-board Processing* (OBP) type satellite will be considered which is able to regenerate and apply on-board routing to the uplink signals for its subsequent transmission to the ground. Among other features, the OBP satellite enables the different links to be decoupled and independently optimized; particularly, different modulation and access schemes can be employed for the mobile and the feeder link. As mentioned above, CDMA offers a number of advantages which make it most interesting for the mobile environment. This paper focuses on the study of the mobile link, for which a *Direct-Sequence Code-Division Multiple-Access* (DS-CDMA) scheme will be considered.

In a CDMA system, all the users transmit over the same frequency band. Let R_s be the basic user *information rate*. A different Pseudo-Noise (PN) sequence of length L is assigned to each user, which is employed to spread the basic user information stream to form a transmitted signal at *chip rate*, $R_c = L \cdot R_s$. The spreading factor, R_c/R_s, is hence equal to the length of the PN sequence, L. At the receiver, the desired user's transmission is discriminated by using a conventional correlation scheme, in which the received signal is multiplied by a synchronized replica of the desired user's PN sequence and integrated over a symbol period. The PN sequences considered here belong to a family of *Preferentially phased Gold codes*. Gold PN sequences present optimum cross-correlation properties at the origin, this is, synchronized PN sequences are quasi-orthogonal. In the forward direction, the signals transmitted to the different users are spread with synchronized PN sequences. The signals are quasi-orthogonal and, therefore, the mutual interference between them is negligible. This is referred to as a *Synchronous CDMA* (S-CDMA) link. Conversely, the signals transmitted in the return link are not synchronized, and hence, they are not orthogonal at the satellite transponder input. The non-orthogonality of the PN sequences employed in an *Asynchronous CDMA* (A-CDMA) link gives rise to the problem of *self-jamming*, this is, nonzero interference contributions arise from the transmissions of the other users in the network. Associated to the self-jamming is the so-called *near-far* problem.

We concentrate on the asynchronous return link, for which the use of adaptive digital beamforming on board the satellite is proposed in order to overcome the problems associated with CDMA. The effect of the adaptive antenna in an A-CDMA system is illustrated in figure 1, which has been obtained by computer simulation. This figure compares the bit error rate (BER) versus the E_s/N_o for S-CDMA, A-CDMA and A-CDMA with adaptive beamforming. The self-interference, which strongly degrades the performance of A-CDMA, is drastically cancelled by the antenna in such a way that the performance of A-CDMA with adaptive beamforming is comparable to –or even better than– that of S-CDMA.

We assume that the available bandwith is occupied by a frequency multiplex of N_c contiguous CDMA carriers. The satellite antenna generates one independent beam per user which is automaticaly steered to point the maximum gain in the direction of the mobile terminal while nulling the co-channel interferences arriving from other users. The adaptation of the radiation pattern is illustrated in figure 2. Users allocated to the same CDMA carrier should be as spread as possible over the satellite coverage, in order for the satellite antenna to have sufficient resolution to point the beam to one user while nulling the others. Nevertheless, a limited number of co-channel interferers can be tolerated within the desired user's main-beam coverage which are discriminated by the PN code. A low spreading factor will be considered, so that the CDMA carriers are relatively narrowband. This will have important implications in the implementation.

3 INTEGRATION OF ADAPTIVE BEAMFORMING IN A DS-CDMA SYSTEM

The objective of an adaptive array antenna is to improve the reception of a certain desired signal in the presence of undesired interfering signals. The antenna radiation pattern must be conformed in such a way that the main lobe is pointed in the direction of the desired signal, while the nulls are steered in the direction of the interferences. In this way, the signal-to-interference-plus-noise-ratio (SINR) at the array output is maximized.

The achievable performance in an adaptive array has two basic limitations: these are associated with the *degrees of freedom* and the *resolution* of the array. An N-element array has only N-1 degrees of freedom in its pattern. Requiring a beam maximum at a given angle uses up one degree of freedom, the same as requiring a null. Thus, the array is able to point the main beam to the desired user direction and still null up to N-2 interferences. Another limitation the designer must be aware of is the fact that a given array has only a certain ability to resolve signals in space. If the arrival angle of the desired and interfering signals are too close, the array cannot simultaneously null the interference and form a beam on the desired signal. The minimum angular separation between a maximum and a null in the radiation pattern depends primarily on the array aperture size but also to a lesser extent on the element patterns and the number of elements.

In order to apply adaptive beamforming, the desired signal must be different from the interfering signals in some respect. Two different classes of adaptive techniques can be distinguished: *time reference* beamforming and *spatial reference* beamforming. Time reference beamforming can be applied when a time *reference signal* is available which is correlated with the desired signal and uncorrelated with the interferences. Instead, if the *direction of arrival* of the desired signal is known, a spatial reference technique is to be utilized.

Due to the *a priori* knowledge of the desired user PN sequence, a DS-CDMA system lends itself very easily to the generation of an adequate time reference signal. Therefore, we will mainly concentrate here on a time reference beamforming technique, namely, the well-known LMS (least-mean-square) algorithm. After introducing the LMS algorithm, we will describe the way to generate the reference signal. The hardware implementation of this algorithm in a CDMA system will be presented later. Finally, the adaptive algorithms *with main-beam constraints* will be introduced which overcome the problems associated with the limited resolution of the antenna.

3.1 The LMS Algorithm

The *Least Mean Square* (LMS) algorithm is a gradient-based algorithm that minimizes the mean-squared value of the *error signal* $\epsilon(t)$, which is the difference between a locally generated reference signal $r(t)$ and the array output $y(t)$. The (discrete) LMS algorithm is given by the following equations:

$$W(n+1) = W(n) + \gamma \cdot \epsilon(n) \cdot X^*(n) \tag{1}$$

$$\epsilon(n) = r(n) - y(n) = r(n) - X^T(n) \cdot W(n) \tag{2}$$

where $W(n)$ and $X(n)$ are complex vectors of samples at instant n of the antenna weights and the signals in the antenna elements respectively, $\epsilon(n)$ is the corresponding sample of the

instantaneous error. The parameter γ is called the *step-size*. In order for the LMS algorithm to converge, the step size γ must meet the following stability condition:

$$0 < \gamma < \frac{1}{P_t} \tag{3}$$

where P_t is the total power received by the array. The speed of convergence of the algorithm increases with the step-size γ; once in steady-state the weights oscillate with a variance which is also proportional to γ.

As explained in [2], the depth of the null created in the direction of arrival of the interference increases with the interference power; strong interferences are deeply cancelled by the antenna. In our system, this performance characteristic provides an excellent robustness in the presence of the near-far problem.

3.2 Reference signal generation

In order to apply a time-reference adaptive algorithm, the main challenge is to find a way to obtain a suitable reference signal which is highly correlated with the desired signal and uncorrelated with the interferences. In a CDMA system, the reference signal can be derived from the array output as shown in the reference signal generation loop illustrated in figure 3. The reference signal generation comprises the despreading and demodulation[1] of the desired user signal using a conventional correlation receiver, and subsequent re-spreading of the demodulated data with the same PN sequence. The generated reference is an almost perfect replica of the desired user signal: the desired signal component at the array output passes through this loop unchanged –except for the amplitude adjustment and a certain delay–, while the interference signal waveform is drastically altered and its correlation with the reference signal is essentially destroyed by the loop.

The reference signal generation loop has a certain delay which is mainly determined by the integrator contained in the spread-spectrum demodulator. If a full demodulation is performed, the delay is equal to one information symbol period T_s. Instead, partial demodulation can be used, this is, the integration time can be reduced and the decision on the transmitted symbol can be taken on the basis of a fraction of the received symbol waveform.

3.3 Hardware Implementation

The delay incurred in the generation of the reference signal has important implications in the hardware implementation, calling for some modifications in the basic LMS algorithm. The block diagram illustrated in figure 4 represents the implementation of an adaptive array antenna using the *delayed LMS algorithm* in a DS-CDMA system. Let us assume that the reference signal generation circuit introduces a delay equal to D samples. Both the signals in the array elements and the signal at the array output are stored during D samples to properly obtain the (delayed) error signal. Then, these signals are applied to the so-called *delayed LMS algorithm* which is given by the following equations:

$$W(n+1) = W(n) + \gamma \cdot \epsilon(n-D) \cdot X^*(n-D) \tag{4}$$

[1] Attention should be drawn to the fact that the amplitude of the reference signal must be constant. For this purpose, a hard limiter (detector) has also been included in the reference generation loop.

$$\epsilon(n-D) = r(n-D) - X^T(n-D) \cdot W(n-D) \tag{5}$$

As a consequence of the delay, the step-size γ has to be contrained to a much more restrictive range. The stability condition for the delayed LMS algorithm is given by:

$$0 < \gamma < \frac{1}{D \cdot P_t} \tag{6}$$

Therefore, the delay in the generation of the reference has two major implications. At hardware level, the signals in the array elements and the array output need to be stored. As far as the performance is concerned, the speed of convergence of the algorithm is severely reduced. The acceptability of the reduced speed of convergence will depend on the application; for slowly varying scenarios the delayed LMS algorithm will exhibit in general a satisfactory performance.

3.4 Adaptive algorithms with main-beam constraints

Due to the limited resolution of the antenna, when the directions of arrival of the desired and the interfering signals are too close, nulling the interference may cause the gain in the direction of the desired signal to drop. In order to avoid the problem of signal cancellation in the main beam, linear constraints can be placed in the adaptive algorithm [3]. The processor will then maintain a constant gain in the desired direction and the shape of the pattern will be controlled in the vicinity of that direction (derivative constraint) without responding to interference signals in the main lobe.

These techniques require the information on the direction of arrival of the desired signal, this is, the *steering vector*. In essence, they constitute spatial-reference rather than time-reference beamforming techniques; in practice, however, the steering vector can be estimated by averaging the correlation of the time reference signal with the signals in the array elements over a certain number of samples.

4 PAYLOAD CONFIGURATION

Digital beamforming techniques are currently being considered for future mobile satellite communication payloads. The payload implementation presented here relies upon the use of some technologies currently under development by ESA [4] [5]. In particular, SAW-chirp Fourier transform (CFT) techniques and Digital Signal Processing employing CMOS ASIC technologies are considered. SAW-CFT devices are used to demultiplex the various CDMA carriers. The extensive use of CMOS ASIC technology enables the size and power consumption of the DSP circuitry to be reduced so that the implementation of very complex functions –such as digital beamforming or demodulation– becomes feasible.

As mentioned above, an On-Board Processing (OBP) satellite is considered. By using OBP, the uplinks and downlinks are decoupled and, in consequence, the configuration of the different payload sections becomes fairly independent. Here, we focus on the receive section of the return link, in which the adaptive beamforming concept proposed in this paper is implemented.

The payload configuration for the receive section of the return transponder is illustrated in figure 5. The funcional performance is as follows. A single large mobile-link array antenna is

used which consists of N antenna elements. The signals in the antenna elements are applied to receiver chains which perform the filtering, LNA amplification and downconversion to an intermediate frequency. The N_c contiguous CDMA carriers are demultiplexed by the SAW-CFT processors. The principle of the CFT is to slide a slot filter characteristic across the input band during the course of a given chirp frame. Then, by critically sampling at the output, a single CFT device can operate as a bank of fixed filters. The CFT output is analog-to-digital converted, and the signals corresponding to the different CDMA carriers are separated by means of commutators and applied to separate beamformers.

A low spreading factor is considered, so that the CDMA carriers are relatively narrowband. This has a two-fold effect in reducing the payload complexity. First, the bandwidth of the beamformers is decreased, along with their power consumption. Moreover, the number of users allocated to a particular CDMA carrier is relatively small, therefore requiring a small number of degrees of freedom in the antenna; this reduces the number of antenna elements required, further simplifying the beamformer.

Let us consider that up to N_u users can be allocated to each CDMA carrier. A bank of N_u parallell beamformers –one per user– is then associated to each CDMA carrier. Each beamformer is connected to a particular user's CDMA receiver and controlled by an adaptive processor. The weights calculated by the adaptive algorithm can also be utilized in the Tx forward link, assuming a digital beamforming antenna is used there. The outputs of the CDMA receivers are connected to a baseband switch for on-board routing of the channels. The mobile-to-mobile communication channels can be directly connected to the forward link.

5 SYSTEM CAPACITY. NUMERICAL EXAMPLE

To conclude this paper, we will assess the capacity of the proposed system by means of a numerical example. Let us consider a basic user information rate of 6.4 Kbps, a spreading factor L=31 and let us assume that the signal is QPSK modulated and filtered with 50% roll-off. The bandwidth occupied by a CDMA carrier is then equal to 148.8 KHz. Assuming that 10 MHz of bandwith are available, the number of CDMA carriers is equal to N_c=67. In our case, the number of users N_u that can be supported by a CDMA carrier is no longer limited by the self-interference –since this is drastically cancelled by the beamformer– but by the number of degrees of freedom of the antenna which approximately equals the number of antenna elements N. If we consider a 100 element antenna, the number of users per CDMA carrier is equal to $N_u \simeq N$=100. Hence, the total system capacity is given by $N_c \cdot N_u \simeq 6700$ channels.

This capacity value can be compared with that obtained for a conventional CDMA satellite system utilizing a (fixed) multiple-beam antenna. In such a system, capacity can be increased by reusing the whole frequency band in all the beams [6]. For a BER objective of 10^{-4}, using uncoded QPSK, the number of 6.4 Kbps channels supported in 10 MHz available bandwidth by a 91-beam satellite system is approximately equal to 3800. (This value has been obtained in the assumption of uniform traffic distribution, without considering the near-far effect.)

In conclusion, the adaptive beamforming CDMA payload presented in this paper enables the capacity to be sensibly increased with respect to a more conventional system. Moreover, the system is robust to the near-far problem and the capacity is fairly independent of the traffic distribution.

Contact the Author for References and Figures.

Passive Intermodulation Generation in Wire Mesh Deployable Reflector Antennas

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abstract- Deployable reflector antennas represent a proven technology with obvious benefits for mobile satellite applications. Harris Corporation has provided deployable reflector antennas for NASA's Tracking and Data Relay Satellite System (TDRSS). These antennas utilize a rigid, radial rib unfurlable reflector with a wire mesh surface. This type of mesh has been identified as a potential design risk for multi-channel communications applications based on the potential for generation of Passive Intermodulation (PIM). These concerns are based on the existence of numerous, nonpermanent metal to metal contacts that are inherent to the mesh design. To address this issue, Harris has an ongoing IR&D program to characterize mesh PIM performance. This paper presents the results of the investigation into mesh PIM performance to date and provides background information on the design and performance of the Harris radial rib deployable reflector.

INTRODUCTION

The gain that is available from a spacecraft antenna is a critical parameter in the design and ultimate capability of any satellite communications network. The use of a deployable reflector antenna for these applications provides a high gain, lightweight system that can be compactly stowed for launch, then deployed on orbit. The surface material is a critical component in the deployable reflector design. The surface material is required to provide the desired electrical performance as well as the mechanical properties that are necessary to deploy and maintain the reflector surface on orbit. Of particular interest in multi-channel communications applications is the generation of PIM products at the reflector surface that can result in interference in the receive frequency band.

DEPLOYABLE REFLECTOR DESIGN

Harris Corporation has provided deployable reflector antennas for NASA's TDRSS program that utilize a wire mesh reflector surface. The performance of the TDRSS Single Access (SA) antennas provides a credible indication of the performance achievable for similar designs for mobile satellite applications(see reference [1]). Each TDRSS spacecraft has two SA antennas (reference Figure 1) that are used for communication with user satellites in low earth orbit. Ten of these antennas are currently on orbit and operational with no failures or performance degradation since the first deployment in April of 1983. The SA antennas are dual shaped reflector systems operating at S and Ku band with a deployable 4.9 meter main reflector. Total weight, including the cassegrain feed is less than 55 pounds. The deployed reflector surface accuracy is maintained at approximately .025 inches rms.

The radial rib design concept results in a controlled precision deployment of the umbrella-like rib structure. The radial ribs are deployed from a central hub structure by a motorized deployment mechanism. The mesh surface is held above the ribs by fixed standoffs and a network of dimensionally stable cords and ties. The surface attachment system is fully adjustable, allowing optimization of the surface during the manufacturing process. The key to the surface stability is that the surface shape is determined and maintained by the ribs and backup structure and is not dominated by the mechanical characteristics of the mesh.

The mesh surface is formed by interconnected, gore shaped panels as shown in Figure 2. The mesh is attached to rigid boundary strips along the radial dimension of the panels. The panels join together along the edge strips which are attached to the supporting structure. Front cord assemblies aligned circumferentially along the mesh surface are connected with ties to rear cords that are tensioned between the ribs. These ties are adjustable, allowing the surface to be shaped with precision. The mesh surface effectively floats over a rigid and thermoelastically stable structure of ribs, cords, and ties.

The radial rib design can be adapted to a wide range of antenna diameter versus stowed

envelope and surface accuracy requirements. The SA antennas utilize fixed ribs which limit the stowed axial dimension to near the radius of the reflector. Mature design concepts exist for multi-section folding rib systems that avoid this limitation. Demanding surface accuracy requirements can be accommodated by choosing the appropriate number of cords and ties per unit area to provide the required surface adjustability.

WIRE MESH DESCRIPTION

The mesh surface material consists of 1 mil diameter, gold plated molybdenum wire in a tricot knit. The tricot knit results in a complex pattern as shown in Figure 3. Surface currents induced on the mesh must flow over numerous bends and crossover junctions. It is well known that electrical performance characteristics of the mesh are largely dependent on the conditions at these crossover junctions [2]. Any condition that impedes the flow of current through these junctions will result in poor reflectivity performance and substantial loss due to transmission leakage through the mesh. Successful implementation of a deployable reflector design using wire mesh requires strict attention be paid to the wire plating and knitting processes to ensure good electrical performance.

The existence of nonpermanent metal to metal contacts at the crossover junctions in the mesh is the root of concerns over PIM generation. Indeed, eliminating this type of condition is a basic design principle for microwave systems with PIM requirements.

There are properties of the mesh design however, that tend to preclude sensitivity to PIM generation and may provide an explanation for the favorable experimental results presented in the next section. Another design guideline for avoiding PIM is to reduce current densities at potentially sensitive areas. For the case of a wire mesh reflector, the transmit power is distributed over a large surface area that is extremely dense with conductive wires. Mesh knit at 18 openings per inch has over 13 feet of wire and 1000 crossover junctions per square inch.

Another key factor influencing PIM generation at metal to metal contacts is the amount of oxides or other contaminants between the conductors. Gold, which is used to plate the mesh wire, does not oxidize in air like other metals. In fact, gold plating is commonly used to avoid PIM at coaxial connector interfaces. The contact pressure at metal to metal interfaces is also important since high pressure can displace any contaminants that do exist and ensure a clean contact (see references [3] for discussion on PIM dependence on metallic composition and contact pressure). For wire mesh, the contact area that results when 1 mil diameter round wires are in contact is extremely small so that minimal planar tension in the mesh will result in high pressure at the junction contact areas.

EXPERIMENTAL RESULTS

Interest in mesh PIM performance has increased in the 1990's with growth in the market for large deployable reflectors for multi-channel communications applications. Over the past several years Harris has performed a series of tests at L and X band on the standard wire mesh like that used for the TDRSS SA antennas. These tests were performed on planar mesh samples using a test set-up similar to that shown in Figure 4. The samples were 18 x 18 inches of mesh bonded to wooden frames. The sample under test was illuminated by two carriers which are transmitted using separate antennas. A third antenna is used to monitor PIM generation. Extensive filtering and low noise amplification of the receive signal are required to eliminate harmonics and achieve the required measurement sensitivity.

A summary of the test results is listed in Table 1. The first series of tests were for 7th order PIM at L-band. The mesh samples were the standard 10 opening per inch (opi) mesh like that used on the TDRSS SA antennas. Additional samples with surface hardware and edge terminations were also tested. The results showed that PIM generated by mesh alone was not measurable while inclusion of the standard termination and surface hardware components tended to increase PIM susceptibility.

The second series of tests were for 3rd order PIM at X-band. The objective for the X-band tests was to compare the relative performance of different types of mesh so a lower order PIM was chosen to enhance sensitivity. The samples consisted of 10 opi, 18 opi, and conditioned 18 opi mesh. The conditioned samples were exposed to simulated operational environments prior to PIM testing including random vibration, thermal vacuum, and thermal strain (the thermal strain associated with the calculated orbital temperature cycling was simulated by a repetitive, induced mechanical displacement at the center of the sample). The objective of conditioning the samples was to determine if operational environment effects would influence conditions at the wire crossover junctions, and specifically whether they would increase PIM levels. The conclusions drawn from these tests were that the

conditioning did not have significant effects on PIM generation and that there is an inverse relationship between mesh density and PIM generation levels. This relationship supports the theory that the distribution of currents over a large number of wire crossover junctions in the mesh reduces PIM sensitivity.

The third series of tests involved measuring 18 opi mesh for 7th and 5th order PIM at L-band over a thermal profile. Temperature can effect PIM generation at metal to metal contacts by changing the junction properties including the contact pressure which varies due to differential contraction and expansion. This type of test addresses an important question regarding conditions at the wire crossover junctions as temperature changes on orbit. No measurable PIM was generated.

While further testing is required to fully characterize mesh PIM performance, these results suggest that implementation of a wire mesh deployable reflector for multi-channel satellite communications applications is feasible. One area that requires more testing and development work is the design of mesh edge terminations and surface hardware interfaces. Test results indicate that the standard designs like those used on TDRSS are susceptible to PIM and will require modification. This issue does not warrant the level of concern that the PIM performance of the mesh itself does since it represents a more treatable problem. These aspects of the design can be addressed with relatively minor modifications using standard PIM mitigation techniques like avoiding metal to metal contacts (isolating or using non-conductive interface components) and shielding sensitive areas.

Extrapolating system performance predictions from these test results requires some subjective judgements and is unique for each system. In general, results from this type of test should be used conservatively to estimate system level PIM performance. The assumption is made that the sample and test conditions are representative of the final system implementation. A example system performance prediction based on sample level test results is shown in Table 2.

CONCLUSIONS

While wire mesh has been considered "PIM sensitive" based on an abundance of nonpermanent metal to metal contacts that are fundamental to the mesh design, careful consideration of the mesh characteristics and aspects of the deployable reflector design implementation reveal conditions that may reduce mesh PIM susceptibility. Experimental results presented in this paper indicate that PIM generation in the type of wire mesh supplied by Harris Corporation for the TDRSS program may be well within the requirements for typical systems. In view of the well established flight record of the Harris radial rib deployable reflector, consideration of its use for applications with PIM requirements is certainly warranted.

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Table 1. Mesh PIM Test Results

NOTE: "<" indicates no PIM measured over the noise floor.

Test Series I: L-band, 7th order PIM, 52 mW/cm^2 combined incident power, 35 cm from sample to measurement plane

Sample Type	Number of samples	Maximum PIM Flux Density
10 opi mesh	6	<-159 dBW/m^2
10 opi mesh with edge terminations and surface hardware	5	-123 to -159 dBW/m^2
18 opi mesh	1	<-159 dBW/m^2

Test Series II: X-band, 3rd order PIM, 23 mW/cm^2 combined incident power, 60 cm from sample to measurement plane

Sample Type	Number of samples	Maximum PIM Flux Density
18 opi mesh	4	-122 dBW/m^2
conditioned 18 opi mesh	2	-118 dBW/m^2
10 opi mesh	2	-90 dBW/m^2

Test Series III: L-band, 5th and 7th order PIM, 21 mW/cm^2 combined incident power, 60 cm from sample to measurement plane

Sample Type	Number of samples	Maximum 5th order PIM Flux Density	Maximum 7th order PIM Flux Density
18 opi mesh	3	<-154 dBW/m^2	<-169 dBW/m^2

Table 2. Example System Performance Prediction from Sample Test Results

INCIDENT POWER DENSITY		
Maximum operational incident power flux density	5 mW/cm^2	
Sample test incident power flux density	20 mW/cm^2	
Incident power density margin	**6 dB**	minimum of 3 dB recommended
PIM INTERFERENCE LEVEL		
Measured sample PIM power flux density	-160 dBW/m^2	
Sample vs. system mesh surface area	+19 dB	0.5 x 0.5 meter sample and 5 meter reflector
Sample test vs. system effective mesh to receive antenna separation	-24 dB	30 cm vs. 5 meters
System receive antenna effective area	-30 dB·m^2	-5 dBi effective gain in the direction of the transmit reflector surface
PIM power at receive antenna output	**-195 dBW**	

NOTE: A conservative assumption is made that PIM generated over the reflector surface will add coherently and the difference between modulated and CW carriers is not accounted for.

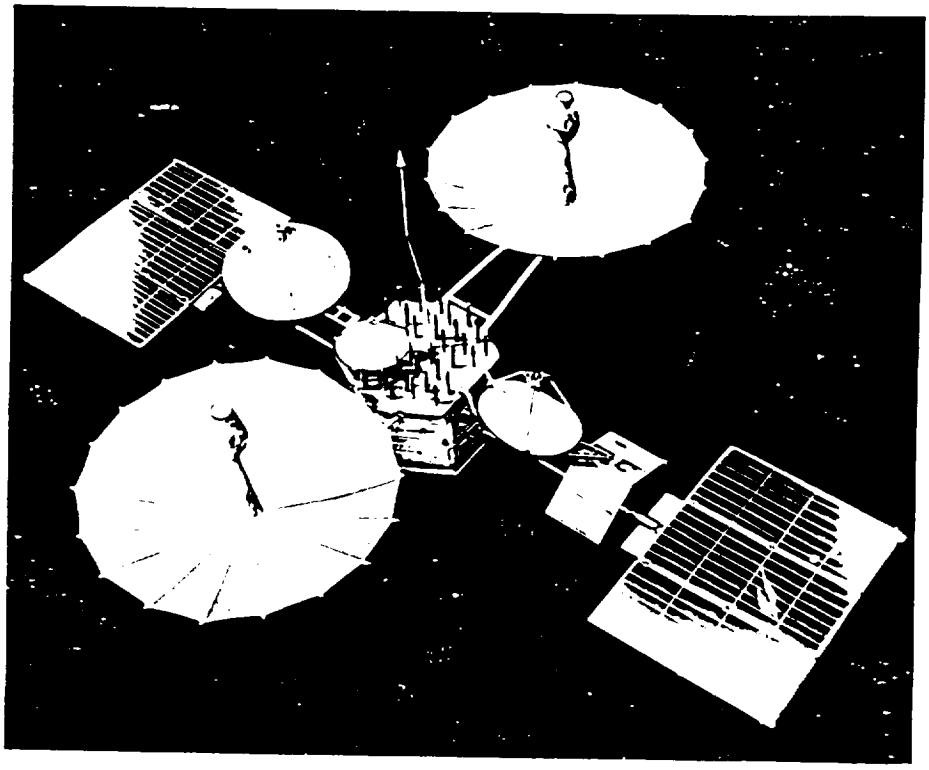

Figure 1. TDRSS Satellite

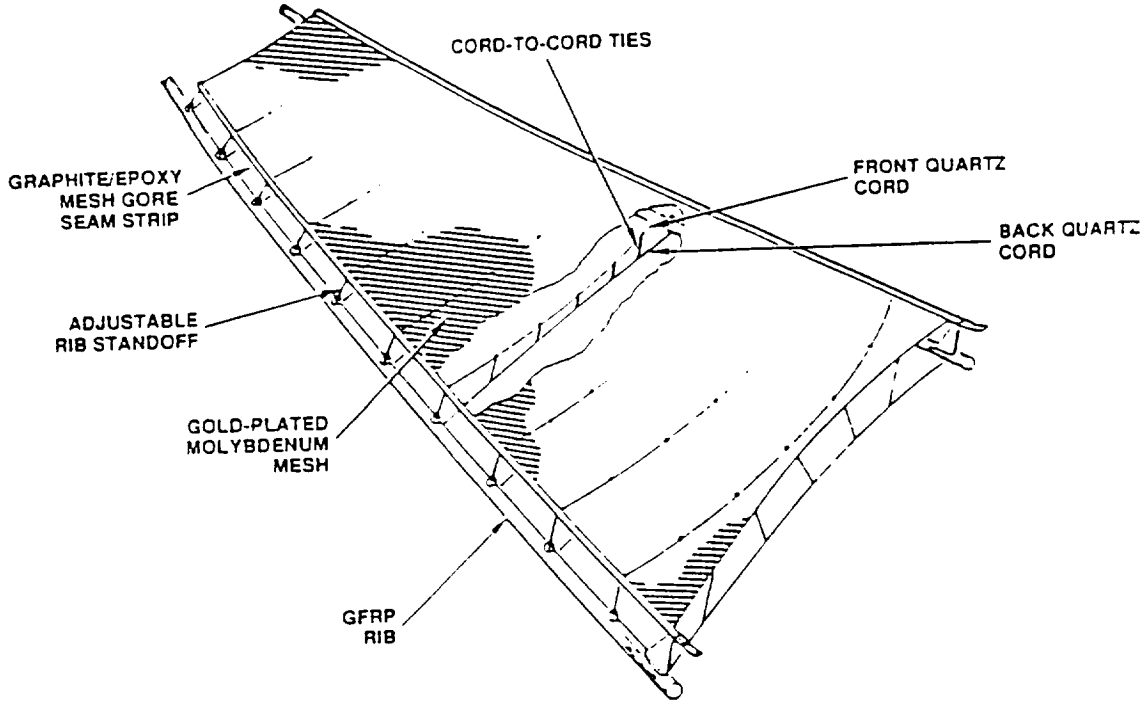

Figure 2. TDRSS SA Antenna Deployable Reflector Design

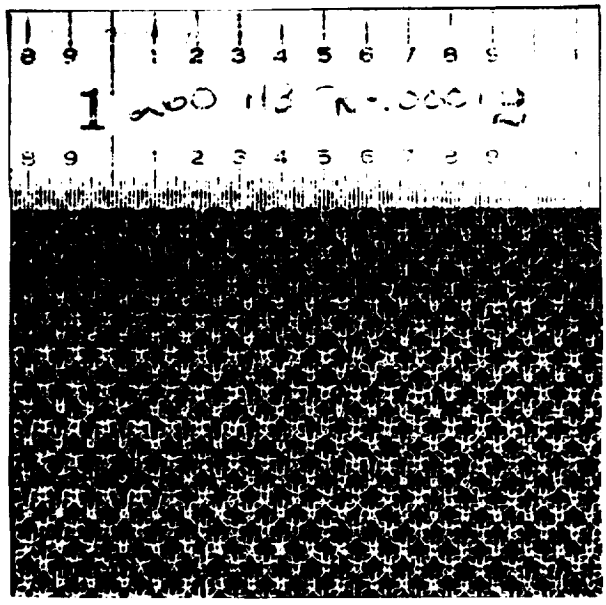

Figure 3. Harris 18 opi Wire Mesh

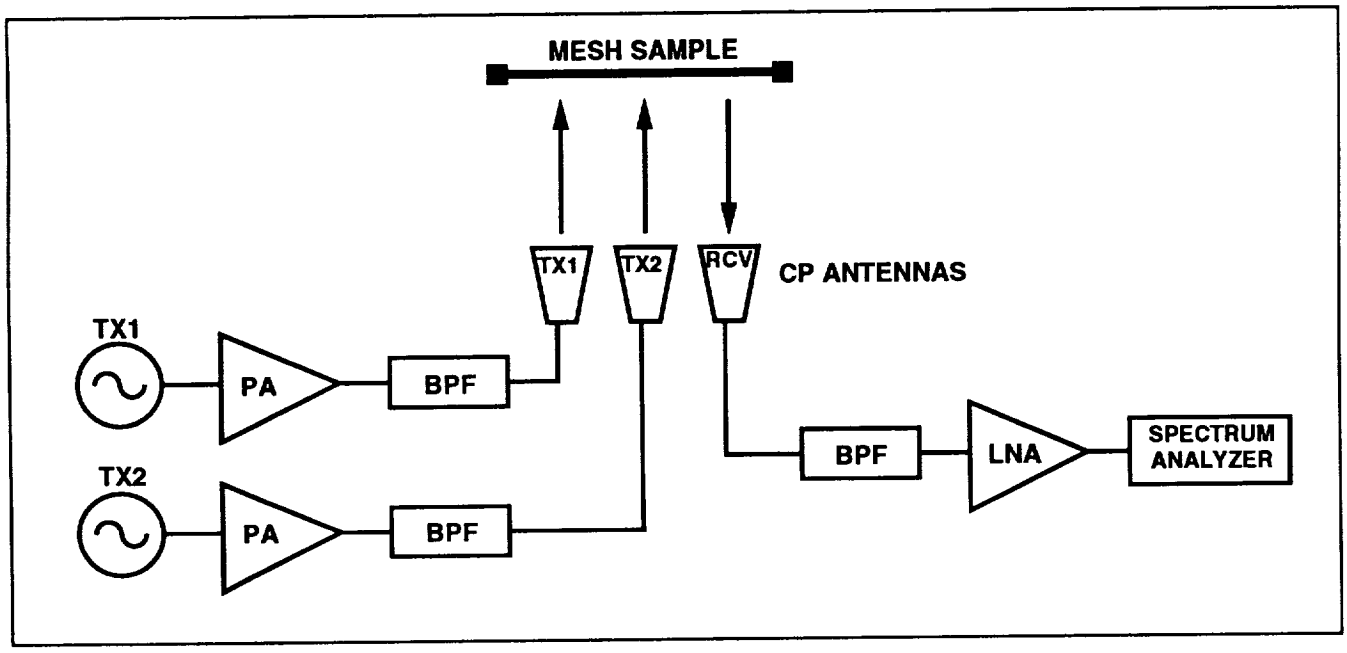

Figure 4. Mesh PIM Test Configuration

The possibilities for Mobile and Fixed Services up to the 20/30 GHz frequency bands

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INTRODUCTION

Satellite Communications and broadcasting is presently in a period of considerable change. In the fixed service there is strong competition from terrestrial fibre optic systems which have virtually arrested the growth of the traditional satellite market for long distance high capacity communications.

The satellite has however made considerable progress in areas where it has unique advantages; for example, in point to multipoint (broadcasting), multipoint to point (data collection) and generally in small terminal system applications where flexibility of deployment coupled with ease of installation are of importance.

In the mobile service, in addition to the already established geostationary systems, there are numerous proposals for HEO, MEO and LEO systems. There are also several new frequency allocations as a result of the WARC 92 to be taken into account. At one extreme there are researchers working on Ka band 20/30 GHz mobile systems and there are other groups who foresee no future above the L-band frequency allocations.

Amongst all these inputs it is difficult to see the direction in which development activities both for satellites and for earth segment should be focused. However, as an aid to understanding, this paper seeks to find some underlying relationships and to clarify some of the variables.

THE IMPACT OF USER REQUIREMENTS

One possible starting point in trying to gain a better insight into the basic relationships which affect the economics of various satellite system designs is to consider the user requirements. In the formative days of the satellite communications industry this was not really of the highest importance because the systems were organised and operated by large carriers and PTT administrations and the end user was not directly involved. A high and growing proportion of traffic is now carried by small terminal systems. Satellites communications earth stations are operated directly from user premises and in the case of mobile systems from the users vehicles and ultimately his person.

The size of the earth station antenna is now a vitally important element in user acceptability. Large antennas are unsightly and

difficult to install and they are a definite disincentive to the use of satellite communications. For the fixed service the user can probably accept earth stations having an equivalent diameter of around 1.5 metres. For the mobile service a good starting point is probably an equivalent diameter of 15 cm.

Another important factor for the user is the power level of the earth station. Stations which consume Kilowatts of power and require large and failure prone tubed amplifiers are unlikely to be popular with the user community. For the fixed service this means that solid state power amplifiers are needed and depending on the frequency this places a limit on the radio frequency (RF) power which can be applied to the antenna. For the mobile service the RF power output is constrained by mobility and human safety considerations.

Fixed Service Link Budget

For the satellite up-path the most important parameter is the RF power available per bit to feed the earth station antenna. The remaining variables do not change dramatically from one system to another. The satellite receive noise temperature is heavily influenced by the temperature of the earth and the satellite antenna size and gain are determined by the up-path coverage requirement from the earth surface.

Figure 1 illustrates the up-path link budget situation for the fixed service with the following assumptions:

- earth station equivalent diameter - 1.5 m
- satellite system temperature - 30 dBK
- propagation margin - 6 dB
- modulation BPSK/QPSK
- Eb/No required (uplink only) - 10 dB

This curve is independent of frequency and can therefore be used as a general guide to choose the approximate up-path parameters applicable to a given system. It also applies in the case of multi-beam systems where the beamwidth of each beam is shown on the X-axis.

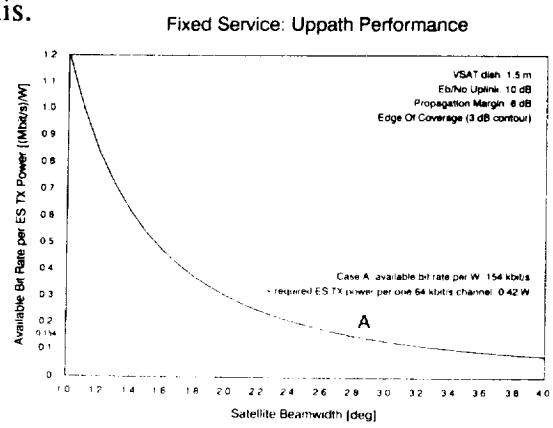

Figure 1: uplink situation
(fixed service satellite system)

The same techniques can be used in the downlink which leads to the curve shown in figure 2. This time the critical parameter is satellite RF power allocation per Mbit/s of required downlink capacity.

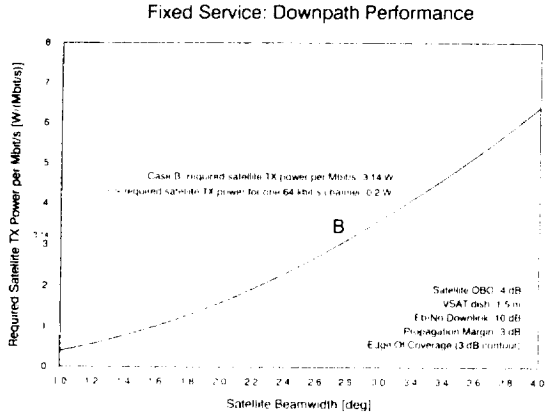

Figure 2. Downlink situation
(fixed service satellite system)

Mobile Service Link Budget

If, as previously discussed, the user terminal equivalent antenna diameter is 15 cm both the uppath and the downpath situations

are quite different from the fixed service case. In the mobile case, the antenna diameter of the earth station has gone down by a factor of ten from 1.5 to 15 cm. This represents a loss to the link budget of 100 to 1 or 20 dB. Additionally, an allowance of about 10 dB must be made to ameliorate the effects of shadowing due to trees, buildings, etc. This margin can partially overlap the propagation margin since the joint probability of rain and shadowing is less than the sum of the two. Nevertheless an additional margin with respect to the fixed service case of 7 dB would seem to be necessary.

Thus the overall disadvantage with respect to the equivalent fixed service situation is approximately: 27 dB. Part of this can be regained by the use of bandwidth compression techniques. In the case of telephony, for example, a reduction of the required bit rate for a channel from 64 kbit/s to 4.8 kbit/s (vocoded speech) can be assumed. This is equivalent to 11.3 dB. In summary:

smaller antenna	20.0 dB
additional shadowing margin	7.0 dB
bandwidth compression (telephony)	-11.3 dB
net mobile disadvantage	15.7 dB

This shortfall has to be found in the satellite by a combination of narrower antenna beams to provide more satellite antenna gain and in particular by the provision of a much higher power density in the satellite for the downlink.

The uplink performance is doubly restricted due to the small size of the earth station antenna and the low power of the earth station amplifier.

The equivalent curves to figures 1 & 2 for the up and downlink situation in the mobile case are shown superimposed in figure 3.

It will be noted that whereas the power required in the satellite for the fixed service could be expressed in Watts/(mbit/s), for the mobile service the density is expressed in Watts/(kbit/s). This reflects the disadvantage

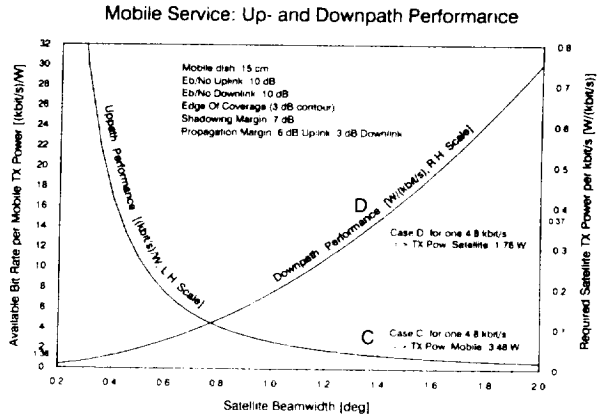

Figure 3. Uplink and downlink (mobile service satellite system)

of approaching one hundred to one experienced by the mobile system with respect to the fixed service system. Nearly all of this disadvantage has to be compensated for in the satellite power output. For a typical satellite the most significant mass elements are the output stages of the payload and the power generation subsystem (solar panels power conditioning etc.). Hence, irrespective of the frequency band employed, as a general rule satellites for the mobile system will always be substantially heavier for a given capacity than the fixed service equivalent. This of course is reflected in the cost and ultimately in the price of the calls to the consumer.

The case of a geostationary satellite has been taken in the examples but it is interesting to note that reducing the altitude of the satellite (the MEO and LEO orbits) brings no improvement in the power density requirement if the same area of earth is to be illuminated.

Individual link budgets for point A, B, C and D respectively in figures 1, 2 and 3 are given in table 1. All the non variable parameters assumed in the curves are thereby defined.

For the up path link budgets the effect of propagation margins would require the use of power control to avoid overload in clear air conditions. For the purposes of these calculations such control is assumed to exist.

THE IMPACT OF FREQUENCY BAND

The curves presented in the previous section are independent of frequency. However, there are a number of factors which do affect the choice of frequency band.

Available spectrum

The available spectrum for the mobile service in the L-band is limited to a few tens of megahertz. Even with considerable re-use of frequencies this is somewhat limited and there is a case for targeting the much larger bandwidths available at Ku band and Ka band for some mobile services.

The higher frequencies also have some attractions for the mobile service because it may be possible, with appropriate processing, to operate these services using existing satellite capacity in parallel to the existing fixed service and broadcast transmissions. This has obvious advantages since it permits mobile systems to be established on a marginal cost basis thus avoiding the high initial investments necessary for a dedicated mobile system. Such systems are already in operation in a limited way for low bandwidth data exchange in the Ku band, both in North America and Europe.

However, it is difficult to operate small terminal or mobile systems in an environment where large earth stations are already in use. The required satellite gain settings and the interference environment are normally quite different. However, in the Ka band it would be less difficult to operate a wide range of services e.g. broadcast, fixed service, mobile since there are no existing systems and the parameters could be adjusted to enable small terminal systems to be used.

Propagation effects

It is well known that the Ku band and particularly Ka band suffer from atmospheric attenuation due to rainfall. This has the effect of increasing the required link margins and/or increasing the unavailability of the system to the user. There is now a great deal of experience in using Ku band throughout the World. However, experience with Ka band for satellite communications and broadcasting is more limited.

The Olympus satellite has two transponders in the 20/30 GHz frequency band and has provided the opportunity for European and Canadian organisations to gain experience in these frequencies over a period of four years. In general the experience has been very positive and it has been possible to use the band extensively for broadcasting, VSAT systems, video conference and news-gathering on a regular basis with good results without the use of excessive propagation margins. This anecdotal information has been supplemented by extensive propagation beacon measurements of a more scientific nature.

The results indicate that 20/30 GHz can be used successfully for all types of service provided the availability requirements of the user are modest.

The band appears to be unsuitable for high availability trunk connections, unless special fade countermeasures are employed, but is very suitable for small terminal user oriented communications where availabilities of typically 99.5% are acceptable. Hence low cost is an important element to be traded against availability. Figure 4 shows propagation statistics derived for 650 geographically separated locations within Europe and based on a propagation model which has been verified using Olympus data. It will be seen that with uppath and downpath margins of 6 dB and 3 dB respectively almost 100% of sites can be served with an unavailability of 1% and 50% of sites achieved 0.5% unavailability. With margins of 8 dB and 4 dB, an unavailability of 5% can be achieved in all but the very worst locations.

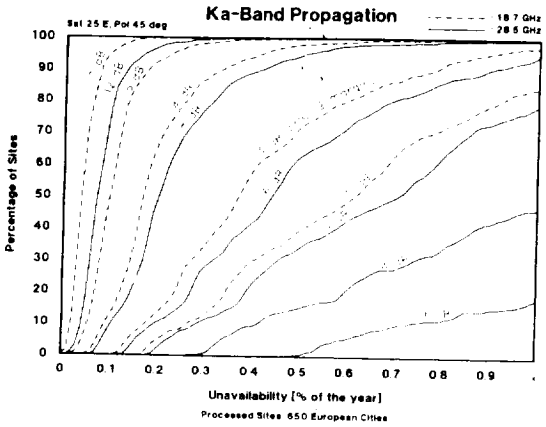

Figure 4

Doppler effects

At high centre frequencies the doppler shift caused by the movement of vehicles or people is proportionally higher. This means that special measures have to be taken in the receivers and transmitters to overcome the frequency offsets. These problems have already been successfully addressed in experimental designs.

Earth station beamwidth

Clearly, the beamwidth of the earth station antennas becomes proportionally narrower as the frequency is increased. Tracking antennas therefore become necessary. This is a severe disadvantage in increasing the complexity of the mobile terminal. On the other hand the narrower beamwidth involved progressively limit the interference to and from adjacent satellites.

Satellite mass

If we select an operating point on the power/coverage curves and look at the variation of satellite mass as the frequency goes from L-band to Ka-band one finds that to first approximation the mass remains constant. This, at first sight, surprising results was obtained by taking several satellite configurations and applying the known mass of the various payload and power system elements for the various frequencies. The outcome is mainly due to the interaction between two factors. As the frequency increases the antenna size for a given coverage reduces as well as the size of the microwave components thus reducing the mass of the satellite. However the lower power efficiency of the HPA and the losses in the microwave components result in an increasing power demand by the payload and an increase in mass of the satellite. There is a small (10%) but noticeable step increase in the mass at Ku and Ka-band due to the change from SSPAs to TWTAs in the HPA.

The above results assume that the number of beams on the satellite is constant. In a practical system as the frequency increases the link margins need to be increased to compensate for fade conditions, this can either be accomplished by increasing the power of the mobile terminal or by increasing the gain of

the satellite. If we select to increase the gain of the satellite the antenna beam size will go down and to keep the same coverage we will have to increase the number of beams to compensate. With a hand held system we do not have the option of increasing the terminal power because of the safety aspects. This reduction of beam size and the consequent reduction in power does have a mass advantage as the frequency is increased even though the number of beams is increased. The mass saving at Ka-band is about 5%.

Thus there is little variation in satellite mass as the frequency changes in a mobile system. However the increase in number of beams significantly increases the complexity of the payload hardware and hence the cost. This together with the general increase in cost of gain at higher frequencies will tend to favour the lower frequencies from the satellite viewpoint even though mass is not an important factor.

CONCLUSIONS

It is concluded that a mobile system tends to be intrinsically much more expensive than a fixed service system. This is because the satellite power and mass has to be greatly increased to satisfy the need to reduce earth station diameters. The additional satellite mass per unit of use is reflected in the investment and running costs of the system.

The calculations made are based on a set of assumptions which do not change greatly with the type of system envisaged. They therefore apply as a first order to any geostationary system single or multibeam. However, they also apply to low earth orbit systems when equal area coverage on the ground is required.

From a system point of view there are no intrinsic advantages or disadvantages in the choice of frequency band for mobile or fixed services. However, there are some factors which will affect the choice of a particular frequency band for a particular system. These are:

- higher unavailability with increase in frequency due to propagation conditions;
- more complexity at higher frequencies due to the need for tracking ground antennas and better doppler compensation;
- more spectrum available in the higher frequency bands;
- possibilities to operate mixed services broadcast, fixed service, mobile with consequent improvement in the spread of risk and cost;
- better interference characteristics for higher frequency systems;

From the satellite point of view, in theory, the mass of the satellite payload should decrease with frequency due to smaller and lighter components. However, the technology tends to be more advanced and mature at the lower frequencies and it is estimated that satellites for the mobile service at Ku-band and Ka-band will be considerably more expensive for some time than the lower frequency equivalents. If a high availability service is required at the higher frequencies the additional propagation margins necessary will impact heavily on the number of beams required for a given coverage and thereby on the cost and complexity of the satellite.

In general one can envisage that the L-Band frequency allocations will tend to attract the high availability but relatively expensive mobile systems. The higher frequencies and particularly the 20/30 GHz Ka band allocations can absorb small terminal systems in the

Contact the Author for Conclusion and Table.

GEOLOCATION APPLICATIONS of the GONETS LEO MESSAGING SATELLITES

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INTRODUCTION

Geostationary satellites carry a majority of the international telecommunications traffic not carried by transoceanic cable. However, because the radio path links to and from geostationary satellites total at least 70,000 km and because of inherent on-board spacecraft power limitations, earth stations used in conjunction with geostationary satellites are usually large and expensive. This limits their installation to areas with a well-developed industrial and economic infrastructure.

This reality helps perpetuate a chicken-egg dilemma for the developing countries and isolated regions. Economic integration with the developed world requires being "networked". But for many developing entities, even the initial price of entry exceeds their modest resources.

Exclusion from the global information highways virtually assures retardation of economic growth for developing nations, remote and isolated areas.

Very Small Aperture Terminal (VSAT) earth stations are often thought of as a solution for networking developing regions. But economic considerations often forecloses this option. If VSAT size and cost is to be minimized, powerful spot beams from the satellite need to be focused on relatively small regions. This is not often feasible because of the high cost of the satellite itself. To dedicate a high power spot beam to a small region is usually not economically feasible.

Further improvement of the space segment could provide some relief for cash-strapped, low-density user populations. Some visions have been put forth of massive spacecraft with 30 m antennas, huge solar arrays generating several kilowatts and spacecraft masses exceeding 4 to 6 metric tons. Realistically however, the costs of building and launching such massive, complex payloads renders this possible approach to some future era. It will clearly be impractical for the near term.

Low Earth Orbiting (LEO) satellites offer a practical solution to this dilemma for many potential applications.

All LEO communications fall into one or two categories depending on the services they provide and their technical sophistication:

- data transmission
- voice communications

GONETS PACKET DATA RELAY LEO SYSTEMS

The category including projects such as Gonets, Leosat, Orbcomm, Starsys, Vitasat [1-2] can provide the following services:

- Digital data transmission of: text, imagery, databases, environmental data to/from control and sensors; Supervisory Control and Data Acquisition (SCADA)
- Paging
- Remote geolocation

Many applications do not require

uninterruptable links. Unlike a voice telephone conversation wherein a real-time link is essential, many data transmission applications allow for some enroute delay. Non-realtime data forwarding is vastly more cost-effective than providing realtime links.

All this considered, a practical, useful, low-cost, packet LEO data transmission network needs to be based on the following principles:

1. The use of a quasi-random constellation of satellites each of which has attitude control mechanisms but no station/orbit keeping facility. The number of satellites then depends on the specific orbital parameters and the allowable message delivery transit time from originator to addressee.

2. The use of VHF/UHF links (130-400 MHz) allocated for mobile satellite communications together with polar, circular orbits (700-1500 km). This allows global coverage and the use of simple, 0-3 dbi, low gain "omni" antennas, 2-10 W transmitters and very simple (gravitational) quasi-passive spacecraft attitude control.

3. The use of packet transmission mode to minimize power consumption of both the earth and space segments and to allow effective spectrum sharing by multiple users. The packet protocol minimizes channel contention and reduces overhead by simplifying channel control and supervisory intervention.

4. The use of an orbital constellation with quasi-random access windows is extremely easy to control and operate using a single master control center.

When realized in a practical network, these basic principles yield the following results:

1. Satellites can be very small (50-200 kg) and inexpensive capitalizing on the latest achievements in micro-miniaturization and satellite technology. Relatively low spacecraft mass and low orbital altitude allows a single launcher to carry several spacecraft thus reducing the overall cost of the space segment.

2. Ground terminals can be small, simple, inexpensive and user-friendly devices lowering maintainability requirements and the training of the "maintainers" themselves.

Thus, the foregoing principles allow the development of affordable LEO satellite networks for packet data transmission at an estimated cost of between $50 and $200 million depending on the range and complexity of services provided. Such networks are end-user oriented and do not require developed terrestrial land-line infrastructure. They thus provide instant network connectivity in "islands" of often urgent communications requirements. The time required to establish a node on any square meter of earth is the time needed to open an attache case and turn on a switch.

The "Gonets" LEO system is thoroughly based on the foregoing design philosophy and first principles. Gonets is programmed to be operational with an eventual total of 36 satellites organized as six planes of six satellites beginning in 1994 and building to a 1996 full operational constellation.

In the current system development phase, the "demonstration" phase called "Gonets-D" has already been placed in orbit. Two Gonets-D satellites were launched in July, 1992 and have since provided scores of demonstrations around the world.

Gonets-D has been demonstrated to various governments, industry, and financial institutions in Russia, other CIS countries, as well as in Australia, India, Africa, and elsewhere. A major series of Gonets-D demonstrations is planned in Western Europe later in June and South Asia in the July-August time frame.

The demonstration system will be expanded by Smolsat later in November or December 1993 to include an additional 6 satellites with 3 in each of the two orbital planes. That system, called Gonets D-1, will be capable of supporting up to 30,000 portable transceive terminals and a virtually unlimited number of SCADA terminals.

The Gonets-D1 advanced development demonstration system has the following performance values:

- 2 hours maximum access wait at the 0.8 probability level
- 3-6 hours average maximum message in-transit delays depending on the system completeness (number of spacecraft in service at that point

The above limitations resulted in the following communications protocol.

Communication between any two stations simultaneously in the 5000 km diameter footprint is quasi-realtime, quasi-bent-pipe mode.

The satellite periodically sends a preamble signal carrying data necessary to establish radio contact with a user. Users can exchange information when they are both in the footprint of the satellite using the preamble which contains the necessary subscriber identification information (callsign) and the particular geographic area information. The geographic area identification can be both satellite and Area Station (AS) generated. The latter is simpler and therefore employed by the Gonets system.

Various types of data transfers between User Terminals (UT) (UT1-satellite-UT#) and to a Stationary User Terminal (SUT) linked to the Area Station (UT2-satellite-AS1 SUT).

Users not simultaneously in the footprint of a satellite use the store-and-forward mode for communication. Data received by the satellite is stored in the on-board memory. When the message addressee is heard by the carrying satellite, the message addressed to him is downlinked to that station.

Even in its late developmental phase (1993-94), Smolsat will be offering precise geolocation services for mobile users by relaying Global Positioning System (GPS)/Global Navigation System (GLONASS) derived vehicle position data to corresponding central service stations via Gonets-D1 by using a synthesis of Gonets and GPS terminals in a convenient package.

Vehicles and other mobile platforms (be they icebergs or high-value cargo) which require highly accurate location determination reporting will use a synthesis of GPS/Glonass receivers and GONETS transceivers to provide this information to managers. The GPS/Glonass-Gonets synthesis will provide the facility to accurately and quickly telemeter the location and status of a vehicle anywhere on earth to a command center with an accuracy within several meters.

While these terminals locate the vehicle (or other mobile object), status and/or message traffic is transferred to central stations via Gonets user terminals. A standard RS-232C interface is used to connect the various equipment.

DIFFERENTIAL NAVIGATION

Commercial GPS/Glonass navigation receivers are limited to the GPS standard position service (SPS) accuracy of 100 meter available worldwide for civil use and similar accuracy for the Russian Glonass system.

Navigation receivers which use differential corrections can significantly improve performance. Typical differential GPS accuracy is from 0.5 to 5 meters. Differential Glonass accuracy can expect similar improvements over autonomous receiver operation.[4]

The accuracy of differential navigation

is limited by the distance between the base station and remote receiver, the age of the differential correction data (update rate), and the differential data link.

The corrections remove most of the error from the major error sources affecting the accuracy of satellite-range measurements: satellite orbit estimation, satellite clock estimation, ionospheric error, and tropospheric error. After the correction is applied, the residual error is on the order of one millimeter for every kilometer of separation between the base and remote receiver.[5]

It is estimated that over 500 base differential stations would be required to cover the United States. Techniques are being investigated which may reduce the number of base stations required to provide differential range corrections for a wide area.[6][7]

The differential corrections must be transmitted to the remote receiver at a data update rate sufficient to eliminate the effects of time varying satellite errors and atmospheric effects. Update rates from two to six seconds are sufficient to minimize these effects.

The differential data message can also include information on the integrity of the differential corrections and the real-time health of the navigation satellites which is critical for some applications.

The differential data link requires selection of an appropriate transmission frequency to assure reception at the remote receiver and meet local governmental licensing requirements. The selection of a Gonets system as the data link provides an ideal solution to these problems.

GEOLOCATION APPLICATIONS

Applications for differential navigation encompass a wide range of user needs and uses. Equipment complexity is dictated by user requirements. Some applications require continuous reception of differential corrections and other applications need a correction at a distinct location or time. Some users require knowledge of the position of the remote units.

These user requirements can be met simply with just a GPS/Glonass receiver and Gonets user terminal. Gonets protocol is built into the standard interface of the Ashtech GPS/Glonass-Gonets capable receiver.

Users requiring map or navigation displays can add a common personal computer to the basic configuration. Geographic information systems (GIS) could use a bar code reader to easily enter attribute information for the landmark.

Typical applications include: worldwide accident investigation (aircraft, ship, oil spills, earthquakes, hurricanes, and other infrastructure damage), worldwide rescue operations, locating & tracking icebergs, exploration geophysics, oil rig positioning, vessile docking, channel dredging, installing remote communications sites, harbor depth mapping, and a host of many other GIS applications.

Vehicle tracking systems or fleet management systems could perform worldwide tracking and route management control of vehicles (ship, truck, automobiles, and aircraft). It is even possible to apply this technology to unmanned ships traversing the oceans. The system could then be used by a pilot to safely navigate the harbors.

Agricultural equipment would benefit from accurate position data for planting, applying fertilizers and pesticides leading to improved yields. Navigation and control of unmanned combines and tractors may also be feasible.

All users would have confidence they can depend on the accuracy of the GPS/Glonass-Gonets position data from the health data built into the satellite differential correction messages.

Table 1. GONETS Technical Data

GONETS Orbital Specifications
General Orbital Characteristics:
Type:LEO, polar
Inclination angle: 82.6degrees
Period: 114minutes
Apogee:1420km
Perigee:1420km
Footprint:5000km
Characteristics of the GONETS-D Orbits
Number of satellites: 2
International Designators:
Cosmos 2199, Object 22036
Cosmos 2201, Object 22038
Launched: 13 Jul 92 from Plesetsk

GONETS Spacecraft General Specifications
Bus Description:
Mass:225kg
Dimensions: Length150cm
Diameter100cm
Max span, antennas deployed: 140 cm
Attitude control: Gravity gradient boom, magnetic assisted
Attitude accuracy:5 - 10degrees
Power:
Orbital average power: 45W
Peak power available:160W
Thermal control:Maintains 0 - 40 °C
Launcher:Cyclone 6 per launch

GONETS Communications Characteristics
Subscriber/user terminal characteristics
Earth-to-Space Direction
Maximum gain:+2.0dBi
Polarization:RHC
Service area:Regions 1, 2, 3
Class of station: CP, TG, TU
Receiving system noise temp: 700 °K
Frequency range:259.450 - 259.550 MHz†
261.850 - 262.150 MHz†
264.375 - 264.525 MHz†
387 - 390 MHz
Emission designator:20K0G1W
Total peak power:+10.0 dBW
Maximum power density:-37.8dBW/Hz
EIRP:+5.19 dBW
Typical earth station:Type UT-P

Space-to-Earth Direction
Spacecraft Characteristics
Maximum gain:+2.0dBi
Polarization:RHC
Service area: Regions 1, 2, 3
Type of service: EG, EU, CP
Frequency range: 258.900 - 259.100 MHz†
261.085 - 261.1350 MHz†
262.900 - 263.100 MHz†
264.400 - 264.600 MHz†
312 - 315 MHz†
Emission designator: 20K0G1W, 10K0G1W
Total peak power: +10.0 dBW
Maximum power density: -37.4 dBW/Hz
Space station EIRP +7.6 dBW
Receiving system noise temp: 490 °K

Communications Link Parameters
General:
UHF uplink, UHF downlink
Signaling rate: 2.4 kbps†
2.4, 9.6, 64 kbps‡
Modulation: DPSK
Coding: Reed-Solomon coding (32,38), M=8
Decoding: Viterbi (R=1/2, K=3)
Link Margins:
Portable terminal UT-P 5-7 dB
Fixed terminal UT-S 5-7 dB
Link control protocol: DAMA using FDMA/TDMA
Marker signal present
Aloha mediated assignment channel
Channelization (36 satellite network system):
Preamble signals: 72 physical chan
Signal communications: 10,800 TDMA chan
Data channels: 72 physical chan
Packet transmission: 21,600 16kbit slots/min

Network Performance:

System Throughput at 13% 3x10E04 Mbit/day
or 3x10E06 pages/day
(GONETS)
Number of users: Up to 1,000,000
Wait time: 20 minutes @ 0.8 probability
Delivery time (worst case): 1 hour

† GONETS-D only
‡ GONETS-D1 only

Program Phasing:

Phase Event	Schedule	Capacity (pages/day)	On-board memory (MByte per satellite)
Launch of two Gonets-D (demonstration)	13Jul92	3x10E2	0.019
Launch of 6 Gonets D-1 (isolated user groups)	Nov.1993-Jan.1994	1.2x10E4	2
Full GONETS constellation	1994-1996	3x10E6	8/16
Start of commercial use	1994/5		

Programmatics:

Organizations in consortium:
- SMOLSAT (Moscow): Program management
- NPO AM (Krasnoyarsk): spacecraft bus; system/launch integration
- NPO PI (Moscow): spacecraft subsystems
- Izhevsk Radio Manufacturer: communications payload, user terminals
- Kievpribor Manufacturer: communications payload

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LOW EARTH ORBIT SATELLITE/TERRESTRIAL MOBILE SERVICE COMPATIBILITY

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ABSTRACT

Currently the geostationary type of satellite is the only one used to provide commercial mobile-satellite communication services. Low earth orbit (LEO) satellite systems are now being proposed as a future alternative. By the implementation of LEO satellite systems, predicted at between 5 and 8 years time, mobile space/terrestrial technology will have progressed to the third generation stage of development.

This paper considers the system issues that will need to be addressed when developing a dual mode terminal, enabling access to both terrestrial and LEO satellite systems.

THE FUTURE ROLE OF A MOBILE SATELLITE SERVICE

Terrestrial mobile communication services are now entering the so called "second generation" phase of development. One such example is the pan-European digital GSM service[1][2]; this system is now gradually being introduced into service throughout Europe.

The development of mobile-satellite communication services is progressing in parallel to that of terrestrial services. The first mobile service was introduced by Inmarsat in the late '70s to the maritime sector; Inmarsat is now establishing a land-mobile service with the introduction of the Inmarsat-C and Inmarsat-M systems[3].

Where a terrestrial mobile service is well established, such as in Western Europe, it is unrealistic to think of a competitive satellite service, it is more likely that satellites will provide a complimentary back-up service. This scenario has attracted considerable interest in Europe over the past few years, especially integrating a satellite service with GSM where initially there will be gaps in terrestrial coverage, particularly in rural areas and Eastern European countries[4][5]. Satellite mobile services can play a more dominant role in areas where the mobile/fixed telecommunication infrastructure is non-existent, this will be true in large areas of the third world[6] for example.

By the end of the decade satellite systems will have advanced significantly from current transparent wide beam geostationary systems. Proposals are now being considered

for multi-satellite low earth orbit systems with spot beam facilities, such as Iridium[7]. The satellite configuration in an integrated environment has considerable scope for variation.

The three types of satellite orbit generally considered as being able to provide the space element in an integrated service are: geostationary orbit (GEO), highly elliptical orbit (HEO) and low earth orbit (LEO). The advantages and disadvantages of each type of orbit in an integrated network will need to be considered, some of the more obvious of which are summarised in Table 1.0.

LOW EARTH ORBIT SYSTEMS

LEO satellites orbit the earth at altitudes in the range 500 - 2000 km. The orbital period of a LEO is in the region two hours, consequently a satellite will only illuminate a certain coverage area for approximately 2-3 minutes. Hence, for a continuous global communication service it is necessary to place a number of satellites in orbit. LEO satellites can be placed in either an inclined or polar orbit, or a combination of the two.

When used for mobile communications LEO satellites offer several advantages [8]; the altitude of the orbit means that it is possible to relax the constraints on the mobile terminal's transmit power and G/T. Additionally, the round trip propagation delay will be in the region of tens of milliseconds compared with the 250 ms delay of a geostationary satellite. Furthermore, due to the requirement for multiple satellite orbits, at least one satellite will always be in view of a mobile terminal (MT), thus it should be possible to optimise the satellite to MT link when multiple satellites are in view. However, the orbital velocity of a LEO satellite means that transmissions will be subject to a significant Döppler variation. For example, a satellite at an altitude of 800 km, transmitting at 2 GHz, would be subject to a Döppler shift in the region of 45 kHz for a 20° mobile to satellite elevation angle. Additionally, some means of implementing handover between satellites is required to maintain a continuous real time transmission. This will require a large degree of on-board processing (OBP) if the satellite is to control handover. This contrasts with GEO satellite systems where OBP is now only being considered as a future development for commercial services.

NETWORK ENTITIES

An integrated network will consist of a space segment, ground segment, gateway/base stations for fixed/private network access, and some form of network management station, the function of which is to a certain extent dependent on the level of OBP on the satellite.

To enable the routeing of calls it has been proposed[9] that the earth is divided into segments corresponding to satellite coverage areas. Each satellite has an address corresponding to the ground area that it illuminates. A call instigating from one location is routed to the satellite which covers the area of the destination address.

When a satellite crosses from one coverage area to another its address is updated. Consequently, the network configuration will be continuously changing, hence some means of updating each satellite of

its position relative to the earth must to be established. There are two possibilities, either:

(a) Each satellite can be updated on its position from the ground;

(b) The satellite's onboard processing will determine its position. This will increase the complexity requirement of the satellite.

SATELLITE VISIBILITY

The number of satellites visible to a terrestrial terminal at any one time is dependent the satellite orbital configuration, the minimum elevation angle to the satellite, and the location of the mobile. LEOs are generally classified as being of either polar or inclined orbital type. Inclined orbit systems provide coverage optimised for low to mid latitude regions, however a truly global service can only be provided by a polar type configuration. Polar orbits maximise the satellite density over the polar regions. To illustrate this point a 24 satellite configuration, equally divided into 4 planes, at an orbital altitude of 2000 km, was simulated using SatLab[10]. The result is shown in Figure 1.0.

COVERAGE DURATION

In terrestrial cellular systems handover between cells occurs when a mobile moves from one cellular coverage area to another of better signal quality. Satellite systems can also provide cellular type coverage, to increase spectral efficiency, by the use of multi-spot beams. However, in a satellite system it is the cells, rather than the mobile, that are moving, ie. the mobile appears fixed relative to the cellular motion caused by the satellite. This can easily be illustrated by, for example, considering the velocity of a car travelling at 110 km/h (approximately 70 mph), or in other words 0.03 km/s, to that of satellite at an orbital altitude 2000 km, resulting in a velocity of 6.9 km/s. It can be seen that the mobiles velocity is virtually negligible.

Figure 2.0 illustrates how the time spent within a cell is affected by satellite altitude and the guaranteed minimum elevation angle from a mobile to the satellite. It can be seen that even for a call duration of 3 minutes there will be a requirement for handover between beams.

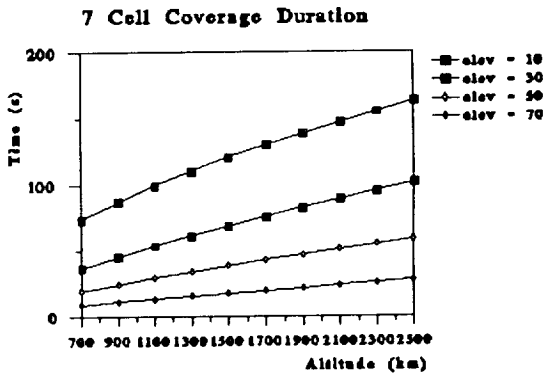

Figure 2.0 7 Cell Coverage duration

TERMINAL POWER REQUIREMENT

The available transmit power of a terminal will be constrained by its physical characteristics. For example GSM terminal classification ranges from vehicle-mounted, through transportable units to hand-held portables. The following link budgets were calculated between a satellite transmitting a 7 beam cellular pattern and a hand-held

terminal.

General Link Parameters

Satellite Altitude	2000	km
Minimum Elevation Angle	5	o
Max. Dist. mobile to sat.	4905	km
Satellite Velocity	6.90	kms^{-1}
Orbital Period	127	mins
Pass Duration per Cell	2 mins 42s	
$Propagation\ Delay_{max}$	16.35	ms

Mobile To Satellite Link

EIRP	-2.0	dBW
Frequency	1.62	GHz
Free Space Loss	170.4	dB
Atmospheric Atten.	0.2	dB
$Gain_{sat}$	19.8	dB
T_{sat}	30.0	dK
G/T_{sat}	-10.2	dBK^{-1}
C/N_0	45.8	dBHz
$Doppler_{max}$	37.1	kHz

Satellite To Mobile Link

EIRP/channel	19.8	dBW
Frequency	2.5	GHz
Free Space Loss	174.2	dB
Atmospheric Atten.	0.2	dB
$Gain_{mob}$	0.0	dB
T_{mob}	25.0	K
G/T_{mob}	-25.0	dBK^{-1}
C/N_0	49.0	dBHz
$Doppler_{max}$	51.7	kHz

CONCLUSION

It can be seen that creating an integrated space/terrestrial network is a complex task. This is especially true for LEO type systems where the space network configuration is constantly changing.

To achieve an integrated network several key issues need to be addressed, for example: the criteria for handover between terrestrial and space links needs to be established. Current terrestrial handover criteria based on signal strength will need to be adapted to take into account the scarcity of the satellite resource; switching between satellite cells, and possibly between satellites, will increase the complexity of the space segment; a terminal capable of handling up to 50 kHz doppler with the possible circuitry required to implement an adaptive modulation and access schemes will need to be developed.

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ACKNOWLEDGEMENT

The authors would like to thank COMDISCO SYSTEMS, UK Ltd, for the use of the SatLab simulation software.

	Geostationary	Low Earth Orbit	Elliptical
No. of Satellites	1-2	20-70	3-4
Visibility	Poor	Good - Excellent	Good
Relative Network Complexity	Low	Multi-Satellite Switching (Iridium) Low (Transparent Satellites)	Low 2-3 Satellite Switching/Day

Technology	Established	New	Experimental
Round Trip Propagation Delay (ms)	240	7-15	200-260

Table 1.0 Orbital Configuration Performance Summary Chart

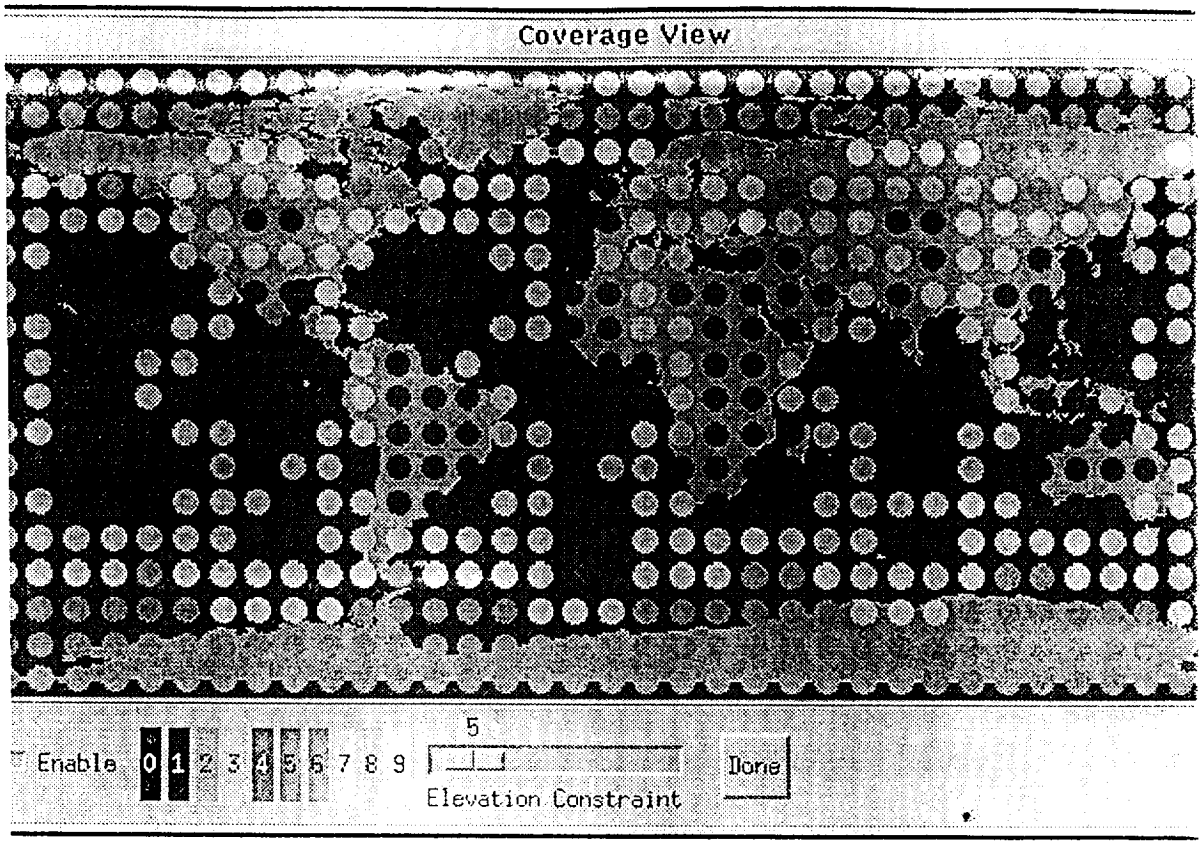

Figure 1.0 24 Satellite - 6 Satellites per Plane, 2000 km Altitude Configuration

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. 93-009 Addendum	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Addendum to the Proceedings of the Third International Mobile Satellite Conference IMSC'93		5. Report Date June 16-18, 1993 6. Performing Organization Code
7. Author(s) Compiled by R. Kwan and J. Rigley Edited by R. Cassingham		8. Performing Organization Report No.
9. Performing Organization Name and Address JET PROPULSION LABORATORY California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109		10. Work Unit No. 11. Contract or Grant No. NAS7-918 13. Type of Report and Period Covered JPL Publication
12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Washington, D.C. 20546		14. Sponsoring Agency Code RE4 BP-669-00-00-00-00

15. Supplementary Notes

16. Abstract

Satellite-based mobile communications systems provide voice and data communications to users over a vast geographic area. The users may communicate via mobile or hand-held terminals, which may also provide access to terrestrial cellular communications services. While the first and second International Mobile Satellite Conferences mostly concentrated on technical advances, this Third IMSC also focuses on the increasing worldwide commercial activities in Mobile Satellite Services. Because of the large service areas provided by such systems--up to and including global coverage--it is important to consider political and regulatory issues in addition to technical and user requirements issues.

The official Proceedings included approximately 100 papers presented in 11 sessions: the direct broadcast of audio programming from satellites; spacecraft technology; regulatory and policy considerations; hybrid networks for personal and mobile applications; advanced system concepts and analysis; user requirements and applications; current and planned systems; propagation; mobile terminal technology; modulation, coding and multiple access; and mobile antenna technology. This Addendum contains papers that were presented at the Conference but arrived too late to be included in the Proceedings, which was distributed at the Conference. In addition, this document contains the final attendee list for the Conference.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Aircraft communications and navigation Communications Methods and equipment (general) Logistics	Unclassified; unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	50	