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Proceedings of the Advanced
Communications Technology
Satellite (ACTS) Conference 2000

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Proceedings of the Advanced Communications Technology Satellite (ACTS) Conference 2000

Proceedings of a conference sponsored by
Istituto Internazionale delle Comunicazioni (IIC)
and held at the Renaissance Cleveland Hotel
Cleveland, Ohio, May 31, 2000

National Aeronautics and
Space Administration

Glenn Research Center

December 2000

Acknowledgments

I would like to thank those who contributed and helped make the last ACTS conference a success: those who presented papers, those who participated in the evening reception, and those who organized the myriad details and managed the event. Last but certainly by no means least, I would like to thank all those who attended.

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Introduction

Since the ACTS launch in September 1993 and the Experiments Program's beginning in December 1993, the ACTS project has made significant contributions to retiring the risk of advanced satellite communications technology. Conceived with an initial 2-year plan, the Experiments Program provided a forum for 103 experiments and many demonstrations that grew to cover a 78-month period. The ACTS Conference 2000 (AC2000) was held to report the results of the program since the 1995 ACTS Results Conference and celebrate the end of a very successful satellite program.

The conference was held on May 31, 2000, as part of the 6th Ka-band Utilization Conference (May 31 to June 2, 2000) in Cleveland, Ohio at the Renaissance Cleveland Hotel. The sponsoring organization was Italy's Istituto Internazionale delle Comunicazioni (IIC), which has sponsored all previous Ka-band Utilization Conferences. The NASA Glenn Research Center was the local host. The conference was an ideal venue in which to discuss the ACTS program as its technical program focused on next-generation satellite communications systems. Furthermore, the timing of the Ka-band conference coincided with the ending of the ACTS Experiments Program. Approximately 280 representatives of industry, academia, and government attended.

The conference was organized into two parts: a technical program during the day and an evening reception. The technical program consisted of 5 technical sessions that included 17 papers covering the results of the experiment activity and technical performance of the satellite. The written papers and presentations are included in these proceedings (except one paper and one presentation, which were not submitted; and one presentation was a video, for which we've included a brief summary).

In the evening, a reception was held to celebrate the end of the ACTS Experiments Program. The keynote address was provided by NASA's Associate Administrator for Space Flight, Joseph Rothenberg. Industry VIP's (Dr. Tom Brackey on behalf of the U.S. satellite industry, Edward Fitzpatrick on behalf of the Hughes Spaceway program, Jeffrey Grant on behalf of the Lockheed Martin Astrolink program, and Edward Ashford on behalf of SES-ASTRA) provided their perspectives on the significance and impact ACTS has had on the industry. The daylong event brought together many people from industry, academia, and government who have participated and benefited from ACTS. These proceedings were developed to capture the entire event, including the evening reception.

I'd like to thank those who contributed and helped make the last ACTS conference a success: those who presented papers, those who participated in the evening reception, and those who organized the myriad details and managed the event.

Last, but by no means least, I'd like to thank all those who attended!

Robert Bauer
ACTS Project Manager
NASA Glenn Research Center

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Wednesday, May 31, 2000

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Speakers: F. Marconicchio, *Agenzia Spaziale Italiana, Italy*
F. Gargione, *Analex Corporation, USA*
D. Campbell, *NASA Glenn Research Center, USA*
R. Bauer, *NASA Glenn Research Center, USA*

Session 1: ACTS System Results

Chairpersons: L. Ignaczak, *NASA Glenn Research Center, USA*
F. Gargione, *Analex Corporation, USA*

- 1.1 **The Advanced Communications Technology Satellite - Performance, Reliability and Lessons Learned**
R. Krawczyk, L. Ignaczak, *NASA Glenn Research Center, USA*
- 1.2 **ACTS Ka-Band Earth Stations: Technology, Performance and Lessons**
R. Reinhart, *NASA Glenn Research Center, USA*; S. Struharik, *COMSAT Laboratories, USA*; J. Diamond, *Analex Corporation, USA*; D. Stewart, *GTE Technology Organization, USA*
- 1.3 **T1 VSAT Fade Compensation Statistical Results**
S. Johnson, R. Acosta, *NASA Glenn Research Center, USA*

Session 2: ACTS Propagation

Chairpersons: R. Gedney, *Advanced Communications Technology, USA*
R. Acosta, *NASA Glenn Research Center, USA*

- 2.1 **Summary of the ACTS Propagation Experiments**
L. Ippolito, *ITT Industries, USA*; R. Bauer, *NASA Glenn Research Center, USA*
- 2.2 **Rain Attenuation Model Comparison and Validation**
C. Meyer, B. Jaeger, *University of Alaska Fairbanks, USA*
- 2.3 **Propagation Effects Handbook for Satellite Systems Design**
L. Ippolito, *ITT Industries, USA*
- 2.4 **Special Effects: Antenna Wetting, Short Distance Diversity and Depolarization**
R. Acosta, *NASA Glenn Research Center, USA*

Luncheon Address:

Astronaut Dr. J. Newman

Session 3: Advanced Applications

Chairpersons: F. Buzzard, *NASA Johnson Space Center, USA*
R. Bauer, *NASA Glenn Research Center, USA*

- 3.1 **Survey of Advanced Applications over ACTS**
R. Bauer, *NASA Glenn Research Center, USA*, P. McMasters, *Analex Corporation, USA*
- 3.2 **NASA/DARPA ACTS Project for Evaluation of Telemedicine Outreach using Next-Generation Communications Satellite Technology: Mayo Clinic Participation**
B. Khandheria, B. Gilbert, M. Mitchell, A. Bengali, *Mayo Clinic, USA*

- 3.3 ACTS Satellite Telemammography Network Experiments**
B. Kachmar, *Analex Corporation, USA*; R. Kerczewski, *NASA Glenn Research Center, USA*
- 3.4 Satellites and the Internet as a "Passport to Knowledge": A New Model of Teaching and Learning**
G. Haines-Stiles, *Passport to Knowledge, USA*
- 3.5 Advanced Shipboard Communications Demonstrations with ACTS**
R. Axford, *Space and Naval Warfare Systems Center, USA*; T. Jedrey, *Jet Propulsion Laboratory, USA*; M. Rupar, *Naval Research Laboratory, USA*

Session 4: Protocol Enhancements and Interoperability

Chairpersons: K. Bhasin, *NASA Glenn Research Center, USA*

- 4.1 A History of the Improvement of Internet Protocols over Satellites using ACTS**
M. Allman, *NASA Glenn Research Center/BBN Technologies, USA*; H. Kruse, S. Ostermann, *Ohio University, USA*
- 4.2 Mobile Internet Protocol Performance and Enhancements over ACTS**
D. Johnson, B. Bennington, *Carnegie Mellon University, USA*
- 4.3 NASA and Industry Benefits of ACTS High Speed Network Interoperability Experiments**
M. Zernic, *NASA Glenn Research Center, USA*; D. Beering, D. Brooks, *Infinite Global Infrastructures/LLC, USA*
- 4.4 Global Interoperability of High Definition Video Streams via ACTS and Intelsat**
E. Hsu, *Jet Propulsion Laboratory, USA*; N. Kadowaki, *Communications Research Laboratory, Japan*

Session 5: Future NASA Glenn Plans in Space Communications

Chairperson: R. Bauer, *NASA Glenn Research Center, USA*

- 5.1 Partnering to Change the Way NASA and the Nation Communicate Through Space**
P. Vrotos, J. Budinger, K. Bhasin, D. Ponchak, *NASA Glenn Research Center, USA*

Evening Reception

Opening Remarks:

Gerald Bama, *Acting Deputy Director, Glenn Research Center, USA*

Keynote Address:

Joseph H. Rothenberg, *Associate Administrator for Space Flight, NASA, USA*

Industry Perspectives on ACTS:

Dr. Thomas Brackey, *Hughes Space & Communications representing the TIA Satellite Communications Division*

Edward Fitzpatrick, *Hughes Network Systems, representing Spaceway, USA*

Jeffrey Grant, *Astrolink, USA*

Ed Ashford, *SES-ASTRA, Belgium*

ACTS Shutdown Ceremony Video

Reception

Technical Program Presentations

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1.1 - The Advanced Communications Technology Satellite: Performance, Reliability and Lessons Learned

R.J. Krawczyk
NASA Glenn Research Center
Cleveland, Ohio

L.R. Ignaczak
NASA Glenn Research Center
Cleveland, Ohio

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio



Outline of Presentation

- ACTS Background
- Satellite Subsystem Operational Performance
including lessons learned
- Reliability discussion
- Concluding Remarks
- ACTS Disposal comments



Glenn Research Center

ACTS Background

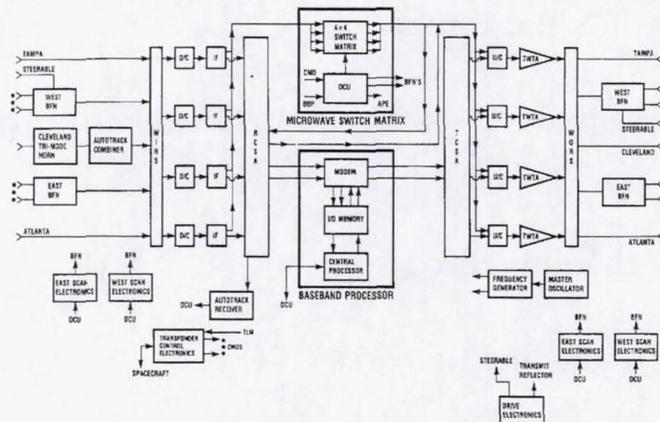
- US Congress sponsored NASA to conduct ACTS program in 1984 to pioneer technologies and services envisioned for future commercial application.
- Ka band - components and rain fade compensation
- Spot beam antennas with multiple hopping beams
- On-board processing and microwave switching
- Wideband transponders
- Objectives: Demonstrate, verify and characterize technology for comsats and evaluation of Ka band systems.
Provide a reliable GEO experimental testbed.
- Original 2-year mission extended twice to take advantage of excellent performance of hardware.



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Ka-Band Payload Operational Performance

- Over 58,000 hours on orbit without failure.



- 590 power/thermal cycles on communications payload subsystems (battery sized for bus only during eclipse).
- Versatile switching and multiple daily payload reconfiguration allows efficient, flexible scheduling of experimenters/users.



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Successful Ka-Band Comsat Technology

30 GHz Low Noise Receivers

- Four LNRs. HEMT LNA with 3.8 dB noise figure at antenna. Down converts to C band IF amp. Good configuration for production since 30 GHz, 900MHz bandwidth LNA needed new methodology in manufacturing, alignment and test.

20 GHz Transmitters

- Each (of 4) upconverter/TWTA provides 46 w. output, from 19.2 - 20.1 GHz.
- Almost 200K total tube hours accumulated.
- No spurious shutoffs after 590 power/thermal cycles proves robust hi-voltage and thermal package design.
- Extensive telemetry instrumentation (Pin, Po, Vk, Ik, Va, Ihtr, Ihlx) shows excellent stability - many parameters within one count (of 256) of original value.
- Original concept was dual power TWTA for rain fade - insignificant net advantage due to weight and efficiency per 1988 study.

Beacons

- 20 and 27.7 GHz beacons provide reliable signals for long term propagation studies.
- Primary TT&C at Ka band but C band backup used for omni contingency coverage.



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Successful Ka-Band Comsat Technology

Multi-beam Antenna (MBA)

- 48 high gain, 0.3° spot beams - enable frequency reuse, small terminals and high data rates.
- High speed hopping beams (ferrite switched) enable TDMA networks.
- Thermal and mechanical effects peculiar to ACTS design and materials evaluated:
 - Diurnal thermal distortion effects on Rx subreflector and Tx reflector compensated by routine daily procedures. Shows need for comprehensive thermal model at other than max temperature gradients and extremes.
 - Low level, 1-Hz on downlink attributed to pitch control impulses exciting Tx reflector resonance. Negligible effect at beam center. Shows need for low frequency dynamic analysis.
- One meter steerable beam reflector (SBA) has enabled links, from Antarctica to Arctic Circle, to fixed, airborne and shipboard terminals. Manual peaking can assure users of max signal - point by shaft position telemetry plus command step count.

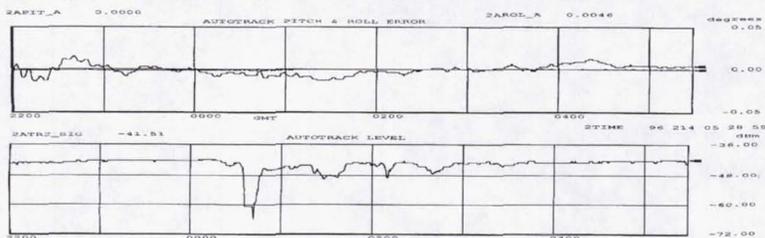


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Attitude Control for Spot Beams

Attitude Determination

- Narrow spot beams require more precise pitch/roll pointing ($\pm 0.025^\circ$).
- RF autotrack system using command carrier provides error signals over 22 dB fade depth.



- Temporary switch to less precise Earth Sensor compensates for 0.1° autotrack transients during MBA subreflector thermal distortion periods. Autotrack sensitive to antenna construction and materials, needs non-RF backup.
- Yaw requirement ($\pm 0.15^\circ$) implemented by sun sensors and yaw estimator. This method can be operator intensive to regain estimator convergence during geomagnetic storms.

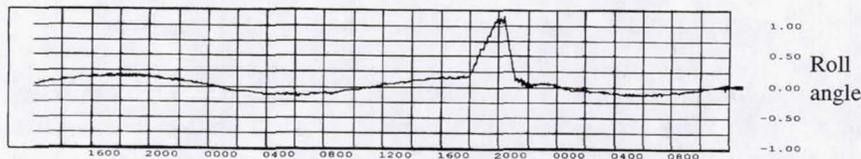


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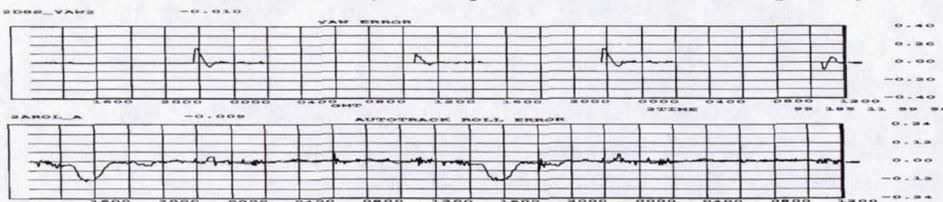
Attitude Control

Attitude Control

- Excellent pitch control ($< 0.01^\circ$) maintained by quick reacting momentum wheel.
- Roll and yaw controlled by less responsive magnetic torquer - simple devices but have relatively slow time constants and can saturate during large geomagnetic storms.



- For Inclined Orbit operation: attitude processor reprogrammed to execute autonomous momentum axis bias, and roll and yaw compensation to maintain MBA pointing.



- Inclined orbit has not introduced perceptible degradation to beam pointing



Successful Ka-Band Systems Technology

Baseband Processor (BBP) Mode

- On-board BBP provides single hop, full mesh, bandwidth-on-demand to T1 VSAT network.
- Adaptive compensation is a complex process but adds 10 dB margin to enhance availability in those spot beams experiencing rain fade, for 5.0E-7 BER or better.
- No hard failures of memory or processing after 590 power/thermal cycles.
- Occasional Single Event Upset may occur but is near imperceptible.

Microwave Switch Matrix (MSM) Mode

- 4X4 crossbar switch provides static or dynamic connection of any uplink to any downlink.
- Unique features include 16 GaAsFET switch/amplifier modules with 1 GHz IF bandwidth, 1000 states/frame and control of spot beams.
- Routinely enables connectivity for Ka-band technology experiments with mobile or propagation terminals, service demonstrations from 0.6 m. USATs and 155 to 622 Mbps SS-TDMA interconnection of fiber networks.

Pre-launch Full Systems Test

- End-to-end test done to verify system integrity and interface compatibility.



Providing a Reliable Experimental Comsat

Reliability Modeling

- Used during design process to assure adequate performance and identify areas of risk.

Mode	Probability of Survival (Ps)	
	At 2 years	At 4 years
Full BBP/VSAT capability 36% duty cycle	0.77	0.55
Full BBP/VSAT capability 100% duty cycle	0.45	0.16
Half BBP/VSAT capability 100% duty cycle	0.66	0.33
Partial T1 VSAT capability 100% duty cycle Timeshare mode	0.74	0.41
3 Beam MSM 36% duty cycle	0.95	0.88

Almost 60K hours with no failures of payload

Robust Product Assurance Program

- Highest quality parts or upgrade screening
- Radiation hardness analysis plus testing where necessary
- Accelerated life testing from RF chips to hybrid modules to TWTA
- Accepting cost/schedule impact to replace questionable devices
- Final end-to-end polarity verification

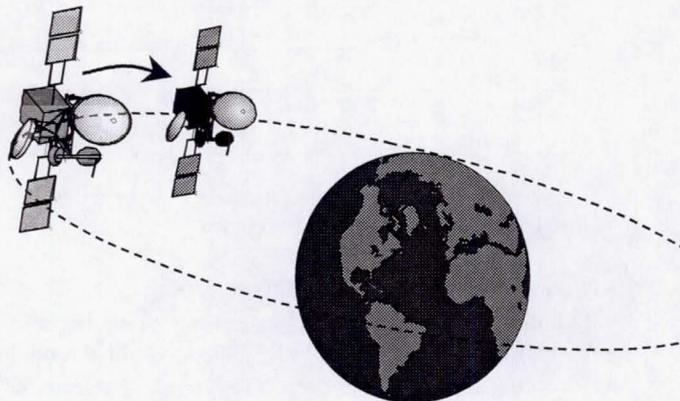
ACTS - A Well-Executed Program

Concluding Remarks

- Although an experimental satellite, the reliability and product assurance efforts were an integral part of the program.
- The Ka-band components and satellite communications concepts implemented by ACTS have operated without failure or loss of capabilities for over 6.5 years and almost 600 power/thermal cycles.
- ACTS has successfully continued experiment operations including Ka-band spot beam pointing and autotracking into inclined orbit.
- The capabilities of a versatile Ka-band satellite test bed and earth stations and a dedicated project team has enabled ACTS to evolve with advancing technologies of fiber, networks and terminals to continue its unique contributions to the satellite industry.

ACTS Retirement

- Move spacecraft to orbital gravity well at 105.2°W starting mid-June.
- Coordinate fly-by with commercial operators.
- 35 days to arrive at 105.2 °W
- Monitor spacecraft for 2 months
 - Settle into well - minor adjustments if needed
- Inert all energy sources on spacecraft ~9/21/00



1.2 - ACTS Ka-Band Earth Stations: Technology, Performance, and Lessons Learned

Richard C. Reinhart
NASA Glenn Research Center
Cleveland, Ohio

John. J. Diamond
Analex Corporation
Brookpark, Ohio

Steven J. Struharik
COMSAT Laboratories
Clarksburg, Maryland

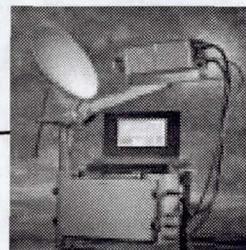
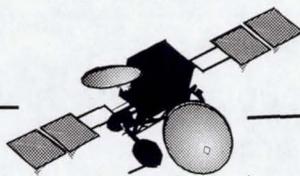
David Stewart
GTE
Cleveland, Ohio

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

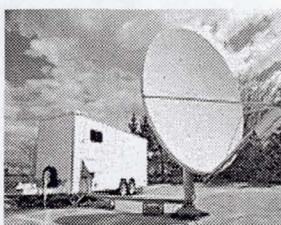
ACTS Ground Stations



1.2 m VSAT



0.35/0.6m USAT



3.4 m HDR



5.5 m NASA
Ground Station



4.7 m Link Evaluation
Terminal



Transmit - 1st Generation TWTA

- **Design & Performance (NGS & LET)**
 - 60 Watt helix type TWT's
 - RF power fluctuations degraded link
 - Low reliability/spontaneous shut down/high helix current
 - Removed from service after 7,000-10,000 hours
- **Lessons Learned**
 - Tube redesign minimized RF "ticks"
 - Insulation, material, and wire changes
 - Operation procedure changed
 - Limited standby operation
 - RF drive always applied
 - Extended 2nd Generation TWT life to > 20,000 hrs



3

Transmit - 2nd Generation TWTA

- **Design & Performance**
 - 100-200 Watt coupled cavity and helix TWT's
 - Overall performance good
 - High failure rate of outdoor installed TWT (HDR)
 - Water penetrating connectors
 - High voltage shorts
 - TWT defocus due to temperature
- **Lessons Learned**
 - Commercial design improvements continued
 - Material change, precision tolerances, delay line stability
 - Increased TWT lifetime to 20,000-30,000 hours
 - Operational procedure different for HDR TWT's
 - Low duty cycle



4

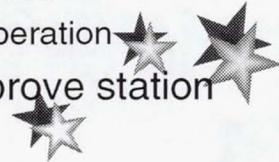
Transmit - VSAT

- **Design & Performance**

- Combined 40W Ku-Band TWT and frequency doubler
- HPFD located near feed in separate housing from TWT
- Ku-Band TWT achieved ~ 30,000 hours
- Low high power frequency doubler reliability
 - RF fluctuations from TWT damage diodes over time

- **Lessons Learned**

- Issues with high power frequency doubler configuration
 - Difficult to maintain stable external dc voltage bias
 - Redesigned for self biasing diodes and CW operation
- Operations data enabled personal to improve station availability

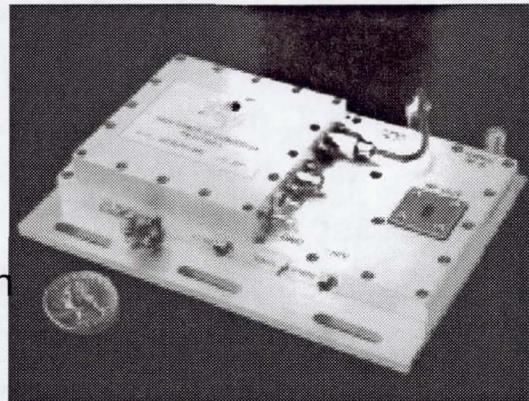


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Transmit - USAT/SSPA

- **Design & Performance**

- Small integrated block upconverter & SSPA
- Advancements from 0.25W to 2W MMIC amplifiers
- Good performance
- Commercial advancements in integration



- **Lessons Learned**

- Low and medium power SSPA's available but.....cost, size, efficiency, & lead time



6

Receiver/LNA

Station	Gain (dB)	NF (dB)	Lessons Learned
NGS (20 GHz) (27 GHz)	30 20	3 4.5	HEMT LNA – Good performance, long life
LET (LNB) (LNA only)	25 50	4-5.5 3.5	Prototype/POC High gain, wider BW, good performance
HDR	50	3.5	High gain, wide BW, good performance
VSAT (LNB)	45 ± 5	5 ± 2	Wide range of performance
USAT (1 st Gen) LNB (2 nd Gen)	26 32	4.5-5 2-2.5	Advancements in NF enabled higher rate links



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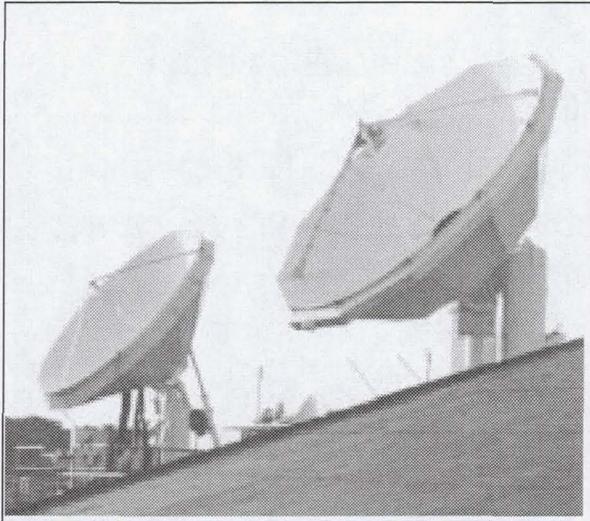
Antenna - Field Stations

- **Design & Performance**
 - Parabolic offset-fed reflectors
 - Ku-Band commercial reflectors proved adequate for Ka-Band operation
- **Lessons Learned**
 - Recommend design changes to reduce wet antenna effects
 - Losses due to water coverage and dielectric thickness
 - Panel design for 3.4m antenna. Surface tolerance and alignment sufficient at Ka-Band.



8

Antenna - Gateway Stations



LET

NGS



- Cassegrain
- LET - Center feed/hub mounted electronics
- NGS - Beam waveguide/ indoor electronics
- Cost/benefit analysis
- Thermal distortions caused by deicer heaters



9

VSAT/NGS Modem/Network

- Design (SMSK)
 - Custom TDMA 27.5/110 Mbps burst modem
 - Automatic rain fade mitigation (network)
 - half-rate burst rate reduction with FEC
 - no impact or data rate reduction to user (T1)
- Lessons Learned
 - Most problems were low-tech: ps & fans
 - Only anomaly - sensitive to long strings of 1's or 0's. Corrected with S/W mod
 - Burst modems difficult to troubleshoot



Modems (cont)

- **HDR (O-BPSK, O-QPSK)**
 - Custom made SS-TDMA 384/696 Mbps burst modem with SONET interface
 - Four channels of OC-3 or single OC-12 throughput
 - Key technologies: fast acquisition circuitry & carrier & clock recovery functions
 - Simplify modem and digital electronics interface
- **USAT (BPSK, QPSK)**
 - Commercial variable rate (kbps to 45 Mbps) modems
 - Various serial & network interfaces
 - Diagnostics built-in, Good reliability

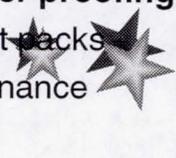


11

VSAT Design



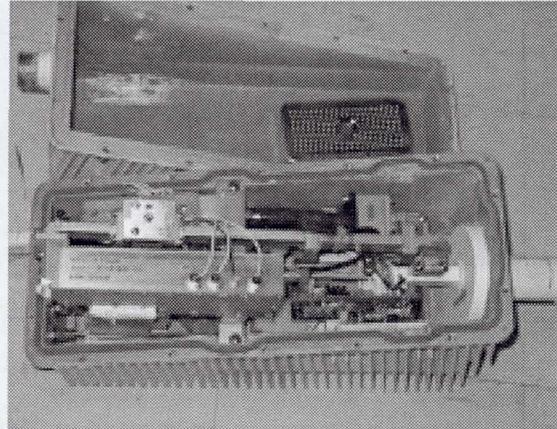
- **Extensive remote capability to monitor station (Eb/No, U/L BER, D/L BER, call parameters)**
- **Load and configure station by dial-up access or by satellite link**
- **VSAT RF enclosure**
 - Heat from HPFD effected surrounding electronics
 - Moisture damage to LNC
- **RF enclosure weather proofing**
 - Replace desiccant packs
 - Feed horn maintenance
 - Gaskets & seals



12

VSAT Recommended Modifications

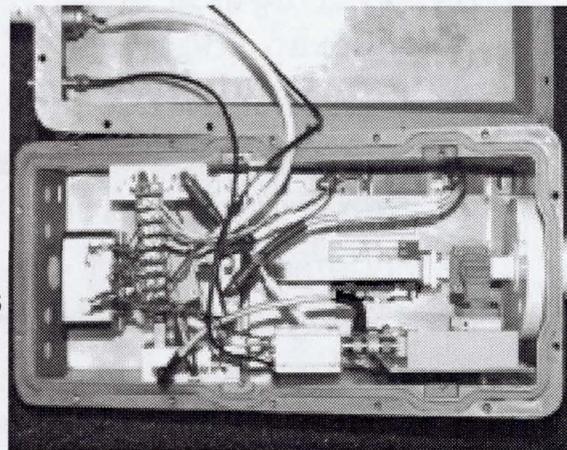
- Add RF test points and IF or RF loopback capability (relied upon TDMA network for troubleshooting)
- Move HPFD to TWT enclosure
 - Protection circuitry for RF fluctuations
 - Eliminate heat issues within enclosure
 - Adds additional WG losses
- Use Ka-TWTA or SSPA transmit @ 12-14 Watt



13

USAT Design

- Single electronics package
- Indoor equipment - COTS modem and antenna controller provided status & control & IF loopback capability
- Limited station diagnostics by design to reduce cost and size
- 70 MHz interface



14

USAT Recommended Modifications

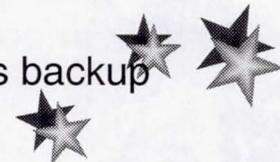
- **Reduce part count through RF design**
 - Common oscillator frequency
 - Single stage u/c
- **Reduce terminal size**
 - Integrated power supply (from indoor equipment)
 - Continued technical advancements
- **Add monitor/test points for field service**
 - oscillator lock indicator
 - output power detector
 - power supply indicator
 - RF test ports



15

HDR Design

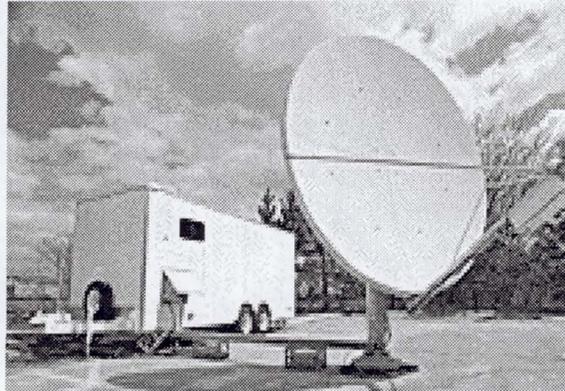
- **Used waveguide equalizers to compensate for long waveguide runs**
 - TWT mounted at antenna feed
- **High rate QPSK performance degraded by hard limiting channel & spectral re-growth**
 - Modems modified for O-QPSK, O-BPSK
- **Any station could serve as reference terminal**
- **Only station to use Internet for routine remote control & status**
 - Used dial-up and satellite link control as backup
 - Security/availability



16

HDR Recommended Modifications

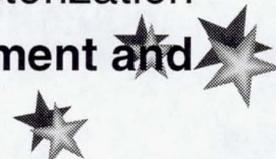
- Reduce waveguide runs to reduce group delay effects
- Strengthen antenna mount/platform or add tracking
 - Fixed mount required periodic re-pointing
- Add RF loopback to characterize station performance



17

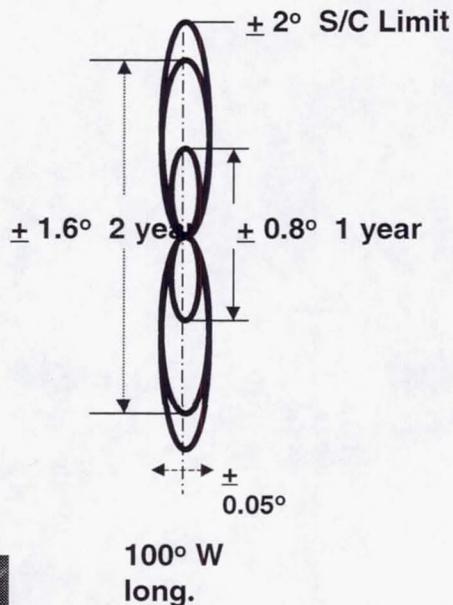
Gateway Station Design

- Extensive diagnostic capability proved invaluable
 - IF & RF station loopback
 - Built-in test equipment
 - satellite simulator
 - modem STE
 - Pre-launch testing and check-out
 - On-orbit troubleshooting & characterization
- Validated need for stable environment and electrical power

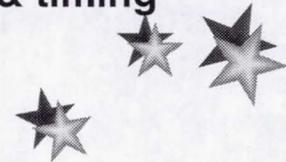


18

Inclined Orbit



- Satellite drift in N/S direction increasing by $\sim 0.8^\circ$ per year
- Maintain East/West station keeping at $+ 0.05^\circ$
- Impacts antenna tracking & TDMA acquisition & timing



19

Inclined Orbit - Ground Station Modifications

- All stations used combination of closed loop tracking and memory track
- Antenna step tracking added to all field stations
 - Commercial controller
 - I/O mounts designed & fabricated in-house
- Modifications made to VSAT & HDR TDMA acquisition & timing s/w

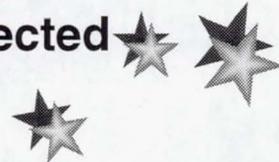


20



Inclined Orbit - Lessons Learned

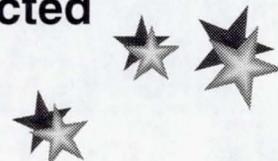
- **Step/incremental actuators proved adequate for field station antennas < 3.4m**
- **2-axis mount and closed-loop tracking with memory track proved successful**
- **Open-loop tracking evaluated/rejected**
 - periodic updates to controller
 - earth station position accuracy/stability
- **Single axis tracking evaluated/rejected**
 - installation & accuracy concerns



21

Inclined Orbit - Lessons Learned

- **Step track proved sufficient for Ka-Band operation.**
 - Both field and gateway earth stations
 - Fade variations affect tracking
 - Compensate with fade thresholds, fade rates, memory track
- **HDR/VSAT experienced acquisition problems late in program as expected**
 - Affected by range rate



22

Summary

- **Technology/Performance**
 - Highlight Ka-Band technology enabled by ACTS
 - Highlight commercial advancements of SOA
 - TWTA, HPFD/Receiver/Modems/Antenna
- **Full report in NASA publication:**
 - Station integration/operations & lessons learned
 - Inclined Orbit Operations
 - Available at Ka-Band Conference

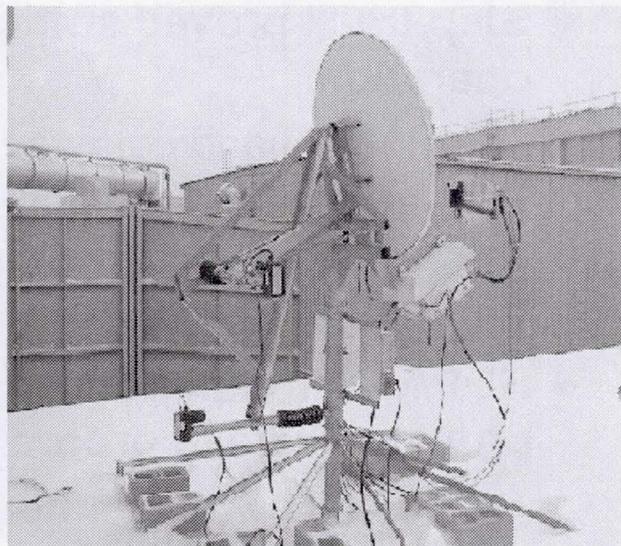


23

Inclined Orbit - VSAT Mount Modifications



Fixed Mount

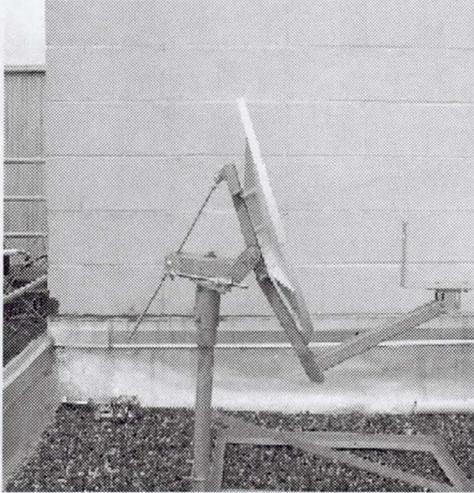


IO Mount

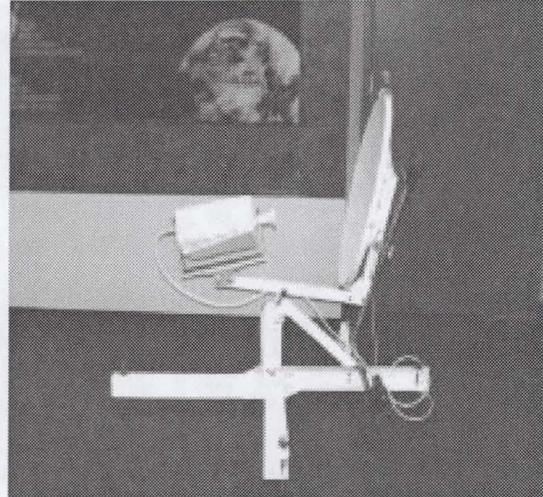


24

Inclined Orbit - USAT Mount Modifications



Fixed Mount



IO Mount

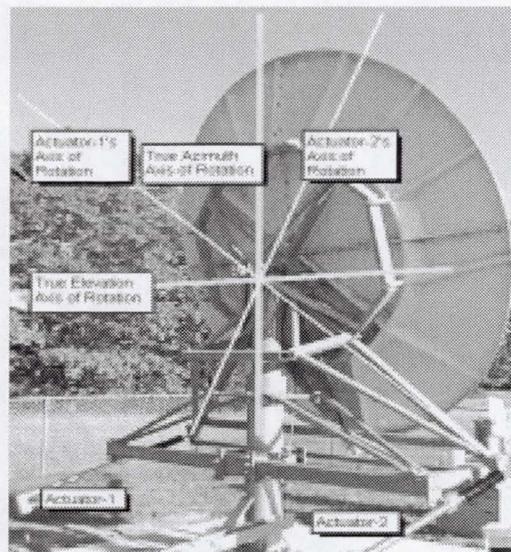


25

Inclined Orbit - HDR Mount Modifications



Fixed Mount



IO Mount



26

ACTS Ground Stations

NAME	MODE	ANTENNA (m)	HPA (Watt)	EIRP (dBW)	G/T (dB/K)	BURST RATES (Mbps)	DATA RATES (Mbps)	MODULATION
NGS	BBP	5.5	200	78	30	U/L: 27.5 or 110 D/L: 110	64 kbps to multiple T1 & T2	SMSK
VSAT	BBP	1.2, 2.4	12	60, 66	16-18	U/L: 27.5 D/L: 110	1.792 (max)at 64 kbps increments	SMSK
USAT	MSM	0.6, 1.2	.25, 1.0, 2.0	35-51	15, 21	Up to 2.5 Mps	U/L: low kbps to 8 Mbps D/L: up to 45 Mbps	BPSK, QPSK, CDMA
HDR	MSM	3.4	120	76	28	Up to 696	311 or 622 Mbps	O-BPSK (OC-3) O-QPSK(OC-12)
LET	MSM	4.7	100	78	27	Up to 696	low kbps to 622 Mbps	BPSK, QPSK, SMSK



1.3 - T1 VSAT Fade Compensation Statistical Results

Sandra Johnson
NASA Glenn Research Center
Cleveland, Ohio

Dr. Oke Ugweje
University of Akron
Akron, Ohio

Dr. Roberto Acosta
NASA Glenn Research Center
Cleveland, Ohio

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

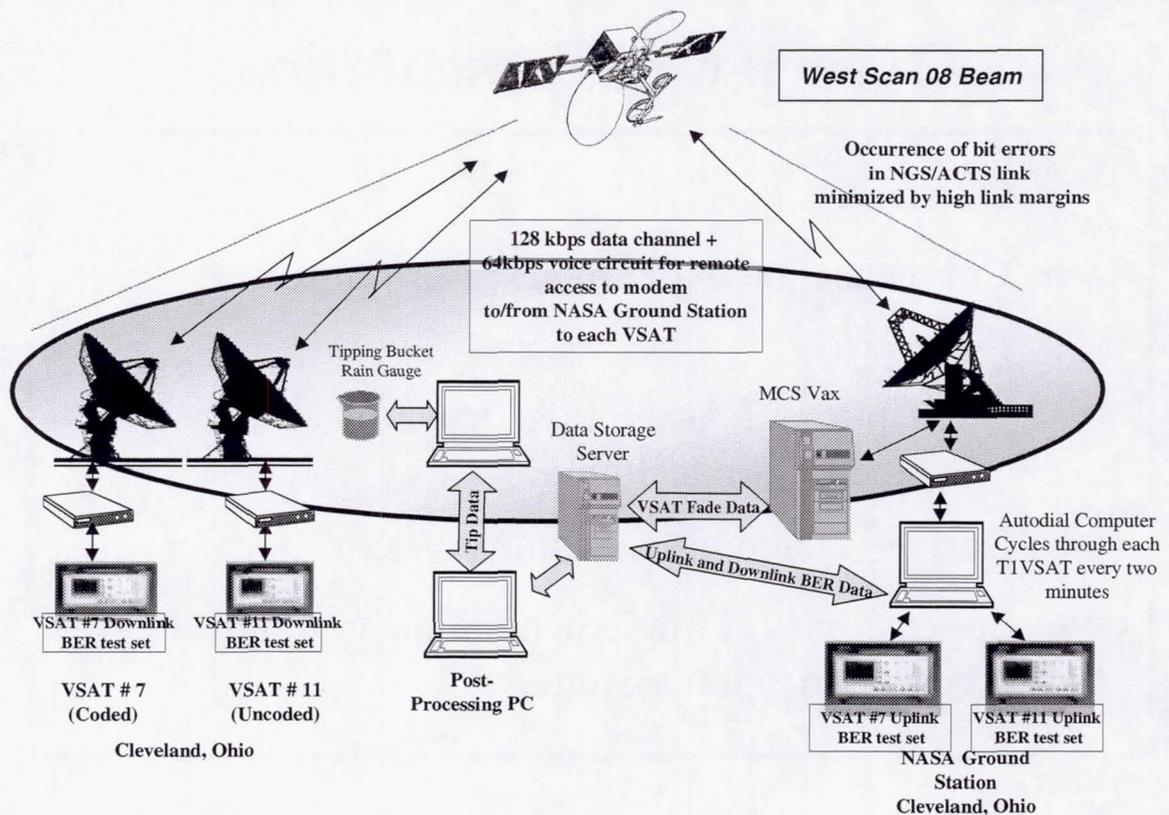
Overview of Presentation

- ➔ Objective
- ➔ Compensation experiment description and analysis
- ➔ Description of ACTS fade detection and compensation technique
- ➔ Derived technique for future system analysis
- ➔ Suggestions for implementations on future communication systems

Objective

- Perform a statistical investigation and validation of the rain fade detection and compensation algorithm in an end-to-end Ka-band satellite system
- Provide analysis and results from this investigation
- Develop an algorithm to determine the impact of data compensation techniques, which can be used for future system analysis

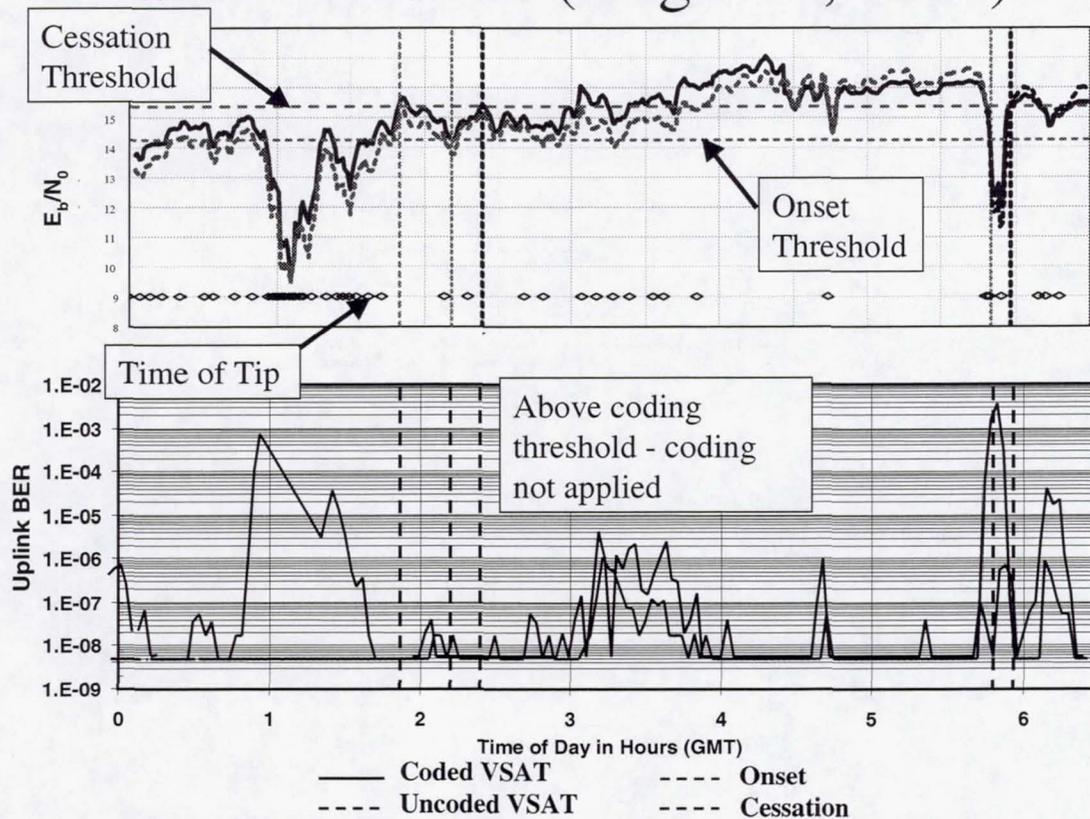
Compensation Experiment Hardware Connectivity



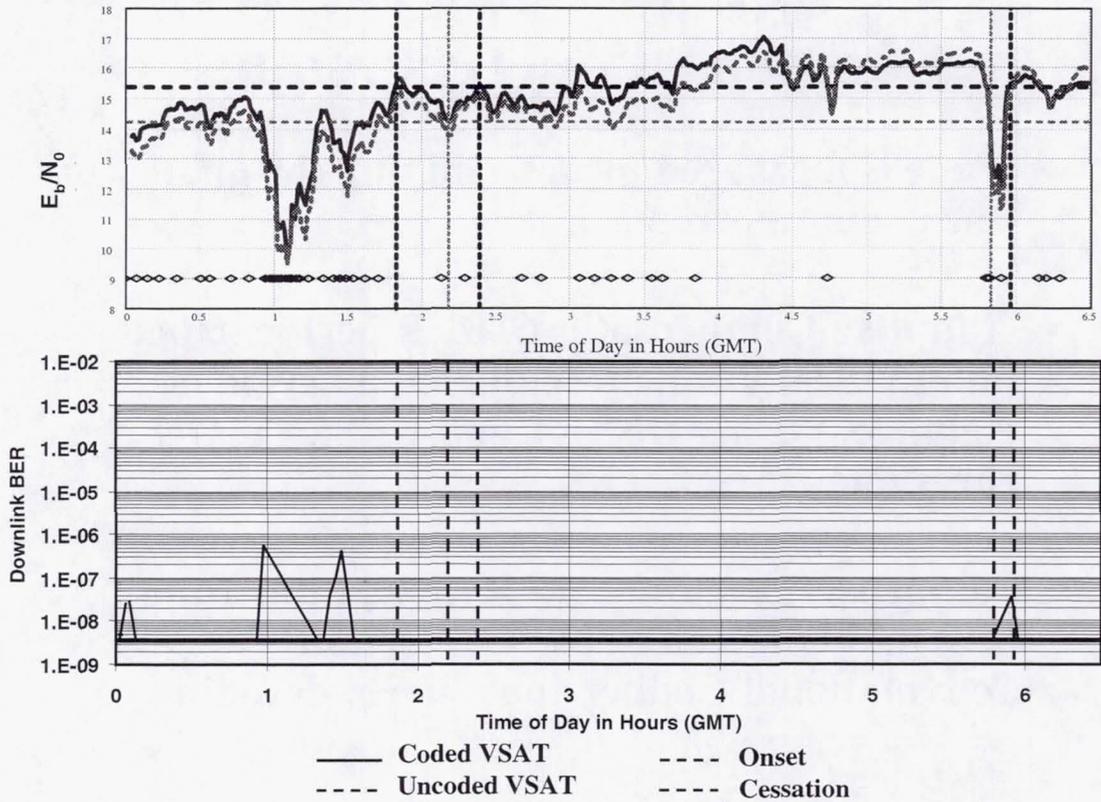
ACTS Fade Detection and Compensation Techniques

- Fade is measured by determining the quality of the communications link
- Adaptive Compensation: BER performance automatically enhanced during a period of signal loss using ONSET and CESSATION thresholds
- Compensation Protocol: Rate $\frac{1}{2}$, Constraint Length 5 Forward Error Correction Convolutional Coding and Viterbi decoding

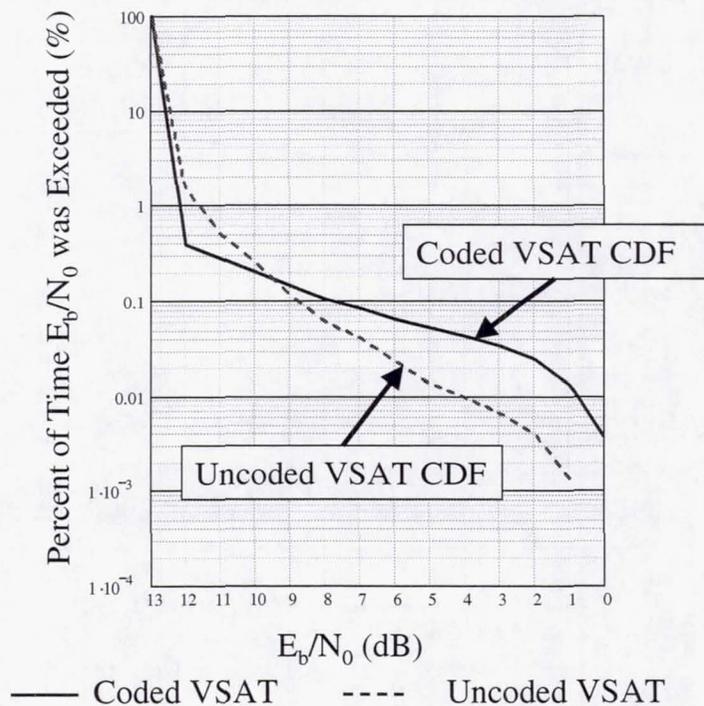
Rain Fade Event (August 8, 1999)



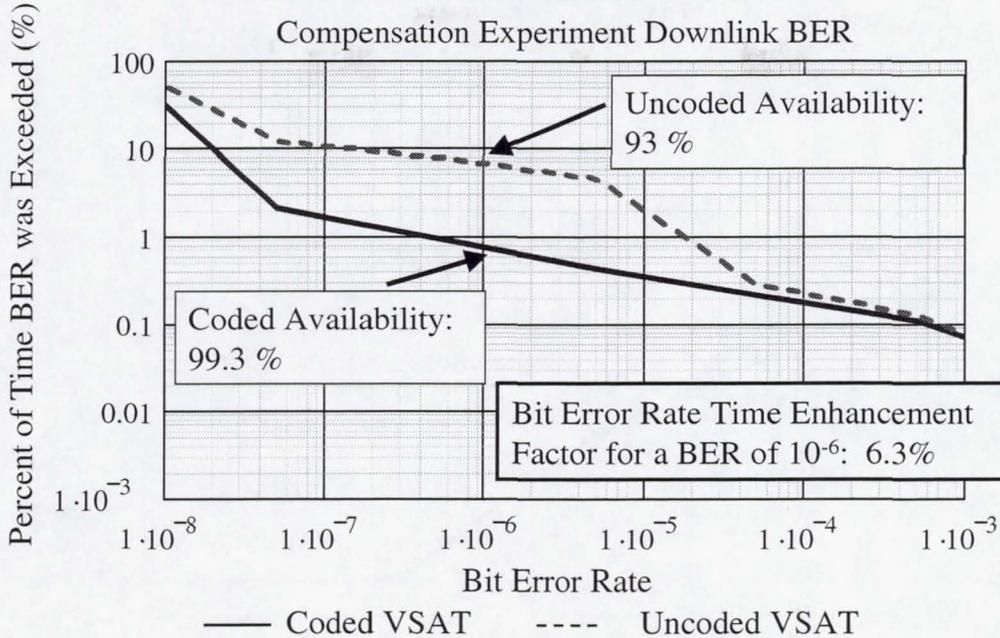
Rain Fade Event (August 8, 1999)



Compensation Experiment Statistical Results

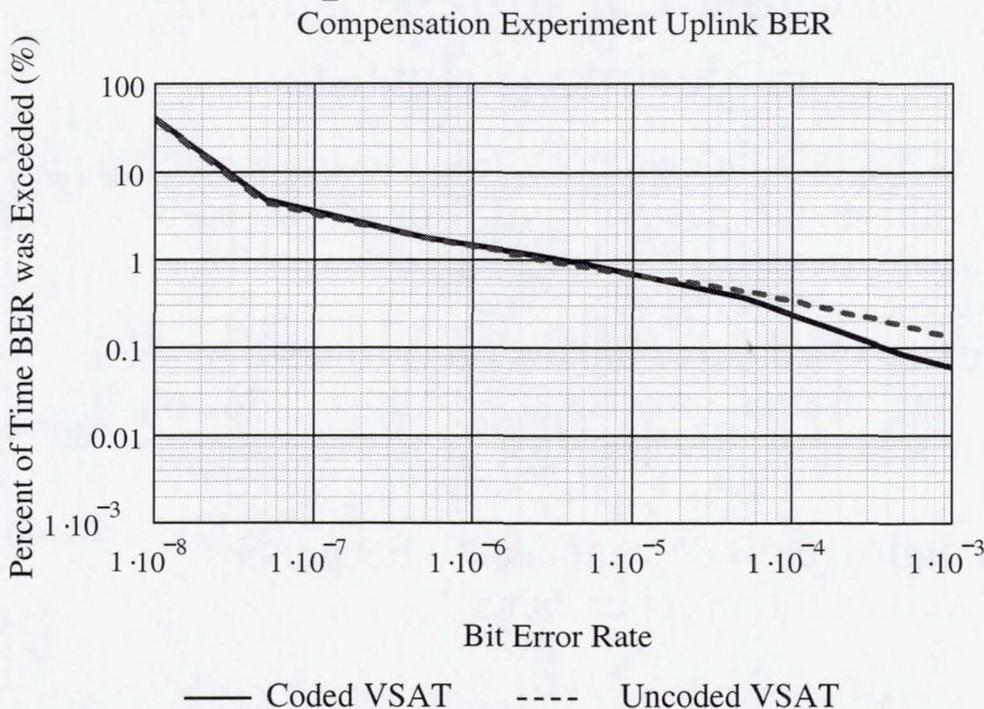


Compensation Experiment Downlink BER CDF

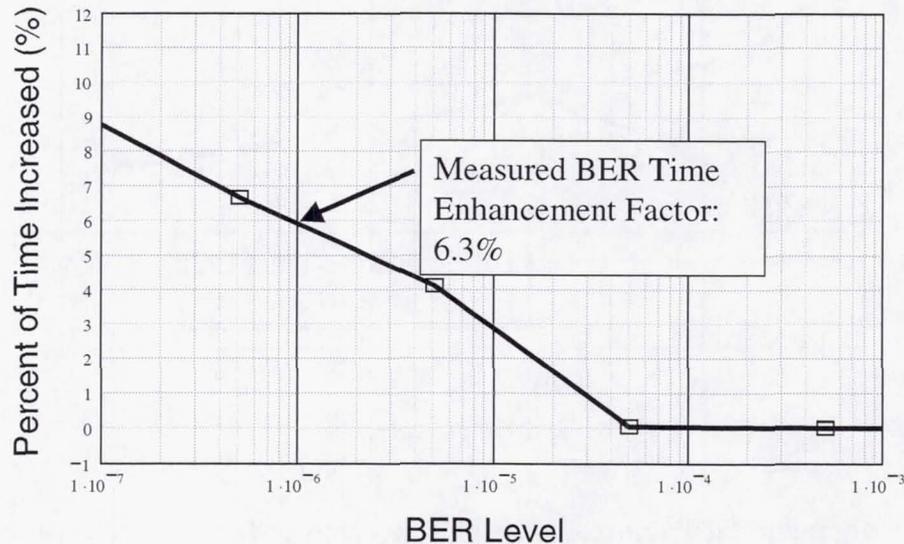


BER Time Enhancement Factor: Additional percent of time which a coded link will maintain or exceed a given BER level over a link system that is not coded.

Compensation Experiment Uplink BER CDF



Measured BER Time Enhancement Factor for the Compensation Experiment



Summary of Compensation Experiment Results

- ACTS rain fade compensation technique complies with design specifications with no observed anomalies
- 10 dB of adaptive link margin provided by data compensation provides 6% additional downlink BER availability at a BER of 10^{-6}
- Margins (3 dB downlink and 5 dB uplink) adequate for most rain fades.

Derived Technique for Future System Analysis

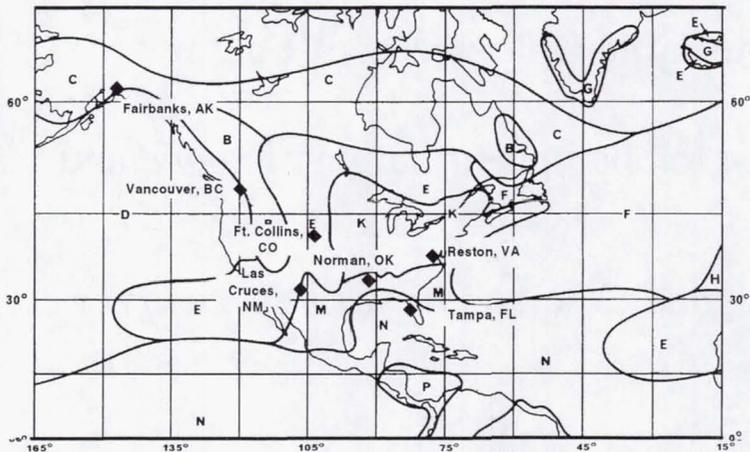
Bit Error Rate Time Enhancement Factor

- ⇒ Measured: Need to obtain distribution of *coded* and *uncoded* BER
- ⇒ Derived: Using *fade CDF* and *performance curves*

Input to Derived Technique for Computing BER Time Enhancement Factor

- Measured or model data of the fade CDF
- Link calculation for clear sky E_b/N_0
- Probability of error for coded and uncoded modulation scheme (through equation or simulation)

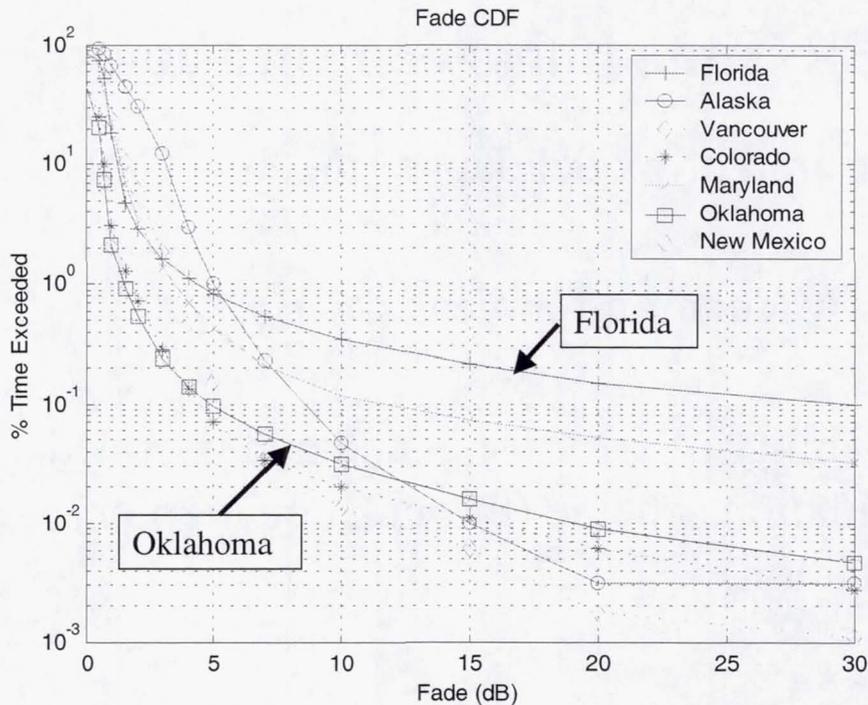
BER Time Enhancement Factor Simulation Example



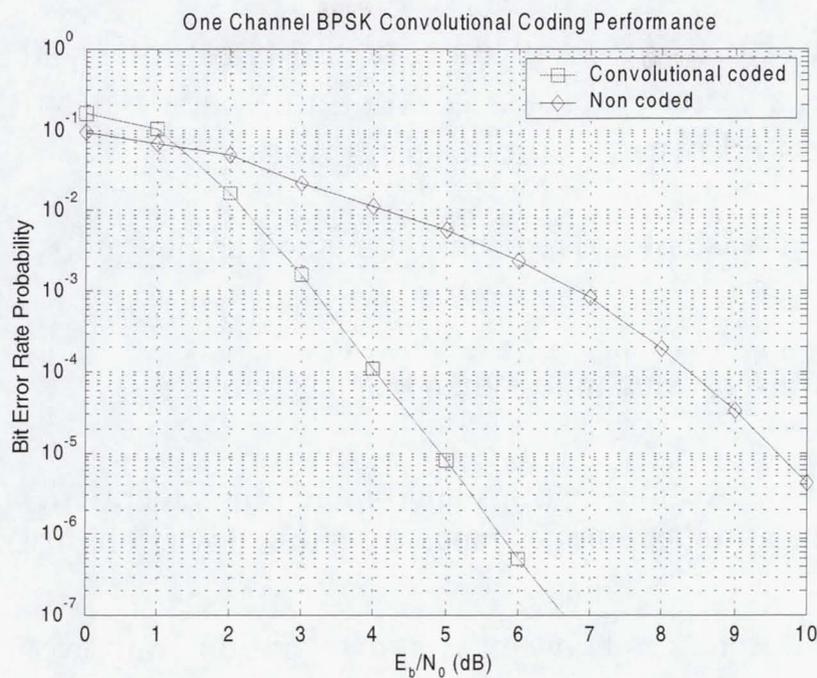
Location of 7
ACTS Propagation
Terminals for the
ACTS Propagation
Campaign

Location	ITU-R Rain Zone	Lat. (North), deg.	Long. (West), deg.	Az. From North, deg	Path Elevation deg.
Vancouver, BC	D	49	123	150	30
Ft. Collins, CO	E	40	105	173	43
Fairbanks, AL	C	65	148	129	9
Reston, VA	K	39	77	214	39
Las Cruces, NM	M/E	32	107	168	51
Norman, OK	M	35	97	184	49
Tampa, FL	N	28	82	214	52

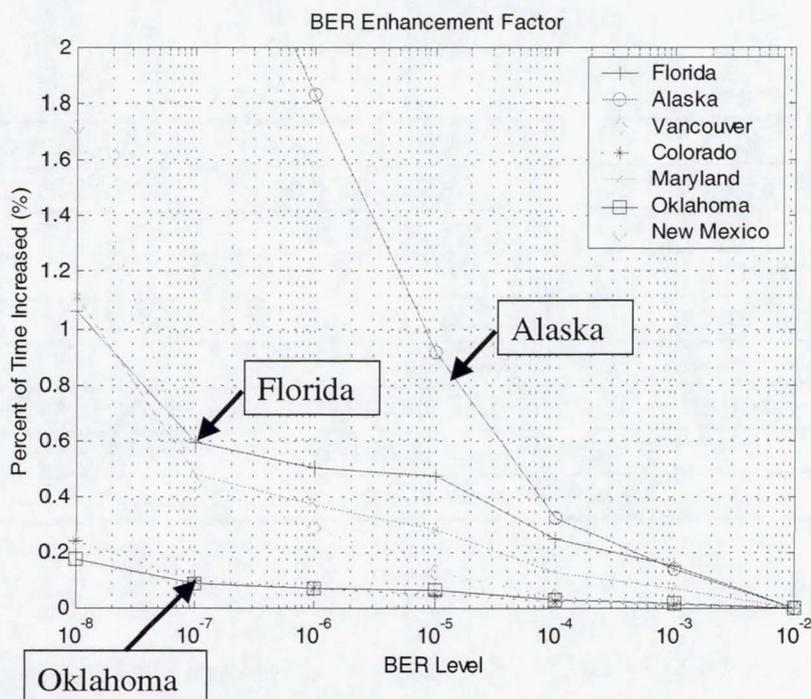
Fade CDF for Simulation Example



Performance of Uncoded and Coded BPSK



BER Time Enhancement Factor Results for Simulation Example



Suggestions for Implementations on Future Communication Systems

Suitable for use in future proposed Ka-band systems such as Teledesic, Astrolink, and Spaceway with suggested improvement techniques:

- Insure consistent E_b/N_0 detection method among units for mass production
- Detect E_b/N_0 value in less than 0.25 seconds
- Optimize threshold settings and/or add other adaptive compensation techniques (such as uplink power control)
- Detect differences between system events and rain events

T1 VSAT Operational Features

Uplink Burst Rate:	27.5 Mbps uncoded	13.5 Msps coded
Downlink Burst Rate:	110 Mbps uncoded	55 Msps coded
Antenna size:	1.2 m or 2.4 m	
Transmit Power:	12 W	
Uplink Frequency:	29.236 GHz and 29.291 GHz	
Downlink Frequency:	19.440 GHz	
Modulation Format:	Serial Minimum Shift Keying (SMSK)	
Power frequency doubler with Ku-band TWTA		
Dialable bandwidth on demand		

Summary of Compensation Experiment Results

- Limitations of ACTS technique and experiment setup restrict measurable results
 - Limited dynamic range of T1 VSAT
 - 1 minute averaging of fade vs. 2 minute averaging of BER
 - Inaccuracies of E_b/N_0 detection and estimation process
 - Uplink E_b/N_0 not measured
 - Thresholds optimized for downlink
 - BER downlink collection method via satellite

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2.1 - Summary of the ACTS Propagation Experiments

Louis J. Ippolito
ITT Industries
Advanced Engineering & Sciences
Ashburn, Virginia

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

Topics

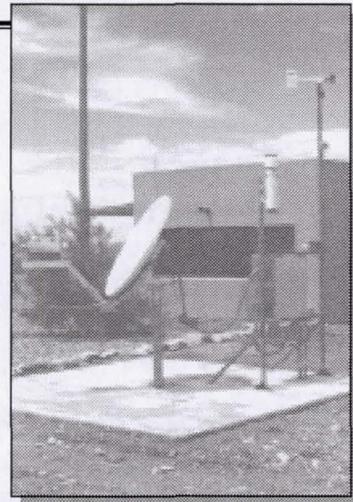
- Overview of ACTS Propagation Measurements Program**
- Major Results and Accomplishments**
 - **Link Availability**
 - **Rain Attenuation Modeling and Prediction**
 - **Scintillation Effects**
 - **Wet Surface Effects**
 - **Rain and Ice Depolarization**
- Summary**

Advanced Communications Technology Satellite (ACTS) Propagation Program

- ACTS Launched on September 12, 1993
- GSO @ 100° W
- ACTS Propagation Beacons
 - 20.185/20.195 GHz
 - 27.505 GHz
- NASA Selected seven sites in North America for comprehensive propagation measurements campaign
 - Identical APTs at each location

ACTS Propagation Terminal (APT)

- 1.2 m offset feed receive-only
- Dual channel receiver/radiometer
- Measured Parameters
 - 20.185/20.195 GHz Beacon
 - 27.5 GHz Beacon
 - 20 GHz Radiometer
 - 27 GHz Radiometer
 - Rain Rate (CRG, TBG)
 - Temperature, Relative Humidity, Water Vapor Density, Wind Vector
- Data acquisition and pre-processing software



ACTS Propagation Experimenters

Location	Principal Investigator	Elevation Angle (degrees)	ITU-R Rain Region
Vancouver, British Columbia	U. of British Columbia/ CRC	29	D
Ft. Collins, Colorado	Colorado State University	43	E
Fairbanks, Alaska	University of Alaska, Fairbanks	8	C
Clarksburg, Maryland Reston, Virginia	COMSAT Laboratories	39	K
Las Cruces, New Mexico	Stanford Telecom, Inc/ New Mexico State Univ.	51	E
Norman, Oklahoma	University of Oklahoma	49	M
Tampa, Florida	University of South Florida/ Florida Atlantic University	52	N

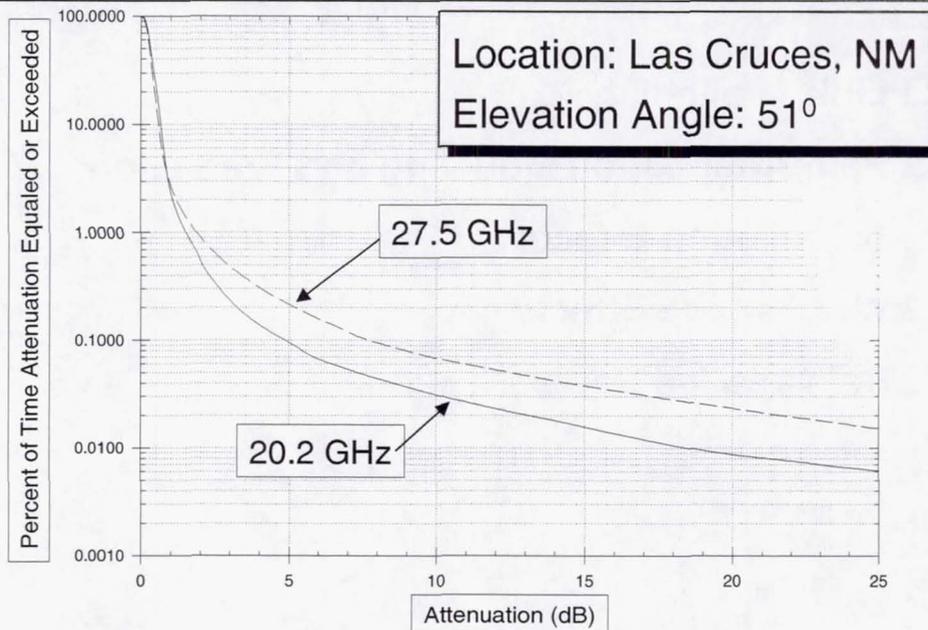
Major Areas of ACTS Propagation Campaign Accomplishments

- Link Availability
- Rain Attenuation Modeling and Prediction
- Scintillation Effects
- Wet Surface Effects
- Rain and Ice Depolarization



Link Availability

Five Year Cumulative Distribution of AFS for Las Cruces, NM APT



AFS - Attenuation with respect to Free Space

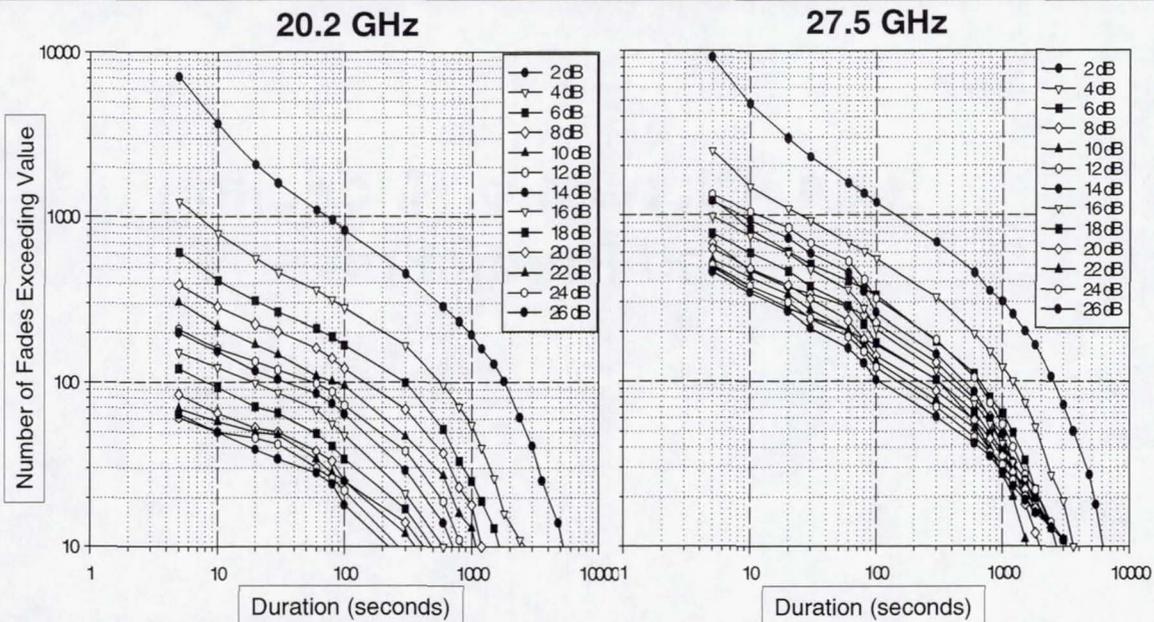
Link Availability Margin Statistics for the ACTS Locations

60 month continuous measurement period, unless otherwise noted

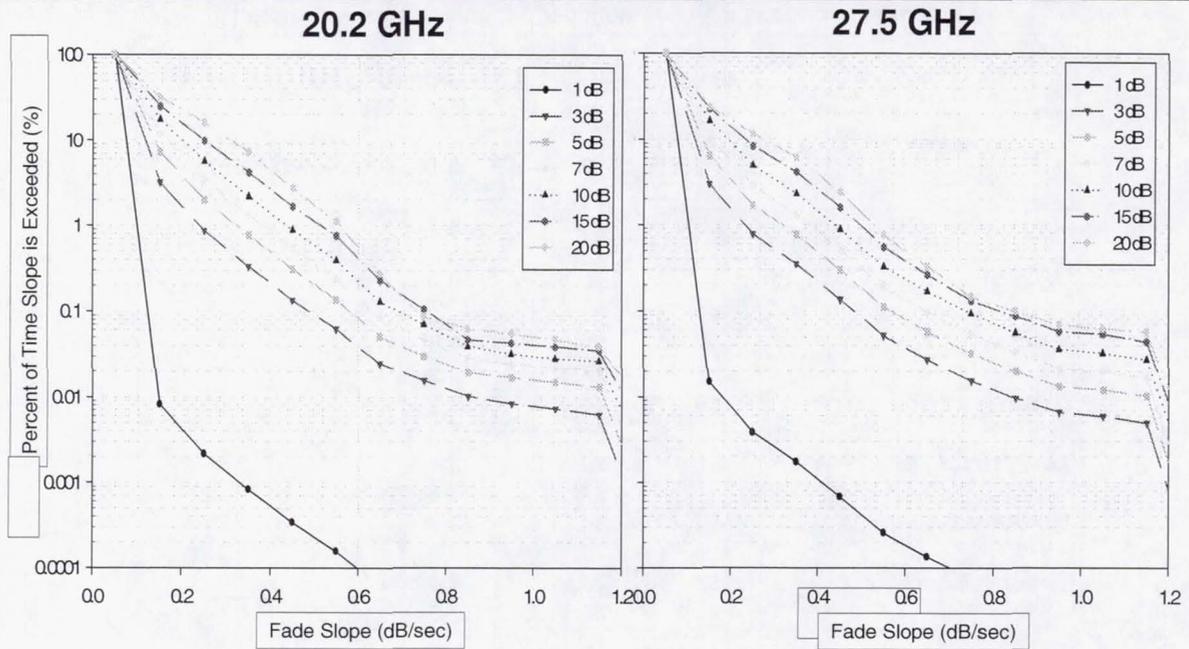
Location	Elev. Angle (deg)	Frequency (GHz)	Amplitude Margin (in dB) Required to Achieve the Given Annual Link Availability		
			99%	99.9%	99.99%
			Vancouver, BC	29	20.2
Ft. Collins, Colorado	43	20.2 *	0.8	3	13.5
		27.5 **	1.2	5.6	22
Fairbanks, Alaska	8	20.2	1.5	4.2	13.5
		27.5	2.3	7.4	20.5
Reston, Virginia	39	20.2	0.9	6.5	20
		27.5	1.8	10.5	>25
Las Cruces, New Mexico	51	20.2	1.1	5	18.5
		27.5	1.6	7.5	>25
Norman, Oklahoma	49	20.2	0.7	7.8	24.4
		27.5	1.2	11.0	>25
Tampa, Florida	52	20.2	4.4	>25	-
		27.5	7.3	>25	-

* 48 months (1/94 - 12/98) ** 56 months (12/93 - 8 98)

Five Year Cumulative Fade Duration for Las Cruces, NM APT



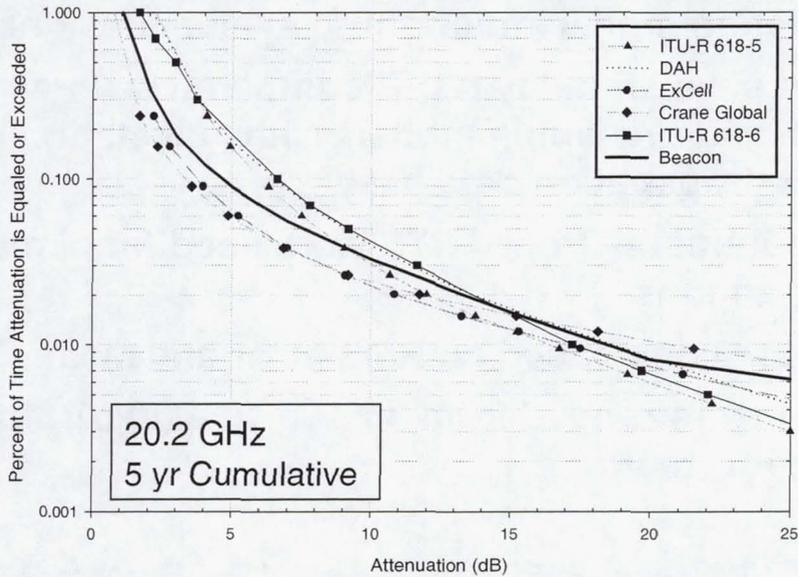
Five Year Cumulative Fade Slope for Las Cruces, NM APT



Rain Attenuation Modeling and Prediction

Comparison of Measured ACA* Distributions to Attenuation Prediction Models

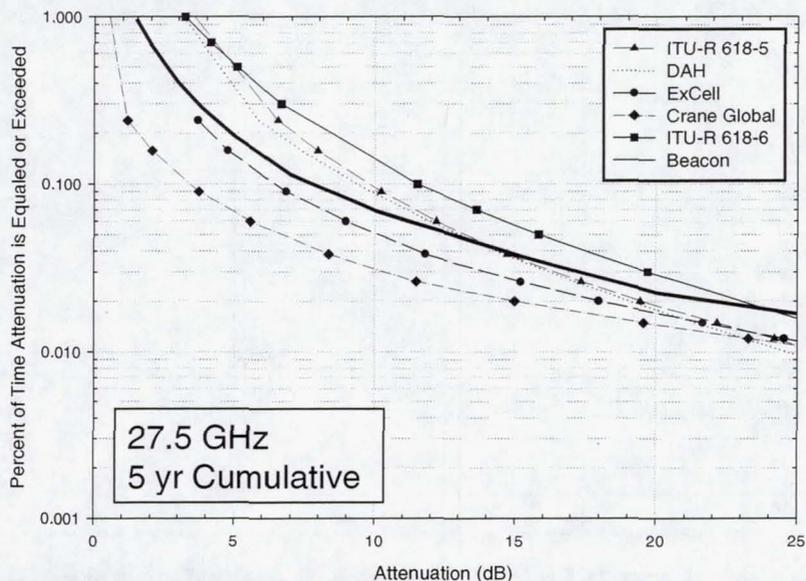
New Mexico APT: Rain Models + Wet Surface Effects



* ACA - Attenuation with respect to Clear Air = AFS - A (gaseous absorption)

Comparison (cont'd)

New Mexico APT: Rain Models + Wet Surface Effects



* ACA - Attenuation with respect to Clear Air = AFS - A (gaseous absorption)

Comparison of Performance of Rain Attenuation Prediction Models

- Selection of appropriate rain attenuation prediction model important to system designers
- Exhaustive study by ITU-R compared several published prediction models with 186 station year ITU-R propagation data base *
- Measurements from ACTS were used for similar comparisons **
- Comparisons based on RMS error and Mean Error
- RMS errors ranged from 30% to 40% (in dB) for top performers

* ITU-R WP 3M, June 1996 ** Feldake & Ailes-Sengers, 1997

Summary of Performance of Rain Attenuation Prediction Models

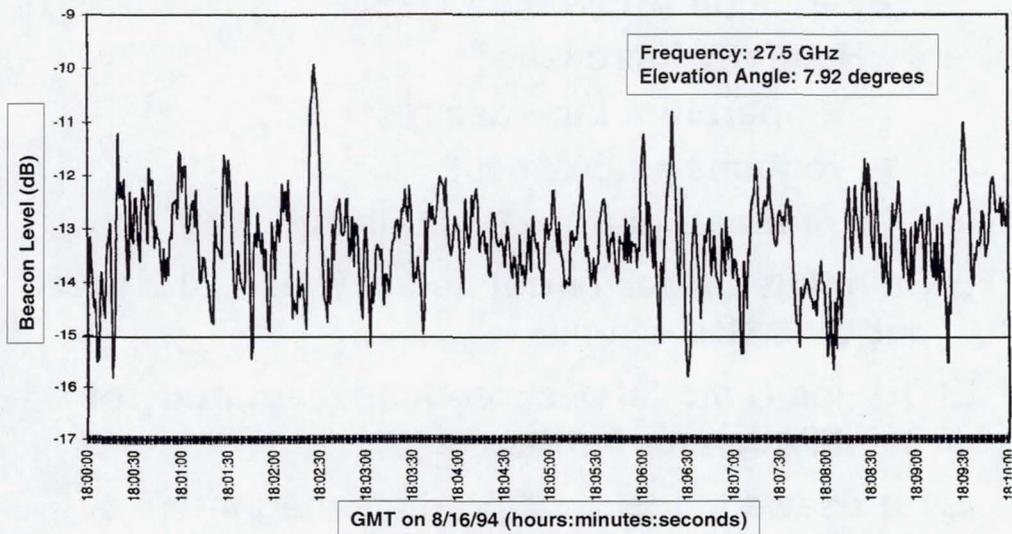
Model	Evaluation with ITU-R Data Base *		Evaluation with ACTS Data **	
	Overall	15 – 35 GHz	20 GHz	27 GHz
DAH	1	2	1	1
ITU-R	2	3	3	4
ExCell	3	8	2	2
Japan	4	5	8	8
Brazil	5	6	6	6
CCIR	6	7	5	5
Leitao-Watson	7	4	11	11
Misme-Waltdeufel	8	10	N/A	N/A
Crane Two-Component	9	9	4	3
Spain	10	1	9	9
Crane Global	N/A	N/A	7	7
SAM	N/A	N/A	10	10

* ITU-R WP 3M, June 1996 ** Feldake & Ailes-Sengers, 1997



Scintillation Effects

Low Elevation Angle 27.5 GHz Scintillation Fairbanks, AK APT



ACTS Scintillation Study *

- Scintillation measurements on ACTS links and evaluation of prediction models
- Primary interest on low elevation measurements at Fairbanks (7.92 degrees)
- Models evaluated
 - Karasawa, Yamada, Allnutt, 1988
 - ITU-R, 1990
 - Ortgies -N, Ortgies-T, 1993
 - DSSP, MPSP, 1997
 - Tervonen, van de Kamp, Salonen, 1998

* Mayer, et al, University of Alaska, Fairbanks (NAPEX XXII, June 1999)

Scintillation Study Conclusions

- Scintillations Increase as: ↑
 - Elevation Angle Decreases ↓
 - Humidity Increases ↑
 - Temperature Increases ↑
 - Frequency Increases ↑
 - Antenna Aperture Decreases ↓
- Scintillation well correlated between 20.2 GHz and 27.5 GHz signals
- Ortgies-N model best predicts magnitude of Scintillation for Fairbanks
- Karasawa Model best predicts magnitude of scintillation for 4 of 6 lower 48 states

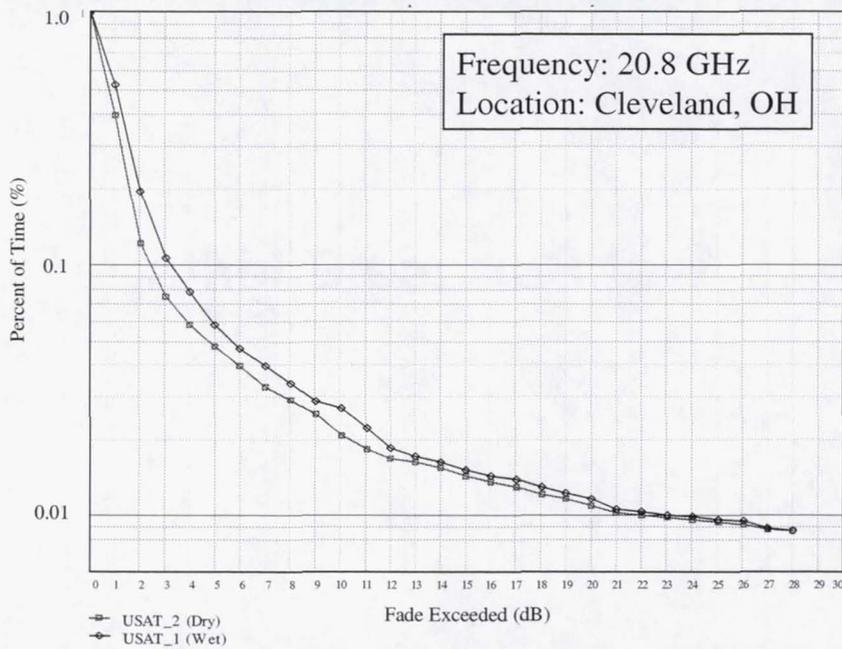


Wet Surface Effects

Wet Surface Effects

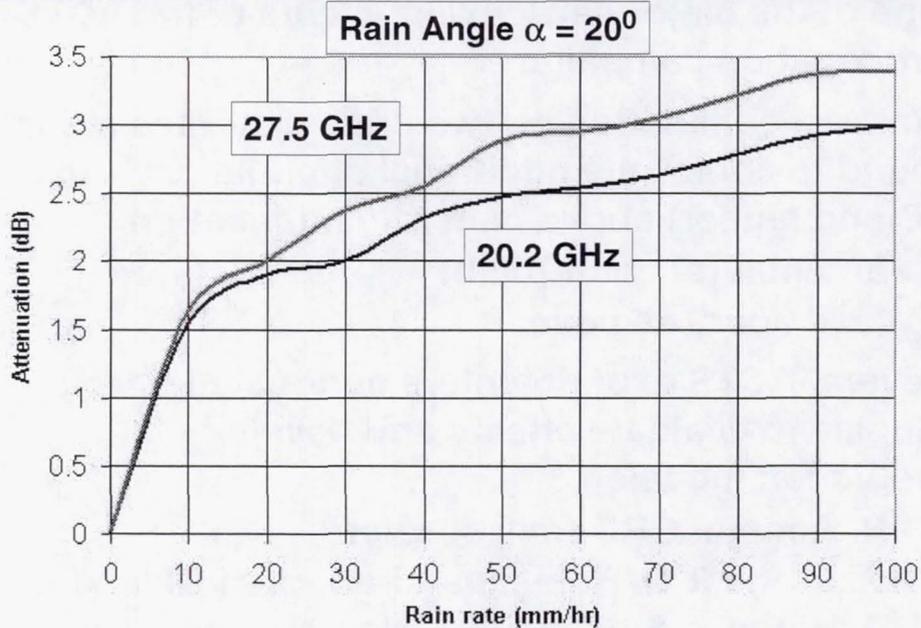
- ❑ One of the major new developments of the ACTS propagation campaign
- ❑ Water accumulation on two critical surface areas found to contribute additional attenuation (1 to 3 dB and higher) above path rain attenuation
 - antenna reflector (dish)
 - feed aperture cover
- ❑ Several ACTS experimenters conducted special studies to evaluate effects and develop prediction models
 - R. Acosta, GRC (this session)
 - R. Crane & D. Ramachandran, U. of Oklahoma
 - S. Horan & A. Borsholm, New Mexico State U.

Fade Distributions for Identical Sheltered and Un-sheltered 1.2 m Antennas



Source: Acosta et al, NAPEX XXII Proceedings, Nov. 1997

Simulation Prediction of Attenuation Due to Water on Feed



Source: Crane et al, NAPEX XXI Proceedings, June 1997

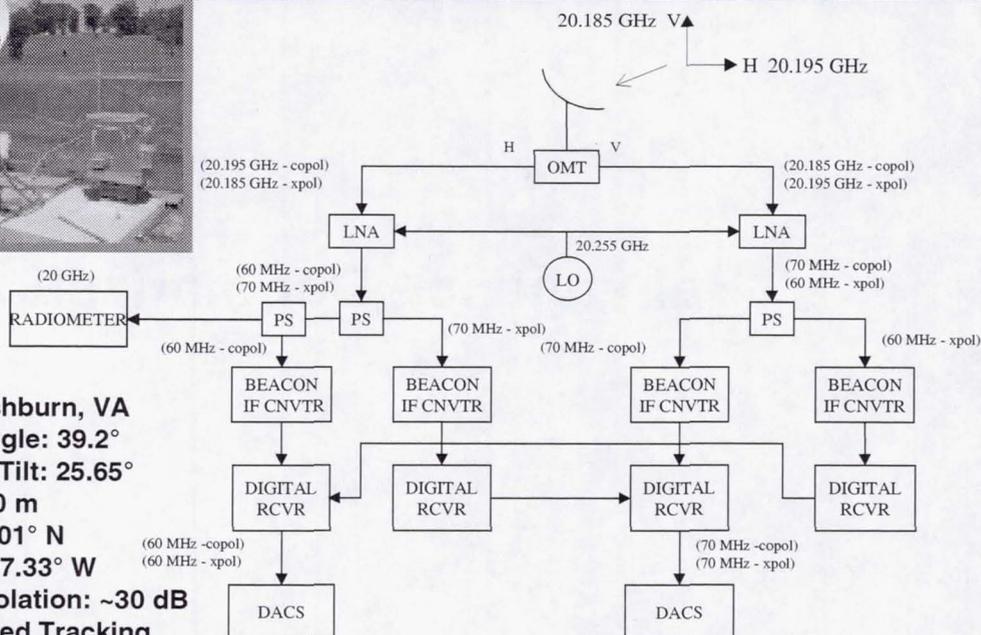


Rain and Ice Depolarization

STel/ITT Dual-Polarization Measurements with ACTS

- ACTS Propagation Program not originally designed for dual polarization measurements
- Depolarization effects important for design and performance evaluation of Ka-band systems planning frequency reuse services
- Stanford Telecom (now ITT) with IR&D funds, and with GRC support, developed a depolarization measurements experiment
 - Two APTs modified near end of ACTS lifetime to provide simultaneous dual-pol measurements
 - Simultaneous transmissions of both 20.185 and 20.195 GHz signals utilized
 - Terminal at STel/ITT location in Ashburn, VA
 - Measurements: 5/99 through 4/00

ACTS Dual-Pol Receiver System



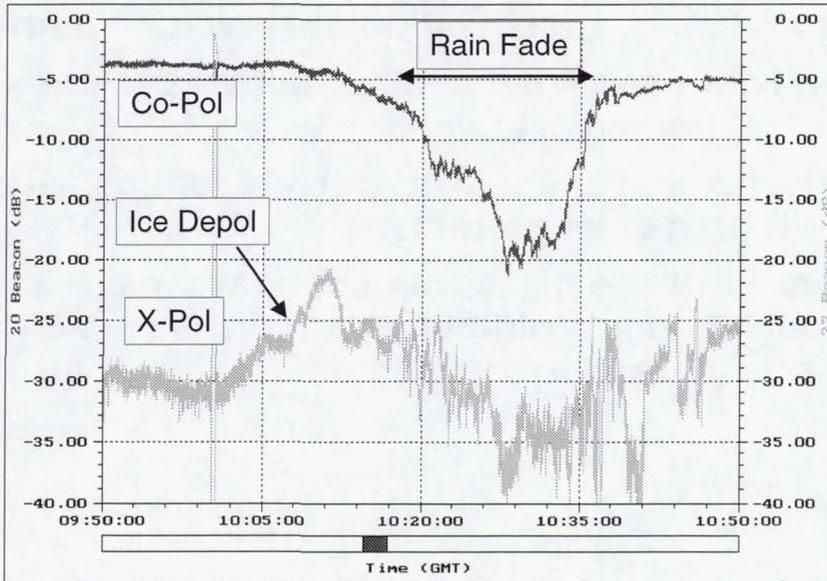
- Location: Ashburn, VA
- Elevation Angle: 39.2°
- Polarization Tilt: 25.65°
- Altitude: 250 m
- Latitude: 39.01° N
- Longitude: 77.33° W
- Measured Isolation: ~30 dB
- NASA Installed Tracking Hardware included

Parameters Measured

- CPA Magnitude and XPD Magnitude & Phase
 - Full Atmospheric Depolarization Characterization at 20 GHz
 - 20.185 GHz: transmit vertical, receive horizontal & vertical polarization
 - 20.195 GHz: transmit horizontal, receive horizontal & vertical polarization
 - 1 sample per second recording standard
 - Up to 20 samples per second available
- Radiometer: 20 GHz
- Weather: Rain rate (CRG, TBG), Temperature, Relative Humidity, Wind Vector, Barometric Pressure

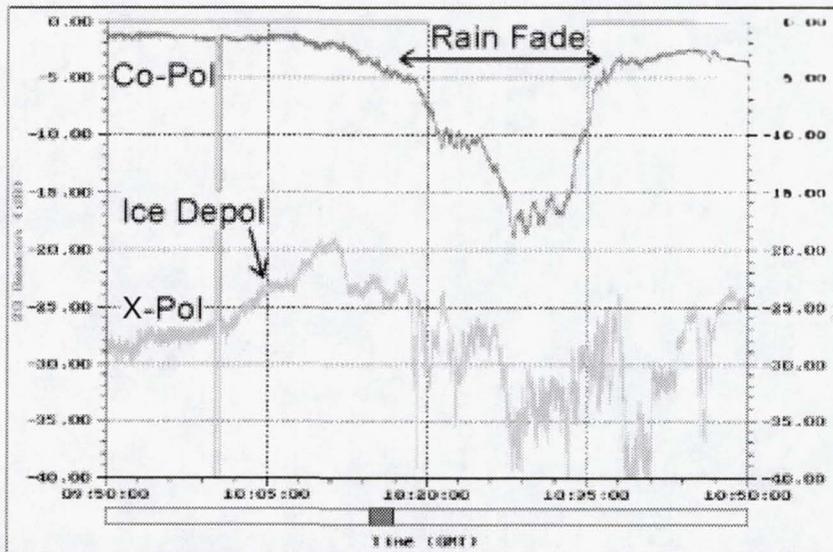
Example of Depolarization Event 5/24/99

20.185 GHz - Vertical Polarization Channel



Example of Depolarization Event 5/24/99

20.195 GHz - Horizontal Polarization channel



ACTS Depolarization Measurements Preliminary Results

- Ice and rain depolarization observed on path
- Behavior nearly identical for horizontal and vertical transmission channels
 - Horizontal channel co-pol attenuation ~1-2 dB greater as predicted
- Relative phase measurement between co- and cross- channels difficult to obtain. Results inconclusive



Summary

Summary - ACTS Propagation Measurements Campaign

- ❑ The ACTS propagation campaign has developed over 35 station years of reliable, high quality, digital data records for the evaluation of Ka-band systems
- ❑ ACTS offers the systems designer access to a comprehensive source of data for the development and validation of propagation effects modeling and prediction
- ❑ Significant accomplishments have contributed to our understanding of space communications in the Ka-band for the next generation of applications and services

Full Conference Paper Available: Louis.ippolito@itt.com

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2.2 - Rain Attenuation Model Comparison and Validation

Charlie Mayer
University of Alaska
Fairbanks, Alaska

Brad Jaeger
University of Alaska
Fairbanks, Alaska

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

Outline of Presentation

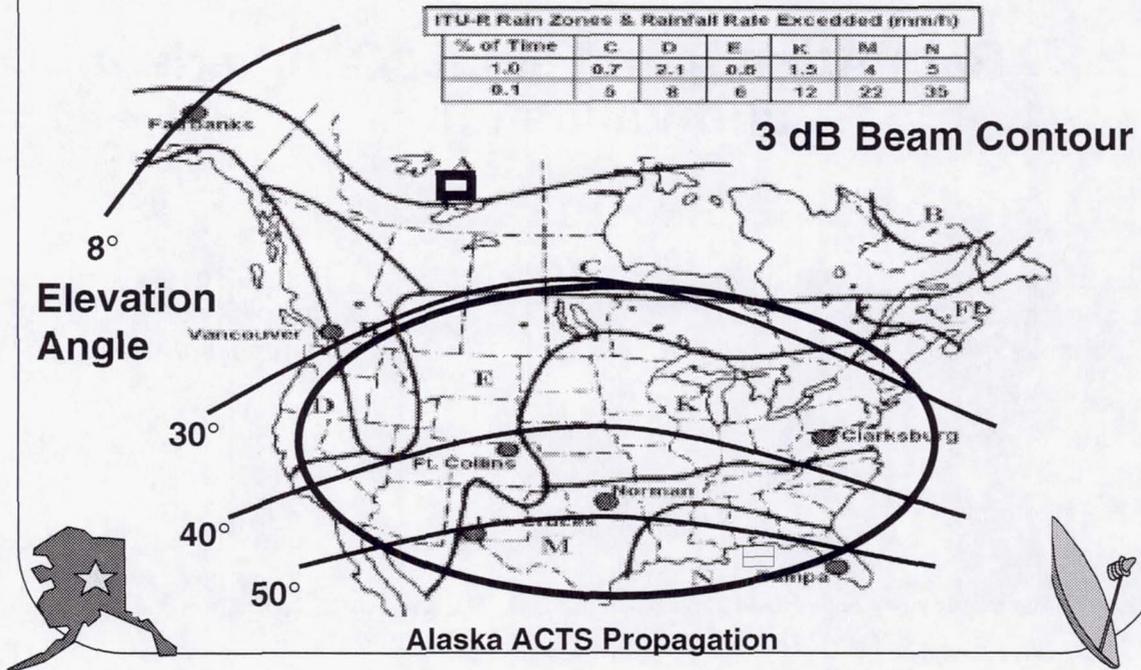
- Overview of Propagation Experiment and Objectives
- Propagation Impairments
- Procedure to go from Measurements to Rain Attenuation
- Rain Attenuation Models
- Comparison Results
- Conclusions



Alaska ACTS Propagation



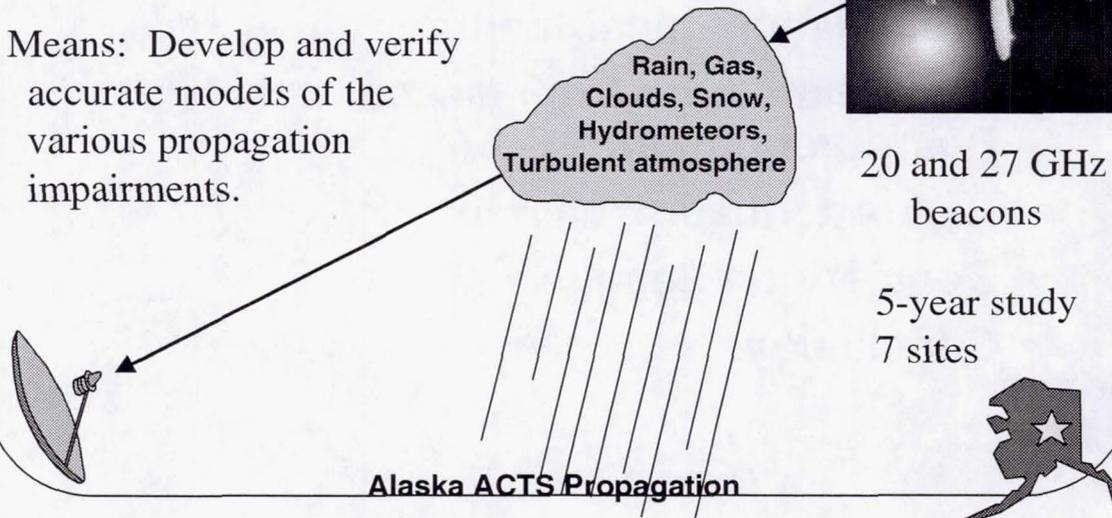
Site and Rain Zone Map



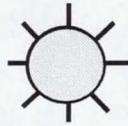
ACTS Propagation Studies

Objective: Characterize Ka-band satellite electromagnetic wave propagation to enable the design of economic and reliable communication systems.

Means: Develop and verify accurate models of the various propagation impairments.



Propagation Impairments



Clear sky

- Atmospheric gases (O₂, H₂O)
- Turbulence
- Ice crystals
- Attenuation & Refraction
- Scintillation
- Depolarization



Alaska ACTS Propagation



Propagation Impairments



Degraded sky

- Rain
 - Clouds
 - Fog
 - Other hydrometeors
 - Attenuation & Depolarization
 - Attenuation
 - Attenuation
 - Little effect
- » Hail, Ice, Snow



Alaska ACTS Propagation



Propagation Impairments

Equipment effects

- Curved antenna
- Wet antenna
 - » Feedhorn
 - » Reflector surface
- Depolarization
- Attenuation



Alaska ACTS Propagation



Propagation Impairments Pertinent to Rain Attenuation Modeling

Rain Attenuation	0 to 30+ dB
Gaseous Attenuation	few tenths to a few dB
Wet Antenna Effects	0 to a few dB
Cloud Attenuation	0 to a few dB



Alaska ACTS Propagation



Procedure to get to Rain Attenuation

- Measured Attenuation, A_{meas}
- Preprocess
 - Remove: Ranging tone effects & satellite diurnal motions
 - Discard times of beam blockages & equipment downtime
 - Calibrate “zero” level of beacon using radiometer
- Result is Total Attenuation, A_{total}



Alaska ACTS Propagation



Total Attenuation Components

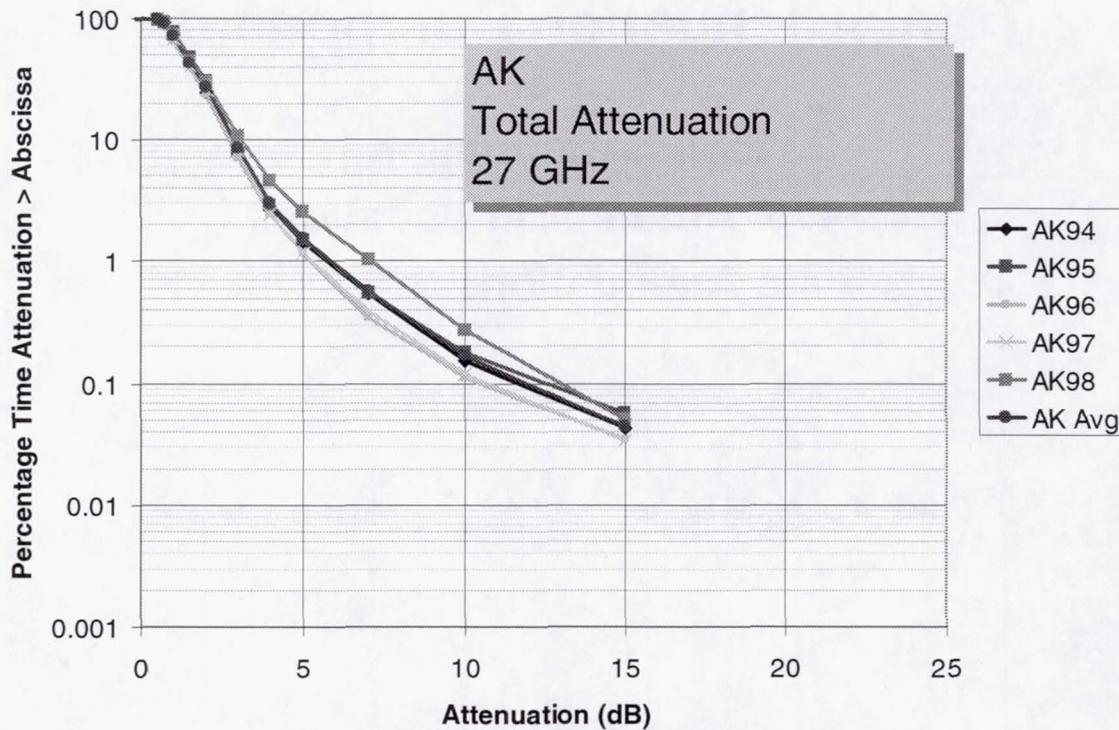
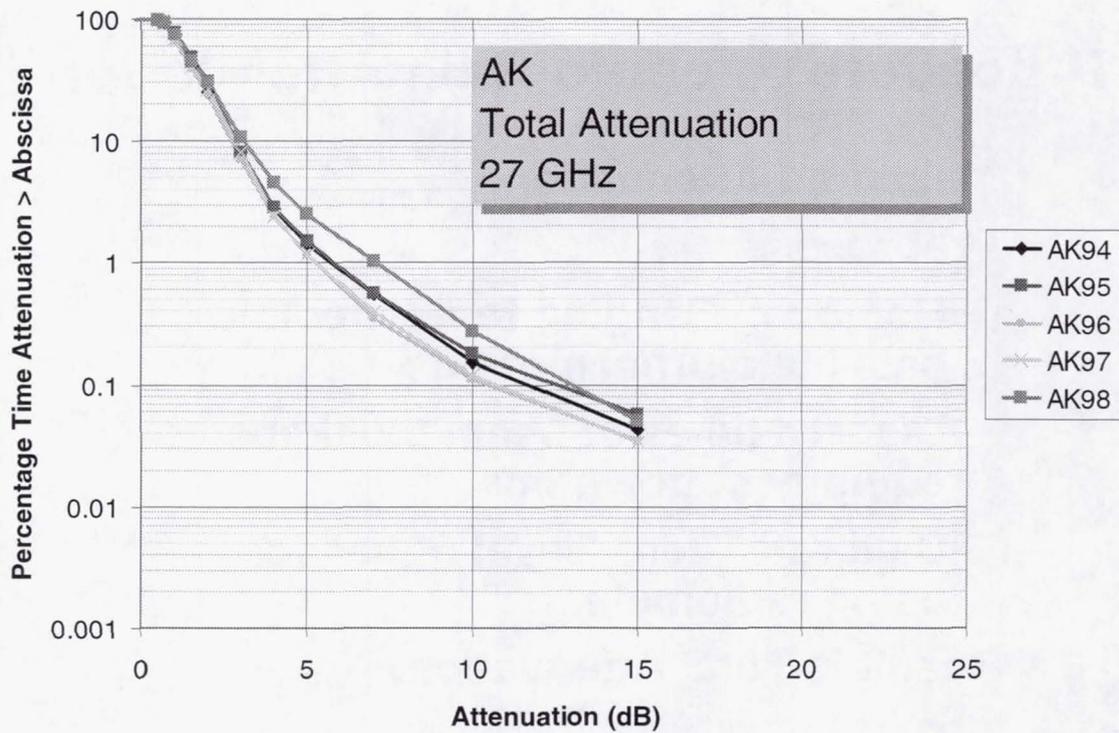
- AGA -- Gaseous Attenuation
- AWA -- Wet Antenna Attenuation
- A_{rain} -- Rain Attenuation

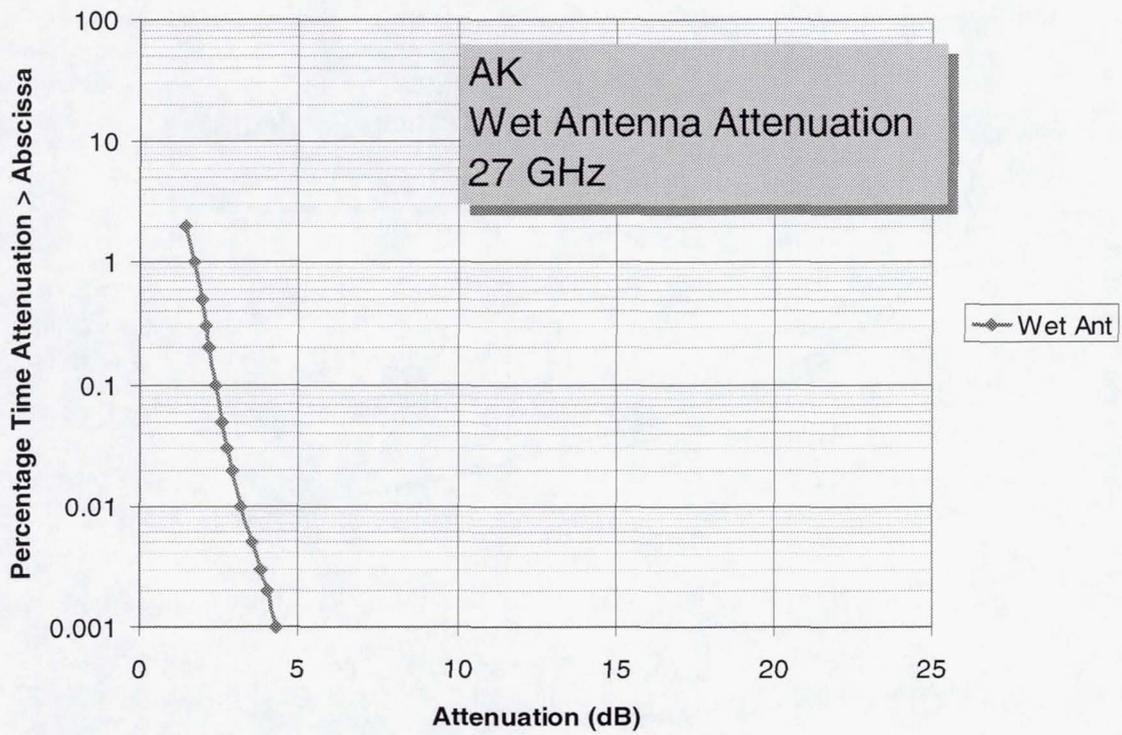
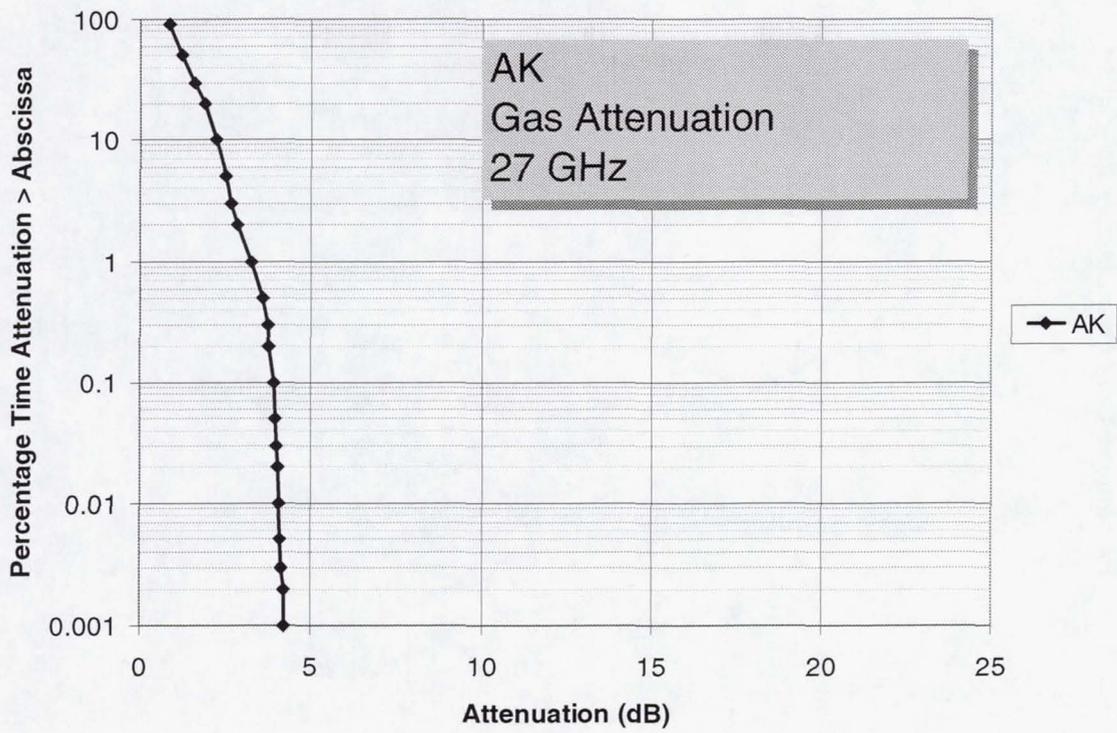
$$A_{\text{total}} = \text{AGA} + \text{AWA} + A_{\text{rain}}$$

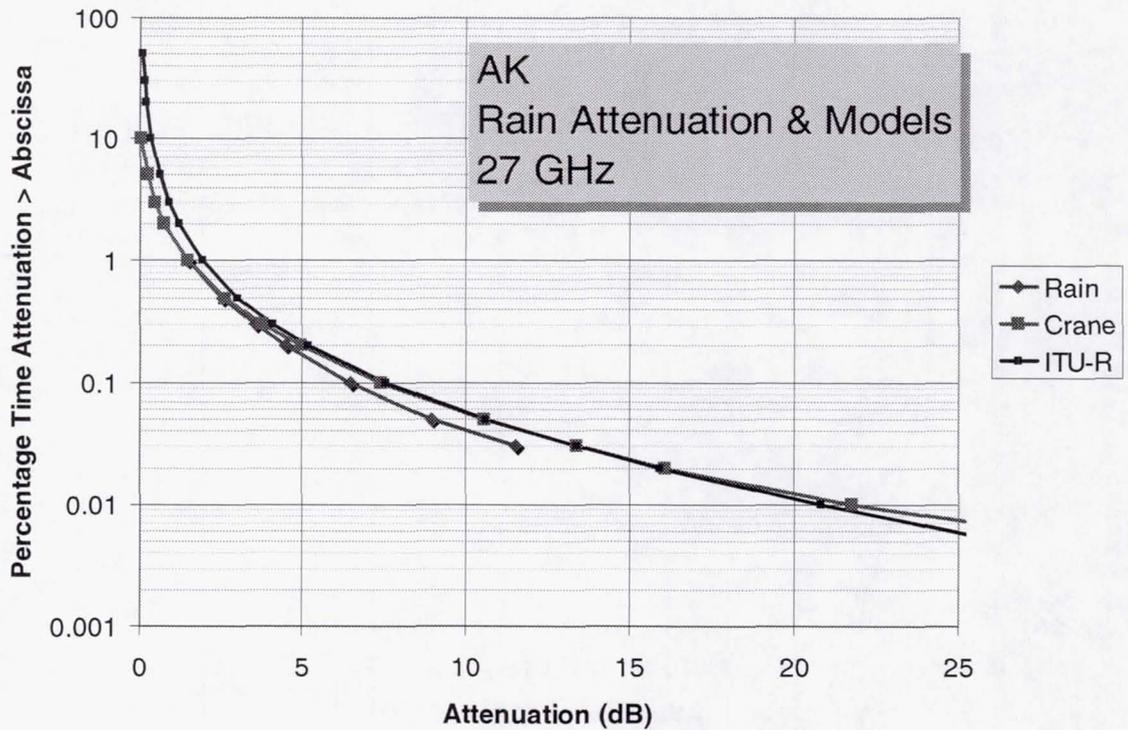
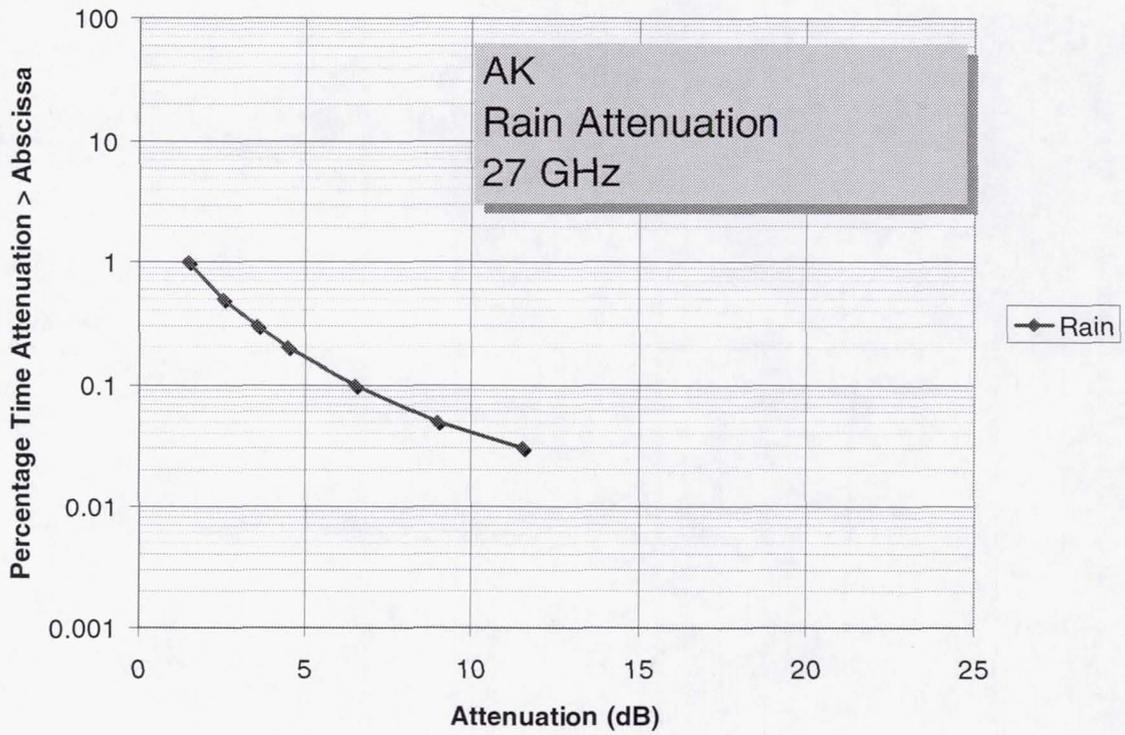


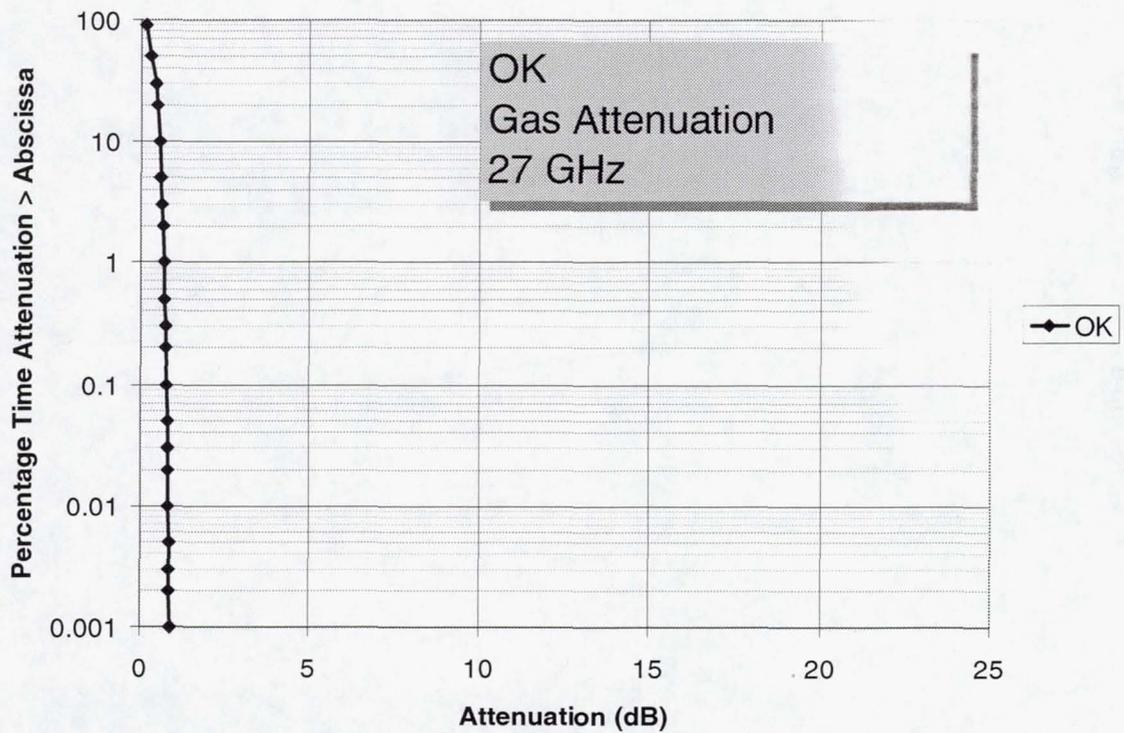
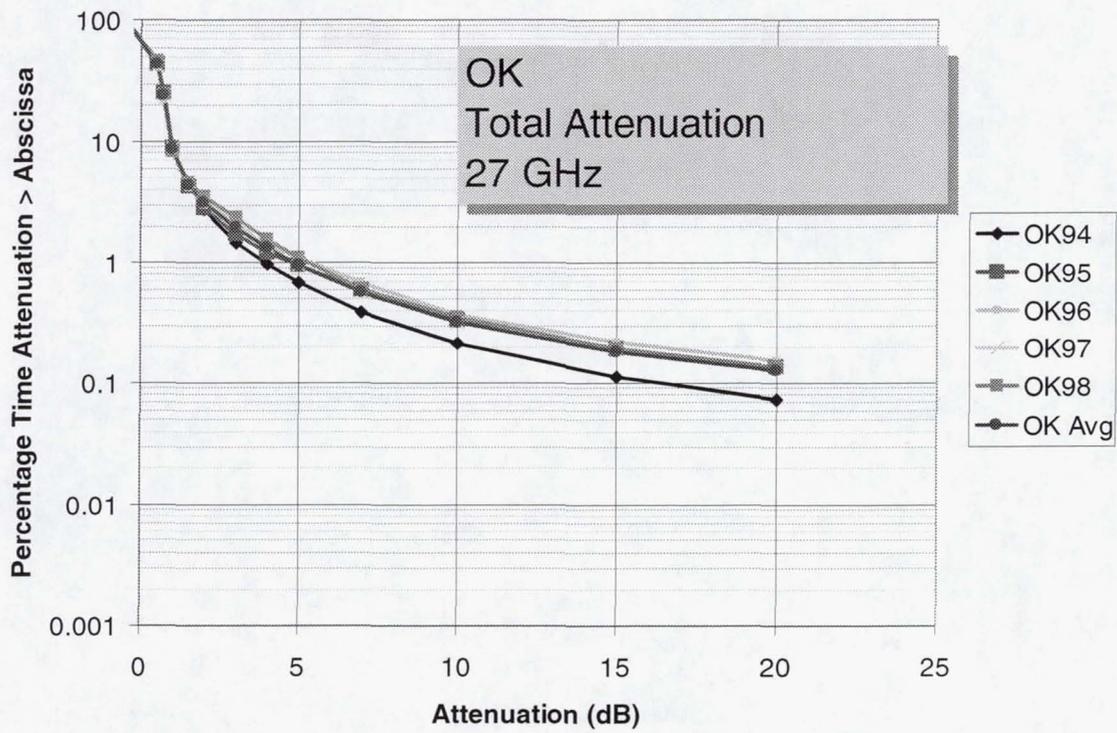
Alaska ACTS Propagation

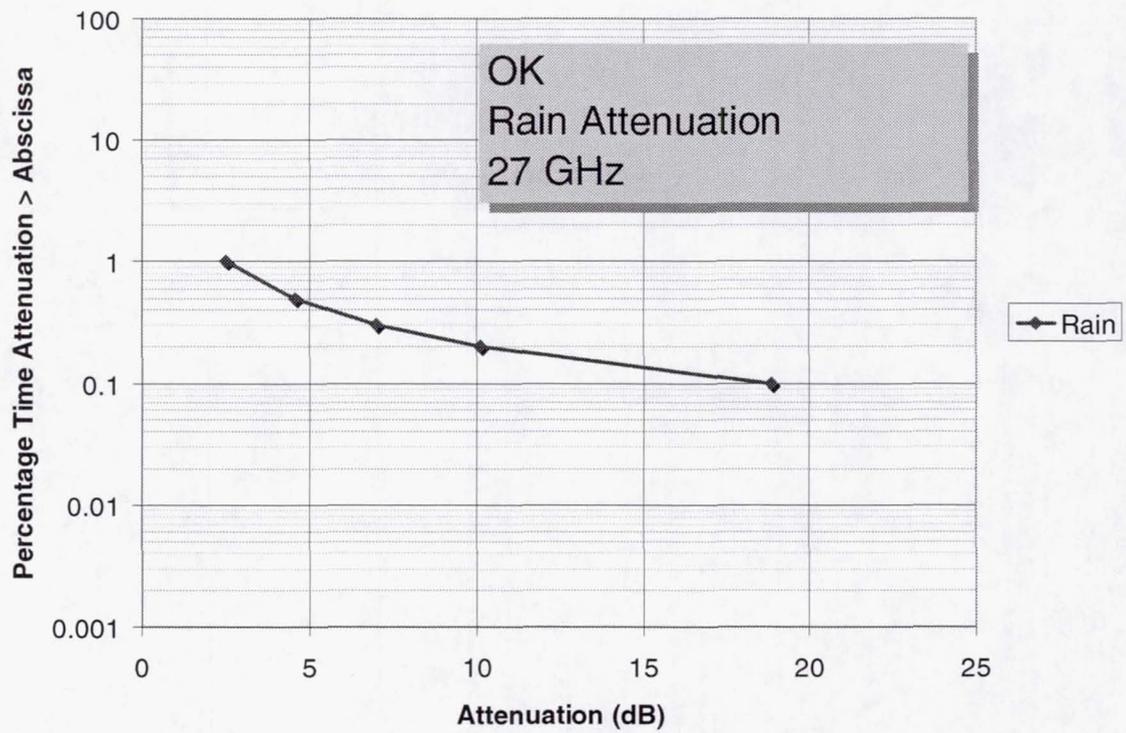
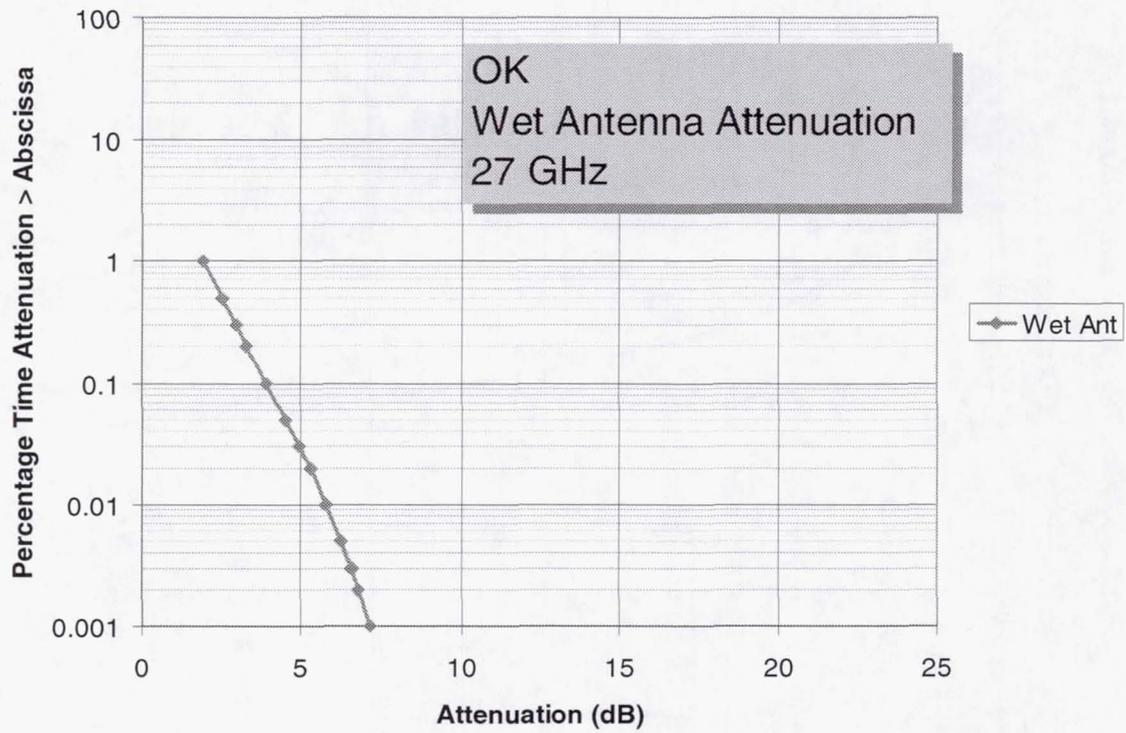


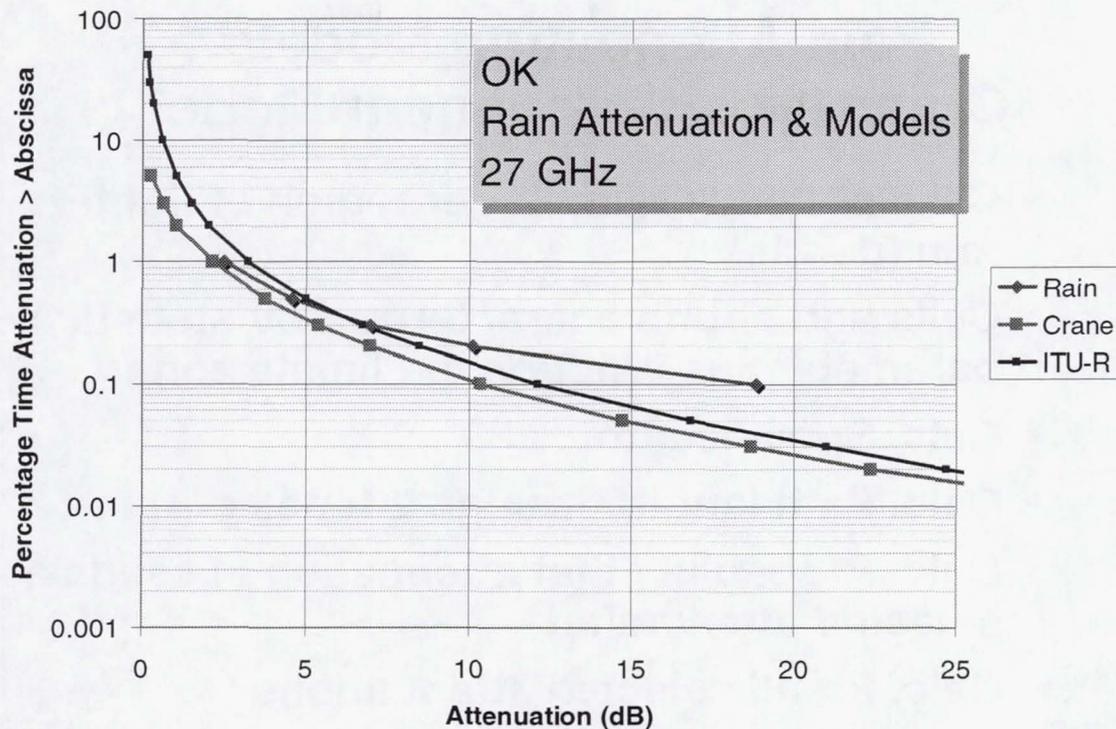












Rain Attenuation Models ITU-R (DAH) Model

- **Determine 0.01% rain rate, R (mm/hr)**
 - was zones, now continuous world map
- **Calc. Specific attn., $\gamma = k R^\alpha$ (dB/km)**
 - function of frequency and polarization
- **Calc. Path length through rain, L**
 - function of el. angle, station height and latitude
- **$\text{Attn}_{0.01} = \gamma \cdot L$ (dB)**
- **Calc. Attn. at other percentage times**



Alaska ACTS Propagation



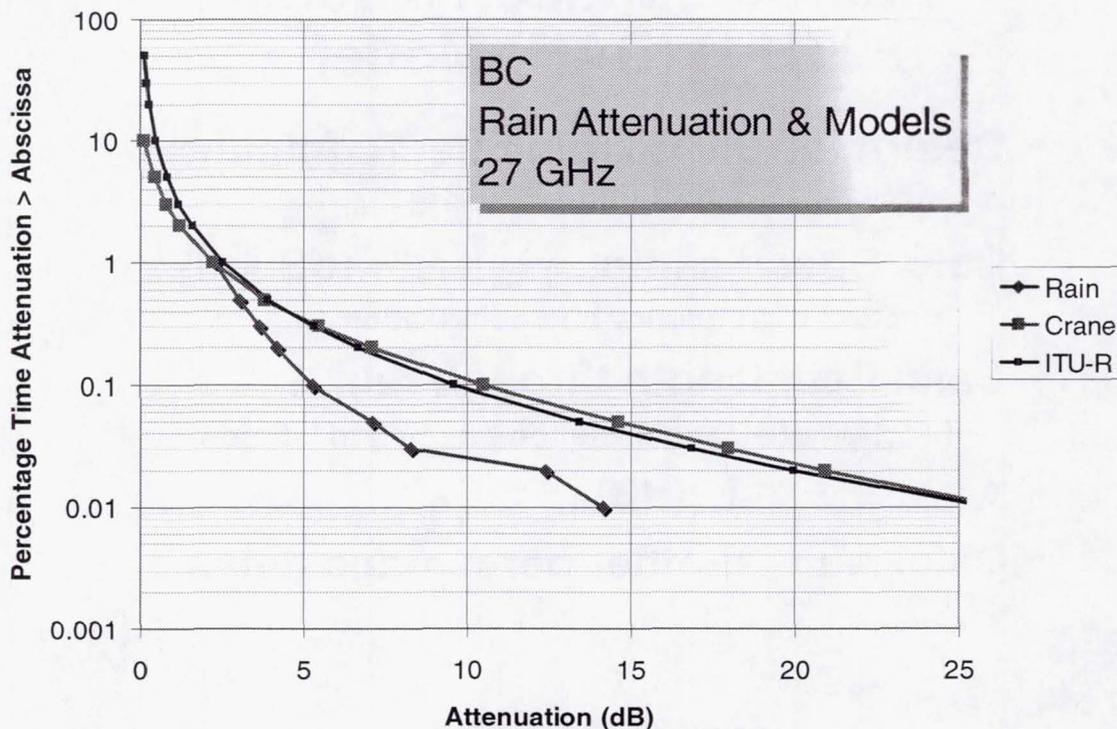
Rain Attenuation Models

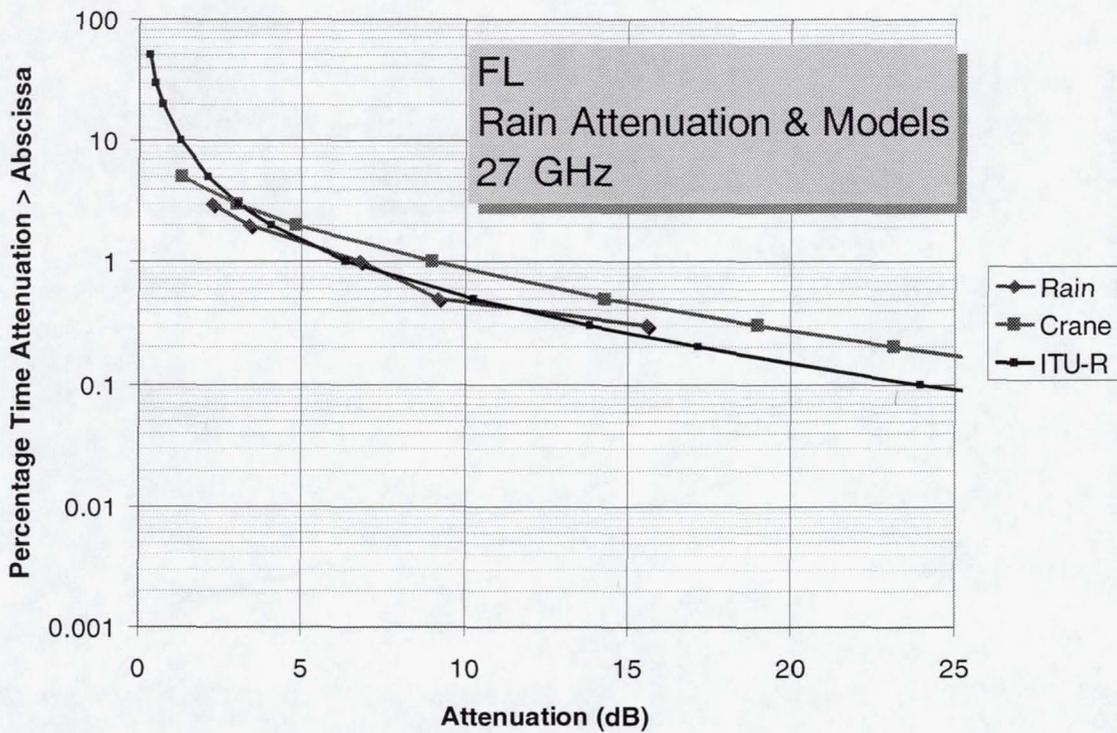
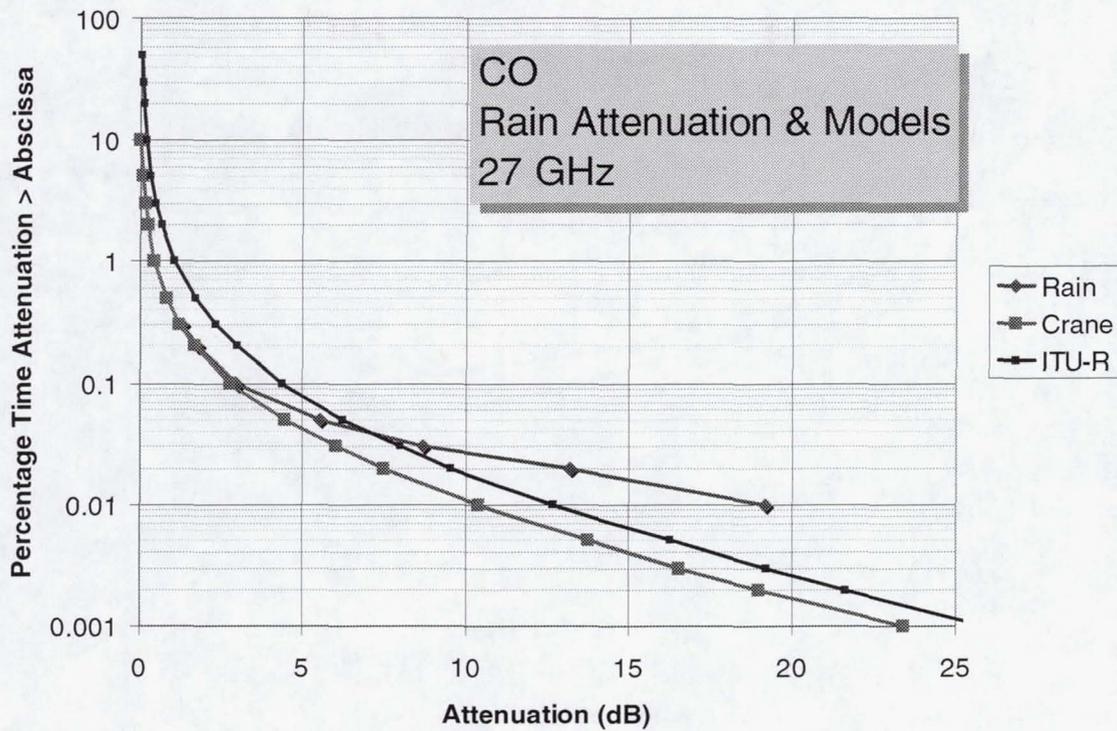
Crane Two-Component Model

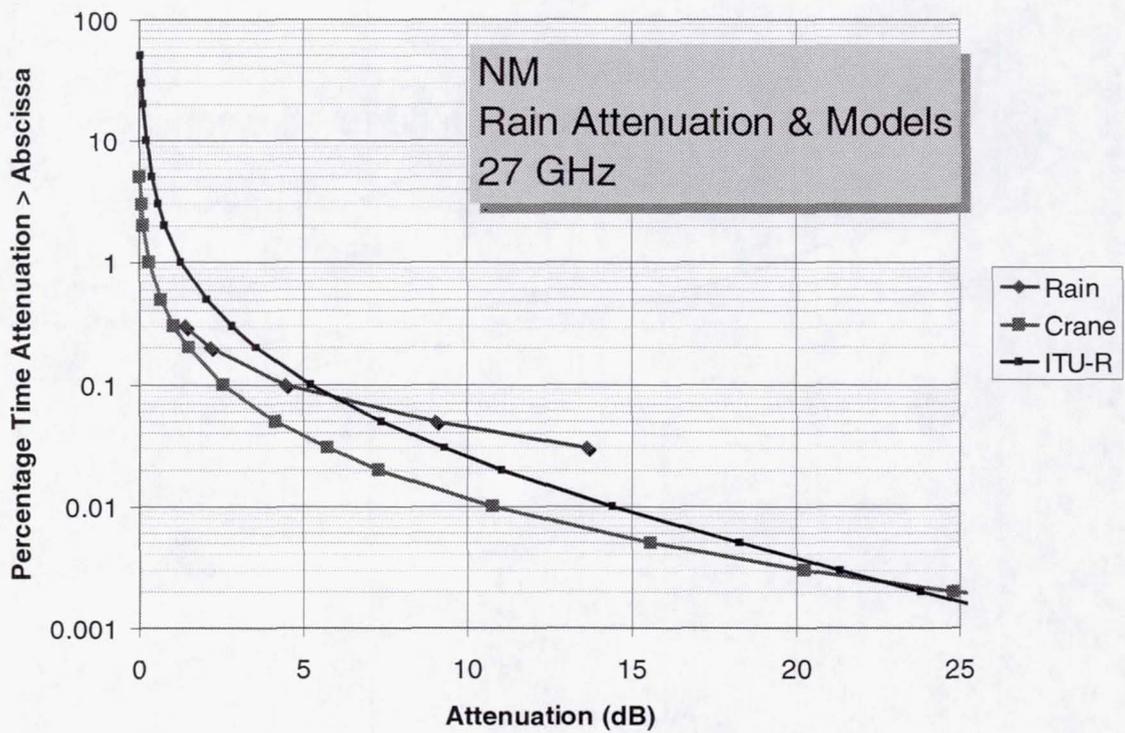
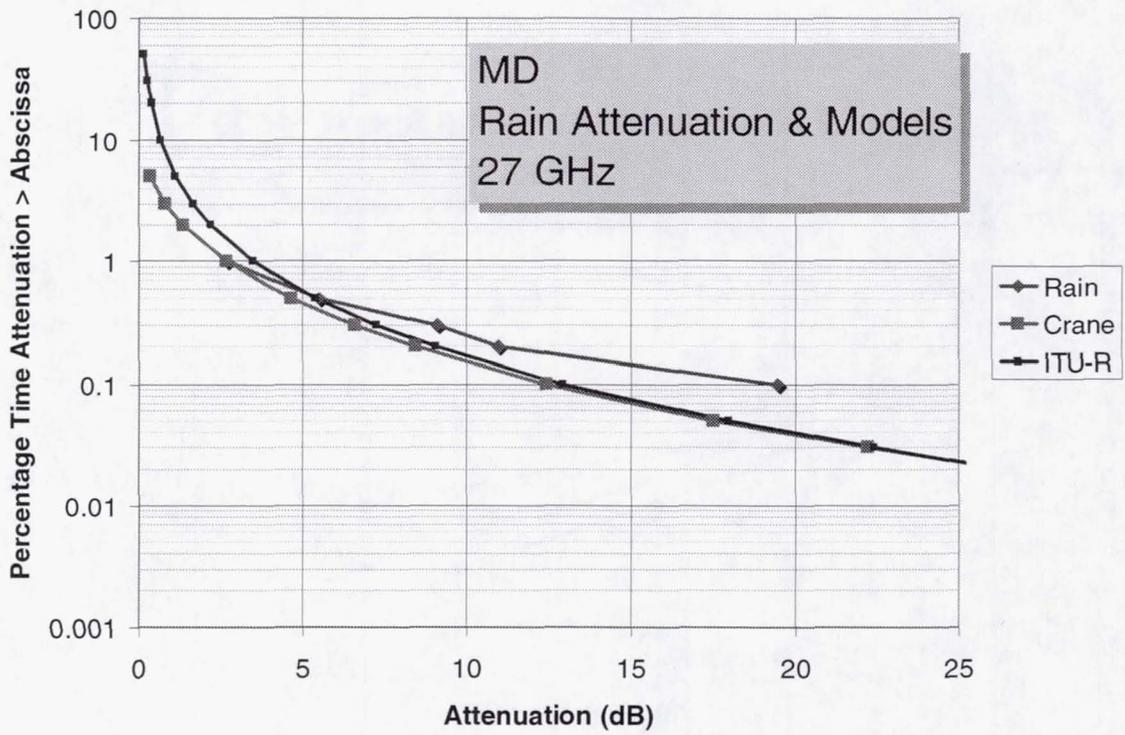
- Cells of heavy rain; larger region of lighter rain (debris)
- Cells and debris characterized by statistical parameters as function of climate zone
- Calc. Specific attn.
- Calc. Path length through 2 types of rain
- Calc. Probability that attenuation exceeds a selected attenuation
- Calc. for all selected attenuations



Alaska ACTS Propagation







Rain Attenuation Model Comparison

For valid equi-percentage points on CDF:

Calculate $(A_{\text{model}} - A_{\text{rain}}) / A_{\text{model}} * 100\%$

Perform statistical analysis on these points for each site, and for all 7 sites.



Alaska ACTS Propagation



Rain Attenuation Model Results

ITU-R	AK	BC	CO	FL	MD	NM	OK	All 7 Sites
Avg.	-23.7	-66.5	-34.7	0.4	4.1	-15.5	0.3	-19.4
Stdev.	8.2	31.5	50.4	15.7	24.9	52.6	22.3	29.4
RMS	25.1	74.1	61.4	16.1	25.3	55.8	22.8	40.1
Crane	AK	BC	CO	FL	MD	NM	OK	
Avg.	-14.0	-73.7	17.5	-41.2	15.4	43.4	20.4	-4.6
Stdev.	11.8	44.4	16.0	19.8	14.9	14.6	11.9	19.1
RMS	18.3	87.0	23.7	45.8	21.7	45.8	24.2	38.1



Alaska ACTS Propagation



Conclusions

7 sites X 5 years = 35 site-years of data

Rain models work better in some climate zones than others

Rain models work about equally well

Climatology of the U.S. is vastly different than Europe and Japan

Important that propagation measurements continue in the U.S. in higher frequency bands



Alaska ACTS Propagation



2.3 - Propagation Effects Handbook for Satellite Systems Design

Louis Ippolito
ITT Industries
Advanced Engineering & Sciences
Ashburn, Virginia

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

Basic Objectives for NASA Propagation Handbook

- Combine Scope of the Previous NASA Handbooks
into a Single Comprehensive Document**
- Eliminate Duplication**
- Provide a More Cohesive Structure for the Reader**
 - **Offer Several Levels of “Entrance” into
Handbook**
- Include Tailored Propagation Analysis Procedures
For Specific Types of Satellite Applications**

Prior Editions Above 10 GHz Handbooks

- First Edition ORI Technical Report TR 1679
R. Kaul, R. Wallace, G. Kinal
March 1980

- Second Edition NASA Reference Publication 1082
L. Ippolito, R. Kaul, R. Wallace
December 1981

- Third Edition NASA Reference Publication 1082(03)
L. Ippolito, R. Kaul, R. Wallace
June 1983

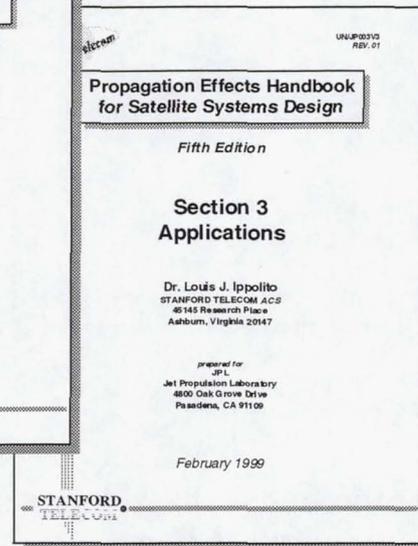
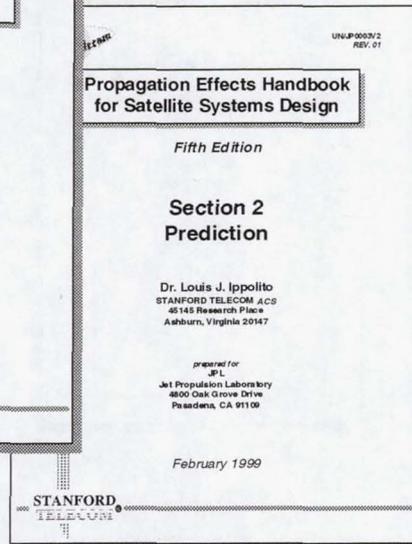
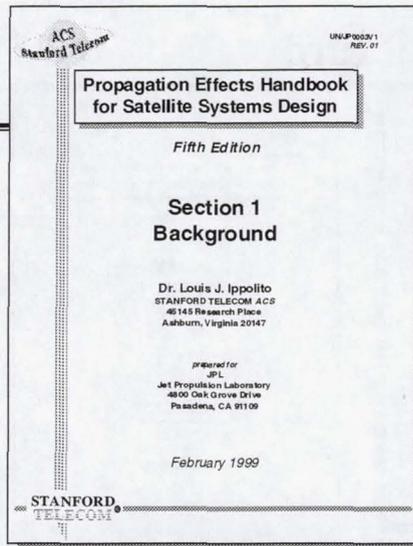
- Fourth Edition NASA Reference Publication 1082(04)
L. Ippolito
February 1989

Prior Editions Below 10 GHz Handbooks

- First Edition NASA Reference Publication 1108
W. Flock
December 1983

- Second Edition NASA Reference Publication 1108(02)
W. Flock
December 1987

Fifth Edition



- **Fifth Edition**
 - Released Oct 1998
- **Fifth Edition, Rev. 1**
 - Released Feb 1999

Basic Structure of Handbook

Three Sections

SECTION 1 BACKGROUND

Provides Overview of Propagation Effects, including Theory and Basic Concepts, Propagation Measurements, Available Data Bases

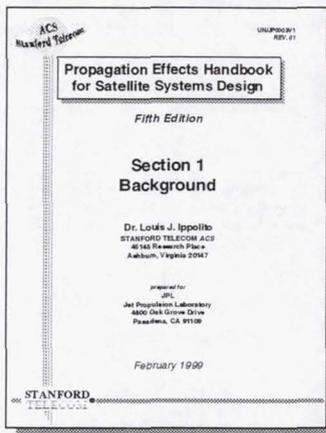
SECTION 2 PREDICTION

Provides Descriptions of Prediction Models and Techniques, Organized By Effect. Provides Step-by-Step Procedures For Each, Where Appropriate. Includes Sample Calculations

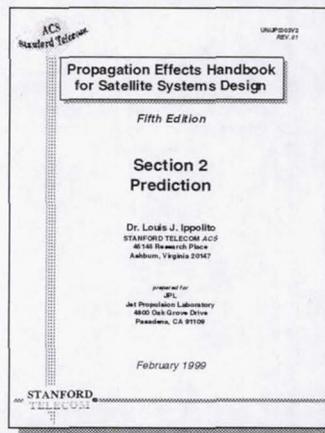
SECTION 3 APPLICATIONS

Provides "Roadmaps" (i.e. flow charts) of Application of Prediction Models in SECTION 2 to Specific Satellite Systems and Applications. Includes Evaluation and Impact on Systems Design and Performance

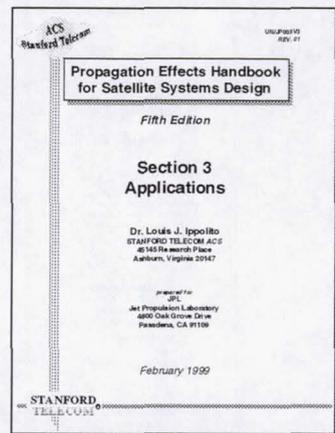
Three Section Structure



**Researcher, General Interest
Enters Here**



**Link Analyst
Enters Here**



**Systems Designer
Enters Here**



Handbook Contents Summary

Section 1 BACKGROUND

1.1 OVERVIEW: PROPAGATION EFFECTS ON COMMUNICATIONS

- 1.1.1 Developments Since Last Handbook
- 1.1.2 Frequency Dependence

1.2 IONOSPHERIC EFFECTS

- 1.2.1 Introduction
- 1.2.2 Effects Due to Background Ionization
- 1.2.3 Effects Due to Ionization Irregularities
- 1.2.4 Transionospheric Propagation Predictions

Section 1 (cont'd)

2

1.3 TROPOSPHERIC EFFECTS

- 1.3.1 Atmospheric Gases
- 1.3.2 Clouds, Fog
- 1.3.3 Rain Attenuation and Depolarization
- 1.3.4 Ice Depolarization
- 1.3.5 Tropospheric Scintillation

1.4 RADIO NOISE

- 1.4.1 Uplink Noise Sources
- 1.4.2 Downlink Noise Sources

Section 1 (cont'd)

3

1.5 PROPAGATION DATA BASES

1.5.1 Meteorological Parameters

1.5.2 Point Data

1.5.3 Path Data

1.5.4 Miscellaneous Sources of Atmospheric Data

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2.1 PREDICTION METHODS FOR SATELLITE LINKS OPERATING BELOW 3 GHz

2.1.1 Total Electron Content

2.1.2 Faraday Rotation

2.1.3 Time Delay

2.1.4 Dispersion

2.1.5 Ionospheric Scintillation

2.1.6 Auroral Absorption

2.1.7 Polar Cap Absorption

2.1.8 Summary – Ionospheric Effects
Prediction

Section 2 (cont'd)

2

2.2 PREDICTION METHODS FOR SATELLITE LINKS OPERATING ABOVE 3 GHz

2.2.1 Atmospheric Gaseous Attenuation

2.2.1.1 Leibe Complex Refractivity Model

2.2.1.2 ITU-R Gaseous Attenuation Models

2.2.2 Cloud Attenuation

2.2.2.1 The ITU-R Cloud Attenuation Model

2.2.2.2 Practical Issues in Using the ITU-R Model

2.2.2.3 Slobin Cloud Model

2.2.3 Fog Attenuation

2.2.3.1 Altshuler Model

Section 2 (cont'd)

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2.2.4.2 Global Model

2.2.4.3 Two-Component Model

2.2.4.4 DAH Model (“USA Model”)

2.2.4.5 ExCell Rain Attenuation Model

2.2.4.6 Manning Model

Section 2 (cont'd)

4

2.2.5 Rain Depolarization

2.2.5.1 Chu Empirical Models

2.2.5.2 ITU-R Rain Depolarization Model

2.2.6 Ice Depolarization

2.2.6.1 Tsolakis and Stutzman Model

2.2.6.2 ITU-R Ice Depolarization Prediction

2.2.7 Wet Surface Effects

2.2.7.1 Wet Antenna Surface Experiments

2.2.7.2 Wet Antenna Effects Modeling

2.2.7.2.1 The Smooth Conductor Model

2.2.7.2.2 The ACTS Reflector Model

2.2.7.2.3 Attenuation Due to Water on the Feed

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2.2.8 Scintillation

2.2.8.1 Tropospheric Scintillation

2.2.8.1.1 The Karasawa Model

2.2.8.1.2 ITU-R Scintillation Prediction Method

2.2.8.1.3 Scintillation Dynamics

2.2.8.2 Cloud Scintillation

2.2.8.2.1 Vanhoenacker Model

2.2.9 Worst Month Statistics

2.2.9.1 ITU-R Worst Month Prediction Model

2.2.10 Fade Rate and Fade Duration

Section 2 (cont'd)

6

2.2.11 Combined Effects Modeling

2.2.11.1 Feldhake Combined Effects Model

2.2.11.2 DAH Combined Effects Model

2.2.11.3 ESA Combined Effects Studies

2.3 RADIO NOISE

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2.3.2 Noise from Atmospheric Gases

2.3.3 Sky Noise Due to Rain

2.3.4 Sky Noise Due to Clouds

2.3.5 Noise From Extra-Terrestrial Sources

Section 2 (cont'd)

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2.5 LINK RESTORATION MODELS

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2.5.1.1 Hodge Site Diversity Model

2.5.1.2 ITU-R Site Diversity Model

2.5.2 Orbit Diversity

2.5.3 Link Power Control

2.5.3.1 Uplink Power Control

2.5.3.2 Downlink Power Control

2.5.4 Adaptive FEC

2.5.4.1 Block Codes

2.5.4.2 Convolutional codes

2.5.4.3 Concatenated Codes

2.5.4.4 Trellis codes

Section 3 APPLICATIONS

- 3.1 APPLICATION OF PREDICTION MODELS TO SYSTEM DESIGN AND PERFORMANCE
 - 3.1.1 General Link Analysis Procedures
 - 3.1.2 Design Considerations
 - 3.1.3 Selection of a Rain Attenuation Prediction Model
- 3.2 PROPAGATION EFFECTS ON SATELLITE SYSTEMS OPERATING BELOW 3 GHZ
 - 3.2.1 General Link Propagation Parameters
 - 3.2.2 Mobile Satellite System Service Links

Section 3 (CONT'D)

2

- 3.3 PROPAGATION EFFECTS ON K_U -BAND SYSTEMS
 - 3.3.1 K_U -band FSS Systems
 - 3.3.2 Low Margin K_U -band Systems
- 3.4 PROPAGATION EFFECTS ON K_A -BAND SYSTEMS
 - 3.4.1 K_a -band FSS Systems
 - 3.4.2 Low Margin K_a -band Systems
- 3.5 PROPAGATION EFFECTS ON Q/V-BAND SYSTEMS
 - 3.5.1 Q/V-Band Rain Attenuation Evaluation Procedure

3.6 PROPAGATION EFFECTS ON DIRECT BROADCAST SATELLITE SYSTEMS

3.7 PROPAGATION EFFECTS CONSIDERATIONS FOR NGSO SYSTEMS

3.7.1 NGSO Links and Rain Attenuation Statistics Evaluation

Handbook Highlights



Statistical pattern of scintillation measured on observation of 11.45 MHz SSB signal

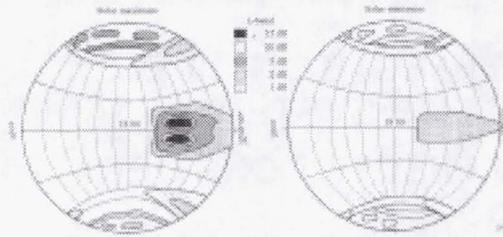


Figure 1.2.3.2-1 Pattern of ionospheric scintillation based on observations at 11.45 MHz (16/11/12) (Source: ITU-R Rec. P.367-2 (1977))

Several measures or indices of scintillation have been used. Attention was given to the subject of indices by Briggs and Padua (1963) who introduced indices designated by S_1 , S_2 , S_3 , and S_4 . The index S_4 , representing the standard deviation of received power divided by the mean value is said to be the most useful of the several indices (Kishcha and Working Group, 1978). It is given by

$$S_4 = \frac{1}{P} \left[\overline{(P^2 - P^2)} \right]^{1/2} \quad (1.2.3.2-1)$$

where P is field intensity. A similar index, m , is defined as the ratio of rms fluctuations to mean value of power.

The index S_4 has been proposed as a convenient approximate measure of scintillation (Whitney, Aarons, and Maki, 1969). It is defined by

$$S_4 = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} \quad (1.2.3.2-2)$$

where the P 's represent power. In order to avoid over-emphasizing extreme conditions, it is recommended that the third peak down from the maximum and the third minimum up from the absolute minimum be used to define P_{max} and P_{min} .

Propagation Effects Fundamentals Overview

- Background Theory
- Measurements
- Analytic Descriptions
- Extensive References
- Example:

➤ Ionospheric Scintillation Patterns

Step-by-Step Procedures Example: ITU-R Rain Model

2.2.4.1 ITU-R Rain Model

The ITU-R rain attenuation model is the most widely accepted international method for the prediction of rain effects on communications systems. The model was first approved by the ITU in 1962 and is continuously updated to take atmospheric modeling to newer understandings. This section describes the ITU-R model as described in the latest version of Recommendation ITU-R P.838-6 (1997), and includes revisions incorporated by ITU-R Working Party 5-4 at the October 1999 meeting (ITU-R Document 3.24, 1999). The modeling procedure calculation consists of path attenuation at a given location for frequencies up to 100 GHz.

The input parameters required for the ITU-R Rain Model are:

- f : the frequency of operation, in GHz
- θ : the elevation angle of the satellite, in degrees
- h_p : the altitude of the ground station, in degrees PL or SL
- τ : the polarization tilt angle with respect to the horizontal, in degrees
- h_g : the altitude of the ground station above sea level, in km
- $R_{0.01}$: path available rain rate for the location of interest for 0.01% of an average year, in mm/h

The step-by-step procedure follows:

1) Calculate the rain height h_R at the ground station of interest

The freezing rain height (or 0°C isotherm) is the upper atmospheric altitude at which rain is the dominant near horizon rain and ice. The rain height is defined in km above sea level. Rain height is calculated as a function of ground station latitude ϕ . The rain height, latitude and elevation angle are then used to calculate the slant path L , through a rain cell and the horizontal component of the slant path L_h .

The ITU-R rain height assumes that the rain height is a function of latitude ϕ . The rain height h_R is found as follows:

$$h_R = \begin{cases} 5 - 0.875\phi - 23 & \text{for } \phi = 39^\circ \\ 3 & \text{for } -21^\circ \leq \phi \leq 23^\circ \\ 5 + 0.25\phi + 23 & \text{for } -\phi \leq \phi \leq -23^\circ \\ 3 & \text{for } \phi = -39^\circ \end{cases} \quad (2.2.4.1-1)$$

where ϕ is the latitude of the ground station location. Positive ϕ corresponds to the Northern Hemisphere, and negative ϕ corresponds to the Southern Hemisphere. The rain height is expressed in km and is expected to be a value greater than zero. The model is only valid for latitudes less than 39.6° or greater than 39.6°.

2) Calculate the slant path length L , and horizontal projection L_h , from the rain height and elevation angle and the altitude of the ground receiver site.

Rain attenuation is directly proportional to the slant path length. The slant path length L , is defined as the length of the non-horizontal path that is affected by a rain cell (see Exhibit 2.2.4.1-1).



- A) Slant path length
- B) rain height
- C) Slant path projection
- D) earth's surface path

Exhibit 2.2.4.1-1 Slant Path through Rain

The slant path length L , expressed in km, is determined from:

$$L = \frac{h_s - h_g}{\sin \theta} \quad \text{for } \theta \leq 9^\circ$$

$$L = \frac{h_s - h_g + h_R}{\sin \theta} \quad \text{for } \theta > 9^\circ \quad (2.2.4.1-2)$$

where:

- h_s = the satellite height (km), from Step 1
- h_g = the altitude of the ground receiver site from sea level (km)
- θ = the elevation angle
- h_R = 5000 km reflective earth radius

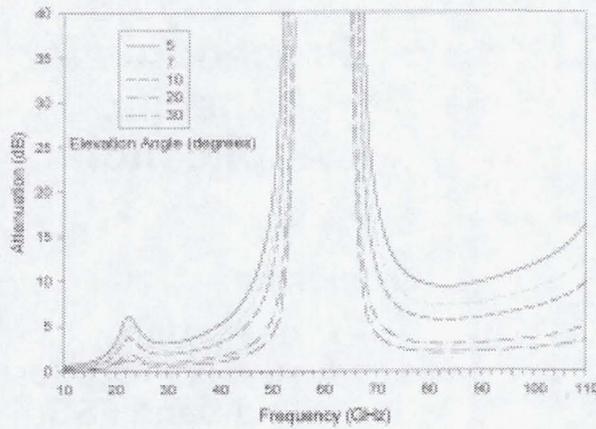


Exhibit 1.3.3-2
Total path gaseous attenuation versus frequency for elevation angles from 5 to 30 degrees.
Location: Washington DC.

Atmospheric Effects Dependencies

- Example:
 - Total Gaseous Attenuation
 - Elevation Angles from 5 to 30 degrees
 - Frequency from 10 to 110 GHz

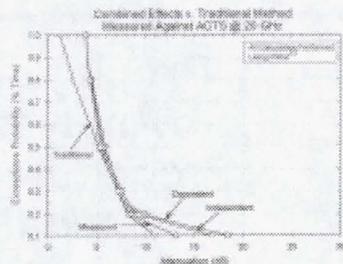


Exhibit 2.2.11.1-5
Independent, Dependent, and Traditional Prediction Techniques Compared with Measured ACTS Data at 25.185 GHz.

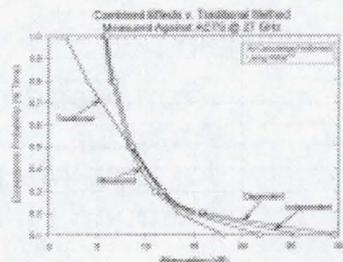
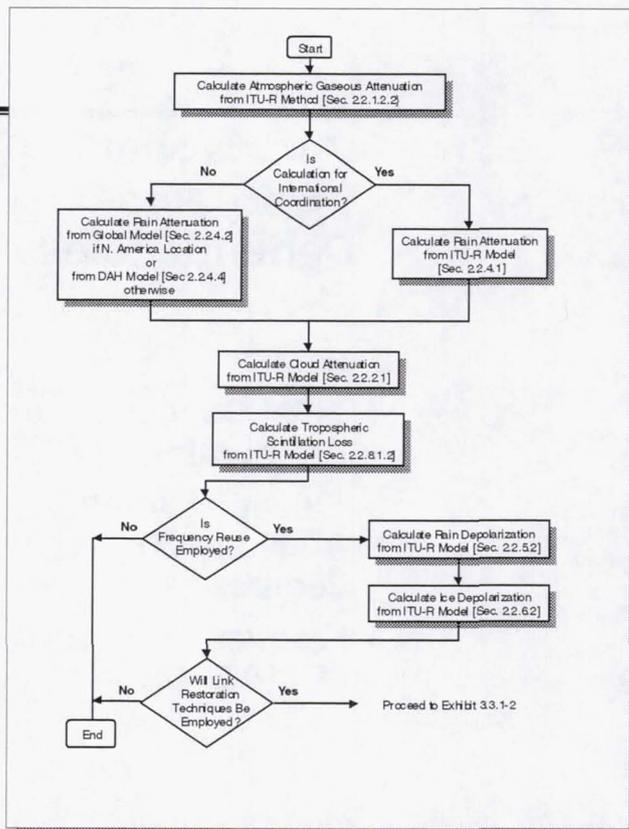


Exhibit 2.2.11.3-G
Independent, Dependent, and Traditional Prediction Techniques Compared with Measured ACTS Data at 27.585 GHz.

Application of ACTS Data

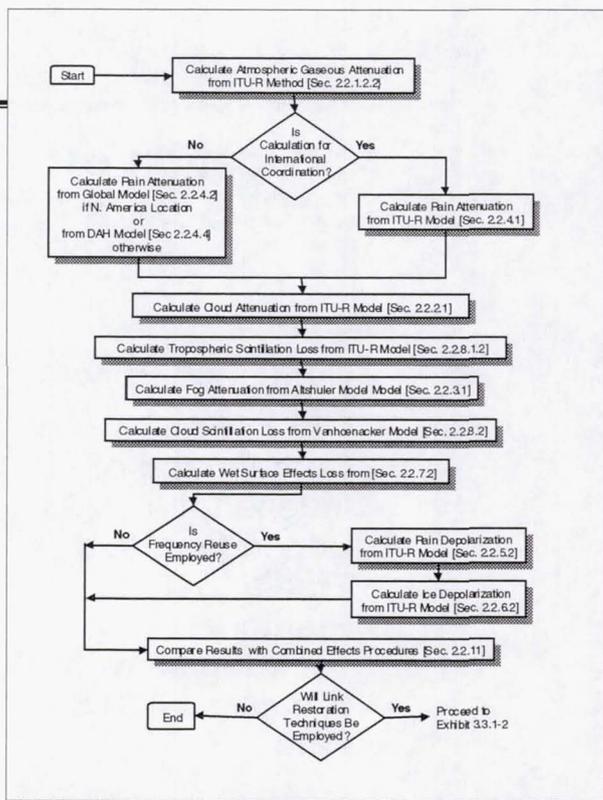
- Example:
 - Combined Effects Modeling
 - Comparison of Independent, Dependent, and Traditional Prediction Techniques with Measured ACTS Data



Propagation Analysis Procedures for Specific Applications

□ Example:

➤ Propagation Analysis Procedure for Ka-band FSS Links



Propagation Analysis Procedures for Specific Applications

□ Example:

➤ Propagation Analysis Procedure for Low-Margin Ka-band Links

Link Outage Evaluation for Non-GSO Satellite Constellations

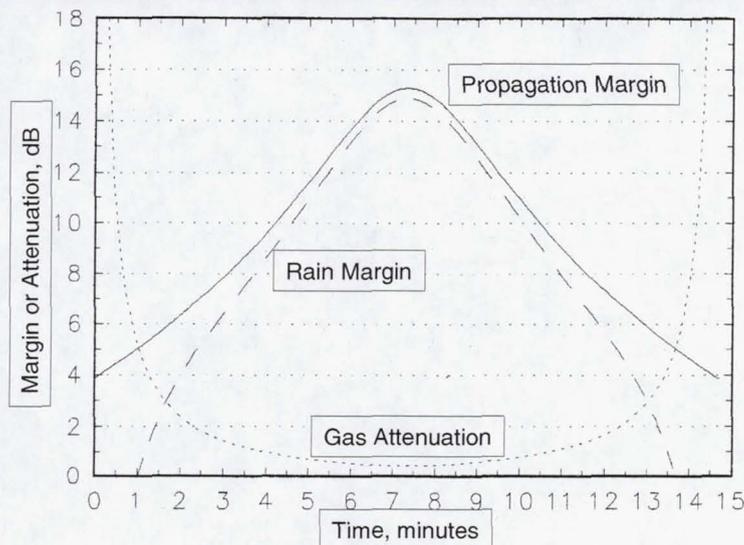


Exhibit 3.7-2

Total Propagation Margin and Allocation of Margin to Gaseous Attenuation and Rain Attenuation, for Single Pass of a LEO Satellite
Frequency = 20 GHz

Summary and Future Plans

- Handbook Delivered to JPL October 23 1998
- Revision 1 Released February 1999
- Electronic Version on-line at JPL
 - <http://propagation.jpl.nasa.gov/>
- On-going Peer Review
- JPL/ITT extension to update handbook signed May 2000
 - Revision 2 to Fifth Edition
 - Corrections, Minor Changes from Peer Review
 - Add index, list of symbols
 - Add ACTS 5 year Data Base
 - Update ITU-R Models

Full Conference Paper Available: Louis.ippolito@itt.com

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2.4 - Special Effects: Antenna Wetting, Short Distance Diversity and Depolarization

Dr. Roberto Acosta
NASA Glenn Research Center
Cleveland, Ohio

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

Outline of Presentation

-  Antenna Wetting Physics and Modeling
-  Antenna Wetting Experiment and Model validation
-  Propagation Data Correction Example
-  Depolarization Experiment and Results
-  Short Distance Diversity Experiment and Results
-  Conclusive Remarks

Team Members

ITT Industries

- Cynthia Grinder
- Lynn Ailes-Sengers

Westenhaver Wizard Works Inc.

- David Westenhaver

Florida Atlantic and South Florida Universities

- Henry Helmken
- Rudolph Henning

Florida Solar Energy Center

- Carol Emrich
- Jerry Ventry

NASA Glenn Research Center

- Bill Gauntner
- Dave Kifer
- Walber Feliciano

FADE CHARACTERISTICS

Rain Induced (random)

$$S_{\text{rec}}(t) = S_{\text{clear}}(t) \times A_T(t) + n(t)$$

$$\text{Attenuation}(t) = A_r(t) + A_w(t) + A_d(t) + A_s(t) + A_g(t) + A_c(t) + A_m(t)$$

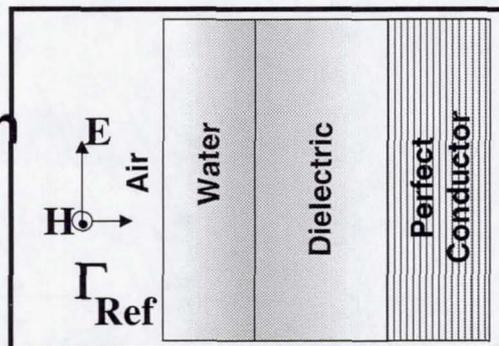
	<u>Rain fade depth</u>	(A _r)
	<u>Wet-antenna</u>	(A _w)
	<u>Depolarization</u>	(A)
	Rain	
	Ice	
	<u>Tropospheric Scintillation effects</u>	(A _s)
	<u>Gaseous absorption</u>	(A _g)
	<u>Cloud attenuation</u>	(A _c)
	<u>Melting layer attenuation</u>	(A _m)

Impact of Wet Antenna

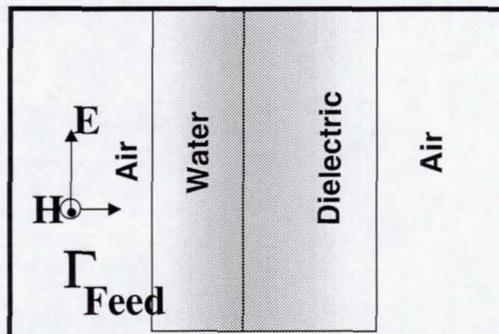
- Propagation model verification and system design
 - ➔ Required the attenuation measurements to be referenced to clear sky (no antenna wetting or gaseous attenuation)
- Ka band ground station reflector design
 - ➔ Required minimum attenuation due to wet surfaces (reflector and feed)

Wet Antenna Attenuation Physics

Reflector attenuation Mechanism

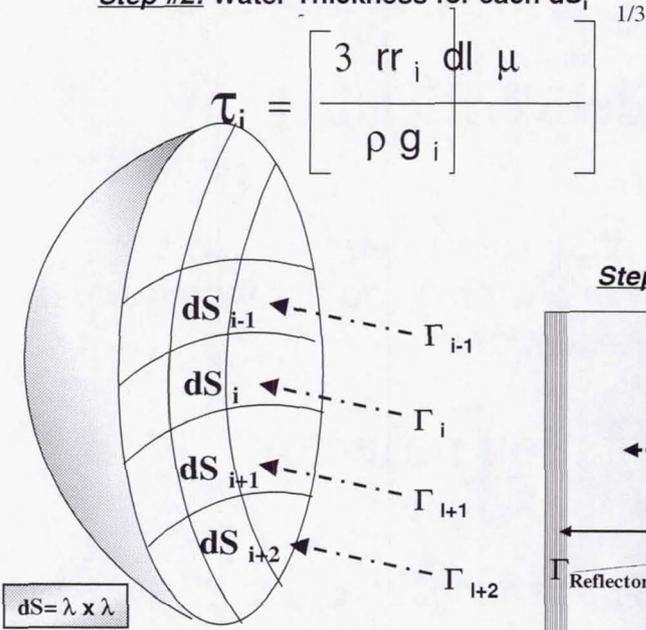


Feed attenuation mechanism



Wet Antenna Model

Step #2: Water Thickness for each dS_i



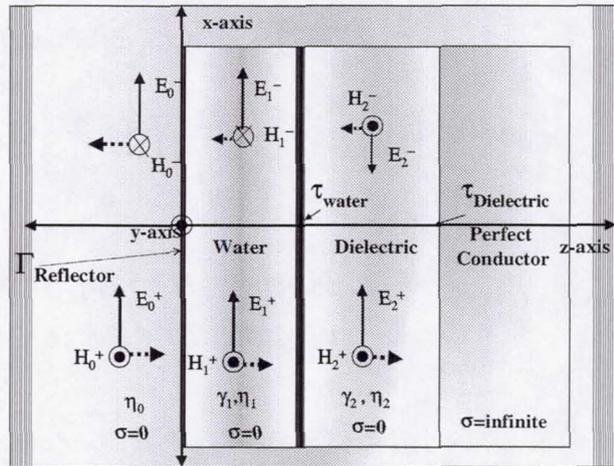
$$\tau_i = \left[\frac{3 rr_i dl \mu}{\rho g_i} \right]^{1/3}$$

- rr_i : rain rate normal vector
- g_i : gravity normal vector
- μ : Viscosity of water
- dl : Square length
- ρ : Density of Water
- τ_i : Water Thickness

Step #1: Segmented Reflector

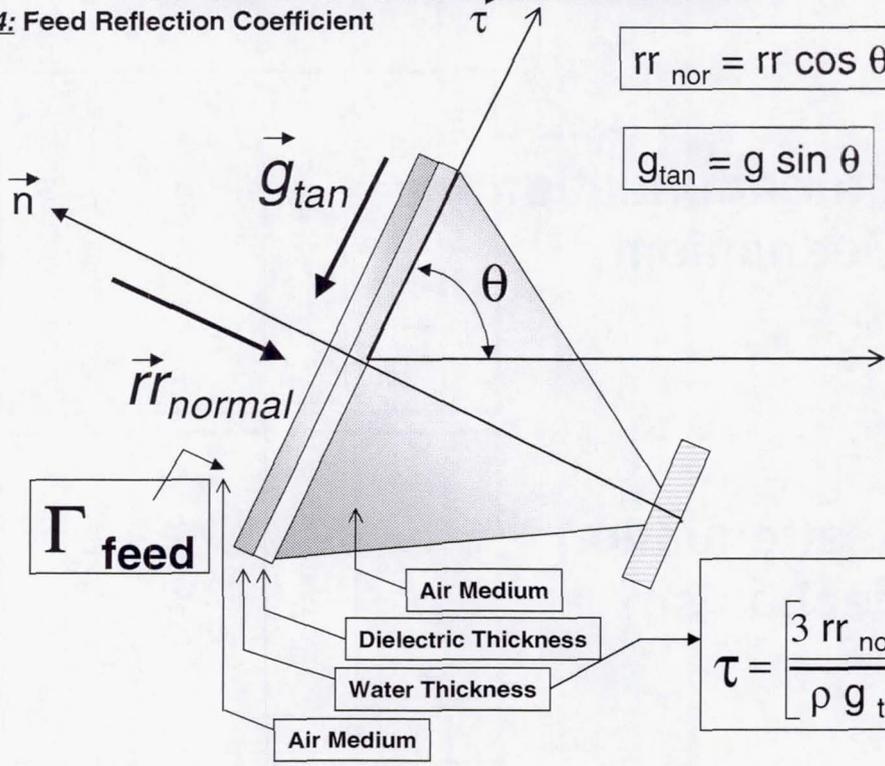
(1.2 m - 80 x 80 points)

Step #3: Reflection Coefficient for each dS_i



Wet Antenna Model

Step #4: Feed Reflection Coefficient



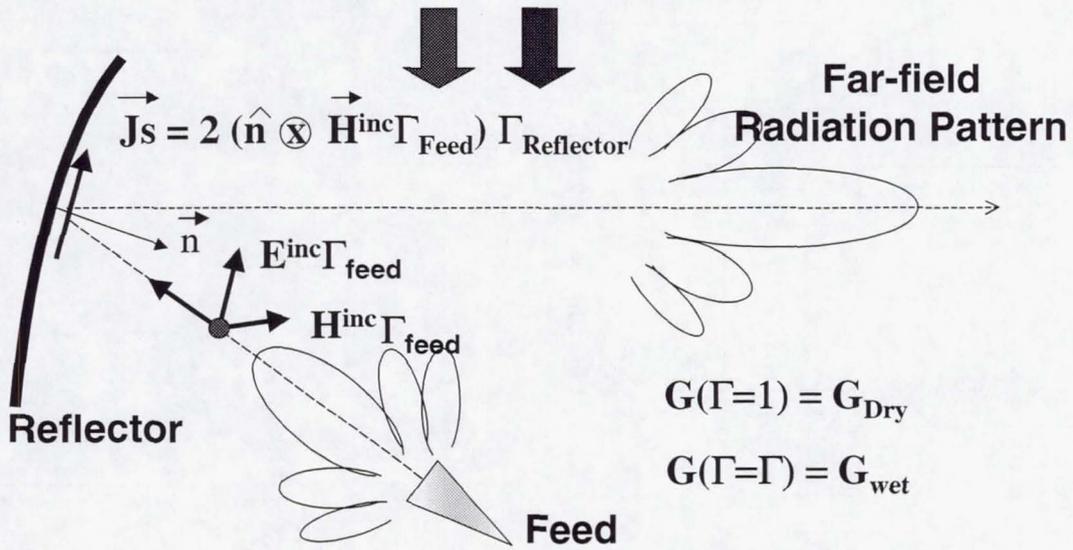
$$rr_{nor} = rr \cos \theta$$

$$g_{tan} = g \sin \theta$$

$$\tau = \left[\frac{3 rr_{norm} dl \mu}{\rho g_{tan}} \right]^{1/3}$$

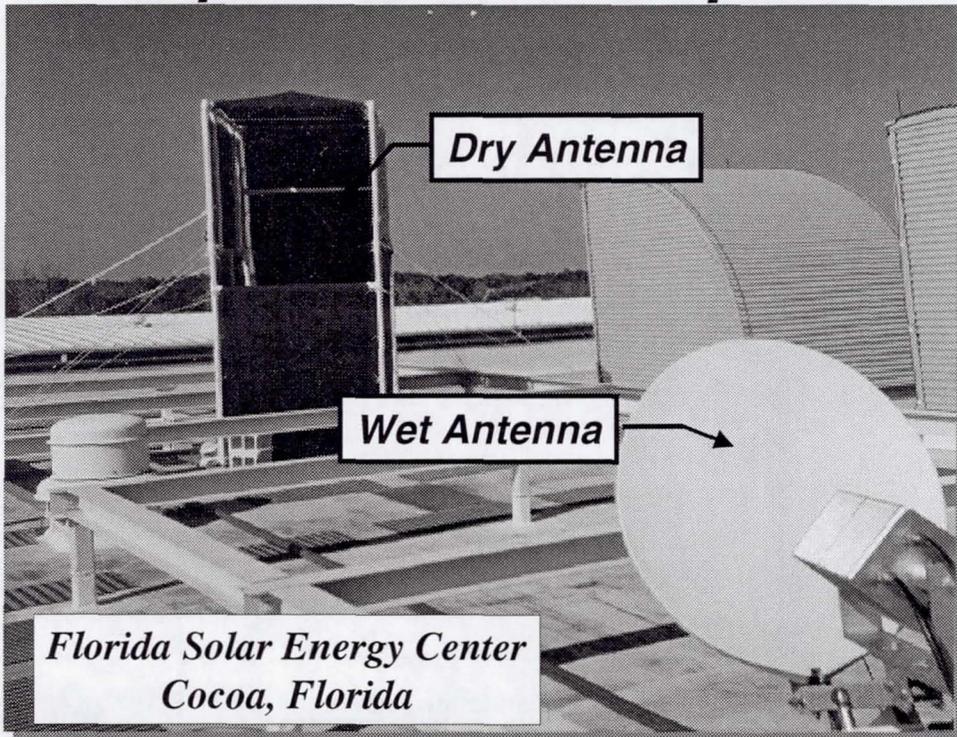
Wet Reflector Antenna Model

Step #5: Antenna Gain Calculation

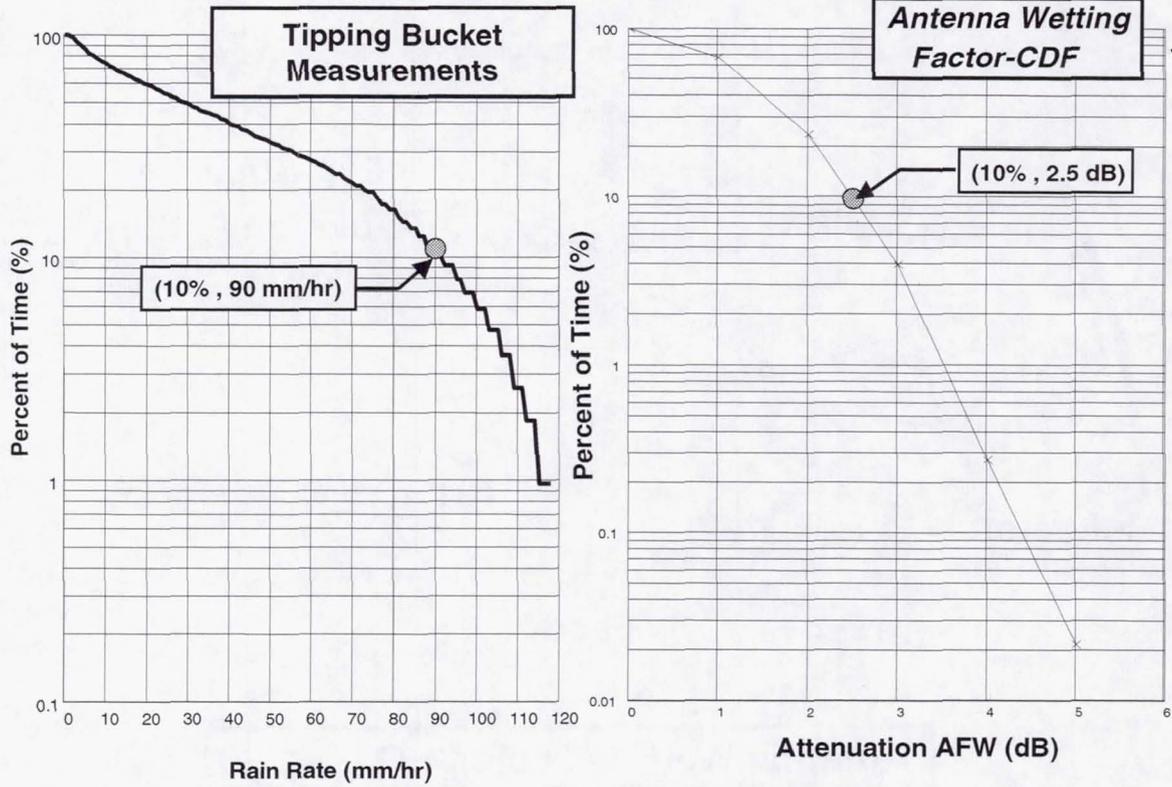


Antenna Wetting Factor = $G_{Dry} - G_{wet}$

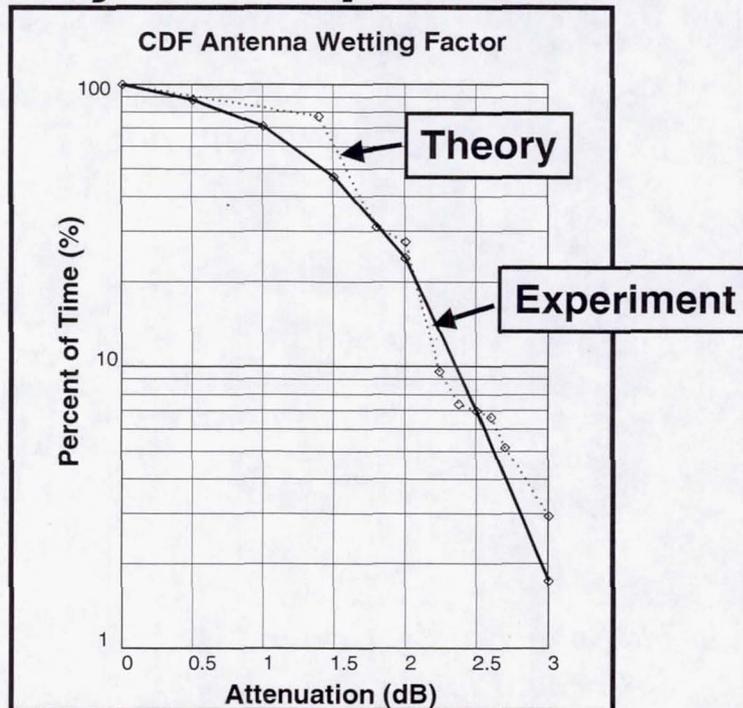
Experiment Description



Experiment Results



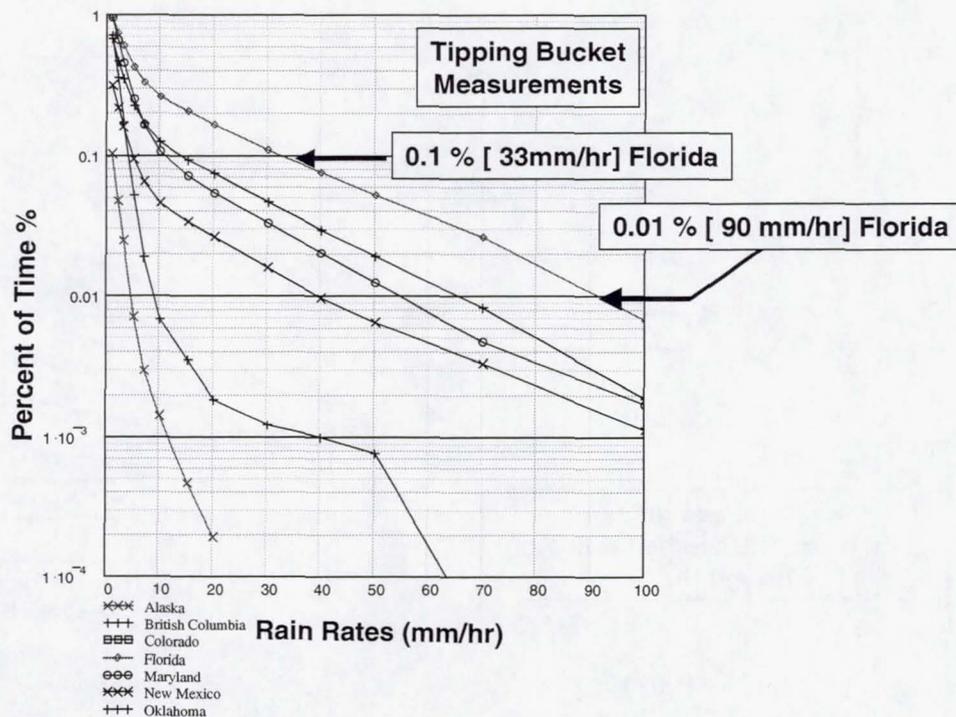
Model Validation Theory vs. Experiment



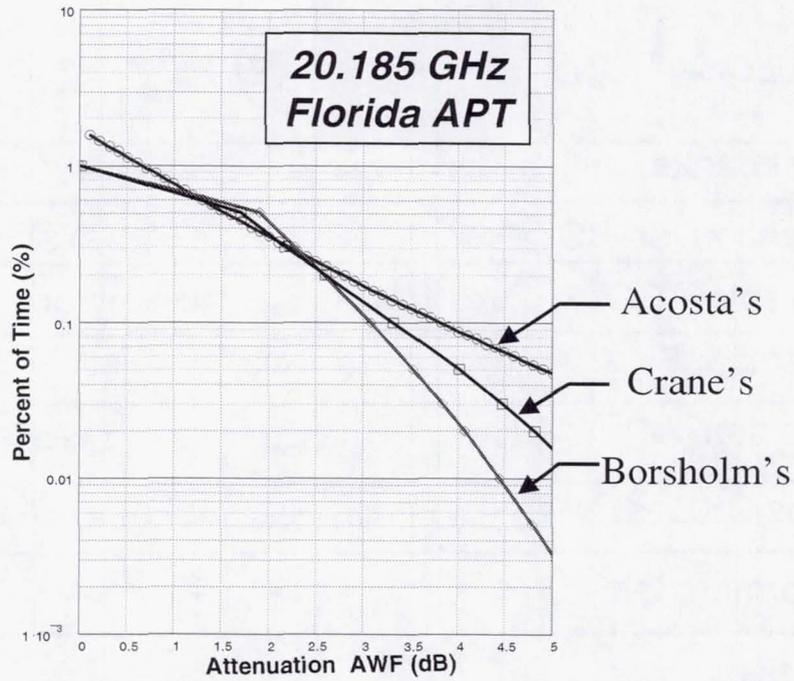
Propagation Site Parameters

LOCATION	Latitude (Deg.)	Longitude (Deg.)	Height (Km)	Elevation (Deg.)	Azimuth (Deg.)	Feed Plate Angle From Horiz. (Deg.)	Tilt Angle From Horiz. (Deg.)	Ref. Plate Ang. From Horiz. (Deg.)
Fairbanks, AK	64.85	147.82	0.18	8.0	129.3	53.4	70.6	84.6
Vancouver, BC	49.25	123.22	0.01	29.3	150.5	74.7	71.1	76.9
Greeley, CO	40.33	104.61	1.90	43.1	172.8	88.5	84.6	59.1
Tampa, FL	28.06	82.42	0.05	52.0	214.0	97.4	60.4	47.0
Reston, VA	38.95	77.33	0.08	39.2	213.3	84.6	64.4	64.3
Las Cruces, NM	32.54	106.61	1.46	51.5	167.8	96.9	79.7	47.7
Norman, OK	35.21	97.44	0.42	49.1	184.4	94.5	86.4	50.9

Measured Rain Rates

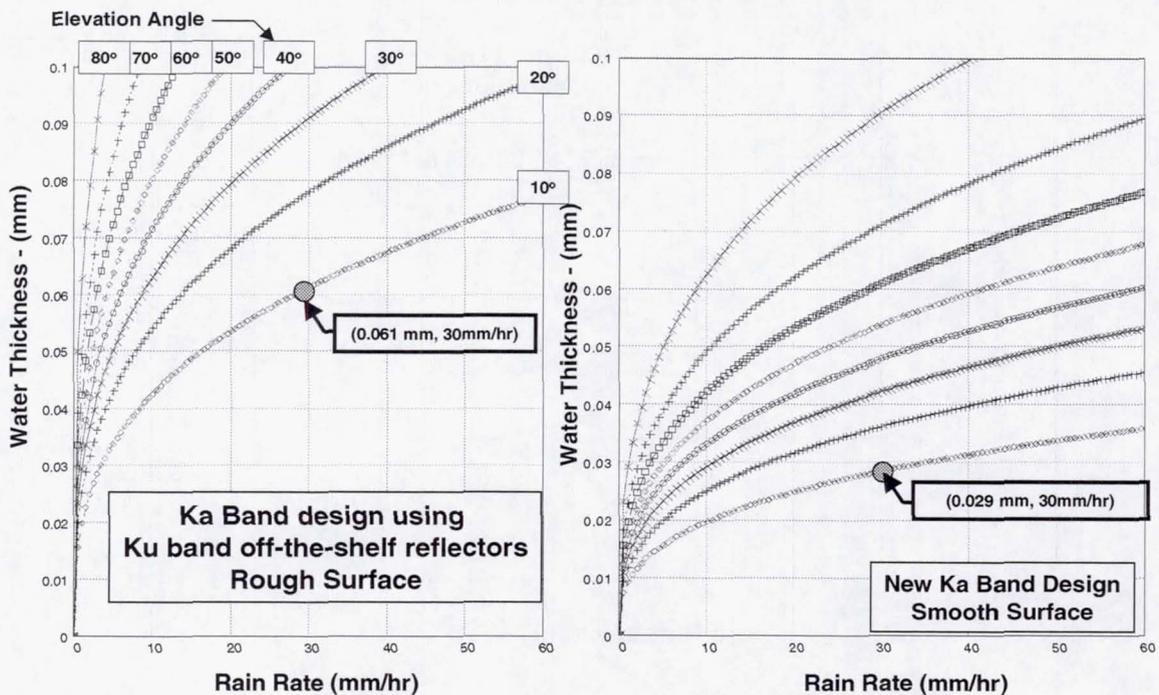


Example of Correction for Wet Antenna - CDFs



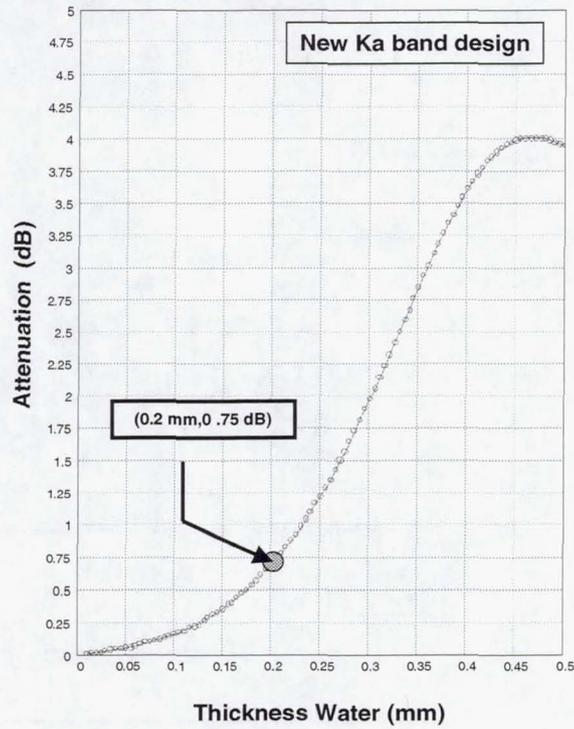
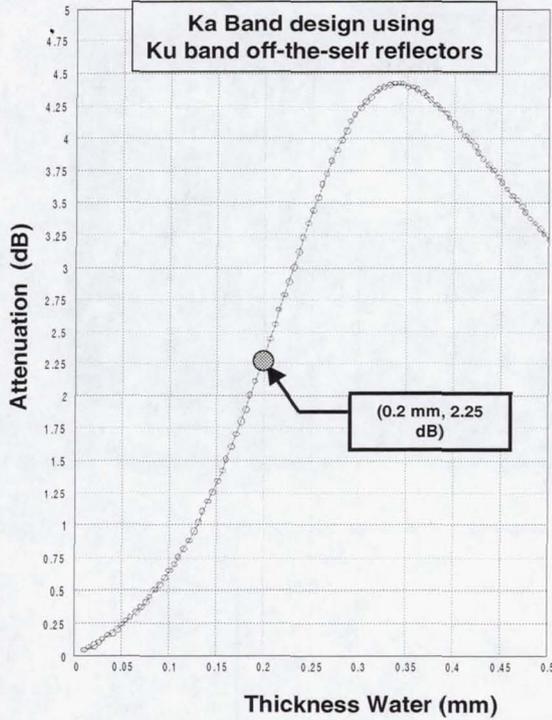
Reflector Design Procedure

Step #1 - Smooth Surface



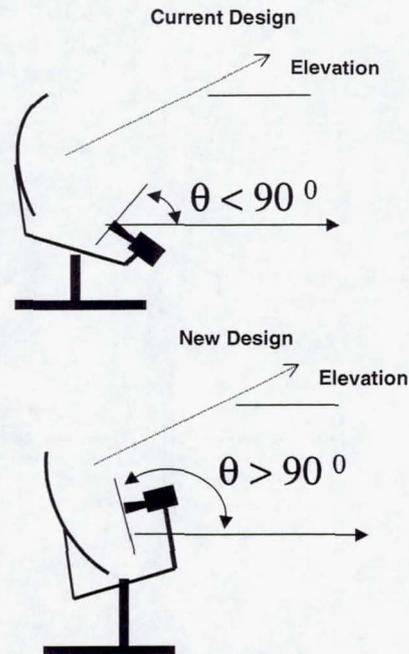
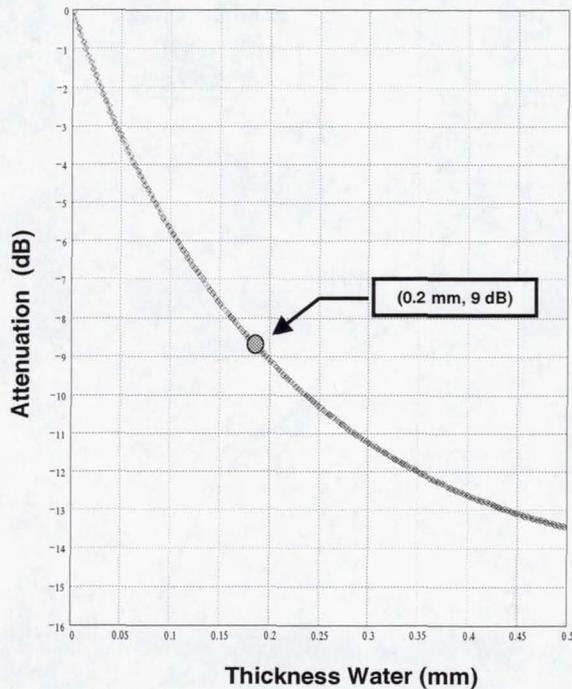
Reflector Design Procedure

Step #2- Minimize Dielectric Thickness

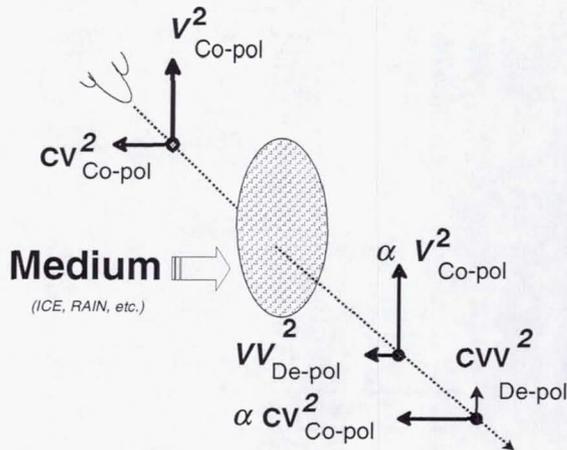


Reflector Design Procedure

Step #3 - Offset Reflector Geometry

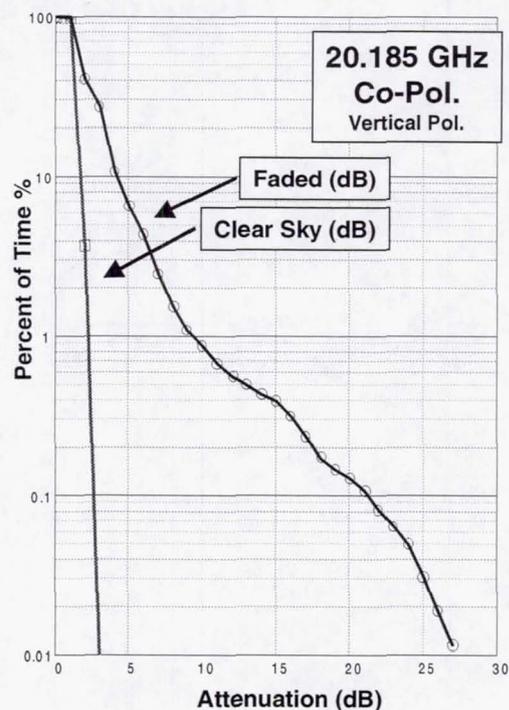
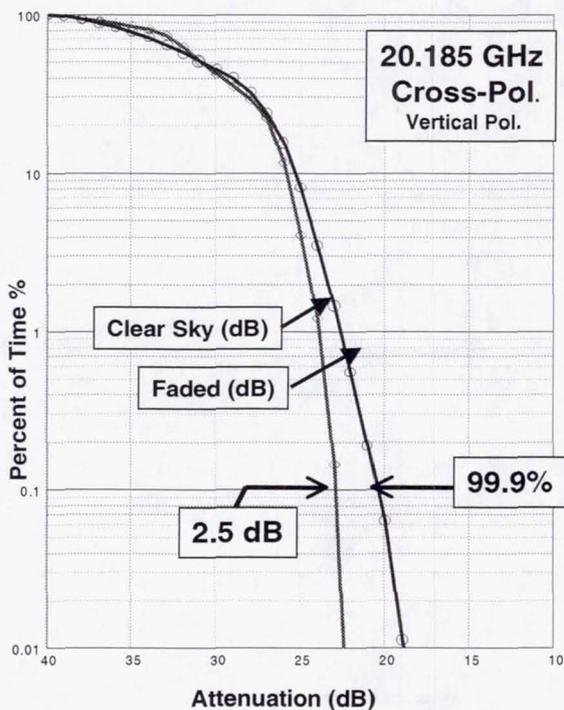


Depolarization Experiment

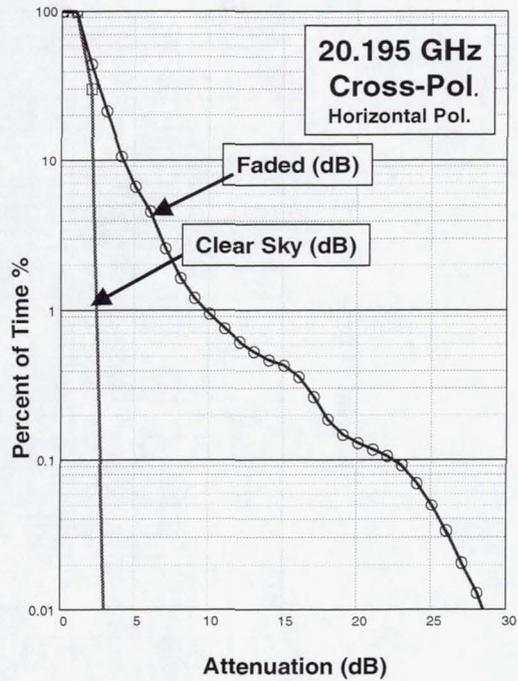
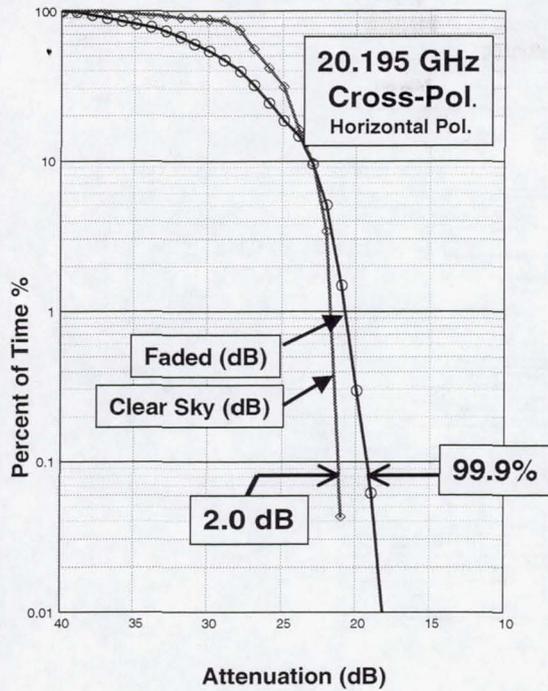


Total Field	Co-pol = $\alpha V^2_{\text{Co-pol}} + CVV^2_{\text{De-pol}}$
	Cross-pol = $\alpha VV^2_{\text{De-pol}} + CV^2_{\text{Co-pol}}$

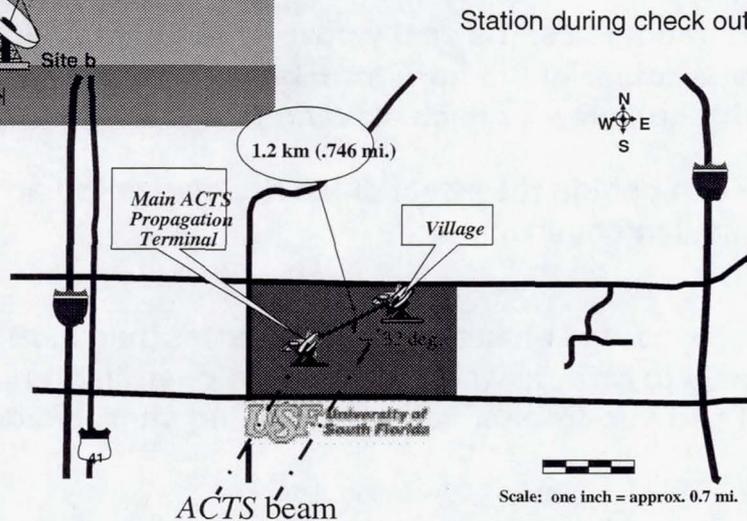
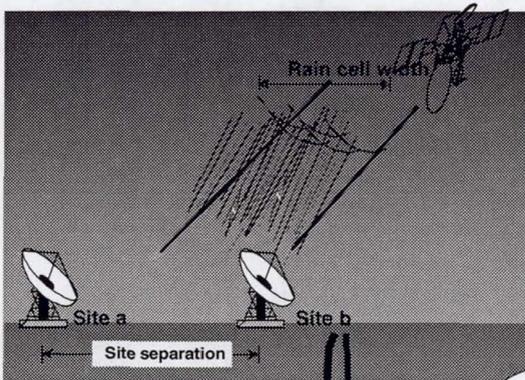
Depolarization Experiment



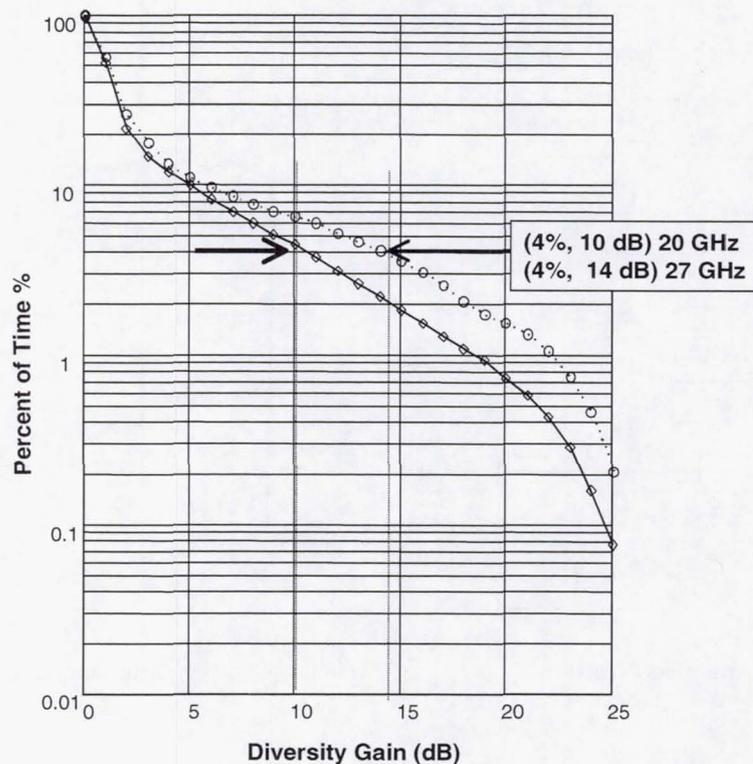
Depolarization Experiment



Short Distance Diversity Experiment



Short Distance Diversity Experiment



Conclusive Remarks

- ➔ In order to minimize the effect of wet reflectors, the dielectric thickness of the reflector needs to be reduced and the surface has to be smooth in order to reduce the losses in the presence of a water layer.
- ➔ The feed radome can be easily covered on the topside to protect the phase center of the horn from being exposed to water. Offset geometry optimize for each elevation angle.
- ➔ For system design the effect of ice depolarization appears to be small in occurrence.
- ➔ A typical expected enhancement of greater than 5 dB is more likely to be achievable in systems operating in tropical and sub-tropical rain zones using short distance diversity.

3.1 - Survey of Advanced Applications Over ACTS

Robert Bauer
NASA Glenn Research Center
Cleveland, Ohio

Paul McMasters
Analex Corporation
Cleveland, Ohio

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio



Experiment Categories

- **Technology Verification & Characterization**
 - ACTS-specific technologies
 - Ka-band component/subsystem
- **Propagation**
 - Ka-band characterization - fixed and mobile
 - Other effects - de-pol, dispersion
 - Mitigation techniques - diversity, power control
- **Applications & Networking**
 - Business Development and Service Improvement
 - Health, Education, and Public Wellness
 - Telescience
 - Broadband Network Interoperability & Protocol Verification



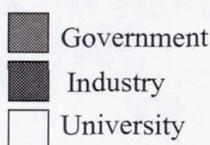
Experiment Program Goals

1. Demonstrate transitioning to future commercial satellite services in support of NASA & other government missions
2. Test, verify & resolve technical issues using Asynchronous Transfer Mode (ATM), Internet Protocol (IP), or other protocols over satellite, including interoperability issues with terrestrial networks
3. Characterization of the ACTS system and operations in inclined orbit
4. Verify new satellite Ka-band technology and hardware

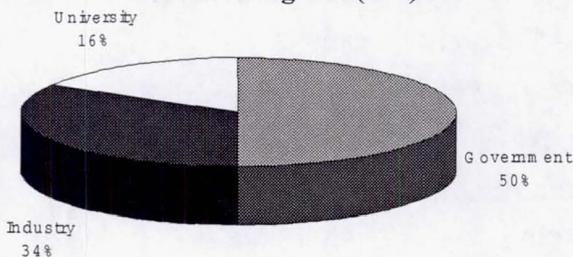
* Defined for inclined orbit operations phase



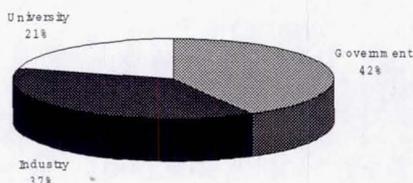
Selected Experiments



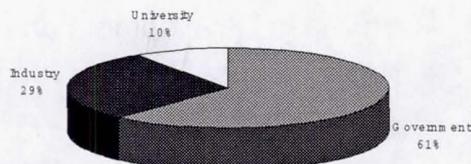
Entire Program (104)



FY94-95 (59)



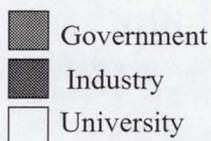
FY96-00 (45)



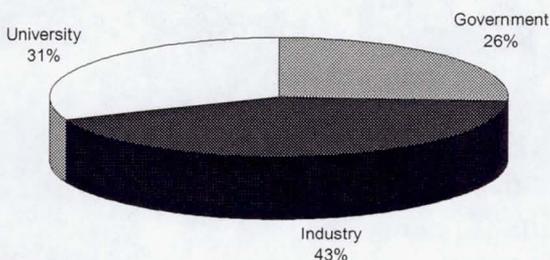


Glenn Research Center

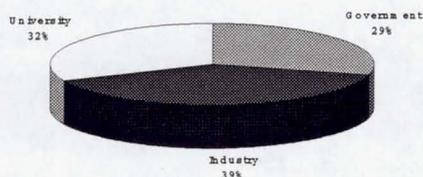
Unique PI Organizations



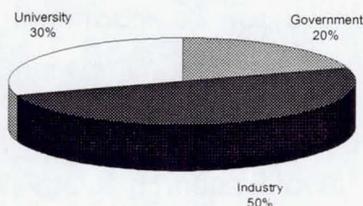
Entire Program (61)



FY94-95 (40)

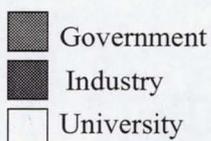


FY96-00 (21)

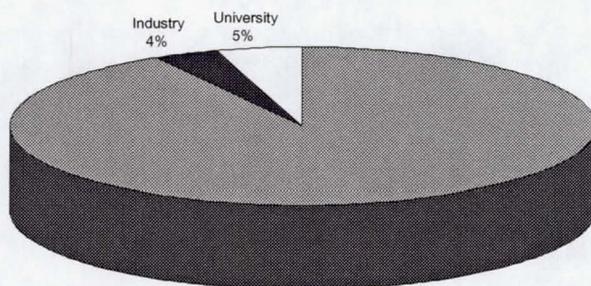


Glenn Research Center

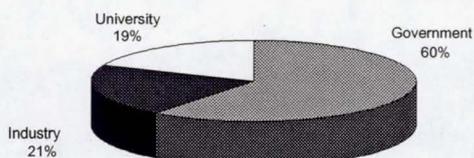
Experiment Hours Used



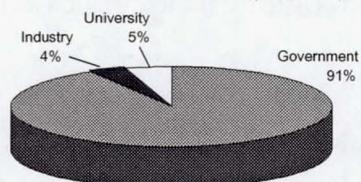
Entire Program (74,248)



FY94-95 (18,937)



FY96-00 (55,311)





Advanced Applications

Business Development & Service Improvement



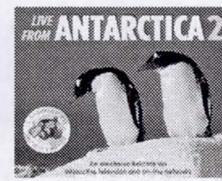
- AT&T
- Globalstar
- NASA GRC - Advanced Air Trans. Tech'gy
- Lockheed Martin Systems, Inc.
- Intelsat
- Raytheon Telecommunications Company

- Caterpillar
- Lockheed Martin/JPL
- Naval Research & Development (now SPAWAR)
- Savannah State Univ/FL Solar Energy Ctr.



Advanced Applications

Health, Education & Public Wellness



- University of Hawaii
- Southwest Research Institute
- Montana Telemedicine Demonstration

- Mayo Clinic
- NASA GRC/Cleveland Clinic/Univ. of Virginia
- Passport to Knowledge

Advanced Applications

Telescience



- NASA HPCC - Keck Observatory
- NASA HPCC - Global Climate Modeling
- Houghton Mars Project

Advanced Applications

Broadband Network Interoperability & Protocol Verification



- NTIA/Institute for Telecommunications Science
- California State University - Hayward
- ACT Corporation
- NASA GRC

- Air Force Research Laboratory - Rome
- Ohio University
- Naval Research Laboratory
- 118x/154 Industry Consortium
- Carnegie Mellon University

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3.2 - NASA/DARPA ACTS Project for Evaluation of Telemedicine Outreach Using Next-Generation Communications Satellite Technology

B.K. Khandheria
Mayo Clinic
Rochester, Minnesota

M.P. Mitchell
Mayo Clinic
Rochester, Minnesota

B. Gilbert
Mayo Clinic
Rochester, Minnesota

A. Bengali
Mayo Clinic
Rochester, Minnesota

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio



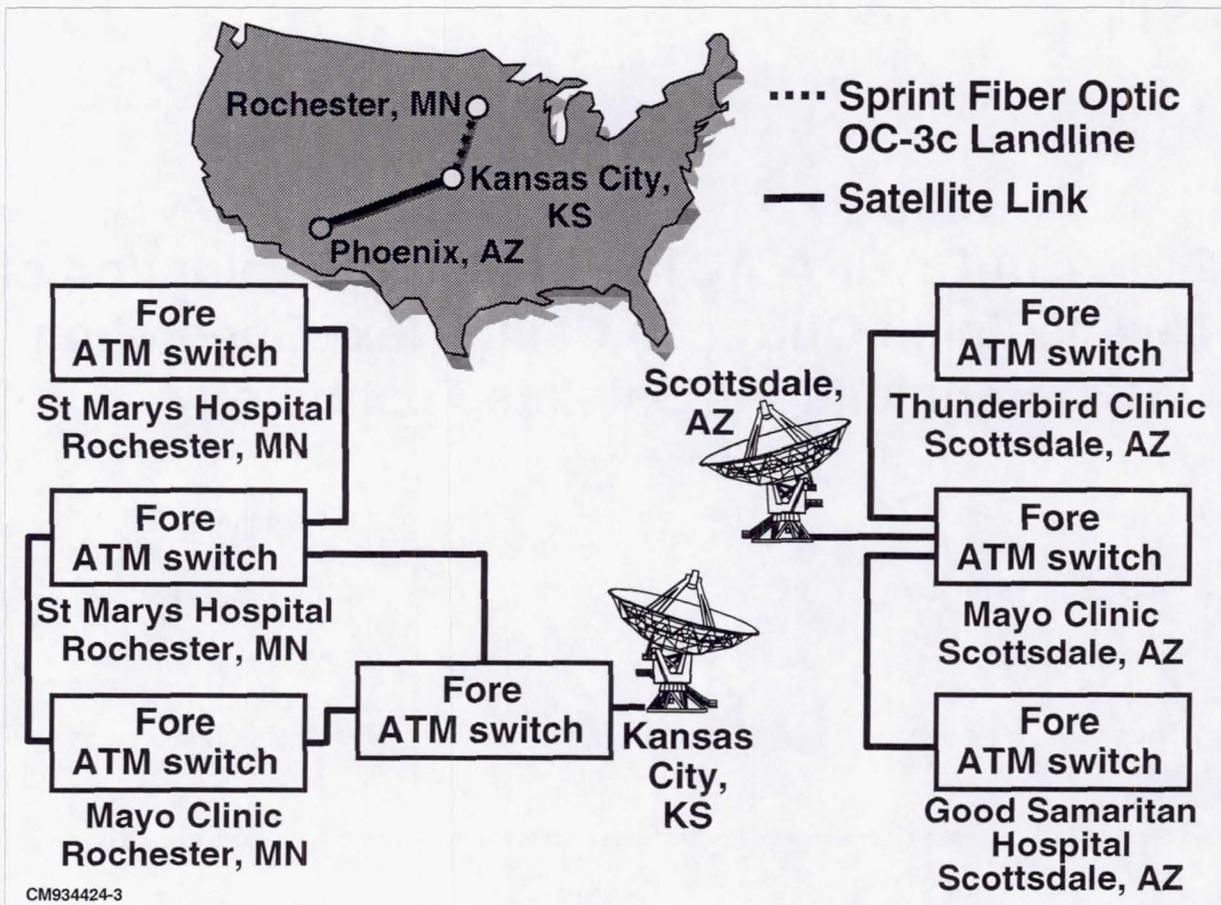
NASA/DARPA ACTS HDR

Objective

**Evaluate feasibility,
practicality**

Remote consultation

Diagnostic technique



NASA/DARPA ACTS HDR

Projects

- Remote digital echocardiography
- Store and forward telemedicine
- Cardiac catheterization – remote diagnosis
- Teleconsultation for congenital heart disease



NASA/DARPA ACTS HDR

Digital Echocardiography

**Validated accuracy of
digital Echo transmitted via
ACTS ATM link 156 cases –
99% concordance**



Digital Echocardiography

Outcome

- **Remote transfer of cardiac ultrasound is a part of clinical practice at Mayo**
- **26 locations in Midwest send data via terrestrial link**



NASA/DARPA HDR

Store and Forward n=15

Compare SAF with face-to-face

- **100% concordance**
- **Clinically acceptable**

Mayo Clin Proc, 1997



Store and Forward Outcome

**In clinical practice between
Mayo Clinic and UAE**

Issues

- **Requires electronic records**
- **Integration of diagnostic tools
with desktop**
- **Packaging of correct
information is laborious**



NASA/DARPA ACTS HDR

Cardiac Catheterization

- Transmission of uncompressed high-fidelity digital angiographic image achieved
- System can facilitate access to remote expertise

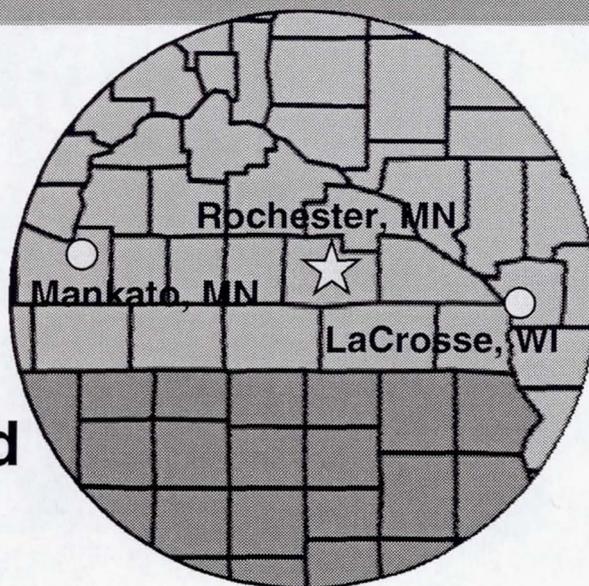
In Press



Cardiac Catheterization

Outcome

- Implemented for clinical practice at 2 sites
Mankato, MN and LaCrosse, WI



- 1-year experience – very +ve



NASA/DARPA ACTS HDR

Congenital Heart Disease

54 Teleconsultations

- **High degree of concordance**
- **Dynamic display – very useful**
- **Interobserver agreement at 98%**

3.3 - ACTS Satellite Telemammography Network Experiments

Brian A. Kachmar
Analex Corporation
Cleveland, Ohio

Robert J. Kerczewski
NASA Glenn Research Center
Cleveland, Ohio

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio



Outline

- Introduction
- Satellite Telemammography Network (STN)
- Main Accomplishments
- Other Highlights of STN Project
- Impact on Telemedicine
- Importance of ACTS
- Future of Satellite Telemedicine
- Summary



Introduction

- Breast cancer
 - ◆ leading cause of death in women age 35 - 50
 - ◆ second leading cause of death in all women
- Mammography screening
 - ◆ increases survival rates
 - ◆ need for certified experts for interpretation
 - ◆ needed for more than 60 million Americans
- X-ray film
 - ◆ shipping is costly in time and money
 - ◆ digitization is advancing rapidly
 - ◆ will be replaced by totally digital solutions soon



Introduction (cont.)

- Teleradiology
 - ◆ can address problems with film
 - ◆ using satellite communications, can reach remote and mobile sites
- Telemammography
 - ◆ most difficult and data extensive modality
 - ◆ can serve millions living in remote locations
 - ◆ subject of this research



STN Experiment: Accomplishments

- Application of standard transmission protocols
- Transmission of over 5000 digitized mammography images through ACTS - all error-free
- First ever real-time telemammography session - compression, transmission, interpretation, and diagnosis
- Complete evaluation of end to end process - image capture, scanning, (de)compression, transmission/reception, viewing, and diagnosis



Highlights: Image Compression

- *Lossless* compression can achieve about 3:1 ratio
- To meet project goal to transmit a case in under one minute, *lossy* compression was required

Image Type	Images per case	Total data required (Mbytes)	Time to transmit at 56 kbps, mins.	Time to transmit at DS1, mins.	Compression ratio required for <1 min. to transmit at DS1
Mammography digitized film, 100 microns	4	24	57	2.1	4:1
Mammography digitized film, 50 microns	4	96	228	8.3	12:1
Mammography direct digital	4	192	457	16.6	20:1



ORIGINAL



**COMPRESSED
80:1**



Highlights: Clinical Studies

- Evaluation of Wavelet-Compressed Digitized Film Mammography
 - ◆ Sixty sets compressed at 8:1 using Daubechies wavelet
 - ◆ Mammographers reviewed in controlled study
 - ◆ Clinical accuracy comparable to original film
- Investigation of Optimum Wavelet for Mammography
 - ◆ On-going OSU grant
 - ◆ Early results promising



Highlights: Asymmetrical Links over Satellite

- Evaluated Cisco Internetworking Operating System (IOS) modified to perform over asymmetrical links
- Permits uplink through satellite on high-bandwidth channel with return link on a slower path
- Cisco router modification now available as COTS option



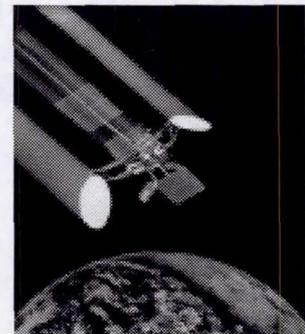
Impact of Satellite Telemammography Work

- Improved teleradiology processes
- Demonstrated feasibility of a totally digital mammography solution
 - ◆ University of Virginia and CCF progressing towards digital mammography systems
- Asymmetrical links can be integrated into medical networks with COTS products



Importance of ACTS

- Demonstrated to medical community the use of satellite links
 - ◆ high-quality DS1 links
 - ◆ very small earth stations
 - ◆ availability to remote locations





Future of Satellite Telemedicine

- Telemedicine is in its infancy
- Future will see growth of remote locations served by a specialized central hub with satellite links
- STN team currently participating in other telemedicine activities



Summary

- Proved feasibility of satellite-based teleradiology and telemammography
- Demonstrated new paradigm in medical care
 - ◆ experts centrally located with remote centers providing personalized care
- Fostered acceptance in medical community of compression to medical imagery
- Promoted use of TCP/IP over satellite links

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3.4 - Satellites and the Internet as a “Passport To Knowledge” A New Model of Teaching and Learning

Geoffrey Haines-Stiles
Project Director
Passport To Knowledge
Morristown, New Jersey

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

Passport to Knowledge*

Our mission is to:

- Excite students about science and technology
- Connect them to real scientists at real locations
- Enliven the curriculum by connecting key concepts to the real world.

*This presentation has been extracted by the editor from a video Mr. Haines-Stiles offered to the conference in his absence.

Sixth Ka-Band Utilization Conference/ACTS Conference 2000

Passport to Knowledge

Three ambitious and successful interactive learning projects that would not have been possible without ACTS:

- “Live from the Stratosphere”
- “Live from Antarctica”
- “Live from the Rainforest”

Sixth Ka-Band Utilization Conference/ACTS Conference 2000

Passport to Knowledge

“Live from the Stratosphere” (1995)

- Eight hours of live and interactive video
- First time 2-way video transmitted between ground and jet in flight
- Real astronomical observations in real time
- Connected to schools and science centers across the nation

Sixth Ka-Band Utilization Conference/ACTS Conference 2000

Passport to Knowledge

“Life from Antarctica 2” (1997)

- Live broadcast from NSF’s Palmer station in Antarctica
- Southernmost ACTS deployment ever
- It made students all across America eye-witnesses to life in extreme environments

Sixth Ka-Band Utilization Conference/ACTS Conference 2000

Passport to Knowledge

“Live from the Rainforest” (1998)

- First time ever 2-way educational TV out of the Amazon Rainforest
- Wettest ever deployment for the ACTS satellite
- Produced in cooperation with Brazil’s National Institute for Amazonian Research and the Smithsonian Institute

Sixth Ka-Band Utilization Conference/ACTS Conference 2000

Passport to Knowledge

Our thanks to all the people in the ACTS program who made our projects possible, including those at:

- NASA Glenn
- NASA/Caltech at JPL
- NASA Ames
- NASA Headquarters
- Lockheed Martin
- Mississippi State University

Sixth Ka-Band Utilization Conference/ACTS Conference 2000

3.5 - Advanced Shipboard Communications Demonstrations With ACTS

Roy A. Axford
Space and Naval Warfare
Systems Center
San Diego, California

Michael A. Rupar
Naval Research Laboratory
Washington, DC

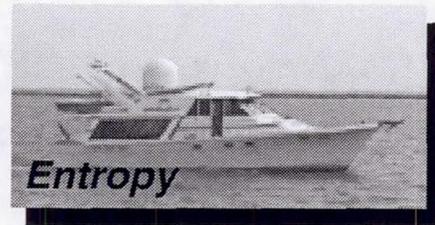
Thomas C. Jedrey
Jet Propulsion Laboratory
Pasadena, California

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

Potential for Ka-band SATCOM

- Smaller equipment required
- 30/20 GHz band well above most maritime radar systems
- Reduced radar cross sections (RCS)
- Additional Bandwidth!

Three Ships



M/V Geco Diamond

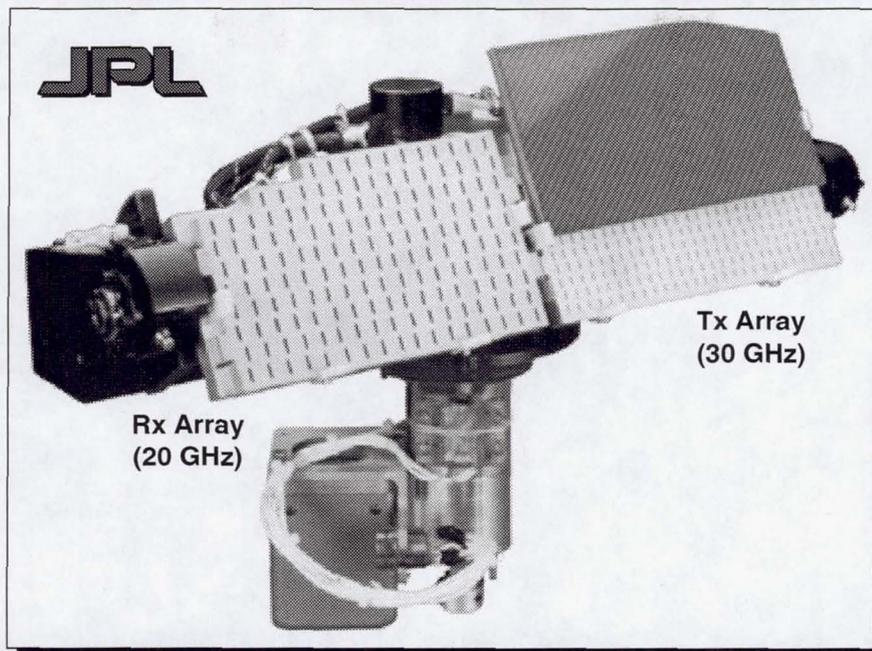
February 1996

- Seismic survey ship, mapping the ocean floor
 - Hundreds of Gbytes/day
 - Store to tape, analyzed much later
- ATM Research and Industrial Enterprise Study (ARIES)
- Multiple node demonstration
 - 2 Mbps full-duplex, ship to NASA LeRC
 - G.Diamond - San Francisco, Houston and Minneapolis
 - Telemedicine demo, Texas Medical Center



JPL's AMT Antenna

Shown with meandering line polarizers partially removed to reveal arrays of slots.



EMS Technologies

ACTS Mobile Terminal (AMT) on USS PRINCETON (CG 59)

"An At-Sea Testbed for HDR SATCOM for Surface Combatants"



Looking aft from starboard bridge wing.

OBJECTIVES

- Demonstration of Full-Duplex K/Ka-Band SATCOM at T1 Data Rates with an AEGIS Surface Combatant via ACTS
 - » INTERNET (E-Mail, FTP, Telnet, WWW)
 - » DCTN (VTC, TeleMedicine, TeleTraining)
 - » POTS (SECRET & SI STUs (JWICS), MWR)
- Characterization of K-Band Downlink Signal Fading and K/Ka-Band EMI in the AEGIS Shipboard Environment
- Validate Antenna Tracking Capabilities

ACCOMPLISHMENTS

- Provided Full-Duplex T1 to CG 59 from July '96 to Sep '97 including a 6-Month Solo Deployment (Western Hemisphere)
- Successful Operation of ACTS Mobile Terminal in all AEGIS EM & ESM Modes
NO EMI PROBLEMS
- Excellent Antenna Tracking in Heavy Seas (20 degree rolls - Beaufort 7)
- Collection of K-Band (20 GHz) Downlink Signal Fading Data: Rain & Clear Weather



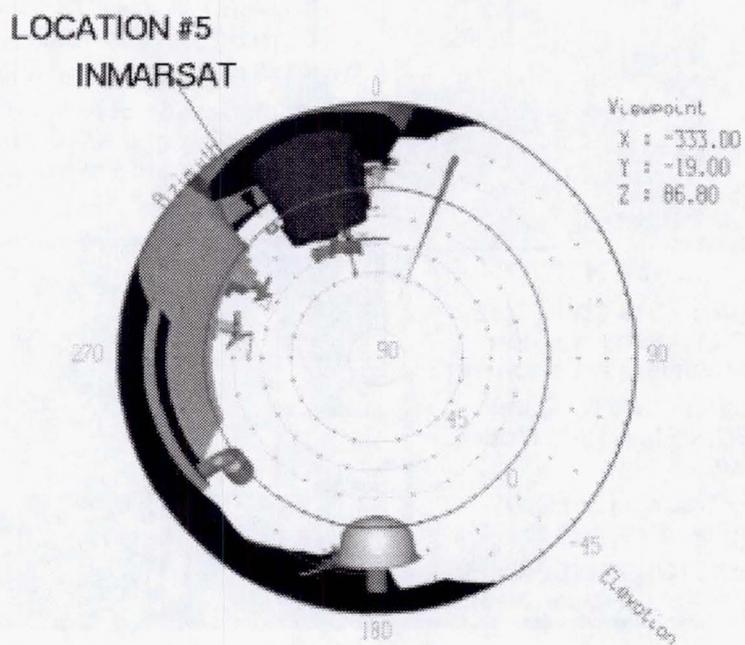
Full Duplex K/Ka-Band Antenna

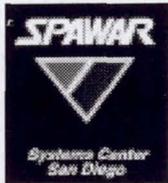
16" Wide, 4.5" High
 Rx: 19.954 GHz, 0 dB/K
 Tx: 29.734 GHz, 46 dBW

ACTS Mobile Terminal on USS PRINCETON (CG 59)



**Blockage Diagram for AMT Location
on USS *Princeton* (CG 59)**



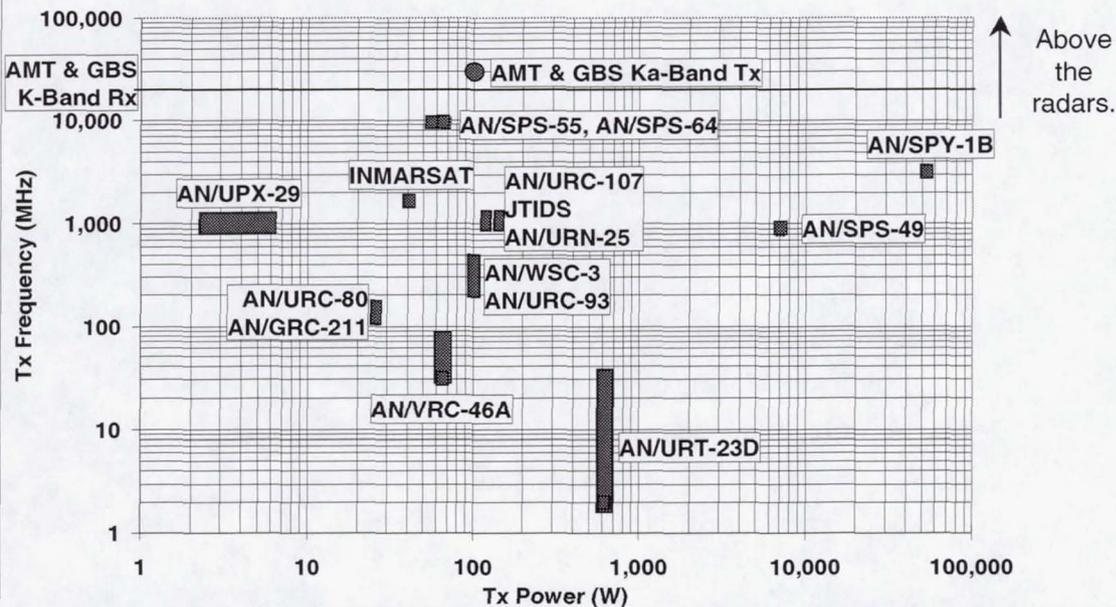


CG 47 Class EM Emitters

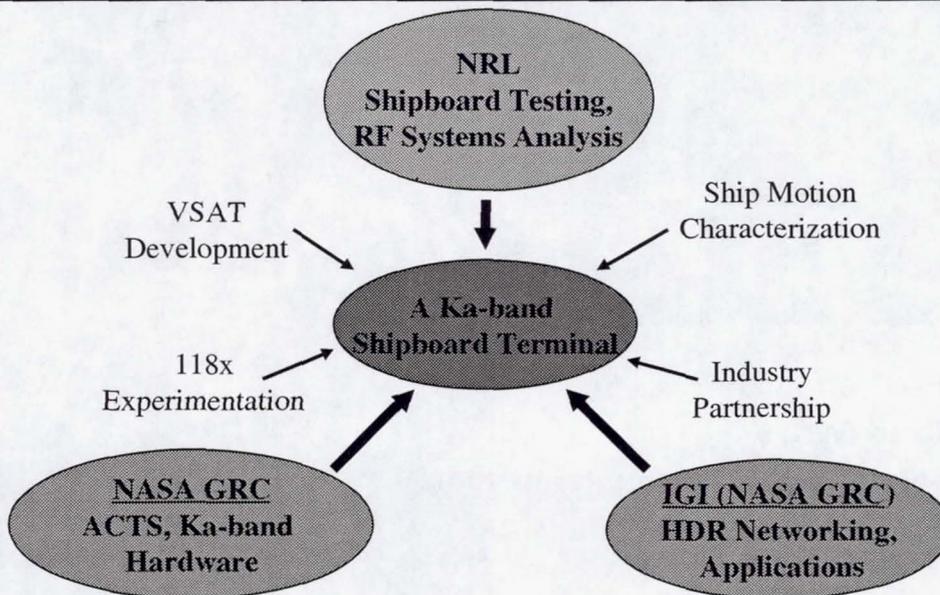
No Operational Restrictions Were Required Over the 14 Months That the AMT was Installed on CG 59.



Tx Frequency (MHz) vs. Tx Power (W)



Shipboard ACTS Ka-band Experiment (SHAKE)

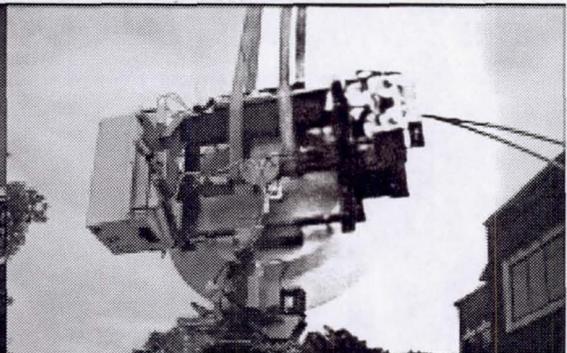


4 month window!

NRL/NASA Partnership with Industry

- Infinite Global Infrastructures, LLC
 - Networking, ATM, shipboard & at GRC
 - Vessel integration
- Sea-Tel, Inc.,
 - Shipboard Transceiving Terminal
 - System Integration
- FORE Systems (ATM Switches, Video CODECs)
- Xicom Technologies (Ka-band Power Amplifier)
- Comsat Laboratories (ATM FEC equipment)
- Raytheon Marine Company (Gyrocompass)
- Hill Mechanical Group
 - Vessel, Chicago staging facility
 - Manufactured antenna mount for vessel

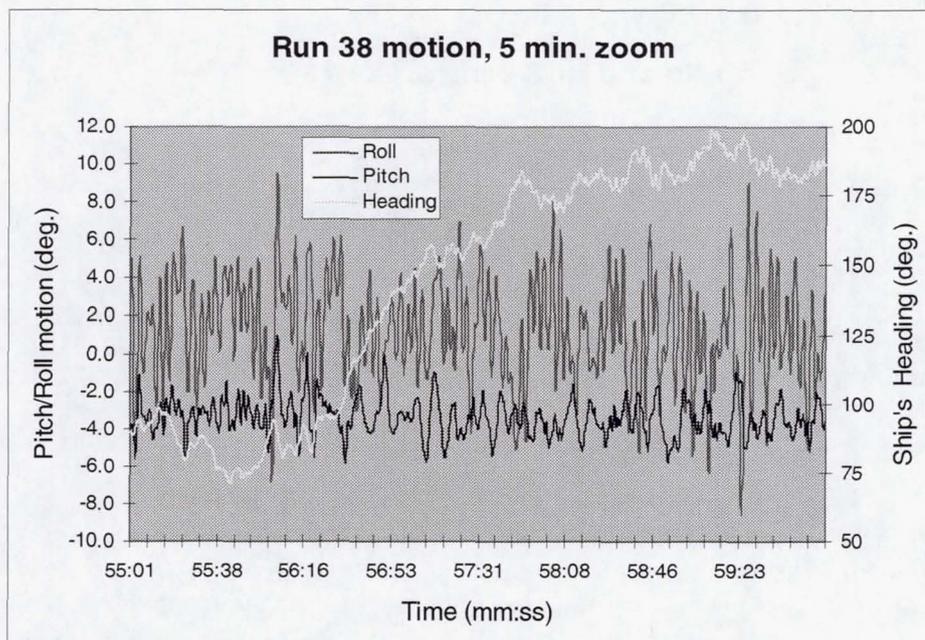
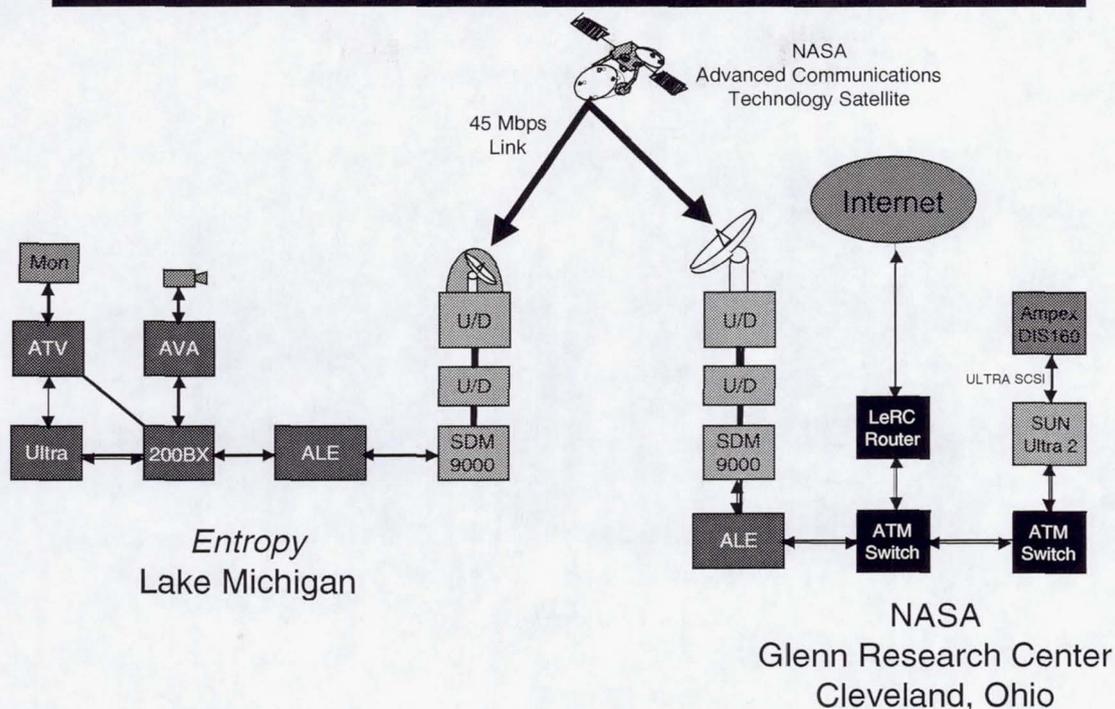
The *Entropy*

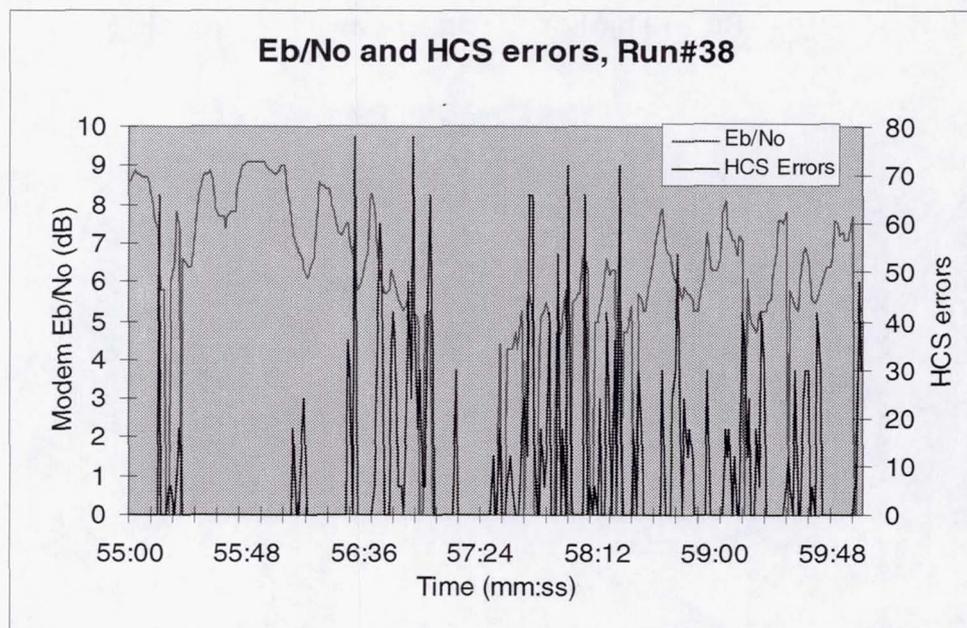
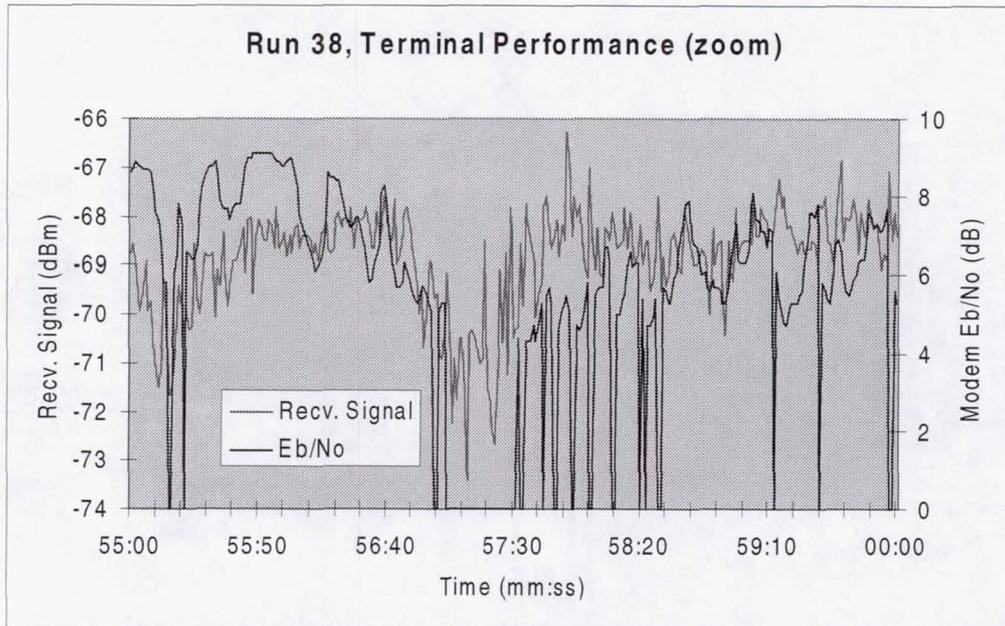


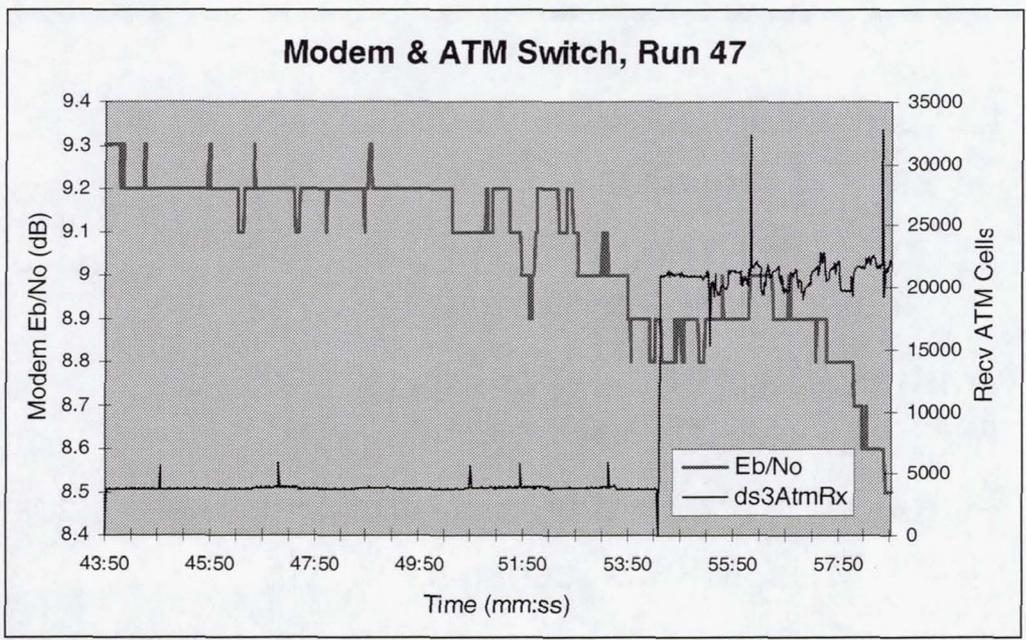
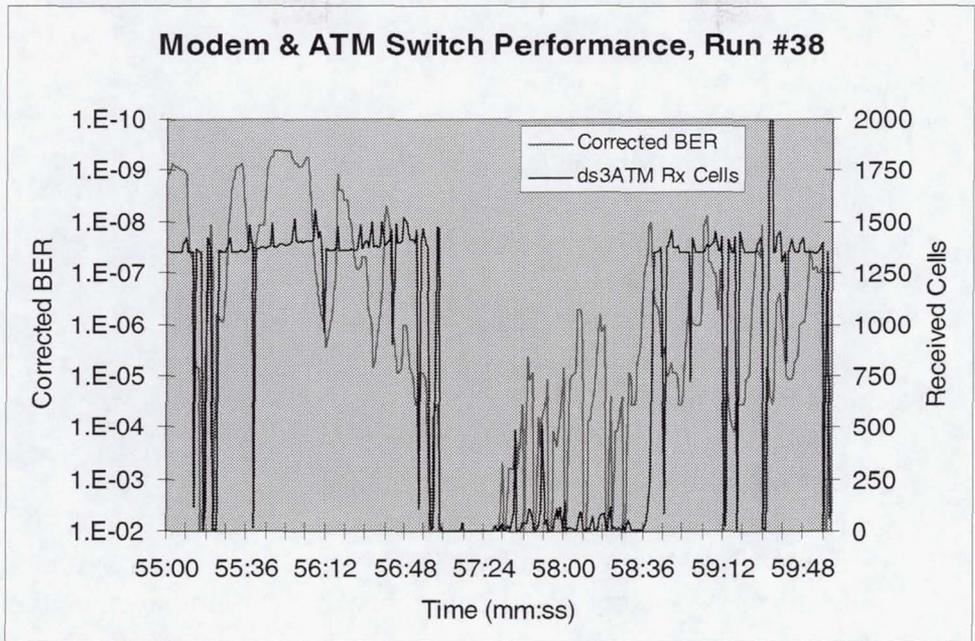
- 1m VSAT terminal
- Stabilized Gyro
- 45 Mbps full-duplex throughput
- Sun Workstation, Dolch PCs



End-to-End Shipboard Configuration







SHAKE Results

Applications Run:

- TCP/IP file transfers (FTP)
 - documented 34.5 Mbps averaged, 40.5 max.
- Motion JPEG VTC (17 Mbps), full duplex
- Multiple independent web-based data streams, GRC to the Entropy, 500 kbps each
- 300- 400 kbps per transfer, up to ten simultaneously

Terminal Performance

- Conditions from calm to Sea State 6
- Consistent tracking in full motion, turns
- Accelerations, gyrocompass limits
- Ramp-up recovery for ATM, TCP, etc.
- Some apps perform better under unstable conditions than others

Ka-band Issues

- COMMERCIAL Ka-Band Satellites, equipment:
 - Satellite Providers as ISPs
 - Constellation-specific terminals
 - Non-standard Intermediate RF

Potential allocation problem

for future MSS users at Ka-band:

- 100 MHz for MSS on a co-primary basis
- 400 MHz, MSS is secondary to FSS

Conclusions

- Demonstrated High Data Rate connectivity to and from vessels at sea
- Demonstrated sophisticated multimedia applications over satellite
- Identified upgrades in technology necessary for Ka-band shipboard technology
- Utility of VSAT technology - new opportunities for wideband shipboard applications
- ATM successful in supporting mixed-media applications

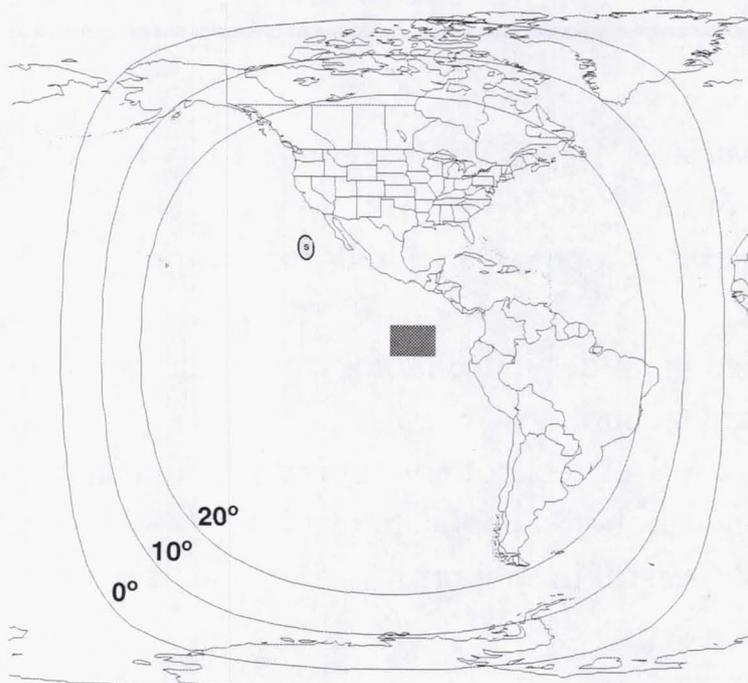
Future Efforts

- Ka-band Testbed at NRL (154 Experiment)
 - 2 -8 Mbps link
 - Correlating Apps performance with lower layers
 - Transition to Ku-band in June 00
- Continued analysis of existing SHAKE data
- Navy demonstration using ITALSAT, tentatively scheduled for FY02

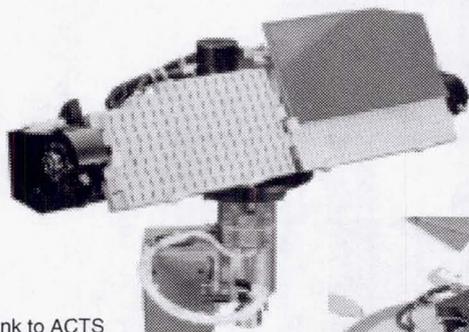


ACTS Steerable Beam

Range of Coverage



Mobile Ka-Band Antenna Tracking System



Link to ACTS Satellite at 20 / 30 GHz

Platforms

- Airborne
- Ground
- Sea
- Train



NASA Kuiper Observatory



Installed Configuration



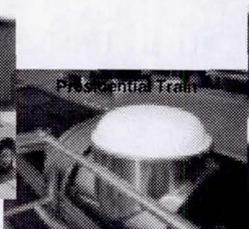
Alenia Aerospazio ABATE Experiment
ITALSAT / Dornier-Calm 228 Airplane



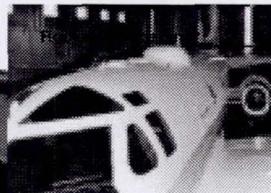
USS Princeton



JPL AMT Van



Princeton Train



Train





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4.1 - A History of the Improvement of Internet Protocols Over Satellites Using ACTS

Mark Allman
NASA Glenn Research Center/BBN
Cleveland, Ohio

Shawn Ostermann
Ohio University
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Hans Kruse
Ohio University
Athens, Ohio

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

Motivation

- Delivering Internet content via satellite to places that are not necessarily well covered by good terrestrial connectivity.
- NASA is interested in possibly using off-the-shelf products for space communication.

Network Setup

- Half-to-full T1 ACTS channels
 - Some loop-back, some between GRC and OU
- $\approx 560\text{--}575$ ms RTT
- Unless otherwise noted we used standard ACTS FEC
- NetBSD workstations as data clients and servers
- Cisco 25xx routers

TCP Problem 1

- The TCP *window size* (W) required to fill a network channel with BW bits/second of capacity and a round-trip time of RTT is:

$$W = BW \cdot RTT$$

- For a T1 ACTS circuit $W \approx 100$ KB
- As originally written, TCP's maximum window size is 64 KB.
- So, TCP's maximum rate over an ACTS link is roughly 117 KB/second regardless of the amount of capacity available.
 - For instance, an ACTS T1 circuit (≈ 192 KB/second) can never be fully utilized.
 - (Note: This limit has been significantly raised since these experiments).

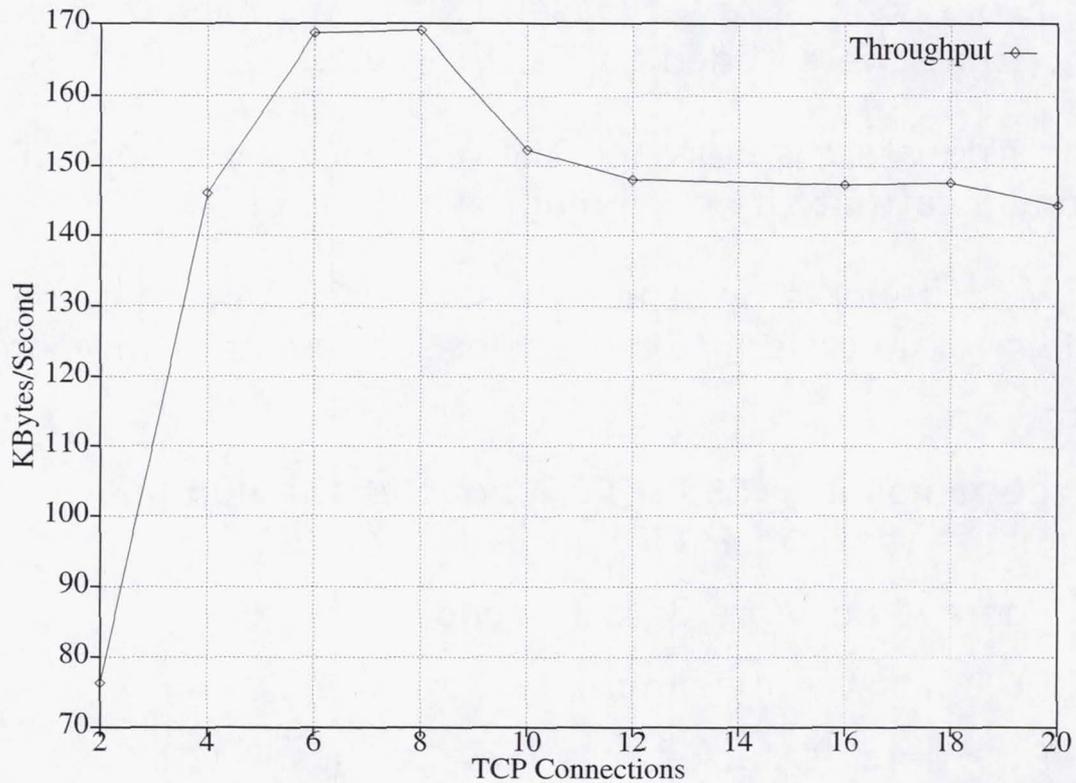
TCP Problem 2

- To avoid congestion collapse, a set of *congestion control* algorithms were added to TCP in 1988.
- The *slow start* is designed to gradually increase TCP's sending rate at the beginning of a transfer.
- Slow start works by sending a single segment into the network and waiting for the corresponding acknowledgment (ACK).
- In the remaining RTTs TCP doubles the number of segments sent per RTT, until...
 - There is no more data to send
 - TCP hits the maximum window size
 - TCP detects packet loss (i.e., congestion)

An Application Level Mitigation

- Our first cut at a "solution" to these problems was an application-layer modification to the FTP protocol.
- We designed an FTP client and server that would use multiple TCP connections to transfer a file, rather than the standard single connection.
 - This effectively increased TCP's maximum window size.

An Application Level Mitigation (cont.)



Standards-Based Solutions

- The IETF has come up with two mechanisms that help TCP over satellite channels:
 - RFC 1323 defines an option that allows TCP to use window sizes much larger than 64 KB.
 - RFC 2018 defines a selective acknowledgment (SACK) option that allows TCP to recover from lost segments more effectively.

Standards-Based Solutions (cont.)

- Congestion-free network:
 - TCP+Window Scaling performed nearly as well as *xftp* with 4 connections (i.e., full utilization for a long transfer)
- Congested network:
 - TCP+Window Scaling+SACK performed much better than TCP without SACK, but was outperformed by *xftp*.
 - *xftp* is more aggressive during congestion than standard TCP, so this result is understandable

Experimental Solutions

- Beginning slow start with an *initial congestion window* larger than 1 segment.
 - Our ACTS experiments show a 25% performance improvement when using a 4 segment initial congestion window to transfer a short file.
- Using *byte counting* rather than standard ACK counting to increase the congestion window.
 - Basing congestion window increase on the number of bytes acknowledged rather than the number of ACKs received makes the increase more accurate (due to delayed ACKs, ACK loss, etc.).
 - Our ACTS experiments show a 17% performance improvement when using byte counting.

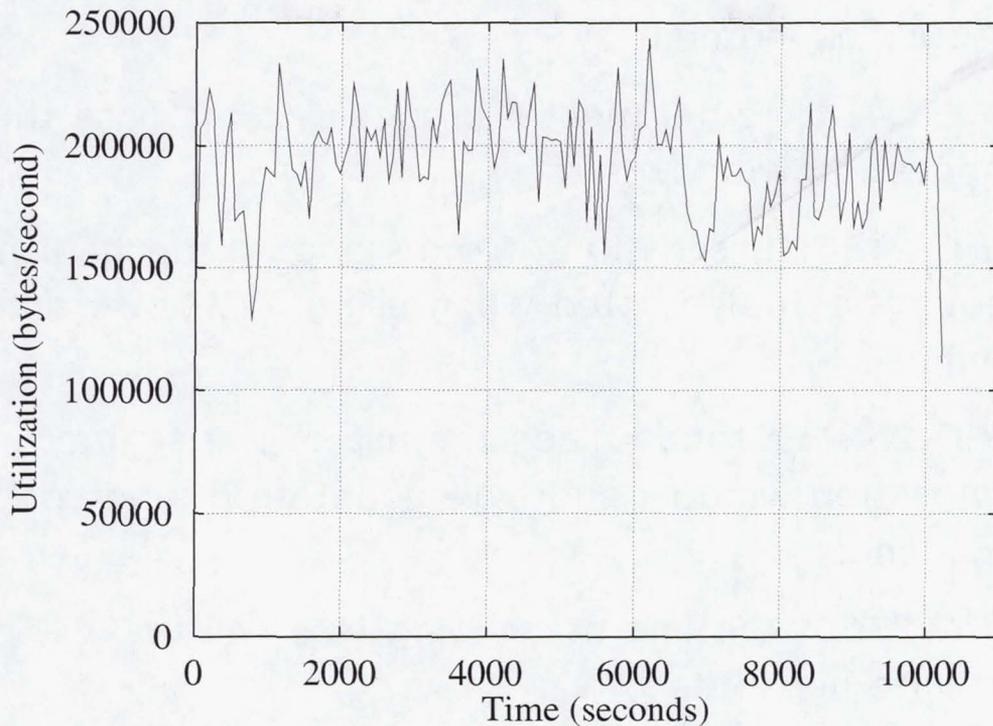
HTTP Experiments

- We used both HTTP/1.0 and HTTP/1.1 in our ACTS experiments, in conjunction with several options on both protocols.
- We found at least a factor of 2 difference in performance between the best set of options and the worst.
- Using a single HTTP/1.1 connection with the pipelining option provided the best performance.
- This set of experiments illustrates the importance of good design in application protocols and highlights the need to remain constantly vigilant as new application protocols are developed.

Representative Network Traffic

- Up to this point our experiments had consisted of only a handful of flows traversing the network simultaneously. But, this is not a realistic condition for production networks...
- Therefore, we wrote a tool that generates random network traffic that is based on network traffic observed in production networks.
 - Generates: WWW, FTP, SMTP, NNTP, Telnet
- We wanted to gauge how well a significant amount of network traffic could utilize a network path with a satellite channel.

Representative Network Traffic (cont.)



Impact of Bit-Errors

- As expected, a non-zero bit-error rate has the effect of reducing TCP performance because the segment losses are interpreted as indications of network congestion.
 - TCP reduces the sending rate when detecting network congestion.
- A more verbose discussion of our ACTS tests and results will be given on Friday morning.

Standards Contributions

- These IETF RFCs were directly or indirectly influenced by our ACTS experiments:
 - *RFC 2414*: Experimental proposal to increase the initial congestion window size.
 - *RFC 2488*: Discussion of the standard mechanisms that should be implemented when using TCP over satellite channels.
 - *RFC 2581*: Standardized the use of a 2 segment initial congestion window and byte counting during congestion avoidance.
 - *RFC 2760*: Outline of ongoing research in TCP over satellite networks.

Conclusions

- TCP *can* use the full capacity of a satellite channel when transferring large amounts of data.
- Short transfers often underutilize the capacity.
 - We have mitigated this, but future research is needed.
- Application layer protocols can have a big impact on performance. We must be vigilant when we design these protocols.
- A realistic mix of network traffic *can* fully utilize the available capacity of a satellite channel.
- Future work (starting tomorrow!) includes investigating additional host and router mechanisms to further increase data transmission performance over satellite links.

Acknowledgments

Our work simply would not have been possible without the assistance, patience and hard work of many people in the ACTS operations team and the research community. Our thanks to all!

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4.2 - Mobile Internet Protocol Performance and Enhancements Over Acts

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Pittsburgh, Pennsylvania

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

Project Background

A 3-year research program between *Caterpillar* and *Carnegie Mellon University*:

- A *global mobile communication system*
- Supporting all corporate, operations, dealerships, and end users
- Mine sites, construction sites, agricultural systems, support operations, ...

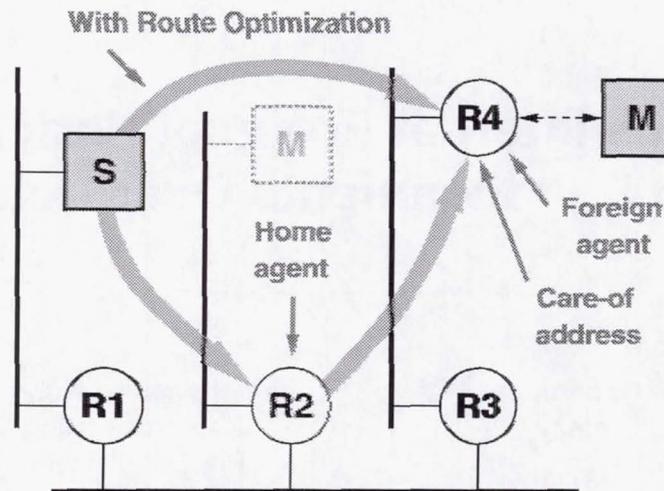
Overview of the CMU system and protocol architecture:

- Runs standard Internet-style IP-based protocols and applications
- Common interfaces regardless of type of wireless technologies used
- *Mobile IP* allows transparent mobility between sites
- *Ad hoc networking* extends mobility away from base stations and supports dynamic, automatic configuration and operation

Experimented with ACTS to test Mobile IP and TCP performance ...



IETF Mobile IP



An IETF (Internet Engineering Task Force) Internet protocol standard (RFC 2002)

Route Optimization extension allows routing directly to a mobile node

Smooth handoff feature forwards packets from old foreign agent to new

Mobile IP Registration and Binding Updates

Each time a mobile node moves:

- Mobile node sends **Registration Request** to its home agent
- And gets **Registration Reply** back from home agent
- Can take a long time if path to home agent is over satellite link

Route Optimization and smooth handoff.

- Mobile node sends **Binding Update** to old foreign agent, giving mobile node's new care-of address
- First packet from a correspondent node to mobile node after movement goes to old foreign agent and is forwarded to new foreign agent and mobile node
- Old foreign agent then sends **Binding Warning** to mobile node's home agent
- Home agent then sends **Binding Update** to correspondent node
- Correspondent node caches care-of address and sends future packets directly to mobile node (without going through home agent)
- Path to home agent, to old foreign agent, or to correspondent node could be a high delay satellite link

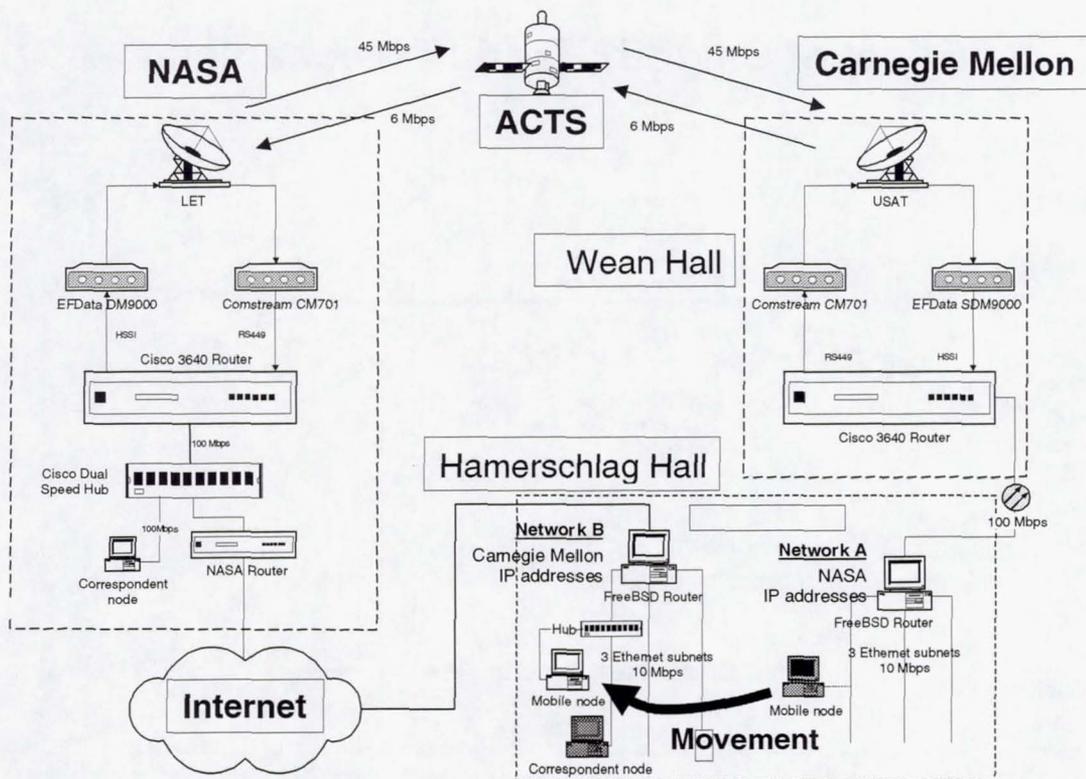
Mobile IP, TCP, and ACTS

Mobile IP largely designed for terrestrial networks with reasonable delays:

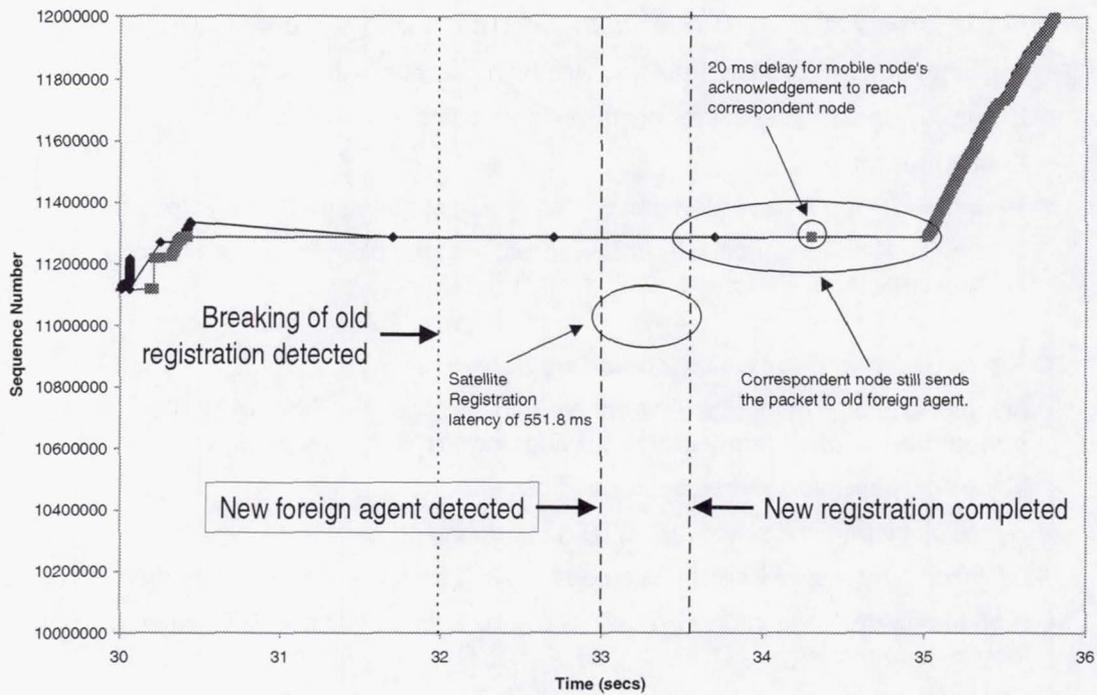
- Are there any unforeseen problems with high delay links like ACTS?
- Example: What happens if retransmission timeouts are too short?
- Another example:
 - Mobile IP requires **replay protection** on registration and Binding Updates
 - One defined mechanism is **timestamps**, but long delay increases chance that timestamp will look “old” as if it is a replay

TCP is largely tuned for wired, stationary networks:

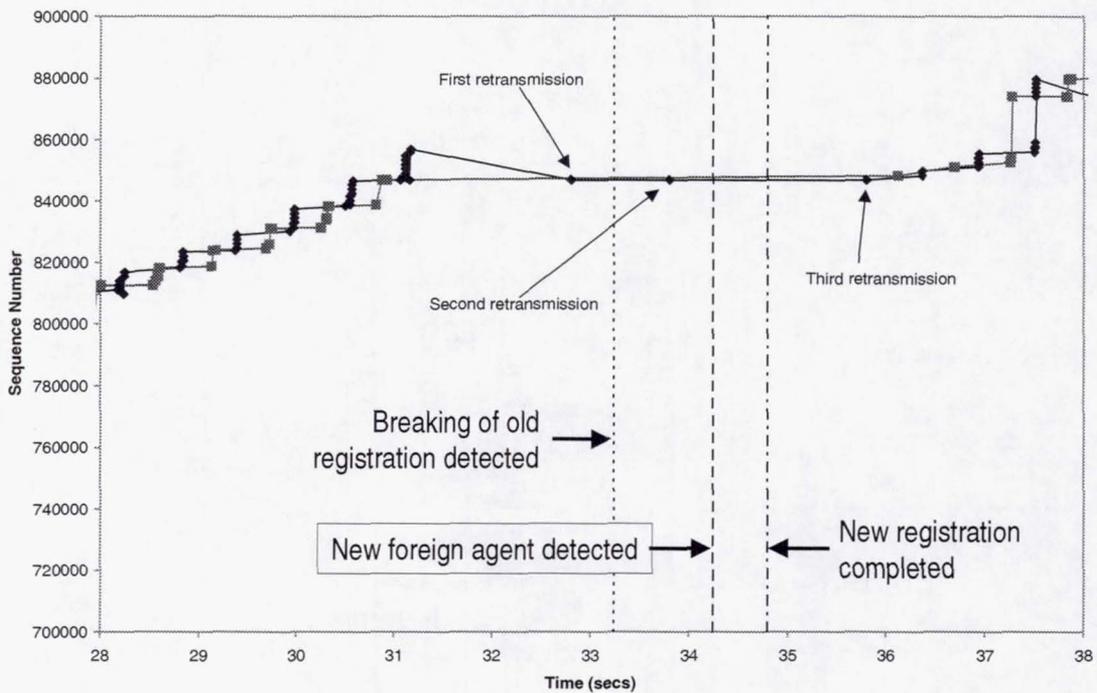
- Any dropped packet increases retransmission timeout and triggers TCP's **congestion control (slow-start)**, slowing down rate of transmission
- Many new possible sources of dropped packets:
 - Wireless transmission over ACTS (e.g., during rain)
 - Incorrectly routed while mobile node moving from one subnet to another
- High bandwidth-delay product of ACTS means a lot of data is in flight when a mobile node moves



Mobile IP and TCP during Handoff



Effect of Smooth Handoff Mechanism



Single-Buffering Extension during Handoff

Buffering packets during Mobile IP handoff to improve TCP performance:

- Buffer packets arriving at old location after mobile node is gone
- Once handoff completes, resend buffered packets to new location

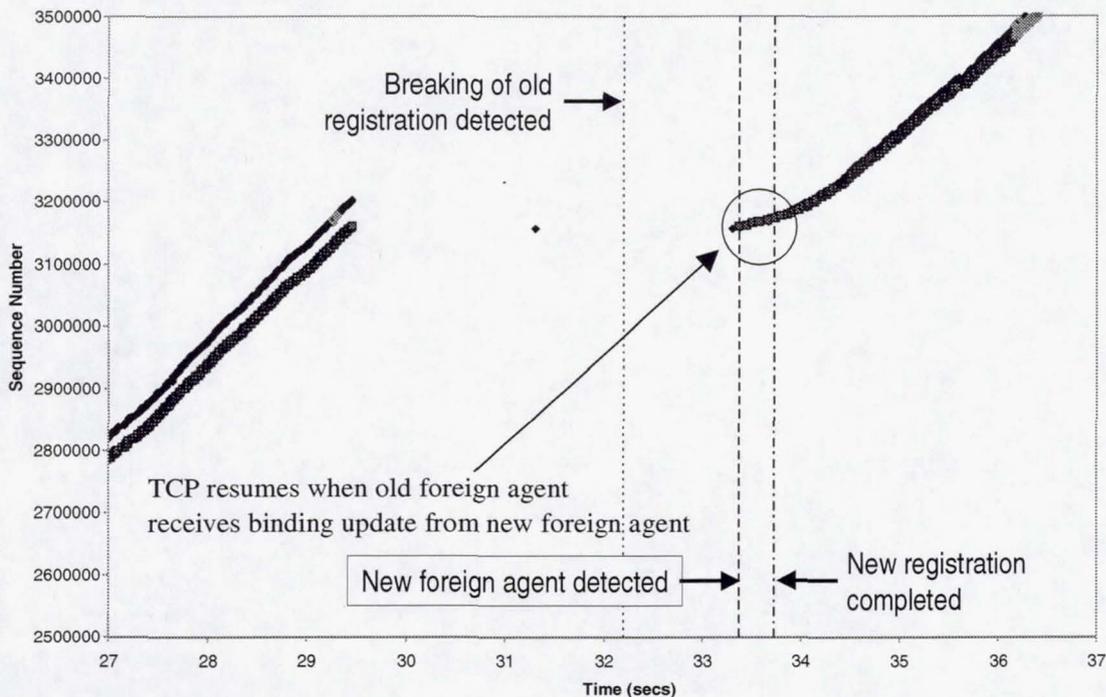
An old idea, but some complications related to this type of optimization:

- When to start buffering?
- How large does the buffer need to be?
- How to resend buffered packets without creating congestion?

We implemented a very simple and effective variant of this optimization:

- Only buffer one packet — buffer space is easily manageable
- Don't worry about when to start buffering — just always buffer last packet
- No congestion when resending buffered packet since there's only one
- ACK from mobile node receiving this one packet restarts TCP sender to send next data packet, and so on ...
- Avoids waiting for normal TCP retransmission timeout to restart

Using Single-Buffering Extension



Conclusions

TCP and Mobile IP performance may be substantially affected over ACTS:

- High bandwidth-delay product of ACTS link
- Delays inherent in Mobile IP's detection of movement between subnets
- Route Optimization and smooth handoff help some but don't solve it

New ***single-buffering extension*** is simple and effective:

- Only one packet of buffer space required for each connection at foreign agent
- ACK from retransmitted packet restarts TCP sender

For more information:

- Roy Laurens, Parag Manihar, Ioannis Pavlidis, and Satish Shetty, "***Simulation and Enhancements of Internet Protocols over ACTS***", M.S. Thesis, INI, Carnegie Mellon University, May 1999
- <http://www.ini.cmu.edu/WIRELESS/Caterpillar/>
- <http://www.monarch.cs.cmu.edu/>

4.3 - NASA and Industry Benefits of Acts High-Speed Network Interoperability Experiments

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David Brooks
Infinite Global Infrastructures, LLC
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David Beering
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Wheaton, Illinois

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

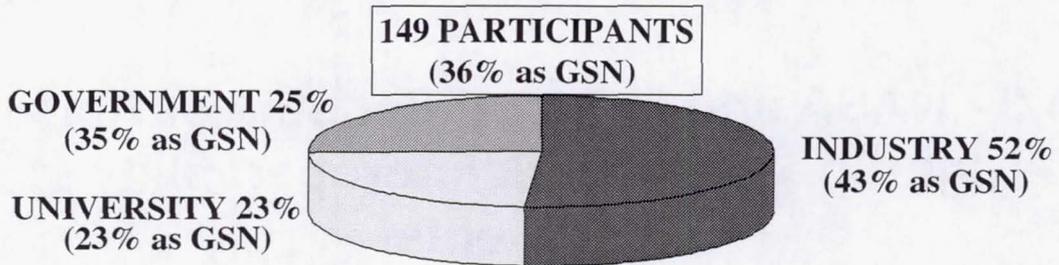
ACTS Experiments Program Objectives

- Characterize ACTS Technologies
- Promote New and Innovative Applications
- Demonstrate Use of Future Satellite Services
- Evaluate Satellite-Terrestrial Interoperability
- Evaluate ACTS in inclined orbit operations
- Verify new Ka-band Advancements

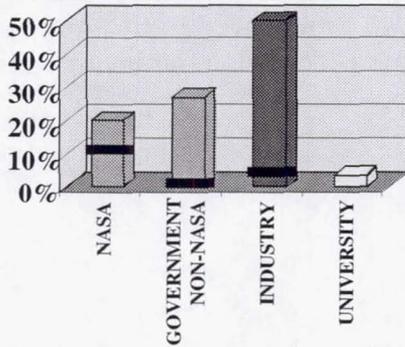
**Inclined Orbit Operations has enabled
18 networking experiments (27 total) and over
50 government and industry partners**



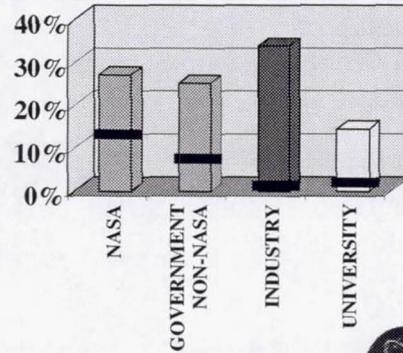
ACTS Experiment Utilization



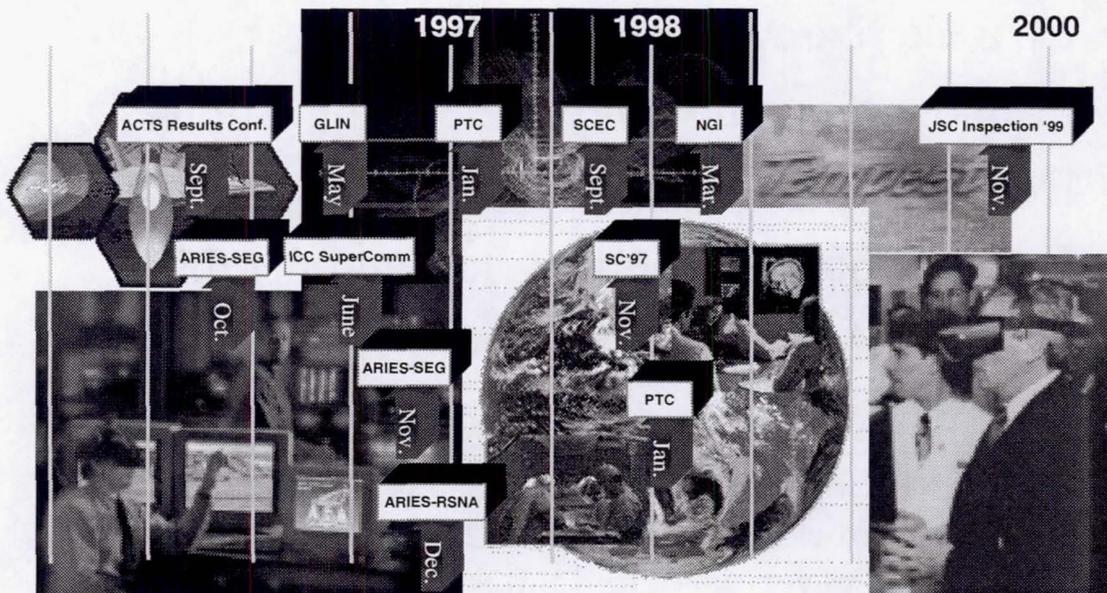
86 DEMONSTRATIONS (14% as GSN)



104 EXPERIMENTS (18% as GSN)



ACTS GSN Demonstration Timeline



ACTS Experiment 154 Objectives

- Develop a recognized, interoperable, high-performance TCP/IP implementation across multiple computing / operating platforms, working in partnership with the computer industry
- Work with the satellite industry to answer outstanding questions regarding the use of standard network mechanisms (e.g. TCP/IP and ATM) for the delivery of advanced data services, and for use onboard as a part of emerging spacecraft architectures
- Test and evaluate available and emerging network mechanisms that distinguish between losses due to link errors vs. congestion in order to advocate and develop a standard version of TCP/IP that supports this capability



ACTS Experiment 154 Consortium

Computing

- ❖ Sun Microsystems
- ❖ Compaq
- ❖ Microsoft
- ❖ Intel
- ❖ IBM
- ❖ Hewlett-Packard

Spacecraft Manufacturers

- ❖ Hughes Space & Communications
- ❖ Lockheed Martin
- ❖ Space Systems/Loral
- ❖ Spectrum Astro

Communications

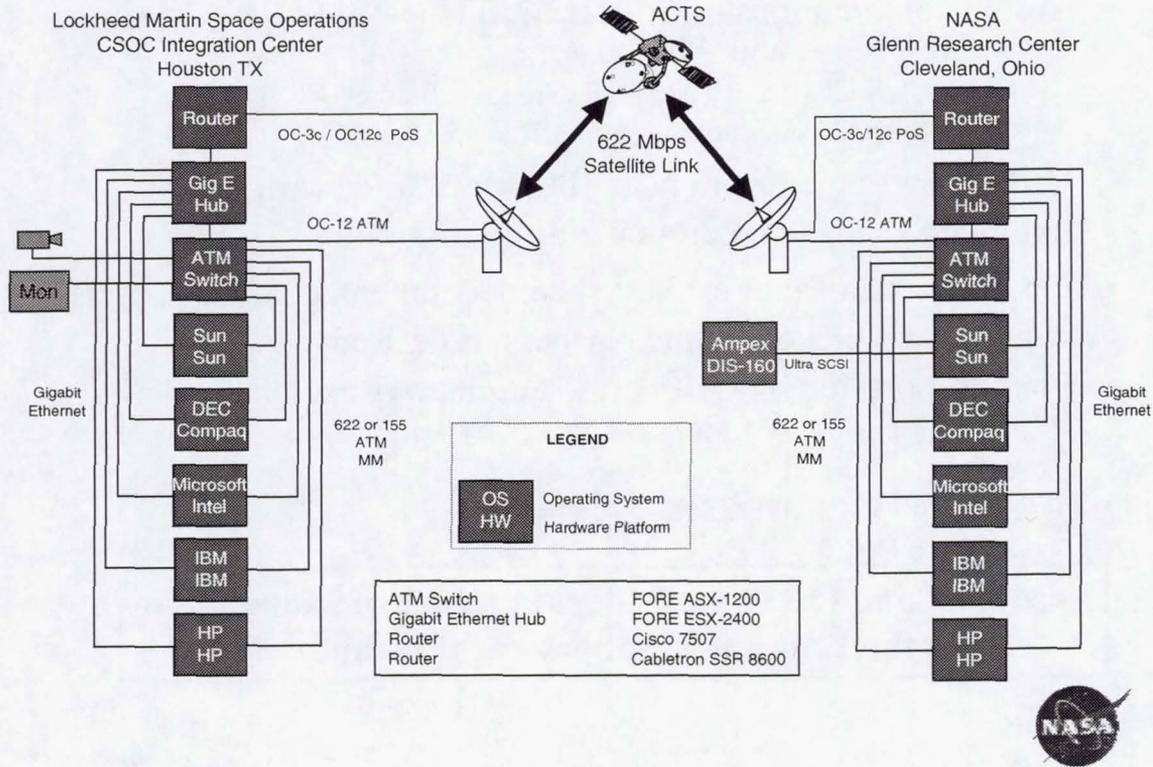
- ❖ Ampex Data Systems
- ❖ Comsat Laboratories
- ❖ Cisco Systems
- ❖ FORE / Marconi
- ❖ Raytheon Telecom
- ❖ Cabletron Systems

U.S. Government Laboratories

- ❖ NASA Glenn Research Center
- ❖ NASA Ames Research Center
- ❖ NASA Johnson Space Center
- ❖ NASA Goddard Space Flight Center
- ❖ NASA Jet Propulsion Laboratory
- ❖ U.S. Naval Research Laboratory



ACTS Experiment 154 Diagram



Test Tools and Methods

- Examine the performance and behavior of bulk TCP/IP data transfers across a high bandwidth*delay path
- Document the progressive steps necessary to reach {near} optimal TCP/IP data rates using:
 - tcp, tcptrace, netstat, tcpdump, vendor feedback, grabportstats, and other tools
 - Show the improvements of data rates using tcptrace and grabportstats
- Testing was an iterative process:
 - Bulk TCP/IP data transfer, examining the results of various network and workstation data points, work with vendors to optimize the next test, repeat until we reach the limits of the platform{or reach "LAN rates"}
 - GRC's "tcp_script" used to automatically document receiver and transmitter workstation states for homogenous-heterogeneous runs



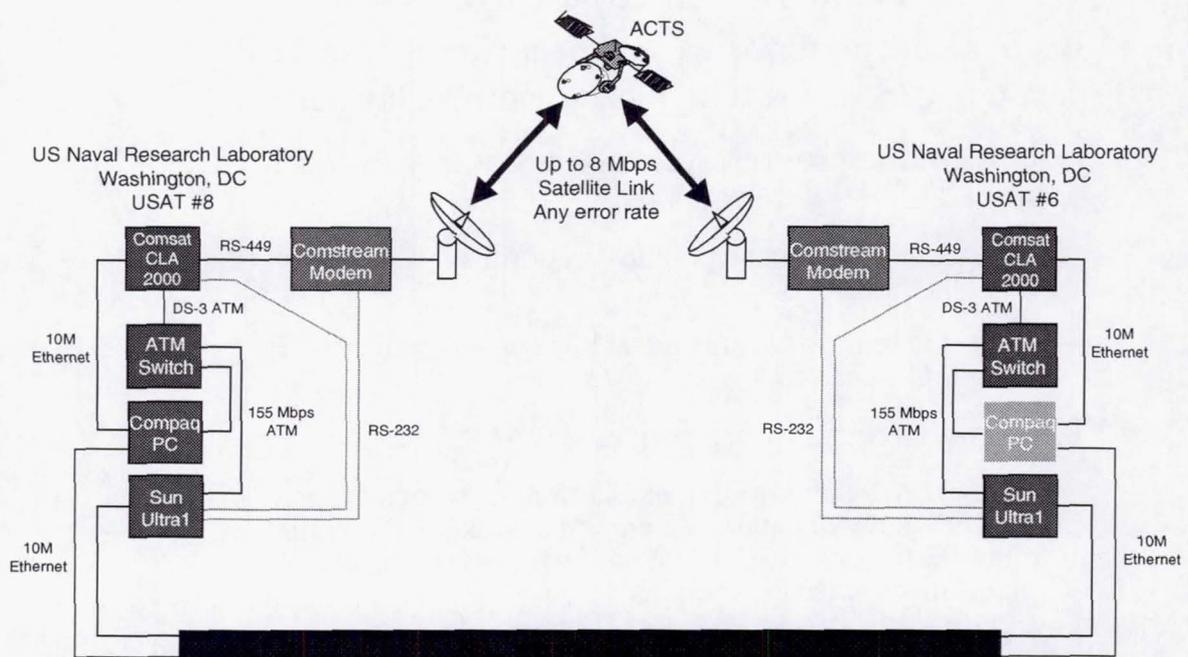
General Preliminary Results

- Tested combinations of Solaris2.7, TU64-V4.0f, Windows 2000, HPUX 11, and AIX4.3.4
 - Used ATM CLIP and 100BaseT/Gigabit Ethernet ATM
 - OC12 SONET satellite link with a $Rtt \approx 532ms$
- Utilization ranged from near 100% to 2% for various homogeneous and heterogeneous configurations
- Observations of interest have been documented so the work can be picked by the partners, if desired
- Final Report due by October; Preliminary Results:
 - Win2k - Gigabit 431 Mbps(SAT)
 - Solaris - ATM CLIP ~510 Mbps(SAT)
 - AIX - ATM CLIP(OC3c) ~130 Mbps
 - TU64 to HPUX - ATM CLIP ~ 330Mbps(SAT)

Feedback and Other Considerations are of More Value than Actual Numbers - at this time



154 Errors-vs.-Congestion Configuration



NASA / SOMO / Industry Benefits

- Develop strong relationships with commercial and U.S. Government organizations in a number of critical areas with live experiment as a backdrop
- Rapid evolution of new capabilities readily incorporated into commercial platforms – ready to be used to solve NASA's problems
- Strong potential for lower lifecycle cost and lower implementation risk
- Unique technical environment able to test hardware and software /operating platforms at the leading edge of the performance envelope



What's Next ... ?

- Continued TCP/IP Errors-vs.-Congestion testing on Telstar 11 (Ku-Band) from Loral/SkyNet at Naval Research Laboratory
- Transition of high-performance test environment to work with NASA's Tracking & Data Relay Satellite System (TDRSS)
- Ground network extensions to space links in order to more realistically emulate NASA's operational environment (via NREN, Internet2, Abilene, etc.)



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4.4 - Global Interoperability of High Definition Video Streams Via Acts and INTELSAT

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California Institute of Technology
Pasadena, California

Naoto Kadowaki
Communications Research Laboratory
Ministry of Posts and Telecommunications
Japan

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

Introduction

Trans-Pacific High Data Rate Satellite Communications Experiments

A series of activities arising from the Japan-U.S. Science, Technology, and Space Applications Program Workshop

Satellite Communications in the Global Information Infrastructure

- Emerging global information infrastructure involving broadband satellites and terrestrial networks
- Access to information by anyone, anywhere, at any time
- Collaboration of government, industry, and academic organizations
- Wide area technologies and services

Introduction (cont.)

The first of the series, *Trans-Pacific High Definition Video Experiment*, established the first broadband digital link for the transmission of HDV signal over Asynchronous Transfer Mode network over two satellites (NASA ACTS and INTELSAT)

Conducted real-time remote cinematography HDV post-production activities

Showed the feasibility of virtual studios and digital theatres at locations without terrestrial broadband connections

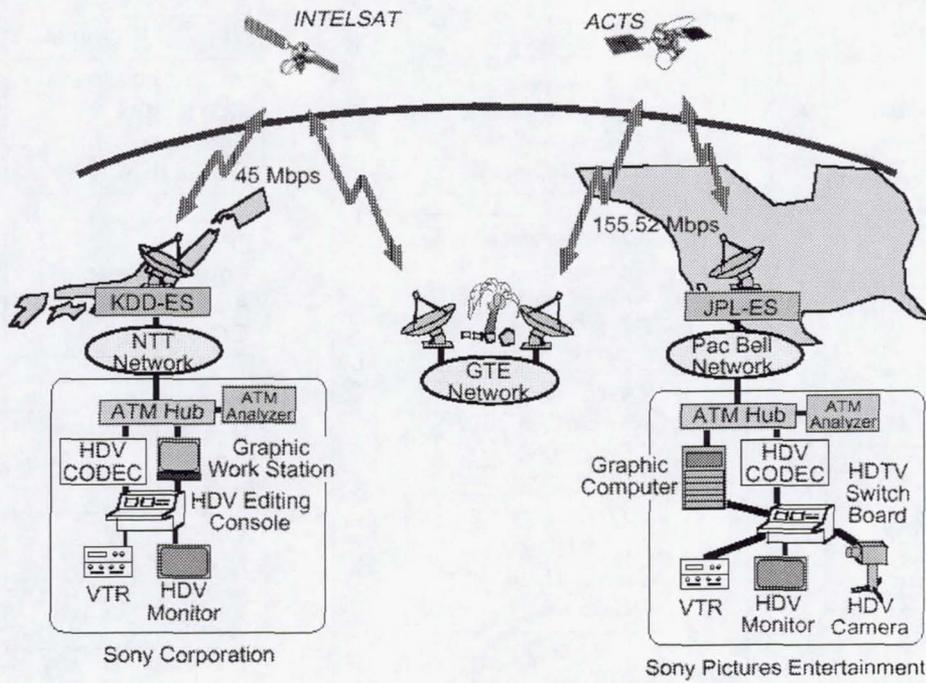
Demonstrated that satellites can deliver digital image traffic at data rates and quality comparable to fiber optic cable

Collected satellite channel and ATM link performance data

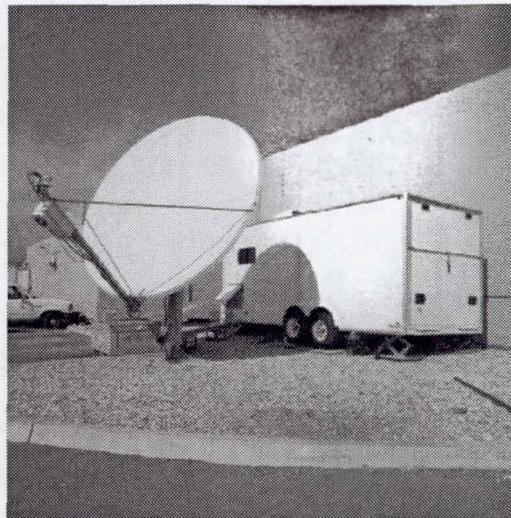
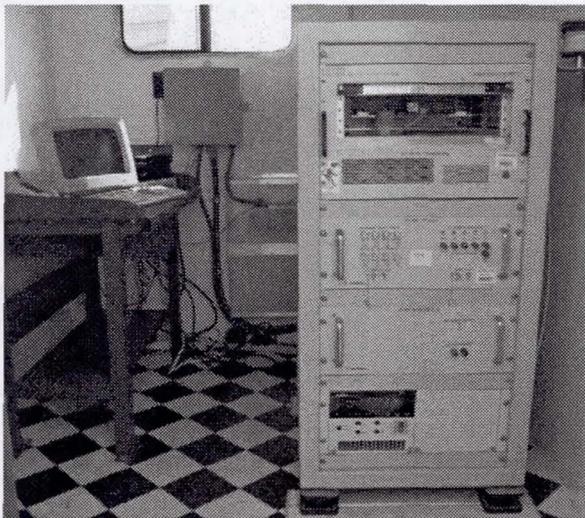
Team members

Communications Research Laboratory
Comsat
George Washington University
GTE Hawaiian Tel
INTELSAT
Japan-U.S. Science, Technology and Space Applications Program
Kokusai Denshin Denwa, Ltd.
Ministry of Posts and Telecommunications
Mitsubishi Electric
NASA Glenn Research Center, Headquarters, Jet Propulsion Laboratory,
NASA Research and Education Network
Newbridge Networks Inc.
Nippon Telegraph and Telephone Corporation
Pacific Bell
Pacific Space Center
Sony Pictures High Definition Center
Sony Visual Communication Center
State of Hawaii
Tripler Army Medical Center

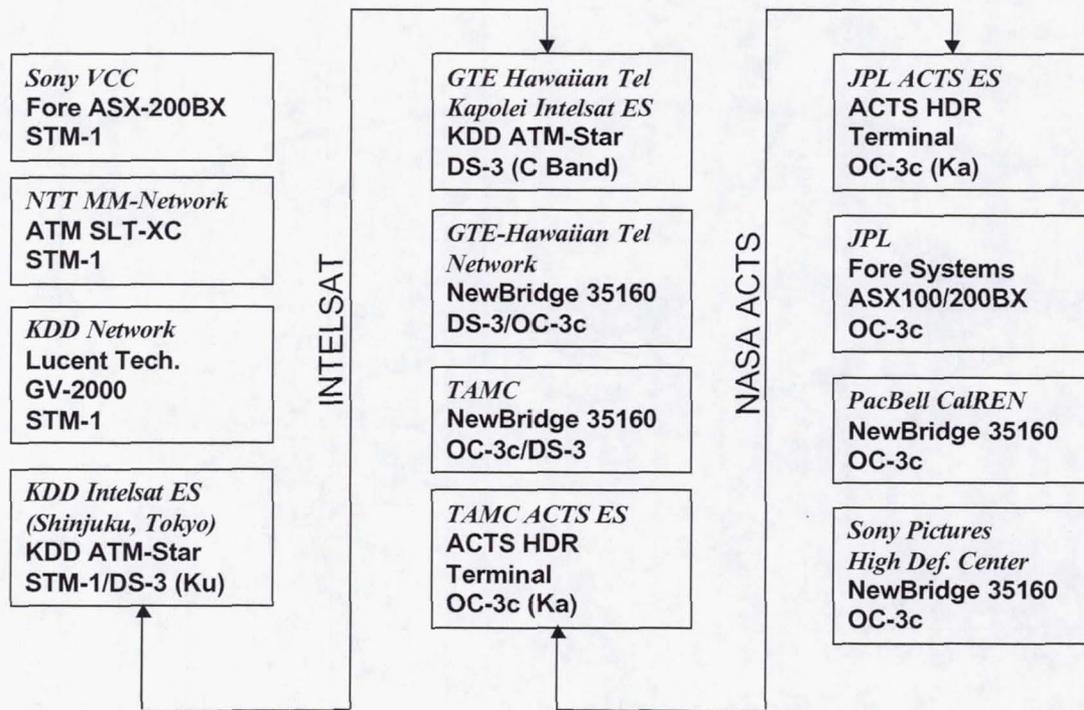
Trans-Pacific Network Configuration



ACTS Transportable Earth Station at JPL



Trans-Pacific Network Configuration (cont.)



- *The High Definition Format*
is a motion picture medium that captures high resolution images in a digital format. A new production system that matches or exceeds the quality of film while delivering the convenience of electronic production and the benefits of digital post.
- HDV source material: SMPTE 240M-1994
 - Raw real-time bit rate of 1.2 Gbps
 - 1035 active lines per frame
 - 16:9 aspect ratio
 - Sony HDD-1000 VTR
 - Sony 1" CCD camera HDC-500
 - Sony High Definition Video System Monitor
- Experimental Mitsubishi MPEG-2 CODEC:
MPEG-2 compression down to ~22 Mbps peak rate
Also capable of ~60 and ~120 Mbps rates.

- Digital transmission systems will create the *virtual studio* bringing distributed studio assets to production crew location(s)
 - Pictures are shot on location in all continents
 - Interactive collaborative work on a global scale
 - Unlimited generations and transmission distances
 - Application of powerful signal processing techniques for effects
 - Instantaneous direct broadcast to theaters
 - Have effects directly influence live action photography

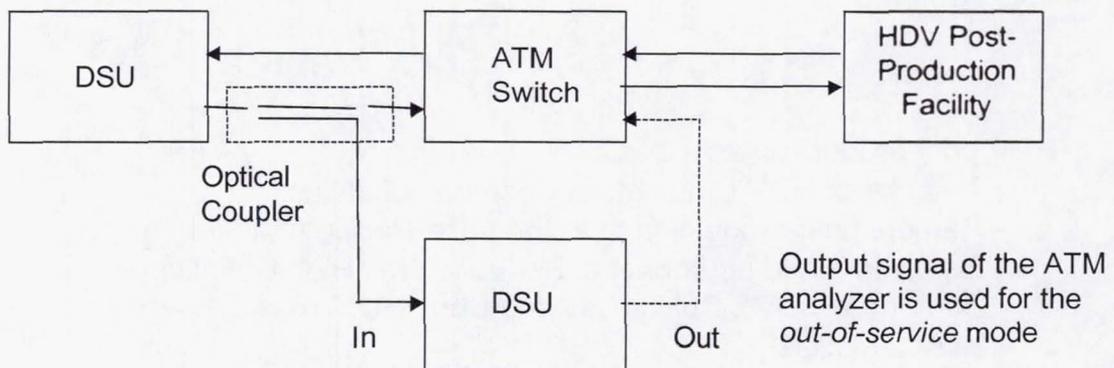
- Digitization is now appearing in all phases of the production chain:
 - cameras
 - recorders
 - effects

- HDV post-production activities:
 - Transfer of HDV clips between remote locations
 - Remote post-production over the trans-Pacific ATM link
 - Equipment and personnel at Sony Pictures High Definition Center (SPHDC), Culver City and Sony HQ, Tokyo
 - HDV test clips
 - Green-background clips for post production processing
 - Viewing of results at remote site

• Satellite channel and ATM link performance characterization:

- Atmospheric effects on ATM cell loss and CODEC performance
- QOS:
 - Cell error ratio, transfer delay, delay variations
 - Cell address and payload integrity
 - Bit error rate
- ATM analyzer at SPHDC (Culver City) and Sony VCC (Tokyo)
- Public weather data (NOAA/NWS)
- Satellite operations log files (ACTS)

ATM Analyzer Configuration



ATM Analyzer Results

- Loop-back delays and variations measured from SPHDC.
- Connection to Sony VCC via JPL and NREN/GRC
- Stable link in terms of delay variation performance

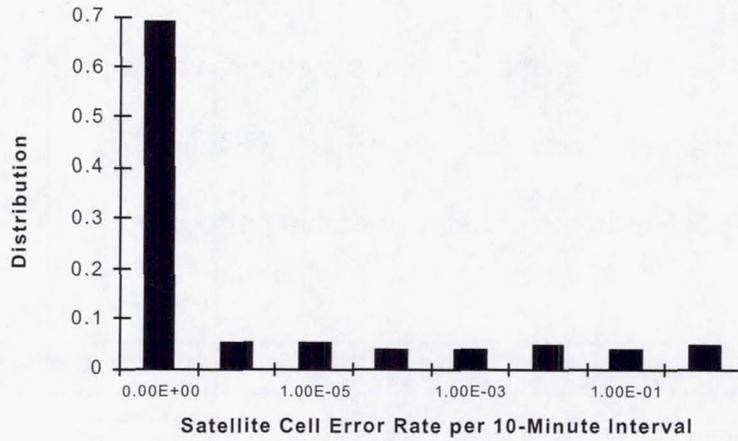
Source	Loop-back point	Cell delay	Cell delay variation
SPHDC	TAMC earth station	555000 μ s	2 μ s
SPHDC	KDD earth station	1069547 μ s	2 μ s
SPHDC-JPL-GRC	TAMC earth station	555745 μ s	2 μ s

ATM Analyzer Results (cont)

Date (U.S.)	Honolulu Weather	ACTS BER Log	ATM Tester Results
Mar 10	05:56-08:56pm PST 3000 ft few, 3500 ft <i>Rain/Overcast Layer</i> few, 13000 ft broken, 23000 ft overcast. Rain showers in vicinity, south east.	No error for four hours. Bursts of errors in the last ten minutes of the experiment.	Looped back at Tripler, Hawaii. No error in 9.5×10^8 cells (2 hr and 50 min). Cell loss ratio of 4.2×10^{-4} and error ratio of 1.9×10^{-5} for last 10 minutes.
Mar 18	04:50-07:50pm PST 4000 ft scattered, <i>Broken Layer</i> 8500 ft broken - 4000 ft few.	No errors for two hours.	Looped back at Sony VCC. No error in 1.34×10^8 cells.
Mar 20 ¹	06:50-09:20pm PST 5500 ft broken, <i>Broken Layers</i> 7000 ft broken, 14000 ft broken, 23000 ft broken.	A few errors in a ten-minute block in the first hour. Otherwise, error- free.	Looped back at GTE, Honolulu. No error in one hour. Looped back at Sony VCC. No error in 10 minutes.
Mar 27	06:50-09:50pm PST 3500 ft broken. <i>Broken Layer</i>	No errors in six hours.	Looped back at Sony VCC. One cell error in six hours. ²

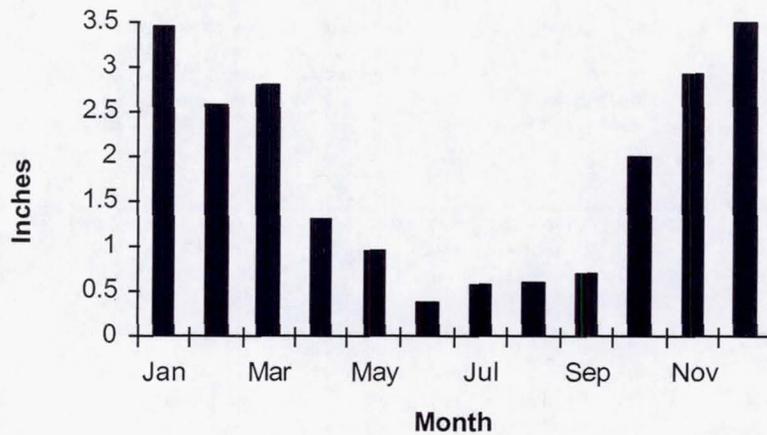
1. Most of the time used for end-to-end HDV transmission.
2. ATM tester used to monitor the end-to-end traffic.

S-Cell Error Rate from TAMC to JPL HDR



Histogram of ACTS S-Cell error rate from the Tripler to the JPL HDR Term.

**Average Rainfall, Honolulu, HI
(10/1/1949-1/31/1997)**



Average Rainfall
Honolulu, Hawaii (Oct. 1 1949 - Jan. 31 1997)
National Weather Service

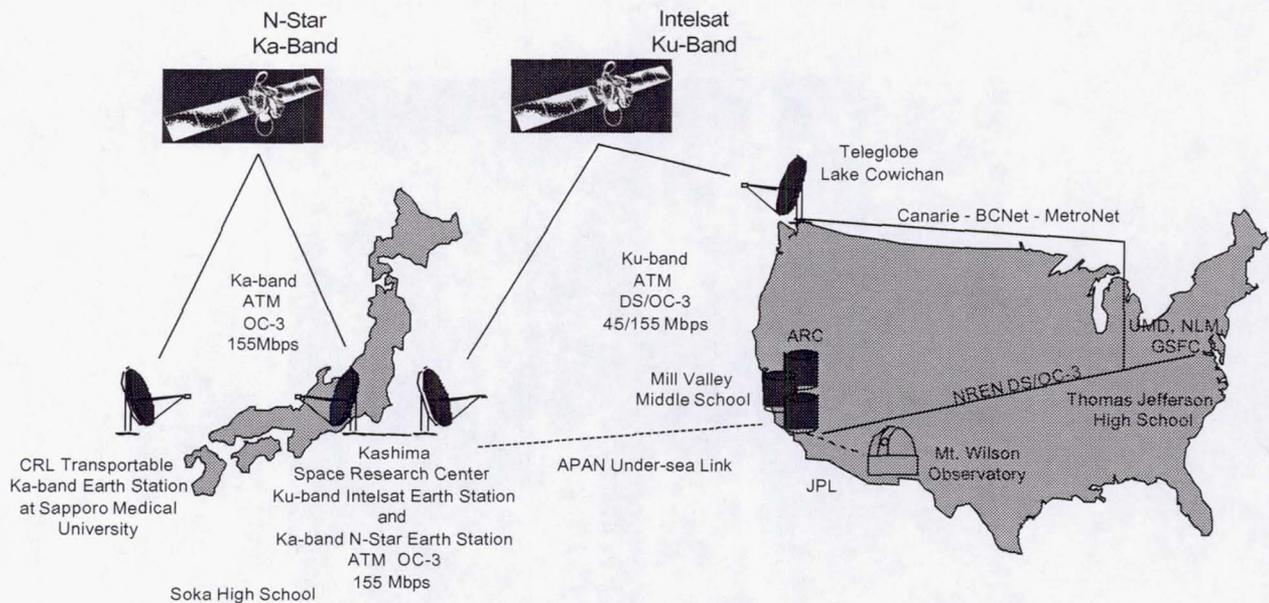
Real-time Compositing at the Sony Visual Communications Center, Tokyo, Japan



Phase 2 Activities

- Internet Protocol (IP)-centric applications
 - IP-based applications are readily available to the general public
 - Involvement of schools and network researchers
 - Migration of research results to user applications
- An opportunity to study issues of scale and interoperability
 - IP Multicast (voice, video, and application data)
 - Distributed file access
 - Wide area technology and services

Phase 2 Trans-Pacific Connections



Visible Human Telemedicine

- Large image database services over high speed networks
- Digital image library of volumetric data representing a complete adult male and female cadaver (Visible Human Project)
- Interactive segmentation, multilingual labeling, classification and indexing
 - Processing recognize each anatomical object using Visible Human Viewer at Sapporo Medical University
 - Attachment of anatomical terms with National Library of Medicine's Unified Medical Language System
- Also transferred to and from researchers via Next Generation Internet

Remote Astronomy

- Interactive control of Mt. Wilson Observatory's 14"/24" telescopes
- Wide area environment for distance learning and collaborative observations and discussions
- Students at Soka High School, Mill Valley Middle School, and Thomas Jefferson High School in association with the Mt. Wilson Institute (California)
- The use of distributed systems and IP multicast technologies to permit global-scale discussions and image post-processing
- Sessions: Structures of Galaxies, Lives of Stars, and Where are all the Stars?
- Comparative studies with Hubble Space Telescope images

Conclusion

- The first digital two satellite-hop broadband ATM link to transfer high definition video streams between Tokyo and Culver City
- Seamless interoperation between satellite and terrestrial fiber optic infrastructure
- Real-time remote cinematography and post-production capabilities
 - virtual studio and digital broadcast theatre
- Atmospheric attenuation and effects on video quality
- Satellites shown to provide data rates and quality comparable to those in the terrestrial fiber optic networks

(cont.)

Conclusion (cont.)

- Preparing to demonstrate Internet Protocol based applications in telemedicine and distance education
 - visible human
 - remote astronomy
- Distributed applications, technology, and services
- Permits students and perhaps the general public to participate
- Explore and develop satellite transmission techniques, standards, and protocols in order to determine how best to incorporate satellite links with fiber optic cables to form high performance global networks
- Help examine issues in the next generation Internet and solar-system-wide networks

5.1 - Partnering to Change the Way NASA and the Nation Communicate Through Space

Pete Vrotos
NASA Glenn Research Center
Cleveland, Ohio

Kul Bhasin
NASA Glenn Research Center
Cleveland, Ohio

Jim Budinger
NASA Glenn Research Center
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Denise Ponchak
NASA Glenn Research Center
Cleveland, Ohio

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

GRC Space Communications Historical Perspective

- From the early 1970's to 1998 GRC's Space Communication program's (SCP) primary responsibility was to open new frequency bands and provide enabling communications technology to the commercial SATCOMM industry
- The successful emergence of commercial Ka-band systems and explosion of the commercial SATCOM provided services has enabled NASA and GRC Space Communications program to shift our technology investment focus to enable NASA's use of these commercial services in support of its future missions.
- The shift in GRC's Space Communication focus is to develop communications and networking technologies that leverage to the maximum extent possible the commercial SATCOM industry for the benefit of NASA Enterprises and missions



Glenn Research Center

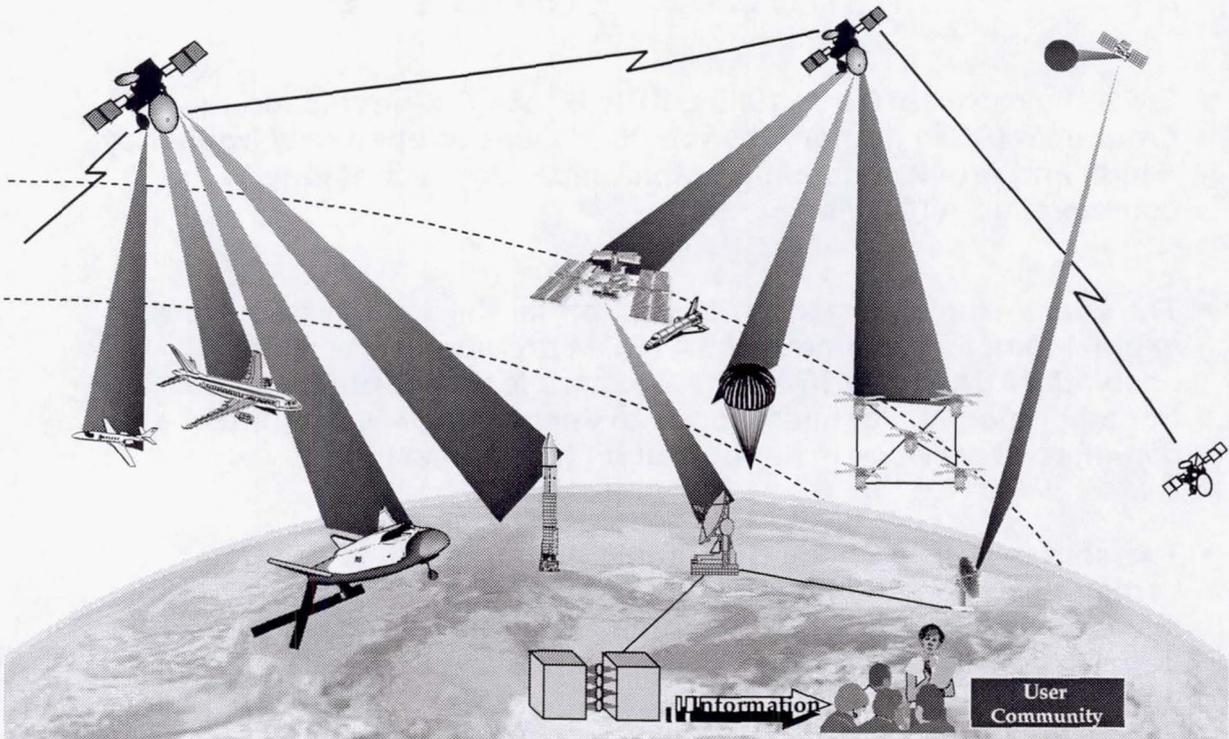
GRC Space Communications Focus

- Develop revolutionary space communication systems and networking technologies for NASA Enterprises
- Develop advanced communications and networking technologies that will enhance NASA's current communications infrastructure
- Develop gap-filling technologies that will enable NASA's transition to commercial communications services
- Develop communication and networking technologies that will enhance the National Airspace System



Glenn Research Center

Space Communications Program Vision to Enable NASA Communications Infrastructure

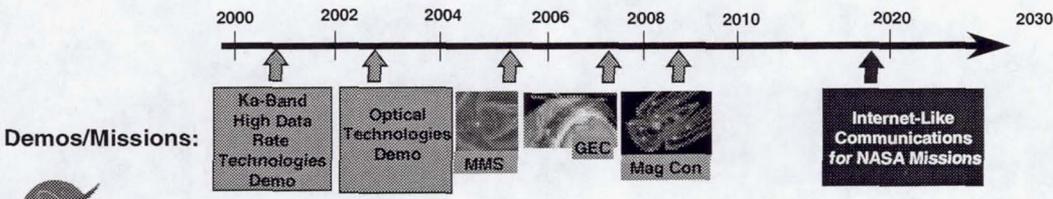


High Rate Data Delivery Program

Goal: Enable affordable virtual presence throughout the solar system by increasing volume and timeliness of space data transfer directly to users while minimizing the cost and the impact of communications subsystems on future spacecraft.

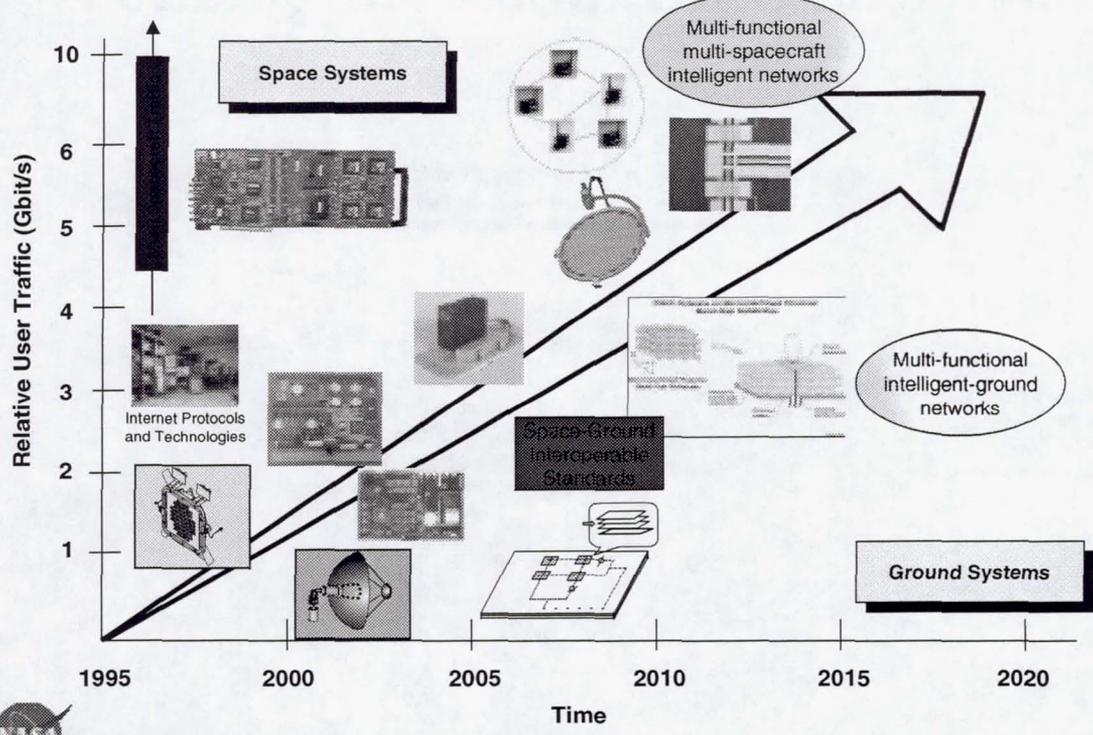
- Technology Development:**
- Ka-Band Amplifiers, Receivers, Modems, Antennas
 - Optical Technologies - 1st Generation
 - Internet Protocols and Network Technologies Space Environment
 - Hyperspectral Imaging
 - On-Board Processing
 - Multicasting Networks
 - Low Cost, Miniature, Low Power Integrated Components
 - 10 Gbit-Rate Comm. Systems
 - Ad-Hoc Networks for Multiple Spacecrafts
 - Seamless High Data Rate Information Delivery
 - Intelligent, Ad-Hoc User-Centric Communication Networks
 - Communication Technologies for Multiple Spacecraft Networks Connected to Deep Space Backbone

Capabilities: Point-to-Point Communications Point-to-Multipoint Communications Autonomous, Ad-Hoc Multiple Comm.



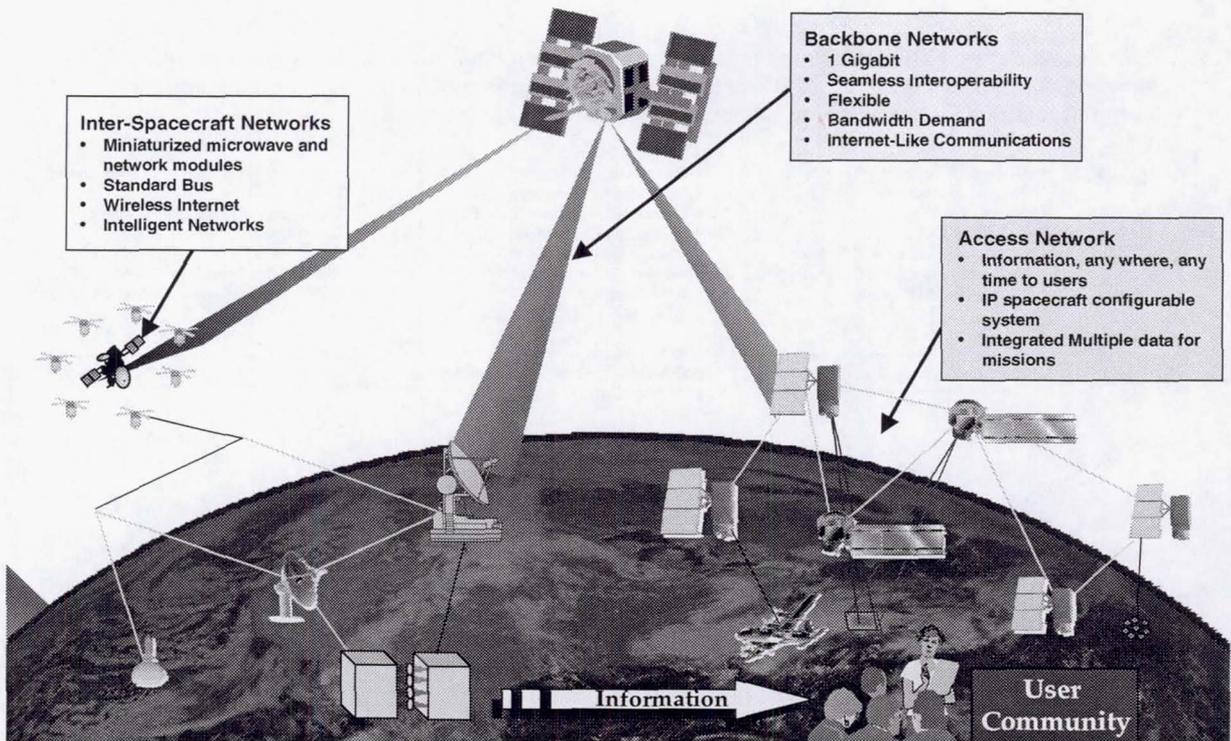
NASA
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High Rate Communication Network Technologies

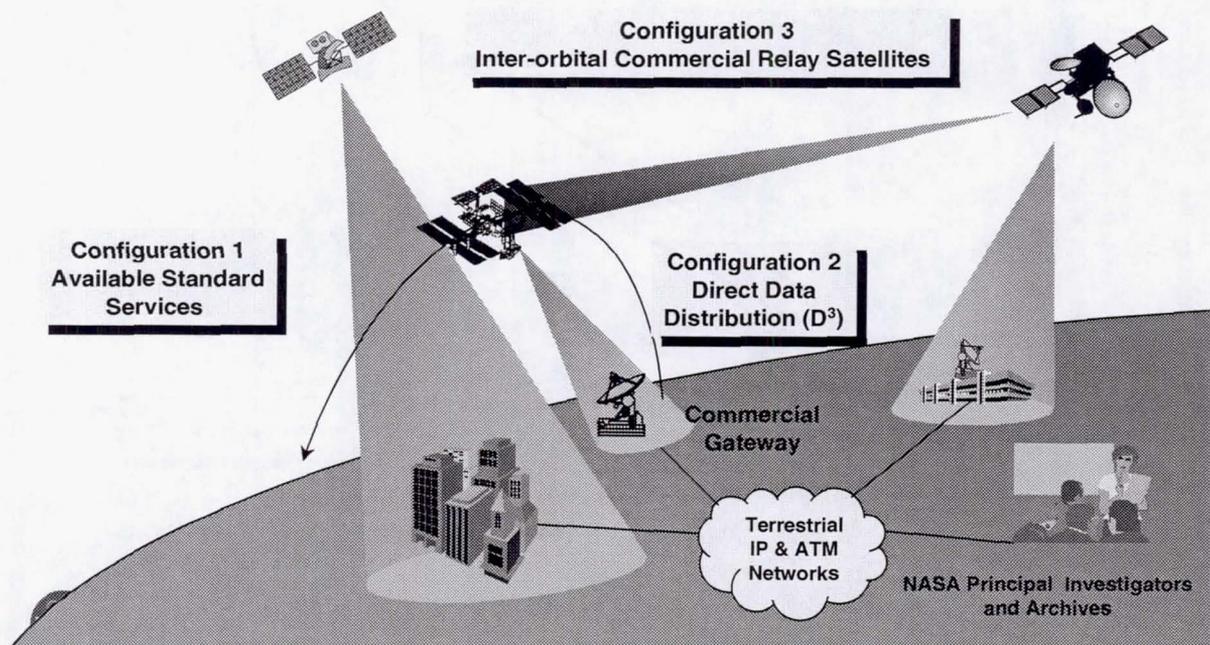


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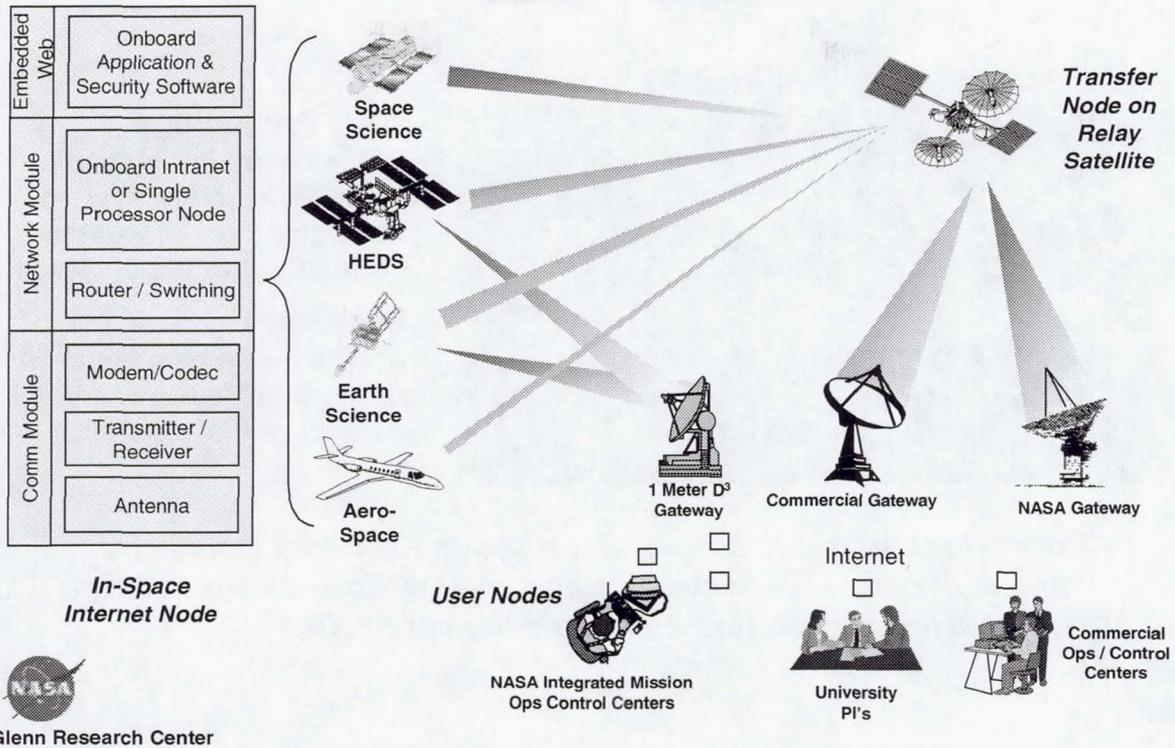
Future Directions



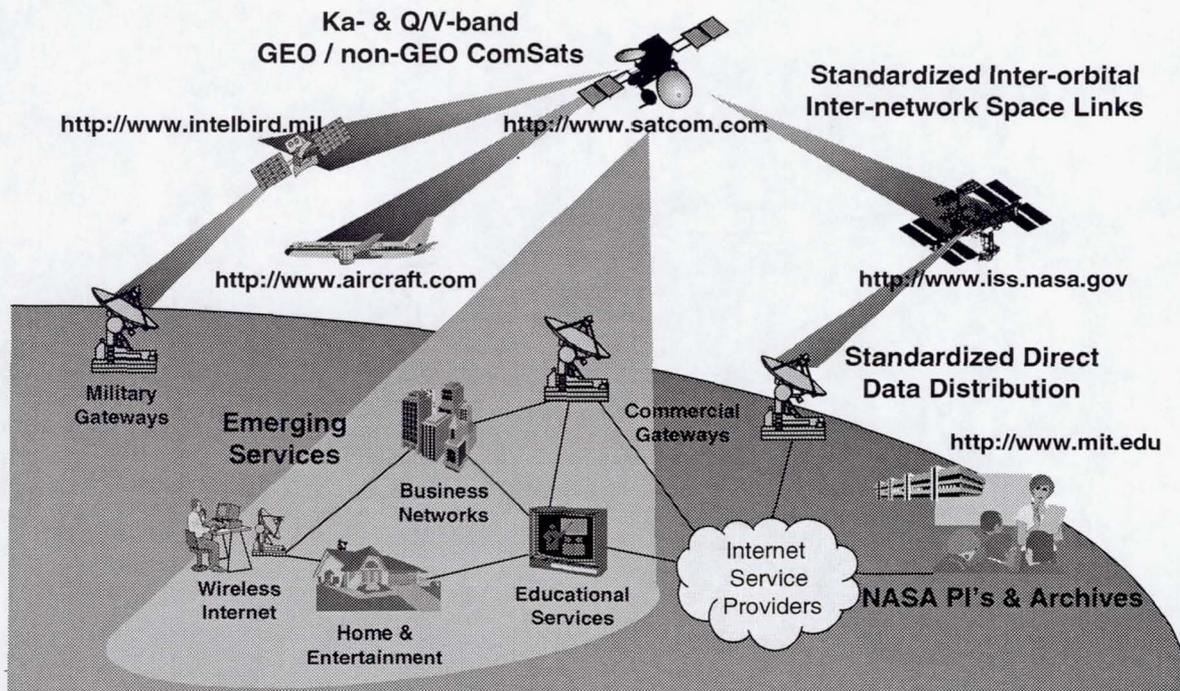
Commercial Utilization Configurations



Common Interface Architecture

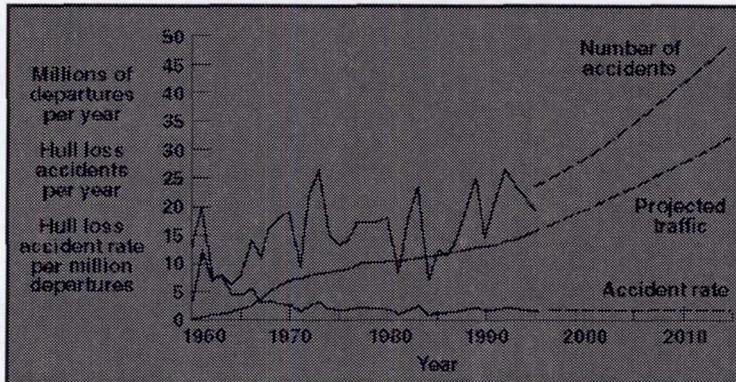


Space Internet Vision For Commercial Space & Ground Interoperability



The Aviation Capacity and Safety Challenge

Air Traffic to Triple in Next 20 Years



NASA Technology Goals

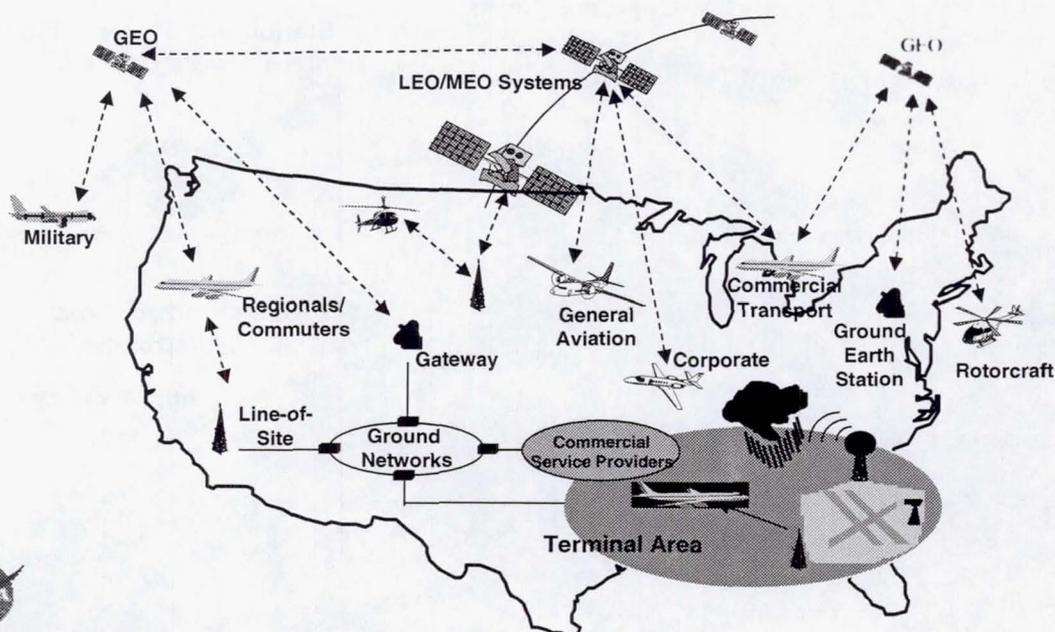
- While maintaining safety, triple the aviation system throughput, in all weather conditions, within 10 years
- Reduce the aircraft accident rate by a factor of five within 10 years, and by a factor of ten within 25 years

The current air traffic management system is near its capacity limits with extensive system delays and inefficiencies resulting in annual losses to users estimated at over \$3.5B.



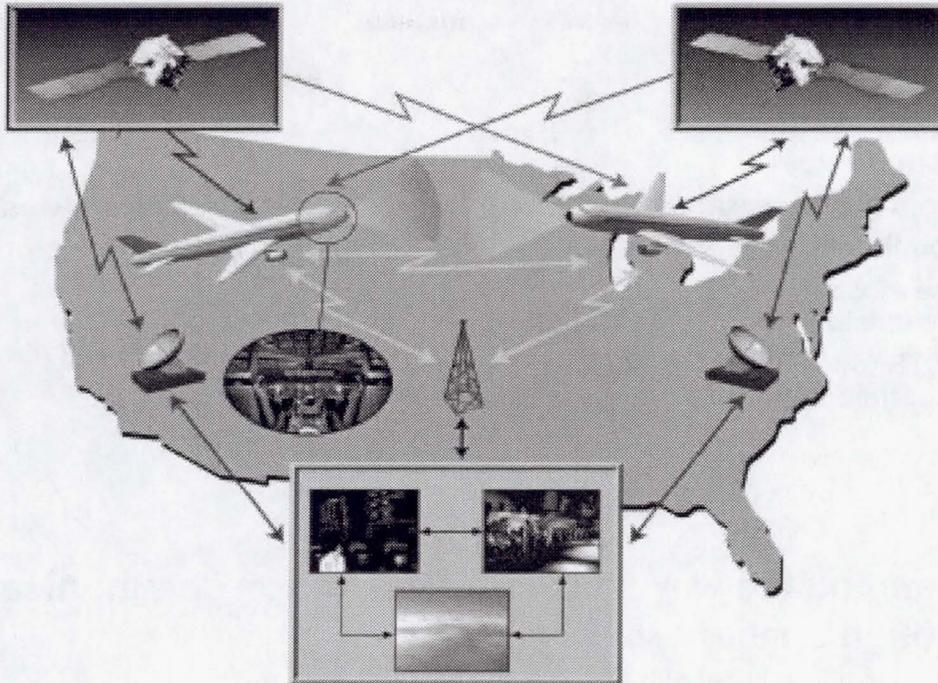
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Next-Generation NAS Communications

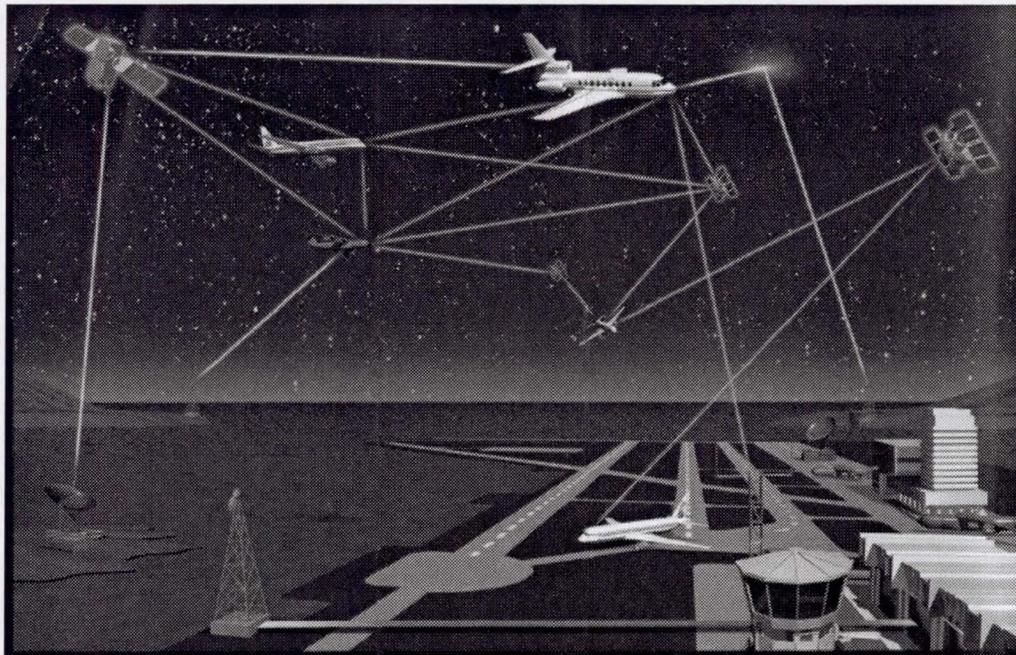


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Weather Information Communication



Glenn Research Center



Courtesy of Rockwell Collins

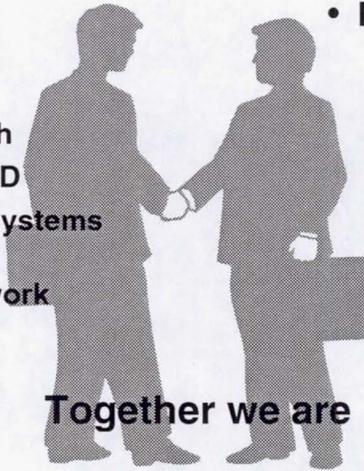


Glenn Research Center

Partnering with Industry

- **NASA**

- Ka-band research & technologies
- Propagation research
- Communications R&D
- Use of Commercial systems & services
- ACTS follow on network experimentation



- **INDUSTRY**

- Global competition
- Interoperability with terrestrial systems
- Ka-band technologies and services
- Satellite-delivered spacecraft and aircraft services

Together we are

Changing the way NASA and the Nation communicate through space



Glenn Research Center

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1.1 - The Advanced Communications Technology Satellite – Performance, Reliability and Lessons Learned

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1.0 Abstract

The Advanced Communications Satellite (ACTS) was conceived and developed in the mid-1980s as an experimental satellite to demonstrate unproven Ka-band technology, and potential new commercial applications and services. Since launch into geostationary orbit in September 1993, ACTS has accumulated almost seven years of essentially trouble-free operation and met all program objectives. The unique technology, service experiments, and system level demonstrations accomplished by ACTS have been reported in many forums over the past several years. As ACTS completes its final experiments activity, this paper will relate the top-level program goals that have been achieved in the design, operation, and performance of the particular satellite subsystems. Pre-launch decisions to ensure satellite reliability and the subsequent operational experiences contribute to lessons learned that may be applicable to other comsat programs.

2.0 Introduction

The general concept formulated by NASA in the early '80s for the ACTS program was to focus the development of satellite communications technology for the effective utilization of the frequency spectrum. The technologies to be implemented included a high gain, multi-beam antenna and wideband, higher power (46 watt) transponders for use at the undeveloped Ka-band, along with on-board processing and microwave switching to enable various new ground station and network capabilities. Specific mission objective requirements - related to fundamental satellite and earth station hardware capabilities - were identified by NASA as a metric to gauge mission success. These original basic objectives have all been met and surpassed many times over as the experiment program evolved, but can be distilled down to two top level objectives:

1. Demonstrate, verify and characterize technology for Ka-band comsats and evaluation of Ka-band systems
2. Provide a reliable experimental geosynchronous testbed

The original program plan specified a two-year life, but critical hardware was designed for four years. The continuing health of the satellite and a robust experiment program and expanding ground terminal fleet made a logical case for program extension. The unique results of the ACTS experiments program have been reported at many technical conferences since launch in September 1993. Inclined orbit operation to conserve fuel was determined feasible and worthwhile in 1998 with little added resources. ACTS is the only US operational Ka-band test bed for geosynchronous communications. The following sections provide a retrospective view of experience with the satellite and ground subsystems in achieving the above two program objectives, while contributing to the comsat knowledge base.

3.0 Technology for Ka-band comsats

System and market studies into the early 1980s identified potential satellite applications for trunking and customer premises services. Since the ACTS system was focused on the next generation of technology for commercial applications, its experimental frequency authorization covered the commercial Ka-band from 29.0 to 29.9 GHz uplink and 19.2 to 20.2 GHz downlink, not the nearby government portion of Ka-band. Anticipated high capacity applications called for transponder channels with 900 MHz bandwidth. Figure 1 (see

the appendix) is a block diagram of the experimental payload that was developed to implement the new technologies.

3.1 Receivers

The low noise receiver (LNR) at each transponder input provides a 3.8 dB noise figure, yielding peak G/T values of 19.17 to 24.26 dB/°K for the uplink spot beams. Almost seven years of operation on the external antenna panel have shown no evidence of degradation of the HEMT low noise amplifiers based on links and margins currently achieved by the various earth stations. The LNR consists of two separate assemblies - the 30 GHz downconverter and the 3.5 GHz intermediate frequency module - to simplify manufacturing and testing. This configuration separates the Ka-band components - which require a unique skill set for manufacturing - from the C-band components and provides the capability to optimize performance more precisely. The 900 MHz bandwidth at 30 GHz required the development of new methodology in manufacturing, alignment and test to provide accurate and repeatable data. [1]

3.2 Transmitters

The four wideband transmitters each include an IF to RF (3.5 to 20 GHz) upconverter followed by a 46 watt TWTA. A limiting amplifier in the upconverter maintains TWT input constant at the saturation point across the 19.2 to 20.1 GHz band, operating predominantly single carrier TDMA operation. The TWTA includes more instrumentation than is common on commercial satcom transmitters, even though it results in a reduction in DC to RF efficiency, so that NASA could evaluate the long-term stability of the amplifiers and collect data to aid the commercial satellite industry. The ACTS TWTs have a long life M-type dispenser cathode, -6.6kV cathode voltage, a dual-stage depressed collector and have accumulated nearly 200,000 tube hours on-orbit. Inspection of telemetry data from the TWTA instrumentation, comparing 24-hour data taken in 1993 and 1999, confirms operational experience for the excellent stability of these devices. Helix current stability implies many more years of life.

There have been no spurious shutoffs or indications of high voltage problems. The Electronic Power Conditioner (EPC) and TWT internal design and assembly and high voltage encapsulation techniques continue to perform as intended after 590 power/thermal cycles during eclipses. Packaging techniques include corona balls, void free, thermally conductive polyurethane, potted splices and compartmentalized high and low voltage circuits [2]. Operational procedures minimize thermal stresses by controlling the minimum operating temperatures at post eclipse turn-on and avoiding tube operation without rf drive.

The original concept for ACTS called for dual power TWTAs to mitigate Ka-band rain fade that could occur for a few channels of a multi-channel operational system while minimizing power subsystem requirements. A study concluded that there was no major advantage over a fixed-power system after considering the variable attenuator needed to maintain TWT saturation, additional EPC complexity and the reduced TWT efficiency in the low power mode. The ACTS TWTs were actually qualified for dual mode operation at 11 and 46 watts output but the EPC was designed for the higher power only.

3.3 Multibeam Antenna

The multiple spot beam antenna system (MBA), provided high gain 0.3° beams to enable smaller terminals and frequency reuse by spatial and polarization isolation. The hopping spot beams are electronically selected by high speed (800ns) low loss ferrite switches in two orthogonally polarized groups (east and west) of beam forming networks. Biasing the satellite in pitch and roll allowed determination of beam centers and contours and evaluation of various outside perturbations peculiar to the ACTS MBA design and materials. It was determined that diurnal thermal distortion effects were occurring as solar flux illuminates different parts of the MBA assembly but could be adequately compensated by daily operational procedures [3].

Subreflector distortions which affect the autotrack uplink signal and thus degrade satellite attitude control are compensated by temporarily switching from autotrack to earth sensor pointing reference as discussed in the next section. Since ACTS has separate receive and transmit reflectors the MBA design included a biaxial gimbal drive to adjust receive and transmit beam alignment. Although intended for seasonal adjustments this feature ended up being used for east-west bias on a daily basis to compensate for thermally induced downlink beam center drift of the transmit reflector. The thermally induced distortions and resultant beam wandering encountered by the MBA, in spite of careful thermal analysis, indicates the need for more comprehensive modeling at other than the maximum temperature extremes and gradients. Modeling was complicated by the

folded optics and nested, gridded subreflector implementation. An additional antenna design consideration is adequate low frequency structural analysis of the large reflectors to avoid another source of beam pointing degradation for satellites with narrow spot beams. A low-level one Hz modulation of the MBA downlinks is attributed to momentum wheel control impulses exciting a transmit reflector resonance. This was negligible at beam center but noticeable at beam edges due to gain slope.

3.4 Attitude Control

A requirement for Ka-band spot beam application is precise attitude determination and control of the satellite. ACTS satisfied the pointing requirements as an experimental system and demonstrated both pros and cons that could be considered for commercial systems. ACTS implements a 30 GHz autotrack subsystem where the MBA is the primary source for attitude determination signals to satisfy requirements of $\pm 0.025^\circ$ in pitch and roll. Table 1 shows attitude control requirements, predictions and typical performance in the first three columns, respectively. The MBA feed system and autotrack receiver process the Cleveland uplink reference signal to provide the pitch and roll error signals that are input to the attitude control system. The autotrack receiver has demonstrated over 22 dB of dynamic range to accommodate severe uplink rain fades. Figure 2 (see the appendix) shows that excellent pitch and roll sensing and control is maintained even during the occasional deep rain fade experienced at Ka-band.

The previously mentioned MBA subreflector thermal distortion can introduce over 0.1° autotrack error at certain times of the day, 1430 to 1730 GMT in Figure 3, bottom, if not compensated by switching to the less precise earth sensor (ESA) for its better average stability during these periods. This illustrates the sensitivity of this method of attitude determination to Ka-band antenna technology issues and the need for a non-RF sensing method as backup.

Pitch control, better than 0.01° , (see Figure 2, top) is maintained by a quick reacting momentum wheel while roll and yaw are each controlled by a less responsive magnetic torquer. Torquers have a relatively slow time constant and can saturate during large geomagnetic disturbances that may occur a few times per year but are less expensive than additional momentum or reaction wheels. Figure 4 shows roll error during a magnetic storm.

To meet the 0.15° yaw requirement the yaw error is sensed by east- and west-facing sun sensors, providing approximately eight hours of yaw input data for direct control during spacecraft local morning and evening windows. This data also feeds into an estimator algorithm that provides yaw pointing control input for the other 16 hours. Figure 3, top, shows yaw error data over one 48-hour period in 1999, typical of good estimator performance. Maintaining or regaining convergence of the estimator, which can take a few days, can be operator intensive during geomagnetic storm conditions. Other implementation schemes such as additional sun sensors or even star trackers could be alternatives to minimize operational impact.

A related lesson demonstrated by ACTS was the ability to maintain spot beam communications during the stationkeeping maneuvers needed to maintain the spacecraft in its assigned geostationary position at 100° West. Experience has proved that antenna pointing and experiment operations could continue uninterrupted through these maneuvers since rate gyros and thruster firing maintain adequate attitude stability.

The excellent performance of the spacecraft bus and communications payload provided opportunity to conduct significant new ACTS experiments in inclined orbit with little expenditure of fuel, starting in July 1998. Although this mode of operation is not new for satcom operators ACTS is unique for precise pointing of the spot beams. Modifications to flight software and ground processing enabled ACTS to continue operation with little degradation of beam pointing even though this was not considered in the original design. Column 4 of Table 2 indicates predicted worst case performance after 2.5 years in inclined orbit. Figure 3 actually shows yaw and autotrack roll after one year in inclined orbit. This data is virtually identical to the non-inclined performance [4].

A significant fact of life for all comsats is the constraints of fuel on operational lifetime. During the planning of inclined operations it was discovered that there was an error in bookkeeping of fuel consumption. The lesson here is that adequate on-board instrumentation and baseline ground calibration testing is necessary to provide on orbit data to supplement fuel bookkeeping.

3.5 Command, Ranging and Telemetry Links

The daily operation of ACTS is coordinated from the Master Ground Station (MGS) at NASA Glenn Research Center in Cleveland, Ohio, USA and executed via Ka-band command and telemetry links. Single station ranging for five minutes per hour, over 24 hours, provides data for orbit determination. Measured link margins from the MGS were:

- 18 dB for high rate payload commands (29.975 GHz)
- 24 dB for low rate bus commands "
- 14 dB for telemetry (20.185 GHz via CONUS antenna)

Backup telemetry and command capability requires a C-band system with on-board omni antenna since even a CONUS antenna can be inadequate for pre-operational and attitude recovery operations. C-band support is leased from a commercial station and can be quickly called up if the need arises. Experiment coordinators at the MGS generate an experiment schedule that defines the configurations required of the communications payload and provide an experimenter liaison/ customer interface function. Spacecraft monitoring and control actually occurs from a duplicate set of computers and consoles at the Lockheed Martin (LM) facility in Newtown, PA while the MGS serves as backup. This was not the most cost-effective configuration for a long-term program, but provides immediate access to experiment or spacecraft experts at the respective sites.

Heavy rain exceeding the above margin has caused occasional telemetry dropouts as expected for a site with no diversity. Dropouts from momentary to up to one half hour or more have occurred, but this has been totally acceptable for ACTS operations, since the spacecraft autonomously maintains correct pointing and maintains experiment connectivity for those sites not impacted by heavy rain. Essential or critical commands can be executed at 100 bps for maximum margin. Although not specifically recorded, our experience suggests that one or more of the leased lines between the MGS and LM sites have had more down time than the Ka-band link. The MGS antennas have a step track system to maintain pointing whether tracking a geostationary or inclined satellite but can require operator intervention if track is lost during a rain fade event

4.0 Technology Evaluation for Ka-band Systems

4.1 Baseband Processor (BBP) Mode

The BBP on-board processing demodulates 27.5 and 110 Mbps uplink bursts, routes individual 64 kbps circuits, and regenerates downlink bursts at 110 Mbps. The BBP provides network connectivity via the hopping spot beams and applies adaptive compensation to enhance availability in those spot beams experiencing rain fade conditions. The Baseband Processor (BBP) provides bandwidth on-demand, enabling a full mesh, single hop TDMA network at rates from 64 kbps to T1 using Very Small Aperture Terminals (VSATs) equipped with 1.2 meter antennas. The largest network tested has been a total of 21 terminals spread over 12 spot beams, although the BBP architecture is designed accommodate a fleet of up to 40 terminals.

No memory or processing failure has been encountered in BBP operation to date and the architecture inhibits the effect of any potential SEU-induced bit errors. An occasional soft error of this type would be cleared by the error detection and correction if occurring within control memories or it would contribute imperceptibly to Bit Error Rate (BER) if occurring in the data memories.

With a payload availability factor of 97.4% this mode has enabled the accumulation of statistical performance data from VSATs in different rain zones in CONUS. The minimum design margin for the network is 5 dB uplink and 3 dB downlink but adaptive rain fade compensation can add 10 dB additional margin. The resulting BER remains within the specification value of 5.0×10^{-7} , for service availability in the US exceeding 99.5% [5]. Phone service routed through the BBP demonstrated very good voice quality using digital echo cancellation.

4.2 Microwave Switch Matrix Mode

The ACTS Microwave Switch Matrix (MSM) implements another form of on-board switching applicable to multibeam communications satellites. It has a 4X4 crossbar switch architecture consisting of 16 GaAs FET switch amplifier modules with 100 ns switching speed and flat gain across the 3.0 to 4.0 GHz IF band. The MSM's digital control unit is implemented with CMOS ICs and is routinely programmed, via the command uplink, for the required uplink to downlink connectivity. This can be static or dynamic satellite switched connectivity, with 1 or 32 ms frames, using fixed or hopping spot beams.

The surge in fiber optics transmissions in the late 80's and Internet traffic in the 90's has caused this mode of system operation to be much in demand. The MSM mode capability has enabled a broad range of Ka-band users, from mobile terminals and USATs in the static bent-pipe mode to 622 Mbps Satellite Switched-TDMA for point-to multipoint full duplex interconnection of fiber networks. Typically, the MSM/transponder channels are initially programmed for a loopback mode to verify the experimenters earth station setup then reconfigured for full duplex connectivity. No problems have been encountered with the control logic or the hybrid switch modules of the MSM. A memory clear function would have required circuit board redesign but would have saved thousands of commands, especially on post-eclipse restarts.

4.3 Steerable Beam Antenna (SBA)

One of the beams within the west hopping beam family is actually a one-meter reflector (SBA), which can be mechanically steered over the entire hemisphere visible from 100° West longitude. Although not new technology, and its gain is over 6 dB lower than the spot beams, the SBA has extended ACTS system to sites from Antarctica to the Arctic Circle. Ground software was developed to automatically generate and execute SBA pointing commands based on real-time GPS position reports from mobile users. This capability has enabled unique experiments through ACTS with forward and return links automatically tracking airborne and shipboard terminals. A more typical use of this software is direct point-to-point moves of the SBA without going via the MGS reference point. Azimuth and elevation command steps are the primary verification of correct movement followed by telemetry readouts of coarse and fine shaft potentiometers. Some users occasionally request peaking the SBA position at their site to ensure maximum signal level.

4.4 Propagation Beacons

The move to a new, higher frequency band requires providing adequate propagation data to system designers. For the last six years ACTS has provided a CONUS signal stable to within 1 dB from the 20.185 GHz telemetry beacon and the unmodulated 27.505 GHz uplink fade beacon. The primary telemetry beacon has remained stable since launch even though it exhibits periodic variations now familiar to propagationists. These variations include a 0.4 dB shift during spacecraft ranging, pattern variations due to diurnal thermal gradients on the CONUS antenna feed tower and frequency shifts with bus voltage variations during eclipse entry/exit. The statistical interpretation of this data has been made available by NASA and academia to aid comsat systems designers worldwide.

4.5 System Lessons

The ACTS satellite with its on-board switching and multiple beams, coupled with the various ground elements, represents a system with many opportunities for difficult to isolate problems. The execution of a comprehensive end-to-end ground test, although it had many technical and logistical challenges, was essential to verifying system integrity and interface compatibility. Prior to the full system test a single string engineering model of the payload supported development and test of the TDMA network control functions for risk reduction at the earliest opportunity.

5.0 A Reliable Experimental Geosynchronous Comsat

5.1 Reliability Modeling

Specific reliability goals were established in the initial contract specifications based on the technology goals of the program. Reliability analysis was a tool used during the satellite design process to assure adequate performance and identify areas of risk. Reliability modeling of the satellite subsystems, components and parts allowed comparative evaluations of design configurations and various tradeoffs. A fundamental requirement was no mission critical single point failures with a probability greater than 0.001 and no single point failures that eliminate both east and west hopping beams. A concession made for reliability modeling, consistent with being an experimental program, was a 36% duty cycle for communications modes. This equates to 12 hours, five days per week operation. Cost and weight constraints limited redundancy but accomplishing the program goals within two years and identifying alternative operational modes allowed for the higher failure rates identified for the complex communications payload subsystems. Table 2 summarizes the reliability model for the ACTS mission (using MIL-HDBK-217D failure rates). The space proven satellite bus had, of course, much better reliability values than the new design payload and allowed maximum concentration of resources on the new subsystems. The complex functionality and high parts count of the BBP made it the overall driver of payload

reliability. Since the BBP enabled critical program objectives yet was the weakest link in the reliability model an ingenious workaround was devised to continue partial east/west beam throughput using the timeshare mode as indicated in Table 2. Simple redundancy would have been an alternative had it not been previously eliminated for cost, weight and power constraints.

5.2 Additional Product Assurance Steps

Additional product assurance steps were also taken at various points in the satellite development, starting with a comprehensive parts program. Newly designed boxes were required to use the highest reliability "Class-S" parts as the standard, where available. Otherwise, lower grade parts were considered non-standard and were tested and screened to upgrade to the equivalent of S level. Electronics boxes with a reliable space flight history were considered to be assembled with heritage, source-controlled parts that were acceptable unless part unavailability forced that item into the non-standard category. Custom developed LSI integrated circuits, RF semiconductors and hybrid modules had lot qualification and accelerated life testing to establish reliability.

Radiation survivability was also a major task contributing to the robustness of the parts program. Radiation modeling and shielding analysis was used to determine two-year total dose levels for all parts throughout the satellite. If available data was inadequate to guarantee a hardness margin equal to two or more then the parts were radiation tested. This included many custom built LSI circuits for the BBP where 50 Krad was the lowest test level.

Since the ACTS TWTA was a new design one of the flight spare units was put on life test to detect any early signs of degradation under simulated on-orbit thermal vacuum conditions. After several hundred simulated eclipse cycles with no hint of problems this ground based test was discontinued after launch when cumulative on-orbit time exceeded ground test time.

5.3 Actual Reliability

As previously mentioned the reliability model for the communications components used a 36% duty cycle to meet contract specifications. During the planning of the operational phase of the mission it was concluded that the implied daily component turn-off was not prudent given well-designed satellite components. Transient stresses and electrical and thermal cycling are generally viewed as detrimental to electronics and should be avoided as much as possible.

The actual reliability of the satellite has been much better than predicted given the results of the reliability modeling shown in Table 2. Since launch the satellite has accumulated 58000 hours with no failures of the Ka-band subsystems. The payload has additionally seen 590 power cycle and thermal transients during 14 eclipse seasons, conditions not seen by commercial satellites equipped with high capacity batteries to maintain continuous operation. The only hard failure as of this writing has been a C band transmitter.

A problem reporting system has been in place since launch to track all anomalies that have been encountered. Of 42 spacecraft operations problem reports, the most common cause has been the general category of procedure or operator error not actual hardware problems. This is understandable for a satellite test bed where many dozens of command lists are sent daily to implement configurations for a variety of experimental users.

5.4 Reliability and Product Assurance Lessons

The successful operation achieved on-orbit can be attributed to a well-managed design and development program where risks were identified and resolved as early as possible. The robust parts program was a challenge to execute with minimal impact to manufacturing and integration schedules but ensured reliability from the lowest level. Some might argue that S Level parts were not really needed for an experimental satellite but conservative design was essential for the first flight demonstration. When accelerated life testing identified defective RF semiconductors late in the program the impact of replacement was significant since unit acceptance testing was completed, but it avoided potential failures that could have shortened the mission.

Electromechanical devices also came under scrutiny when test data showed inconsistent results from an established vendor. Last minute replacement of co-axial switches had a major interface and integration impact but removed a potential failure and preserved payload redundancy options (yet unused) thus improving reliability for a longer mission.

One switch problem that was encountered shortly after launch was not fully investigated until six years later due to conservative operations policy. The primary 27.5 GHz beacon was 4 dB low when first turned on, possibly due to a misalignment of the waveguide switch. When the redundant beacon was turned on and provided the expected output the troubleshooting was put on hold rather than risk additional cycling and possible jamming of a malfunctioning switch to compromise the beacon signal for the next several years. Switching back to the primary beacon late in the mission verified the correct level and confirmed the initial diagnosis of temporary switch misalignment.

The one other early mission mechanical anomaly that could possibly be attributed to launch vibration was a slight shift in antenna beam alignment. Although the friction joints provided structural alignment with rigidity analytically verified, pinning the joint at final assembly would have precluded any possibility of slippage. The biaxial gimbal drive allowed on-orbit adjustment of the transmit reflector to correct the slight initial misalignment.

One final experience on avoiding problems involved end-to-end polarity verification of all sensors, motors or actuators after final system assembly and integration. Comprehensive reviews of existing lower level test data and the addition of quickly devised top-level tests, where necessary, removed any uncertainty. Launch base tests were inserted even after transfer orbit stage mating and avoided a major problem with the ACTS autotrack system.

A cursory review of project documents indicates that the prime contractor product assurance management task was less than 3% of the contract. However, when the pervasive efforts to design, manufacture and test for reliability are considered, along with subcontractors efforts, plus NASA oversight, the figure is probably several times this value.

6.0 Conclusions

ACTS has far surpassed its original objectives. Although designated as an experimental satellite the product assurance and reliability efforts invested in ACTS were significant and commensurate with being a highly visible first step into Ka-band services. In spite of additional stress of nearly 600 power/thermal cycles there have been no failures of the Ka-band payload or reduction in communications capability in almost seven years on orbit. Along with reliability, the capabilities designed into ACTS have made it a flexible Ka-band test bed, allowing it to evolve with emerging technology and applications. ACTS has successfully continued experiment operation including precise spot beam pointing into inclined orbit.

Many things were done right before the satellite was launched and after launch it was learned that some could have been done even better. ACTS is likely the last satellite of this type for NASA, but it should remain an excellent example of a well-formulated, well executed program.

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Table 1. ATTITUDE CONTROL POINTING ERROR (AUTOTRACK MODE)

AXIS	SPECIFICATION REQUIREMENT	PRE-LAUNCH PREDICTION	TYPICAL PRE-INCLINE	INCLINED 2° PREDICTION
Pitch	0.025°	0.0213°	0.01°	0.0164°
Roll	0.025°	0.0235°	0.02°	0.0475°
Yaw	0.150°	0.144°	0.15°	0.217°

Table 2. MISSION RELIABILITY

Probability of Survival (Ps)		
Mode	At 2 years	At 4 years
Full BBP/VSAT capability 36% duty cycle	0.77	0.55
Full BBP/VSAT capability 100% duty cycle	0.45	0.16
Half BBP/VSAT capability 100% duty cycle	0.66	0.33
Partial T1VSAT capability 100% duty cycle Timeshare mode	0.74	0.41
3 Beam MSM 36% duty cycle	0.95	0.88

Figure 1. ACTS PAYLOAD BLOCK DIAGRAM

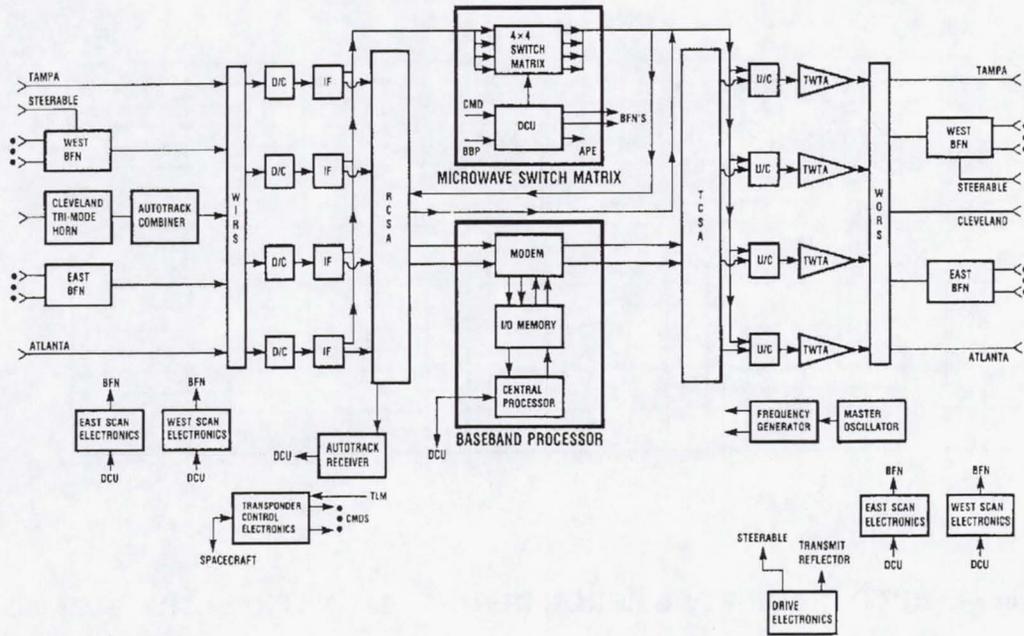


Figure 2. AUTOTRACK PITCH AND ROLL ERROR (TOP) AND SIGNAL STRENGTH

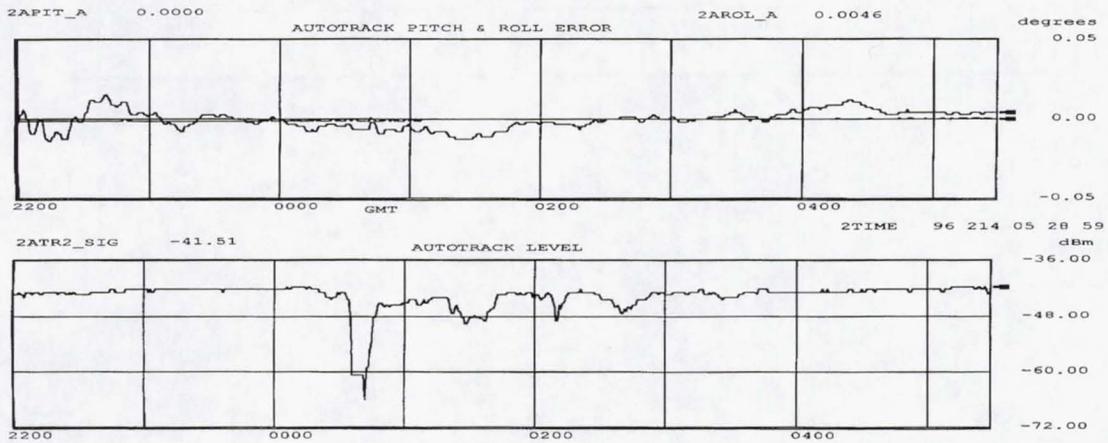


Figure 3. YAW ERROR (TOP) AND AUTOTRACK ROLL ERROR AT 0.8° INCLINATION

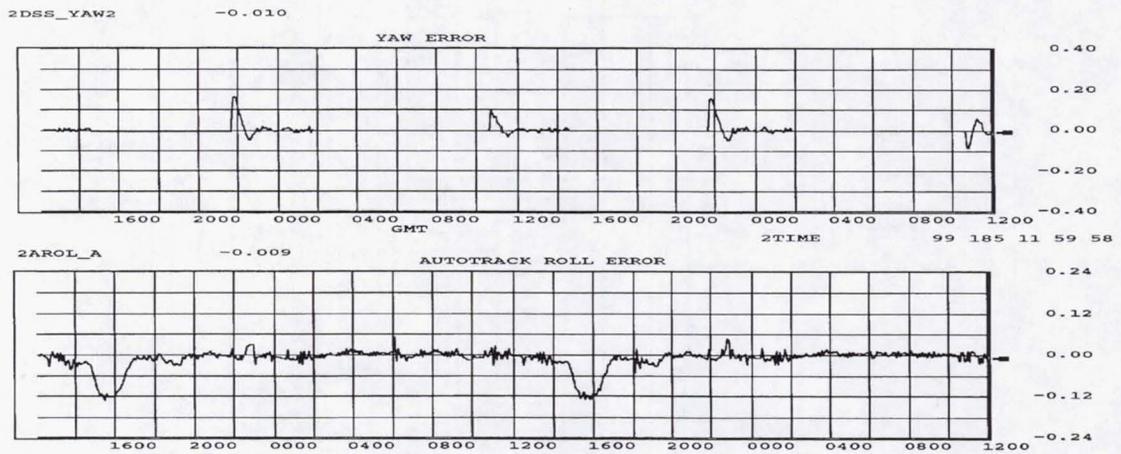
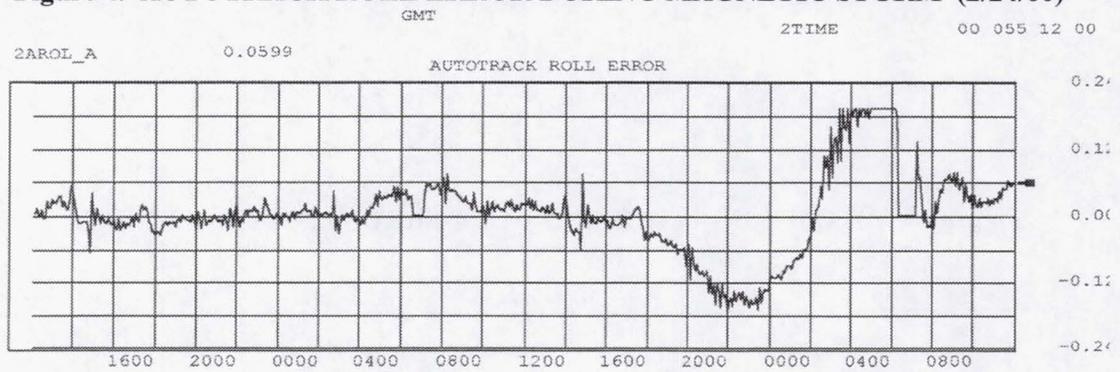


Figure 4. AUTOTRACK ROLL ERROR DURING MAGNETIC STORM (2/24/00)



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1.2 - ACTS Ka-Band Earth Stations: Technology, Performance, and Lessons Learned

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Abstract

The Advanced Communications Technology Satellite (ACTS) Project invested heavily in prototype Ka-band satellite ground terminals to conduct an experiments program with the ACTS satellite. The ACTS experiment's program proposed to validate Ka-band satellite and ground station technology, demonstrate future telecommunication services, demonstrate commercial viability and market acceptability of these new services, evaluate system networking and processing technology, and characterize Ka-band propagation effects, including development of techniques to mitigate signal fading.

This paper will present a summary of the fixed ground terminals developed by the NASA Glenn Research Center and its industry partners, emphasizing the technology and performance of the terminals (Part I) and the lessons learned throughout their six year operation including the inclined orbit phase of operations (Full Report). An overview of the Ka-band technology and components developed for the ACTS ground stations is presented. Next, the performance of the ground station technology and its evolution during the ACTS campaign are discussed to illustrate the technical tradeoffs made during the program and highlight technical advances by industry to support the ACTS experiments program and terminal operations. Finally, lessons learned during development and operation of the user terminals are discussed for consideration of commercial adoption into future Ka-band systems.

The fixed ground stations used for experiments by government, academic, and commercial entities used reflector based offset-fed antenna systems ranging in size from 0.35m to 3.4m antenna diameter. Gateway earth stations included two systems, referred to as the NASA Ground Station (NGS) and the Link Evaluation Terminal (LET). The NGS provides tracking, telemetry, and control (TT&C) and Time Division Multiple Access (TDMA) network control functions. The LET supports technology verification and high data rate experiments.

The ground stations successfully demonstrated many services and applications at Ka-band in three different modes of operation: circuit switched TDMA using the satellite on-board processor, satellite switched SS-TDMA applications using the on-board Microwave Switch Matrix (MSM), and conventional transponder (bent-pipe) operation. Data rates ranged from 4.8 kbps up to 622 Mbps. Experiments included: a) low rate (4.8-100's kbps) remote data acquisition and control using small earth stations, b) moderate rate (1-45 Mbps) experiments included full duplex voice and video conferencing and both full duplex and asymmetric data rate protocol and network evaluation using mid-size ground stations, and c) link characterization experiments and high data rate (155-622 Mbps) terrestrial and satellite interoperability application experiments conducted by a consortium of experimenters using the large transportable ground stations.

Ground Stations Overview

The ground stations developed by NASA Glenn Research Center and its industry partners included five different size terminals each with unique capabilities designed to meet a set of applications for experiments and demonstration at Ka-band. The large ground station facilities of the ACTS/GRC program are the NASA Ground Station (NGS) and the Link Evaluation Terminal (LET). The NGS serves as a) primary tracking telemetry and control (TT&C) station of ACTS, b) reference station of the Baseband Processor (BBP)/VSAT TDMA network, c) two VSAT traffic terminals, and d) backup facility to the LET for MSM experiment operations. The LET serves as a) hub for USAT star network experiments, b) High Data Rate terminal in the Gigabit Network, c) experimenter station used to conduct technology verification experiments such as wideband dispersion and antenna wetting, d) on-orbit test-bed for ACTS s/c characterization measurements including frequency response, and multi-beam antenna characterization, and e) backup facility for the TT&C function of the ACTS satellite.

The family of experimenter or transportable ground stations includes the Very Small Aperture Terminal (VSAT), the Ultra Small Aperture Terminal (USAT), and the High Data Rate (HDR) Terminal. Each terminal was originally designed to support certain applications. As advances in technology occurred over the course of the program each terminal demonstrated more advanced applications further demonstrating the capabilities of ground stations at Ka-Band. The VSAT terminal and ACTS TDMA network was initially used for 1.544 Mbps video and voice conferencing based on 64kbps channels and fade compensation algorithm evaluation. Over the course of the program the terminals were deployed for protocol networking experiments, propagation data collection & analysis, statistical availability for a TDMA network, and technology experiments to evaluate the satellite multi-beam antenna performance. The USAT ground stations were originally designed to demonstrate supervisory control and data acquisition for remote electric utility stations using kbps data rates. Advances, primarily in solid state amplifier technology, enabled the stations to demonstrate >1.544 Mbps video conferencing, highly asymmetric (1.544/45 Mbps) product and content distribution applications, and 2 Mbps full mesh TDMA/FDMA IP and ATM network experiments. The HDR station was first deployed to demonstrate interconnectivity of super computers to conduct interactive computer modeling at high data rates. Over the duration of the program the stations were re-deployed to demonstrate high rate commercial IP protocol augmentation, optimized FTP file transfer, and technology verification experiments and characterizations.

The ACTS satellite has two modes of operation; the MSM and BBP. The MSM mode of operation functions as a bent-pipe memory-less repeater with frequency translation. A microwave switch at the satellite IF frequency connects uplink antennas to appropriate downlink antennas for static point-to-point connections. The MSM may also be programmed using a repeatable uplink/downlink connection sequence for a satellite switched TDMA (SS-TDMA) network for HDR operations. The BBP provides on-board storage and routing of base-band signals for the VSAT TDMA network. Signals from each transmitting VSAT are demodulated by the BBP on-board the satellite and routed to the appropriate receiving station by illuminating the appropriate spot beam over the respective transmitting and receiving station¹. The satellite burst time plan dynamically updates based on orderwire requests from stations entering the network or if existing stations change their bandwidth requirement².

Table 1. ACTS GROUND STATION SUMMARY

NAME	MODE	ANTENNA (m)	HPA (Watt)	EIRP (dBW)	GT (dB/K)	BURST RATES (Mbps)	DATA RATES (Mbps)	MODULATION
NGS	BBP	5.5	200	68/74	26.5	U/L: 27.5 or 110 D/L: 110	64 kbps to multiple T1 & T2	SMSK
VSAT	BBP	1.2	12	60/66	16	U/L: 27.5 D/L: 110	1.792 (max) at 64 kbps increments	SMSK
USAT	MSM	0.6, 1.2	25, 1.0, 2.0	35-51	13/16	Up to 2.5 Msps	U/L: low kbps to 8 Mbps D/L: up to 45 Mbps	BPSK, QPSK, CDMA
HDR	MSM	3.4	100	76	28	Up to 696	311 or 622 Mbps	O-BPSK (OC-3) O-QPSK (OC-12)
LET	MSM	4.7	10-60	68-76	27	Up to 696	low kbps to 622 Mbps	BPSK, QPSK, SMSK

Table 1 identifies each ground station, its primary mode of operation, and typical link characteristics. The LET, HDR, and USAT terminals operate in the MSM mode and each use various modulation schemes. Because the transponders use hard-limiting amplifiers higher order modulation schemes above QPSK were not used. The NGS and VSAT operate in the BBP mode of the ACTS satellite. The modems on both the spacecraft and ground stations employ Serial Minimum Shift Keying (SMSK) modulation.

The ACTS ground station program enabled the commercial industry to make advancements in the design and performance of traveling wave tube amplifiers (TWTA's), low noise amplifiers, high rate modems, solid state power amplifiers, and high power frequency doublers. In addition, although outside the scope of this paper, the development of the on-board processing TDMA network enabled various satellite and ground station technologies not addressed here. The implementation of commercial terrestrial interfaces laid a foundation for terrestrial and satellite interoperability experiments, commercial protocol research and augmentation, and other technical advancements. The RF technologies developed for the ACTS ground terminals, with a few exceptions, were mainly extensions of technologies developed at lower frequency bands. Still, the design challenges were quite real and required significant engineering effort to overcome. The final result was high-quality ground station equipment that continued to perform well beyond the intended operational life of the system.

Ground Stations Technologies

Transmitter

Development and operation of 30 GHz Ka-band traveling wave tube amplifiers (TWTA) proved challenging in the early years of ACTS. The NGS and LET were the first to procure 30 GHz TWTA's. The NGS and LET began ground station integration and testing in the late 1980's and early 1990s. The NGS purchased four 54-Watt units and later the LET purchased three 60-Watt units from the same vendor. The TWT design used in the LET was similar to those used in the NGS. The TWT's were linear beam devices with a helix type slow-wave microwave circuit.

These first TWTA's experienced several problems. The first anomaly was reported in 1992³ that described a spontaneous shut down of the TWTA protection circuitry. Testing revealed random output power spikes (1-3 dB RF power fluctuations) present at certain frequencies. Naturally, the random power spikes contributed to loss of data bits and resultant increase in Bit Error Rate (BER). The effect would appear in the 10⁻⁸ BER range. Strong spikes resulted in the spontaneous shut down of the TWTA. Test data and analysis provided to the vendor contributed to modifications in TWTA design to minimize the effect of the power spikes. Although TWTA's in general experience RF fluctuations, the low BER experiments conducted in the ACTS program were more susceptible to these types of component characteristics. Other problems that occurred were high helix current shut off and an inability to power a unit on. Over time the latter problem was attributed to the operational procedure of the TWTA's.

The operations procedure at the start of the program was to allow the TWTA to run without RF drive during short periods of inactivity and turn the TWTA off during longer periods of inactivity (e.g., overnight). Regularly turning the unit off and on or leaving the unit turned off for short periods of time tended to create gas in the vacuum envelope of the tube. This resulted in a high helix current causing the helix protection circuitry to power the unit off or prevent the unit from turning on. It is also believed that the operational practice lead to shortened TWTA life. These practices and the technical problems mentioned resulted in regular occurrences of TWTA malfunctions and lengthy repair cycles. The TWTAs were routinely sent to the vendor to repair high voltage components or to degas the unit. Due to the sporadic shut-offs and operational difficulties, the original TWTA's were never run to end of life and were replaced by a next generation TWT from the same vendor (for LET) and new TWTAs from other vendors for both NGS and LET. The original TWTA's had 7,000-10,000 hours before removal from service.

The TWTA operations procedure for both LET and NGS was changed such that energized tubes were never permitted to idle for long periods of time, without high voltage applied. They were always operated with an applied carrier, either radiated or transmitted into a dummy load. Particular attention was also paid to maintaining proper cooling. This resulted in a very stable operating environment, significantly extending TWTA service life.

The combination of change in operational procedures and improvements made in the second-generation TWTAs used in the LET increased TWTA service life. The new TWTA (from original vendor) was removed from service with over 20K hours of operation. The helix current remained stable and only increased near end of life, as expected. The LET TWTA from the second vendor provided 100 Watts output power using a 120-Watt tube. Internal components, primarily the output isolator, account for the losses. The TWTA's also employed a helix type structure tube and power supply in a single housing. The second vendor's TWTA has been in service at LET for over 22,000 hours as of this writing.

Replacement TWTAs for both the NGS and LET were procured from new and different vendors than the original TWTAs. The NGS tubes are capable of 200-Watt output, but internal component losses and biasing result in a saturated power level of 150 Watt at the amplifier output. The slow-wave structure of the tube is a coupled cavity, i.e., the tube does not have an actual helix, but rather an inter-digital delay line that performs the same function as a helix. The circuit was developed as a better way of realizing the slow-wave structure, given the high power level and the stringent size and accuracy requirements in the mm-wave range. This design, however, is not as broadband as tubes using actual helices. The NGS TWTAs use a split mount design with separate units for the TWT and power supply.

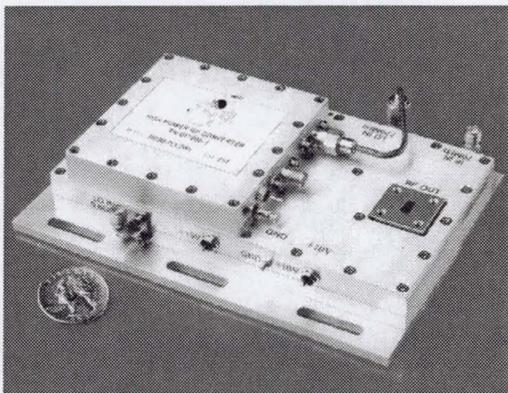
The design life of the second generation NGS TWT collector and electron gun are 20,000 to 30,000 hours. The original tubes delivered with the new TWTAs lasted 10,000 to 12,000 hours, with one premature failure at 2,700 hours. The failures occurred for various reasons, including materials used in the tube, mechanical shock, and the precision tolerances required in the tube structure at Ka-band. Another factor was the stability of the delay line inside the tube. The attenuation of each section must be stable over the operating temperature range to avoid problems with gain ripple. As experience was gained with tube operation in the NGS and with other users, the vendor examined tube failures and made improvements in the tube design and materials used. The design changes resulted in similar tube design life but achieved a much longer operating life - closer to 30,000 hours.

The VSAT transmitter used Ku band TWTs operating at 14.6 GHz combined with a High Power Frequency Doubler (HPFD). The TWT, power supply, and fault circuits were enclosed in the Intermediate Power Amplifier (IPA). The unit produced +45 dBm with a -5 dBm input signal. The IPA drives the HPFD to produce the final output frequency of 29.2 GHz at +40.5 dBm. The IPA burst with a 25 % duty cycle under normal conditions. AC power is applied to the unit at all times and monitored on an hour meter. The average life of each IPA is about 26,000 hours or three years. The IPA power supplies were typically the first to fail. Repairing the power supply units would extend the TWT life to about 30,000 hours.

With the decision to extend the ACTS program in late 1995, after the initial experiment phase (2 years), most VSAT TWT's and HPFDs were in their third year. Due to the IPAs reaching end-of-life and design issues with the HPFD, the project had to decide to stay with the IPA and HPFD design or use new 30 GHz Solid State Power Amplifiers (SSPA) capable of the required 10-12 Watt output power. The SSPA's were available from a limited supply of vendors. However, the output power specification was difficult to meet and some manufactures could not guarantee a reliable product. Because the change in technologies would incur

substantial cost and increase risk, the project stayed with the IPA/HPFD design and replaced the IPAs entirely and redesigned the HPFDs.

**Figure 1. USAT 1-WATT
UPCONVERTER/AMPLIFIER MODULE**



the original units continued to fail. Although the new HPFD design was more reliable than the original, the units were still the source of many VSAT failures. Experience and testing with the VSAT determined that the IPA's produced voltage spikes that degraded the HPFD over time. The IPA/HPFD redesign significantly improved the system availability of the VSAT network. Although the technology used required regular terminal maintenance, the reliability data of both the IPA and HPFD enabled system engineers to plan repairs and service each station before unexpected failures occurred and reduced troubleshooting time to minimize impact to the experiments program.

The USAT transmitters employed low power solid state power amplifiers. In the early 1990s, cost and availability limited these discrete component amplifiers to .25 Watt. Combined with a single-stage upconverter from 800 MHz to 30 GHz, the resultant package was a small 5"x3"x1" upconverter/amplifier integrated near the feed of the antenna to minimize loss. As solid state technology matured a second version of the block upconverter was produced in 1997. The second generation used 1-Watt Monolithic Microwave Integrate Circuit (MMIC) amplifiers with a two-stage upconverter (70 MHz to 30 GHz), yet only a small increase in size resulted. The new units measured 5"x4"x1" as shown in Figure 1. In addition, 2-Watt units were also produced in the same size package by combining two 1-Watt MMIC chips. The challenge of these higher power units was achieving good component yield and hand selecting the highest power chips for integration. This resulted in good overall performance and stable operation over temperature with losses of only 1-1.5 dB at 80°C. Solid state amplifiers in the 4-10 Watt range were also available in the late 1990's but cost and integration prohibited their use. The goal of the USAT was modest data rate (>1.544 Mbps) with small packaging, which was achieved with the one and two watt units. As successful as these units were in size, operation, and performance, advances are still needed in device yield and unit production and integration to make these products affordable for the mass market.

The HDR station also employed 30 GHz high power TWTAs. The units were a split-mount design with a 12m umbilical cord to remotely control and supply power to the TWT. The TWTA was mounted on the boom of the antenna near the feed with the power supply and pre-amp rack mounted inside the HDR equipment trailer. Like the LET the TWT was designed around a helix type slow-wave microwave circuit with an output of 100-120 Watts with > 1 GHz bandwidth. Unlike other terminals, HDR TWTAs remained powered down for the majority of the time, per recommendation of the TWTA vendor (different from NGS & LET), despite the experience gained in the NGS and LET operations. TWTA operations without high voltage applied were limited to only a few minutes.

The TWTA used in the beginning of the project had an extremely high failure rate. The high failure rate was contributed to the following: (a) water penetrating the outdoor high-voltage connectors shorting out the power supply; (b) high-voltage shorting out to chassis due to faulty potting process; and (c) temperature fluctuations causing the TWT to defocus. In addition to the high failure rates, turn-around time on defective units was excessive. In mid-1997 a different vendor was selected to provide TWTAs for the HDR project. TWTA performance and reliability improved.

The first HPFDs used in operation were not designed to operate with a continuous wave (CW) signal applied. Prior to launch, the project identified the need to characterize and test the HPFD with a CW signal during operations. A second problem with the original HPFD was they operated at high temperatures and several units failed after only a few months due to diode failures. Each HPFD had four diodes that produced the output power and frequency doubling. The new units produced were designed for CW, operated at lower temperature and used a different diode biasing design. Other design changes included a new balanced diode assembly and additional heat sinks applied to each individual diode. Reduced VSWR made the diode less susceptible to standing waves and voltage spikes. The entire fleet of VSAT's (19) was upgraded with a new HPFD as

Table 2. TRANSMITTER TECHNOLOGY SUMMARY

Station	Technology	Initial Issues	Advancements / Lessons Learned
NGS	54 Watt Single Chassis	<ul style="list-style-type: none"> - Sporadic shutdowns - RF power transients - Low reliability 	<ul style="list-style-type: none"> - Improved gun insulation and insulation application procedure.
	150 Watt TWTA-split mount	<ul style="list-style-type: none"> - TWT failure at 10000-12000 hours - Cooling fans 	<ul style="list-style-type: none"> - Modified tube design and operational changes led to >30000-hour tube life with minimal service.
VSAT	12 Watt Ku-Band TWT, HPFD	<ul style="list-style-type: none"> - HPFD reliability 	<ul style="list-style-type: none"> - New HPFD diode and heat sink design - Technology gaps remain for affordable Ka-band 10-12 Watt SSPA.
USAT	.25-2 Watt Solid State/MMIC	<ul style="list-style-type: none"> - Solid state and MMIC cost and availability 	<ul style="list-style-type: none"> - Single integrated block upconverter/amplifier - Advancements in MMIC made devices more available. - Reduction in cost & integration required enabling consumer terminals.
HDR	120 Watt TWTA-split mount	<ul style="list-style-type: none"> - Low reliability - Environmental effects 	<ul style="list-style-type: none"> - Identified potential high voltage interface issues of outdoor installed split mount TWTA's - Environmental concerns remain for precision tolerances required for Ka-band TWTA operation.
LET	60 Watt TWTA Single Chassis	<ul style="list-style-type: none"> - Sporadic shutdowns - RF power transients - Low reliability 	<ul style="list-style-type: none"> - Improved gun insulation and insulation application procedure.
	100 Watt TWTA Single Chassis	<ul style="list-style-type: none"> - None 	<ul style="list-style-type: none"> - Operational changes led to >22000-hour tube life with minimal service.

Table 2 summarizes the transmitter technology used in each ground station. A number of different approaches were taken with each station because of its experiment and application requirements. Design changes in TWTA material and integration, changes to TWTA operation procedures, and advancements by industry in solid state and MMIC amplifiers were highlights of this technology area.

Receiver

Receiver technology experienced modest advancements during the ACTS program. The majority of the low noise amplifiers and low noise converters (LNA/LNC) were built to specification often at or slightly advance of state of art at the time. Most of the devices used, with the exception of the VSAT LNC, were technically good devices lasting many years of service.

The NGS LNAs employed quarter-micron HEMT FETs, which were the state of the art in the late 1980s when the station was built. Two sets of LNAs are used, one at 20 GHz for the TDMA downlink and telemetry beacons, and one at 27.5 GHz, for the transmit band propagation beacon.

The 20 GHz LNA subassemblies are implemented in a cascade of two stages, each with a gain of 30 dB and a noise figure of 3.0 dB. The station employs three such LNA subassemblies, in a 3-for-2-redundancy configuration. The total system noise temperature, referenced to the antenna output, is 570K. This value includes an antenna temperature of 123K and an effective system electronics temperature, including waveguide loss, of 447K.

The 27.5 GHz LNAs also employ two stages, each with a gain of 20 dB and a noise figure of 4.5 dB. The total system noise temperature, referenced to the antenna output, is 1687K. This value includes an antenna temperature of 121K and an effective system electronics temperature, including waveguide loss, of 1566 K.

The NGS LNAs have been in nearly continuous operation, either in test facilities or on the air, since 1991. They have proven to be a robust technology. Few failures occurred over their 9 years of operation, most explained by environmental incidents, i.e., periods of high ambient temperature due to facility HVAC failures or inadvertent signal overload, rather than device failure. Periodic maintenance checks indicated little or no degradation in device performance over the period of service.

The original LET 20 GHz receiver/downconverter used a four-stage HEMT LNA followed by an MMIC mixer and amplifier stages to downconvert the signal to the Intermediate Frequency (IF) frequency of 3-4 GHz. There were three such units produced under a proof-of-concept (POC) development effort. The LNA and downconverter had a combined noise figure of approximately 4 -5.5 dB, with a nominal gain of 25 dB. While the POC units exhibited excessive gain slope across the full 1 GHz downlink band, they exhibited only modest gain slope across their operational band (300 MHz) and were quite usable for applications within that bandwidth. Consequently, they were incorporated into the initial station build-up and used for relatively narrow band signal applications, as an efficient use of existing hardware and a cost saving measure early in the program. However, because of their gain slope across the full band, the POC units proved unusable for wideband applications, such as on-orbit link and spacecraft characterization experiments of the entire transponder bandwidth, and emerging high data rate modem technology requiring larger bandwidths with minimum gain slope. To accommodate these wider bandwidth applications, it was eventually necessary to replace the POC units with receivers tailored for that purpose.

The LET receivers were replaced with commercially available low noise amplifiers and an in-house designed downconverter. The LNA selected was identical to that used in the HDR stations. The LNA's exhibited 50 dB of gain with noise figure of 3.5 dB with minimal slope across the GHz band. The LNA's used in HDR and LET proved reliable over the project. Many have been in service since 1995 with little or no performance degradation. The few failures that did occur were mainly the result of physical damage to the amplifier.

The VSAT stations encountered significant challenges in the receiver design. The VSAT LNC is a 3-stage HEMT low noise amplifier, RF bandpass filter, mixer, silicon MMIC IF amplifier, voltage regulator and fault circuit. Developed in the early 1990's, the receivers exhibited a wide range in performance. The receiver gain was specified at 45 dB and the noise figure was specified at 5 dB. The performance from unit to unit differed significantly. Each unit was hand tuned at the factory as a result of the design and performance. The total receiver gain (multiple stages) ranged from 40 to 52 dB and the noise figure varied from 3 to 9 dB. These variances required that the downlink of each station be adjusted to ensure like performance and operation compared to other VSATs. Because the receiver performance varied so much between units, the entire receiver characteristics drastically changed when different receivers were installed due to failure or service. This lengthened the service time at a particular station to allow time to make necessary adjustments to account for differences in the receivers.

The first generation USAT ground stations used combined LNA and single stage block downconverters from 29 GHz to 70 MHz. Performance, small size, and low cost were the primary goals of the USAT low noise downconverters (LND's). The original LND's exhibited 25 to 28 dB gain with a 4-4.5 dB noise figure over 40 MHz bandwidth⁴. The units measured 4.25x2.25x.4 in. The LND could operate with 40 MHz bandwidth increments from 19.7-20.4 GHz by varying the downlink oscillator. The first generation LND's failed after three years of operation. Coincidentally, four of five units failed within the same month after varying scenarios of operation. The fifth unit failed a short time later. Each LND had a similar amount of operation time but was often located in different geographical and temperature locations. No particular operational parameter was identified as the cause of the failure.

Improvements made by industry during the 1990's resulted in improved performance for the second generation LNDs. With a similar size package, the new LND's had 32 dB gain with a 2-2.5 dB noise figure over 50 MHz bandwidth. A total of 15 units were purchased in 1997 with all units exhibiting similar gain and noise figure performance. These units also covered the 19.7-20.04 GHz spectrum but had larger receive bandwidths of 50 MHz (compared to 40 MHz). With the improved noise figure, these units raised the available data rate between small ground stations making them more adaptable to a variety of applications⁵.

Antenna

All the antennas used with the transportable experimenter ground stations were offset fed parabolic reflectors. The USAT and VSAT reflectors were actually Ku-band reflectors, which proved adequate for operation at Ka-band. However, propagation experiments conducted on the antennas revealed that wet antenna effects of Ku-Band antennas operating at Ka-Band resulted in greater loss due to the rainwater and the thickness of the Ku-band dielectric. Minimizing the dielectric thickness at Ka-Band is needed to reduce loss in the presence of water on the reflector⁶. As much as 2-5dB is lost due to wet antenna and feed radome effects.

The HDR station was the only experimenter station antenna in the ACTS program made up of individual panels. The USAT and VSAT reflectors (.6m, 1.2m, and 2.4m) were all one-piece structures. The 3.4m HDR antenna was made up of four individual panels. Station performance validated that using this type of sectioned reflector is a viable alternative for Ka-band operation compared to a single piece reflector. Surface tolerance and feed alignment were adequate for operation.

Both the NGS and LET antennas employ cassegrain-type feed systems. The LET antenna uses the more conventional configuration, in which the feed horn extends from the apex of a 4.7m dish and couples the reflector optics to transmit and receive equipment located in a hub assembly immediately behind the reflector. The NGS employs a beam waveguide system, which couples an aperture at the apex of a 5.5m dish to a feed horn located at the base of the antenna. The feed horn then connects to transmit and receive equipment located indoors in a room directly beneath the antenna.

The NGS feed network follows the feedhorn and consists of a half-wave polarizer and orthogonal mode transducer (OMT) connected by rotary joints. This network allows the antenna to receive and transmit in dual orthogonal linear polarizations, with two 20 GHz receive ports and two 30 GHz transmit ports. The 27.505 GHz transmit band satellite beacon is also received at one transmit port and is separated from the transmit signal at that port by a multiplexer and filter assembly. The antenna polarization angle is adjustable through 360 degrees by rotating the polarizer, to match the antenna polarization to that of the satellite signals.

The LET antenna feed network is a combined corrugated horn and OMT assembly. Waveguide for both transmit and receive extend past the polarizer and into the antenna hub. The polarizer has 4 slots along its radius corresponding to bolts on the antenna structure to allow polarization adjustments upon installation. Polarization is adjusted by physically rotating the combined polarizer/feed assembly until peak signal is reached. Polarization of LET was an iterative process because of the rigid waveguide connections inside the hub. Flexible and rotary joint waveguide would ease the procedure, but it remains a physically challenging task.

Early in system operations a correlation was noted between a decrease in signal level and operation of the NGS antenna deicing system⁷. At the time it was thought that the observed effect could be a combination of antenna wetness from melting snow and thermal distortion of the antenna reflector. Further investigation confirmed both theories. Antenna wetting effects at Ka-band have been investigated by several people and have been quantified as an additional source of link degradation⁸. Also, subsequent maintenance of the NGS antenna revealed that the deicer heating system did cause thermal distortion of the antenna structure, which reduced antenna gain. Modification of the heating system reduced the effect, although it is still observable, particularly at high heat settings.

These heating effects will vary with antenna design, but the experiences gained point out the need for careful attention during the design process to all potential sources of mechanical deformation to maintain the close surface tolerances required of Ka-band antenna reflectors. The potential usefulness of specific design features to mitigate water and icing effects on the antenna structure should be noted, e.g., through the use of shields or other devices to reduce water accumulation on particularly sensitive areas of the antenna.

Modems

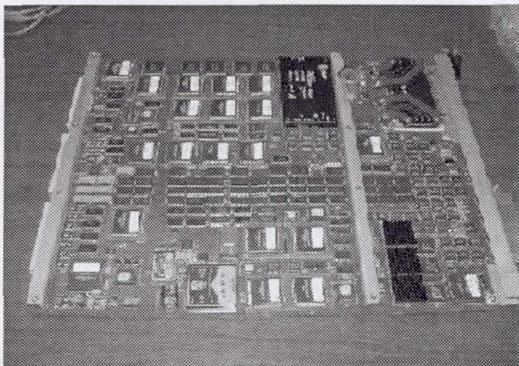
The combination of the ACTS satellite and the extensive ground station program enabled a number of advances in modem technology and the demonstration of various modem implementations. From custom ground and on-board processing TDMA network medium rate burst modem to satellite switched TDMA high rate burst modems to the use of commercial off-the-shelf low rate continuous wave modems and ground-based TDMA/FDMA network low rate modems, the ACTS program enabled flexible network architectures and system configurations.

The VSAT and NGS modems supported TDMA/FDMA operation of the spacecraft onboard processor and the associated TDMA network. The spacecraft and ground station modems were the same design and operated in burst mode at 110 or 27.5 Mbps using SMSK modulation. The VSAT modems were limited to 27.5 Mbps on the uplink. As part of the network fade mitigation design, the modems could also be operated at one half their normal burst rates, 55 or 13.75 Mbps, with rate 1/2 Forward Error Coding (FEC) coding, to achieve a 10 dB increase in system up-link and down-link margins.

The NGS and VSAT modem design proved to be stable and well executed, and modem performance was generally excellent over the course of the program. Maintenance problems were infrequent and involved power

supplies, oscillators or cooling fans, which are normal failures associated with age and facility environmental upsets. Only one design idiosyncrasy was noted - Sensitivity to certain data patterns, e.g., long strings of 1's or 0's. This was present in both the spacecraft and ground modems, and was obviated by locking out certain data combinations.

Figure 2. DT NETWORK PROCESSOR BOARD



Because of the burst mode operation and the data rates involved, fault diagnosis was more challenging, particularly in the case of intermittent failures. However, the modems were delivered with special test equipment designed to exercise the 3 different modem pairs (110 Mbps uplink, 27.5 Mbps uplink, and 110 Mbps downlink). The modem special test equipment proved to be a valuable tool in stand-alone modem fault diagnosis. However, it was also incorporated into the station test equipment suite so that the modems could be exercised over the station transmit and receive chains, to verify overall station performance. Regular BER measurements were performed as part of station periodic maintenance as a check on both the modems and the amplitude and group delay characteristics of the station transmit and receive equipment.

The HDR burst modem is a dual-mode device capable of operating in offset binary phase-shift keying (OBPSK) or offset quadrature phase-shift keying (OQPSK) modulation. The symbol rate of the burst modem is 348 MS/s, providing data-rates of 311 Mb/s in OBPSK or 622 Mb/s in OQPSK. Of the six modems designed and built for the HDR program three remained in service and fully functional to the end of the inclined orbit program, operating for over two years without repair. Although the modems performed soundly, it is believed the addition of adaptive equalizers to the demodulator front-end to compensate for the satellite non-linear transponder and changes in the system due to aging would have enhanced performance.

The companion to the high data rate burst modem was the Digital Terminal (DT). The DT interfaced the high rate terrestrial SONET interface to the burst modem. The DT also managed/controlled the TDMA network scheduling, the Reed-Solomon FEC encoding/decoding, bit scrambling, and the operator interface. The network processor board of the digital terminal depicted in Figure 2 is one of six boards that make up the digital terminal. The DT and high data rate burst modems were custom-made equipment and the DT is arguably the most sophisticated component of the HDR station. Due to the complexity of the equipment, its interfaces, and operational issues, a large portion of the problems associated with the HDR stations were attributed to the DT.

The USAT ground stations were designed to support a wide variety of applications. Designed with a 70 MHz IF interface the station could be used with a variety of commercial modems employing standard 70 MHz interfaces. Configured with a 1Watt transmitter and .6m antenna the USAT could support 2-4 Mbps between stations with adequate margin. Configured with a 1.2m reflector, experiments were conducted using 6-8 Mbps. Higher data rates could be achieved by employing Reed Solomon coding or reducing the available link margin on clear days. The modems allowed the stations to offer a variety of serial and data interfaces such as RS-232, RS-449, DS-1/E1, IP, ATM, Frame Relay, ISDN, DS3, and HiSSi, (high-speed serial interface). All the interfaces mentioned were used with the USAT ground stations for testing or experiment applications during the program.

Because the stations were not dependent nor required a specific modulation, various modulation schemes were used. Most experiments used either QPSK or BPSK, however CDMA was also used on one occasion. Although the USAT station did not prohibit higher order modulation schemes, the hard limiting amplifiers on-board the ACTS satellite degraded the performance of these schemes and they were therefore not used⁹. The USATs also demonstrated a ground based TDMA/FDMA mesh network using commercial products. A four node full-mesh USAT network was configured and demonstrated. Burst rates of 5 Mbps using QPSK modulation yielded nearly 2 Mbps per node with rate 1/2 Viterbi and Reed Solomon coding. ATM, IP, and Frame Relay networks operated simultaneously between stations.

The LET also provided modem flexibility. A set of variable rate burst modems from 1 to 220 Mbps operating at 3 GHz IF were built into the station. The modems were part of a proof of concept program in the late 1980's.

The modems were similar to the VSAT and NGS modems employing SMSK modulation. A custom digital interface was developed in-house to handle satellite tracking and timing and included a custom bit error rate test capability. The modems were used to test and characterize the station prior to satellite launch. Shortly after launch a 70 MHz interface was designed for the LET allowing commercial modems used by the USAT stations to operate with LET. The commercial modems handled all satellite tracking functions and standard bit error rate test sets were used. The proof-of-concept SMSK modems were considered the high data rate capability prior to HDR concept in early 1990's. The drawback of the custom capability was the lack of user interfaces to conduct applications or experiments using the modems. Although the use of the modems was limited to system characterization BER measurements, they still provided valuable data on the performance of the ground station and subsystems and were used to conduct high rate interference experiments with a companion ground station at GRC with identical modems¹⁰.

Conclusion

The ACTS program developed, demonstrated, and characterized Ka-Band technology and provided lessons learned for consideration to future commercial Ka-Band systems. Advancements in traveling wave tube amplifiers low noise receivers, antennas, modems, solid state power amplifiers, and other high frequency devices, were made by the communications industry to support the ACTS ground stations.

The ACTS project had two types of ground stations; transportable field earth stations and gateway earth stations. Field stations ranged in size from 0.35m to 3.4m and conducted experiments using data rates from 4.8 Kbps to 622 Mbps. The gateway earth stations provided a) telemetry, tracking, and control of the satellite, b) the reference station of the BBP TDMA network and MSM SS-TDMA network, and c) conducted high data rate interoperability experiments and link characterization experiments. The Ka-Band technologies described in this report were applied in various ways among the field and gateway earth stations.

This report summarizes the Ka-Band technologies used in each earth station during the program. Highlights of TWTA development, LNA performance, SSPA advancements, and modem performance were described. The reader is referred to the full report describing the integration and operations of the ACTS Ka-Band ground station technologies. The full report summarizes the ACTS inclined orbit operations and modifications of the ground stations to provide tracking capability.

Acknowledgement

The authors wish to thank the many people and organizations who have contributed to the work described herein. Throughout the ground station development and operations, many technical and non-technical contributions were made. We would like to acknowledge the feedback from the experimenter community to improve station operations, the industry partners who advanced Ka-band technologies and the earth station teams and all support personnel that implemented the experiments program.

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1.3 - T1 VSAT Fade Compensation Statistical Results

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Abstract

New satellite communication systems are steadily seeking to use higher frequency bands to accommodate the requirements for additional capacity. At these higher frequencies, propagation impairments that did not significantly affect the signal at lower frequencies begin to have considerable impact. In Ka-band, the next logical commercial frequency band to be used for satellite communication, attenuation of the signal due to rain is a primary concern. An experimental satellite built by NASA, the Advanced Communication Technology Satellite (ACTS), launched in September 1993, is the first U.S. communication satellite operating in the Ka-band. In addition to higher carrier frequencies, a number of other new technologies, including on-board baseband processing, multiple beam antennas, and rain fade detection and compensation techniques, were designed into the ACTS. Verification experiments have been conducted since the launch to characterize the new technologies.

The focus of this paper is to characterize the method used by the ACTS T1 Very Small Aperture Terminal (T1 VSAT) ground stations in detecting the presence of fade in the communication signal and to adaptively compensate for it by the addition of burst rate reduction and forward error correction. Measured data obtained from the ACTS program was used to validate the compensation technique. A software process was developed and demonstrated to statistically characterize the increased availability achieved by the compensation techniques in terms of the bit error rate time enhancement factor. Several improvements to the ACTS technique are discussed and possible implementations for future Ka band system are offered.

ACTS Compensation Experiment

An experiment was conducted by NASA to specifically characterize the performance of the ACTS T1 VSAT compensation technique. Two ACTS T1 VSATs were located next to each other at the NASA Glenn Research Center in Cleveland, Ohio. Adaptive coding was enabled on one of the T1 VSATs and disabled on the other. Fade and BER data was collected between May 1999 and February 2000. Seven parameters were collected over the 10 months (3 on each T1 VSAT and rain data) providing 6 station years of data for analysis. Only days with recorded rain events are used in the analysis [1]. This is the first time that two T1 VSATs were dedicated to rain fade compensation data collection. Locating the two T1 VSATs in the same location and collecting data during the same conditions allowed for the opportunity to directly compare the affect of coding.

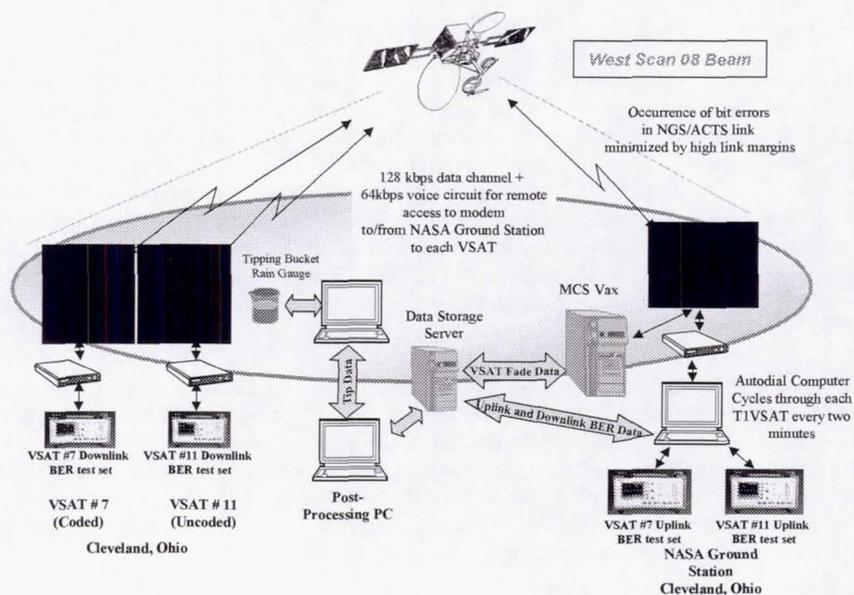
T1 VSAT and ACTS Fade Compensation Description

The T1 VSATs operate with uplink frequencies of 29.236 and 29.291 GHz and a downlink frequency of 19.440 GHz [2], [3]. The rain fade compensation protocol provides 10 dB of margin by reducing burst rates by half and invoking rate $\frac{1}{2}$, constraint length 5 Forward Error Correction (FEC) Convolutional Coding and Viterbi decoding [4], [5]. The result is a reduction of the 110 Mbps burst rates to 55 Msps and the 27.5 Mbps burst rates to 13.75 Msps. The protocol is adaptive in that it includes a decision process so that fade compensation is implemented only when needed using ONSET and CESSATION thresholds. This allows for the sharing of the spacecraft's decoding capacity. The theoretical fixed margin for a T1 VSAT operating in Cleveland, Ohio at a BER of 5×10^{-7} is 3.541 dB for the uplink signal and 7.866 dB for the downlink signal.

Hardware Connectivity

Figure 1 depicts the layout of the equipment and the flow of the data for the compensation experiment. Two ACTS T1 VSATs, labeled T1 VSAT #7 and T1 VSAT #11, were used. Each T1 VSAT was connected locally to an HP 3770B T1 bit error rate test set. A duplicate test set for each T1 VSAT was located at the ACTS Master Control Station (MCS). Whenever these T1 VSATs were configured to operate within the ACTS Baseband Processor (BBP) network, a 6 channel, 2-way data connection (384 kbps) was placed between the test set at the MCS and the test set at the T1 VSAT site. This allowed the uplink and downlink BER to be monitored between the MCS and the T1 VSAT through the satellite. Every two minutes, the BER at the T1 VSAT site (downlink BER) and at the MCS (uplink BER) was recorded on a computer located at the MCS. The downlink BER was obtained remotely by placing a call through the satellite to the BER test set, through the T1 VSAT modem. After these values were recorded, the BER test sets were reset.

Figure 1. HARDWARE CONFIGURATION FOR BER MEASUREMENT



T1 VSAT #7 was configured to operate in the coded mode with an ONSET threshold of 14.25 dB and a CESSATION threshold of 15.35 dB. Compensation was disabled for T1 VSAT #11. Also co-located with the T1 VSATs was a tipping bucket to collect rain. When the water level reaches 1/100" the bucket tipped, and a time stamp recording the time of the tip was stored on a PC.

Compensation Experiment Data Analysis

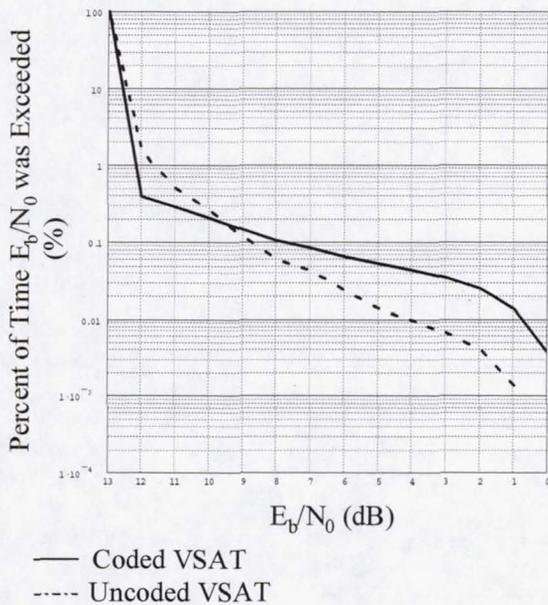
Statistical and time series analysis was performed with the data. Limitations in the experiment configurations and the T1 VSAT operating abilities restricted the range and accuracy of the results. Any E_b/N_0 above 13 dB will have such a high BER that no bit errors will be experienced, so the BER reading during the two minute interval will be equal to zero. This zero value is changed to 5×10^{-9} in the BER database. When the uplink BER reaches 10^{-2} , the T1 VSAT generally loses synchronization, invalidating any BER data. The downlink BER from the remote test set is downloaded to the control station via a modem using the satellite link to the T1 VSAT. When the downlink BER exceeds 10^{-4} , the uplink is so degraded that the BER modem can no longer obtain data. This results in only obtaining downlink BER up to a value of 10^{-4} . Therefore, the valid range of E_b/N_0 (and corresponding uncoded BER) is limited to 6 to 13 dB, which corresponds to an uncoded BER of approximately 10^{-4} to 10^{-9} .

Statistical Results

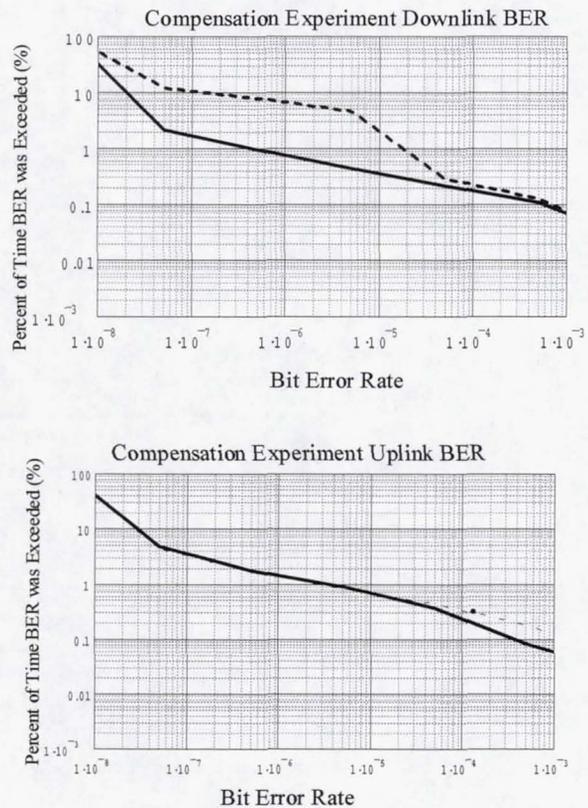
Figures 2 and 3 show the statistical results from the compensation experiment. From Figure 2 it is observed that the dynamic range of the coded T1 VSAT is approximately 6 dB higher than the dynamic range of the uncoded T1 VSAT. This is because the inbound orderwire, used to determine synchronization with the network, is not coded unless the T1 VSAT is in the coded mode. For this reason, the coded T1 VSAT can remain acquired with the BBP network for an additional 6 dB over the uncoded T1 VSAT. Approximately 1 dB difference in fades in the low fade regions is observed. This is due to the different operational characteristics of the hardware. For clarification, it should be noted that the experimental fade distribution should not be compared to that of a typical medium rain zone fade distribution due to the fact that only days with observed rain events are included. This limitation allows for a better opportunity to examine the characteristics of the T1 VSATs compensation technique.

Figure 3 shows the distribution of the downlink and uplink BER for the compensation experiment. The downlink BER improvement in the low ranges exceeds 6% between the coded and uncoded values. Hardware anomalies on the coded T1 VSAT #7 produced bit errors in the downlink signal temporarily when no errors should have occurred. Once the failing units were replaced, the BER returned to its expected value. If all subsystems are operating correctly, the coded T1 VSAT should experience very few downlink bit errors in the limited range which it operates. Also, the characteristics of the measurement system, causing the uplink signal to lose synchronization first, and the limitations of the BER collection modem, reduce the accuracy of the BER distribution results.

Figure 2. DISTRIBUTION OF FADE



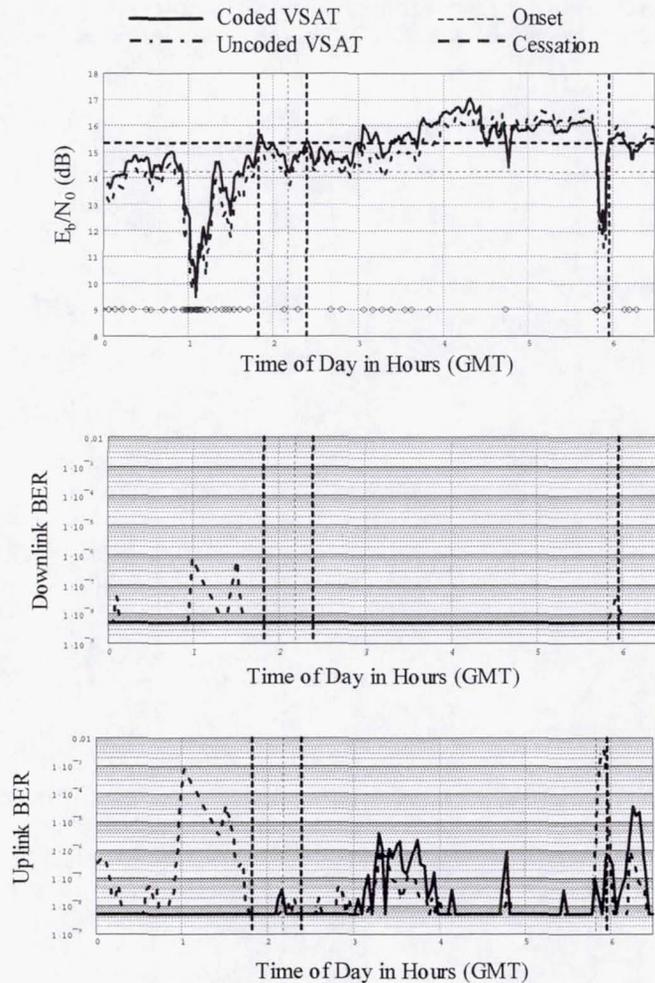
Figures 3a & b. Distribution of Downlink and Uplink BER



Time Series Results

Figure 4 depicts the fade and BER during a typical rain event in a time series representation. The onset and cessation times (shown as vertical dashed lines) are approximations. The ability of the coded T1 VSAT to correct for bit errors can be observed from this figure. Extremely close correlation between the uplink and downlink BER, E_b/N_0 , and tip times (shown with a diamond on the top figure) are seen. From time 0 to approximately time 1.6, coding is enabled for T1 VSAT #7. Although the downlink BER of the uncoded T1 VSAT reached 10^{-6} , the coded T1 VSAT did not experience any measurable errors in the downlink. In the uplink, the coded BER remained error-free during the rain event occurring between 0 to 2 hours. Once coding is removed at hour 2.25, the uplink channel experienced errors until the E_b/N_0 exceeded approximately 16.5 dB. This shows the effect of setting the thresholds on the downlink E_b/N_0 value. Increasing the downlink thresholds or the use of an additional compensation technique on future satellite systems, such as uplink power control, could be used to compensate for the lower signal in the uplink. Overall performance during rain events shows that there are no anomalies and system specifications are met.

Figure 4: E_b/N_0 , DOWNLINK AND UPLINK BER FOR RAIN FADE EVENT (MAY 24, 1999)



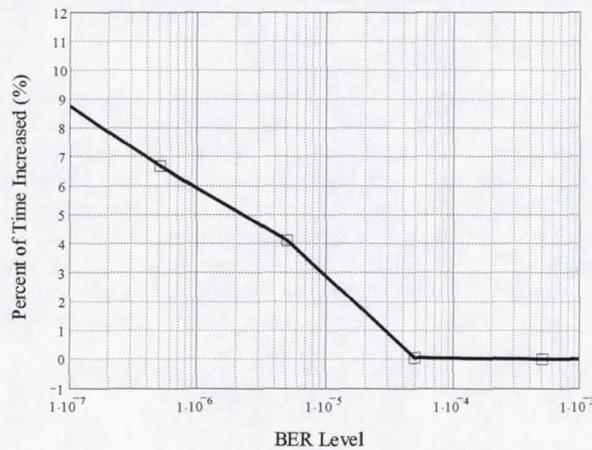
Bit Error Rate Time Enhancement Factor

The bit error rate time enhancement factor is the additional percent of time which a coded link will maintain or exceed a given BER level over a link that is not coded. Once the BER cumulative distribution function for coded and uncoded operation is obtained, the BER time enhancement factor can be obtained by subtracting the availability of the coded system from the availability of the uncoded system at selected bit error rates.

Experimental BER Time Enhancement Factor

The measured BER distribution has been obtained using the compensation experiment and is shown in Figure 4. The experimental uplink BER time enhancement factor is approximately 0 in the range of interest because the T1 VSAT uplink availability was not increased considerably due to the addition of coding, especially in the lower BER values. This was as expected because the decision to enact coding and the threshold limitations are based on the downlink BER. The uplink BER has already exceeded the lower BER values when this decision is implemented. The downlink BER, on the other hand, was greatly enhanced by the addition of coding. Most observed anomalies in the BER values were removed, such as inaccurate values when the T1 VSAT first synchronizes with the network. Some invalid points do remain. If all invalid points were determined and removed, there would be very few coded BER points greater than 10^{-7} , and the enhancement factor for BER values in the 10^{-7} to 10^{-4} range would be approximately equal to the uncoded BER availability.

Figure 5: EXPERIMENTAL BER TIME ENHANCEMENT FACTOR



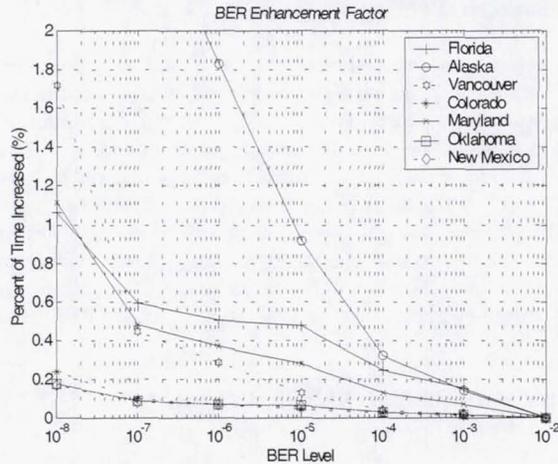
BER Time Enhancement Factor Software Model

The BER cumulative distribution function can also be derived from the fade cumulative distribution function and the performance curves. A software model has been developed to determine the BER time enhancement factor based on the particular environment, modulation and compensation technique. This allows the system engineer to determine whether adding compensation to a system can improve the availability to meet required specifications. This model requires as inputs the measured or propagation model of the fade CDF; the link calculation for the clear sky E_b/N_0 value; and the probability of error for the coded and uncoded modulation. Given this input, the BER enhancement factor is created by first generating a 4th order polynomial for the coded and uncoded functions for the range of E_b/N_0 values that are being evaluated. Then the fade from the fade CDF is converted to E_b/N_0 by subtracting the fade value from the clear sky E_b/N_0 . Using the polynomials (or the performance equation if available), the corresponding coded and uncoded BER distribution using the fade distribution is obtained from the system curves. For the range of BER enhancements being considered, the expected coded and uncoded availability is found and the BER time enhancement factor for the selected values of error is obtained by subtracting the coded BER availability from the uncoded BER availability value.

Results from Software Model using APT Data

Using the measured fade CDFs from the ACTS propagation campaign [6], [7], the BER time enhancement factors for each site is derived and the results are shown in Figure 8. BPSK with rate $\frac{1}{2}$, Constraint Length 5 Convolutional Coding and a clear sky E_b/N_0 of 15.3 dB is assumed.

Figure 6: BER TIME ENHANCEMENT FACTOR USING ACTS PROPAGATION TERMINALS



From this figure, it can be shown that coding only adds approximately 0.2 percent additional availability for bit error rates exceeding 10^{-8} for dry rain zones such as Colorado, New Mexico, and Oklahoma. It appears that coding can greatly enhance the availability in Alaska; however, the types of fades experienced in Alaska are due largely to the low elevation angle to the ACTS satellite. At this low elevation angle a terminal experiences greater scintillation in the fade than a CONUS based terminal. Scintillation effects cannot be corrected by adaptive coding, and adjusting the fixed margin to compensate for these events may be a waste of resources. The ACTS Propagation Terminal (APT) located in Vancouver also experiences this phenomena. This result demonstrates that sites in mid-Atlantic and sub-tropical rain zones such as Maryland and Florida, can best be enhanced by coding. With coding implemented in similar zones, the occurrences of BER values exceeding 10^{-8} will be reduced by 1.5%.

Conclusion

The results from the compensation experiment show that the ACTS rain fade compensation technique complies with its design specification with no observed anomalies [6], [7]. The 10 dB of adaptive link margin provided by data compensation provides 6% additional downlink BER availability in the region of interest (10^{-6}). Additional uplink BER availability is provided at the higher BERs because of its higher carrier frequency. The results also show that the fixed margin of approximately 3 dB in the downlink and 5 dB in the uplink is adequate for most rain fades.

The process developed for this paper can assist satellite system engineers in choosing the type of modulation and coding techniques to be incorporated for mitigation of rain fade in their system. With this technique, future system engineers can rely on estimating the expected performance based on the system specifications that they are using. If additional margin is required to meet the demands of the system, additional fixed margin or other adaptive techniques can then be incorporated.

Suggestions for Improvement

The method used to estimate the signal to noise ratio of the ACTS T1 VSAT inherently has limitations and non-linearities. The E_b/N_0 detection method must be reliable between units for mass production in order to allow for reliable transfer of data. Variances of less than 0.5 dB are acceptable, but the ACTS system experienced variances of up to 2 dB between production units which created inaccuracies. The E_b/N_0 detection system must be able to detect the E_b/N_0 value in less than 0.25 seconds to compensate for fades greater than 10 dB..

Additional adaptive compensation techniques, such as uplink power control, would mitigate the number of uplink errors experienced when the downlink data is used to enact coding. Because the technique used to derive the BER time enhancement factor is based on proven theory, the results stated using measured data from the ACTS Propagation Campaign are mathematically accurate. A more controlled experiment to validate the results would be useful in the future. In this future experiment, a number of variables that existed in the past experiment, such as the BER collection method and hardware anomalies, should be eliminated. In addition, known BER performance curves for coded and uncoded operation must be measured.

Suggestions for Implementation on Future Communication Systems

The technique used by ACTS with the suggested improvements would benefit the operation of future satellite systems intending to operate in Ka-band and beyond. These proposed systems, such as Teledesic, Astrolink, and Spaceway, use many of the technologies that allow them to make use of the ACTS techniques. The additional costs required to design and build an adaptive data compensation technique similar to ACTS is minor compared with the cost of adding the same amount of fixed margin. The experiments conducted on ACTS have proven that the quality of the data will not be degraded due to adaptive compensation. If configured properly, employing adaptive compensation will not overload the traffic of the system. These methods, combined with other techniques such as site diversity, can meet most availability requirements in all rain regions.

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2.1 - Summary of Advanced Communications Technology Satellite Propagation Experiments

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1.0 Introduction

The development of link performance specifications for Ka-band systems is dependent on a reliable source of propagation effects data and on validated prediction methods for the propagation environment. The NASA ACTS (Advanced Communications Technology Satellite) provided long term, continuous Ka-band propagation measurements for over five years to locations in North America.

The design and performance of broadband Ka-band satellite communications systems is heavily dependent on the propagation characteristics of the earth-space path. Both GSO (geosynchronous orbit) and NGSO (non-geosynchronous orbit) systems have been proposed and filed with the ITU-R, internationally, and with the Federal Communications Commission, FCC, in the United States. These systems are being designed with broadband communications capabilities to provide a wide array of fixed (FSS), broadcast (BSS), and mobile (MSS) satellite services.

A common characteristic of the Ka-band systems is that the service links operate with small user terminals with inherent low link margins. This makes the impact of atmospheric effects even more critical in the design of these systems. The performance of low margin broadband systems will be affected by atmospheric impairments in a different manner than for C-band or Ku-band high margin systems. Rain attenuation is still critical, however other effects such as gaseous attenuation, cloud attenuation, tropospheric scintillation and wet surface effects can increase in significance. Depolarization and phase distortion effects are also important for frequency reuse systems, and for systems employing high order modulation techniques. Broadband systems must account for dispersion effects caused by the atmosphere, including amplitude and phase dispersion from rain and tropospheric scintillation.

2.0 The ACTS Propagation Program

ACTS was launched on September 12, 1993, and was placed in geosynchronous orbit at 100°W longitude. The ACTS communications payload incorporates onboard switching and antennas providing hopped, fixed and steerable spot-beams. ACTS program objectives are to develop the high-risk, high-cost, advanced communications technologies applicable to a wide range of future satellite communications.

Beacons are provided in two Ka-band frequency bands on ACTS, one set at 20.185 and 20.195 GHz, and a single beacon at 27.505 GHz, which provide continuous signal sources for propagation experiments and measurements. The two beacons in the 20.2 GHz band are cross-polarized (linear). The 27.5 GHz beacon is also linear polarized.

NASA selected seven North American sites for the ACTS propagation measurements campaign and provided each site with identical ACTS Propagation Terminals (APTs) for long term amplitude measurements. The APTs are 1.2m receive only terminals, with dual channel receivers and dual radiometers operating in the 20.5 and 27.5 GHz bands. Table 1 lists the terminal locations and the major characteristics of each.

Location	Principal Investigator	Elevation Angle (degrees)	ITU-R Rain Region
Vancouver, British Columbia	U. of British Columbia/CRS	29	D
Ft. Collins, Colorado	Colorado State University	43	E
Fairbanks, Alaska	University of Alaska, Fairbanks	8	C
Clarksburg, Maryland Reston, Virginia	COMSAT Laboratories	39	K
Las Cruces, New Mexico	Stanford Telecom, Inc/New Mexico State University	51	E
Norman, Oklahoma	University of Oklahoma	49	M
Tampa, Florida	University of South Florida/Florida Atlantic University	52	N

Table 1. ACTS PROPAGATION EXPERIMENTERS

3.0 Link Availability

Most of the ACTS experimenters developed full five years of continuous amplitude measurements for the evaluation of Ka-band link availability statistics. The major propagation effects observed were rain attenuation, cloud attenuation, atmospheric gaseous attenuation, and scintillation effects. Rain attenuation was found to be the most prevalent degradation at all locations, and was the most significant contribution to link outages. The link statistics reported by each of the experimenters are summarized in Table 2 ((NAPEX XXIII, 1999). Results are for a 60-month reporting period, from Dec 1993 through Nov 1998, unless otherwise noted.

Location	Elev. Angle (deg)	Frequency (GHz)	Amplitude Margin (in dB) Required to Achieve the Given Annual Link Availability		
			99%	99.9%	99.99%
Vancouver, BC	29	20.2	3.3	5.6	14
		27.5	5	9.2	20
Ft. Collins, Colorado	43	20.2 *	0.8	3	13.5
		27.5 **	1.2	5.6	22
Fairbanks, Alaska	8	20.2	1.5	4.2	13.5
		27.5	2.3	7.4	20.5
Reston, Virginia	39	20.2	0.9	6.5	20
		27.5	1.8	10.5	>25
Las Cruces, New Mexico	51	20.2	1.1	5	18.5
		27.5	1.6	7.5	>25
Norman, Oklahoma	49	20.2	0.7	7.8	24.4
		27.5	1.2	11.0	>25
Tampa, Florida	52	20.2	4.4	>25	-
		27.5	7.3	>25	-

* 48 months (1/94 – 12/98) ** 56 months (12/93 – 8/98)

Table 2. LINK AVAILABILITY MARGIN STATISTICS FOR THE ACTS LOCATIONS

4.0 Rain Attenuation Modeling and Prediction

The selection of an appropriate rain attenuation prediction model from the many published versions available to the systems designer is perhaps the most perplexing issue related to propagation effects and satellite systems. Each prediction model has some merit and each has been validated to some extent by direct comparison with measured path attenuation data. All of the available models, however, even those with the best validation history, still do no better than 35% to 40% (RMS dB error) in predicting rain attenuation. This means that a prediction of 10 dB has an RMS error of ± 3.5 to 4.0 dB, for the average year, for the location of interest. This uncertainty is often overlooked in specifying rain margins based on a rain model prediction.

Measurements from the ACTS locations were used to perform a prediction comparison with ten of the more popular published rain attenuation models (Feldake and Ailes-Sengers, 1997). The analysis was compared with the results of an exhaustive study by the ITU-R, at Working Party 3M, in June of 1996, of a comparison of several rain attenuation models with 186 station years of earth-space path measurements contained in the ITU-R database.

The results from both studies showed that the DAH Rain Attenuation Model (sometimes referred to as the USA model) and the ITU-R models were consistently in the top four or five in performance through most of the groupings, based on RMS error and Mean error. The ExCell Model also tended to fall in the upper end, for frequencies above 15 GHz. Typical RMS errors ranged in the 30% to 40% range, however, even for the best performing. The mean error ranged in the 20% to 25% range for the top performers. Detailed procedures for the application of these and other rain attenuation model is available in the NASA Propagation Effects Handbook for Satellite Systems Design (Ippolito, 1999).

5.0 Scintillation Effects

Ka-band satellite communications links are subject to tropospheric scintillation effects that can degrade the transmitted radiowave. Tropospheric scintillation is produced by refractive index fluctuations in the first few kilometers of altitude and is caused by high humidity gradients and temperature inversion layers. The effects, in the form of rapid fluctuations of the amplitude and phase of the transmitted wave, are seasonally dependent, vary day-to-day, and vary with the local climate. Tropospheric scintillation has been observed on line of site links up through 10 GHz and on earth space paths at frequencies to above 30 GHz. Scintillation increases as elevation angle decreases, humidity and/or temperature increases, and as the frequency of operation increases. Effects can be particularly severe at elevation angles below 10 degrees.

The study of scintillation for the ACTS propagation program was focused at the Fairbanks, Alaska location, which operated with an elevation angle of 7.92 degrees. A summary of the major conclusions was presented by C. Mayer, University of Alaska (NAPEX XXIII, 1999). The results showed that amplitude scintillations are well correlated between the 20 and 27 GHz ACTS frequencies. Scintillation prediction models were applied to five years of ACTS measurements and the Ortgies-N model was found to give the best prediction for Fairbanks, while the Karasawa model gave the best prediction for the other 6 (higher elevation angle) ACTS locations. Procedures for the application of these and other rain attenuation model is available in the NASA Propagation Effects Handbook for Satellite Systems Design (Ippolito, 1999).

6.0 Wet Surface Effects

One of the major developments of the ACTS measurements campaign was the recognition of the significance of wet surface effects on the performance of Ka-band earth stations. Water accumulation on the antenna reflector (dish) surface and in the area of the feed aperture cover were found to contribute significant additional attenuation (3-4 dB and higher) beyond the attenuation observed on the free space link. ACTS propagation experimenters conducted several experiments to specifically address wet antenna surface effects. Empirical models to predict the effects of wet surface effects were developed by R. Acosta and by R. Crane, which are described in the NASA Propagation Effects Handbook (Ippolito, 1999). The models provide separate algorithms for attenuation due to water on the reflector surface and for attenuation due to water on the feed. The level of the attenuation was found to be heavily dependent on the material used for the reflector surface, and only slightly dependent on elevation angle, rain rate, and antenna reflector diameter.

7.0 Summary

This paper has summarized the major measurement results of the ACTS propagation campaign and has highlighted the major conclusions related to link availability margin requirements, rain attenuation modeling, and scintillation effects.

The ACTS propagation campaign has developed over 35 station years of reliable, high quality, digital data records for the evaluation of Ka-band space systems. ACTS offers the systems designer access to a comprehensive source of data for the development and validation of propagation effects modeling and prediction. Significant accomplishments of the ACTS campaign have contributed to our understanding of space communications in the Ka-band for the next generation of applications and services.

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2.2 - Rain Attenuation Model Comparison and Validation

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I. Introduction

The Advanced Communications Technology Satellite (ACTS) propagation experiment has yielded five years measurements of rain rates and attenuation at 20.185 GHz and 27.505 GHz in seven diverse climate regions throughout North America. Figure 1 shows the former locations of ACTS propagation terminals. In the pursuit of rain attenuation models, rain has generally been classified as stratiform, convective, or cyclonic. Location has everything to do with how much of each of these types of rain a communications link will experience. In addition, changes in drop size distribution, drop shape, and canting angle are to be expected. Perturbations in average rain characteristics are common with El Niño. This paper discusses the ACTS propagation measurements in contrast to the Revised Two Component model and the DAH model.

© ACTS Propagation Terminal (APT) Site

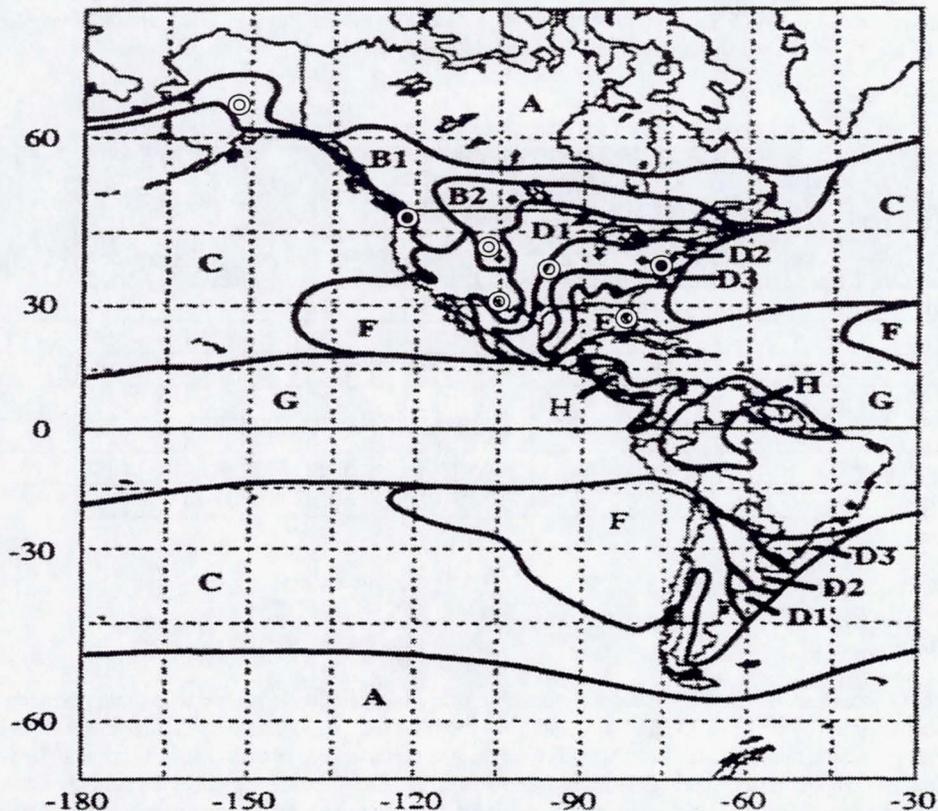


Figure 1. PLACEMENT OF ACTS PROPAGATION EXPERIMENT SITES IN CRANE GLOBAL RAIN ZONES

II. Procedure

Depending on location, rain rate measurements were obtained from one or both of two types of rain gauges. Rain rates from a capacitive gauge were calculated using a simple linear regression for the slope of rain accumulation over one minute. This method, developed by Stephen Horan, helped to reduce the unwanted electronic noise in the rain rate measurement. Rain rates from tipping bucket gauges were calculated using the equation, $rate = 3600.0 \cdot 0.254 / (tip_time - last_tip_time)$ [mm/hr].

The reference level for beacon attenuation measurements was set using a calibration program, written by Robert Crane, which matched theoretical estimates of sky temperature, in clear conditions, to sky temperatures obtained from APT radiometer measurements [1]. Quality control was handled in the calibration program by way of a text file experimenters could edit to specify removal of sun or moon intrusions, equipment adjustments, etc. The differing propagation effects which beacon and radiometer measurements represent dictated that beacon attenuation empirical distributions and radiometer attenuation empirical distributions should match between 2 dB and 6 dB. The beacon attenuation, or attenuation with respect to free space (AFS), can be thought of as composed of gaseous attenuation (AGA), clear air attenuation (ACA), and antenna wetting factor (AWF) so $AFS = AGA + ACA + AWF$. Uncorrected clear air attenuation is $ACA + AWF$. Since antenna wetting factor is highly dependent upon antenna design, rain attenuation models do not predict it. In order to isolate attenuations representative of rain, gaseous attenuation was subtracted from the time series of total beacon attenuation and antenna wetting factor was subtracted from the empirical distributions of uncorrected clear air attenuation. Regressions by Robert Crane allowed hourly surface measurements of temperature, pressure, and water vapor density to be used to predict sky temperature, medium temperature, and hence gaseous attenuation. Antenna wetting factors were calculated using Matlab code written by Atle Borsholm [2]. The cumulative distributions for antenna wetting factor rain rates were obtained from Crane's summary files on the 5-year propagation data compact disks. The expected value of the difference of the annual uncorrected ACA empirical distribution (which is random) minus the true cumulative distribution for antenna wetting factor (which is constant) is the difference of the true cumulative distribution of uncorrected ACA minus the true cumulative distribution of antenna wetting factor. This is the true cumulative distribution of clear air attenuation. Table 1 shows parameters, for each of the ACTS propagation terminals, relevant to rain attenuation prediction models. In the discussion of the Revised Two Component and DAH models to follow, the Crane Global model rain zones will be used [3].

Table 1. SITE PARAMETERS FOR ACTS PROPAGATION TERMINALS

Location	Organization	N. Lat. (°)	W. Long. (°)	Height (km)	Crane Global Rain Zone	Elev. (°)	Az. (°)	Tilt Angle from		
								Horiz. (°)	20.18 GHz EIRP (dBW)	27.505 GHz EIRP (dBW)
Fairbanks, AK	U. of AK	64.85	147.82	0.18	B1	8.1	129.3	70.6	9.5	10
Vancouver, BC	U. of BC	49.25	123.22	0.01	C	29.3	150.5	71.1	14	14
Greeley, CO	CO State U.	40.33	104.61	1.9	B2	43.1	172.8	84.6	19	17
Tampa, FL	U. of South FL	28.06	82.42	0.05	E	52	214	60.4	16	15
Reston, VA	COMSAT	38.95	77.33	0.08	D2	39.2	213.3	64.4	17	16
Las Cruces, NM	NM State U.	32.54	106.61	1.46	F	51.5	167.8	79.7	18	17
Norman, OK	U. of OK	35.21	97.44	0.42	D2	49.1	184.4	86.4	19	17

III. Results

A. Rain Rate

The continuous sampling of rain rates, at a given location, over yearly intervals is used to estimate the mean empirical distribution of rain rates, the annual cumulative distribution. Since the ACTS propagation experiment spanned multiple years, the empirical distributions for rain rate collected can also be used to estimate the year to year variability in empirical distributions. Figure 2 shows average 1-minute least squares capacitive rain rate empirical distributions in dashed lines. The solid lines indicate the Revised Two Component model. Markers for empirical distributions are the same as for the model for each site. Figure 3 displays tipping bucket rain rate empirical distributions.

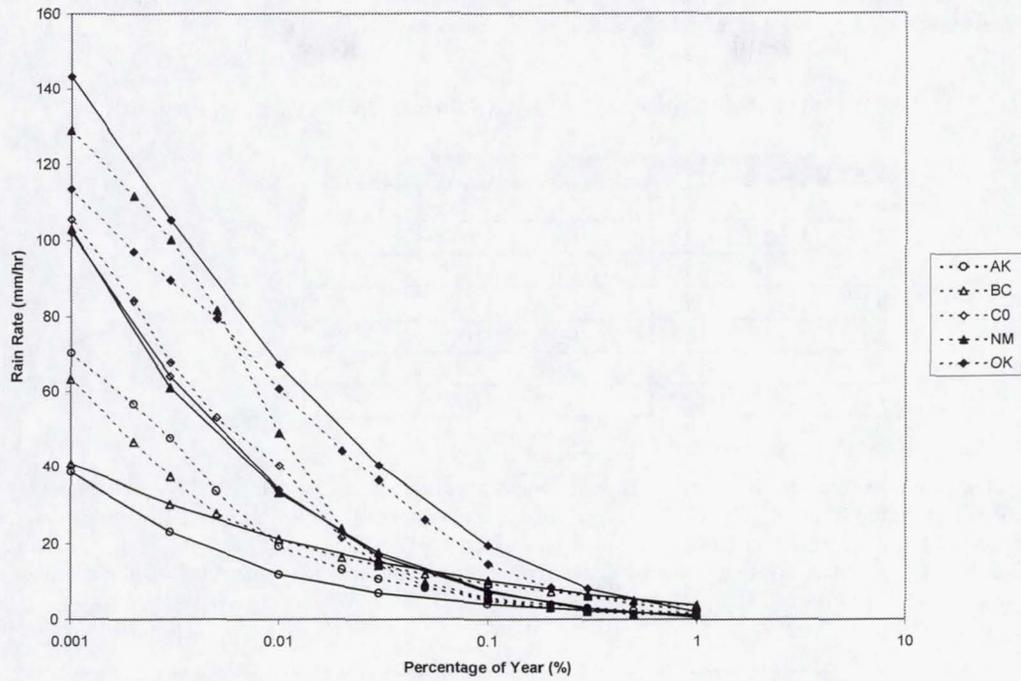


Figure 2. 1-MINUTE LEAST SQUARES CAPACITIVE RAIN RATE AVERAGE ANNUAL EMPIRICAL DISTRIBUTION

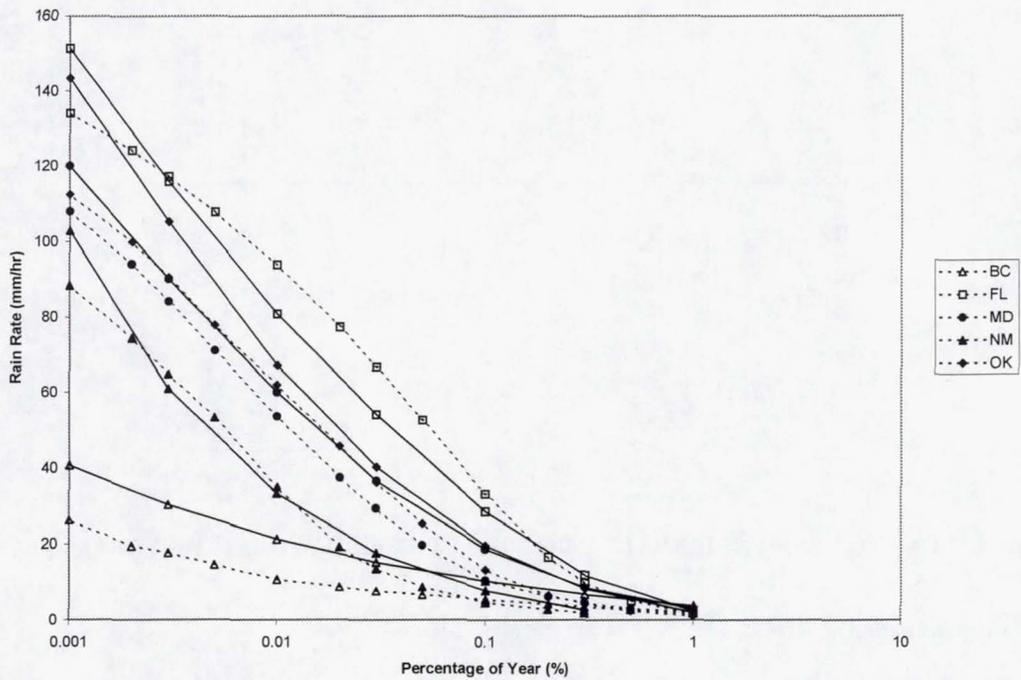


Figure 3. TIPPING BUCKET RAIN RATE AVERAGE ANNUAL EMPIRICAL DISTRIBUTION

The Revised Two Component model estimates rain rates using the four climate dependent parameters probability of a cell, average cell rain rate, probability of debris, and average debris rain rate. Bias error in each

year was calculated using the convention $\text{bias} = \ln(R_{\text{meas}}/R_{\text{model}})$. Table 2 shows bias errors by site for all capacitive gauge and tipping gauge rain rate empirical distributions.

Table 2. REVISED TWO COMPONENT MODEL ANNUAL RAIN RATE BIAS ERRORS

	Avg	Stdev	Rms	#Points
AK	0.37	0.41	0.55	28
BC	-0.16	0.41	0.44	42
CO	0.06	0.32	0.33	30
FL	0.03	0.19	0.19	24
MD	-0.31	0.35	0.47	24
NM	-0.06	0.41	0.41	52
OK	-0.27	0.24	0.37	33

Model validation requires that a collection of yearly empirical distributions not excessively breach model bounds at a specified level of risk. As part of constructing model bounds, the Revised Two Component model specifies that the standard deviation of $\ln(R_{\text{meas}}/R_{\text{model}})$ is constant, $D_R=0.21$, across percentages of time between 1 and 0.001 [4]. Qualitatively, there is no real pattern of bias or low variability in the standard deviations plotted in figure 4.

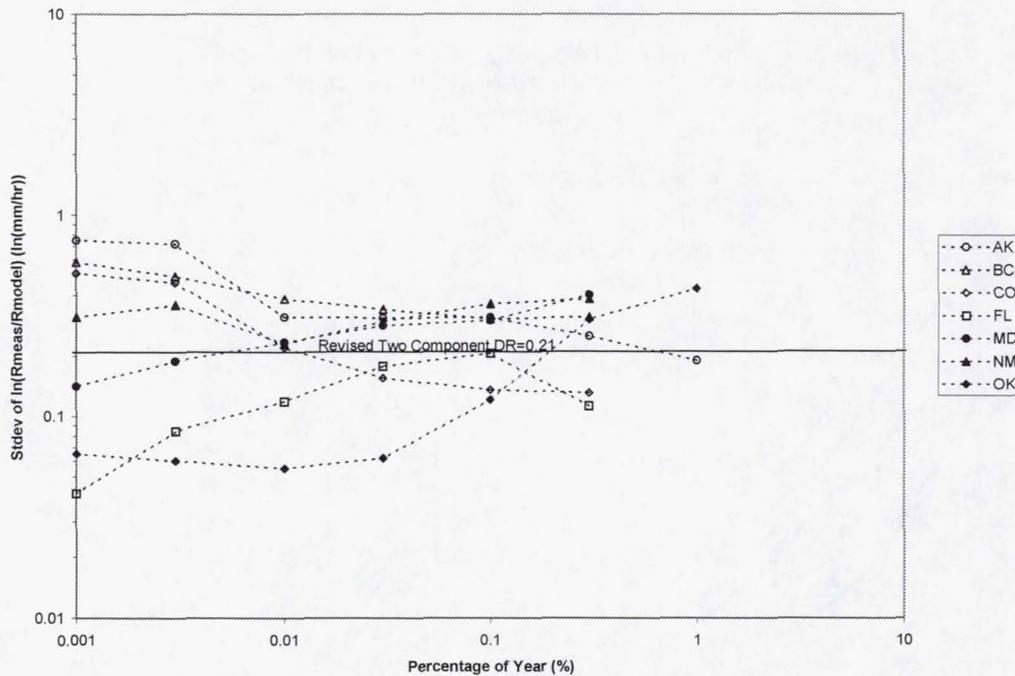


Figure 4. YEAR TO YEAR VARIABILITY IN RAIN RATE EMPIRICAL DISTRIBUTIONS

B. Rain Attenuation

The multiple years over which beacon attenuation measurements were taken were intended to narrow an uncertainty in average attenuation at any percentage of time to 11% [1]. Figure 5 shows 20.185 GHz clear air average annual empirical distributions by site, indicated by dashed lines. Solid lines indicate the Revised Two Component model.

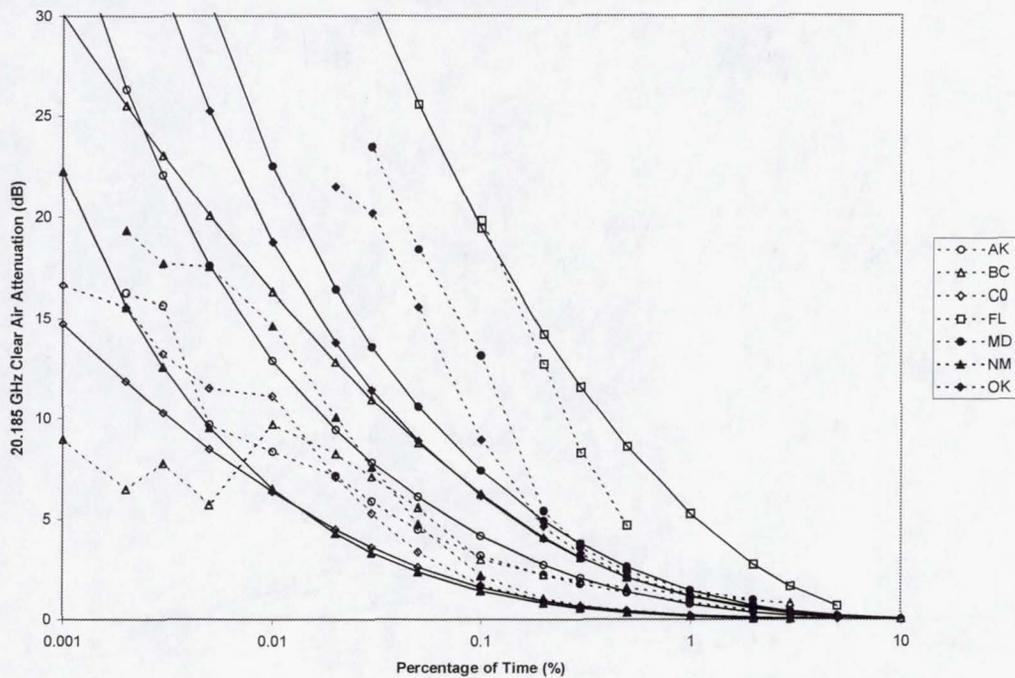


Figure 5. AVERAGE ANNUAL 20.185 CLEAR AIR ATTENUATION EMPIRICAL DISTRIBUTIONS

The Revised Two Component model and the DAH model take two different approaches to rain attenuation modeling. The Two Component model is based on climate dependent probability distributions for rain in a cell and rain in debris. Its climate dependent parameters were discussed previously. The DAH model takes the approach of assuming the best fit to all available attenuation data. Its climate dependent input parameter is the rain rate at 0.01% of the time. Table 3 shows computed bias errors for the Revised Two Component model and the DAH model at 20.185 GHz.

Table 3. 20.185 GHZ CLEAR AIR ATTENUATION ANNUAL BIAS ERRORS

	Revised Two Component				DAH			
	Avg	Stdev	Rms	#Points	Avg	Stdev	Rms	#Points
AK	-0.32	0.42	0.53	26	-0.41	0.39	0.56	26
BC	-0.64	0.58	0.87	30	-0.62	0.56	0.83	30
CO	0.25	0.62	0.67	26	-0.11	0.64	0.65	26
FL	-0.24	0.23	0.34	7	0.18	0.21	0.28	7
MD	0.18	0.44	0.47	14	0.11	0.50	0.52	14
NM	0.44	0.66	0.79	20	-0.14	0.84	0.85	20
OK	0.23	0.33	0.40	19	0.05	0.42	0.42	19

27.505 GHz average annual empirical distributions are shown in figure 6. Empirical distributions are truncated to account for limited dynamic range. Anything below -5 dBW EIRP in table 1 was considered below the dynamic range of the APT receiver.

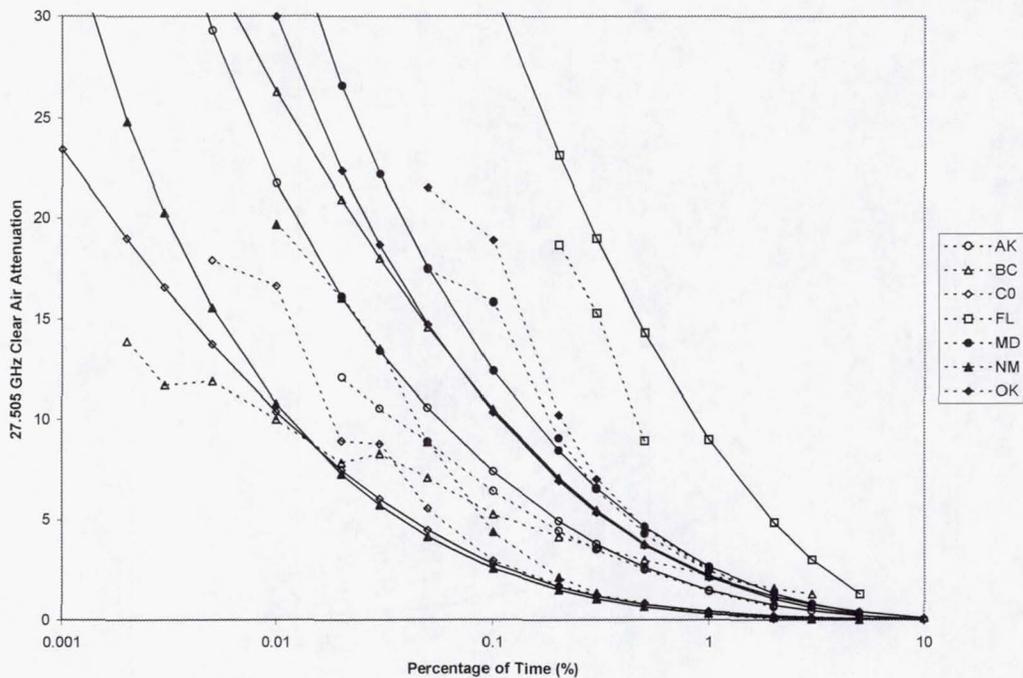


Figure 6. AVERAGE ANNUAL 27.505 GHZ CLEAR AIR EMPIRICAL DISTRIBUTIONS

Table 4 shows bias errors by location for 27.505 GHz rain attenuation.

Table 4. 27.505 GHZ CLEAR AIR ATTENUATION ANNUAL BIAS ERRORS

	Revised Two Component				DAH			
	Avg	Stdev	Rms	#Points	Avg	Stdev	Rms	#Points
AK	-0.14	0.28	0.31	18	-0.24	0.29	0.38	18
BC	-0.62	0.42	0.75	26	-0.61	0.38	0.72	26
CO	0.15	0.81	0.83	21	-0.31	0.86	0.91	21
FL	-0.23	0.22	0.32	5	0.08	0.22	0.24	5
MD	0.03	0.25	0.25	12	-0.10	0.31	0.32	12
NM	0.47	0.53	0.71	17	-0.20	0.68	0.71	17
OK	0.33	0.30	0.44	15	0.06	0.37	0.37	15

Figure 7 shows that the mean standard deviation $D_A=0.23$ is used by the Revised Two Component model to establish bounds on attenuation. The year to year variability in attenuation empirical distributions is plotted by percentage of time. Both 20.185 and 27.505 GHz data are plotted. Qualitatively, there is no apparent pattern, considering both frequencies.

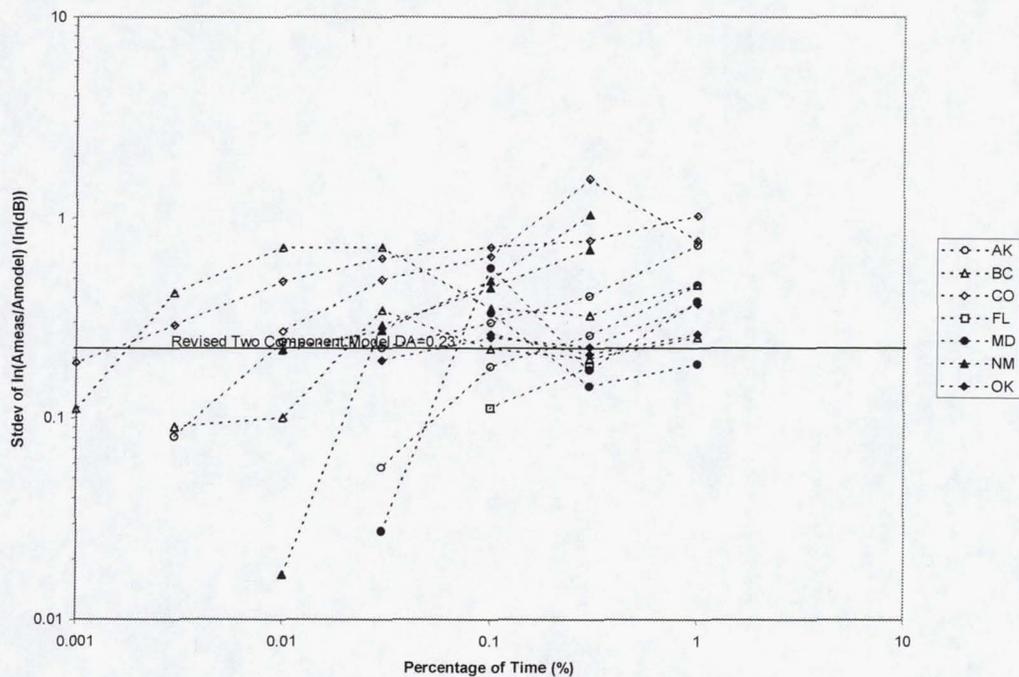


Figure 7. YEAR TO YEAR VARIABILITY IN CLEAR AIR ATTENUATION, BOTH FREQUENCIES

IV. Conclusions

Since Crane has established that bias, as defined above, follows a normal distribution, it is possible to test the hypothesis that the Revised Two Component and DAH models predict rain attenuation equally well [4]. An F-test for unequal variance of average bias values (both frequencies) is not significant, $p\text{-value}=0.106$. A t-test for unequal mean average bias is also not significant, $p\text{-value}=0.208$. In summary, in the context of the ACTS propagation data, the Revised Two Component and DAH models do not provide statistically different predictions when used with the Crane Global climate zones.

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2.3 - Propagation Effects Handbook for Satellite Systems Design

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Abstract

This paper describes the latest edition of the NASA Propagation Effects Handbook for Satellite Systems Design and presents a summary of application of the handbook information to satellite link design and performance. NASA, which has supported a large part of the experimental work in radiowave propagation on space communications links, recognized the need for a reference handbook of this type, and initiated a program in the late 1970's to develop and update a document that will meet this need. The Fifth Edition provides, in a single document, an update to two previous NASA handbooks; the fourth edition of a handbook which focused on propagation effects from 10 to 100 GHz (Ippolito, 1989), and the second edition of a companion handbook which covered propagation effects on satellite systems at frequencies below 10 GHz (Flock, 1987). This Fifth Edition covers the full range of radiowave frequencies that are in use or allocated for space communications and services, from nominally 100 MHz up to 100 GHz.

Introduction

The Fifth Edition of the Propagation Effects Handbook for Satellite Systems Design provides, in one complete reference source, the latest information on atmospheric propagation effects and how they impact satellite communications system design and performance. The National Aeronautics and Space Administration, NASA, which has supported a large part of the experimental work in radiowave propagation on space communications links, recognized the need for a reference handbook of this type, and initiated a program in the late 1970's to develop and update a document that will meet this need. This Fifth Edition provides, in a single document, an update to two previous NASA handbooks; the fourth edition of a handbook which focused on propagation effects from 10 to 100 GHz (Ippolito, 1989), and the second edition of a companion handbook which covered propagation effects on satellite systems at frequencies below 10 GHz (Flock, 1987). This Fifth Edition covers the full range of radiowave frequencies that are in use or allocated for space communications and services, from nominally 100 MHz up to 100 GHz.

The basic intention of the Fifth Edition is to combine the scope of the previous handbooks into a single document, with elimination of duplication as much as possible. This Fifth Edition has a completely new outline, different from either of the two previous handbooks. The intent is to provide a more cohesive structure for the reader. The handbook incorporates a unique, new concept with several levels of "entrance" into the handbook.

Several major developments in satellite communications and the study of propagation effects have occurred since publication of the prior NASA handbooks. New propagation measurement campaigns have been completed or are in progress, providing new data for the evaluation of link degradations on satellite links. New propagation models and prediction techniques are available, covering the traditional propagation effects along with several new areas. New satellite applications have been thrust into the forefront of the satellite communications industry, requiring new approaches for the evaluation of propagation effects. The proliferation of new and competing applications in the frequency bands allocated to space communications has increased the importance and priority of understanding spectrum sharing and interference mitigation. Propagation conditions are a critical component of a viable sharing and interference process.

Handbook Structure

The Propagation Effects Handbook for Satellite Systems Design, Fifth Edition, is divided into three sections. Section 1 provides the background, historical development, theory, and basic concepts of the propagation effects of concern to the satellite systems engineer. The prediction techniques developed to address the critical propagation effects are presented in Section 2. Information on how to apply the prediction methods for specific satellite systems applications is provided in Section 3. (see figure 1 below)

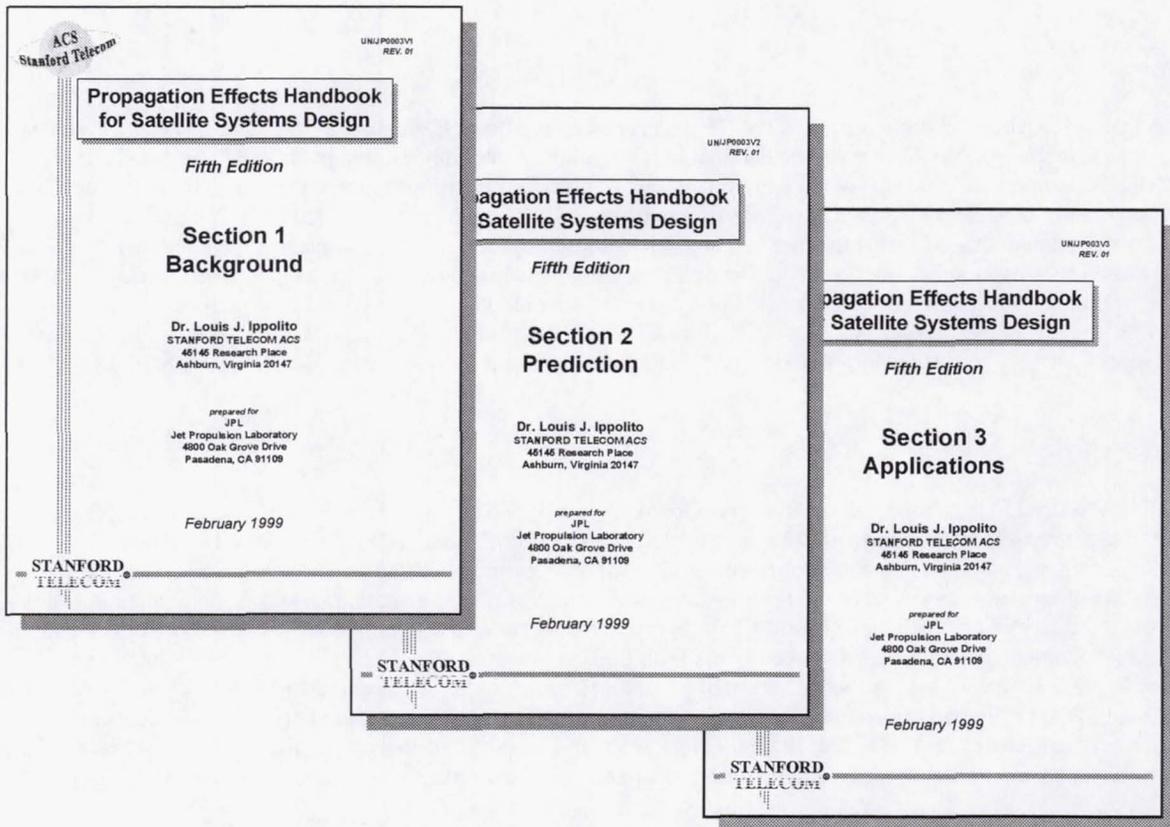


Figure 1. FIFTH EDITION OF THE PROPAGATION EFFECTS HANDBOOK FOR SATELLITE SYSTEMS DESIGN (Revision 1, released Feb. 1999)

Section 1 begins with an overview of propagation effects on satellite communications. The propagation effects are then introduced and background theory and developments are described. The frequency dependence of radiowave propagation is recognized, and the effects are divided into two groups; ionospheric effects, influencing systems operating at frequencies below about 3 GHz, and tropospheric effects, influencing systems operating at frequencies above about 3 GHz. Radio noise, which can affect satellite systems in all operating bands, is then described. The section concludes with a comprehensive description of propagation databases, including points of contact and electronic addresses.

Section 2 provides descriptions of prediction models and techniques for the evaluation of propagation degradation on satellite links. Step-by-step procedures are provided where available. The first two subsections present propagation effects for ionospheric effects and for tropospheric effects, respectively. The third subsection presents prediction methods for radio noise. The fourth subsection describes several general modeling procedures, including

statistical considerations, frequency scaling and elevation angle scaling. The final subsection presents models for the restoration of links subject to propagation impairments, including site diversity, orbit diversity and adaptive FEC.

Section 3 provides roadmaps for the application of the prediction models given in Section 2 to specific satellite systems and applications. Suggested approaches to evaluating link propagation effects and their impact on system design and performance are provided. Section 3 includes evaluation of propagation effects and their impact on systems design and performance

Handbook Approach

The Fifth Edition of the Propagation Effects Handbook for Satellite Systems Design is intended for the systems engineer and link designer who is interested in the latest and most accurate methodology available for the evaluation of radiowave propagation effects on satellite communications. The handbook is structured with several levels of "entrance" into the handbook, as highlighted by Figure 2.

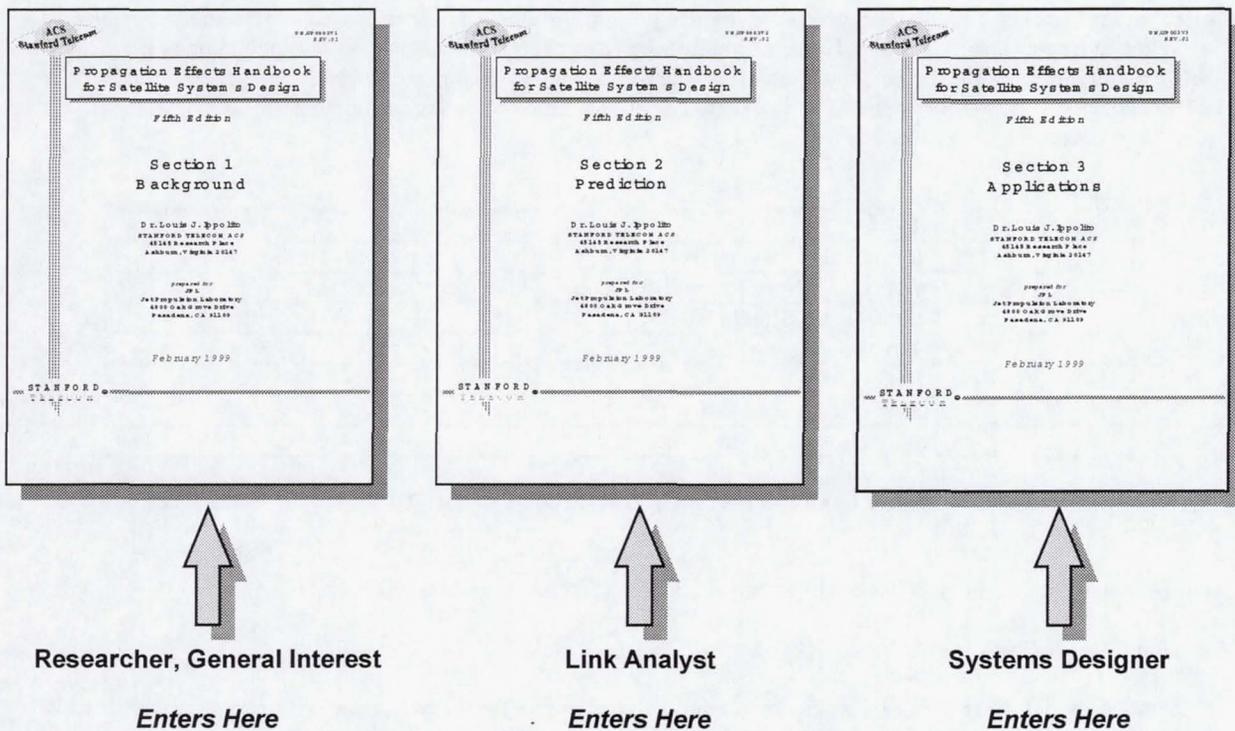


Figure 2. THREE-SECTION STRUCTURE FOR THE HANDBOOK

The general researcher or someone new to the subject who may not have a full awareness of the background and history of propagation effects and their impact on satellite communications could enter in Section 1, which provides an overview of propagation effects and the background theory involved in the prediction methodology. Section 1 also provides an extensive listing of resources for additional information and backup data important to the area of propagation effects and satellite communications.

The link analyst or engineer who is familiar with propagation and satellite communications issues and knows which propagation effects are of interest would enter into Section 2 where concise step-by-step procedures for each effect are available. Section 2 also includes general modeling procedures, including statistical considerations, frequency scaling and elevation angle scaling. Section 2, in addition, presents models for the restoration of links subject to propagation impairments, including site diversity, orbit diversity and adaptive FEC.

The system designer who has a good understanding of the system aspects of satellite communications but may not know just which propagation impairments are important to the particular system or application under consideration would enter through Section 3. Here the reader will find roadmaps for the application of the prediction models given in Section 2 to specific satellite systems and applications. Suggested approaches to evaluating link propagation effects and their impact on system design and performance are also provided in Section 3.

These entrance levels are only suggestions for the reader, to avoid unnecessary reading and to optimize the use of the handbook. Suggestions on ways to improve the document structure, or on specific additional information that would be useful to the reader to include in later editions of the handbook, are always welcome by the author.

Section 1 Background

Section 1 begins with an overview of propagation effects on satellite communications. The propagation effects are then introduced and background theory and developments are described. The frequency dependence of radiowave propagation is recognized, and the effects are divided into two groups; ionospheric effects, influencing systems operating at frequencies below about 3 GHz, and tropospheric effects, influencing systems operating at frequencies above about 3 GHz. Radio noise, which can affect satellite systems in all operating bands, is then described. The section concludes with a comprehensive description of propagation databases, including points of contact and electronic addresses.

Section	Topic
1.0	Introduction to Section 1
1.1	Overview: Propagation Effects on Satellite Communications
1.2	Ionospheric Effects
1.3	Tropospheric Effects
1.4	Radio Noise
1.5	Propagation Data Bases
1.6	References – Section 1

Table 1. CONTENTS OF SECTION 1 INTRODUCTION

The principal topics and associated subsection numbers for Section 1 are listed in Table 1.

Section 2 Prediction

Section 2 provides descriptions of prediction models and techniques for the evaluation of propagation degradation on satellite links. Step-by-step procedures are provided where available. Section 1 provides the background, historical development, theory, and basic concepts of the propagation effects of concern to the satellite systems engineer. The section includes theory and basic concepts, propagation measurements, and available databases. Information on how to apply the prediction methods for specific satellite systems applications is provided in Section 3.

The development of reliable propagation effects prediction models requires measured data to validate the predictions. New propagation measurements in several frequency bands have been accomplished since the last handbook publication. Table 2 lists some of the satellites which had beacons on board specifically intended for the evaluation of propagation effects. Propagation data has also been developed from other sources including terrestrial links, tracking beacons, and from direct measurement of information bearing signals. For example, land mobile propagation data in the 1.5 GHz region was obtained in the Eastern U.S. from MARECS-B2 and in Australia from ETS-V and INMARSAT.

Satellite	Organization	Launch Date	Frequency (GHz)	Polarization	Measurement Region(s)
Olympus	ESA	1989	12.5 19.7 29.7	LP Dual Switched LP @933 Hz LP	Europe And Eastern U.S.
Italsat F1	Italy	1991	18.685 39.592 49.49	Dual LP CP with \pm 500 MHz sidebands Dual switched LP @ 933 Hz	Europe
ACTS	NASA	1993	20.185 27.5	LP LP	CONUS Alaska Canada

Table 2. RECENT SATELLITES PROVIDING PROPAGATION MEASUREMENTS

Propagation research since publication of the last handbooks has resulted in the development and publication of propagation prediction models in several new areas. These include:

- Tropospheric Scintillation
- Cloud Attenuation and Scintillation
- Ice Depolarization
- Wet Surface Effects
- Combined Effects

In addition, extensive modeling updates and revisions have been developed for the traditional propagation factors such as

- Rain Attenuation
- Atmospheric Gaseous Attenuation
- Ionospheric Scintillation
- Frequency Scaling
- Worst Month, and
- Site Diversity.

Section 2 provides detailed step-by-step procedures for all of the new models and for the updated procedures as provided by the authors.

The first two subsections of Section 2 present prediction methods for satellite links operating below 3 GHz (primarily ionospheric effects), and prediction methods for satellite links operating above 3 GHz (primarily tropospheric effects), respectively. The third subsection presents prediction methods for radio noise. The fourth subsection describes several general modeling procedures, including statistical considerations, frequency scaling and elevation angle scaling. The final subsection presents models for the restoration of links subject to propagation impairments, including site diversity, orbit diversity and adaptive FEC.

The principal topics and associated subsection numbers for Section 2 are listed in Table 3:

Section	Topic
2.0	INTRODUCTION TO SECTION 2
2.1	PREDICTION METHODS FOR SATELLITE LINKS OPERATING BELOW 3 GHz
2.1.1	Total Electron Content
2.1.2	Faraday Rotation

2.1.3	Time Delay
2.1.5	Ionospheric Scintillation
2.1.6	Auroral Absorption
2.1.7	Polar Cap Absorption
2.1.8	Summary – Ionospheric Effects Prediction
2.2	PREDICTION METHODS FOR SATELLITE LINKS OPERATING ABOVE 3 GHz
2.2.1	Atmospheric Gaseous Attenuation
2.2.2	Cloud Attenuation
2.2.3	Fog Attenuation
2.2.4	Rain Attenuation
2.2.5	Rain Depolarization
2.2.6	Ice Depolarization
2.2.7	Wet Surface Effects
2.2.8	Scintillation
2.2.9	Worst Month Statistics
2.2.10	Fade Rate and Fade Duration
2.2.11	Combined Effects Modeling
2.3	RADIO NOISE
2.3.1	Specification of Radio Noise
2.3.2	Noise from Atmospheric Gases
2.3.3	Sky Noise Due to Rain
2.3.4	Sky Noise Due to Clouds
2.3.5	Noise From Extra-terrestrial Sources
2.4	GENERAL MODELING PROCEDURES
2.4.1	Application of Statistical Data
2.4.2	Frequency Scaling and Attenuation Ratio
2.4.3	Elevation Angle Scaling
2.4.4	Simultaneous Scaling
2.5	LINK RESTORATION MODELS
2.5.1	Site Diversity
2.5.2	Orbit Diversity
2.5.3	Link Power Control
2.5.4	Adaptive FEC
2.6	REFERENCES – SECTION 2

Table 3. CONTENTS OF SECTION 2 PREDICTION

Section 3 Applications

A wide array of new satellite applications has appeared in the decade since publication of the last handbooks. Each application has unique design and performance characteristics requiring new approaches for the evaluation of propagation effects. Also, the extension of satellite communications to non-geosynchronous orbit (NGSO) constellations has added a new level of concern on the proper evaluation of link conditions for proper system operation.

The last decade has seen a proliferation of VSAT (very small aperture terminal) systems in the Ku-band, designed primarily for data applications. The VSAT typically are low margin systems, with margins of 1 to 3 dB. VSAT networks can be global, and operate in the domestic and international fixed satellite service (FSS) bands.

Direct Broadcast Satellites (DBS) also operating in the Ku-band provide direct-to-home entertainment video services. DBS systems are one of the fastest growing segments of the satellite industry. They are multi-channel digital systems with small (0.6m) rooftop type antennas. DBS systems are deployed in the U.S., Europe, Japan.

The past few years have also seen the initiation of rapid development of the Ka-band for a range of applications. Ka-band systems filed with the U.S. Federal Communications Commission (FCC) number fourteen employing geosynchronous orbit (GSO) satellites and three employing non-geosynchronous orbit (NGSO) satellites. Ka-band applications to the International Telecommunications Union Radiocommunications Sector (ITU-R) have been tendered by twenty-one countries, with over 380 GSO satellites and eight countries have filed for over 200 satellites in NGSO constellations. The Ka-band is also allocated for feeder links for NGSO systems, including NGSO/FSS, NGSO/FSS/MSS, and NGSO/MSS services.

Another area of rapid development involves "Big LEO" mobile satellite personal communications systems. The big LEO systems are NGSO constellations, with 10 to 66 satellites, and operate in low earth orbit (LEO), medium earth orbit (MEO) and elliptical earth orbit (HEO). The primary service of the Big LEO systems is personal voice communications. The service links operate in the bands 1610-1626.5 MHz (uplink) and 2483.5-2500 MHz (downlink). They operate with multiple satellite antenna beams, and employ CDMA or TDMA/FDMA access techniques

"Little LEO" mobile satellites systems are smaller in size and in capabilities than the big LEO systems. They provide lower rate services including paging, messaging, and position location (no voice). They operate in NGSO (LEO) constellations of 20 to 24 satellites. The service links operate in the 137-138, 148-149.9, 400-401 MHz bands.

The last year has seen the first interest in satellite systems operating in the so-called Q-band or Q/V-band. These systems operate in the FSS allocated bands of 37.5 - 40.5 GHz (downlink) and 47.2 - 50.2 GHz (uplink). Twelve organizations filed fourteen Q/V-band systems with the FCC in September 1997. These systems are designed to provide broadband multimedia services, VSAT and direct to home services. Q/V-band systems typically have higher data rates than Ku or Ka band systems, with data rates of up to 3 GBPS being considered. The proposed systems include GSO, NGSO, and mixed constellations.

Each of these applications has unique propagation characteristics. Section 2 of this handbook provides the tools to evaluate the propagation degradations of these systems, and this section, Section 3, offers "roadmaps" to adequately identify and analyze the specific propagation factors important to the application.

Another area where recent developments have changed the "playing field" in satellite communications is the increased emphasis on spectrum sharing and interference mitigation. The explosion in global satellite systems has required the system designer to include spectrum sharing as a critical part of the system design. The radio spectrum is a fixed and limited resource, and the available bandwidth in most of the bands allocated for satellite applications is not adequate for all of the systems under consideration for deployment. Sharing is required, and often, if band segmentation cannot be employed, mitigation techniques including power control and exclusion zones have to be evaluated. Also, the sharing of GSO and NGSO systems operating in the same allocated bands adds another critical element to the spectrum sharing process.

The inclusion of the appropriate propagation effects in the desired and the interfering links is essential to an acceptable solution. The models and procedures described in this handbook are elements of a comprehensive spectrum sharing process that often includes simulations and analytic procedures of the full range of applications and satellite orbits.

Section 3 begins with an overview of general link analysis procedures for satellite communications systems. Design considerations and recommendations for the selection of a rain attenuation prediction model are included. Section 3.2 covers propagation effects on systems operating below 3 GHz. Sections then follow on Ku-band systems, Ka-band systems, Q/V-band systems, and direct broadcast systems. A discussion on propagation considerations for non-geosynchronous (NGSO) is also included.

The principal topics and associated subsection numbers for Section 3 are listed in Table 4:

Section	Topic
3.0	INTRODUCTION TO SECTION 3
3.1	APPLICATION OF PREDICTION MODELS TO SYSTEM DESIGN AND PERFORMANCE
3.2	PROPAGATION EFFECTS ON SATELLITE SYSTEMS OPERATING BELOW 3 GHZ
3.3	PROPAGATION EFFECTS ON KU-BAND SYSTEMS
3.4	PROPAGATION EFFECTS ON KA-BAND SYSTEMS
3.5	PROPAGATION EFFECTS ON Q/V-BAND SYSTEMS
3.6	PROPAGATION EFFECTS DIRECT BROADCAST SATELLITE SYSTEMS
3.7	PROPAGATION EFFECTS CONSIDERATIONS FOR NGSO SYSTEMS
3.8	REFERENCES – SECTION 3

Table 4. CONTENTS OF SECTION 3 APPLICATIONS

Summary and Future Plans

The latest version of the NASA Propagation Effects Handbook for Satellite Systems Design was delivered to NASA JPL on October 23, 1998. Revision 1 was released in February 1999. JPL has recently negotiated with ITT Industries for an extension contract to update the handbook. Revision 2 to the Fifth Edition will include corrections and minor updates based on an on going peer review; the addition of an index and list of symbols; the inclusion of the complete ACTS data base; and updates to ITU-R and other prediction models that have occurred in the last twelve months.

The Fifth Edition of the Propagation Effects Handbook for Satellite Systems Design continues the long process of a continuing commitment to provide a comprehensive reference document which provides the latest information on atmospheric propagation effects and how they impact satellite communications system design and performance.

Acknowledgements

I would like to acknowledge the contributions of the many members of the staff at Stanford Telecom (now ITT Industries) who helped with the development of this handbook. The contributions of Dr. Lynn Ailes, Glenn Feldhake, Dr. Frank Hastings, Chris Pearson, Jennifer Pinder, and John Weinfield are gratefully appreciated. The contributions of previous members of the staff, Jay Gible, Julie Feil, and Chris Hofer are also acknowledged. The assistance of Ivy Cooper and Marian Montigny in the production of the handbook is also appreciated.

I would like to thank the reviewers for their thoroughness and diligence in the review process. A special thanks goes to Dr. Ernest K. Smith for his excellent comprehensive review and comments. I also would like to acknowledge the contributions of Warren Flock, Ken Davies, and Glenn Feldhake to the review process.

A special thanks also to Dr. Nasser Golshan, NASA JPL, who guided the development of the handbook and has been a valued associate over the entire history of the Fifth Edition program.

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2.4 - Special Effects: Antenna Wetting, Short Distance Diversity and Depolarization

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Abstract

The Advanced Communication Technology Satellite (ACTS) communications system operates in the Ka frequency band. ACTS uses multiple, hopping, narrow beams and very small aperture terminal (VSAT) technology to establish a system availability of 99.5% for bit-error-rates of 5×10^{-7} or better over the continental United States. In order maintain this minimum system availability in all US rain zones, ACTS uses an adaptive rain fade compensation protocol to reduce the impact of signal attenuation resulting from propagation effects. The purpose of this paper is to present the results of system and sub-system characterizations considering the statistical effects of system variances due to antenna wetting and depolarization effects. In addition the availability enhancements using short distance diversity in a sub-tropical rain zone are investigated.

I. Introduction

The Advanced Communications Technology Satellite (ACTS) was launched in September 1993 and is now operating in inclined orbit of 0.8 degrees per year. The primary objective of the technology verification experiment (TVE) program is to obtain a deeper understanding and full statistical characterization of ACTS Ka band sub-systems. These measurements, obtained in an operational space environment, are needed to accurately evaluate ACTS technology and to promote the development and characterization of prototype Ka band sub-system technologies

This paper describes two propagation effects and a rain fade compensation technique that should be considered when designing a Ka-band satellite system. The contribution of wet reflector antennas and depolarization to the signal path losses in a Ka-band, low margin system is statistically documented. Two-station diversity is experimentally investigated in a sub-tropical rain zone.

The amount of water in ground reflector antennas (reflector and feed radomes) can cause additional signal loss (up to 4 to 5dB) from the expected propagation attenuation due to rain at Ka-band. This is one reason that the standard techniques for predicting rain fade statistics (using propagation models) are not aligned with ACTS Ka-band RF beacon measurements.

All ACTS ground reflectors, including the propagation terminal (APT) utilized off-the-shelf hardware that was mainly designed for Ku-band operations. The ACTS reflector surfaces were coated with a very thick and rugged dielectric layer, that in the presence of water, created a large reflection coefficient causing larger (2-5 dB) attenuation of the signal.

The problem of wet antenna can be described as high perturbation on the feed standing wave ratio. In contrast, the reflector losses can be explained by an additional scattering losses and absorption due to raindrops' size at the surface of the reflector. Borsholm, Crane and Acosta [1,2,3] have studied the problem of signal loss due to wet reflector antenna and radome surfaces. In this paper, extensive measurements are presented to statistically characterize the wetting effect.

Rain induced depolarization is produced from a differential attenuation and phase shift caused by non-spherical raindrops. As the size of raindrops increase, their shape tends to change from spherical (the preferred shape because of surface tension forces) to oblate spheroids with an increasingly pronounced flat or concave base produced from aerodynamic forces acting upward on the drops.

A second source of depolarization on an Earth-space path, in addition to rain, is the presence of ice crystals in clouds at high altitudes. Ice crystal depolarization is caused primarily by differential phase shift rather than differential attenuation, which is the major mechanism for raindrop depolarization. Ice crystal depolarization

can occur with little or no co-polarized attenuation. The amplitude and phase of the cross-polarized component can exhibit abrupt changes with large excursions.

Atmospheric depolarization effects were measured using the ACTS beacons and collected for 1/2 of a station year. Depolarization due to rain is not an issue at Ka-band since the cross-pol and co-pol signals are attenuated by the same amount; therefore making the system margin a dominant function of the co-pol attenuation. Another depolarization effect is due to ice crystals. This depolarization phenomenon is characterized by an increase of cross-pol level and a small but negligible co-pol attenuation. Experimental data using the ACTS beacon at 20.185 GHz showed that the cross-pol can increase by 10 dB with negligible co-pol attenuation. This effect is important when designing polarization reuse, and multiple beam systems at Ka-band.

Spatially diversified ground stations must be close enough to minimize the cost of connecting terrestrial lines, but still realize an increase in link availability. By utilizing the signal from whichever station is experiencing the least attenuation, the overall link availability is increased. Site diversity is a method for increasing the system availability at the expense of adding at least one more ground station. In tropical and sub-tropical rain zones the rain cells are compact (<10-km) therefore implying that short distance diversity might be employed. The data collected in this investigation use two-station diversity geometry with a separation distance of 1.2 km. The experiment shows typical diversity gain of 5 to 10 dB. These measurements clearly establishes a method for compensating rain fades in a sub-tropical rain zones.

The primary objective of this paper is to experimentally determine the magnitude of the signal loss when the ACTS antenna reflector is wet, depolarization effects on cross-pol, and gain enhancement of short distance diversity in a sub-tropical rain zone.

II. Experiment Description

Antenna Wetting Experiment

The objective of the antenna wetting experiment consisted in measuring the magnitude of the effect and its correlation to rain rate for the ACTS 0.6-m Ultra Small Aperture Terminal (USAT) reflector antenna. Figure 1. describes the outdoor experiment set-up. It consisted into two identical reflector systems located side-by-side, one reflector was protected from rain and the other exposed to rain. The protected reflector is covered everywhere except in the aperture plane. The received continuous wave 20 GHz RF signal is digitally recorded at 1/2 sec sampling rate and filtered at 40 kHz with a bandpass filter centered at 70 MHz. The receiver has a signal to noise ratio of at least 30 dB, therefore fades up to 30 dB can be recorded without distortion.

The antenna-wetting factor is defined as the difference between the dry reflector signal and the wet reflector. In addition to measuring the signal power, a small weather station is operated next to the USAT terminals. Rainfall data are collected using a tipping bucket rain gage. The experiment was located in sub-tropical region in Cocoa, Florida. The data collection period extended between April 1999 to April 2000.

Depolarization Experiment

The objective of the depolarization experiment consisted of measuring the magnitude of the received beacon cross polarization signal in wet and dry conditions. Figure 2a. depicts the experiment outdoor unit and Figure 2b. describes the system block diagram. The experiment terminal is a modified ACTS propagation terminal (APT) with a 4 channel, dual polarization receiver. The experiment was located in medium rain zone region in Ahburn, Virginia. The data collection period extended between August to December 1999.

The hardware modifications made to original APT RF enclosure were basically to remove the 27 GHz components and replace them with 20 GHz components. Within each receiver enclosures are the co-pol and cross-pol IF. The digital receivers are configured so that the co-pol units are the master subassemblies at the physical location of the original APT 20 GHz hardware and the cross-pol are the slave subassemblies at the physical location of the original APT 27 GHz hardware. The significance of this is that the master subassemblies provide the fixed 65 MHz 2nd LO and 3rd LO (-4.54 MHz) from digital receiver and the digital receiver clock to slave subassemblies.

Several modifications were made to the original APT data collection software to accomplish the measurement goals and to accommodate the hardware modification.

Short Distance Diversity Experiment

The objective of the short distance experiment consisted of measuring the magnitude of site diversity gain using two ACTS APT 1.2-m VSAT reflector antenna separated by 1.2-km. Figure 3a. describes the experiment outdoor units during checkout and Figure 3b. shows a block diagram of the APT. The experiment was located in sub-tropical region in Tampa, Florida. The data collection period extended between September 1999 to December 1999.

The experiment consisted of locating two identical propagation terminals separated by a distance of 1.2 km. The propagation terminals are capable of tracking and receiving the ACTS beacons at 20 and 27 GHz co-polarized beacon signals. The terminals also measured the sky noise temperature close to the beacon frequencies. This allows the elimination of equipment effects from the measured beacon signal levels and accurate isolation of propagation effects during post processing of the collected data. Most of the RF hardware used in the terminals is identical. The APT uses digital receiver technology. In addition to the beacon signals, several meteorological parameters are recorded at the two sites. These include rain intensity, ambient temperature, humidity and pressure. The auxiliary parameters are useful in calibrating the radiometer channels and interpreting the propagation results.

III. Experiment Results

Antenna Wetting Experiment

This paper discusses the impact of signal loss as a result of water layer on the USAT antenna reflector surfaces and the antenna feed horn radomes. The measured impact of wet antennas proved to be significant. Figure 4a. shows the cumulative distribution function (CDF) of two station years for the antenna-wetting factor. Figure 4b. presents the tipping bucket rain rate CDF for the site and notice that it describes a typical sub-tropical region behavior. Notice the antenna-wetting factor exceeds 2.5 dB for 10 % of the time. At this percent of time rain rates are greater than 90 mm/hr, which is considered extremely heavy rain. At low rain rates (< 5 mm/hr) the antenna-wetting factor is about 1 dB.

In order to minimize the effect of wet reflectors the dielectric thickness of the reflector needs to be minimized to reduce the losses in the presence of a water layer. The feed radome can be easily covered on the topside to protect the phased center of the horn from being exposed to water. If an extended radome is used, careful offset design needs to be used in order to prevent signal loss or blockage loss.

Depolarization Experiment

The experiment studied the effect of the cross-polarization signal in rainy and faded conditions. Figure 5. depicts the two orthogonal components CDF's. The antenna misalignment effects can be seen from the dry CDF. Notice there is an increase of cross-pol signal for about 0.1 % of the time. We can infer that this is due to ice-depolarization since it is the only probable cause for increase of cross-pol signal under faded conditions when compared to dry or clear sky conditions. Also from Figure 5. it can be seen that both components increase by about the same amount, therefore confirming the expectation that ice-depolarization is non-polarized event. The data contains a total of about 7 weeks of clear sky and about 2 weeks of faded conditions. In order to make a complete assessment of depolarization due to ice, a complete set of amplitude and phase measurements are required with at least one year of data collection.

Although the experiment goals were met, future work is still required for a complete statistical characterization of the ice-depolarization. For system design the effect of ice-depolarization appears to be small (~0.1 % of total time the signal was faded) and only needs to be considered in polarization reuse systems.

Short Distance Diversity

This experiment documents the gain enhancement that can be obtained in sub-tropical rain zone when using 2 stations separated by a distance of 1.2 km. Figure 6a. shows the corresponding CDF for the sites at both 20 GHz and 27 GHz. Notice that they are very close over the useful fade range of 20 dB. The diversity gain is defined in this experimental study as the difference in fade observed simultaneously by the two stations. Figure 6b. presents the CDF for the gain at 20 and 27 GHz. Notice that 27 GHz gains are larger than expected at 20 GHz. Gain enhancement exceeding 10 dB occurs at about 5% of time. A typical expected enhancement of greater than 5 dB is more likely to be achievable in systems operating in tropical and sub-tropical regions.

This experiment documents the boundaries for what is achievable in two-station diversity in the sub-tropical region. To complete the characterization of short distance diversity, a more extensive data set needs to be collected and station separation needs also to be investigated.

VI. References

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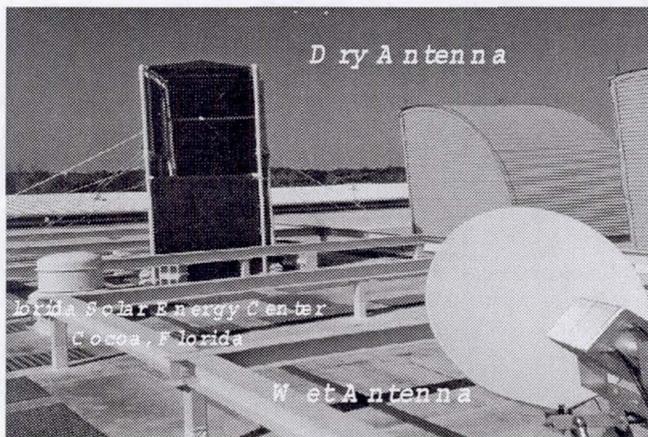


Figure 1. ANTENNA WETTING UNITS



Figure 2a. DEPOLARIZATION UNIT

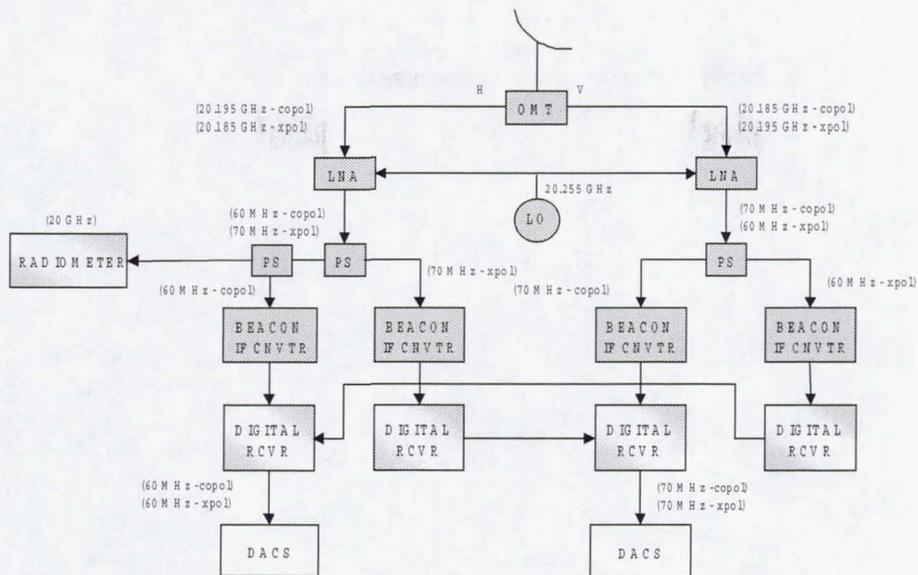


Figure 2b. SYSTEM BLOCK DIAGRAM FOR THE MODIFIED ACTS PROPAGATION TERMINAL



Figure 3a. SYSTEM UNITS AT CHECKOUT

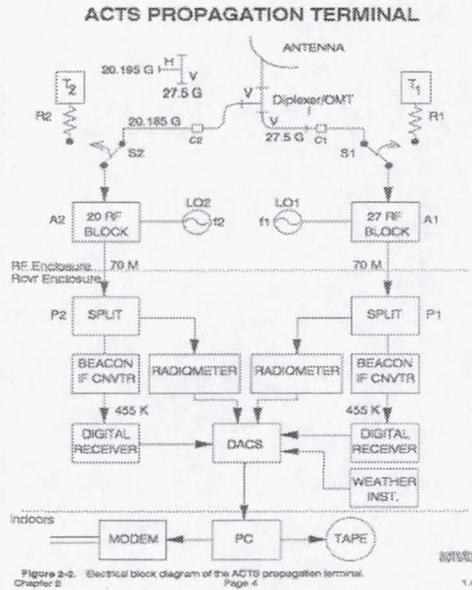


Figure 3b. SYSTEM BLOCK DIAGRAM OF APT

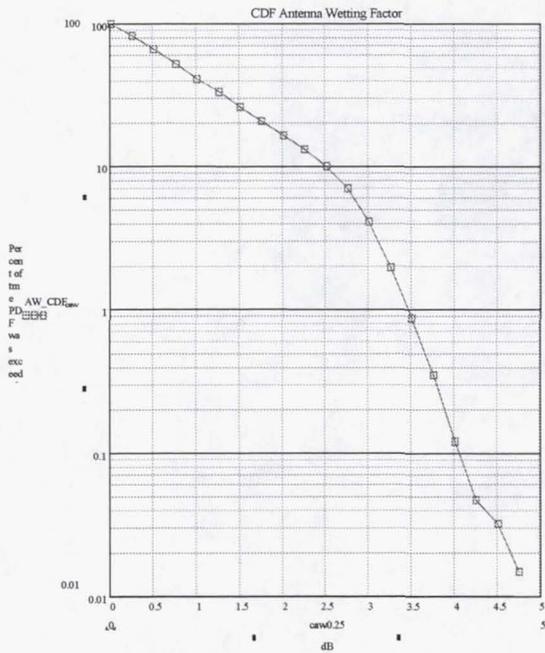


Figure 4a. CDF FOR ANTENNA WETTING FACTOR

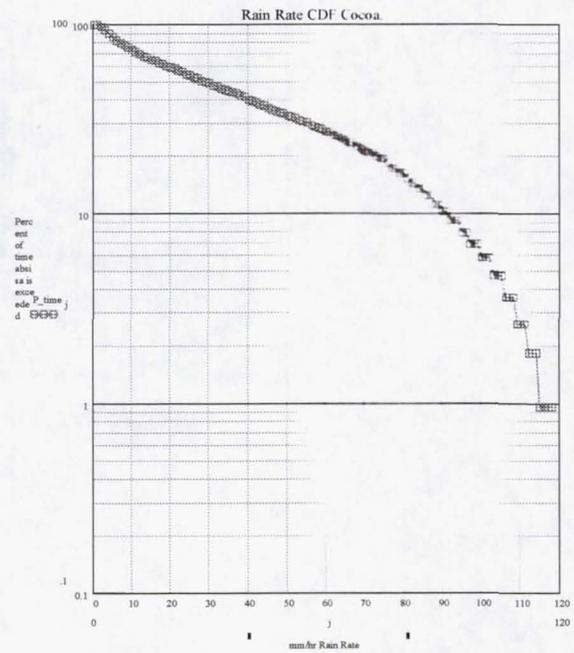


Figure 4b. CDF FOR THE RAIN RATES

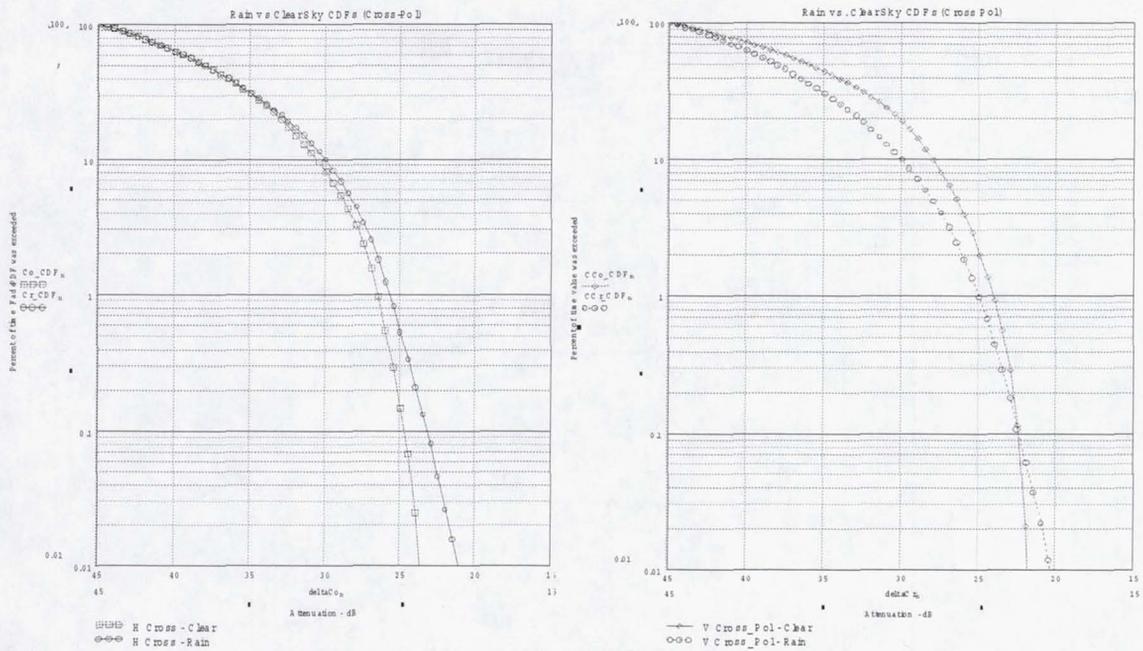


Figure 5. CROSS-POLARIZATION SIGNAL, DRY VS. WET

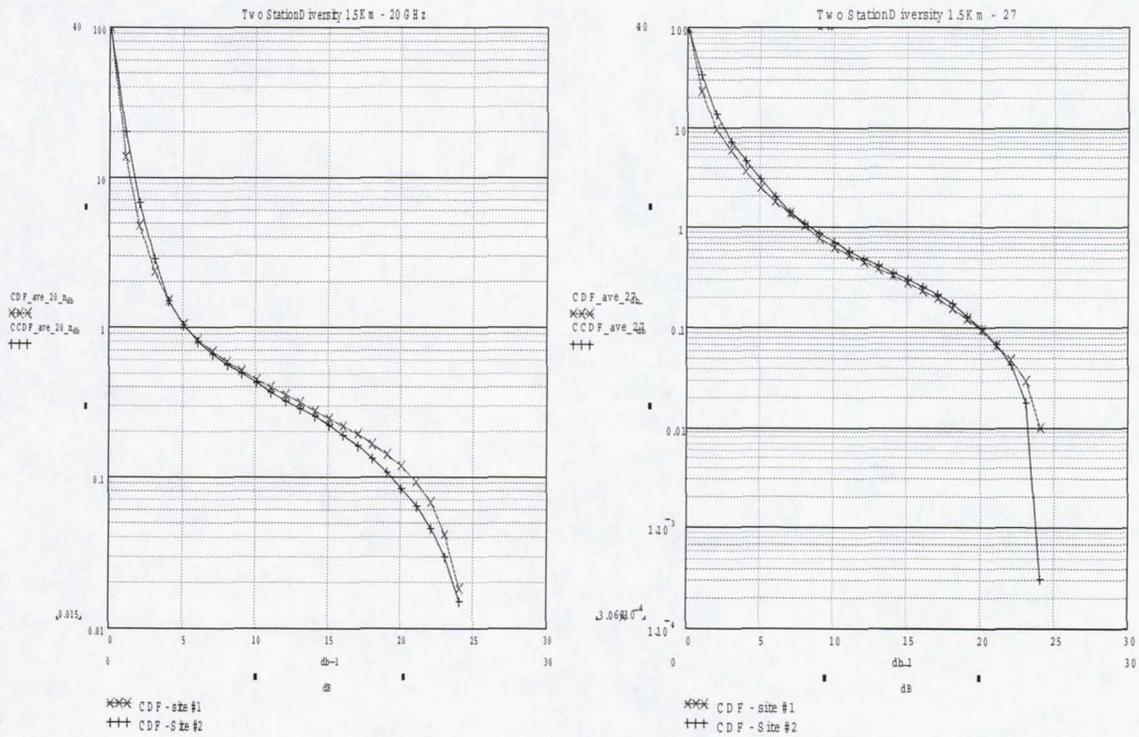


Figure 6a. ATTENUATION CDFS FOR BOTH SITES AND FREQUENCIES

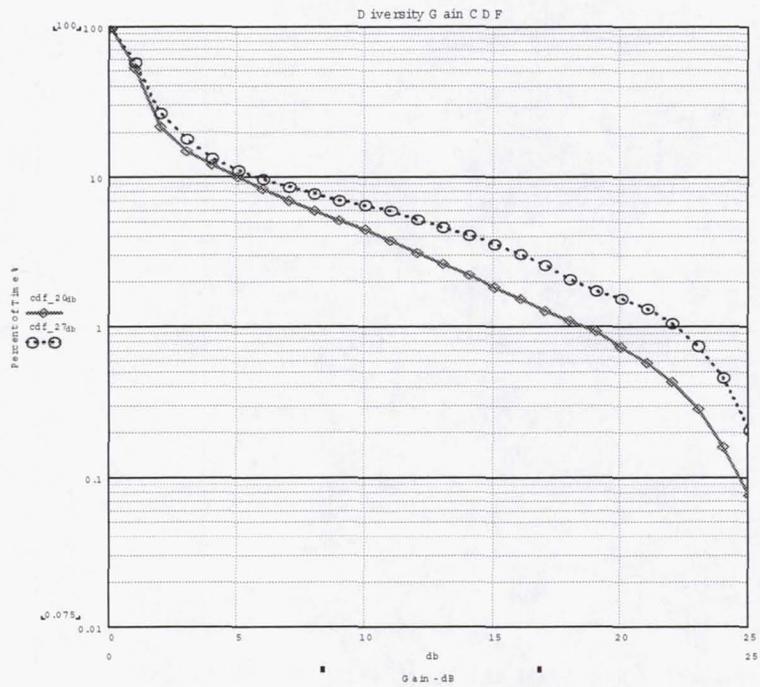


Figure 6b. CDF SITE DIVERSITY GAIN AT 20 GHZ AND 30 GHZ

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3.1 - Survey of Advanced Applications Over ACTS

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1.0 Abstract

The Advanced Communications Technology Satellite (ACTS) system provided a national testbed that enabled advanced applications to be tested and demonstrated over a live satellite link. Of the applications that used ACTS, some offered unique advantages over current methods, while others simply could not be accommodated by conventional systems. The initial technical and experiments results of the program were reported at the 1995 ACTS Results Conference, in Cleveland, Ohio. Since then, the Experiments Program has involved 45 new experiments comprising 30 application experiments and 15 technology related experiments that took advantage of the advanced technologies and unique capabilities offered by ACTS. The experiments are categorized and quantified to show the organizational mix of the experiments program and relative usage of the satellite. Since paper length guidelines preclude each experiment from being individually reported, the application experiments and significant demonstrations are surveyed to show the breadth of the activities that have been supported. Experiments in a similar application category are collectively discussed, such as, telemedicine, or networking and protocol evaluation. Where available, experiment conclusions and impact are presented and references of results and experiment information are provided. The quantity and diversity of the experiments program demonstrated a variety of service areas for the next generation of commercially available, advanced satellite communications.

2.0 Overview of the Experiments Program

Communications satellites have made tremendous technological strides since the early 1960's first passive reflector of the orbiting balloon ECHO, the first real-time transponder of TELSTAR I, and the first geosynchronous SYNCOM series. To encourage new business development and economic growth as well as ensure national security, the US Government has historically supported programs to make the long-term, high risk research, development and applications investment needed to achieve revolutionary technology advances for communications satellites.

NASA's ACTS program was the most recent example of this. It developed high-risk, advanced communications technologies usable in multiple frequency bands and applicable to a wide range of future communications systems for industry, NASA and other government agencies. The approach was to flight test the high-risk technologies that fell outside the sponsorship of the private sector and then validate them through an Experiments program. The flight validation of the technology allowed industry to adapt the technology to its individual commercial requirements at minimal risk. The Experiments program provided an opportunity to demonstrate user applications over satellite that showed improved services, and verified new services and opportunities made possible from the higher frequency system's smaller earth stations and broadband data rates.

After the satellite's launch in September 1993 and two-and-a-half month on-orbit system checkout, the Experiments program began on December 1, 1993. The program had an initial duration of two years. The results from these two years of operations were thoroughly presented and documented at the ACTS Results Conference held in Cleveland, Ohio in 1995 [1]. With a highly successful experiments program underway and fully functional payload, the program was extended two more years. At the end of the four years, experimenter interest and unresolved issues involving broadband satellite/terrestrial network protocol interoperability warranted further extension of the program.

In August 1998, the spacecraft's operations were altered to allow the system to drift on-orbit in the North/South attitude so that extended operations could be carried out with the little remaining on-board fuel. New goals were also defined for the Experiments program that provided a more focused program with an emphasis on supporting the goals of NASA's four Enterprises [2]. These latest goals were to use ACTS as a testbed to: 1) demonstrate NASA's and other government agencies' transition to commercial systems; 2) test, and evaluate communications protocols for their interoperability with terrestrial systems; 3) evaluate narrow spot beam, Ka-band satellite operations in an inclined orbit; and 4) use ACTS in verifying Ka-band satellite technologies. After 81 months of operations with the close of the Experiments Program on May 31, 2000, the satellite will have supported 104 experiments and over 80 demonstrations.

3.0 Experiments Operations Summary

In reviewing the Experiments Program from 1993 through March 2000, the organizational mix of experiments and experimenters offers top level insight into the usage of the satellite. Organizationally, three categories are considered: industry, university, and government. Generally, two periods are considered. The first covers the initial two years of operations whose results were reported on in great length at the 1995 ACTS Results Conference [1]. The second covers the remaining four years of operations from 1996-2000. Quality and impact of the experiments are difficult to quantify; however, presenting statistics about the experiment operations reveals the composition of the experiments program and relative usage of the system. Overall, 104 experiments were initiated over ACTS, with 59 during the years '94-'95, and 45 during the years '96-'00. Experiment hours on the spacecraft totaled over 74,000 throughout the whole program.

3.1 Unique Participating Organizations

The 104 experiments were proposed by fewer than 104 organizations. Several organizations were involved in more than one experiment. Of all the selected experiments, how many unique organizations were represented? The 104 experiments were proposed by 61 unique principal investigator (PI) organizations coming from government, industry, or academia. Repeating organizations performed 43 of the experiments. Another 68 unique organizations participated as co-investigators.

Of the 61 unique PI organizations over the course of the whole program, 43% came from industry (26) while those from government and academic sectors were fairly balanced with 26% (16) and 31% (19), respectively (see Table 1, first line of the three sub-tables). In comparing the unique organization mix between the first and second periods of the experiments program, the most noticeable change is a 14% increase in industry participation during the second period (from 38% to 52%). For universities, the participation remained about the same from the first period to the second. The number of government organizations decreased from 30% to 19% during that same time.

3.2 Selected Experiments

Of the 104 experiments, if just the type of organization (industry, government or academia) that proposed each is categorized without concern of multiple experiments coming from the same organization, another mix can be developed. This mix indicates that overall, the most number of selected proposals came from government organizations. The PI mix of selected experiments over the whole program is composed of 50% (52) from government organizations, 34% (35) from industry, and 16% (17) from academia (Table 1, second line of the three sub-tables). The strong government involvement can be attributed largely to NASA being identified as the PI in 14 experiments that involved industry and academia partners. The second period of the experiments program saw a 21% increase in government organization experiments (from 41% to 62%) from the first period. The contribution from universities dropped 13% (from 22% to 9%), while the involvement from industry PI's slipped 8% (from 37% to 29%) during the second period.

3.3 Experiment Usage

A third look at usage of ACTS is made by experiment hours used. Here there is also a predominance of government usage at 84% over the whole program and 91% over the second period (see Table 1, third line of the sub-tables). Industry usage represented 21% during the first period and only 4% during the second, while academia used 19% during the first period and 5% in the second. This heavy government usage can be ascribed to the shift in the Experiments Program goals that emphasized NASA/government benefit, and to several NASA-led, statistically oriented, technology verification experiments requiring long-term data collection. Weekends

and off-hours during the weekday evenings were often assigned to these experiments when autonomous data collection occurred. Other experimenters seldom used these hours preferring to utilize the highly contentious daytime weekday hours. Especially true of the industry experimenters, non-government experiments were usually very focused on testing something specific, or demonstrating an application that resulted in completion within a short duration. Another factor that influenced spacecraft usage was the introduction of the ACTS Usage Policy in April 1997. Users were often charged for their satellite time during most of the second period depending on several factors. This resulted in very intense experiments that, for the most part, lasted hours or days instead of weeks and months when charges were involved.

Table 1: ACTS USAGE AND PARTICIPATION

	FY94-95							Totals	
	G		I		A				
Unique PI Organizations	12	30%	15	38%	13	33%	40	100%	
Selected Experiments	24	41%	22	37%	13	22%	59	100%	
Experiment Hours Used	11409	60%	3979	21%	3549	19%	18937	100%	

	FY96-00							Totals	
	G		I		A				
Unique PI Organizations	4	19%	11	52%	6	29%	21	100%	
Selected Experiments	28	62%	13	29%	4	9%	45	100%	
Experiment Hours Used	50671	91%	2035	4%	2605	5%	55311	100%	

	Entire Program							Totals	
	G		I		A				
Unique PI Organizations	16	26%	26	43%	19	31%	61	100%	
Selected Experiments	52	50%	35	34%	17	16%	104	100%	
Experiment Hours Used	62080	84%	6014	8%	6154	8%	74248	100%	

G = Government, I = Industry, A = Academia

4.0 Experiment Types

Within the ACTS Experiments Program, experiments are grouped into three general areas identified as Technology Verification, Propagation, and Applications. A listing of all the approved ACTS Experiments can be found at <http://acts.grc.nasa.gov/about/experiments> as a table with experiment number, Principal Investigator (PI) organization, experiment title, organization category, earth station category, experiment focus, and experiment period.

4.1 Technology Verification and Characterization

Experiments that verify and characterize the specific technologies on ACTS are classified as technology verification experiments. For the purposes of this paper, this category is expanded to also include technology characterization experiments, that is, experiments that primarily needed to utilize a Ka-band satellite link to characterize new Ka-band hardware. Since the 1995 Conference, nine technology verification experiments were initiated by NASA Glenn Research Center (GRC) that verified and characterized the basic ACTS technologies, such as, multibeam antenna (MBA) performance, Ka-band communications, on-board baseband processing operations, wideband channel operations, and rain fade compensation in the TDMA mode. Five of these completed in 1998.

Since the beginning of inclined orbit (I/O) operations in 1998, four new technology verification experiments were implemented by NASA GRC to investigate the effect of inclined orbit operations on system performance. "T1VSAT Statistical Performance in Inclined Orbit" reports Ka-band propagation and systems effects on the ground segment during baseband processor mode operations [3]. "ACTS Fade Compensation Algorithm Characterization in Inclined Orbit" investigated Ka-band propagation and systems effects on the performance of the baseband processor's fade compensation technique using a time domain analysis. Similar measurements were made in "Ka-band Propagation Effects on Communications Link Performance" which involved a time domain analysis of Ka-band propagation effects on the USAT performance in a tropical or sub-tropical rain zone

especially antenna wetting. "Multibeam Antenna Performance in Inclined Orbit" examined the overall pointing stability of the MBA on a regular basis throughout inclined orbit operations to record how well the pointing of the narrow spot beams was maintained while the spacecraft drifted. The results of these last two are reported in [4].

Two other experiments utilized ACTS Ka-band transponders to verify and characterize new commercial Ka-band ground segment hardware. The first is Lockheed Martin Western Development Laboratory which used ACTS to characterize the performance of a large (~8-m) reflector for a Ka-band ground station for an undisclosed customer. The other was by Bellcore working with the Glenn Research Center in verifying high speed data traffic measurement using the wideband channel of ACTS and a new piece of test equipment being developed by Bellcore.

4.2 Propagation

The introduction of Ka-band for satellite communications to the US brought with it the need to characterize the increased impairment effects of the atmosphere on this frequency band. The propagation experiments were a very important part of the Experiments Program, and perhaps may have been the most enduring contribution ACTS made to the communications satellite community. The majority of the effort focused on an extensive 5-year data collection program that finished in March 1999. The spacecraft's beacons in the uplink frequency band (27.5 GHz) and downlink band (20.2 GHz) were monitored using identical receive-only stations located in seven sites across North America. The data has been processed and analyzed and used to verify and improve propagation fade models. The results of this campaign were well documented and reported through the ACTS Propagation Studies Workshops organized by the Jet Propulsion Laboratory [5], and various journals and technical papers [a good sample is cited in 6]. Since the 1995 Results Conference, two other experiments were added. One by NASA GRC looked at atmospheric depolarization effects. Another experiment by NASA GRC and Florida Atlantic University made use of two propagation terminals after the 5-year data set was collected to investigate short distance site diversity gain at Ka-band using different diversity separations. The results of these activities are being reported at this conference [7]. Another propagation-related experiment involved NASA GRC and ITT which, in the spring of 2000, investigated wideband dispersion effects by making amplitude and group delay measurements over a 300 MHz bandwidth with special interest in data collected during convective rain events.

4.3 Applications and Networking

The majority of ACTS experiments used the system to test, evaluate, and demonstrate activities. Many of the activities included showing the improved capabilities that wider bandwidth communications using relatively small Ka-band terminals can provide; demonstrating new services to customers and business strategists; and networking, protocol evaluation and interoperability between terrestrially and space-routed networks. These experiments are discussed further in section 5.0.

5.0 Application Experiments

Since the 1995 ACTS Results Conference, 45 new experiments were approved for using ACTS. Of these, 30 were applications oriented. The applications experiments were sub-categorized into 4 areas: business development and service improvement; health, education and public wellness; telescience; and broadband network interoperability and protocol verification. All of these experiments utilized some aspect of ACTS technologies that precluded them from achieving their results with current commercial satellites. There are many papers and reports of these activities available in the literature; key papers are referenced. Some activities were brief or proprietary, and therefore, very little documentation can be found. Others were ongoing at the time of this writing and results were not yet available.

5.1 Business Development and Service Improvement

This type of experiment included activities where the major intent was to develop, in a broad sense, some business line or product of the organization, or improving the service it provides to its customers using ACTS-like technology. Government or academia could also be included here when the focus was improving their operations.

- Lockheed Martin hosted a very successful experiment in late 1996 through the spring of 1997 that was done in cooperation with a team of nearly twenty organizations from Japan and the US. Key organizers included the Jet Propulsion Laboratory (JPL), the Communications Research Laboratory, and Sony Studios. It involved a duplex double satellite hop using ACTS from JPL to Hawaii and Intelsat 701 at 180° E from Hawaii to Japan for the purpose of demonstrating high definition television near real time editing between two very distant studios. Further description of this can be found at [8], [9].
- American Telephone and Telegraph (AT&T) was involved in a short week-long experiment in April 1997 that involved characterizing a CDMA transmission technique that was being considered for its proposed Ka-band satellite venture, *Voicespan*. Coincidentally, this system was withdrawn about two weeks after the ACTS experiment.
- The Naval Research and Development Center (NRaD) worked with JPL in 1997 to install the JPL ACTS Broadband Aeronautical Terminal on the Navy vessel, USS Princeton. This link provided unprecedented data rates of 1.5 Mbps to the ship at sea that demonstrated how a very small Ka-band terminal with two-axis tracking can operate in the heavy EMI environment of a Navy ship while providing wideband duplex communications. The communications link provided other non-operations related benefits, such as a near real time email link for the crew. It was also cited as perhaps the key to saving the life of an ill Greek freighter's master that was diagnosed over the satellite link while at sea [10].
- Globalstar did a brief few-day experiment in the fall of 1997 with the JPL and a New Zealand firm, CES, Ltd. that looked at a time-smearing coding technique to be applied to mobile and personal satellite communications.
- Caterpillar implemented a month long experiment in the summer of 1997 primarily through Carnegie Mellon University that looked at the feasibility of using very small terminals and satellite communications to support advanced embedded control and information systems to improve the quality, performance and serviceability of its products (large earth-moving and construction vehicles).
- NASA's Advanced Air Transportation Technology (AATT) project is developing new technologies and tools to enable free-flight – an operating system in which pilots will have the freedom to select their path and speed in real time. This activity was supported by NASA GRC's Space Communications Office using T1VSATs in a link between GRC and the Lockheed Martin facility in Atlanta, Georgia for several months in early 1998. The tests utilized TCP/IP with the free-flight software to demonstrate and evaluate its performance under actual satellite link conditions. The use of high-bandwidth small size terminals and demand assigned multiple access which allowed varying data rates to be routed to multiple locations were identified as important in showing that satellite communications could provide a feasible solution to supporting the project's distributed communications architecture.
- Lockheed Martin Systems, Inc. utilized ACTS in the spring of 1998 in a very important demonstration to a potential customer that demonstrated the use of TCP/IP and satellite communications to reduce the cost space network operations. The live demonstration was part of the proposal by the contractor team led by LMSI. The demonstration, no doubt, helped the team to win the business from NASA for the Phase 2 Consolidated Space Operations Contract worth about US \$3.4 B [11].
- A demonstration experiment was performed for INTELSAT at its headquarters in Washington, DC in February 1999. The goal was to compare side-by-side various Ku- and Ka-band services to the consortium's senior management, technical committee and planning committee. The results of the demo were expected to give the attendees realistic expectations on the capabilities of both current (Ku-band) and future (Ka-band) satellite technologies. Because of the corporate sensitive nature of the results, no reference on this activity is available.
- The lack of electrical energy in rural communities of developing countries is well known. The portability of a USAT and the versatility of ACTS as well as the advantages of Ka-band satellites provided an opportunity for Florida Solar Energy Center and NASA GRC to test Supervisory Control and Data Acquisition (SCADA) with a photovoltaic/diesel hybrid power generator designed for rural communities in developing countries. Initial tests in the late spring of 1999 showed that the satellite link supported 2-second data transfers with an error rate of less than 1%. Using SCADA to monitor these systems in remote areas allows technical assistance to be provided from remote experts [12]. Results from work being done in 2000 are forth coming.
- The promise of widely accessible wideband two-way communications via satellites operating at Ka-band frequencies will only be realized when low-cost ground terminals are readily available. These higher frequencies impact ground stations in overcoming the propagation impairments and the production of devices such as power amplifiers. The new systems are using switched-beam TDMA architectures, which demand the use of a burst modem. Raytheon Telecommunications Company saw an opportunity to be such a provider. Prototype earth stations were built and tested in the summer of 1999 over ACTS as being representative of future Ka-band satellite systems that incorporate a 1-m dish and 2.5 W SSPA with a receiver noise figure of about 4 dB. The performance was adequate to demonstrate many applications that will take advantage of broadband terminals soon to be operating at Ka-band [13].

5.2 Health, Education, and Public Wellness

Improving health care service especially to the rural populations is a very specific type of application that can be greatly enhanced by satellite communications. In addition, as the costs of health care rise, it is hypothesized that costs may be reduced by pooling physician specialists in centers of excellence, which can be linked to small and medium sized medical practices. While the immediate use of telemedicine is often associated with remote interaction of a physician with a patient, it also includes bandwidth intensive applications involving large file transfers such as for radiology, post procedure and intra-procedure image analysis, as well as research and records keeping.

- A telemedicine demonstration was performed in July 1996 in the rural state of Montana that allowed physicians to get a taste of space-aged medicine. Using a portable diagnostic package developed for Space Station astronauts by Krug Life Sciences and USAT links provided by NASA GRC, examinations were performed between remote clinics at an Exxon refinery and the Indian Health Service Hospital at Crow Agency, and the local hospital, St. Vincent Hospital and Health Center. The participants thought the small size of the terminal was very impressive and easy to accommodate, and the voice and picture clarity was very good [14].
- The Mayo Clinic's use of High Data Rate (HDR) Earth Stations built on its earlier T1VSAT experience with ACTS. During a yearlong activity from the spring of 1996 through 1997 Mayo expanded to wideband applications. This second experiment included studies of remote digital echocardiography, store-and-forward telemedicine, cardiac catheterization, and tele-consultation for congenital heart disease where terrestrial data transmission were combined with satellite communications [15].
- The University of Hawaii worked with Georgetown University Medical Center and Tripler Army Medical Center using HDR terminals from February 1997 through January 1998 to improve radiological techniques in fighting prostate cancer. The technique combined distributed high speed computing to allow 3-D volume rendering of radiation therapy planning images for treatments. While the bandwidth needed for this is about 300 Mbps, OC-3 rates were determined adequate. Background on the application can be found at [16].
- NASA GRC in cooperation with the University of Virginia, the Cleveland Clinic, and the Ashtabula County Medical Center in northeast Ohio utilized T1VSATs beginning in the autumn of 1998 to demonstrate satellite transmission of mammography images. Using image compression, TCP/IP protocols, and multicasting transmission techniques, improved mammography imagery distribution between rural areas and major medical centers was achieved [17]. This activity is being reported at this conference [18].
- Expanding the classroom to areas around the globe can enhance a student's schooling experience as well as enlighten the student with experiences that would be difficult to obtain otherwise. Two primary activities utilized different aspects of ACTS technologies for bringing interactive sessions with scientists from remote locations to grade school classes. The first activity, called "Live from Antarctic-2" was a revisit to Palmer Station, Antarctica in early 1997 by the Passport to Knowledge group, but this time with an ACTS terminal. The station utilized the hardware from the Jet Propulsion Laboratory's ACTS Broadband Mobile Terminal but with a fixed 1.2-m reflector set-up as a fixed station. A half-rate T1 link (512 Mbps) provided live video and audio over the ACTS bent-pipe mode which was the highest speed link achieved by this group from such a remote location. The second activity was also coordinated by Passport to Knowledge about one year after the first in 1998 and was called "Live from the Rainforest." The experiment used a T1VSAT set-up in the jungle of Amazonia, Brazil. Using only a 1.2-m dish, a full T1 rate was achieved with the ACTS digital baseband processor that provided for high quality video during the live broadcasts, as well as a data link for internet access and large file transfers back to the US. This activity is being reported at this conference [19].
- The detection and rapid response to major accidents or other emergency incidents is a problem in most of the world and is compounded in rural areas where detection and response can be very slow. Southwest Research Institute's (SwRI, in San Antonio, Texas) SatLink project is helping to resolve these problems by investigating using advanced satellite communications to improve communications to emergency vehicles. The ultimate goal is to automatically obtain and maintain satellite connectivity in both a mobile and static environment for remote emergency management and control. A demonstration of this occurred in September 1999 in Scottsdale, Arizona; however, limited funding prevented a complete analysis [20].



5.3 Telescience

Science can benefit from satellite communications in ways such as where an observing station has limited accessibility (e.g., large telescopes and remote areas), or interconnectivity between dispersed data sets and

computing facilities is needed (e.g., global weather modeling). For example, with remote observing, all members of large consortiums can participate in obtaining the data. One part of the team can focus on obtaining the observations while another part can be analyzing the scientific results from the last observation. Two experiments were sponsored by NASA's High Performance Computing and Communications (HPCC) program that involved remote science applications with ACTS.

- The first activity supported tele-astronomy from from the 10-m Keck II Observatory on Mauna Kea in Hawaii. The observatory was linked by a fiber ATM network to the HDR terminal located at the Tripler Army Medical Center on Hawaii. The 155 Mbps link to another HDR terminal at JPL in Pasadena, CA provided bandwidth not terrestrially available to Hawaii, from May 1996 through September 1997. While being an ideal real-world application for experimenting with high-speed satellite networking, concerns were expressed with the adequacy of TCP/IP being used over the HDR wide bandwidth, long-delay networks [21].
- The second activity utilized HDR terminals to connect super computing sites at NASA Goddard Space Flight Center and JPL to develop global climate modeling techniques. The experiment took place from March 1996 through January 1997. An important part of this was to extend the network to other supercomputer centers that are on the National Research and Education Network (NREN) and the HPCC terrestrial networks. Background information can be found at [22].
- A demonstration also was done in June 1999 by the Canadian Research Centre using the US Air Force Research Laboratory's Ka-band suitcase terminal at a remote Arctic location called the Houghton Mars Project. The Ka-band link provided a half T1 rate link (512 kbps) which was about 10 times greater than the highest offering from commercial sources [23].

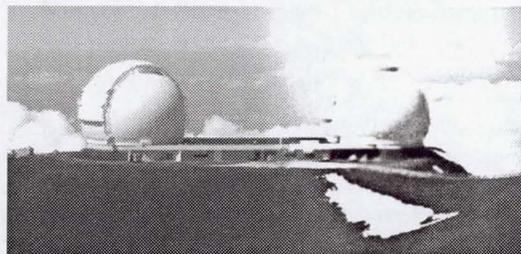
These experiments clearly suggest that future commercial wideband satellites may provide the reliability and affordability necessary for long distance science while enabling greater collaboration in the process.

5.4 Broadband Network Interoperability and Protocol Verification

While terrestrial networks will likely be adequate for major population centers, satellites will be a primary provider of access to anybody in rural areas and networks not yet interconnected. To ensure that total interoperability is preserved between terrestrial and space-based solutions, the protocols used must be verified and modified to ensure ubiquitous usage regardless of the transmission path.

- Ohio University led a series of experiments over ACTS using TIVSATs that investigated hypertext transmission protocol (HTTP) and web browsing performance over satellite links and ways to improve transmissions. A traffic generator was developed based on real firewall traffic. Technical objectives included web-based traffic generation and scaling; internet-like delay scenarios; modified error control; protocol performance and strategy evaluation; and station coding comparisons. This activity is being reported at this conference [24].

- The development of small terminals and using them for space protocol verification has been of prime interest to the Air Force Research Laboratory in Rome, NY. The early work in the summer of 1997 developing a suitcase terminal evolved into an even smaller 44-cm briefcase terminal capable of supporting 500 kbps links. Working with the Canadian Research Centre, the experiment conducted terminal characterization and a variety of demonstrations over ACTS including some during military exercises [25]. Activity is planned through the end of the ACTS Experiments Program.



- Protocol verification has been of great importance to the Naval Research Laboratory. An activity in the fall of 1998 involved a link to a ship in Lake Michigan. It demonstrated unparalleled data rate transmission at 45 megabits per second (Mbps) using TCP/IP between a moving vessel at sea and a fixed-earth station [26]. NRL also participated in the industry/government consortium experiment investigating high speed transfers and platform interoperability over ACTS, and then developed its own experiment plan utilizing USATs in the spring of 2000. The experiment is to investigate high speed transfer to/from remote network nodes and simultaneous applications using the internet and world wide web access, TCP/IP based file transfers, and interactive and variable TCP/IP based multi-media production video. Results of the work being completed in 2000 are forth coming.

- An experiment by an industry/government consortium evaluated the performance of TCP/IP, SONET, and ATM over satellites at high speed transfers and over various computer platforms (experiment #118x, [27]). Its success prompted a follow-on experiment (experiment #154) that involves many of the same participants in the team and is building on the results of 118x. This latest activity is investigating large windows, fast-retransmit, fast recovery, selective acknowledgement, congestion, and error detection/correction. The collective work from

both of these experiments is being reported at this conference [28]. Results of the work being completed in 2000 are forth coming.

- The available bandwidth and significantly smaller earth stations at Ka-band make it potentially viable for mobile communications. Carnegie Mellon University (CMU) investigated the interoperability of satellite communications with a wireless local area network and the modifications needed to Mobile IP for operation in a long delay path to transfer a message from one node to another. Asymmetric links of 6 Mbps Tx/45 Mbps Rx between a USAT at CMU and NASA GRC were used. It was shown that mobile IP could be improved to eliminate packet drops during handoffs thereby eliminating unnecessary transmissions [29].
- After an earlier experiment on ACTS centered about measurement standards over satellite links, the National Telecommunications and Information Agency's (NTIA) Institute for Telecommunications Science (ITS) performed a follow-on experiment using a T1VSAT in late 1995 to early 1996 that incorporated ISDN with national security and emergency preparedness communications [30].
- A brief experiment by NASA GRC investigated ATM/TCP capabilities over high-bandwidth satellites utilizing the Link Evaluation Terminal in Cleveland, OH. However, the PI changed jobs and the experiment did not reach conclusion.
- California State University - Hayward used a High Data Rate terminal in an experiment that began in late 1999 and is planned through the end of the Experiments Program in May 2000. The experiment will explore and prototype a unique integrated infrastructure using the Internet, optical, and multi-media satellite communications. Results of the work being completed in 2000 are forth coming.
- A small consulting firm in Cleveland, ACT Corporation, performed a Web browser test to evaluate the retrieval of Web pages over a geosynchronous satellite with and without satellite optimized protocols in April 2000. For the case of satellite optimized protocols, software (SatBooster) by Flash Networks was incorporated. Results of the work being completed in 2000 are forth coming.

6.0 Conclusion

The ACTS Experiments Program, while initially conceived as only a 2-year program, evolved into a nearly 7-year program that involved a broad variety of organizations from industry, academia and government. The mix of principal investigator organizations, selected experiments and satellite usage were presented with the change in the mix between the first period of experiments ('94-'95) and the second ('96-'00). Many of the experiments were applications-focused as opposed to being technology verification or propagation focused. For the application experiments, four areas were identified: 1) business development and service improvement; 2) health, education and public wellness; 3) telescience; and 4) broadband network interoperability and protocol verification. Their results impacted the specific fields and application areas, but also demonstrated the flexibility and advantages of Ka-band systems in smaller terminals with higher throughput rates that will become commercially available with the next generation of wideband communications satellite systems under development. The experiments provided the technical implementers with a real-world testbed to resolve the technical issues in networking high-speed Ka-band satellites with terrestrial networks. The experiments also demonstrated the effectiveness of resolving technology gaps through collaborative teams comprising organizations from government, industry and academia.

Within the ACTS Project, continued interest has been expressed in using ACTS after the May 31, 2000 conclusion of the Experiments Program. This interest indicates that a commercial follow-on to ACTS as the next generation of Ka-band satellites should be well received. But for now, it is so long to this reliable partner! Those experimenters whose appetites for wideband satellite communications were whetted with ACTS are eagerly awaiting undoubtedly the initiation of a commercially available Ka-band wideband system.

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3.2 - NASA/DARPA ACTS Project for Evaluation of Telemedicine Outreach Using Next-Generation Communications Satellite Technology: Mayo Clinic Participation

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Objective

To describe the development of telemedicine capabilities – application of remote consultation and diagnostic techniques – and to evaluate the feasibility and practicality of such clinical outreach to rural and underserved communities with limited telecommunications infrastructures.

Material and Methods

In 1992, Mayo Foundation (Rochester, Minnesota; Jacksonville, Florida; and Scottsdale, Arizona), the National Aeronautics and Space Administration (NASA), and the Defense Advanced Research Projects Agency (DARPA) collaborated to create a complex network of fiberoptic landlines, video recording systems, satellite terminals, and specially developed data translators linking Mayo sites with other locations in the continental United States on an on-demand basis. The purpose was to transmit data via the asynchronous transfer mode (ATM) digital communications protocol over the Advanced Communications Technology Satellite (ACTS). The links were intended to provide a conduit for transmission of data for patient-specific consultations between physicians, evaluation of medical imagery, and medical education for clinical staffs at remote sites.

Results

Low-data-rate (LDR) experiments went live late in 1993, Mayo Clinic Rochester successfully provided medical consultation and services to two small regional medical facilities. High-data-rate (HDR) experiments included studies or remote digital echocardiography, store-and-forward telemedicine, cardiac catheterization, and tele-consultation for congenital heart disease. These studies combined landline data transmission with use of the satellite. The complexity of the routing paths and network components, immaturity of available software, and inexperience with existing telecommunications caused significant study delays.

Conclusions

These experiments demonstrated that next-generation satellite technology can provide batch and real-time imagery for telemedicine. The first-generation ATM and satellite network technology used in these experiments created several technical problems and inconveniences that should be overcome as the network infrastructure matures.

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3.3 - ACTS Satellite Telemammography Network Experiments

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Abstract

The Satellite Networks and Architectures Branch of NASA's Glenn Research Center has developed and demonstrated several advanced satellite communications technologies through the Advanced Communications Technology Satellite (ACTS) program. One of these technologies is the implementation of a Satellite Telemammography Network (STN) encompassing NASA Glenn, the Cleveland Clinic Foundation, the University of Virginia, and the Ashtabula County Medical Center.

This paper will present a look at the STN from its beginnings to the impact it may have on future telemedicine applications. Results obtained using the experimental ACTS satellite demonstrate the feasibility of Satellite Telemammography. These results have improved teleradiology processes and mammography image manipulation, and enabled advances in remote screening methodologies. Future implementation of satellite telemammography using next generation commercial satellite networks will be explored.

In addition, the technical aspects of the project will be discussed; in particular how the project has evolved from using NASA developed hardware and software to commercial off the shelf (COTS) products. Development of asymmetrical link technologies was an outcome of this work. Improvements in the display of digital mammographic images, better understanding of end-to-end system requirements, and advances in radiological image compression were achieved as a result of the research.

Finally, rigorous clinical medical studies are required for new technologies such as digital satellite telemammography to gain acceptance in the medical establishment. These experiments produced data that were useful in two key medical studies that addressed the diagnostic accuracy of compressed satellite transmitted digital mammography images. The results of these studies will also be discussed.

Introduction

Radiology and more specifically, mammography, require the services of trained experts or radiologists. In order to support these specialists, a reasonably large patient base is required. Therefore, most specialists are located in large medical institutions. To add to this, the Food and Drug Administration (FDA) requires that radiologists perform a minimum number of readings annually to remain certified. In fact, every site performing mammography in the United States must now be accredited by a nationally based accreditation program or by a state agency¹. As a result, a large amount of diagnostic images are either shipped to a larger medical facility for review or are held for review by a roaming radiologist.

Teleradiology, the electronic transmission of digitized images, addresses the issues stated above. Radiologists would be certain to maintain their quota by reading additional images sent electronically; electronic transmission eliminates the need for the traveling radiologist. A significant benefit is the availability of improved healthcare to remote, rural and underserved areas where the population is insufficient to support medical specialists.

Breast cancer is the leading cause of death for women from 35 to 50 years of age in the United States². Each year sees an increase in the number of women who enter the age range for which a mammography screening is

recommended. This, coupled with the millions of women who live great distances from mammography interpretation centers, makes telemammography a practical and viable option, and of great importance to study within satellite telemedicine. Also, telemammography is the most challenging subset of teleradiology due to the very high image resolution required, resulting in very large data files to be transmitted. Hence, techniques developed in this study can be easily applied to the less challenging types of teleradiology.

To achieve the needed advances in satellite telemammography, a simple project goal was established: To develop and demonstrate techniques allowing the transmission of a complete set of mammography images for a typical breast cancer screening (4 images) over a basic DS1 rate (1.544 Mbps) satellite link in one minute or less.

Approach

The University of Virginia was in the forefront of teleradiology in the early 1990s. At that time, however, much of the telecommunications was performed over Plain Old Telephone Service (POTS) with transmission rates limited to 9.6kbps, requiring hours for the transmission of a mammography image set.

The mid-90s brought digital communications at DS1 to a more affordable level. That decade also produced a new generation of satellites and communication technologies. The NASA Advanced Communication Technology Satellite (ACTS) was the first to incorporate this digital technology on board the spacecraft³. In particular, it demonstrated data rates up to 622Mbps by taking advantage of the 30/20GHz Ka Frequency Band. The higher frequency band also provided for savings in another area, physical space. Essentially, the Ka-band antenna can be one-half the size of a Ku-band antenna and obtain the same antenna gain, enabling the placement of small, inexpensive satellite earth stations at small remote clinics and on mobile medical vehicles.

The Internet was in its infancy in the mid-90s. Routing and switching equipment was costly and in very limited deployment. Therefore, the first phase of the Satellite Telemammography Network (STN) experiments used "routers" that were developed in-house by the Satellite Networks and Architectures Branch. These black boxes acted as a data buffer between the high-speed serial interfaces of the UNIX workstations and the T1 cards of the ACTS Earth Stations. Application specific software was developed to control these black boxes and ultimately transmit and receive the mammography images. This allowed seamless and continuous data flow, although without error detection/correction.

As the Internet evolved, routers became more readily and economically available as commercial off the shelf (COTS) products. The black boxes were replaced with Cisco 2501 routers in Phase II of the STN. The NASA-developed application specific software was replaced by a Transmission Control Protocol/Internet Protocol (TCP/IP) file transfer application, FTP (File Transfer Protocol). This allows interoperability of the satellite link with terrestrial networks, including Internet based networks and medical campus local area networks (sometimes known as Picture Archiving and Communications Systems, or PACS) which operate using TCP/IP protocols. The Phase II experimental setup is illustrated in Figure 1.

Throughout both phases of STN, major accomplishments were achieved. Phase I saw the simultaneous transmission via ACTS of over 5000 digitized mammograms to both the University of Virginia and the Cleveland Clinic Foundation, all of which were received free of data errors. Phase II was highlighted by the first ever real-time compression and transmission via ACTS of a four-view mammography case, including real-time interpretation by a Cleveland Clinic radiologist, and the subsequent diagnosis relayed back to the sending station.

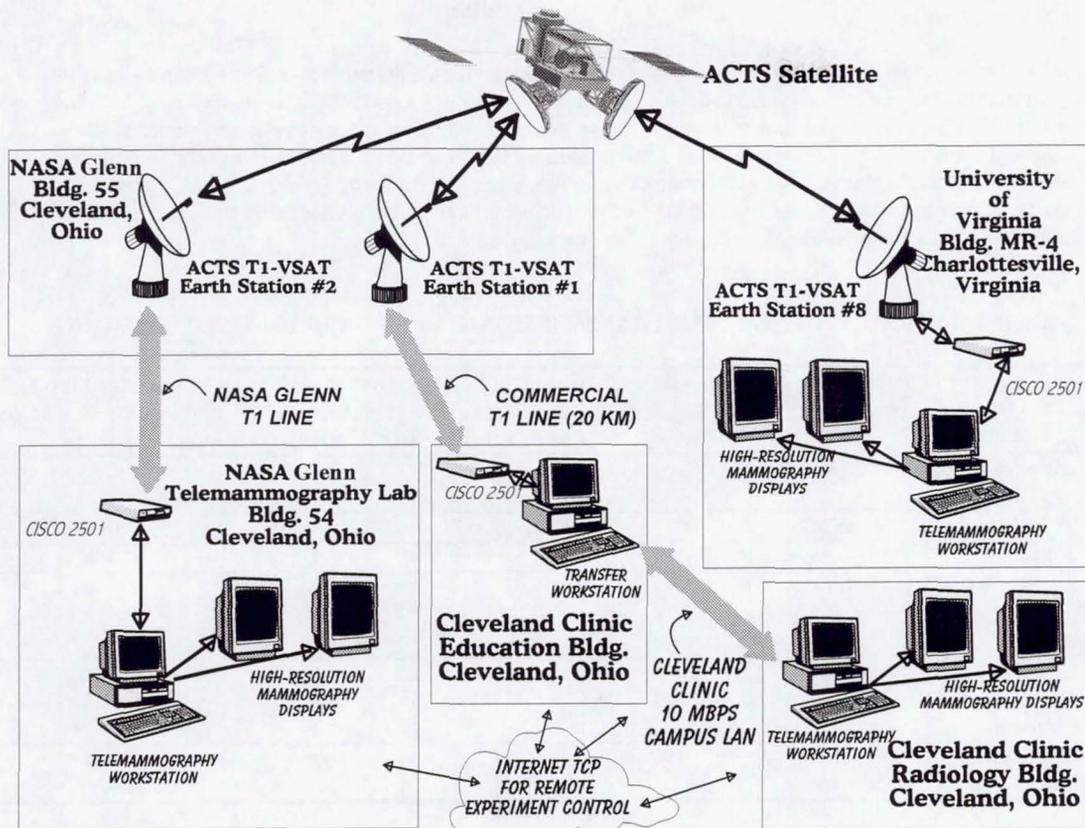


Figure 1. PHASE II CONFIGURATION OF THE SATELLITE TELEMAMMOGRAPHY NETWORK EXPERIMENT

Role of Telemedicine

This highlight strengthened the commitment of the medical community to expand the use of telemedicine. With the proliferation of major hospitals building and purchasing remote medical locations, the need to centralize certain services is obvious. Without centralization, the specialized professional would always be mobile, traveling to and from several locations. Not only are the services of these specialists lost while they are in transit, the medical institution typically compensates for the travel expenses. Through telemedicine the time of these specialists can be better utilized. In fact, some larger hospitals are now selling radiology services to smaller medical establishments through teleradiology.

In sparsely populated areas of the country or world, having a roaming specialist is impractical. Satellite-based telemedicine enables the provision of specialized services with easily installed connectivity where the terrestrial infrastructure is inadequate or non-existent.

However, the benefit of telemedicine is limited by the ability to quickly move large amounts of data. If the time to transmit and receive the data is greater than the time to travel to the remote location and perform the procedure, and results in high telecommunications costs, there is no advantage. Therefore, it is imperative that transmission times for various types of diagnostic imaging over various data links be examined. Table 1 outlines this information. From the table, it can be seen that medical imagery is data intensive. Transmitting any of these types of image modalities over a 56kbps modem is impractical. Even at DS1 data rates, some of the transmission times become excessive.

Image Compression

Image compression is an approach to overcome this obstacle. With a STN project goal to transmit a case (4 images) in less than one minute at DS1, compression ratios between 4:1 and 20:1 were necessary. Much has been written in the past decade about various forms of compression. One of the more recent publications illustrates the advantages of using a wavelet compression for digitized mammography images⁴. Therefore, a commercially available wavelet compression package, AccuPress for Radiology (Aware, Inc., Bedford, Massachusetts) was chosen for testing in this project to achieve faster telemammography transmission times. The impact of image compression on diagnostic accuracy is discussed below.

Table 1. TYPICAL FILE SIZE AND TRANSMISSION TIMES FOR DIAGNOSTIC IMAGING

Image Type	Images per case/study	Total data required (Mbytes)	Time to transmit at 56 kbps, mins.	Time to transmit at DS1, mins.	Compression ratio required for <1 min. to transmit at DS1
Plain film x-ray	2 to 6	8 to 84	19 to 200	0.7 to 7.3	8:1
CT, MR	20 to 300	5 to 150	12 to 357	0.4 to 12.9	16:1
Ultrasound	300 frames	40	95	3.5	4:1
Mammography digitized film, 100 microns	4	24	57	2.1	4:1
Mammography digitized film, 50 microns	4	96	228	8.3	12:1
Mammography direct digital	4	192	457	16.6	20:1

Compression Studies

Before the medical community will accept compression of mammographic images, clinical evaluations comparing compressed images to standard film are needed. One of the successful medical studies performed by the Cleveland Clinic Foundation (CCF) as a part of this project is described in a paper entitled "Clinical Evaluation of Wavelet-Compressed Digitized Film Mammography⁵." In this study, sixty sets of mammograms were digitized at a spatial resolution of 100 μm . The images were compressed at 8:1 using a wavelet algorithm. Several mammographers reviewed the images in comparison with the original films in a controlled study. The study revealed that the mammographers' mean diagnostic accuracy using compressed images and films was 0.832 and 0.860, respectively. In other words, the ability of a mammographer to obtain the correct clinical result using compressed images and films were similar.

The success of the CCF Study on compressed images versus film, led to a study by the Ohio State University (OSU) to investigate the optimum wavelets for application to mammography. This work is still in progress. This study is examining orthogonal wavelets from Haar, Daubechies, Coffiman, and Belykin as well as several biorthogonal wavelets. The results from this work are to be completed shortly, to be followed by a clinical evaluation by the CCF.

An additional study⁶ performed at the NASA Glenn Research Center showed that if the wavelet is tuned specifically for mammography, greater compression ratios are possible. In this effort it was found that by using a biorthogonal wavelet as opposed to the Daubechies order 3 wavelet used in the AccuPress software, a compression ratio of 34:1 was possible. This has not yet been clinically evaluated.

Asymmetric Links

In addition to compression, another area of interest to telemedicine is in asymmetric links. While data flow through the satellite link transmitting images may be quite high, the return data link may consist of only requests for images, data acknowledgements, and return of diagnoses, resulting in a highly asymmetric link. This problem can be addressed by a technique known as Unidirectional Link Routing (UDLR). The NASA Glenn

Research Center in cooperation with Cisco Systems has been experimenting with this type of network architecture. Cisco Systems has modified some of the layer 2 and layer 3 code in its router Internetworking Operating System (IOS) software. UDLR provides a method for receiving data over a simplex high bandwidth satellite link and returning the data over a terrestrial (and possibly a lower bandwidth) network. This technology has been used successfully in the STN to distribute mammograms to several locations simultaneously.

Impact of Project

The STN project has produced results that have significantly improved satellite teleradiology processes. The demonstration of most of the end-to-end satellite tele mammography process (including image compression, satellite transmission and reception, decompression, image display and evaluation, and return of diagnostic result) performed within five minutes validates the utility of satellite-based teleradiology. Adding the step of image digitization at the front end of this process will be attempted before the completion of the ACTS Experiments Program. The first step of the process, the initial image capture, will not be attempted due to the logistic difficulties in having real patients participate. However, it is a physically disconnected step that can be added to the process without difficulty.

The teleradiology process developed and demonstrated by STN can also be adapted to the new direct digital imaging equipment which is being introduced. The direct digital image capture will eliminate the steps of film developing and digitizing and make the satellite teleradiology process faster and simpler.

The Cleveland Clinic Foundation (CCF) has begun shifting its radiology processes from film-based to all digital image-based. CCF is also actively marketing radiology services to other medical establishments, emphasizing the availability of its world class diagnostic radiologists in an easy and cost-effective way through teleradiology. These initiatives result in part from the successful technology developments and demonstrations of the STN.

The development and demonstration of asymmetrical link technology over satellite links was a significant outcome of the STN experiments. Use of asymmetrical links will lower the overall cost of operating satellite-based telemedicine links by allowing the minimal use of satellite resources, resulting in minimum access charges. STN has shown that asymmetrical satellite links can be integrated into common Internet and PACS networks using TCP/IP through standard commercial routing equipment. This integration demonstrates the seamless interoperability potential of satellite links within digital telemedicine networks.

Next Generation Satellite Systems

In the next few years, several regional and global satellite networks plan to be in operation (see Table 2). Conservative estimates suggest that nearly 500 broadband satellites will be operational in the next 10 years⁷. Many of these proposed systems encompass the technologies of ACTS. Some of the technologies that are obvious spin-offs from ACTS are the use of multiple spot beams, on board processing, and the use of the Ka frequency band. Most of the proposed systems plan to offer services at DS1 or fractional DS1 rates. The STN experiment has shown that these types of systems will be adequate for effective satellite tele mammography and teleradiology.

As the number of satellites in service increase in the coming years, costs for satellite services will be driven down. Although it is probably too early to predict actual costs, various publications have projected costs of earth stations to be under \$2000 and DS1 service to be under \$2 per minute. This compares favorably with a dedicated terrestrial T1 line and can actually be more cost effective when considering that satellite services only charge for time used. The STN experiment shows that costs of electronic transmission of radiology images over satellite will be lower than courier-based transportation of radiology films, which is in widespread use today.

Table 2. PROPOSED SATELLITE CONSTELLATIONS

System	Proposer	Orbit	No. of Satellites, Coverage	No. of Antenna Beams	On-board switching/processing	Service Data Rates
Astrolink	Lockheed-Martin	GEO	9, Global	96	Yes	.25DS1
Ka-Star	Ka-Star Communications	GEO	1, Regional	52	Yes	.25DS1 to DS1
OrbLink	Orbital Sciences Corp.	MEO	7, Global	100	Yes	DS1 to DS3
SkyBridge	Alcatel	LEO	64, Global	45	N/a	E1
Spaceway	Hughes Communications	GEO	20, Global	24	Yes	DS1 to DS3
Teledesic	Teledesic Corp.	LEO	288, Global	64	Yes	DS1 to E1
V-Stream	PanAmSat	GEO	2, Regional	12	Yes	56 Kbps to DS3
WEST	Matra Marconi	GEO/MEO	11, Global	N/a	N/a	STS-3

Notes: DS1 is 1.544 Mbps; DS3 is 44.736Mbps; E1 is 2.048 Mbps; STS-3 is 155.520 Mbps; N/a is not presently publicly available.

Satellites and Telemedicine

In the early 90's there was concern about the performance of TCP/IP over satellite links. There was much discussion about the latency of the satellite link and the effect this would have on TCP/IP. As it turned out, there were many reasons for this misconception – out of date implementations, improperly configured TCPs, and poor testing techniques⁸. A simple upgrade to a newer implementation can improve the data rate significantly. However, the STN has demonstrated that even with current technology the performance of TCP/IP over satellite is adequate for teleradiology.

The integration of satellite-based teleradiology with currently available PACS and other telemedicine and medical information networks is beyond the scope of the STN project. But based on the technical demonstration of TCP/IP based interconnectivity of satellite links, this integration should be relatively easy to accomplish. The end-to-end teleradiology process, the majority of which has been demonstrated during the STN project, will be an easy to use process once fully commercially developed. Assuming small, inexpensive and easily installed earth stations providing DS1 service through the new generation of communications satellites, connecting remote medical facilities to large urban medical centers for teleradiology services will be easily realizable.

However, of particular interest to the medical community is the addition of the Digital Imaging and Communications in Medicine (DICOM 3.0) standard to satellite communication links. Since data transmission using DICOM depends upon the TCP/IP protocol, problems encountered by TCP/IP and satellite links will affect DICOM performance. This is of particular concern in cases where DICOM database queries require multiple question and answer transmissions between the database and the requester. Hence, the performance of DICOM over satellite must be examined before complete integration of a hybrid network with a medical LAN is considered complete.

Growth of Telemedicine

There is little doubt that telemedicine is a growing field and that satellite-based telemedicine is in its infancy. The STN has brought to the forefront many of these technologies to the medical community. This was achieved through studies published in medical journals and through general articles written in medical oriented magazines⁹. It was probably never more evident than in the many conversations that were a part of the STN exhibit at the Radiological Society of North America's (RSNA) annual conferences in 1997 and 1998. It was there that the project presented an awareness of satellite technology to thousands from across the globe; it was there that numerous parties expressed a genuine interest in satellite-based telemedicine.

The awareness of the role satellites must play in telemedicine is apparent by the inquiries the STN project has received from outside sources. The STN project has interfaced with personnel from abroad, in particular,

Telespazio in their efforts to provide telemedicine in Italy. STN personnel have also participated in radio interviews and television broadcasts have aired on the subject¹⁰.

Importance of ACTS

The ACTS satellite represents the first of a new generation of commercial communications satellites and satellite services. As such, it was the ideal and necessary platform for the STN experiments, which have brought satellite teleradiology technologies and methodologies in line with the next satellite generation. In particular, ACTS provided a demonstration platform for high-gain spot beams enabling high-quality DS1 rate satellite links through very small earth stations. These qualities, enhanced through the use of Ka-band frequencies and on-board processing for improved link error performance, were essential to the development and demonstration of satellite-based teleradiology.

Summary

The Satellite Telemammography Network Experiment has proved the feasibility of satellite-based teleradiology and telemammography through experiments performed with NASA's Advanced Communications Technology Satellite. The availability of high quality specialized medical expertise to nearly every remote location, nationally and globally, and the potential to reduce costs for radiological services, can be achieved with the deployment of the next generation of commercial communications satellites and the commercial offering of integrated telemedicine systems.

The STN has achieved significant advances in satellite-based teleradiology and telemammography, including: improved teleradiology processes; application of image compression to medical imaging resulting in faster transmission and lower costs; use of TCP/IP protocols in satellite-based teleradiology, enabling integration of satellite-based telemedicine with TCP/IP-based Internet and medical campus LANs; and demonstration of asymmetrical satellite teleradiology links using commercial network routers, allowing more efficient and lower cost connectivity.

Acknowledgements

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In addition, over the years several others have contributed their knowledge and time to the STN Project. They are Paul G. Mallasch, Quang Tran, Diepchi T. Tran, Gerald J. Chomos, and Duc H. Ngo of the NASA Glenn Research Center, Communications Technology Division. The authors gratefully acknowledge their dedicated efforts.

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3.4 - Satellites and the Internet as a "Passport To Knowledge" A New Model of Teaching and Learning

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Abstract

While business and government research agencies have begun to take full advantage of the Information Age, many secondary schools (at least in the United States) continue to operate on a "19th century model" of teaching and learning. Science education often relies on textbooks and "lab." (hands-on) projects that are implemented without real world context. From 1995-1998 PASSPORT TO KNOWLEDGE (P2K) worked with NASA's ACTS satellite project on 3 interactive learning adventures and effectively demonstrated that a new model of science education is practical and effective. Project evaluation by a nationally-recognized education research group provided convincing evidence of increased mastery by students of factual content, improved attitudes towards science and high technology, and useful practice in the research skills needed in the world of 21st century work beyond school.

Examples of video and other content, together with a review of statistically-meaningful results, are provided from all 3 P2K Modules that used ACTS: LIVE FROM THE STRATOSPHERE (1995), LIVE FROM ANTARCTICA 2 (1997) and LIVE FROM THE RAINFOREST (1998.) Each project relied on a technical "first" only possible at that time through the use of ACTS. These included the first live video from a plane in flight at 41,000 feet (NASA's Kuiper Airborne Observatory carrying an infrared telescope); the first-ever video interaction from America's Palmer Station off the Antarctic Peninsula; and the first interactive video broadcast from the heart of the Amazon rainforest. The results, however, were much more than purely technical achievements: P2K, utilizing the full duplex communications possibilities enabled by ACTS, was able to structure educationally meaningful interactions and experiences involving not just satellite television, but also Internet based opportunities. ACTS also provided invaluable project coordination between home base and the remote sites. P2K has continued with LIVE FROM THE SUN and LIVE FROM THE STORM, incorporating the lessons of the earlier projects, while utilizing new technologies such as streaming video as they emerge.

1. Introduction And Overview

In 19th century Europe, the so-called "Grand Tour" was considered an essential component of an education appropriate for the aristocrats who would soon lead their nations. Sons (and it was then, of course, mainly males) of rich families would travel the Continent accompanied by knowledgeable tutors to sample the culture and life style of the Renaissance and the Enlightenment at the actual locations in Italy and Germany where the artistic or scientific breakthroughs of Raphael and Michelangelo, Leonardo and Galileo, had occurred.

In the late 20th century satellite communications and the Internet have been able to provide hundreds of thousands of students across America and around the world with access to sites and sights formerly the preserve of the privileged few, taking them—virtually—to scientific frontiers such as the Antarctic or the Amazon. Accompanying the students as guides and virtual "tutors" were some of the world's leading researchers who served as online and on-camera mentors. Instead of paintings and fine arts, students could explore penguin habitats, encounter the birds and insects of the rainforest, or see and hear what astronomers actually do during flights aboard an airborne observatory.

This profoundly democratic revolution in educational opportunities is likely to expand still more in the early decades of the new Millennium and to appeal to "lifelong learners" in homes and libraries, and not just to students in school. From 1995-1998, in 3 separate pilot projects, NASA's ACTS satellite program was instrumental in proving the feasibility of these revolutionary opportunities and in making the possibilities clear to policy-makers as well as students, teachers and parents. The audio and video opportunities afforded by ACTS

prefigure the future of broadband multimedia using the next generation Internet and new software. ACTS helped make the future of educational telecommunications come to life today. This paper details the technical infrastructures employed, the unique interactive opportunities enabled, and the real learning that resulted.

Multiple partners were involved in all three "Modules" described here, principally NASA and NSF and the research centers and individuals supported by the two agencies. Lead in organizing each project was PASSPORT TO KNOWLEDGE (P2K), headed by Geoff Haines-Stiles and Erna Akuginow. Haines-Stiles was Senior Producer and Series Director on Carl Sagan's Emmy-winning COSMOS series, which has now been seen by some 600 million people around the world. Akuginow was formerly a producer/director for CBS Television in news and documentaries. Together they developed and coordinated far-flung teams of producers, cinematographers, online content experts, educational researchers and many more skilled artists and craftspeople to develop, produce and distribute interactive learning experiences known as "electronic field trips." P2K's mission was, and remains, to excite students (primarily middle schoolers, ages 11-14, but also with many upper elementary [ages 8-10] and high schoolers [ages 15-16] participating) about science and the research process. P2K also connects students with researchers who serve both as sources of up-to-date information, and role models for careers in science and high technology.

P2K prototyped and continues to use a unique combination of video, online and hands-on media to bring the remote locations to life, as summarized in the slogan "100% video... 100% hands-on... 100% online" meaning that P2K regards each medium as equally important but that each is used for what it can best contribute to the overall learning experience. Each project includes:

- 1) live satellite television broadcasts, distributed via non-commercial, educational public television and direct to schools and networks equipped with the appropriate downlink equipment. Videotapes are also distributed via multiple channels.
- 2) hands-on activities appearing in printed Teacher's Guides and online, accompanied by worksheets and posters to provide educators with a "turnkey" package to support them in implementing topics on which they may not have received formal or current training. The Guides correlate all activities to key science content suggested in the National Science Education Standards developed by the National Academy of Sciences and the AAAS/Project 2061 "Benchmarks."
- 3) online resources, including both e-mail and WWW, which provide extensive background information, the opportunity for interaction with the researchers, and also support distributed communities of both teachers and students.

Each of the three "Modules" (the name P2K gives to the package of integrated media) discussed in this paper differs in detail, but all relied critically on ACTS, which was itself operated in several different configurations. The dedicated and skilled researchers and engineers from the ACTS project teams at NASA Lewis (now the Glenn Research Center) and the NASA/Caltech Jet Propulsion Laboratory pushed the communications envelope, taking the ACTS satellite and its ground stations literally to "extremes."

In LIVE FROM THE STRATOSPHERE JPL's mobile antenna facilitated the first-ever 2-way video interactions to and from a jet airplane in flight high in the stratosphere during actual scientific observations. During LIVE FROM ANTARCTICA 2 the ACTS uplink dish was situated as far south as it could possibly be and still successfully transmit to the satellite. In LIVE FROM THE RAINFOREST temperatures and humidity were both higher than in any other deployment or test. Through all 3 projects the ACTS teams and P2K worked closely and collegially with each other to identify and resolve complex technical and logistical issues. (Individual acknowledgements for exceptional cooperation appear at the end of this paper.)

2. Live From The Stratosphere

During the initial pilot P2K project known as LIVE FROM OTHER WORLDS (LFOV), which used a dedicated NASA-NSF satellite link from Antarctica to NASA Ames, P2K was approached by the Airborne Astronomy group and networking engineers at Ames about the possibility of incorporating an educational activity within an ACTS project that was to use JPL's mobile terminal aboard the Kuiper Airborne Observatory (KAO), a converted C-141A jet with an infrared telescope pointing through a port on its side. The steerable antenna—the Broadband Aeronautical Terminal custom-built by JPL—automatically tracks ACTS, making it possible to transmit full duplex video, audio, and data between the ground and an aircraft flying anywhere in the Western hemisphere.

The ACTS activity had originally been designed to support in-flight diagnostics of the telescope and other instrument problems, as well as to allow "remote" observers to control the telescope and downlink data. Building on the positive response of teachers and students, and NASA management to LFOV and LIVE FROM ANTARCTICA, LIVE FROM THE STRATOSPHERE was born. (The communications network developed to support LFS appears in figure 1.)

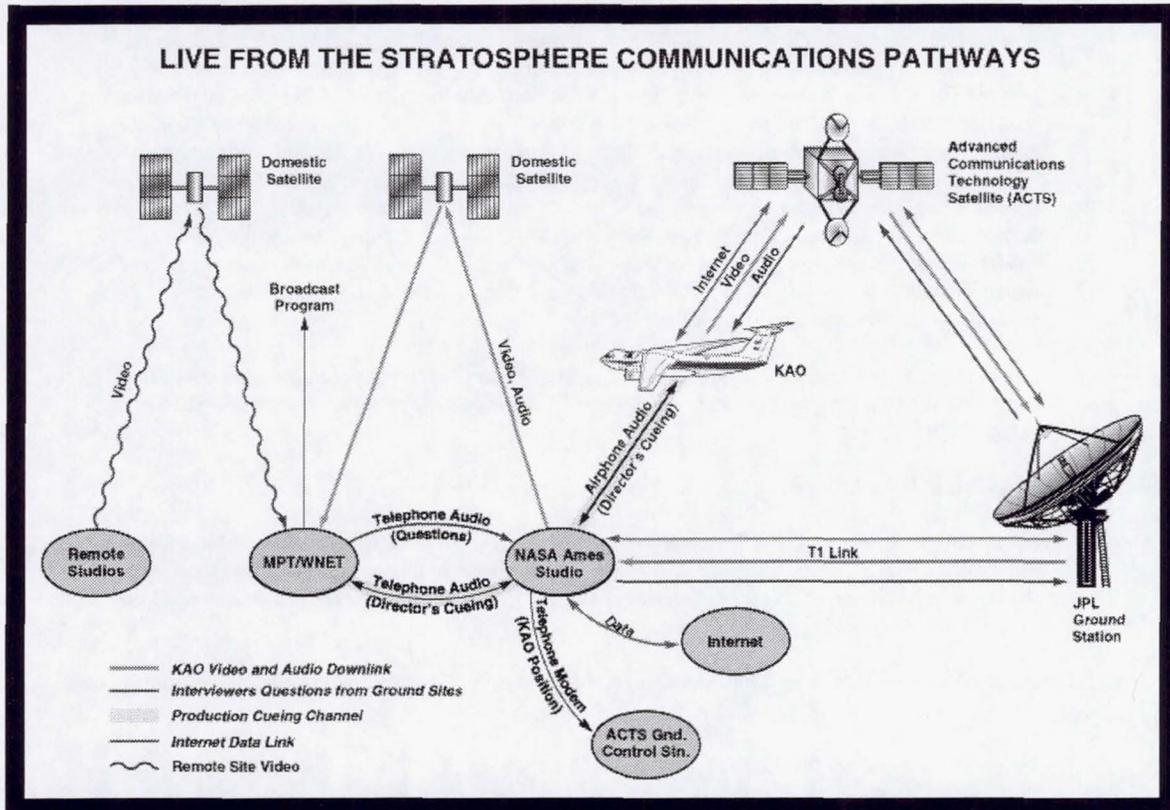


Figure 1. VIDEO AND AUDIO CONNECTIONS SUPPORTING LIVE FROM THE STRATOSPHERE (COURTESY NASA QUEST)

As plans matured it was realized that this was to be the KAO's last research season, after a career which included breakthrough observations of the heart of the Milky Way, close-up views of Supernova 1987a, the measurement of water on Mars, studies of the heat emitted by Jupiter, Saturn and Neptune, and water vapor in Comet Halley. The 4th video in the series, the live, five hour "Night Flight to the Stars", was in fact the last operational flight of the KAO, and was fittingly shared with thousands of students across America using ACTS. Altogether more than 10 hours of TV were produced, 8.5 of which were live and interactive, and 7.5 of which came directly from the KAO in flight. Hundreds of sites were able to downlink video, and about a dozen sites (at museums, science centers, and planetariums in Texas, New Jersey, Washington, DC, Colorado, North Dakota, Hawaii and across the United States) were able to interact via live two-way video and audio.

High points of the programs included students in Chicago at the Adler Planetarium controlling the KAO's telescope; young patients in an Atlanta Hospital interacting directly with the astronomers, showing how satellite communications could liberate those otherwise confined and shut off from the world; an overnight camp-in at the Liberty Science Center, NJ, with nearly 500 students, teachers and parent-chaperones gathering for an evening dedicated to science, and astronomical questions originating from the site of a high school football game in Booneville, MS, and being relayed directly via ACTS to the KAO.

Reactions from teachers and students showed the impact of being able to travel virtually on board the KAO, a capability only made possible through ACTS. As Marilyn Wall, from the John Wayland School, Bridgewater, VA, wrote:

Videos are so important. They give the students a chance to see what people look like and to feel more a part of the program. It helped to generate a feeling of being there and knowing the individuals to whom the students were directing questions ...The most significant motivational factor for the involvement of my students was the "live broadcast." Watching the live broadcasts my students felt as if they were part of the crew, that they were "virtually" aboard the KAO. It made the "Live From..." series truly interactive ...The live broadcasts made my students feel they were a part of this "live" mission, that they were part of the KAO crew ...This was indeed an electronic fieldtrip, taking my students beyond their everyday realm of experience and knowledge. Through the broadcasts the students became active learners, and they had the opportunity to work with scientists, students, and field experts ...It helped them to understand the astronomers aren't all starry eyed and staring off into space ...They were placed in a position to share and exchange information with their peers and experts in other geographic and culturally diverse locations. The live broadcasts enabled my students to work cooperatively with the KAO crew.

I was very excited to find out about LFS and NASA's attempt to involve the public with its work and NASA's efforts to let kids participate in some of their programs of discovery. Keep it up, NASA!

Teacher Jake Chaput from Arlington Elementary in New York state wrote:

My class viewed the Oct. 5 LFS program ...We were able to get one of our question relayed during the program. My class went wild with enthusiasm when they heard "A question from Arlington Elementary School in Poughkeepsie, NY". Questions poured out from the class after the initial success.

Middle school science teacher, Tim McCollum, reported in an e-mail on "Midnight Science Gala in the Land of Lincoln":

On the evening of Friday, Oct 13, 1995, Charleston Jr. High School in Charleston, IL had its first ever midnight science gala. We were fortunate enough to be able to have crystal clear viewing of the LFS transmission on both NASA Select and our local PBS affiliate WEIU-TV at Eastern Illinois University. Over 100 students attended the event which ran from 8:30 pm CDT to midnight. We had 20 parent volunteers and 20 middle school majors from EIU serve as supervisors and helpers (although on computers, the kids were the real teachers!) While the kids loved the activity, the parents and college folks were the ones most impressed with the application of technology—needless to say, a GREAT P.R. booster for the school.

As a 23 year teacher, my greatest pleasure was seeing the kids so excited, having so much fun, and keeping such late hours actively involved in a SCIENCE activity. I doubt if they'll always remember the wavelengths of IR, but I know they'll forever look back to junior high as the time they once met at midnight for a scien-terrific evening of food, fun and discovery.

3. Live From Antarctica 2

The first LIVE FROM ANTARCTICA series had utilized pre-existing NASA and NSF communications assets at McMurdo Station and Amundsen-Scott South Pole station, although P2K had to "borrow" one of NOAA's GOES satellites to create the world's first-ever live video telecast originating directly from the South Pole. However, on the other side of the Continent, across the Drake Passage from South America, no broadband communications whatsoever existed at Palmer Station, America's 40-person research base devoted to marine biology and the study of sea-birds and penguins. Once more, ACTS facilitated the previously impossible.

P2K approached the ACTS team at JPL and found them receptive to what would be a test of the most difficult and remote ACTS uplink ever attempted. NSF communications engineers provided data indicating that while ACTS was visible from Palmer, the angle was extremely low over the horizon. That added to the extreme cold and the fact that re-supply was only by ship and only once or twice during the research season meant that

extremely careful pre-planning was required. Ann Devereaux and Daniel Gutrich of the Satellite Communications Group in the Communications Systems and Research Section 331 at JPL volunteered for the assignment, ably supported by Tom Jedrey and Brian Abbe who coordinated efforts at home base at JPL. At Palmer, Devereaux and Gutrich set up a satellite terminal that linked the video signals through ACTS to JPL. From JPL the signals were sent via a T1 circuit to the Television Center at Mississippi State University (MSU), Starkville, MS, where the final television production was completed and uplinked to satellites accessible by PBS stations across America. JPL engineer Tom Rebold, from the Radio Science Systems Group in Section 331, also assisted in the effort, working at MSU to ensure that the signals were received at their intended targets.

As Devereaux reported in an interview published in JPL's UNIVERSE magazine:

"Dan and I took about 12 crates of material to help us set up the satellite terminal," Devereaux said. "We brought a 1.2-meter antenna dish, which we set up on a patio outside one of the buildings there, and also had a couple of racks of satellite gear—which included electronics used to talk to the satellite—and tons of spares. We brought as much stuff as we could conceivably need," she added. "Obviously, you couldn't go to an electronics store down there."

In order to give the flavor of true field research, LFA2 also connected via a terrestrial microwave relay to several nearby islands on which penguin, petrel and plant research was ongoing. The ACTS team worked closely with NSF communications engineers to ensure end-to-end integration of local phone lines, RF radios and the satellite signals. In the first program, which focused on a marine Long Term Ecological Research project, one live signal originated on board the Research Vessel "Polar Duke," with an additional live link from the on-shore communications facility where the ACTS equipment was situated. Ann Devereaux reported live on how the communications links were organized, and teachers reported that their students were fascinated by how the signals were routed as well as with the natural history and earth science content of the broadcasts.

Despite all the technical and logistical challenges the duplex ACTS satellite link operated nominally throughout the entire 2 month plus period during which the production team was on site, enabling pre-recorded segments to be transmitted from Palmer to MSU to be integrated with the live programming. Audio from the United States, including student questions from Maine, Hawaii, Mississippi and several other states were successfully relayed to the researchers appearing live on camera in the Antarctic.

Once more teachers reported that students were fascinated by the programs and the project. (Each comment originates from a different teacher and school.)

Kids get very excited when they realize this is real science in real places...

I only wish there could be more of these programs. My kids got so excited about learning (during) the weeks we do these kinds of activities. Keep up the good work.

I did this project with a pupil adjustment class (students with severe behavior problems) that range from grade 2-5. The students in this group LOVED the project. We constructed a life size model of Antarctica in a corner of (the gym)

I teach computers and use the program as an example to students as to how Internet communications can enhance learning and scientific understanding of the world...

In comparison with other online programs, this is by far the most superior I have found...

My students were absolutely delighted to have each of their questions answered in a way that they could understand. They were thrilled to have one of their questions answered "live from Antarctica" during broadcast 2...

They found the information very interesting and I don't think fully comprehended the scope of what was happening in terms of the technology involved, but they began to be awed by it. My students are special education L(earning) D(isabled) and EMI...

The kids and I loved it and hated to see it end. Isn't there any way to extend the study and cover other aspects of life and study down there? The fact that it is coming "live" is really a super plus with the kids. It made it so very real...

As part of the 3-year NSF grant awarded to P2K, an extensive evaluation by the Center for Children and Technology of the Education Development Corporation (Newton, MA and NYC) provided qualitative and quantitative feedback on the impact of the project on student learning outcomes and attitudes. Results clearly showed that the project was far more than a mere "pilot" or "demonstration" and resulted in significant learning. These concrete statistical results are more substantial than those reported for other electronic field trips and distance learning projects. (The full report is accessible online via <http://passporttoknowledge.com/storm> under EDUCATORS/EVALUATION.)

Specifically referring to the interactive opportunities enabled by ACTS, the survey found that:

97% of *teachers* thought experts' answers "useful and understandable"
95% of *students* thought experts' answers "useful and understandable"
94% responded that the Q&A format was "an effective way to share information with students about Antarctica"

In terms of student interest in the videos, results showed that:

0% were "bored", and
93% said that the "programs interested students in Antarctica and science"

4. Live From The Rainforest (Lfrf)

The third and final P2K project utilizing ACTS featured the first-ever live educational broadcasts from the heart of the Amazon rainforest, a location that exposed ACTS uplink equipment to the hottest and most humid conditions every experienced.

According to Bauer, et al:

Interestingly, while not as remote (as that experienced during LFA2), it was said that the infrastructure at the rain forest site was poorer than in Antarctica. On-site diesel generators that powered the remote hotel (at the Ariau Jungle Tower) intermittently failed. The reflector and outdoor unit were established on a helipad, while the indoor equipment was in one of the few air-conditioned rooms in the facility. The hotel site is built on stilts and the location was accessible only by boat as it was the end of the rainy season and the river was still high. The daily downpours, nearly continuous 100% relative humidity, and daily temperatures of about 90 degrees F made for perhaps the harshest environment in which ACTS equipment has operated.

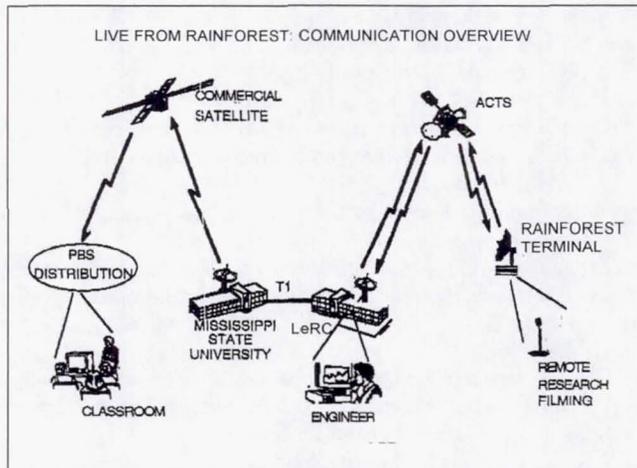


Figure 2. ACTS CONFIGURATION IN SUPPORT OF LFRF (COURTESY SINGHAL)

As reported in an unpublished MSS by LeRC ACTS LFRF project manager Adesh Singhal, this was the first time that NASA LeRC (now Glenn Research Center) took the lead role in providing the communication link. LeRC led the effort to provide the live video link from the field research site in the Amazon over ACTS and terrestrially linking it to Mississippi State University where the interactive segments were formatted into final programs broadcast on April 7, 14 and 21, 1998. These programs were also simultaneously transmitted live across Brazil through collaboration with co-producer NEON RIO, and TV Cultura, Sao Paulo.

Singhal writes:

LeRC's involvement to support this activity also supported NASA's mission to provide and enhance scientific and educational programs for school children across America. This also provided the Public Broadcasting Service's viewing public with an opportunity to learn about NASA's Advanced Communications Technology Satellite and its communications technology using the Ka band, and how it can be used for long distance learning ...In completing the objectives of this experiment., the LFRF activity exercised several of the ACTS communications technologies, including the use of Ka band, the use of steerable and fixed spot beams from single transmit and receive antennas.

Live video and audio of the Rainforest researchers at work was channeled to the on-site TIVSAT terminal, which utilized a 1.2 m dish for transmit and receive out of and into the rainforest site. The TIVSAT took composite video from the rainforest and relayed it through ACTS to the LeRC ACTS fixed station. From LeRC, the video was sent over commercial telephone lines via a T1 circuit (1.8Mbps) to the main production hub at Mississippi State University. After formatting and editing, personnel at the television center then uplinked the signal to a commercial Ku-band television satellite, which made the signal accessible to public television stations and any school or other educational institution with the appropriate downlink dish. The operational mode used for the LFRF operations was the baseband processor bandwidth on demand configuration. The satellite's capability for producing uplink and downlink beams through the steerable antenna was used to allow communications to the remote site in the rainforest. At the same time the spacecraft's Ka band antennas were able to maintain a fixed coverage on the Cleveland, OH, area, where LeRC is located. By using the on-board processing, the ACTS satellite served as a "Switchboard in the Sky", allowing a continuous data flow of up to 1.8 Mbps from the rainforest site (in the steerable beam) to LeRC (in the Cleveland fixed beam), and vice versa. The TIVSAT terminal operates with the fully digital TDMA baseband processor mode of the satellite and was the original workhorse terminal of the ACTS ground segment. It can support a full T1 circuit plus four 64 kbps channels for a total throughput of 1.8 Mbps while bursting to the satellite at 27.5 Mbps. (Terminal and other parameters are appended.)

As the ACTS system provided full two way communications, live feedback video and audio was also sent back to the rainforest via the LeRC ACTS fixed station. LFRF classroom participants were able to send e-mail questions in real time and have their inquiries routed directly to the researchers in the Amazon. Logistical discussions of production details were also supported between with P2K and LeRC personnel located on-site before, during and after the live television broadcasts. Such logistical discussions were crucial in planning and debugging production logistics and should not be ignored in any future such projects. The ACTS link also allowed e-mail exchanges between the rainforest site and elsewhere. FIELD JOURNALS and BIOGRAPHIES, provided online at the LFRF website provided a behind-the-scenes view of life in the rainforest.

Bauer, et al, reported on technical results as follows:

All three live shows were supported with the ACTS link. The video quality was claimed to be the best ever of these "Live from..." series largely because a full T1 link was never feasible before. The 1.2-m dish was shown to be adequate for maintaining an uplink clear-sky margin of 13 dB (with continuous coding used) and a downlink clear-sky margin of 9 dB (with continuous coding used) and using the spacecraft's steerable beam antenna (55 dBW EIRP, 13 dBi/K G/T). The estimated predicted availability at these margins was about 99% at both 30 GHz and 20 GHz during the rainiest season (Feb.-Apr.). Before anything was shipped a 2.4-m dish was considered to obtain 6 dB more margin. But calculations indicated that for the type of rain predicted for the area and the extra hardship in transporting the larger dish to such an inaccessible site, there was little to gain in link availability (about 0.4% at 20 GHz)

considering the relatively short duration of the activity. Experience showed that the terminal remained operational during light rains. Link margins greater than 50 dB are needed to maintain 99.9% availability at 30 GHz and this, in general, is considered impractical to support for ACTS or any operational commercial Ka-band system in this region (ITU-R rain zone P).

Once again, teacher and student responses were extremely positive: verbatim comments may be found in the DISCUSS section of the LIVE FROM THE RAINFOREST website.

5. "Passport To Knowledge" Plans For The Future

P2K has deeply appreciated the opportunity to work with the ACTS program on 3 such ambitious but ultimately successful projects. We are convinced that connecting students and teachers directly with researchers and real-world locations can have a profoundly beneficial impact on science education in the United States and around the world. While ACTS may no longer be operational, the lessons of these 3 Modules will continue to inform and inspire our efforts. In 1999, P2K created and distributed LIVE FROM THE SUN, focusing on the NASA-ESA SOHO mission and behavior of the Sun during Solar Maximum. In 2000 came LIVE FROM THE STORM, part of an ongoing PASSPORT TO WEATHER AND CLIMATE Module in which both NOAA and NASA are supporters. Future plans call for projects looking at the oceans, volcanoes and earthquakes, black holes and the new view of the Universe provided by recent NASA and other missions, and LIVE FROM THE HEART OF THE CELL. Based on results of the past projects involving ACTS, P2K will continue to emphasize real-time interaction and virtual exploration of remote sites. Thanks to the trailblazing work of ACTS, the new "Grand Tour" can include sites all around our world and even across the Universe, and be accessible to anyone, anytime, anywhere. Satellite TV and the Internet can truly serve as a "passport to knowledge" for everyone.

6. Acknowledgements To Acts/NASA Staff Contributing To The P2k/Live From Projects

Passport To Knowledge wishes to thank:

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Ann Devereaux and Daniel Gutrich, NASA/Caltech JPL
Brian Abbe and Tom Jedrey, NASA/Caltech JPL
Tom Rebold, NASA/Caltech JPL
Greg Kubat and John J. Diamond, NASA Glenn Research Center (LERC)
Robert Bauer and Adesh Singhal, NASA GRC
Brian Abbe and Tom Jedrey, NASA/Caltech JPL
Ramon de Paula, NASA HQ
and all the other NASA, NSF and NOAA staff involved in the projects discussed above.

7. References And Further Information

Passport To Knowledge main site: <http://passporttoknowledge.com>
Live From The Stratosphere <http://passporttoknowledge.com/lfs>
Live From Antarctica 2 <http://passporttoknowledge.com/antarctica2>
Live From The Rainforest <http://passporttoknowledge.com/rainforest>
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Appendix

Live From The Rainforest / ACTS Terminal Parameters

ACTS Remote Terminal:	Steerable Beam
ACTS Connection:	Clev. Spot Beam
Service Dates:	4 d/wk, 4hr/day, Mar. 20-Apr 21
Frequency:	Ka band (30ghz uplink, 20ghz downlink)
Data Rates:	Continuously selectable to 1.8Mbps
Communications Mode:	Full Duplex

Channel capacity: 28(64Kbps) channels (One T1 with 24 channels for video/voice plus 4 extra channels for voice/phone/data)
Terminal Specifications:
Location Ariau Tower Lodge (60 kms from Manaus)
Satellite Elevation 43.586Deg
Satellite Azimuth -85.89Deg
Antenna 1.2 Parabolic dish:Gain 89.8 dBm Tx, 85.9 dBm Rx
Transmit Power 41dBm
Bit Coding QPSK
Data Coding Reed Solomon encoder

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3.5 - Advanced Shipboard Communications Demonstrations with ACTS

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Abstract

For ships at sea, satellites provide the only option for high data rate (HDR), long haul communications. Furthermore the demand for HDR satellite communications (SATCOM) for military and commercial ships, and other offshore platforms is increasing. Presently the bulk of this maritime HDR SATCOM connectivity is provided via C-band and X-band. However, the shipboard antenna sizes required to achieve a data rate of, say T1 (1.544 Mbps) with present C-/X-band SATCOM systems range from seven to ten feet in diameter. This limits the classes of ships to which HDR services can be provided to those which are large enough to accommodate the massive antennas. With its high powered K/Ka-band spot beams, the National Aeronautics and Space Administration's (NASA) Advanced Communications Technology Satellite (ACTS) was able to provide T1 and higher rate services to ships at sea using much smaller shipboard antennas. This paper discusses three shipboard HDR SATCOM demonstrations that were conducted with ACTS between 1996 and 1998.

The first demonstration involved a 2 Mbps link provided to the seismic survey ship M/V *Geco Diamond* equipped with a 16-inch wide, 4.5-inch tall, mechanically steered slotted waveguide array antenna developed by the Jet Propulsion Laboratory. In this February 1996 demonstration ACTS allowed supercomputers ashore to process *Geco Diamond's* voluminous oceanographic seismic data in near real time. This capability allowed the ship to adjust its search parameters on a daily basis based on feedback from the processed data, thereby greatly increasing survey efficiency.

The second demonstration was conducted on the US Navy cruiser USS *Princeton* (CG 59) with the same antenna used on *Geco Diamond*. *Princeton* conducted a six-month (January-July 1997) Western Hemisphere solo deployment during which time T1 connectivity via ACTS provided the ship with a range of valuable tools for operational, administrative and quality-of-life tasks. In one instance, video teleconferencing (VTC) via ACTS allowed the ship to provide life-saving emergency medical aid, assisted by specialists ashore, to a fellow mariner - the Master of a Greek cargo ship.

The third demonstration set what is believed to be the all-time SATCOM data rate record to a ship at sea, 45 Mbps in October 1998. This Lake Michigan (Chicago area) demonstration employed one of ACTS' fixed beams and involved the smallest of the three vessels, the 45-foot Bayliner M/V *Entropy* equipped with a modified commercial-off-the-shelf one-meter antenna. A variety of multi-media services were provided to *Entropy* through a stressing range of sea states. These three demonstrations provided a preview of the capabilities that could be provided to future mariners on a more routine basis when K/Ka-band SATCOM systems are widely deployed.

1.0 Introduction

Recent years have seen an increased demand for full-duplex, high data rate (HDR) digital communications services for maritime customers. These customers include the commercial cruise ship industry, the oil exploration and drilling industry and the military. Because the space available on ships and offshore platforms is limited, satellite communications (SATCOM) in the 30/20 GHz bands is an attractive option for providing HDR services to maritime customers. The National Aeronautics and Space Administration (NASA) launched

the Advanced Communications Technology Satellite (ACTS) in September 1993. Now scheduled for a June 2000 de-orbit, ACTS afforded the maritime community its initial opportunities to demonstrate the potential of high-power K/Ka-band satellites to provide full-duplex HDR services with shipboard terminal equipment possessing significantly smaller aperture sizes than those presently required to provide equivalent data rates in the C- and X-bands. This paper discusses three shipboard HDR SATCOM demonstrations that were conducted with ACTS between 1996 and 1998. It also considers the near future of 30/20 GHz SATCOM in the United States Department of Defense (DoD) with a brief discussion of the Wideband Gapfiller Satellite (WGS) System. DoD is scheduled to launch its first WGS satellite in the fourth quarter of 2003. Lessons-learned from the shipboard ACTS experiments have effected the US Navy's WGS terminal plans.

1.1 Potential Benefits of K/Ka-Band SATCOM for Maritime Customers

Besides the obvious benefit of smaller terminal equipment for already overcrowded topsides, K/Ka-band SATCOM is also attractive from an electromagnetic interference (EMI) standpoint in the maritime environment, particularly aboard military ships. The 30/20 GHz bands are well above the bands used by current maritime radar systems. The same cannot be said about the C- and X-bands. Today, naval C- and X-band shipboard SATCOM terminals require supplemental EMI rejection filters to allow them to operate in a battle group environment, especially in close proximity with Aegis surface combatants. In the demonstration of the Jet Propulsion Lab's (JPL) ACTS Mobile Terminal (AMT) aboard the Aegis cruiser USS *Princeton* described below in this paper, supplemental filtering was not required. The AMT was unaffected by any of *Princeton's* radar systems. This was one of the most significant findings of the demonstration on *Princeton*.

Another warship concern for which K/Ka-band SATCOM can provide benefit is reduced radar cross section (RCS). It is not the case that navies expect to make their warships entirely invisible to radar. Rather the elimination of highly reflective hot spots in a warship's topside is of paramount importance in the face of threats from increasingly sophisticated sea-skimming anti-ship cruise missiles. The smaller a topside SATCOM antenna system is, the less it will contribute to a ship's RCS.

An obvious benefit of K/Ka-band SATCOM for all users, commercial and military alike is the additional bandwidth. The C- and X-bands each have 500 MHz of bandwidth and they are already crowded with users. The government and non-government K/Ka-band allocations form a contiguous 3.5 GHz band. The entire government K/Ka-band allocation (30.0-31.0 GHz Earth-to-space and 20.2-21.2 GHz space-to-Earth) is designated for fixed and mobile SATCOM services (FSS and MSS) on a co-primary basis. Portions of the non-government K/Ka-bands are also allocated for MSS. In the space-to-Earth band (17.7-20.2 GHz) a 500 MHz segment (19.7-20.2 GHz) has been allocated for FSS and MSS on a co-primary basis. However, in the Earth-to-space band, only a 100 MHz segment (29.9-30.0 GHz) has been allocated for MSS uplinks on a co-primary basis with FSS uplinks. In the 400 MHz segment from 29.5 to 29.9 GHz, MSS uplinks are allowed, but they have secondary status whereas FSS has primary status. See [18] for further discussion of this MSS/FSS allocation issue.

All SATCOM frequency bands have pros and cons for delivering maritime wideband services. Table 1 lists the pros and cons of these frequency bands from the perspective of the US Navy.

1.2 Non-Government K/Ka-Band SATCOM and the DoD

On 5 August 1998, the DoD SATCOM Senior Steering Group (SSG) tasked the Navy and the Defense Information Systems Agency (DISA) to co-lead, with joint participation, the evaluation of commercial business cases for emerging commercial SATCOM systems in K/Ka-band. Navy members of the DoD study team have published a paper [17] that summarizes their first year of work. Their observations thus far include the fact there is no consensus on what the potential total market is, let alone confident predictions of which particular commercial K/Ka-band SATCOM offerings may become profitable. Therefore, it is difficult to defend decisions that might lock DoD into any particular commercial SATCOM venture that is unproven in the marketplace. DoD is currently reluctant to enter into anchor tenancy agreements that would require significant Government capital investments prior to the establishment of a sustaining commercial customer base. This reluctance has been reinforced by the recent unfortunate experience with the now defunct Iridium LEO system.

The DoD study team met with several companies planning to launch commercial K/Ka-band systems. None of the emerging commercial K/Ka-band ventures studied by the team is yet planning to provide MSS, let alone MMSS (Maritime Mobil Satellite Service) services. Furthermore, none of them are yet planning to include steerable satellite antennas that could provide not only part time open ocean coverage, but also would allow them to respond to contingencies anywhere within a satellite's field-of-view for any type of potential customer (DoD, humanitarian relief or otherwise). These findings are discouraging from DoD's perspective and the study effort is on hiatus in Fiscal Year 2000.

Table 1. PROS AND CONS OF VARIOUS WIDEBAND SATCOM BANDS FROM THE US NAVY'S PERSPECTIVE

Band	Pros	Cons
L	<ul style="list-style-type: none"> Worldwide open ocean coverage without the need to re-point spot beams Terminal technology mature Allocated for MMSS Little rain fade loss Allied interoperability 	<ul style="list-style-type: none"> Service costs are high Geolocation vulnerabilities Throughput limited to 64 kbps/channel (INMARSAT B HSD) EMI from maritime radars
C	<ul style="list-style-type: none"> Worldwide open ocean coverage without the need to re-point spot beams Terminal technology mature Little rain fade loss 	<ul style="list-style-type: none"> Not allocated for Gov use Not allocated for MSS Transponder leasing is expensive EMI from maritime radars Possible EMI with/from FS users Large terminal equipment
X	<ul style="list-style-type: none"> Dedicated DoD space segment (DSCS) <ul style="list-style-type: none"> Worldwide coverage Allocated for Gov use Allocated for MSS Terminal technology mature Large existing terminal population Little rain fade loss Potential for increased Allied interoperability 	<ul style="list-style-type: none"> Limited available bandwidth EMI from maritime radars EMI from various terrestrial users in some locations outside of the United States EMI from Gov X-band FS users Medium to large terminal equipment
Ku	<ul style="list-style-type: none"> Terminal technology mature Smaller terminal equipment Possible SATCOM and tactical data link shipboard terminal equipment commonality Moderate rain fade loss Transponders on aging INTELSAT satellites may be available at reduced cost 	<ul style="list-style-type: none"> Not all Ku bands allocated for Gov use Not all Ku bands allocated for MSS Transponder leasing is expensive Limited open ocean coverage EMI from maritime radars Many transponders are linearly polarized, a complicating factor for mobile users
K/Ka (Non Gov)	<ul style="list-style-type: none"> Smaller terminal equipment Ample available bandwidth Little EMI from maritime radars Some allocation for MSS 	<ul style="list-style-type: none"> Not allocated for Gov use Unknown if MSS services will be offered Service arrangements uncertain No open ocean coverage planned Terminal technology maturing Considerable water vapor & rain fade losses Increased Doppler shifts for mobile platforms compared to lower bands
K/Ka (Gov)	<ul style="list-style-type: none"> Smaller terminal equipment Ample available bandwidth Dedicated DoD space segment <ul style="list-style-type: none"> Near worldwide coverage with WGS Likely worldwide coverage with AWS Allocated for Gov use Allocated for MSS Little EMI from maritime radars 	<ul style="list-style-type: none"> Terminal technology maturing Considerable water vapor & rain fade losses Increased Doppler shifts for mobile platforms compared to lower bands
Band Definitions		
	Earth-to-Space (GHz)	Space-to-Earth (GHz)
L	1.6265 - 1.6605	1.5250 - 1.5590
C	5.925 - 6.425	3.700 - 4.200
X	7.90 - 8.40	7.25 - 7.75
Ku	Various	Various
K/Ka (Non Gov)	27.5 - 30.0	17.7 - 20.2
K/Ka (Gov)	30.0 - 31.0	20.2 - 21.2
Acronyms		
AWS - Advanced Wideband Satellite System (DoD, 2008 time frame)		
DSCS - Defense Satellite Communications System (DoD, currently deployed)		
EMI - Electromagnetic Interference		
FS - Fixed Service (Line-of-Sight Microwave Links)		
HSD - High Speed Data		
INMARSAT - International Maritime Satellite		
MMSS - Mobile Maritime Satellite Service		
MSS - Mobile Satellite Service		
WGS - Wideband Gapfiller Satellite System (DoD, 2004 time frame)		
<p>Note It should be recognized that the ability to support higher data rates with smaller shipboard terminals comes at the expense of the need to point spot beams. For instance, while it is necessary to use a large shipboard antenna at C-band, it is not necessary to schedule the movements of C-band spot beams. On the other hand, narrow spot beams allow frequency re-use that is not possible with Earth coverage beams.</p>		

1.3 Government K/Ka-Band SATCOM - DoD's Wideband Gapfiller Satellite (WGS) System

The DoD's use of the government 30/20 GHz bands will expand rapidly after the launch of the Wideband Gapfiller Satellite (WGS) System starting in the fourth quarter of 2003. WGS was designated an ACAT ID¹ program on 15 October 1999 by the Under Secretary of Defense for Acquisition and Technology (USD(A&T)) [15]. From [14]: "This system is intended to support a worldwide terminal population with greatly increased system capacity relative to current military systems and the addition of a two-way Ka-band² capability. The Gapfiller satellites, in conjunction with the remaining [X-band] Defense Satellite Communications System (DSCS) satellites and [K/Ka-band] Global Broadcast Service (GBS) capabilities on UHF Follow-On (UFO) satellites, will sustain a significant level of worldwide wideband satellite connectivity for the Department of Defense (DoD) until the advent of an Advanced Wideband System [in the 2008 time frame]. The [WGS] satellite system consists of at least three geosynchronous satellite configurations and ground equipment and software associated with Gapfiller payload and platform control." The most likely orbital positions for the three WGS satellites are 60 East, 175 East and 12 West.

WGS will be a dual-band SATCOM system supporting terminals operating in the Government K/Ka-bands and X-band (see Table 1). In the baseline conceptual design, the K/Ka-band portion of each satellite will support from 4 to 6 "narrow coverage areas" (NCAs) and 1 to 2 "expanded narrow coverage areas" (ENCAs) [14], [16]. The NCAs and ENCAs will be covered with $\sim 1.5^\circ$ and $\sim 4^\circ$ (respectively) beams that are steerable anywhere within the field of view of the satellite. (The NCA beams will be slightly broader than ACTS' steerable beam, which was $\sim 1^\circ$ at 20 GHz.) As of this writing, the detailed specifications of the WGS satellites have not been finalized. Nonetheless, it is expected that the satellite's K-band EIRP will approach 60 dBW per carrier in the NCAs, similar to ACTS. The uplink G/T in the NCAs will likely be in the neighborhood of 10 dB/K at Ka-band, also similar to ACTS.

The US Navy's shipboard SATCOM terminal for use with the Defense Satellite Communication System (DSCS) X-band space segment is the AN/WSC-6(V). The newest variants of the WSC-6, the (V)7 (7.75-foot diameter parabolic reflector) and (V)9 (5-foot diameter parabolic reflector) have pre-planned product improvement (P3I) options to add 30/20 GHz transmit/receive capabilities for the Government K/Ka-band portion of WGS.

2.0 Advanced Shipboard Communications Demonstrations with ACTS

This section describes three high data rate shipboard SATCOM demonstrations/experiments that were conducted with ACTS in the 1996-1998 time frame. These efforts have been reported previously - references are provided. An attempt has been made to include previously unpublished material and discuss the long-term significance of the work rather than specific details, which are available in the references.

2.1 JPL's ACTS Mobile Terminal on M/V *Geco Diamond*

Seismic survey ships search for structures in the ocean floor that are consistent with oil reserves. The ships tow hydrophone arrays that pick up the echoes of acoustic impulses (compressed air blasts from the ship at regular intervals, e.g., 15 seconds) from layers of the ocean bottom. The data are fed into computationally intensive seismic deconvolution routines to produce an estimate of the impulse response of a layered earth model. Experts must then interpret these estimates to select sites that are worthy of the expense of exploratory drilling.

A typical seismic survey vessel might collect 100's of Gbytes of data per day. In the past, these data have been stored on tapes and analyzed ashore, sometimes months after they were collected. A more economically competitive approach would evaluate the data in near-real time. This would enable the ship to re-examine initially promising areas, perhaps with varied acoustic array parameters to elevate the level of confidence about the possible presence of oil. What if the data could be sent from the ship via a wideband SATCOM link to a supercomputer center ashore as they were collected?

On 26 February 1996, the American Petroleum Institute hosted a press conference at the National Press Club in Washington, DC. At the front of the room was a large projection screen, a few racks of equipment behind a curtain and a panel of people seated at a long table. Two of the authors of this paper participated in this press conference, Axford as an attendee and Jedrey aboard the M/V *Geco Diamond* operating in the Gulf of Mexico.

¹ Acquisition Category (ACAT) I programs are major defense acquisition programs, defined as programs estimated by the USD(A&T) to require eventual expenditure for RDT&E of more than \$355 million (FY 1996 constant dollars) or procurement of more than \$2.135 billion (FY 1996 constant dollars), or those designated by the USD(A&T) to be ACAT I. The USD(A&T) is designated the milestone decision authority (MDA) for ACAT ID programs. In other words, DoD is making a significant investment in WGS.

² In the DoD, the 30/20 GHz bands are referred to collectively as "Ka-band."

The following is the relevant weekly report segment that Axford wrote for his management chain on 6 March 1996.

"I attended the ARIES (ATM Research and Industrial Enterprise Study) demonstration and press conference at the National Press Club in Washington, DC on 26 February 1996. This was the "Shipboard ATM Demo" described in e-mails forwarded on 22 & 23 February. It came off as advertised and oil exploration researchers located in San Francisco, Houston and Minneapolis really did interact with the seismic acquisition vessel *M/V Geco Diamond* (at sea collecting data in the Gulf of Mexico) in real time. In addition, a telemedicine demonstration connected Dr. Michael DeBakey from the Texas Medical Center with a dramatized cardiac arrest case aboard *M/V Geco Diamond*. The proceedings (live audio & video, computer graphics) were displayed on a SPARC 20 and shown to the audience on a large screen above the stage during the course of the two-hour demonstration. The shipboard link operated over NASA's ACTS Ka-band satellite at a data rate of 2 Mbps, full duplex. However, the effective throughput to the ship was roughly 4 Mbps in each direction thanks to the COMSAT ATM Link Accelerator, which performs both adaptive forward error correction coding (FEC), and data compression on an ATM-cell by ATM-cell basis. (Mr. David Beering, the ARIES Coordinator and Chair of the ATM Forum Enterprise Network Roundtable, referred to this COMSAT device as "a golden spike.") The punch line at the end of the demonstration was the display of a "first pass" of processing (performed at the Minneapolis Supercomputer Center) on the seismic data that *M/V Geco Diamond* had been collecting *during the course of the press conference.* "Ladies and gentlemen, welcome to the era of real time seismic oil exploration." This same shipboard terminal, owned and operated by NASA/JPL is scheduled for an ONR [Office of Naval Research] -sponsored demonstration/experiment aboard USS *Princeton* (CG-59) this summer."

The terminal used in both the *Geco Diamond* and USS *Princeton* demonstrations was the "Broadband Aeronautical Terminal" described on pp. 182-187 of [1]. The two-axis (elevation over azimuth), mechanically steered transmit/receive antenna used in both demonstrations is shown in Figure 15 on p. 187 of [1]. The antenna's manufacturer has also built a Ku-band receive-only version based on the same approach (slotted waveguide array) for the in-flight DBS reception market [10]. (However, it appears that the aeronautical DBS antenna with which this manufacturer has had the most commercial success to date is a version of a simple parabolic reflector [11].)

The *Geco Diamond* demonstration has also been described in [2] and [3]. The significance of this demonstration for the job of searching for oil under the ocean lies in the reduced overall cycle time for acquiring, processing and interpreting seismic data and making decisions based on interpretations. If the only way to do this is to employ supercomputers ashore, then this demonstration showed that it could be done. However, considering the rapidly decreasing cost/performance ratio of computers, a likely future architecture would include some degree of "supercomputing" capability aboard the seismic survey vessel itself. Perhaps the onboard computers could process the data to the point where near-real-time analysis by experts ashore could be supported by SATCOM links on the order of 200-500 kbps.

2.2 JPL's ACTS Mobile Terminal on USS *Princeton* (CG 59)

Following the successful demonstration on *Geco Diamond*, JPL's ACTS Mobile Terminal (AMT) was installed on USS *Princeton*, a San Diego, CA homeported Aegis guided missile cruiser (CG). Personnel from the Space and Naval Warfare Systems Center, San Diego and JPL completed the installation in July 1996. The AMT remained onboard through weekly "work-up" operations in San Diego waters that fall, and continued to serve *Princeton* during a six-month solo deployment off the Pacific and Caribbean coasts of Latin America in support of US Coast Guard law enforcement operations, January - July 1997. The AMT was finally de-installed from *Princeton* in September 1997 and then went on to an aeronautical SATCOM demonstration described in [6] using Italy's ITALSAT F1 K/Ka-band satellite. With the full-duplex T1 (1,536 kbps aggregate user data rate) connectivity made possible by ACTS and the AMT, *Princeton* became a node on the US Navy wideband Naval Tactical Network (NAVTACNET), the first CG to do so³. This enabled *Princeton* to have eight toll quality phone lines (including secure telephone units), general-purpose TCP/IP connectivity (e-mail, World Wide Web,

³ Until that point in time, the only NAVTACNET ships were large decks with X- and/or C-band SATCOM terminals: aircraft carriers (CV, CVN), helicopter assault ships (LHA, LHD) and command ships (LCC, AGF).

FTP and Telnet) and video teleconferencing (VTC) with various shore-based support facilities via the synchronous serial circuits of a programmable multiplexer. This connectivity should be compared to what *Princeton* would have had on that deployment without the AMT: an INMARSAT-A terminal for general-purpose 9600 baud data communications (via modem over an analog connection) and MILSATCOM terminals (UHF and EHF) for special purpose, low rate data communications. Unlike *Geco Diamond*, *Princeton* did not use ATM protocols over ACTS.

The demonstration of JPL's ACTS Mobile terminal on USS *Princeton* has been described previously in [4] and [5]. Since these papers were written, CDR Matthew Sharpe, USN, who was *Princeton's* Executive Officer for the duration of the AMT's time onboard, has made available some of the e-mail messages that he sent to his wife via ACTS during the six-month deployment (January-July 1997). Here is an excerpt from 10 February 1997 that describes a deviation from *Princeton's* routine that occurred earlier that same day.

"We just participated in a rescue and medical evacuation. The 66-year-old master of a Greek freighter took ill. We closed at best speed throughout the night, then launched one of our helicopters to intercept. My air boss [commanding officer of *Princeton's* air detachment, LCDR Joe Beal, USN] had to fly in a high hover, slipping sideways into the wind for over thirty minutes while the crewman lowered by hoist to the deck 120 feet below. We pulled up the master, then my crewman.

Back aboard *Princeton*, we hooked him up to the "crash cart," a vital signs monitor and EKG unit. We ran a blood sample through our new blood analyzer. Diagnosed a swollen prostate that had pinched his urethra and prevented urination for several days. My corpsman started an IV, inserted a catheter and his bladder was back in business. Unfortunately, the blood analysis showed that the master's kidneys had responded to the blockage by shutting down. His blood potassium level was dangerously high and he had developed an unusual abdominal rash.

We established a video-teleconference [via ACTS] with the urology staff at Naval Medical Center San Diego. They were able to examine our patient, view his vital signs, and review our lab work. It was reassuring that they could confirm my corpsman's diagnosis and treatment decisions. The VTC would have been much more important if we needed to perform surgery to place the catheter. (Surgery? You bet. When we are the only game in town, we do what we need to.)

The next morning, the master was feeling better, not quite out of the woods, and we flew him to La Paz [the capital city of Baja California Sur, Mexico] for further treatment. We learned later that our intervention saved his life. Always glad to help a fellow mariner."

The demonstration of JPL's ACTS Mobile Terminal on *Princeton* showed how high-power K/Ka-band satellites like ACTS can enable the US Navy to bring a full spectrum of communications services to a broader range of ship classes than previously possible. Indeed, the K/Ka-band portion of DoD's X/K/Ka-band Wideband Gapfiller Satellite (WGS) System will bring "ACTS-like" wideband SATCOM capabilities to small aperture mobile terminals to support a wide variety of missions. Furthermore, the successful *Princeton* demonstration led directly to the US Navy's ultra small aperture terminal (USAT) project, which is developing phased array antenna technology for both the Government and non-Government 30/20 GHz bands as described in [12] and [13]. However, the most gratifying long-term effect of the demonstration on *Princeton* for the project team was the opportunity to help an individual in medical distress.

2.3 The NASA/NRL "SHAKE" Experiment on M/V *Entropy*

The "Shipboard ACTS Ka-band Experiment" (SHAKE) performed by personnel from the NASA Glenn Research Center and the Naval Research Lab (NRL) over a two-week period in October 1998 has been described previously in [7], [8] and [9] and was significant for at least two reasons. Firstly, this experiment set what is believed to be the all-time SATCOM data rate record to a ship at sea, 45 Mbps. "In order to achieve full-duplex data rates of 45 Mbps using a 1 meter dish, there were many optimizations that needed to be performed. The experiment team documented about ten additional optimizations that we would do the next time, if we were to be able to repeat the *Entropy* experiment." [19]

Secondly, NRL and NASA instrumented the experiment heavily and performed more extensive communications performance measurements than those taken in either of the two previous shipboard demonstrations with ACTS

described in this paper. Communications performance data were collected simultaneously on (1) ship's pitch, roll and yaw and the received RF signal level (thereby evaluating the tracking performance of the antenna), (2) DS-3 layer port statistics, (3) ATM layer statistics, and (4) application performance. Analysis of these data sets is ongoing (beyond what has yet been published and as time allows) and a future comprehensive publication is expected.

The US Navy recognizes the importance of knowing the statistics of shipboard SATCOM system performance, including statistics as simple as link utilization (user traffic volume, e.g., bytes/day in each direction, ship to shore and vice versa). How else can one establish metrics to judge the performance of system upgrades? The SHAKE instrument suite was a model for that which might be adopted for Navy shipboard communications systems developers and evaluators. How much more effectively would taxpayers' money be spent if the information gathered by such a suite was analyzed for each battle group deployment as a matter of routine, and the results then used to guide the selection of communications techniques for fleet insertion?

3.0 Conclusions

It is safe to say that the long term effects of these three experiments will continue to be felt in the civilian and military maritime SATCOM communities for some time to come. At the moment, the chief impediment to the proliferation of large numbers of shipboard K/Ka-band SATCOM terminals is the lack of K/Ka-band space segment providing open ocean coverage. Commercial systems planners must tailor their designs to maximize return on investment and concentrate capacity at revenue generating population centers. How the maritime community might successfully lobby with K/Ka-band SATCOM systems planners to provide steerable beams for ocean coverage is an open question that probably has a simple answer. When will market projections for broadband maritime SATCOM services furnish an incentive to provide the needed technical capabilities on K/Ka-band spacecraft? Are there other markets that require the same technical capabilities on the spacecraft?

Regardless of the frequency band employed, the oil industry recognizes the need to provide its seismic survey ships with the capabilities to access computing facilities ashore. According to David R. Beering, coordinator of both the *Geco Diamond* demonstration and the SHAKE experiment:

“One long-term impact of the *Diamond* deployment is that the oil industry now includes special real-estate high up on the mast of new seismic vessels reserved for relatively large satellite antennas [presumably for any frequency band with available space segment]. In the case of Geco-Prakla, their "Vessel 2000" ship was not only equipped with this prime real estate for one antenna, but additionally, the vessel was equipped with a second spot high on the mast for "something yet to come." This reference is to some Ka-Band advanced SATCOM capability not presently commercially available. ... It's interesting to note that a commercial company, Space Data International, has filed for permission to use NASA's Tracking & Data Relay Satellite System (TDRSS) for use supporting seismic acquisition vessels at-sea.” [19]

In looking back at the opportunities ACTS provided for verifying new technologies for wideband shipboard communications, we commend the visionary decisions made by NASA that led to such an adaptable spacecraft. Our only regrets are that we didn't do more mobile maritime experiments and demonstrations with ACTS, and that there won't be an "ACTS II."

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4.1 - A History of the Improvement of Internet Protocols Over Satellites Using ACTS

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Abstract

This paper outlines the main results of a number of ACTS experiments on the efficacy of using standard Internet protocols over long-delay satellite channels. These experiments have been jointly conducted by NASA's Glenn Research Center and Ohio University over the last six years. The focus of our investigations has been the impact of long-delay networks with non-zero bit-error rates on the performance of the suite of Internet protocols. In particular, we have focused on the most widely used transport protocol, the Transmission Control Protocol (TCP), as well as several application layer protocols. This paper presents our main results, as well as references to more verbose discussions of our experiments.

1. Introduction

The work presented in this paper started in 1994 as a series of experiments to determine the impact of a geosynchronous satellite link in a network path on the standard TCP/IP Internet suite of protocols [Ste94]. Our investigations are important for several reasons. First, commercial satellite companies would like to deliver Internet services to consumers and institutions in remote areas of the world not covered by good terrestrial connectivity (e.g., Hughes DirecPC). Our investigations have helped to define and identify the extensions to the Internet protocol suite that are beneficial to delivering Internet content over network paths containing long-delay satellite channels. In addition, NASA is interested in possibly employing off-the-shelf Internet protocols to meet its near-Earth communication needs. Therefore, our experiments focus on improving standard Internet protocols in ways that are both safe in all network environments and beneficial to long-delay networks.

We utilized NASA's Advanced Communication Technology Satellite (ACTS) to conduct our experiments. We used VSAT ground stations and data rates between roughly 0.75 Mbps and 1.5 Mbps (i.e., between half and full T1 rate) in all our experiments. While these tests were conducted at relatively modest data rates, the results scale with the available bandwidth (as shown in [IBF+99]). Generally, our experiments were conducted with a sender at NASA's Glenn Research Center and a receiver at Ohio University (or vice versa). However, several of our experiments were performed with a loopback circuit, such that the sender and receiver were located in the same location.

The bulk of our experiments focus on the Transmission Control Protocol (TCP) [Pos81]. TCP is the Internet's most used transport protocol. TCP provides reliable, in-order transmission of data to applications. In addition, TCP provides end-to-end congestion control mechanisms that attempt to protect the network against *congestion*

collapse (a state when the network is very busy, but little useful work is being done) [FF99]. Additionally, we have explored several application layer protocols that utilize TCP.

This paper is organized as follows. Section 2 outlines our early work in determining the problems with using standard Internet protocols over ACTS. Section 3 discusses an application layer mitigation to TCP's shortcomings over long-delay networks. Next, Section 4 outlines our experiences using standardized solutions to mitigate TCP's performance problems over ACTS. Section 5 discusses two experimental mechanisms introduced into TCP and the impact of these extensions on performance. Section 6 outlines our investigation of the performance of HTTP, the application layer protocol used on the World-Wide Web. Section 7 discusses our investigation of using a realistic traffic mix across a network path containing an ACTS satellite circuit. Section 8 outlines our experiments into TCP performance over circuits with non-zero bit-error rates. Finally, Section 9 gives our conclusions and outlines future work in this area.

2 Problems with TCP/IP Over ACTS

Our early work [Kru95] illustrates two main causes of performance degradation in TCP file transfers. First, in long transfers the advertised window supported by off-the-shelf TCP stacks is inadequate. The throughput (or bandwidth attained) for long-lived TCP transfers is given by the formula in equation 1 [Pos81], where W is the *advertised window size*, B is the bandwidth of the network link and RTT is the *round-trip time* between the data sender and the data receiver.

$$W = B \cdot RTT \quad (1)$$

The advertised window is the largest amount of data that can be buffered by the receiver. Therefore, the advertised window represents the largest amount of data a TCP sender can transmit before receiving an acknowledgment (ACK) from the receiver. As B and/or RTT grow, W must be increased accordingly. However, TCP places a limit on W by only allocating 16 bits of header space for the value. Thus, the advertised window can be no more than 64 KB¹. The effect of this limit is that TCP cannot fully utilize the bandwidth of a network path with a large *delay-bandwidth product*. In addition, many TCP stacks use advertised window sizes much less than 64 KB by default. For instance, the hosts used in our early experiments [Kru95] utilized advertised window sizes of 24 KB. Therefore, the maximum throughput of a transfer over ACTS was approximately 44,000 bytes/second regardless of the amount of capacity available over the satellite circuit.

The second problem noted in [Kru95] pertains to short transfers. Our experiments illustrate that TCP's slow start algorithm [Jac88, APS99] was the cause of the performance degradation. The slow start algorithm is part of TCP's congestion control mechanism. The algorithm introduces a *congestion window* ($cwnd$), which is the sending TCP's measure of the current capacity of the network. Slow start begins conservatively, by initializing $cwnd$ to 1 segment. For each ACK received, $cwnd$ is increased by 1 segment, providing an exponential increase in the sending rate. The slow start algorithm terminates when loss is detected (assumed to indicate network congestion) or $cwnd$ reaches the advertised window size. For long transfers, this slow probing of the network to determine the capacity is a small percentage of the transfer time and therefore does not have a large negative impact on performance. However, for short transfers, TCP is never able to fully utilize the capacity of the network path. For instance, a 2 segment transfer will take 2 RTTs (or more than 1 second) after TCP's three-way handshake is completed even if the network capacity to transmit both segments was available when the transfer started.

Figure 1 from [All97] illustrates the low utilization of a satellite network during slow start, as compared to a network with a terrestrial delay (80 ms in this model). Just before 4 seconds into the transfer over the satellite link the slow start phase completes. During that same amount of time, the terrestrial network is able to transfer 22 times the amount of data as is sent over the satellite link! After slow start, both networks send the same number of bytes/second, but obviously the slow start phase hurts the performance of the long-delay connection much more than the shorter-delay terrestrial network connection.

3 An Experimental Application Layer Mitigation

The above problems led to the development of an application-level tool to enhance the efficiency of data transfers. We extended the the File Transfer Protocol (FTP) [PR85] to use multiple TCP connections to transfer a given file,

¹For the first sets of experiments we did not consider TCP's optional window scaling mechanism [JBB92], which allows for advertised windows larger than 64 KB, due to the lack of implementations of the mechanism. Later experiments did utilize these TCP extensions, as outlined in section 4.

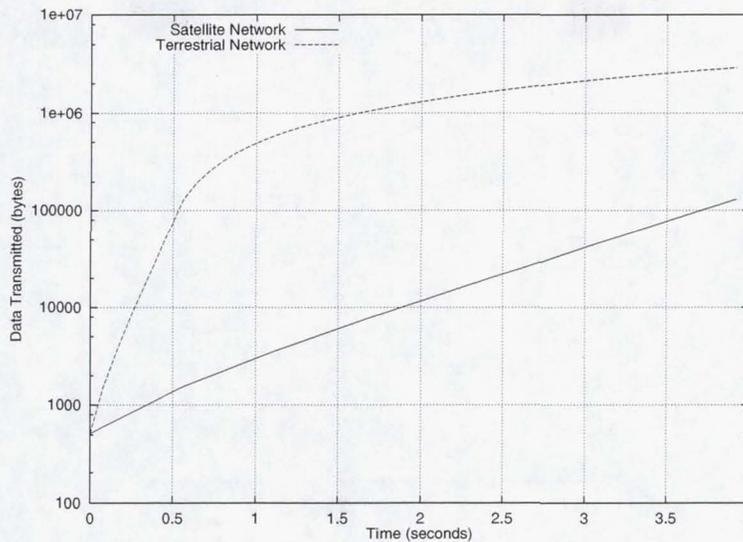


Figure 1: Data transferred as a function of time over satellite and terrestrial network paths.

rather than one connection as specified in [PR85]. This multiplied TCP's aggressiveness by the number of TCP connections being utilized. The syntax and semantics of the extensions to FTP are outlined in [AO97]. The ACTS experiments involving *xftp* are outlined in [AOK95, AKO96, All97].

Figure 2 shows the throughput of a 5 MB transfer as a function of the number of parallel data connections used to transfer the file over an ACTS T1 link. Each connection used an advertised (maximum) window of 24 KB which yields throughput of approximately 44,000 bytes/second, as outlined above. Therefore, we would predict that 4 connections would be required to fully utilize the capacity of the channel (approximately 192,000 bytes/second). However, the best performance is obtained when using 6–8 data connections. We believe it takes more than four connections to reach optimal performance due to segment overhead, as well as lingering slow start effects. When using 6–8 connections we achieve nearly optimal throughput when all protocol overhead is taken into account. Using more than 8 connections leads to sub-optimal performance (but, still much better than using a single connection). This drop in throughput is caused by segment losses due to increased congestion from competing TCP flows. Part of TCP's congestion control mechanism calls for a reduction in *cwnd* when a loss is detected, as the loss is assumed to indicate network congestion. As soon as *xftp* starts over-running router buffer queues, thus losing segments, some of the connections reduce their sending rate, so the time required for the entire transfer increases.

The following are some of our key findings from our *xftp* ACTS experiments:

- Large advertised windows are required. As predicted by the experiments outlined in the previous section, using a larger *effective window size* (i.e., the sum of the advertised window sizes across all connections used by *xftp*) allows full utilization of the available capacity for long-lived data transfers.
- Larger initial congestion window sizes help. Using N connections in parallel speeds up slow start by using an effective initial *cwnd* of N segments. This cuts several RTTs off the transfer time and could be especially useful for short transfers.
- The throughput of the transfer is sensitive to the number of connections employed. Using too few connections results in an effective advertised window less than the delay-bandwidth product and thus an underutilization of the capacity. Using too many connections leads to loss on the channel and a reduction in sending rate due to network congestion. Finding a general mechanism to choose the proper number of connections during the data transfer proved difficult [AKO96].
- The multiple TCP connections acted much like a "selective acknowledgment" (SACK) mechanism. In other words, *xftp*'s loss recovery is more efficient than the standard TCP loss recovery [APS99] because it was

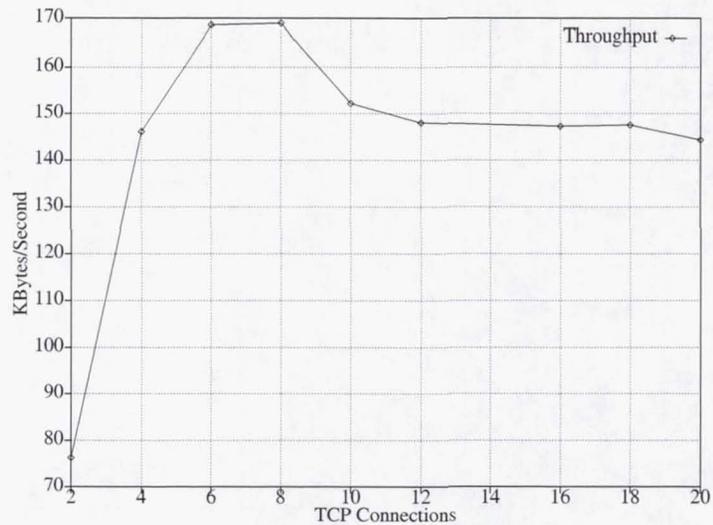


Figure 2: Performance of *xftp* as a function of the number of parallel TCP connections employed over an ACTS T1 circuit.

spread across many connections that each keep track of their own sequence space. Standard TCP can effectively recover from one lost segment per RTT [FF96]. Therefore, *xftp* can effectively recover from roughly N losses per RTT (assuming N parallel connections).

Finally we note that using multiple parallel TCP connections is not “friendly” to the network in general because each indication of network congestion reduces *cwnd* by less than the reduction would be if one connection were used [FF99]. Therefore, while *xftp* is a valuable tool in learning about network dynamics it is *not recommended for general purpose use*.

4. Standard Solutions

During our investigations, the Internet Engineering Task Force (IETF) standardized options to TCP to mitigate some of the problems outlined above. RFC 1323 [JBB92] introduced an option for TCP to advertise windows much larger than 64 KB. Meanwhile, RFC 2018 [MMFR96] introduced a *selective acknowledgment* (SACK) option to TCP. Using the SACK option, receivers can inform senders exactly which segments have arrived, rather than relying on TCP’s cumulative acknowledgment. This allows a TCP sender to efficiently recover from multiple lost segments without reverting to using a costly *retransmission timeout* to determine which segments need to be resent [FF96].

We conducted a series of ACTS experiments using these two new TCP options [AHKO97, Hay97]. Figure 3 shows the throughput for a number of different variants of TCP as a function of transfer size. We used a half-T1 ACTS link for these experiments. The *xftp* experiments use 4 parallel connections. First, we turn our attention to the two experiments run using effective advertised window sizes of the delay-bandwidth product (which produces no network congestion and therefore no segment loss). In this case, *xftp* slightly outperforms the one connection Reno transfer. The amount by which the throughput differs between the transfers gets smaller as the transfers grow longer. This indicates that the difference is due to the *xftp* transfer using a larger initial *cwnd*.

The lower three lines on the plot represent experiments with a larger than necessary advertised window. The increased advertised window leads to dropped segments due to buffer overflow in a router in the middle of the network path. Standard Reno TCP performs the worst in these experiments. As shown, using TCP with the SACK option drastically increases throughput. Using *xftp* provides still better throughput. However, *xftp* has a more aggressive response to network congestion than a single TCP connection. When one loss occurs on the set of parallel connections only one of the four TCP connections reduces its *cwnd* by half, leading to an overall reduction of an eighth in response to a single congestion indication (rather than the standard reduction of one half) in this

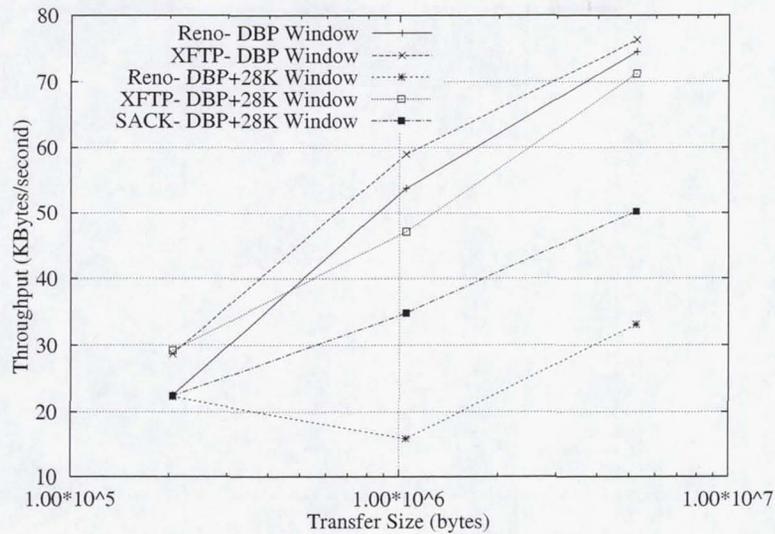


Figure 3: Throughput of various versions of TCP as a function of transfer size.

experiment. The more aggressive response to congestion used by *xftp* explains the throughput benefit shown in the plot.

The following is a summary of our conclusions from this set of ACTS experiments:

- When the network is uncongested, TCP's large window extensions (RFC 1323 [JBB92]) provide nearly the same behavior as *xftp*, modulo the larger initial *cwnd* utilized by *xftp*.
- TCP's SACK option provides drastic throughput improvements in the face of network congestion.
- The results of these experiments alluded to the fact that the throughput of a transfer was quite sensitive to the advertised window chosen. Hayes [Hay97] emulated our ACTS setup and shows the disastrous effects that choosing the wrong advertised window size can have on performance.

The ACTS experiments outlined in this section were influential to the IETF's TCP Over Satellite Working Group as RFC 2488 [AGS99] was prepared. This RFC outlines the standard IETF mechanisms that should be used by hosts transferring data over network paths containing satellite links.

5. Experimental TCP Mitigations

Our next short set of ACTS experiments involved investigating ways to mitigate the underutilization of the network during the slow start phase of a TCP transfer. The first mechanism we studied was using a larger initial *cwnd*, as suggested by the experiments outlined in the last section.

Figure 4 from [All97] shows throughput improvement as a function of the initial *cwnd* size for various transfer sizes. As shown, the throughput increases as the initial value of *cwnd* is increased. The impact is especially significant for short transfers. The impact for the longer transfers is much less due to the relatively short amount of time spent using slow start when compared to the total time required to transfer the file.

These experiments, along with several additional investigations [AHO98, PN98, SP98], influenced the IETF's decision to make the use of a larger initial *cwnd* a sanctioned experimental mechanism [AFP98].

Our second set of experiments involved a slightly modified algorithm for increasing *cwnd* during slow start. As outlined in section 2, *cwnd* is increased by 1 segment for each ACK received during slow start. Many TCP receivers employ the *delayed acknowledgment* algorithm [Bra89, APS99]. That is, receivers are allowed to refrain from sending an ACK for each incoming segment. However, an ACK must be sent for every second full-sized segment received. Furthermore, an ACK can not be delayed for more than 500 ms. By reducing the number of

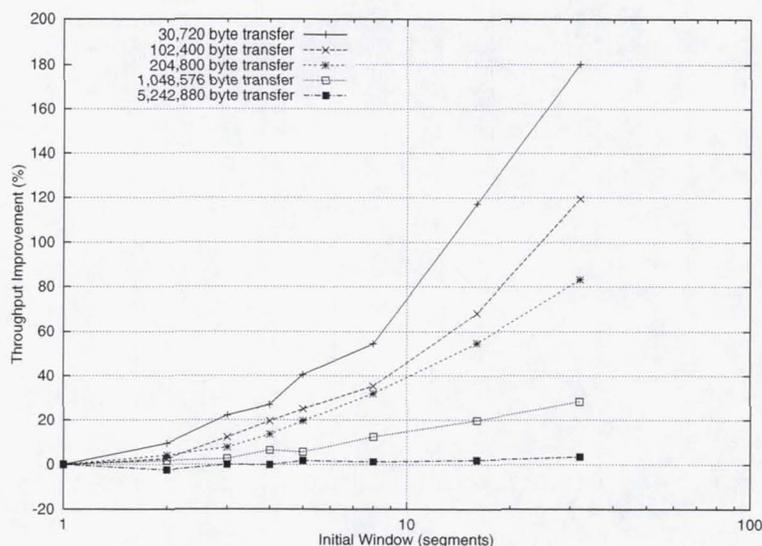


Figure 4: Throughput improvement as a function of initial *cwnd* size.

ACKs sent to the data originator, the receiver is slowing the growth of *cwnd*. We introduced an algorithm called *byte counting* which allows the sender to increase *cwnd* based on the number of new segments acknowledged by each incoming ACK, rather than on the number of ACKs received.

File Size	Throughput Improvement (%)
30 KB	9.4
100 KB	16.9
200 KB	15.3
1 MB	8.5
5 MB	9.5

Table 1: Throughput improvement when using byte counting rather than ACK counting to increase *cwnd*.

Table 1 shows the performance improvement of using byte counting as opposed to traditional ACK counting [All97]. As shown, the improvement for short transfers is better than for long transfers (even though the improvement is good for long transfers, as well). This shows that byte counting is important in slow start, but is also important during congestion avoidance (the phase whereby TCP probes for additional network capacity by increasing *cwnd* linearly).

Byte counting has been adopted by the IETF as a proposed standard during the congestion avoidance phase of TCP connections [APS99]. Further refinements to byte counting have been suggested since the above ACTS experiments [All98, All99]. Our hope is to develop an experimental document within the IETF to allow some form of byte counting during slow start in addition to its already sanctioned use during congestion avoidance.

6 HTTP Experiments

The next set of ACTS experiments we conducted employed the HyperText Transfer Protocol (HTTP) [BLFN96, FGM⁺97], the application layer protocol used for World-Wide Web (WWW) transfers. HTTP uses TCP for reliable transport of its data. Two versions of HTTP have been defined and are in widespread use on the Internet. HTTP/1.0 [BLFN96] transfers a single WWW “object” (HTML document, image file, etc.) per TCP connection. Oftentimes, WWW browsers open multiple HTTP/1.0 connections simultaneously to decrease the time required to

transfer all objects necessary to render a web page. HTTP/1.1 [FGM⁺97] allows a TCP connection to be re-used for transferring multiple WWW objects². In addition, HTTP/1.1 provides a “pipelining” mechanism, whereby a WWW browser can request any number of objects as soon as possible, rather than waiting until the previous object has been transferred to request the next object.

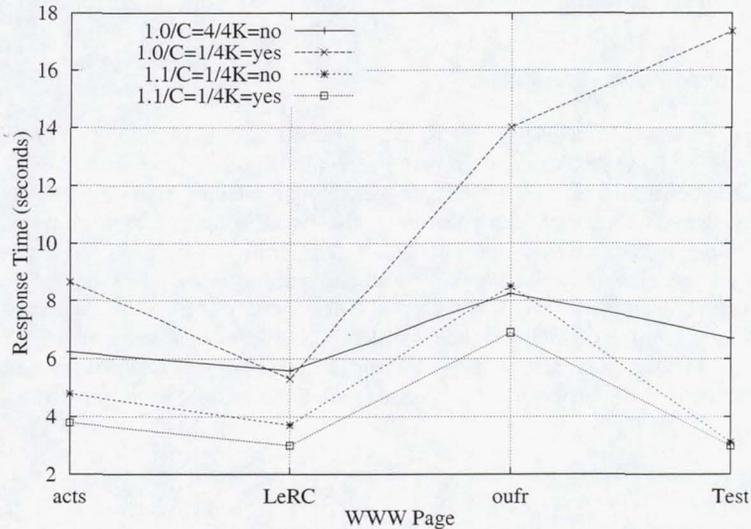


Figure 5: Comparison of HTTP variants.

Figure 5 shows the results of our ACTS experiments with both versions of HTTP. The labels along the *x*-axis represent different WWW pages. The WWW pages used in our study have differing characteristics (number of objects, size of objects, etc.). See [KAGT98, KAGT00] for a description of the page characteristics. Each line on the plot is labeled with three settings used for the particular experiment, as follows.

1. The version of HTTP used (“1.0” or “1.1”).
2. The number of parallel TCP connections employed to transfer the WWW objects (“C = *x*” where *x* is the number of connections used).
3. Whether the underlying TCP stack used a larger initial *cwnd*, per the proposal outlined in [AFP98] (“4K = *z*” where *z* is “yes” when using a larger initial *cwnd* or “no” when using the standard initial *cwnd*).

The following are the key results from our study of HTTP transfers over ACTS.

- HTTP/1.1 generally outperforms HTTP/1.0, even when HTTP/1.0 is used in conjunction with multiple simultaneous TCP connections.
- When using only one TCP connection, HTTP/1.0 performs quite badly, even when using a larger initial congestion window. This happens because each object must endure TCP’s slow start phase. When using a single connection with HTTP/1.1, the effects of slow start are diminished because the TCP connection is reused a number of times. Therefore, the small objects that make up the WWW page are combined to behave more like a bulk transfer and therefore improve network utilization (as discussed in the previous sections).
- As outlined in the previous section, using a larger initial value for the congestion window improves performance for short transfers (which are characteristic of WWW traffic).

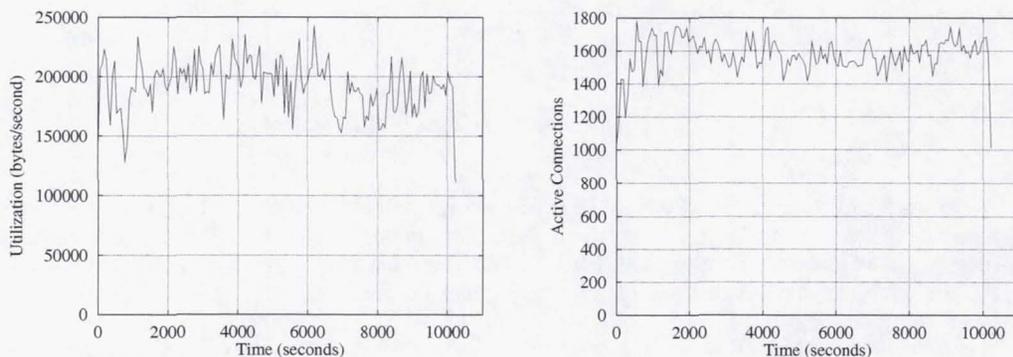
²HTTP/1.0 also has a “keepalive” option for using persistent connections. Use of this option in HTTP/1.0 implementations is limited and the mechanism is equivalent to the base HTTP/1.1 persistent connection mechanism. Therefore, we do not present any results using HTTP/1.0 with keepalives, as our experiments indicated the HTTP/1.1 (without pipelining) case is roughly equivalent.

- Kruse [KAGT00] defines a model for HTTP transfers that accurately predicts the transfer time of web pages of various size.

These experiments aided the IETF in deciding to make the use of a larger initial value for *cwnd* an experimental mechanism [AFP98]. In addition, these experiments highlight the importance of carefully designing application protocols such that the interactions between the application and the underlying transport do not hinder performance.

7. Representative Network Traffic

Up to this point our experiments have involved a single file transfer over an otherwise unloaded network path. In our next set of ACTS experiments, we strive to assess the ability of a realistic group of TCP transfers to utilize the available bandwidth across a network path containing a satellite channel [KAG⁺99]. As shown in the previous sections, short TCP transfers can underutilize the available bandwidth when no competing traffic is present. However, our previous experiments have not assessed the ability of a group of TCP connections to utilize the full capacity of a long-delay network path. We developed a traffic generator called *trafgen* [Hel98], based on *tcplib* [DJ91] for these experiments. First, we take a packet-level trace of network traffic from a production network (e.g., the network connecting NASA GRC to the Internet). The trace is then analyzed using *tcptrace* [Ost97] for traffic characteristics. Finally, these characteristics are imported into *trafgen*, which then generates a realistic mix of TCP connections based on the particular production network that produced the original trace.



(a) Aggregate throughput.

(b) Number of active connections.

Figure 6: Behavior of a realistic mix of traffic as a function of time over an ACTS T1 circuit.

Figure 6 shows the results of a *trafgen* experiment over a T1 ACTS circuit between NASA GRC and Ohio University. As illustrated, the network is fully utilized in many instances, while a large number of TCP connections (or users) is easily supported. This indicates that a representative group of TCP connections can utilize the available bandwidth. While the long RTT may increase the transfer time of some individual TCP transfers (when compared to the same transfer over a network with a shorter RTT), it does not prevent the sum of the transfers from fully utilizing the satellite channel.

8. The Impact of Bit-Errors

The final experiment we conducted over ACTS attempts to quantify the impact of non-zero bit-error rates (BER) on TCP performance. An outline of this experiment and some preliminary results are given in [KOA00]. These experiments were conducted by adjusting the Earth-station at Ohio University such that it did not track the inclined-orbit ACTS satellite. As the satellite moved with respect to the dish, the BERs observed varied. We ran long-lived (1 hour) TCP flows through the network during this time and measured the bit-error rate using an out-of-band channel. Further details can be found in [KOA00]. The TCP stack employed in this set of experiments used a

512 KB advertised window (via the high performance TCP options outlined in section 4). This allows the network path to determine the performance of a TCP connection, rather than having the performance dictated by a limit on the sending or receiving host (this situation simulates socket buffer autotuning [SMM98]). In addition, the stack employed the TCP SACK option with the rate-halving algorithm [MSML99].

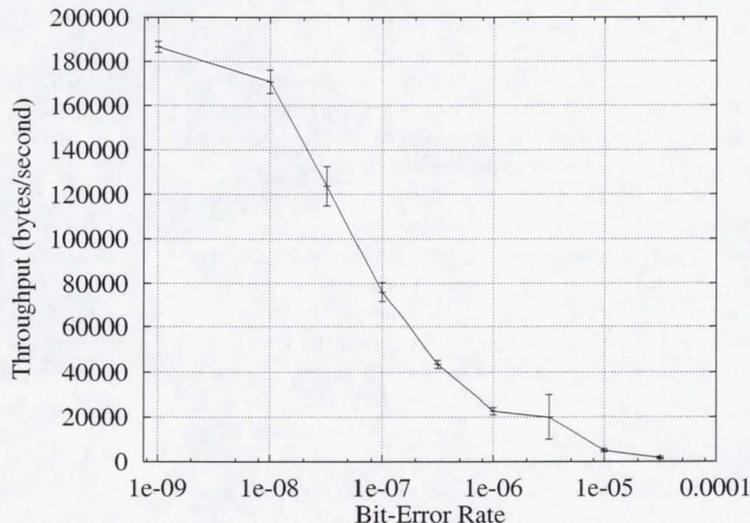


Figure 7: Throughput as a function of bit-error rate.

Figure 7 shows the throughput obtained by a TCP connection as a function of the bit-error rate of the satellite channel with 90% confidence intervals. The figure shows that with no bit-errors (denoted on the plot as 1e-09) the TCP connection is able to fully utilize the T1 capacity of the satellite channel. However, as expected, as the BER increases the throughput obtained by TCP decreases. The root of this problem is the fact that TCP cannot determine why a particular segment was dropped. Therefore, in an effort to behave conservatively, TCP interprets all segment loss as an indication of network congestion and reduces *cwnd* accordingly. Therefore, when a segment is lost due to corruption, TCP mistakenly decreases the sending rate. Research into protocol mechanisms that allow TCP to determine the true cause of a segment loss is ongoing. RFC 2760 [ADG⁺00] contains a discussion of several of these mechanisms. Our results are consistent with analytical models of TCP performance that show throughput is indirectly proportional to the loss rate [MSMO97, PFTK98].

9. Conclusions and Future Work

Over the last six years, our ACTS experiments have shed light on the performance of the Internet protocol suite over networks containing long-delay links. Table 2 gives a summary of each of our experiments, the papers written about the experiments and the IETF standards influenced by our results. The following are the key results from our experiments.

- TCP can fully utilize the capacity of a satellite link when transferring large amounts of data.
- Short transfers often underutilize the capacity of the network, especially in long-delay environments. While we have introduced mechanisms that may mitigate this problem, more research in this area would be useful.
- Application layer protocols can have a large influence on the performance of a data transfer. For instance, using better application level mechanisms drastically decreased the transfer time required to load WWW pages. Careful attention to the design of future application protocols is required to avoid poor interactions between the transport and application layers.
- A realistic mix of network traffic can fully utilize the available bandwidth in a satellite network.

Experiment	Outcome	Papers	Standards Contributions
Preliminary FTP Experiments	Larger effective advertised windows are needed. Slow start decreases performance for short transfers.	[Kru95]	RFC 2488 [AGS99]
<i>xftp</i> Experiments	While throughput improves when using multiple parallel connections, choosing the right number of connections is difficult.	[AOK95] [AKO96] [All97]	RFC 2760 [ADG ⁺ 00]
High Performance TCP Extensions	Large windows help performance but lead to a higher probability of dropping multiple packets from a window of data and thus causing a drastic reduction in the transmission rate.	[AHKO97]	RFC 2488 [AGS99]
SACK Experiments	The SACK option significantly improves throughput throughput over satellite channels.	[AHKO97] [Hay97]	RFC 2488 [AGS99]
Larger Initial <i>cwnd</i> Experiments	Using a larger initial <i>cwnd</i> improves throughput, especially for short transfers.	[All97]	RFC 2414 [AFP98] RFC 2581 [APS99]
Byte Counting Experiments	Using a modified <i>cwnd</i> increase algorithm increases throughput, especially for short transfers	[All97]	RFC 2581 [APS99]
HTTP Experiments	Using old versions of HTTP increases WWW response time significantly. Using HTTP/1.1 with pipelining provides significant benefits over satellite links.	[KAGT98] [KAGT00]	
Experiments with a Realistic Traffic Mix	The Internet protocol suite is able to fully utilize the capacity provided by satellite channels when a representative traffic load is used.	[Hel98] [KAG ⁺ 99]	
Bit-Error Rate Tests	As the BER increases the throughput obtained by TCP decreases due to the mistaken assumption that lost segments indicate network congestion.	[KOA00]	

Table 2: Summary of key results.

- As the BER of a channel is increased the TCP throughput decreases. Future research is needed into ways to distinguish between congestion-based segment loss and corruption-based segment loss.

These key results have been influential in several Internet Engineering Task Force Working Groups. In particular, the results aided the TCP Over Satellite WG in producing RFC 2488 [AGS99] that describes which standard TCP mechanisms should be used when transferring data over satellite channels and RFC 2760 [ADG⁺00] which describes some of the open research topics in this area. Additionally, our ACTS experiments helped the IETF decide to increase the initial value of *cwnd* to 2 segments in RFC 2581 [APS99] and more experimentally to 3–4 segments in RFC 2414 [AFP98].

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4.2 - Mobile Internet Protocol Performance and Enhancements Over ACTS

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1. Project Background

In 1997, Caterpillar and Carnegie Mellon University started a three-year research program to develop a global mobile wireless communication system, one that will support all corporate, operations, dealerships, and end customers' mobile communications reliably. The system is expected to consolidate needs for all Caterpillar business units, from large mining equipment to small construction equipment, from agricultural systems to field support systems. Because of the remote location of many of Caterpillar's customers, for example large mines or quarries, the approach was to assume no common availability of public networks. Caterpillar also wanted the end architecture to be capable of incorporating many competitive IT and radio manufacturer's products, and to have open interfaces for easy usage.

The mining and construction equipment industry, like many other industries, is seeking to differentiate their hard products from those of their competition by adding value with services and applications. The wireless communication system was seen as part of this strategy. The system will support many of these initiatives, for example, it is necessary to implement improved service for machines in the field, by providing remote access to machines and people from anywhere to anywhere. Other immediate uses include, providing direct access for field service technicians to an up-to-date database of service information, hence reducing the problems of using current CDROM technology for frequently changing service information. It is also expected to allow dealers and technicians to do remote diagnosis of a machine's condition using existing and future onboard sensors and data reduction systems. Finally, Caterpillar wants to be able to field intelligent real-time applications such as information support for earth-moving operations, incorporating real time access to and updating of topographical maps, and also wants to be able to field intelligent cooperating robotic machines.

In early visits by the Carnegie Mellon team to Caterpillar's customers at major mines and quarries, and in spending time with both urban and remote service technicians, additional requirements were seen. The mine and quarry owners need a single site system serving all needs, not one for each application (including applications already ported to sites, such as voice radio communication systems and dispatch systems). End customers also stressed that the system has to be easy to install, operate, and maintain, as many sites are remote and they have difficulty getting qualified IT and wireless system staff. Caterpillar's dealerships had other requirements. They indicated the essential need for a simple technician interface and a rugged laptop they could simply turn on, not one where the network and the modem type has to be selected, where the technician has to worry about where they are. Dealership staff also indicated additional requirements in that they want access to their own service database, including manuals, work orders, history, and other technician's experience, and when performing service on a faulty machine, they want this access directly at that machine.

This is a demanding set of requirements, and it raises some difficult issues. The system has to handle a wide variety of communications, from data and file transfers, to real-time data including voice telephony, video, radar, and laser images. In addition, the system needs to handle priorities for different messages, such as for emergency stop messages for a robotic vehicle. The system also has to be able to do this anywhere within a country, accommodating the difference, for example, between downtown Chicago and the remotest areas of the Nevada desert, and has to be able to do it anywhere in the world, bearing in mind that spectrum management is different in different countries, resulting in different technologies being available in different locations. There is also a specific significant problem of being able to communicate with highly mobile machines that move frequently from site to site such as in rental fleets.

There are also a number of miscellaneous issues to be considered, for example: How do you integrate the pieces into a single system as we do with wired computers? How do we deal with robustness in challenging environments? How do we deal with security? Finally, although the mining and construction industry is large it is not large enough for a solution to its unique requirements to emerge spontaneously. The nearest similar industry is that serving the battlefield.

The approach taken in the project considered three aspects: wireless technologies, protocol technologies, and architectural scenarios.

The approach to wireless technologies began with the questions: What is available? What is coming? Where do they cover? What bandwidths are served? How do you integrate them? There is a wide variety of wireless technologies, and each represents a design compromise of bandwidth, mobility, and coverage. All have different costs to build and costs to operate. Some are real and proven technologies, and some are speculative and their adoption will depend upon markets—markets that the construction and mining industry will not greatly influence. These wireless technologies include:

- High speed, low coverage, spread spectrum wireless LANs;
- Low speed, high coverage, licensed radio;
- Packet data services that ride the public voice networks, such as CDPD or GPRS, special packet networks like RAM, ARDIS, or Metricom, and future third generation offerings; and
- A variety of satellite services, from GEOs to LEOs, with various costs and bandwidths.

All of these technologies can play a role, depending on where the equipment or technician is, what the application is, and what economics dictates is reasonable to pay, but none of these technologies can meet all the requirements. Any major application will use several overlaid networks. Consequently, the Carnegie Mellon architecture is a hybrid of fixed and mobile nodes, licensed and unlicensed spectrum, accommodating a variety of wireless technologies, integrated, just like wired systems, with common interfaces.

Examination of protocol technologies also raised questions: How do you tie unlike products and services together? How do you support migration from one to the other? How do you create simple, easily configured and maintained networks? How do you create reliability in high demand areas? To make this work, we use an IP-based architecture, with the standard TCP and UDP protocols riding on top of basic IP. Because the nodes are moving, we use the standard Mobile IP protocol [3,5,7] for migration across technologies and networks. Two other important things have been developed in the project. First, to solve the need for simplicity in creating high-speed networks in mines and quarries, we use new multi-hop wireless ad hoc networking protocols [4,5] for a simple approach to high demand areas. We also use intelligent protocols that can use knowledge of the terrain and vehicle position to enhance reliability and performance.

To focus the research and the development of ideas, several reasonable scenarios were drawn for pieces of the overall architecture. These in essence asked: What technologies are probable for use and where can they be used? How will these unfold over time? How do they relate to populated areas vs. unpopulated areas? Five architectural snapshots were settled on as being representative. These were: populated and unpopulated areas today; at a future "step one" and at a later future "step two", where "today", "step one", and "step two" were defined by existing or proposed technologies, the strength of their markets, and how they have been deployed and used, and by speculated probability of coming technology deployment and capability. In essence "today" is what is available today even if only in selected locations, "step one" is defined by expected increased bandwidth of public network services and increased speed of spread spectrum devices. "Step two" was defined by increased use of broadband satellite technologies (such as Teledesic) and their applicability to fixed and mobile elements. Possible use scenarios were seen as being composed of:

- *Mines or quarries*: characterized by having an intense population of machines, particularly high-end machines, and hence an intensity of high speed, demanding applications and services. Such sites by their nature have justification for custom-built, dedicated networks. Sites typically have work areas with clusters of cooperating machines and these are connected together by site roads. A site also has static structures such as site offices or a crushing plant.
- *Dealerships*: Fixed locations serving multiple customers which can be urban or remotely located. The dealership is the source of roaming elements, namely technicians in service trucks, who may constantly move from populated to unpopulated areas.

- *Urban areas*: characterized by having fewer (often single) machines at locations and these machines typically are smaller, lower-end machines where unit cost is critical and applications and services are hence primitive. There is no justification for a custom-built network and, hence, applications have to use what is available.

Mines, quarries, dealerships, and urban areas are usually interconnected by public roads where, once again, there is no justification for a custom built network and applications have to use what is available.

From this, we determined that satellite communication could form two important pieces of the overall architecture, namely, as a fixed link within subcomponents of the overall system, providing connection between subnetworks from fixed nodes such as site offices, and also potentially as mobile nodes providing interconnection between subnetworks. In each case, this raises the common problem of effectiveness of the fundamental IP based protocols used in the overall architecture. This is particularly true of the use of Mobile IP, which was adopted as the basic method of management of mobility across subnetworks.

We saw the Ka-band technology used by NASA's Advanced Communication Technology Satellite (ACTS) as having the potential for both roles, static and mobile communications, because of its available bandwidth and its use with significantly smaller ground antennas. A combination of an ACTS link and an ad hoc wireless LAN network [4,5] embedded in vehicles within a mine or quarry could be used, so that such mobile vehicles could take advantage of ACTS's large coverage area and a wireless LAN's small propagation time and high bandwidth. With the Mobile IP protocol, the mobile vehicle could seamlessly move from one network to another.

If the Internet Protocol (IP) is used as the network protocol, the ACTS network could be configured as one IP network and each ad hoc network as another. A mobile node could then move from an ad hoc network to the ACTS link, as moved away from a site, so that it could maintain a network connection all the time. Standard IP makes it very difficult for Internet hosts to move from one network to another, since parameters such as the node's IP address, subnet mask, and default router generally need to be changed, making movement both time consuming and error prone. Furthermore, a mobile nodes must also inform its new address to all nodes that want to communicate with it. The Mobile IP protocol has been developed to solve this problem in the Internet.

We conducted experiments using ACTS to observe the performance of Mobile IP. We analyzed the cross-traffic effects of Mobile IP and TCP over ACTS and implemented techniques to improve the performance of Mobile IP over the ACTS link.

2. Mobile IP

Mobile IP [3,5,7] is a standard developed by the Internet Engineering Task Force (IETF) to provide transparent mobility for Internet nodes. Mobile IP can extend the ACTS functionality by enabling mobile nodes to use the ACTS link seamlessly without the need to reconfigure their IP address. However, Mobile IP is generally tuned to perform well in terrestrial wireless networks such as wireless LANs, which have a limited range and a negligible propagation delay. ACTS and other GEO satellite systems pose a challenge to Mobile IP due to their high propagation delay. We have conducted experiments using ACTS and different mobile node movement scenarios to observe how Mobile IP performance is affected.

We have also analyzed the cross-effects between TCP versions optimized for satellite links and Mobile IP over the ACTS link [6]. TCP, the Transmission Control Protocol, is the most commonly used transport protocol in the Internet. It provides reliable delivery of all bytes sent, by retransmitting data until an acknowledgement is received from the destination node. ACTS's high propagation delay and error rate effect TCP performance because data and acknowledgement packets take longer to reach its destination, and these packets might get lost. With Mobile IP, however, TCP also has to manage the loss of packets caused by the handoff. We have implemented and evaluated techniques to improve the performance of Mobile IP over the ACTS link, especially the performance of TCP using Mobile IP during handoff. In particular, we have shown that smooth handoff with a single packet buffer considerably improves TCP performance during handoff without modifying TCP.

In traditional IP routing, if a node has moved to another network, packets destined for it will no longer be deliverable. For a node to be able to communicate on a new network, it must change its IP address, but this makes it impossible to maintain transport and higher-level connections when the node changes locations. Mobile IP is defined as a scalable solution to this routing problem that does not require a mobile node to change its IP address when it moves. Mobile IP enables a host to be identified by a single IP address even when the

device physically moves its point of attachment from one network to another, allowing for the transparent forwarding of data packets to a single address.

2.1 Basic Mobile IP

The operation of the basic Mobile IP protocol is illustrated in Figure 1. Each node is assigned a permanent IP address in the same way as any other node, and this IP address is known as the mobile node's *home address*. The IP subnet indicated by this home address is the mobile node's *home subnet*. When a mobile node is attached to its home network, traditional IP routing will deliver packets to the mobile node using its home address. When the mobile node is away from home, a Mobile IP agent on its home network known as the *home agent* keeps track of the current location of the mobile node and forwards packets to it from its home network. Any network that the mobile node visits is referred to as a *foreign network*. A Mobile IP agent located on the foreign network known as a *foreign agent* may help the mobile node register with its home agent and may also help deliver forwarded packets to a mobile node. Any node with which a mobile node is communicating is known as a *correspondent node*, and may be mobile or stationary.

The mobile node's current location while away from home is known as its *care-of address*. The care-of address will often be the IP address of the foreign agent, and this type of care-of address is known as a *foreign agent care-of address*. Alternatively, the care-of address may be a *co-located care-of address*, which is a local address obtained by the mobile node for its own use in that foreign network; in this case, the mobile node operates without a foreign agent. In this paper, we consider only the case of a foreign agent care-of address.

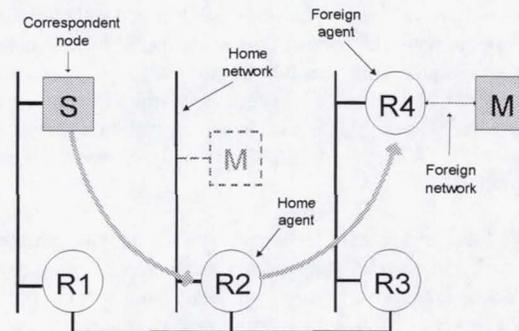


Figure 1: Basic Mobile IP

Mobile IP defines an Agent Discovery mechanism to allow a mobile node to discover whether it is at home or away from home, and to discover a foreign agent in its current network with which it could register. Agent Discovery is based on an extension to the ICMP Router Discovery Protocol [2], with each home agent or foreign agent transmitting periodic *Agent Advertisement* messages, giving the agent's IP address. If the mobile node notices its own home agent's Advertisement, it knows it is at home; it then deregisters with its home agent and no longer uses a care-of address or any support from Mobile IP.

If the mobile node is away from home, it informs its home agent of its current care-of address using a mechanism called *registration*. If the mobile node is not using a foreign agent, it sends a Registration Request message directly to its home agent, which answers with a Registration Reply message; otherwise, it will send its Registration Request to its current foreign agent, which forwards the Request to the mobile node's home agent. Registrations expire after a specified period called the *registration lifetime*. The association of a home address with a care-of address and the remaining lifetime is called a *mobility binding*. When a correspondent node sends packets to a mobile node, the packets are routed normally, to the mobile node's home network. The home agent intercepts those packets and forwards the packets to the mobile node by *tunneling* them to the mobile node's care-of address. To tunnel each packet, the home agent encapsulates it in a new IP header, with the destination address in this outer IP header set to the mobile node's care-of address. If a foreign agent care-of address is being used, the foreign agent will receive the packet, decapsulate it, and deliver it locally to the mobile node. If a co-located care-of address is being used, the mobile node will receive the packet and decapsulate it itself.

2.2 Route Optimization

With the basic Mobile IP protocol, all packets for a mobile node that is away from home must be routed through its home network and home agent, possibly severely limiting the performance and reliability of packet delivery. An extension to Mobile IP, known as *Route Optimization*, enables a correspondent node to learn the care-of address for a mobile node and to tunnel its own packets directly there, bypassing the home agent [8,9].

With Route Optimization, a correspondent node maintains a *binding cache*, in which it caches the binding of one or more mobile nodes. When sending a packet, if the sender does not have a binding cache entry for the destination mobile node, the packet will be delivered to the mobile node's home network, intercepted by its home agent, and tunneled to the mobile node's care-of address. If the home agent supports Route Optimization, it can then inform the original sender of the packet about the mobile node's current binding by sending it a *Binding*

Update, giving the sender an opportunity to cache the binding. When the mobile node later moves to a new care-of address, packets can be forwarded to the new care-of address by the mobile node's old foreign agent, as described in the next section. When it forwards a packet, it sends a *Binding Warning* message to the mobile node's home agent, asking it to send a new Binding Update to this correspondent node to update its cache.

2.3 Smooth Handoff

Another part of Route Optimization is called *smooth handoff* [8,9]. This feature attempts to improve packet delivery during handoff by allowing the foreign agent in a mobile node's previous location to forward packets to it in its new location after it moves. The mobile node sends a Binding Update to this previous foreign agent, informing it of its new care-of address, and the previous foreign agent then tunnels any subsequent packets arriving for the mobile node to this new location. This forwarding allows any packets that were in flight to the mobile node when it moved, and any packets sent by correspondent nodes that have not yet learned the mobile node's new care-of address, to be forwarded rather than being discarded by the foreign agent. This is particularly desirable with TCP, where dropped packets are otherwise interpreted as a sign of congestion in the network, causing TCP to reduce its effective transmission rate [1].

3. Mobile IP, TCP, and ACTS Interaction

As noted in Section 2, Mobile IP is generally tuned to perform well in terrestrial networks, with limited distances and propagation delays. High latency GEO satellite links like ACTS could severely impact the performance of Mobile IP. A long propagation delay might cause Mobile IP to retransmit some control messages during registration, thereby delaying the registration process and increasing handoff time. This could cause higher-layer protocols on the mobile node to react badly, possibly even timing out and dropping the connection altogether.

The Registration Request message sent by a mobile node for registration must be protected by replay protection, which generally uses a *timestamp* in Mobile IP. When the home agent receives a Registration Request, it determines if the timestamp is within an acceptable range. A long propagation delay will increase the probability that this registration is dropped because the message is received too late. In addition, a long propagation delay will require the mobile node to wait a long time for the return Registration Reply message, delaying the mobile node's ability to recover and retransmit the Registration Request in the case that either it or the Reply message are lost by the network.

From the transport protocol's point of view, Mobile IP handoff time will be recognized as a period during which all the transmitted packets are dropped. Since TCP has been designed generally for traditional wired networks, packet drops are assumed to be caused by congestion [1]. Therefore, TCP will reduce its transmission rate and increase its timeout value, resulting in very poor link utilization.

The longer registration time could also make the Mobile IP routes obsolete or stale. For a large bandwidth-delay network such as ACTS, a number of TCP packets may be in flight as the routes are changing, degrading TCP performance. Packets may be lost or additionally delayed due to forwarding from a mobile node's previous foreign agent. Cross-traffic effects between TCP and routing protocols like Mobile IP over satellite links are areas that need further investigation.

We conducted experiments to observe TCP performance during Mobile IP registration: when a mobile node moves from its home network to a foreign network, from one foreign network to another, and from a foreign network back to its home network. Correspondent node behavior when receiving late Binding Updates due to the longer propagation delay was also observed. The experiments also measured the performance of smooth handoff, with the goal of improving performance during handoff.

4. Mobile IP And TCP Performance Over ACTS

Figure 2 shows the network configuration we used in our experiments [6]. We used wired Ethernet rather than wireless LAN subnets for local area network connections, in order to allow greater control over the local network links. Since the experiments placed emphasis on the performance difference between the low latency local area and the high latency ACTS links, the results should also be representative of the performance obtainable using wireless LAN links together with ACTS. In particular, Ethernet has a

maximum roundtrip propagation delay of $51.2 \mu\text{s}$, while a typical wireless LAN with 2 miles transmission range has a maximum roundtrip propagation delay of about $20 \mu\text{s}$. This small difference in propagation delay is negligible compared to the ACTS propagation delay of about 512 ms ($512,000 \mu\text{s}$). Bandwidth differences between Ethernet and wireless LAN should not change the behavior of Mobile IP during handoff, because Mobile IP uses only a small amount of bandwidth for its packets.

We conducted two types of mobile node movement tests to analyze the performance of Mobile IP and TCP during handoff. One set of movements was from a subnet on one side of the ACTS link to one on the other side (e.g., from a subnet of Network A to a subnet of Network B, shown in the lower-right corner of Figure 2). The other set of movements was between subnets on the same side of the ACTS link (e.g., between different subnets of Network B)

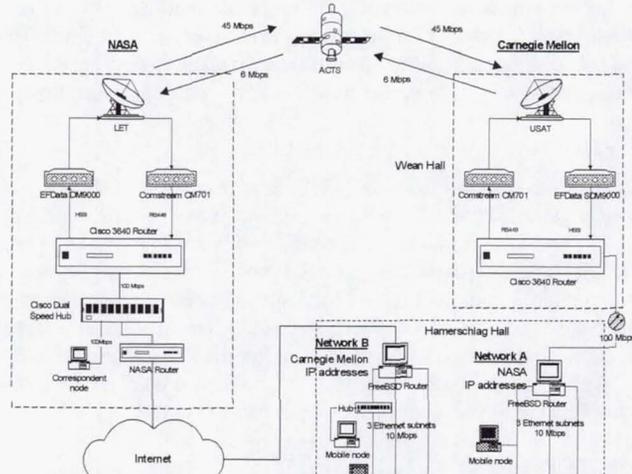


Figure 2: Mobile IP Experimental Network Configuration

4.1 Registration Performance

The first set of experiments we conducted attempted to measure the effect of the ACTS link on TCP during Mobile IP registration. We found that the high propagation delay of the ACTS link significantly reduced TCP throughput due to the additional time required for the registration to complete after the mobile node has moved to a new subnet. For example, Figure 3 shows the sequence numbers of a TCP connection, plotted versus time during Mobile IP registration. In this case, the mobile node has moved from a subnet of Network A to a subnet of Network B (Figure 2), and correspondent node is on Network B, and Mobile IP registration is done over the ACTS link. Each TCP segment transmission by the correspondent node is represented by a black diamond at the correct sequence number and time in the graph, and each acknowledgement from the mobile node is likewise represented by a gray square.

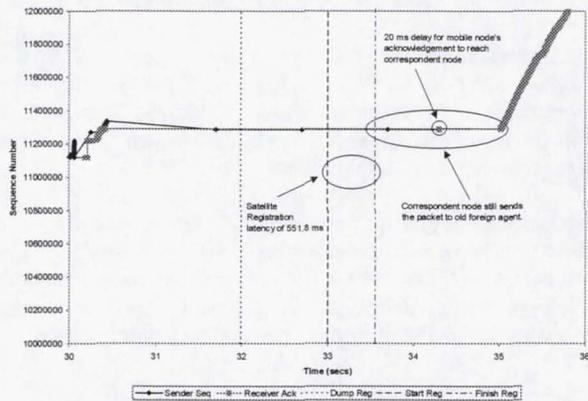


Figure 3: Mobile IP and TCP Performance during Handoff

There are three vertical lines in the graph that show the time at which specific Mobile IP events occur at the mobile node. The "Dump Reg" line represents the time at which the mobile node discards its current foreign agent because it does not receive its Agent Advertisement messages. The "Start Reg" line represents the time at which the mobile node starts the registration process with a new foreign agent. Finally, the "Finish Reg" line represents the time at which the mobile node receives the Registration Reply from its home agent, indicating

that the registration process is complete. In this case, the complete registration process took 551.8 ms, from the time the mobile node initiated the registration to the time it received the Registration Reply message. This delay is due largely to the propagation delay of the satellite link over which the Registration Request and Registration Reply had to be transmitted. The first couple of packets from the correspondent node after the handoff were still delivered to the old foreign agent on the other side of the satellite link, resulting in a delay of 564 ms between the time of packet transmission and the time at which the mobile node acknowledged each. The acknowledgement from the mobile node, however, took only 20 ms, since it was sent directly to the correspondent node. Later, the correspondent node receives a Binding Update message and starts sending each packet to the new foreign agent, which is an address in the same network as the correspondent node. Although Mobile IP and TCP performed correctly over the ACTS link, the performance was significantly hurt by the long satellite propagation delay.

4.2 Smooth Handoff Performance

We conducted a second set of experiments, to observe how smooth handoff would improve the performance of Mobile IP and TCP during handoff from one foreign network to another. Smooth handoff is designed to improve performance by reducing the number of packets that are dropped during handoff, although some packets may still be dropped if they arrive after the mobile node has left the foreign network but before the foreign agent has received the Binding Update giving the new care-of address.

From our experiments, however, we found that smooth handoff did not accomplish its intended goal when using the ACTS link. By examining the sequence numbers during handoff, we found that most of the packets were dropped even before the mobile node realized that it had left the previous foreign network. Figure 4 is one example that shows this behavior.

With Mobile IP, it is common for a mobile node to recognize that it has moved to a new subnet, well after the first retransmission by TCP at the correspondent node, since Agent Advertisement messages are sent at most once per second. Even the very large roundtrip time (about 512 ms) over ACTS cannot prevent TCP from going into slow start, since it is almost always the case that TCP will time out at least once before the handoff completes. When this happens, TCP interprets this as a sign of network congested, and will retransmit only the last unacknowledged segment, doubling the time between successive retransmission attempts using exponential backoff (Figure 4). Even after the registration process in the handoff has finished, the TCP data flow will not resume until an acknowledgement for this segment is received. As illustrated in Figure 4, 2 seconds or more may elapse between the time at which the registration is complete and when TCP actually begins to resume communication. Resumption of data flow in this case depends on TCP retransmission, although it would be better if TCP transmission could be resumed at the moment when the registration actually completes.

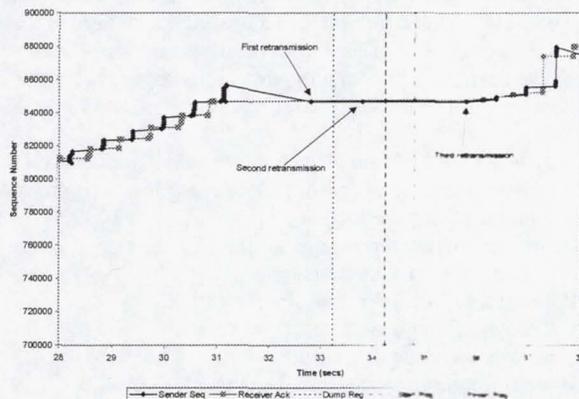


Figure 4: Mobile IP and TCP Performance with Smooth Handoff

5. Improving Mobile IP and TCP Performance Over ACTS

The performance of Mobile IP and TCP during handoff can be improved by extending smooth handoff with the capability of buffering the packets during handoff. Using buffering, packet drops during handoff can be eliminated, and therefore unnecessary TCP retransmissions can be prevented. There are several issues related to the implementation of such buffering.

The first issue is when to start buffering. In order to be efficient with both CPU utilization and memory consumption, buffering should start the moment the mobile node is unreachable or is about to move from the current foreign network. Determining when this happens is very difficult, however, since although some physical and link layers may provide some indications such as signal strength measurements, it is not standard.

A method is needed to solve this problem, independent of the particular lower layers used (possibly augmented by indications from the lower layers).

The second issue is the number of packets to buffer. We would in general like to buffer all packets that may be dropped during the handoff, but it is difficult to calculate the size of buffer this would require. A small buffer might not be enough to prevent packet drops during long handoffs, whereas a larger buffer might unnecessarily waste resources and prevent the foreign agent from serving more mobile nodes.

The final issue related to the implementation of buffering is how to resend the buffered packets back into the network. If the entire buffer is put into the network at once, then these packets might create congestion, which might force some of the packets or others to be dropped, possibly defeating the purpose of buffering.

Our results for smooth handoff performance, discussed in Section 4.2, demonstrated the need to notify the sending TCP layer that the handoff is complete, so that transmission to the mobile node can be resumed immediately. In this case, buffering can be implemented to solve the problem. Instead of preventing packet drops during handoff, we implemented buffering of only a single packet, to trigger an acknowledgement from the mobile node to the correspondent node. As a result, the TCP layer on the correspondent node will receive this acknowledgement and begin retransmitting a segment immediately rather than waiting for the next retransmission attempt scheduled by the exponential backoff.

We implemented this by modifying the foreign agent to buffer the last packet that is transmitted to the mobile node. Upon receiving a Binding Update message from the mobile node's new foreign agent as part of smooth handoff, the buffered packet will be sent to the new foreign agent. This packet will arrive at the mobile node, and the mobile node's TCP stack will acknowledge the packet. This acknowledgement will be sent to the correspondent node, which will then resume its TCP transmission by (re)transmitting the next segment. Only a single packet is needed to initiate this procedure, and hence a buffer size of one packet is sufficient. This reduces the complexity of the buffer handling and also eliminates the problem on how to retransmit the buffer back to the network. Although the exact moment to start buffering is still not known, the foreign agent can simply always buffer the last packet sent to the mobile node.

Figure 5 shows the TCP sequence number behavior over ACTS during smooth handoff with this single-buffering extension. In this case, TCP retransmission begins almost immediately after the mobile node starts the registration process, since the Binding Update message to the old foreign agent is sent at the same time as the Registration Request message. This Binding Update will arrive at the old foreign agent at approximately the same time as the Registration Request message arrives at the home agent. The old foreign agent will send the buffered packet to the new foreign agent, which will deliver it to the mobile node; the mobile node's TCP layer will then acknowledge the packet to the correspondent node, causing it to then (re)transmit the next segment. Each segment sent by the correspondent node will then be forwarded by the old foreign agent to the new foreign agent, until the registration process completes.

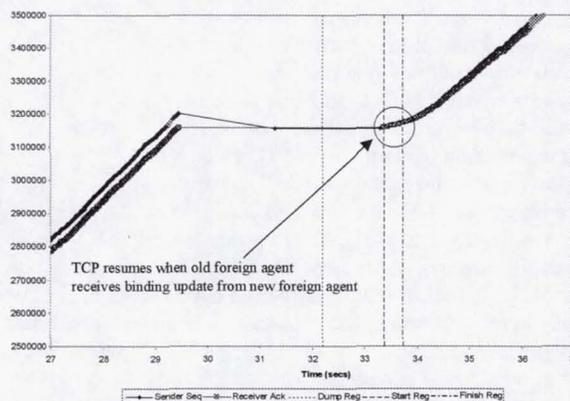


Figure 5: Performance with Single-Buffering Extension in Smooth Handoff

An important aspect of this enhancement is that it does not modify any part of Mobile IP or the TCP protocol. It uses messages that exist in the Mobile IP smooth handoff extension and also uses standard TCP protocol mechanisms. All security aspects of Mobile IP and all TCP end-to-end semantics are preserved.

The performance improvement achieved by implementing this single-buffering extension could be very significant, even for networks other than ACTS. For example, for a 2 Mbps WaveLAN wireless LAN network, 1 second of inactivity could be used to send over 200 kilobits of data. The improvement would be much more significant when the mobile node is frequently moving between subnets.

6. Conclusions

We have examined the performance of Mobile IP and TCP over network connections using ACTS and have analyzed the cross-traffic effects between TCP and Mobile IP in such connections. Our measurements show a substantial performance loss due to the large propagation delay of ACTS and the delays inherent in Mobile IP's movement detection mechanism using Agent Advertisements. The smooth handoff mechanism of Mobile IP Route Optimization reduces but does not eliminate this effect. We have implemented a simple technique that significantly improves this performance yet requires only buffering space at the old foreign agent for a single packet. Our motivation in this work was to examine ACTS and other GEO satellite networks as a part of the global mobile communication system we are developing at Carnegie Mellon together with Caterpillar. This work is applicable to any network connections using large bandwidth-delay networks such as these, and should also be of use in other types of networks such as wireless LANs.

Acknowledgements

The ACTS measurements and analyses presented in this paper are joint work with graduate students Satish Shetty, Roy Laurens, Parag Manihar and Ioannis Pavlidis of the Information Networking Institute at Carnegie Mellon University. This paper draws upon their M.S. thesis work and upon the paper of Shetty and Laurens published at the 1999 International Mobile Satellite Communication Conference [10]. We are also very grateful to Mike Zemic and Adesh Singhal at the NASA Glenn Research Center for helping us with the experiment logistics and for collaborating on the experiments; and to the ACTS Control Room Team, especially Rich Reinhart and Jeffery Glass, for putting up with the equipment configuration issues involved.

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4.3 - NASA and Industry Benefits of ACTS High Speed Network Interoperability Experiments

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Abstract

This paper provides synopses of the design, implementation, and results of key high data rate communications experiments utilizing the technologies of NASA's Advanced Communications Technology Satellite (ACTS). Specifically, the network protocol and interoperability performance aspects will be highlighted. The objectives of these key experiments will be discussed in their relevant context to NASA missions, as well as, to the comprehensive communications industry. Discussion of the experiment implementation will highlight the technical aspects of hybrid network connectivity, a variety of high-speed interoperability architectures, a variety of network node platforms, protocol layers, internet-based applications, and new work focused on distinguishing between link errors and congestion.

In addition, this paper describes the impact of leveraging government-industry partnerships to achieve technical progress and forge synergistic relationships. These relationships will be the key to success as NASA seeks to combine commercially available technology with its own internal technology developments to realize more robust and cost effective communications for space operations.

Introduction

NASA's ACTS has been in operation since 1993. This period of successful operation far exceeds the initial two-year experimentation plan as well as the four-year design life of the system. The current state operation in an inclined orbit with the remaining fuel allows extended usage of the still totally functional payload. Although antenna-tracking systems are now needed on the earth stations, experiment operations continue with very little disruption.

The Experiments Program has validated the key ACTS technologies of Ka-band transmission, very wide bandwidth transponders, on-board switching, and high gain, hopping spot beams. The original goals of the Experiments Program were to:

- 1) Conduct technology verification experiments to evaluate and characterize the ACTS technologies and,
- 2) Conduct a balanced set of experiments and demonstrations to evaluate and promote new and innovative applications enabled by the ACTS technologies.

ACTS remains as the only operational testbed for Ka-band geosynchronous satellite communications over the Western hemisphere. The ACTS experiments program continues to support investigations by industry, government and academic organizations in preparation for the deployment of next generation commercial satellite communications systems. The last two years of operations have involved a number of experiments that integrate terrestrial computer and networking technologies with satellite networks.

By design, the ACTS experiments program seeks to gain greater relevance to NASA's mission from the results of the experiments that are performed.

Thus, the objectives of the Experiments Program during the Inclined Orbit phase of ACTS operations were redesigned to:

- 1) Demonstrate NASA and other Government use of future satellite services
- 2) Evaluate communication protocols for satellite-terrestrial network interoperability
- 3) Evaluate spot beam satellite inclined orbit operations
- 4) Verify new Ka-band technology and hardware.

Of particular interest is the evaluation of NASA's and other U.S. government agencies' transition to commercial space assets in order to meet their respective communications needs. Also, significant to both the government and commercial sectors is the investigation of issues related to interoperability with terrestrial networks of protocols such as TCP/IP and ATM over wide band satellites. NASA uses satellites extensively in near-Earth, inter-planetary, and deep space applications. NASA's goal is to extend the Internet to space to communicate with these systems based on commercial technologies and assets. Therefore, commercial entities have been involved in various activities to ensure that the hardware, software and protocols being used will include the characteristics of satellite links such as large bandwidth-delay products.

Acts High Data Rate (HDR) Background

The ACTS High Data Rate Experiments program, which combined truly unique ground and space capabilities with innovative applications, has exceeded expectations. Besides proving that satellite communications can be achieved at comparable speed and performance as fiber networks, the respective interoperability issues and promising applications have been dispelling conventional the "can't be done" myths.

The NASA Advanced Communications Technology Satellite (ACTS) has the bandwidth and the routing capability to provide wideband networking. This is referred to the Gigabit Satellite Network (GSN) and is comprised of several High Data Rate (HDR) ground stations in conjunction with the spacecraft's capability. The GSN was designed to provide fiber-like service by incorporating Reed-Solomon coding and offset-QPSK modulation to achieve 622 Mbps channels with bit error rates in the range of 10⁻¹². This is comparable to terrestrial OC-12 fiber service. The ground stations were designed with SONET interfaces and the flexibility to utilize either one 622 Mbps or a combination of 155 Mbps channels. Further, using electronically hopped spot beams and an on-board microwave switch matrix, true satellite-switched time division multiple access is achieved. The Defense Advanced Research Projects Agency (DARPA) partnered with NASA on the design, development, and operation of the GSN. In addition to the DARPA sponsorship of some trailblazing experimentation, the GSN has been interconnected with advanced research terrestrial networks such as DARPA's Advanced Technology Demonstration Network (ATDnet), Multimedia applications and Gigabit Internetwork Consortium (MAGIC), the National Transparent Optical Network (NTON), as well as the NASA Research & Education Network (NREN).

This capability enabled a unique and advanced experiments program to examine the feasibility of wideband satellite communications, respective protocol performance over wideband hybrid networks, and several interesting applications. The strategy of the HDR experiments program was to start simple and become increasingly complex in networking scenarios and technical objectives. After an intense GSN integration and test, the first such field experiment commenced in February 1995. A summary of the initial activity is provided in the following experiments and demonstrations: Engine Inlet Simulation (sponsored by NASA's High Performance Computing & communications Program (HPCCP))¹, Distributed 3-D Hydrodynamic and Atmospheric Forecast Modeling (sponsored by DARPA)² and the ACTS Results Conference (Sept. '95).

Since these trailblazing experiments validated the feasibility of wideband satellite communications, many combinations of ACTS and fiber terrestrial networks have been initiated involving a variety of investigations. These included advancing applications that take advantage of the capability and agility that this type of satellite system technology offers. A summary of the follow-on HDR activities conducted using ACTS:

Experiments - Keck Telescope Remote Astronomy (sponsored by NASA's HPCC)³, Global Climate Modeling (sponsored by NASA's HPCCP)⁴, Application of ACTS to Group Practice as a Paradigm for Clinical Outreach (sponsored by DARPA), ACTS and Supercomputing in Remote Cooperative Medical Triage Support and

Radiation Treatment Planning (sponsored by DARPA), TransPacific High Definition Video using ACTS and INTELSAT⁵, Tuning TCP over High Speed Satellite Links, Evaluation of ATM Flow Control and Traffic Monitoring Techniques in a 622 Mbps Hybrid Network, Multimedia Telemedicine Applications over ACTS, Access to Biomedical Databases over High Speed Satellite Networks, ATM Gran Prix, Multi-platform Evaluation of TCP/IP over ATM Interoperability over Hybrid Satellite Environment, Distributed Parallel Storage System Performance in a Hybrid Satellite Environment, High Speed TCP Interoperability Testing⁶, ATM and TCP Interactions, Joint ACTS Student Satellite Testbed Experiments, and High Performance TCP/IP Investigations as the Foundation for Internet in Space Implementation.

Demonstrations - ATM Research & Industrial Enterprise Study (ARIES) for Texas Medical Center in Houston (Oct. '95), Global Legal Information Network in Washington D.C. (May '96), ICC Supercom in Dallas (June '96), ARIES for Society of Exploration Geophysicists in Denver (Nov. '96), ARIES for Radiological Society of North America in Chicago (Dec. '96), Pacific Telecommunications Conference 97 in Honolulu (Jan. '97), Satellite Communications Exposition & Conference in Washington D.C. (Sept. '97), Supercomputing 97 in San Jose (Nov. '97), Pacific Telecommunications Conference 98 in Honolulu (Jan. '98), and Next Generation Internet/DARPA at Highway One facility in Washington D.C. (March '98).

Supercomputing '97 Demonstration

High Speed TCP/IP Data Transfer Demonstration using off-the-shelf application and hardware

Following a second four-month round of TCP/IP tests on ACTS at 622 Mbps called project 118j (one of a suite of experiments numerically designated as ACTS Experiment #118), it was decided to display the results publicly. The venue for this demonstration was SuperComputing '97 (SC97) in San Jose, CA during November 1997. The intent was to demonstrate the feasibility of exchanging a Terabyte of application data between the show floor in San Jose and Cleveland in under five hours using the ACTS as a primary component in a 622 Mbps ATM network. Ampex tape drives and robots were the source of the terabyte of application data and several Sun Ultra workstations were used to optimize TCP and ATM system parameters.

For the demonstration, a contiguous OC-12 link was established from Building 142 at the NASA Lewis Research Center, across the satellite to Lawrence Livermore National Laboratory in Livermore, CA. From there, the OC-12 traversed the backbone of the National Transparent Optical Network (NTON) into the San Jose Convention Center, where it connected, via a dedicated fiber, to the NASA booth on the show floor.

At the time of the demonstration, the only computational platforms that had been thoroughly tested were Sun Microsystems Ultra 2s, running Solaris 2.6. Most of the TCP/IP parameters that had recently been tested and verified in the experiment were now available in the production release of Solaris 2.6, so the implementation that was demonstrated at SC97 was using off-the-shelf TCP/IP capabilities, available to any host running Solaris 2.6.

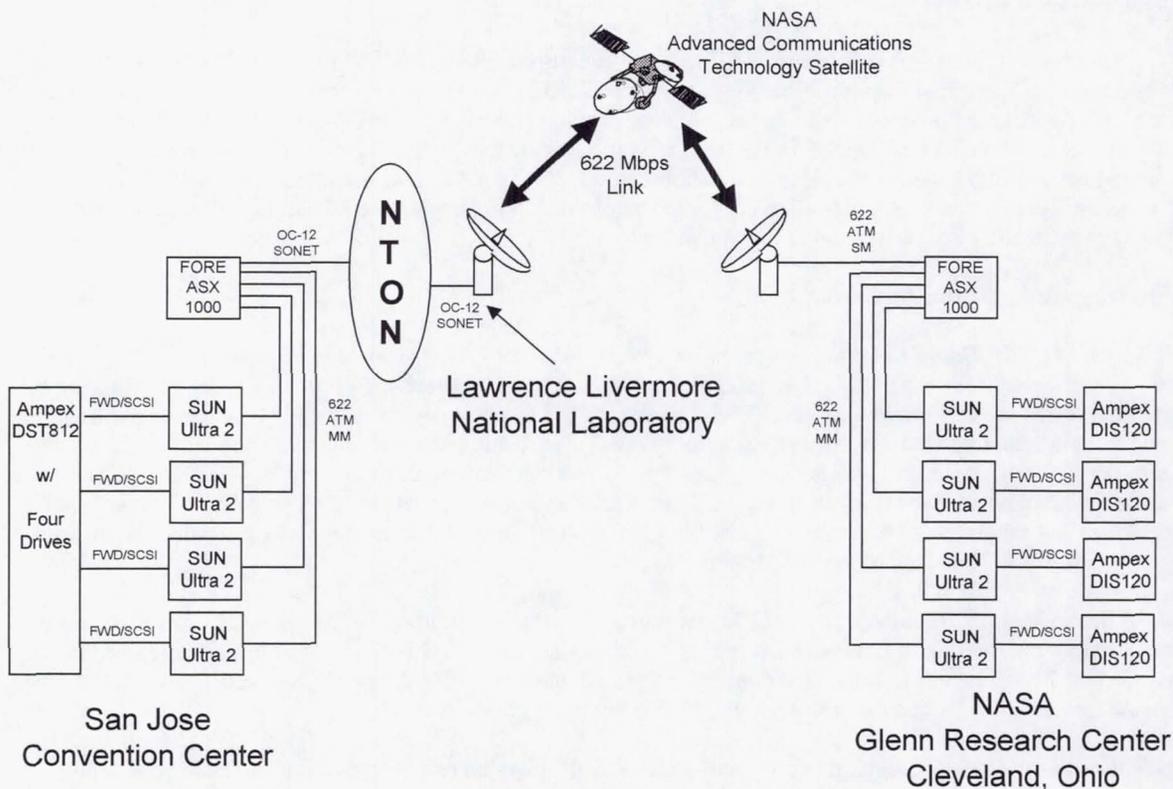
In addition to core protocol work with Sun, the 118j experiment team worked with Ampex Data Systems to gain a better understanding of the complexities of performing data transfer to and from high-performance tape peripheral devices. A data transfer program was written that resided in memory on the Ultra 2s and performed a 'shuttle' operation between the Ampex DIS-160 tape drives and the satellite network. The DIS-160 devices were capable of reading and writing tape at 20 Megabytes per second. In order to allow the tape devices to transfer data at line rate, the data transfer program moved data using optimized blocking factors to the tape devices (which were connected via Fast-Wide-Differential SCSI) and optimized TCP/IP parameters for the high-rate, long-delay satellite network. The goal of this portion of the demonstration was to make the satellite network appear to be transparent to the tape devices. Ampex provided four DIS-160 tape drives at each end of the satellite network to support the demonstration, which were also validated in the experiment.

This part of the demonstration was particularly taxing, since the only time the experiment team would ever have access to these tape assets would be at this particular venue, due to the high value of the borrowed equipment. Therefore, the team performed demonstrations during the day while the exhibits were open - and performed experiments and optimizations during the off-hours. The results were impressive:

Simultaneous tape to tape transfer using three pairs of workstations and tape drives reached an average, per stream, transfer rate of 120 Mbps and a single stream memory to memory transfer of 487 Mbps between an

Ultra workstation in San Jose and one in Cleveland. A peak transfer rate of 96% of the theoretical rate was obtained in this investigation thereby dispelling any myths using TCP/IP over geosynchronous satellites for wideband applications.

End-to-end Demonstration Layout at SuperComputing '97



Geographically Distributed Terrain Database using ACTS

Designed to showcase the high capacity, interactivity, and performance qualities of such hybrid networks, a three-dimensional Terravision⁷, developed by SRI International with NASA virtual reality (VR) extensions, demonstration also took place. ACTS OC-12 connectivity with the National Transparent Optical Network (NTON) and the NASA Research & Education Network (NREN) allowed users at SC97 to transverse through virtual territory by accessing data stored on servers at geographically dispersed servers. The VR equipment manipulated by the user senses the direction of movement and retrieves low resolution Bdata "tiles" adjacent to the direct path. As the direction of movement is confirmed, high resolution data replaces the low resolution "tile" - similar to your vision adjusting as your head movement dictates your ability to focus on any given area. Thus, the robustness of broadband digital satellites coupled with terrestrial fiber networks lets people test drive the technology and stimulate new and innovative applications.

High Speed Interoperability Testing

Beginning May 1998, the next round of 622 Mbps experiments on ACTS was started by the 118 experiment team known as Experiment 118x. These new set of OC-12 experiments tried to optimize point-to-point data transfer over ACTS using TCP/IP across multiple computer platforms and operating systems such as Sun, Silicon Graphics, IBM,

and Microsoft. Further, satellite manufacturers were involved to address, firsthand, any lingering questions concerning the ability/validity of TCP/IP and ATM to deliver advanced services over Geostationary platforms.

While previous experiments had focused on ATM switching equipment provided by FORE Systems and computer hardware provided by Sun Microsystems, there was a strong desire to perform TCP/IP performance tests on other networking hardware, as well as other operating systems and computing platforms. For this phase of the experiment, known as 118x, Sun Microsystems, FORE Systems and Ampex Data Systems were joined by Cisco Systems, Intel, Digital Equipment / Compaq, Microsoft, WindRiver Systems and FTP Software. The Sprint Advanced Technology Laboratory in Burlingame, CA provided laboratory space to the 118x team. The terminal at Lawrence Livermore was used for the experiment, and terrestrial connectivity between Lawrence Livermore and Burlingame was again provided by the NTON.

Additionally, since the experiment was of high interest to the satellite community, the 118x team invited the satellite industry to get involved with the experiments. During the experiment, Lockheed Martin, Space Systems/LORAL, Hughes Space & Communications, and Spectrum Astro all participated in team meetings and helped to keep the experiment configurations and results reporting relevant.

Unfortunately, during the period of time that encompassed the 118x experiment, the ACTS High Data Rate network was plagued with problems that limited the team's aggressive schedule and test productivity. Many of the platforms were successfully tested, however - setting the stage for the next phase of experiments, which became known as '118neXt' or officially as ACTS Experiment #154.

High Performance TCP/IP Investigations As The Foundation For Internet In Space Implementation

Background

Experiment 154 expanded on the partnerships, "lessons learned" and goals resulting from the previous 118 series of experiments. It is currently examining alternative network transports such as Gigabit Ethernet, 100-baseT, and "Packet over SONET" besides a pure ATM transport, active areas research of "Error Vs Congestion" TCP/IP work such Explicit Congestion Notification (ECN), and the newer OS and workstation platforms available.

Original research examined how bulk "TCP/IP over ATM" transfers behaved using "standards-based", "off the shelf" workstation equipment and OSs over the ACTS satellite using a subset of equipment and partners at 622Mps with a ~530ms RTT available to Experiment 154. The goal was to convince system integrators when "standards-based" systems can support hybrid terrestrial/satellite system and where further work was needed. Experiment 154 furthers this goal by revisiting earlier immature software and hardware platforms. Also, it explores technologies and partners previously unavailable by creating two major objectives reflecting the earlier spirit of Experiment 118 and current Experiment 154 goals.

This network was built upon previous configurations, but added participation by Cabletron Systems, Hewlett-Packard, and IBM on the networking and computing hardware side. Also, several other NASA centers became more actively involved in the experiment and dialogue during Experiment 154, including the Goddard Space Flight Center and the Ames Research Center.

Also, during the break between 118x and 154 experiments, the Consolidated Space Operations Contract (CSOC) at the Johnson Space Center became active in the experiment. The Prime Contractor on CSOC is Lockheed Martin Space Operations (LMSO). An ACTS HDR Terminal was installed at the LMSO 'CSOC Central' facility in Houston, TX, about three miles from the Johnson Space Center. For all 154 experiment operations, the satellite link was connected between NASA Glenn in Cleveland and LMSO in Houston. Several LMSO engineers and Co-op students also supported the experiment configuration from the Houston location.

In an effort to stay abreast of advancements in the state-of-the-network, the 154 team endeavored to examine two relatively new networking technologies that were now available - Packet over SONET (POS) across the satellite network and Gigabit Ethernet in the Local Area Network. Cisco Systems and Cabletron Systems provided PoS technology. All new computing platforms were equipped with capability to handle ATM at 155 and

622 Mbps, 10/100 Ethernet, and Gigabit Ethernet. This mix of technologies offered a wide range of new test configurations. However, the small size of the core experiment team, coupled with the continued erratic behavior of the HDR network both limited the team's productivity.

The first objective is "Cross Vendor TCP/IP Interoperability testing over large (Bandwidth*Delay) networks". This explores the homogenous and heterogeneous testing of current commercial TCP/IP stacks using "off the shelf" equipment in high bandwidth and delay environment. This environment is a 540ms RTT, 622Mb OC12c SONET link between Houston, TX and Cleveland, OH using various network protocol transports on the LAN and WAN side. Packet traces, various network, workstation, operating system parameters, experimental tools were used to provide feedback to vendors/researchers on how commercial TCP/IP stacks behave for bulk TCP/IP transfers in an high*BW environment such as ACTS. As of this writing, there doesn't exist a commercial OC12 SONET delay to explore this realm of research. It is anticipated future satellite system supporting these rates or higher can rely on more commercial solutions for data interoperability into existing terrestrial networks.

The second objective examines "errors vs congestion TCP/IP behavior in an high delay and deterministically errorable satellite link". Experiment 154 provides a satellite testbed to examine how network congestion and errors influence commercial and research TCP/IP stacks across the ACTS satellite using deterministic error and congestion environment. Again, it is anticipated the information influences future satellite system to use commercial, "off the shelf" solutions to preserve interoperability between diverse workstation and networking platforms.

As of April 8, 2000, we are preceding to complete the objectives before the end of life of ACTS scheduled for May 31, 2000. The subsets completed will depend on the health and operational status of the satellite network of a system well past its original design life for high data rate experiments. Please see <http://acts.grc.nasa.gov> for any updates not reflected in this paper. These types of high bandwidth delay product investigations need to continue as other hybrid network opportunities become available.

Our present list of partners with no preferential order: NASA Glenn Research Center at Lewis Field's Space Communications Office, Lockheed Martin Space Operations Company (LMSOC) under the Consolidated Space Operations Contract (CSOC), NASA Johnson Space Center, Sun Microsystems, Compaq, IBM, Microsoft, HP, Intel, Marconi(Fore Systems), Cisco Systems, Cabletron, 3Com, Yuri System, Hughes, Boeing, Spectrum Astro, Ampex Data and Jet Propulsion Laboratory.

Our list of equipment with no preferential order: Marconi ASX2400 switch, Marconi ASX1200 ATM switch, Cisco 7507, Cabletron SSR8000, Compaq Alphas(Au600+AXP1000), Compaq Proliant 6400R dual processor PentiumIII, IBM RS6000, SUN Ultra60, Sun Netra, SUN atmcard, Marconi HE622 + PCA200, gigabit cards, and HP J5600 workstation.

Cross Vendor TCP/IP Interoperability Testing Over Large (Bandwidth*Delay) Networks

Background

The primary objective is to document the progressive steps required to reach {near} optimal bulk TCP/IP data transfers between homogenous and heterogeneous platforms across a high bandwidth*delay path. Partner supplied equipment and workstations OS used tcp, tcptrace, netstat, tcpdump, vendor feedback, custom test scripts, network and workstations statistics and netperf to show these incremental data rate improvements. These tests became an iterative process of running simulated TCP/IP bulk transfers using tcp, examining the results at various network and workstation data points, working with vendors to optimize the next test by tuning or documenting kernel or workstation limitations, repeat until we reach the limits of the platform based on results reached by LAN test. These tests will be graphically plotted to see the effects of this tuning and feedback. The goal is to maximize the utilization of the link for TCP/IP.

Actual performance numbers are not intended for performance comparison between various vendors but to show how heterogeneous and homogenous workstations and networks behave in this extreme networking environment. Also, Experiment 154 examines if further work is necessary to get these platforms to interoperate while maximize the utilization of the data path.

Network, platform interconnectivity and equipment list

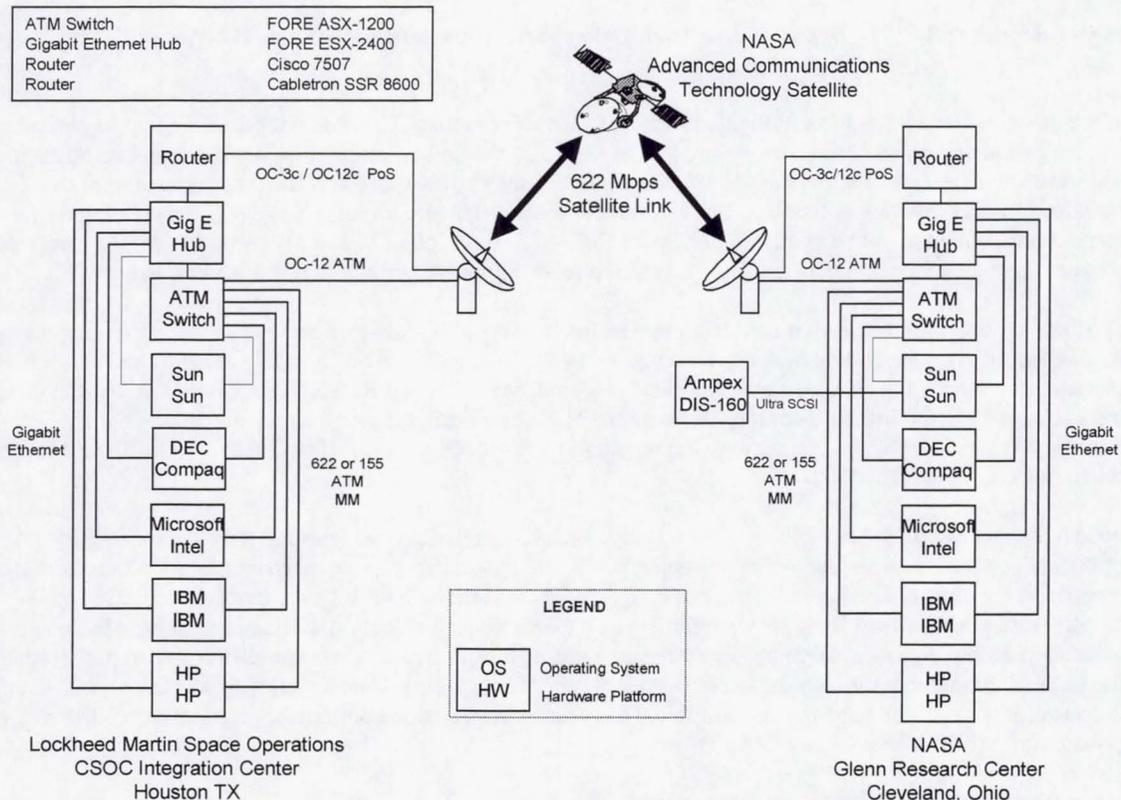
We are presently using these platforms and operating systems from:

- Compaq - Alpha processor-based 600au and AXP1000 platforms running TU64-4.0F and an Intel-based Proliant 6400R server running Windows2000 and Linux2.3.45. INTEL provided an earlier beta platform but was replaced when a COTS platform became available.
- IBM - RS60000 running AIX 4.3.4
- HP - J5600 running HP-UX.
- SUN - Ultra60 and Netra platforms running Solaris7/8

We are using network hardware from:

- Cisco Systems - 7507 series with "Packet over SONET"(POS) interfaces for 100BaseT and Gigabit across ACTS.
- Marconi Systems - ASX1200 ATM switches with FORERunner OC3 and OC12 workstations network cards and ESX2400 edge products for GigaBit and 100 BaseT connectivity using ATM over SONET across ACTS.
- Cabletron - SSR8000 for Gigabit over OC12 PoS between the two sites across ACTS.
- SUN and IBM network cards for Gigabit and "IP over ATM" OC12c support.

A C T S E x p e r i m e n t 1 5 4 e n d - t o - e n d N e t w o r k L a y o u t



Where are we now, as of April 3, 2000?

We have recorded network and platform statistics of Alpha to Alpha, IBM to IBM, Windows2000 to Windows2000, Sun to Sun, and some combinations of cross platform tests using a pure ATM transport at OC3/OC12, Gigabit and 100BaseT ethernet using ATM as the base transport across the satellite. Some of these tests have only verified

connectivity between platforms, while others have recorded TCP packet traces, network level statistics, and ATM cell rate traces during a bulk TCP/IP run.

We are seeing runs as low as 1 Mbps in some configurations to near line rate in other platform across the satellite. Currently, we don't feel comfortable associating vendor names to actual numbers until the end of the 154 experiments, set for May 2000. We are trying to document the steps necessary to bring the network utilizations of these systems up to the expected limits based on network and workstation architecture. If we can't, we need to get this information to the community to address those problems in a follow work. Please see: <http://acts.grc.nasa.gov> for updates during the summer of 2000.

Current test plan and goals until ACTS "end of life" on May 31, 2000

We are trying to finish recording TCP/IP bulk transfer behavior across ACTS with a combination of homogenous and heterogeneous platform using their respective ATM and ethernet interfaces for the three possible network configurations between the Cleveland, OH and Houston, TX.

1. Platform's ATM interface for IP transport using "ATM over SONET" across the ACTS satellite.
2. Platform's 100BaseT and GigaBit ethernet for IP transport using "ATM over SONET" across the ACTS satellite.
3. Platform's 100BaseT and GigaBit ethernet for IP transport using "Packet over SONET" across the ACTS satellite.

We are planning to record as much data as possible, based on the platform selected, for any future follow on work and completion of missed configurations. Please see <http://acts.grc.nasa.gov> for any updates not reflected in this paper. It is hope any missed configuration can be picked up when commercially available OC12c and higher SONET delay simulators and/or satellite links become available.

Errors vs Congestion TCP/IP Behavior in a High Delay and Deterministically Errorable Satellite Link

Background

One of the more challenging aspects of the high-performance work is that TCP/IP is not presently able to distinguish between errors and congestion. As a result, any loss of traffic on the end-to-end connection between two hosts is assumed to be caused by congestion. For satellite data transfer scenarios - especially those at high data rates - this effect can lead to very low link utilization. The experiment team endeavored to gain a better understanding of the various mechanisms that might be available to help TCP/IP do a better job of distinguishing between link errors and congestion. This part of the 154 experiment was referred to as 'Explicit Corruption Notification Testing'.

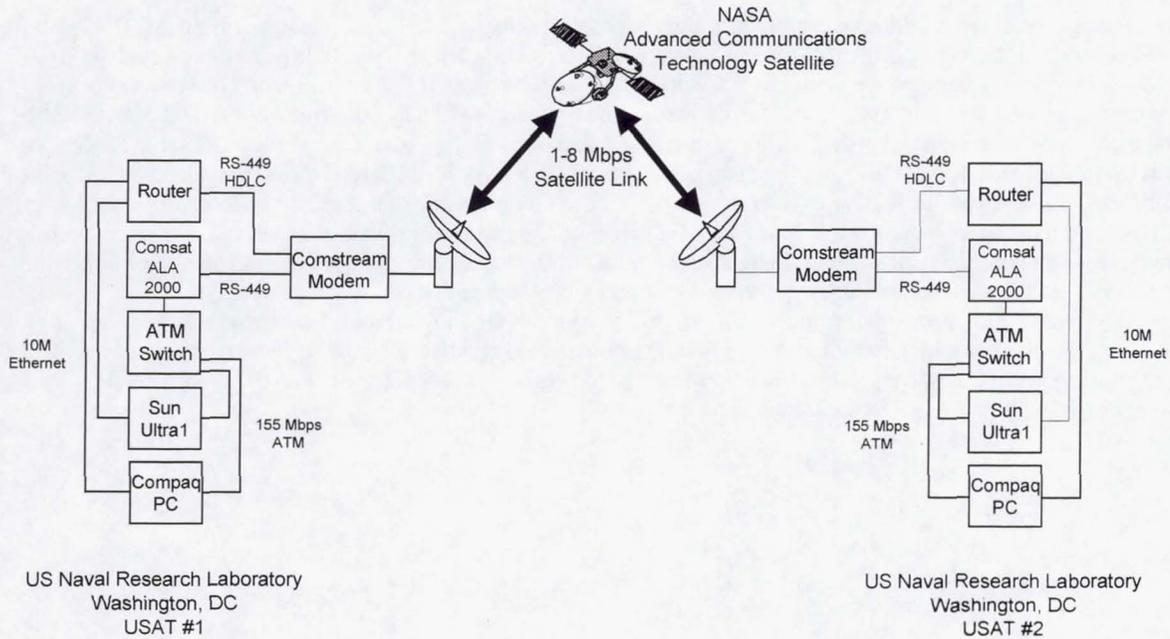
During March of 2000, the 154 experiment team started the process of building a new testbed facility to support links across the ACTS spacecraft at data rates ranging up to 8 Mbps, with any bit error rate. The testbed will utilize laboratories at the NASA Glenn Research Center in Cleveland, the US Naval Research Laboratory in Washington, DC, and Lockheed Martin Space Operations in Houston. The experimenters may leverage the unique ability of ACTS to support satellite links operating at extremely high rates (155Mbps, 622Mbps) for this work, should that be desirable in the context of these tests.

The focus of the new laboratory capability was to study mechanisms that provide explicit notification of link corruption and congestion, with the goal of gaining a better understanding of these mechanisms in order to promote further work on the most promising mechanisms. Insights gained from the Explicit Corruption Notification experiments would hopefully make it possible for Explicit Corruption Notification mechanisms to be safe for implementation in the Internet at-large at some point in the near future. The experiment team solicited participation from the Internet community through personal invitations, and through an announcement that was distributed via the IETF's 'tcpsat', 'pila', and 'end2end' interest groups. This work is expected to continue beyond the end of life of the ACTS spacecraft utilizing another satellite platform.

Network, platform interconnectivity and equipment list

The workstations and networking hardware to support the experiment were assembled initially at the Naval Research Laboratory in Washington, DC. This configuration initially included two Sun workstations supporting Solaris 7, and two PC platforms supporting Linux, FreeBSD and Win2000. Other platforms and operating system environments could be added at a later date depending on requirements.

1 5 4 E C N E x p e r i m e n t L a y o u t



Where are we now, as of April 3, 2000?

A number of experiment proposals were received and evaluated by the team for their ability to be integrated for testing in the new environment. For those mechanisms selected, access to the hardware platforms (in-person and/or remote) was provided, along with satellite time on the ACTS spacecraft for testing and evaluation of the mechanisms. Currently, the initial test configuration has been setup at the Naval Research Laboratory (NRL) and satellite checkouts have commenced.

Current test plan and goals until ACTS "end of life" on May 31, 2000

The current plan is to investigate the relation between congestion and link error detection/correction using various protocols such as TCP/IP, Satellite Communication Protocol Standard (SCPS) and protocol implementation and link characteristics.

Lesson learned to date for these objectives

Commercial equipment and networking hardware can support bulk transfer of TCP/IP using high bandwidth*delay satellite link such as ACTS. It is necessary to test these platforms to address any glitches discovered when running vendor's TCP/IP implementation in this extreme environment. Tuning and locating kernel/driver bugs may be required from the application down to the network card level but with proper tools and partner participation, we can show remarkable improvement of bulk TCP/IP data rates, without resorting to custom hacks to the TCP/IP protocol.

Conclusion

The convergence of the satellite, telecommunications, and computing industries has benefited from ACTS High Speed networking interoperability experiments. Data rates over hybrid terrestrial/satellite links have evolved from 70 Mbps TCP/IP requiring an high end ONYX workstation with beta quality OC3c workstation, networking equipment, and operating systems, in 1995, to achieving near theoretical TCP/IP performance at 622 Mbps/OC12 data rates, in 1999, using off-the-shelf network, hardware, and networking protocols. Thus, a GSN system designed to transport OC3c/OC12c SONET between two points in CONUS back in 1993 for Telcos, has adapted to support emerging COTS network technologies over the years. This evolution is one of our greatest accomplishments with the GSN and its success is greatly due to the government-industry partnerships that have formed to address such complex system issues. By using ACTS High Speed Network Interoperability Experiments to stay the course with commercial off-the-shelf technologies and demonstrate how the work is directly applicable to hybrid terrestrial/satellite systems, without resorting to propriety solutions for moving user data across a network. Therefore, this work has long term impacts upon how future hybrid architectures are implemented for space missions, data services, or even aeronautical applications to achieve a space internet or airborne internet by leveraging the terrestrial internet technologies.

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4.4 - Global Interoperability of High Definition Video Streams Via ACTS and Intelsat

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Abstract

In 1993, a proposal at the Japan-U.S. Cooperation in Space Program Workshop lead to a subsequent series of satellite communications experiments and demonstrations, under the title of *Trans-Pacific High Data Rate Satellite Communications Experiments*. The first of which is a joint collaboration between government and

industry teams in the United States and Japan that successfully demonstrated distributed high definition video (HDV) post-production on a global scale using a combination of high data rate satellites and terrestrial fiber optic asynchronous transfer mode (ATM) networks. The HDV experiment is the first GIBN experiment to establish a dual-hop broadband satellite link for the transmission of digital HDV over ATM.

This paper describes the team's effort in using the NASA Advanced Communications Technology Satellite (ACTS) at rates up to OC-3 (155 Mbps) between Los Angeles and Honolulu, and using Intelsat at rates up to DS-3 (45 Mbps) between Kapolei and Tokyo, with which HDV source material was transmitted between Sony Pictures High Definition Center (SPHDC) in Los Angeles and Sony Visual Communication Center (VCC) in Shinagawa, Tokyo. The global-scale connection also used terrestrial networks in Japan, the States of Hawaii and California.

The 1.2 Gbps digital HDV stream was compressed down to 22.5 Mbps using a proprietary Mitsubishi MPEG-2 codec that was ATM AAL-5 compatible. The codec employed four-way parallel processing. Improved versions of the codec are now commercially available. The successful post-production activity performed in Tokyo with a HDV clip transmitted from Los Angeles was predicated on the seamless interoperation of all the equipment between the sites, and was an exciting example in deploying a global-scale information infrastructure involving a combination of broadband satellites and terrestrial fiber optic networks. Correlation of atmospheric effects with cell loss, codec drop-out, and picture quality were made.

Current efforts in the Trans-Pacific series plan to examine the use of Internet Protocol (IP)-related technologies over such an infrastructure. The use of IP allows the general public to be an integral part of the exciting activities, helps to examine issues in constructing the solar-system internet, and affords an opportunity to tap the research results from the (reliable) multicast and distributed systems communities. The current Trans-Pacific projects, including remote astronomy and digital library (visible human) are briefly described.

1. Introduction

A series of satellite communications experiments and demonstrations involving a combination of broadband satellites and terrestrial fiber optic networks was proposed in the Japan-U.S. Cooperation in Space Program (later renamed the Japan-U.S. Science, Technology and Space Applications Program) in 1993. The experiments and demonstrations were initiated in 1996 by the Japan-U.S. Science, Technology and Space Applications Program (JUSTSAP) as part of the G-7 Nations' Information Society - Global Interoperability of Broadband Networks (GIBN) project, with the High Definition Video (HDV) experiment being the first of the series [1].

In the United States, the GIBN project is coordinated by the White House National Economic Council, the National Science Foundation, and NASA. In Japan, the GIBN project is coordinated by the Ministry of Posts and Telecommunications and the Communications Research Laboratory. And in Canada by the Communications Research Centre (CRC) and by Teleglobe Incorporated.

The experiments and demonstrations are being carried out at various data rates up to OC-3 (155 Mbps), in order to develop and test the transmission techniques and protocols that are needed to incorporate satellite links in high performance global telecommunications networks. The Trans-Pacific series included high definition video, digital library, remote astronomy, tele-medicine, and tele-education and a number of other experiments and demonstrations.

In the HDV experiment, the teams in the United States and Japan demonstrated distributed high definition video (HDV) post-production on a global scale using a combination of high data rate satellites (Intelsat and NASA ACTS) and terrestrial fiber optic asynchronous transfer mode (ATM) networks. HDV source material was transmitted and composited in real-time between Sony Pictures High Definition Center (SPHDC) in Los Angeles and Sony Visual Communication Center (VCC) in Shinagawa, Tokyo, demonstrating that satellites can deliver digital image traffic at data rates up to OC-3 and with quality comparable to that of fiber optic cables [2, 3, 4].

The post-production-phase compositing process was performed in Tokyo on a green-screen HDV clip transmitted from Los Angeles. Test clips were also transmitted from Tokyo and Los Angeles and viewed on both sides in one-way or loop-back modes. The activities successfully demonstrated the global-scale infrastructure's feasibility in rapid transfer of HDV streams between remote shooting locations and post-production facilities. And when coupled with reliable multicast technology and digital cinema projection systems, the combination of broadband satellites and fiber optic networks help efficiently bring high definition

virtual studios and digital theaters to locations never before possible. Additional Trans-Pacific experiments and demonstrations are being conducted and are briefly described.

2. The Participants in the HDV Experiment

The Japanese participants of the HDV experiment included the Communications Research Laboratory (CRL), Japan Ministry of Posts and Telecommunications (MPT), Kokusai Denshin Denwa Company, Limited (KDD), Mitsubishi Electric Corporation, Nippon Telegraph and Telephone Corporation (NTT), and Sony Corporation; the U.S. participants included Comsat, the George Washington University, GTE Hawaiian Tel, Japan-U.S. Science, Technology and Space Applications Program (JUSTSAP), Lockheed Martin, NASA Headquarters, NASA Glenn Research Center (GRC), NASA Research and Education Network (NREN), NASA Jet Propulsion Laboratory (JPL), Newbridge Networks Inc., Pacific Bell California Research and Education Network (CalREN), Pacific Space Center (Pac Space), Sony Picture High Definition Center (SPHDC), State of Hawaii, and Tripler Army Medical Center (TAMC). An international organization, Intelsat, also participated.

In the current phase of the Trans-Pacific experiments and demonstrations, we have added the following participants: AT&T Canada, BC Net (Canada), Canada's Communications Research Centre (CRC), Japan Gigabit Network, JSAT Corporation, Institute of Space and Astronautical Science (ISAS, Japan), Mt. Wilson Institute, NASA Goddard Space Flight Center, National Library of Medicine/National Institute of Health, NTT Communications, Sapporo Medical University, Soka High School, Thomas Jefferson High School, Teleglobe Incorporated, and University of Maryland.

3. Network Configuration and ATM Analyzers

The end-to-end path configuration of the experimental link is shown in Figure 1. A high data rate link between the U.S. and Japan was established by a combination of two broadband satellites and several terrestrial fiber optic networks [2].

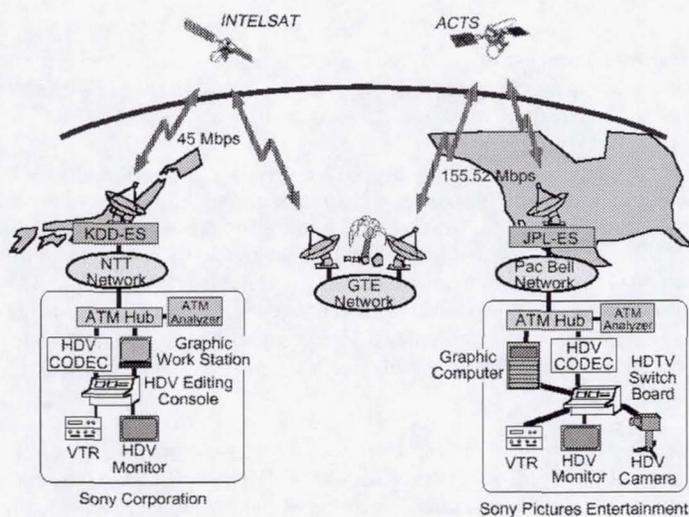


Figure 1. SYSTEM CONFIGURATION OF THE TRANS-PACIFIC HIGH DEFINITION VIDEO EXPERIMENT

On the Eastern Pacific, the NASA ACTS served to link the U.S. mainland and Hawaii. The satellite link operated at rates up to OC-3 (155 Mbps), and connected the fiber optic networks of GTE Hawaiian Tel and Pacific Bell CalREN. The various terrestrial facilities consisted of the GTE Hawaiian Tel network, Tripler Army Medical Center ACTS earth station, JPL ACTS earth station, Pacific Bell CalREN, and Sony Pictures High Definition Center in Culver City, California. The ATM switches used in the GTE Hawaiian Tel and Pacific Bell CalREN networks were manufactured by Newbridge, Cisco and Fore Systems. The ACTS terminal was constructed by Bolt Beranek and Newman Inc. (BBN), and the major components consisted of a 3.4 meter

antenna made by Prodelin, digital terminal electronics made by BBN, and a 696 Mbps modem made by Motorola. The uplink frequency of 29.4 GHz and the downlink frequency of 19.6 GHz were used, and the terminals employed BPSK (binary phase-shift keying) modulation scheme and Reed-Solomon (232, 216) error correction code. The ACTS satellite was used in the bent-pipe mode using the Microwave Switch Matrix (MSM) during the experiment.

On the Western Pacific, the Intelsat 701 satellite served to link Tokyo to Hawaii at rates up to DS-3 (45 Mbps), and connected the fiber optic networks of KDD, NTT, and GTE Hawaiian Tel. The various terrestrial facilities consisted of the GTE Hawaiian Tel network, GTE Hawaiian Tel Kapolei Intelsat earth station, KDD Shinjuku Intelsat earth station, KDD and NTT ATM networks, and Sony Visual Communication Center (VCC) in Shinagawa, Tokyo. The ATM switches used in the KDD and NTT networks were manufactured by Fore, Lucent, and Fujitsu. Intelsat provided the use of its 701 satellite for the experiment, and the transponder was cross-strapped between Ku-band (towards Japan) and C-band (towards Hawaii). The uplink frequency was 14 GHz and the downlink frequency was 11 GHz on the Japan side; the uplink frequency was 6 GHz and the downlink frequency was 4 GHz towards the Hawaii side. The NEC/KDD modem used in the Intelsat earth station was a QPSK (quadrature phase-shift keying) modem with concatenated error correction code of 7/8 Viterbi and Reed-Solomon (255, 239), with bit interleaving to reduce cell loss.

Sony HDD-1000 recorders (VTR's) were used to play and record HDV. Sony HDC-500 High Definition CCD cameras were used to capture images for post-production processing. High definition video system monitors and projectors were used at both locations in console- or theatre-viewing of the images.

4. High Definition Video and Blue/Green-Screen Compositing

The high definition video equipment used conform to the Society of Motion Picture and Television Engineers (SMPTE) 240M-1994 formats [1]. It is a production system that matches or exceeds the quality of film while delivering the convenience of digital production and transmission. The format specifies 1035 active lines per frame and 1920 active samples per line (1035v x 1920h), with the aspect ratio of 16:9. The raw bit rate is 1.2 Gbps.

Blue/green-screen compositing is a process of recording subject images in front of an entirely blue or green background. The background may later be replaced in the post-production process with selected images to create the appearance of subjects being filmed in various locations or with special effects.

In the traditional way of film-making, performing blue/green-screen cinematography with photographic materials often takes weeks and many iterations between the director and the film laboratory to produce images matching the director's vision. The virtual studio concept demonstrated by the experiment would allow the post-production processing to be done in real-time and from locations not served by broadband terrestrial networks. The resulting video may then be viewed at remote locations using a portable HDV monitor. This made possible the instant review of compositing results and permitted the changes in remote HDV cinematography to the director's liking. The real-time post-production activities therefore significantly cut down on the amount of time needed for compositing, as well as shorten the length of time a cinematography team and props needs to be deployed at a remote location.

The HDV codec supplied by Mitsubishi Electric Corporation was a proprietary piece of equipment implementing a four-way parallel MPEG-2 processing for the SMPTE 240M/260M formats. Commercial versions of the codec are now available. The data rates generated by the codec can be selected from 22.5 Mbps, 60 Mbps, and 120 Mbps. The 22.5 Mbps mode was used in the experiment. The experimental codec had a small buffer, and therefore required strict timing synchronization to prevent overrun/underrun situations. An off-sync condition resulted from cell-loss affected the video in the way of frozen images (freeze-frame). There were no large, scrambled blocks or distorted audio as reported in other implementations [5,6]. In this way the codec robustly handled the cell-loss condition. The codec was interfaced to the Trans-Pacific network using ATM AAL-5 through a Cell Layer Assembly and Disassembly (CLAD) device. The MPEG-2 codec transformed the video stream into ATM cells for AAL-5. Typically, AAL-1 would be used compensate delay variation for constant-bit-rate (CBR) applications, but AAL-5 does not have such function. The experiment demonstrated that the Trans-Pacific satellite/terrestrial hybrid network provided a high quality link which did not require AAL-1 function to be used.

A part of the HDV post-production demonstration held involved green-screen cinematography performed at the SPHDC, the transmission of the images to Sony VCC in Japan for post-production processing, and the review of results at both locations.

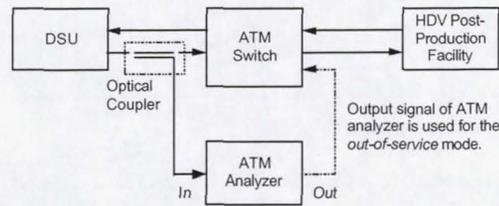


Figure 2. ATM MONITORING SYSTEM CONFIGURATION

5. ATM Link Performance

ATM link performance was measured using two Hewlett Packard 37717C ATM analyzers. A monitoring system was installed at each end point (Sony VCC and SPHDC) to measure the ATM layer transmission performance. Test cells were looped back from various points along the Trans-Pacific network.

The ATM monitoring system is shown in Figure 2. One such system was installed at each of the two end points in the Trans-Pacific infrastructure to measure ATM transmission performance. The ATM Hewlett Packard 37717C analyzer generated test cells and measured, in *out-of-service mode*, ATM layer items including cell loss, cell error, cell delay, HEC error SONET/SDH status. The end-to-end ATM test-cell results measured the performance of both the Intelsat and ACTS links.

The cell delay (CD) and cell delay variation (CDV) were shown in Table 1 were measured from SPHDC, which is reflected in those measured from Sony VCC. CD is the result of various equipment and link propagation delay, particularly over two satellite hops; CDV affects the quality of CBR services. The one-point (round-trip) CDV measured was always within 2 μ Sec. The variation was about 6 cell-times in duration, but the jitter was not expected to affect most applications with sufficient memory buffers. The two-point (one-way) CDV measured was 0 μ Sec, with a round-trip-time of about 1.07 seconds, during a few hours of measurement in this mode. The measurements showed that the end-to-end link was very stable in terms of cell delay and variation performances.

Source	Loop-back point	Cell delay	Cell delay variation
SPHDC	TAMC earth station	555000 μ s	2 μ s
SPHDC	KDD earth station	1069547 μ s	2 μ s
SPHDC-JPL-GRC	TAMC earth station	555745 μ s	2 μ s

Table 1. LOOP-BACK DELAYS AND VARIATIONS MEASURED FROM SPHDC. (A connection was also set up between JPL and GRC, via NREN, to re-route test traffic during JPL ACTS earth station maintenance periods).

Date (U.S.)	Honolulu Weather	ACTS BER Log	ATM Tester Results
Mar 10 <i>Rain/Overcast Layer</i>	05:56-08:56pm PST 3000 ft few, 3500 ft few, 13000 ft broken, 23000 ft overcast. Rain showers in vicinity, south east.	No error for four hours. Bursts of errors in the last ten minutes of the experiment.	Looped back at Tripler, Hawaii. No error in 9.5×10^8 cells (2 hr and 50 min). Cell loss ratio of 4.2×10^{-4} and error ratio of 1.9×10^{-5} for last 10 minutes.
Mar 18 <i>Broken Layer</i>	04:50-07:50pm PST 4000 ft scattered, 8500 ft broken - 4000 ft few.	No errors for two hours.	Looped back at Sony VCC. No error in 1.34×10^8 cells.
Mar 20 ¹ <i>Broken Layers</i>	06:50-09:20pm PST 5500 ft broken, 7000 ft broken, 14000 ft broken, 23000 ft broken.	A few errors in a ten-minute block in the first hour. Otherwise, error-free.	Looped back at GTE, Honolulu. No error in one hour. Looped back at Sony VCC. No error in 10 minutes.
Mar 27 <i>Broken Layer</i>	06:50-09:50pm PST 3500 ft broken.	No errors in six hours.	Looped back at Sony VCC. One cell error in six hours. ²

1. Most of the time used for end-to-end HDV transmission.
2. ATM tester used to monitor the end-to-end traffic.

Table 2. ACTS AND ATM PERFORMANCE

The errors dominating the link were the result of rain attenuation of the Ka-band transmissions from Hawaii. Asymmetric performance was observed in the end-to-end link at times. The JPL-to-TAMC link generally ran error-free regardless of the weather condition in Los Angeles or Hawaii; the performance of the TAMC-to-JPL link depended highly on the weather condition in Hawaii. If it was overcast or raining in Hawaii, the error rate would generally be high. There would also be occasional link outages (Table 2).

The difference in link performances can be partially explained by the fact that the earth station antenna of the TAMC HDR has a very low elevation angle. Signals to Hawaii had to go through relatively thicker cloud layers or precipitation in this low elevation path. It needs to be noted that the ACTS satellite was originally designed to provide communications within the forty-eight contiguous states, but not to communicate with Hawaii. The steerable beam antenna had to be used in the Hawaiian link because the state is located outside the coverage of fixed-beam antennas. The satellite link margin was small with the steerable beam antenna, especially in Ka-band, which the signal underwent fading in rain. The experiment was also conducted in February and March, which are two of the wettest months in Honolulu¹.

The terrestrial fiber network did not contribute to the error statistics significantly. This result was consistent with the characteristics of satellite design and link frequency.

The ACTS HDR earth stations kept a log of the link status. The log files were updated every 10 minutes and included estimates of error rates before and after the Reed-Solomon decoder. The error rates were recorded in terms of the number of erroneous satellite cells (S-cell) in ten-minute intervals as detected by the Reed-Solomon decoder. Each S-cell contained 215 bytes of data and was about 1.03 ms in duration. According to Figure 3, about 70% of the time during the experiment the ACTS links were error free. And the S-cell error rate was approximately the same from 10^{-6} to 1.0.

¹ The weather data used was obtained from the U.S. National Weather Service hourly observations. Average rainfall data, Honolulu, HI, October 1, 1949-January 31, 1997.

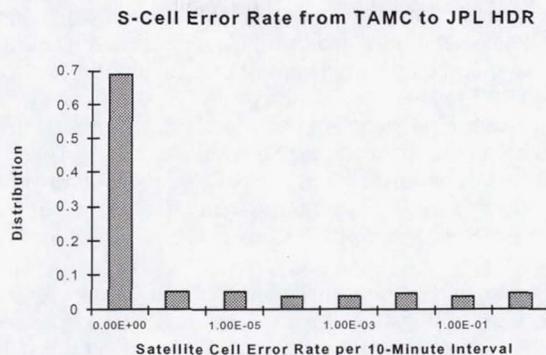


Figure 3. HISTOGRAM OF ACTS S-CELL ERROR RATE FROM THE TRIPLER HDR TO THE JPL HDR TERMINAL.

6. HDV Performance

The experimental codec was originally designed for use with highly reliable terrestrial fiber optic networks. It had performed well in this experiment. Compared to the original uncompressed digital HDV source, the output of the video codec had no visible compression artifacts. In fact, in most instances the imperfections in the original source material were revealed. The only observable effect of the codec and the network was the occasional freeze-frame and/or silenced audio. A freeze-frame typically lasted around one second before the codec re-acquired the frame structure. There were no large, scrambled blocks or distorted audio as reported in other implementations [5,6]. In this manner the experimental device handled the cell-loss condition gracefully. It was observed that there were sporadic freeze-frames even when the codec was connected to an ATM switch in the loop-back mode. This effect was attributed primarily to the small buffer size and the occasional off-sync condition in the experimental implementation.

The observed HDV results drew parallel to those from the ATM monitoring system. When the weather in Hawaii was clear or had moderate cloud covers, the ACTS link generally ran error-free and the performance of the HDV was good. When it rained or when the cloud layer was thick in Honolulu, the ACTS link performance was poor and the HDV codec had a difficult time extracting frame synchronization information, resulting in many freeze-frames. Some of the freeze-frames could last several seconds as the ACTS link continued to be attenuated, particularly on the TAMC-to-JPL link.

7. Current Activity

The Trans-Pacific High Data Rate (HDR) Satellite Communications Experiments included areas of high definition video post-production, remote astronomy, tele-medicine, tele-education, electronic commerce, and digital libraries [7, 8]. The experiments and demonstrations help explore and develop satellite transmission techniques, standards, and protocols in order to determine how best to incorporate satellite links with fiber optic cables to form high performance global telecommunications networks. Participants in these experiments will include the G7 countries, and other non-G7 countries will be invited as well.

At present time, the remote astronomy and visible human experiments are being carried out. The current phase of the experiments and demonstrations focuses on the use of Internet Protocol based technologies at rates up to OC-3 (155 Mbps). The technology also helps the participation of students and perhaps the general public.

The *Visible Human* experiment is the first step in prototype image database services over high-speed communications networks. A digital image library of volumetric data representing a complete, normal adult male and female cadaver. The thinly sliced images of cryosections that are derived from computerized tomography and magnetic resonance reside at the National Library of Medicine (NLM) in Maryland. The dataset is accessible by multiple nations. The current goal of this phase includes segmentation, classification, and three-dimensional rendering of the data set. Distributed processing will be conducted over the infrastructure.

The *Remote Astronomy* experiment aims to create a wide-area environment for distance learning and collaboration using Internet Protocol multicast and distributed file system. The experiment consists of collection of performance data and remote observation and control using multicast [9, 10] and distributed file access technologies. The application will establish a remote astronomy system using the Mt. Wilson 14" and 24" observational facilities from locations in North America and Japan. The initial use of the observatory will be scientists and students in the US and Japan, including Soka High School in Tokyo and Thomas Jefferson High School in Maryland. Wide area lectures, discussions and collaborations (post-processing) will be possible using a multicast teleconferencing system and distributed file system. The team has also developed a software ACTS link model for use with the Virtual InterNetwork Testbed for performance analysis purposes [11].

The capabilities afforded by an emerging global scale broadband information infrastructure emphasize the distributed nature of today's information systems. One such example is the solar system internet. These systems bring with it issues of scale, heterogeneity, robustness, and interoperability [12], and compose part of the questions the team will help address.

8. Conclusion

The Trans-Pacific High Definition Video Experiment tested the ability of satellites to carry high definition video signals for post-production processing between Sony studios in Tokyo and Los Angeles and successfully established an end-to-end Trans-Pacific link over two broadband satellites for streaming HDV traffic. The relatively good results obtained encourage the construction of a global information infrastructure utilizing broadband satellite systems.

The success of the HDV experiment demonstrated the feasibility of a global information infrastructure utilizing a combination of broadband satellites and terrestrial fiber optic networks. It is a result of seamless team work by an international group of participants, and also marked an exciting beginning for the GIBN Trans-Pacific High Data Rate (HDR) Satellite Communications Experiments. The team currently is carrying out new experiments and demonstrations using the Internet Protocol based technology [7, 8, 13]. The technology helps involve students and perhaps the general public in the exciting series of satellite communications experiments in the global information infrastructure, with results also applicable to the emerging solar system internet and next generation internet projects [14].

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The Trans-Pacific team welcomes new participants from AT&T Canada, BC Net (Canada), Canada's Communications Research Centre (CRC), Japan Gigabit Network, JSAT Corporation, Institute of Space and Astronautical Science (ISAS, Japan), Mt. Wilson Institute, NASA Goddard Space Flight Center, National Library of Medicine/National Institute of Health, NTT Communications, Sapporo Medical University, Soka High School, Thomas Jefferson High School, Teleglobe Incorporated, and University of Maryland.

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5.1 - Partnering to Change the Way NASA and the Nation Communicate Through Space

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Introduction

For at least 20 years, the Space Communications Program at NASA Glenn Research Center (GRC) has focused on enhancing the capability and competitiveness of the U.S. commercial communications satellite industry. GRC has partnered with the industry on the development of enabling technologies to help maintain U.S. pre-eminence in the worldwide communications satellite marketplace. The Advanced Communications Technology Satellite (ACTS) has been the most significant space communications technology endeavor ever performed at GRC, and the centerpiece of GRC's communication technology program for the last decade.

Under new sponsorship from NASA's Human Exploration and Development of Space Enterprise, GRC has transitioned the focus and direction of its program, from commercial relevance to NASA mission relevance. Instead of one major experimental spacecraft and one headquarters sponsor, GRC is now exploring opportunities for all of NASA's Enterprises to benefit from advances in space communications technologies, and accomplish their missions through the use of existing and emerging commercially provided services. A growing vision within NASA is to leverage the best commercial standards, technologies, and services as a starting point to satisfy NASA's unique needs. GRC's heritage of industry partnerships is closely aligned with this vision.

NASA intends to leverage the explosive growth of the telecommunications industry through its impressive technology advancements and potential new commercial satellite systems. GRC's partnerships with the industry, academia, and other government agencies will directly support all four NASA's future mission needs, while advancing the state of the art of commercial practice. GRC now conducts applied research and develops and demonstrates advanced communications and network technologies in support of all four NASA Enterprises (Human Exploration and Development of Space, Space Science, Earth Science, and Aero-Space Technologies).

Human Exploration and Development of Space (HEDS)

The Space Operations/Communication Technology Project sponsors development of advanced communications and space Internet technologies at higher levels of readiness for infusion to increase data return and decrease costs for support of NASA's missions. Through strong partnerships with industry leaders and innovators, GRC is committed to the development of high performance communication products for use in future NASA spacecraft and the ground and space assets that support them. GRC is identifying, developing, and infusing high

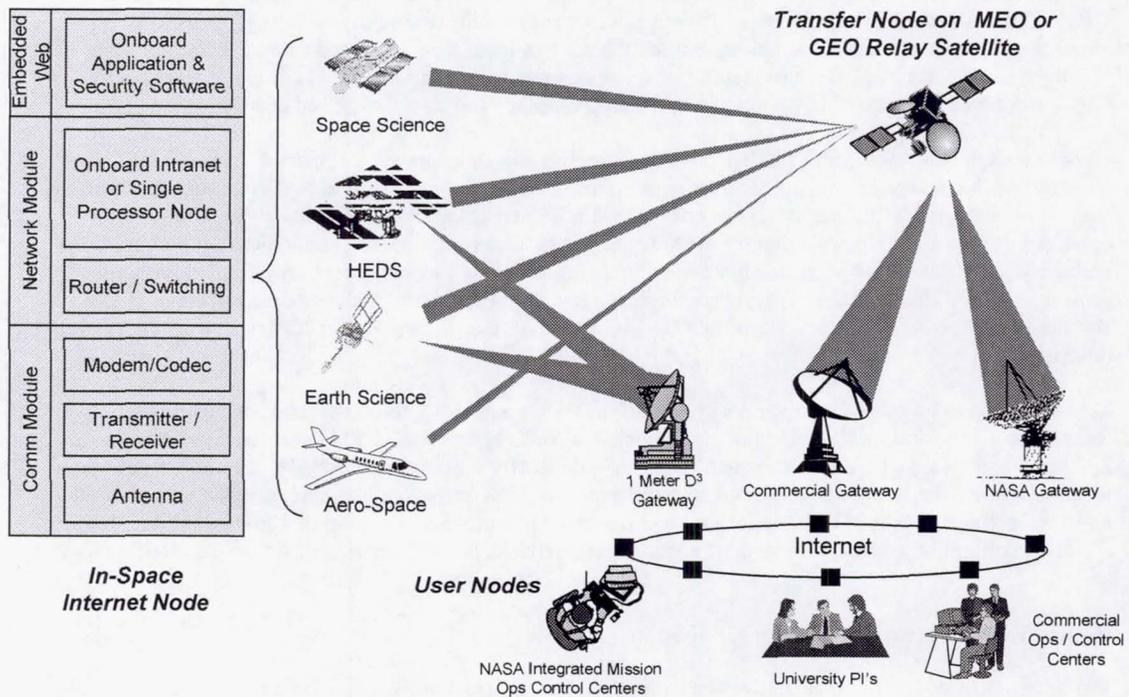
performance communications technologies necessary to enable or enhance mission data services and to achieve seamless interoperability among NASA, commercial satellite, and terrestrial communications systems. These technology products will leverage commercially provided capabilities to support inter-orbital, inter-satellite links with commercial space networks, intra-network links within science spacecraft constellations, while interoperating with terrestrial networks.

As much as possible, future communications system architectures will draw on existing and planned commercial satellite constellations and ground-based infrastructure to meet NASA's needs. Using future NASA systems in conjunction with anticipated commercial space networks at higher frequencies (Ka-Band and above) will provide higher rate capability and enable reduction in component size, thereby reducing NASA mission development and operational costs. Commercial capability (both space-based and terrestrial-based) will enable improved connectivity to mission operations centers, principal investigators, and the technical and science community. Advanced physical and data link layer technologies in both space and ground systems will enable the extension of Internet type services to NASA spacecraft.

Advanced Communications

GRC will continue to partner with the industry on development of new products with enhanced performance and efficiency, and their demonstration in environments suitable to retire operational risk. These products include electronically steered antennas, such as MMIC-based phased arrays and ferroelectric based reflectarrays, bandwidth and power efficient high rate modems, low noise receivers, solid state and traveling wave tube amplifiers at Ka-band frequencies and above, and other service enabling technologies. The advanced components are intended to increase data rate capability, reduce component size and improve power efficiency and spectrum utilization.

New system designs will include the transition to higher frequencies. GRC's propagation data collection and analysis play a key role in satellite link analysis and future component capability and requirements. Ground system architectures will include satellite acquisition and hand-off techniques, and advance tracking algorithms using electronically steered phased array and reflect-array antennas designed to improve and automate station operations and reduce costs.

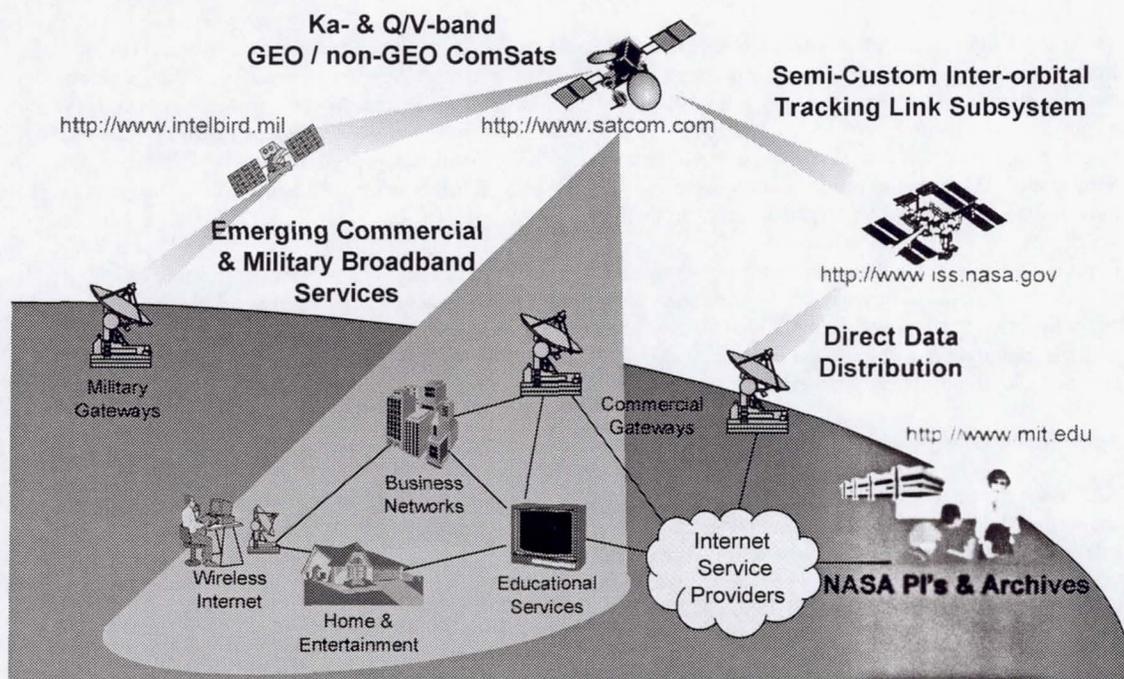


GRC is also integrating these advanced communications technologies into demonstrations of high data rate communications systems. The Direct Data Distribution (D³) project will demonstrate high-performance array antenna and digital modulation system that transmit information from a low-Earth orbit (LEO) spacecraft at

622-Mbps to an ultra low-noise, 1-meter receiving terminal on the Earth. This revolutionary capability will enable the distribution of substantially increased amounts of data from LEO spacecraft directly to NASA field centers, principal investigators, or into the commercial terrestrial communications network. GRC's industry partners on the array (Raytheon), modem (SiCOM) and ground terminal (Teledesic) have invested more than 50% of the cost of these product developments, because of their potential to satisfy commercial needs as well as NASA's.

Space Internet

GRC is investing in network technologies to extend the capabilities of the terrestrial Internet into space. GRC is partnering with key commercial network hardware and software providers, (such as Sun Microsystems, Digital/Compaq, Microsoft, Intel, IBM, Wind River Systems, Hewlett Packard) communications providers (Cisco Systems, Ampex Data Systems, Fore Systems, Raytheon Telecommunications, Cabletron Systems) and spacecraft vendors (Hughes, Boeing, Space Systems/Loral, Lockheed Martin, Spectrum Astro), U.S. government labs (GRC, Johnson Space Center, Goddard Space Flight Center, Jet Propulsion Laboratory, Ames Research Center, Navy Research Laboratory) and universities (New Mexico State, Georgia Tech, Texas A&M, Pittsburgh Supercomputer Center). This consortium works together to develop, test, integrate, qualify, demonstrate, and infuse the best commercially available Internet and supporting communications infrastructure technologies into NASA space missions.



The space Internet technologies include the network architectures, protocols, and hardware components that are unique to NASA's use of the Internet in space. In each enabling technology, GRC will leverage emerging commercial capability, and partner with industry innovators to satisfy both NASA and commercial needs. Special attention will be paid to user authentication and security of remote operations. Once fully developed and infused, the space Internet technologies will enable the vision for transparent operations, enhance the capabilities for remote access and control of space-based assets, and reduce NASA's cost of providing the communications service. Every NASA space asset will be as accessible to approved users as any node on the Internet.

Space Science

GRC manages the High Rate Data Delivery thrust area under the Cross Enterprise Technology Development Program for the Space Science Enterprise. The long-term objective of this advanced research and fundamental technology development is to establish virtual presence throughout our solar system. The integration of high rate communications, networks and information technologies will enable a telepresence for near-Earth and deep

space scientific missions, and for human and robotic exploration. The transmission of data at high rates permits an increasingly rapid conversion of information to knowledge, and knowledge to new discoveries. Global interoperability among space-based assets and terrestrial telecommunications networks will diminish the gap between the sensors and the scientist. Information technology breakthroughs will enable the management of massive, diverse, multi-terabyte data sets needed to produce high-level information products.

Advance microwave communication research and proof-of-concept technology development is intended to increase data rates (in excess of 1 Gbps) for point-to-point near Earth and deep space communications. Novel Ka-band phased array and inflatable antennas, high-speed digital modems and multi-gigabit receivers are being designed to increase the capacity for the backbone communications. The models for space to ground radio-propagation to enable NASA and U.S. community and U.S. industry to utilize K-Band frequencies will be verified and presented in a handbook.

Micro-electro-mechanical systems (MEMS) switching technologies are being investigated to reduce losses in phased-array antennas. Miniature solid-state amplifiers and ferroelectric microwave components are being developed for future use in micro-spacecraft cross-link communications. A number of research and simulation tasks are underway to extend the advances being made in the terrestrial Internet technologies to the space environment as well as to provide connectivity from spacecraft directly to the users.

Earth Science

The Earth Science Enterprise desires to improve data collection from various and diverse platforms ranging from in situ buoys to balloons to polar orbiting satellites. Depending on the platform and its instrumentation, the data relay/transfer needs can vary from 10's to 100's of kilobits per second to 100's to perhaps even 1000's of megabits per second. While the Earth Observing System follow-on missions and the exploratory and process research-oriented missions appear to concentrate on individual platforms, concepts such as the "Sentinel Sensorweb", "Distributed Information System-in-the-Sky", and "Earth Science Information Web" scenarios will look at the various and diverse platforms as an integrated whole.

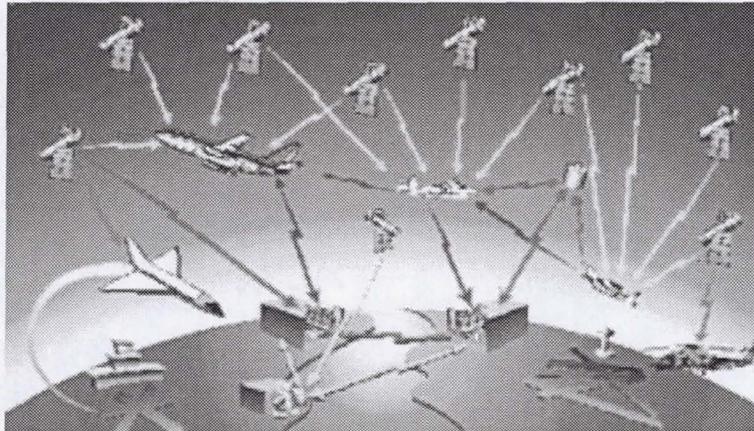
Evolving high data rate communications systems, in support of future Earth observation platforms demand greater attention to subtle aspects of information theory and radio-frequency engineering. GRC is poised to begin developing advanced communications and Internet technologies to provide the Earth Science Enterprise with the high data rate communications components it requires to return ever-increasing science data from advanced Earth observing platforms.

Aero-Space Technologies

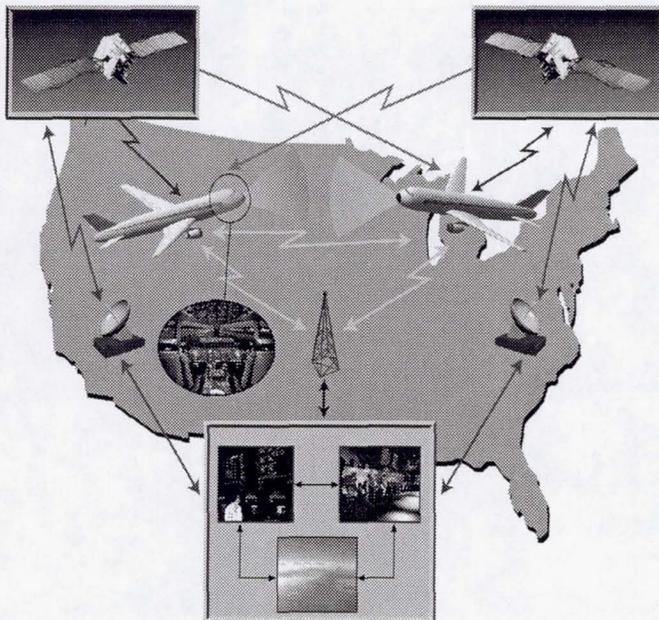
NASA's Aero-Space Technologies Enterprise is organized around three goals and ten objectives. GRC is supporting the Enterprise's first goal, Global Civil Aviation, by helping it meet its objectives in throughput and safety. The throughput objective is to triple the aviation system throughput, in all weather conditions, within 10 years while maintaining safety. The safety objective is to reduce the aircraft accident rate by a factor of five within by 2007, and by a factor of 10 by 2022.

It is widely accepted that today's air traffic infrastructure is capacity constrained due to the use of decades old technology. Twenty-five thousand U.S. daily flights exceed the system's capability to provide efficient service in good weather. Inclement weather further exacerbates the problem. Severe weather in one area can cause delays across the entire national airspace system. The current Air Traffic Management (ATM) system suffers from a number of limitations, including aging computer technology, voice-only communication (primarily), frequency congestion, non-radar coverage (e.g. oceanic) and limited meteorological information.

NASA is addressing the through-put objective in the *Advanced Air Traffic Technologies (AATT) Project* by developing new tools and technologies that enable free-flight, an operating system in which pilots have the freedom to select their path and speed in real-time. Free-flight by itself will not provide the necessary increase in system capacity that is required without a state-of-the-art Communications, Navigation and Surveillance (CNS) Infrastructure that supports new applications, higher data-rates, global connectivity, seamless integration, and, rapid reconfigurability. Automatic Dependent Surveillance-Broadcast (ADS-B) will provide the future surveillance capability, GPS will provide the navigational requirement, and satellite communications will enable transparent, split-second, free-flowing data transfer between all system elements. GRC is responsible for the advanced communications for ATM to enable a CNS Infrastructure that will provide the capacity, efficiency, and flexibility necessary to realize the benefits of the future free-flight environment.



The aviation community has enjoyed one of the best safety records of any form of transportation. Although the aviation accident rate is extremely low, the projected growth in air travel through the early part of the next century poses a serious safety challenge to the aviation community. In response to the White House challenge to achieve an 80% reduction in the rate of fatal accidents within 10 years and a 90% reduction within 20 years, NASA initiated the *Aviation Safety Program* in partnership with industry and other government agencies to address the President's National Aviation Safety Goal. The government/industry team recognized that weather was a major contributing factor in aviation incidents and accidents and recommended a significant effort in weather accident prevention. One of the key objectives of the program is to provide accurate, timely and intuitive information to pilots, dispatchers, and air traffic controllers to enable the detection and avoidance of atmospheric hazards.



GRC is developing the technology under the *Weather Information Communication (WINCOMM)* project that will address the communications specific issues associated with the dissemination of weather data:

1. Implement data link capabilities for Flight Information Services (FIS).
2. Expand and institutionalize the generation, dissemination and use of automated pilot reports (PIREPS) to the full spectrum of the aviation community, including general aviation.
3. Improve aviation weather information telecommunications capabilities for ground-ground dissemination of aviation weather products.

Concluding Remarks

It is unlikely that NASA will ever sponsor a single communications technology satellite project as large and significant as ACTS any time soon. Future technology developments will be smaller and more focused on the needs of NASA's Enterprises. In many cases commercial technologies and services are more advanced than

NASA's. However, the industry does not utilize space as a working environment as much as NASA does, with both data sources and destinations in space. In this regard, NASA has unique needs that are not met by commercially available solutions alone. GRC seeks to leverage the best commercial services and technologies to help satisfy NASA's mission needs. GRC's efforts will continue to serve as a catalyst to make the environment of space more suitable for human and robotic exploration, and increase the capacity and safety of the airspace for the benefit of all. Together with our industry partners, GRC is working to help helping to change the way NASA and the Nation communicate through space.

Evening Reception Presentations

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As part of the evening reception, NASA and industry representatives delivered remarks offering their insights into ACTS, space communications, the government-industry-academic collaboration that was so important to the development of ACTS, and the present and future state of NASA. Excerpts from these presentations appear below.



Gerald Barna, the acting Deputy Director of the NASA Glenn Research Center, noted that he took tremendous pride in the accomplishments of the NASA Glenn-managed ACTS program, and that it was a collaborative effort between government and industry (and, by extension, academia). He also noted that:

As most of you know, ACTS did not have an easy path. It endured not only technical challenges that we all would expect with the very advanced technology program which ACTS was, but it also faced numerous budgetary and other hurdles. With tremendous perseverance, dedication, and skill the NASA industry team turned adversity into a dazzling success. The contributions that ACTS made to advance communications technology surround us today and promise to continue improving our daily lives in the future. We at Glenn Research Center will continue advancing technology for satellite communication systems, even as one of our brightest stars will cease to shine.

There's a lot more excitement to come.



Joseph Rothenberg, NASA's Associate Administrator for Space Flight, spoke about a wide range of NASA-related topics, including Congress' decision to increase NASA's budget for the first time in seven years; NASA's decision to halt the downsizing program of the last few years and embark upon a hiring program in an effort to rebuild the agency's technical capability; how NASA is learning new ways to do business, especially with respect to the infusion of developing technology into agency programs; and how the space science program has a bright future, with several observatories being assembled that will permit detailed observation of Earth's ecosystems from space. He also noted that future space transportation systems and new rocket technologies are being aggressively developed by NASA; that there is reason to be optimistic about the Space Station, in spite of the bad PR its received over the last few years; how, in the space communications area, the agency plans to procure and adapt more existing equipment and systems from commercial vendors rather than build new systems from the ground up; how the launch vehicle business is in trouble because of prohibitively expensive development costs; and the technical challenges that lie ahead for long-term human exploration of space.

With respect to ACTS, Mr. Rothenberg said:

The government wasn't always NASA; the other part of it was, of course, Congress. Many of you know the history of ACTS, how Congress kept putting it in the budget in spite of NASA. On the other hand, it's a resounding success because of the government-industry team that carried it out.

I think you've heard enough today about the successes: spot beams, enabling on-board processing, enabling high-speed communications, distributed computing, and distance learning. Many technologies and applications were demonstrated on ACTS. It set the commercial industry out into the Ka-band. Nineteen US satellites are currently flying Ka-band technology at a value of over 90 billion dollars, and, in the next 20 years, we expect 100s of billions of dollars in Ka-band technology to be flying in space, attributed to the work of this team.

I think you also know that ACTS has made a contribution to the future of space flight and communications as a part of the advanced A-TDRSS satellite. And we use that as relay satellites from the space station, space shuttles and many of our scientific satellites. In the future, you may find that ACTS also played a role in providing Mars communications with deep space Ka-band communications. TDRSS is upgrading its technology to Ka-band frequencies.

You'll also find that, as we're looking at theatres like communications from Mars - communication as both scientific and human exploration on the planet Mars - a network is needed. It is also planned to be based on Ka-band technology. You not only have had an impact on the current communications technology, but the future of space exploration as well. Someday your grandchildren will look back and say "my grandfather or my grandmother had something to do with that technology and communications on Mars." I think you will be able to look back on that with great pride.

If you look around and consider what you did with ACTS, you started out by saying that the central mission was new technology and new techniques. You built it from its inception and you succeeded. Not only with the technical goals but with the commercial success of it. That was part of the original intent: to get technology out there to industry, and try to develop technology that industry and NASA could use.

High speed communications is going to become more and more critical...and ACTS provided an underpinning.



Dr. Tom Brackey, Executive Director, Technical Operations for external affairs and Chief Scientist for internal technical matters at Hughes Space and Communications Company, spoke on behalf of the U.S. satellite industry. He cited the importance of ACTS' radio frequency experiments and propagation measurements over the last five years, and noted:

Perhaps the crown jewel of the ACTS program is the exceptional body of knowledge developing from the measurements. The data in the handbook, the engineering guide, the guidelines, will be a significant enabler for all satellite communications - government, military, civil, commercial - for years to come, perhaps for decades. We should also understand that this is yet another excellent example of NASA leading the way by providing technical advantages that enhance the state of the art and the nation's leadership. This exceptional work and the commitment behind it is deserving of the highest praise.

It gives me great pleasure on behalf of our industry to salute you and say, "Well done ACTS, and many, many thanks."



Edward Fitzpatrick, Vice President of Hughes Network Systems, noted that the Hughes Spaceway program was built on the foundation established by ACTS. He said:

What ACTS has done is really significant. It's made believers out of people who thought Ka-band would never work. That helped me convince the Board of Directors of Hughes to invest 1.5 billion dollars in the Spaceway program. I'd like to think that Spaceway will be an extension of what you have started here with ACTS. By taking advantage of the pioneering concepts which the NASA-industry team on ACTS developed, we are able to lower the cost point and make satellite communications available to small businesses, as well as large businesses and even consumers.

What the ACTS program has done is open up a new chapter in communications and we're pleased to be a part of it.



Jeffrey Grant, Vice President and Chief Technical Officer of Astrolink (a joint venture of communications companies) discussed how important ACTS' demonstrations of technology have been to the development of the Astrolink program:

In these times of raising equity and going to the debt market for services such as Astrolink and Spaceway, the people who make business decisions are used to dealing with business risk. What they do not want is technical risk. They want you to look them in the eye and tell them the truth, based on demonstrated data. On numerous occasions, when confronted with confounding technical questions, I have been able to answer them by going to the web sites of NASA and ACTS, and extracting information. This generated confidence in people, who are concerned about technical risk, that the things we were proposing in this futuristic system of broadband, symmetrical satellite services had, indeed, been demonstrated before. And that was a tremendous advantage to our company.

Thank you all for bringing ACTS to us; it's made a great deal of difference and I appreciate it.



Edward Ashford, Corporate Development Unit Leader at SES-ASTRA, spoke about how significant the ACTS program was as a trailblazer. He noted that:

NASA was one of the first to develop the technology for Ka-band processing data. But, it was also slightly ahead of its time, in terms of the market. It's only recently with the explosion of the Internet and business communications that the need for Ka-band, broadband satellites have become apparent in the marketplace. Many of the prognosticators and foresighted people in this room saw the need for ACTS before the marketplace did. To them goes the credit for generating the market that's now using the ACTS technology.

Not only can U.S. manufacturers and operators be thankful for what ACTS has done, but so can foreign operators and populations around the world.

A Final Ode to ACTS

The ACTS Program is ended,
Our office is a-gloom,
It won't be extended,
The place is like a tomb.

The control room is shuttered,
The curtains are drawn,
The dumpster is cluttered,
The consoles are gone.

But it wasn't always
Depressing and down.
ACTS had glory days
Of satcom renown.

For eighty-one months
ACTS circled our sphere,
And seldom more than once
Did its signals disappear.

Its spotbeam transmitters
Were the first of its kind,
And gave us the jitters
'Til we learned not to mind.

The onboard processing
Took years to perfect,
But proved out a blessing
When we tried to connect.

The tiny Earth Stations
Were distributed everywhere,
All across the nation
With results beyond compare.

From Hawaii to Haiti
The experiments flourished,
Nothing secret nor shady –
With free time they were nourished.

Now the fuel is exhausted
And its time to move on,
We'll just do what TOS did –
Enter oblivion.

The saga of ACTS
Has reached its conclusion.
Were these really the facts?
Or was it all an illusion?

Delivered by Erv Edelman, Master of Ceremonies, at the Evening Reception, May 31, 2000

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Letters, Citations, Media and Photos

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National Aeronautics and
Space Administration
Office of the Administrator
Washington, DC 20546-0001



Mr. Donald J. Campbell
Director
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, OH 44135

MAY 24 2000

Dear Mr. Campbell:

Thank you for the invitation to provide the Keynote address at the evening reception of the 6th Ka-Band Utilization Conference and ACTS Conference 2000. Although other duties prevented me from accepting this honor, I indeed relished the opportunity to discuss past successes and some of the exciting challenges facing NASA today. Please pass along my gratitude and comments below to those attending.

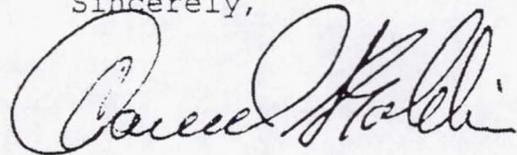
I think it is most fitting that the final ACTS Conference is being held within the larger framework of the international Ka-Band Utilization Conference. After all, the success of the ACTS technology has given huge impetus to commercial utilization as well as further exploration of a very precious resource - that portion of the electro-magnetic spectrum available to communications satellites. This is what government-sponsored science can do well - pioneering advances that are beyond the scope of individual companies, but can be utilized by these companies to bring benefits to the public beyond their expectation.

The excitement in the communications industry today is without precedent. New services, new ways of doing business, mergers, and acquisitions are part of the daily news. The path is not clear and some approaches may not succeed. But the demand for bandwidth has increased beyond our wildest dreams when the ACTS Program was initiated. Fortunately, for all of us, and I include the general public, the ACTS Program had the foresight to step beyond conventional thinking and prove the technology needed for the future, as well as the present.

For the ACTS Program to achieve such distinguished success, every aspect of the program had to perform flawlessly. From concept to build, from orbital insertion to inclined orbit operation, from business experiments to aiding our armed forces in Haiti, the ACTS organization met all the challenges and performed in an outstanding manner! Many institutions with sketchy concepts of the potential of satellite communications _ medical, military, business, university, and more _ became fervent proponents and excellent prospects for commercial services as a result of their experiment experience.

ACTS has been a source of pride to the Nation, NASA, the Glenn Research Center, and the Industry Partners. Let me add my official, and personal, congratulations on a job splendidly done!

Sincerely,

A handwritten signature in cursive script, appearing to read "Daniel S. Goldin".

Daniel S. Goldin
Administrator



United States
of America

Congressional Record

PROCEEDINGS AND DEBATES OF THE 106th CONGRESS, SECOND SESSION

House of Representatives

DENNIS J. KUCINICH
OF OHIO

IN THE HOUSE OF REPRESENTATIVES
IN HONOR OF THE ADVANCED COMMUNICATIONS
TECHNOLOGY SATELLITE

Mr. Speaker, I would like to call the attention of my colleagues to one of the nation's most successful technology transfer programs impacting our daily lives and which promises economic advantage to our great country in the very competitive area of telecommunications. This project, called the Advanced Communications Technology Satellite (ACTS), is the culmination of a decade of satellite technology development by NASA. The ACTS mission will conclude in June 2000 after 81 months of operations far exceeding its 4-year design life. Before this innovative flight project reaches its operational conclusion this summer, permit me to share with you more about its outstanding contributions and examples of how our government research spurs industry growth and jobs, and continues the worldwide preeminence of our technology base.

The explosion of the Information Age and the evolution of the National and Global Information Infrastructure has created a critical need for the next generation of communications satellites. The ACTS Project centers around an experimental payload that incorporates an architecture of advanced technologies typical of what will be found in the next generation of commercial communications satellites. NASA funded this development to maintain America's dominant position in providing communications satellites to the world. This project has been led by a dedicated team of researchers and technologists at NASA's Glenn Research Center, which, I am proud to say, is within my Congressional district.

Mr. Speaker, permit me to tell you more about this success story in space. The technologies selected for ACTS were those that had the potential to enhance dramatically the capabilities of the next generation of satellites. The technologies ACTS pioneered included use of a previously unused high frequency band (called the Ka-band which is 20/30 GHz.), a futuristic dynamic hooping spot beam antenna, advanced on-board processing and switching, and automatic techniques to overcome increased signal fades experienced at these higher frequencies.

(Appeared in the Congressional Record on Tuesday, May 9, 2000, Vol. 146, No. 56)

After its launch in September 1993, NASA partnered with major corporations and small businesses, academia, and other government agencies to demonstrate the new technology in actual user trials. An experiments program involved over 200 organizations that used the satellite for demonstrations, applications, and technology verification across the far reaches of our nation. With an ever-increasing global economy, ACTS was used to demonstrate wideband communications in five other countries (Canada, Colombia, Ecuador, Brazil, and Antarctica).

Applications over the satellite have been done to improve living conditions and ensure a safe and prosperous life style in areas such as telemedicine by transmitting data-intensive imagery for linking urban medical specialists to under served areas of the U.S.; control of power grids for electric utility companies using ultra-small terminals to poll the grid in remote areas; distance learning utilizing high-quality interactive video and audio for delivery of advanced degree, continuing and remedial training to all people without regard to location; integrating design teams for business and industry; natural resource exploration by connecting remote research equipment over high-speed links with major computer analysis facilities; and personal and airborne mobile communications services including technologies enabling advanced passenger services onboard the U.S. commercial airline fleet.

The innovative technologies proved that on-demand, integrates communications are viable, economical, and of national importance for the future of communications. The ACTS users have transformed this space technology into commercial products and services. As a result of the program, the satellite industry is on the cusp of initiating whole new constellations of satellites that represent a market size in the \$10s of billions that use many of the concepts developed and verified through the ACTS program.

Mr. Speaker, I am proud to share other success stories of how ACT has benefitted this country in the area of satellite manufacturing. Motorola used ACTS-type on-board processing and Ka-band communications in the first operational system using ACTS technology--Iridium, and continues to include these technologies in a next generation wideband system. Hughes Space and Communications' Spaceway system will utilize an ACTS-like spot beam antenna at Ka-band frequencies to provide low-cost, global high-speed, communications to both residential and commercial users. Loral's Cyberstar will also incorporate Ka-band ACTS-type technology. Lockheed Martin's nine-satellite Astrolink system being developed includes such advances as Ka-band, on-board processing, and spot beam technology. The Teledesic system will provide service with a network of hundreds of satellites using on-board switching to route information between satellites and users. All of these systems show that our country's satellite manufacturers are integrating the ACTS design concept and technologies into their communications systems. This increases the number of highly technical jobs in the U.S. and improves the balance in trade with the strong international market for communications satellite systems.

Thank you Mr. Speaker for allowing me the opportunity to salute this special project with my colleagues. I congratulate NASA and the men and women who developed and operated this satellite technology for the benefit of our nation. It's because of their personal dedication that this country benefits.

From *Satellite Today*, June 1, 2000. Reprinted by permission.

Top News Today

SATELLITE NEWS and INTERSPACE.

NASA Retires ACTS, 30/20 GHz Experimental Satellite

All good things come to an end, and so it is that NASA's Advanced Communications Technology Satellite (ACTS) has come to the end of its road--81 months after the agency began a program of experiments in Ka-band technology that was expected to last only 24 months.

The satellite lasted almost 3.4 times its expected design life. But its North/South stationkeeping fuel has run out, said *Robert Bauer*, ACTS project manager. So on May 31, NASA's John H. Glenn Research Center outside Cleveland, Ohio, completed the last experiment and shut the satellite down or retired it. The shutdown ceremony was part of the 6th *Annual Ka-Band Utilization Conference*, which is being held in Cleveland this week.

The satellite will be drifted from its permanent slot at 100°W to a parking slot at 105.2°W. When it is settled there, all of its energy sources will be drained or disabled Bauer said.

The ACTS program was highly controversial in its early years. Its funding was threatened repeatedly as part of NASA's annual budget struggle in Congress, as opponents argued that the federal government should not do telecommunications research that companies could undertake on their own.

But the program's supporters argued that only an industry-wide research program would be able to develop technologies for the then-unknown Ka- (30/20 GHz) band. Eventually, they prevailed and when ACTS finally was launched in September 1993 it was a partnership between NASA, the telecommunications industry and the university community.

Today satellites carrying high-capacity Ka-band transponders are under construction by **Hughes Electronics Corp.** [GMH] for Telesat Canada and by **Space Systems/Loral** [LOR] for **NetSat 28**, a majority-owned subsidiary of **EMS Technologies** [ELMG] of Norcross, Ga. In addition, companies are working to develop high-capacity, Ka-band earth stations.

Another beneficiary of NASA's pioneering efforts in Ka-band could be Teledesic, which plans a low-Earth-orbit satellite system to provide two-way connectivity globally.

The 103 experiments carried out with ACTS, involving more than 200 partners, covered a broad range of industries and applications in medicine, education, defense, emergency response services, maritime and aeronautical mobile communications and sciences, particularly astronomy. Among the examples cited by the Glenn Center were:

- ✓ Telemedicine--ACTS transmitted data-intensive imagery that linked urban medical specialists to under served areas of the United States.
- ✓ Electric utilities--The satellite assisted them in controlling their power grids by using ultra-small terminals to poll grids in remote areas.
- ✓ Distance learning--ACTS demonstrated higher-quality video and audio to deliver education and training to people in remote areas.
- ✓ Business--The satellite was used to show how high-speed links could be used with major computer installations to integrate design teams and how remote research equipment could be used in natural resources exploration.

- ✓ Aeronautical mobile communications – ACTS demonstrated technologies for personal communications services to passengers on commercial airliners.

“The ACTS Experiments Program has the foresight to step beyond the conventional thinking and prove the technology needed for the future, as well as the present,” said *Joseph Rothenberg*, NASA’s associate administrator for space flight.

“The timeliness of ACTS technologies could not have been better,” said Bauer, the program manager. “Had they arrived too early, few would have been ready to utilize the bandwidth being offered. Had they arrived too late, fiber may have completely overshadowed consideration [of the satellite industry] in offering wideband services to diverse and remote locations.”

*For more on the ACTS program, read our sister publication *Via Satellite* magazine.

From *Space News*, June 12, 2000. Reprinted by permission.

ACTS Retired After 7 Years in Ka-Band

After nearly seven years experimenting with transmissions in the Ka-band portion of the radio spectrum, NASA's Advanced Communications Technology Satellite (ACTS) retired May 31, according to officials at NASA's Glenn Research Center, operator of the spacecraft.

ACTS helped pave the way for the development of commercial services in the Ka-band, which uses higher-frequency radio waves than the commonly used C- and Ku-bands. The Ka-band permits data, video and other material to be transmitted at high speeds. The Ka-band also is less congested than other satellite bands.

Launched in September 1993 on NASA's space shuttle, ACTS originally was intended to operate for 18 months, but continued working well beyond its projected lifespan. The spacecraft was equipped with a special spot beam antenna system that generated 51 high-power beams. Those beams permitted the satellite to communicate with small ground antennas and helped signals penetrate rain showers.

Rain interference is viewed as a potential obstacle to Ka-band satellite services. Ka-band transmissions are attenuated, or blocked, more by raindrops than are transmissions in lower frequencies like C-band and Ku-band.

NASA spent about \$600 million to develop, launch and operate the satellite, ACTS project manager Robert Bauer said in a telephone interview. The government's objective was to show that the technology was feasible and to ensure the United States would keep pace with other countries involved in Ka-band research, he said.

"Industry often makes evolutionary progress, but with ACTS, we had a revolutionary kind of change in satellite technology," Bauer said.

ACTS conducted 103 experiments, showing how the Ka-band could be used for applications such as telemedicine, distance learning and communications with airplanes in flight, according to a statement from the Glenn Research Center, Cleveland.

The spacecraft is being retired because its fuel supply is exhausted, Bauer said.

Several high-profile Ka-band commercial satellite projects are planned, including the Spaceway system under development by Hughes Electronics Corp., El Segundo, Calif., and a similar system owned by Bethesda, Md.-based Astrolink LLC. Societe Europeenne des Satellites, Luxembourg, recently launched a geostationary satellite with a Ka-band payload to provide high-speed Internet access, and Telesat Canada recently unveiled plans to include Ka-band transponders on its new Anik F2 communications satellite.

NASA has fulfilled its mission of developing Ka-band technology, Bauer said. "We have lots of data and have characterized the Ka-band, and industry can now make these things themselves," he said.

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Li'l satellite that could becomes a NASA star

Cleveland-managed ACTS wins praise for innovations

By JOHN MANGELS
PLAIN DEALER SCIENCE WRITER

When NASA's spindly experimental communications satellite eased out of space shuttle Discovery's cargo bay and headed for high orbit in September 1993, its future seemed as bleak as the craft's airless surroundings.

Already, critics had labeled the Advanced Communications Technology Satellite (ACTS) — planned and managed by Cleveland's Glenn Research Center at Lewis Field — a white elephant, a costly chunk of technology that had no good reason to fly. Though designed to last four years, the \$500 million satellite only had enough money in its operating budget to function for half that time.

What a difference seven years makes. Yesterday, as the last of ACTS' communications experiments ended and its Glenn managers prepared to shut down the craft, it won praise from satellite industry officials for proving that new approaches to beaming high-speed voice, video and computer data from earth to space and back can work. Commercial satellite manufacturers that had been leery of ACTS' technology are planning craft that operate on its higher signal frequency and mimic its transmission methods.

"No company would have done it. I'm convinced, if it hadn't been for ACTS," said Frank Gargione, a satellite systems consultant who was one of several hundred attending a three-day communications satellite conference in Cleveland this week. The conference yesterday was devoted to ACTS' accomplishments.

NASA intended for the 3,250-pound, antenna-laden craft to be a proving ground for communications approaches that commercial satellite firms were unable or unwilling to try themselves be-

Evolution in space technology is slow. With millions on the line, companies are reluctant to gamble on a ballpoint pen when quill and ink work just fine.

cause of the research costs or reliability questions.

"Satellite technology is very evolutionary," said ACTS project manager Robert Bauer of the Glenn Research Center. "It's made in small refinements" rather than in leaps because of the cost and risk involved. With intense competition and hundreds of millions of dollars in develop-

ment and launch expenses on the line, companies are reluctant to gamble on a ballpoint pen when quill and ink work just fine.

But the U.S. satellite industry faced a loss of the lucrative global communications business, particularly to European firms. There also was increased crowding on the frequencies that conventional

satellites use to beam signals to Earth, as more and more cell-phone, pager and other wireless data were sent via space rather than with land-based equipment.

ACTS relied on the relatively wide-open Ka-band radio spectrum, which has five times the available space as the claustrophobic lower frequencies that conventional satellites use. Higher frequencies allow large amounts of data to be sent extremely quickly, like information-packed Internet signals.

ACTS also relayed its messages in as many as 51 tightly focused 150-mile-wide beams that could "hop" from one small, inexpensive earth receiving station to another in milliseconds. Existing satellites broadcast a fixed, single beam that can cover a continent — fine for large-scale, one-way transmissions such as a network TV broadcast but not so good for lots of simultaneous two-way communications, like cell phones or Web surfers.

Satellites using the Ka band have a potential Achilles heel, though. The water molecules in rain gobble up Ka's shorter wavelengths, causing the communication signal to weaken — a phenomenon known as rain fade that had scared off commercial firms.

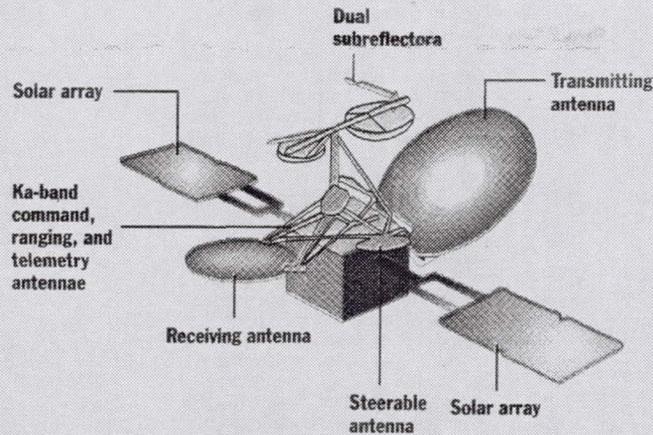
ACTS showed that while some rain fade is inevitable in extremely heavy storms, there are several ways to compensate for it, Bauer said. They include cutting the amount of signal traffic to ensure more gets through or repeating the message.

As ACTS proved its mettle, more and more companies and universities lined up to pay for opportunities to use the satellite for communications experiments. That, in turn, extended its lifespan.

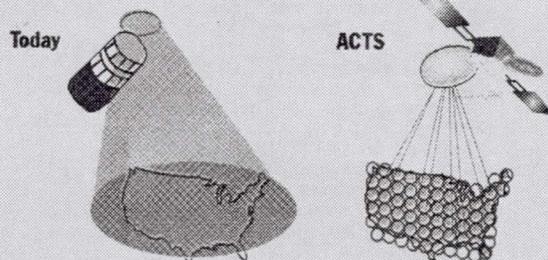
SEE NASA/3-C

NASA retires satellite

Yesterday, NASA retired the Advanced Communications Technology Satellite (ACTS). The 3,250-pound spacecraft, developed at NASA Glenn Research Center and released from the cargo bay of space shuttle Discovery in September 1993, carried out experiments paving the way for a new generation of communications satellites.



Comparing satellite systems



Current satellites relay information in a single beam, or "footprint," that covers thousands of miles. ACTS uses 51 tightly focused beams covering 150 to 200 miles, requiring less power and offering more data-carrying capacity.

SOURCE:
NASA Glenn Research Center

ELIZABETH CUSMANO / PLAIN DEALER GRAPHICS REPORTER

Satellite that could becomes NASA star

NASA FROM 1-C

A total of 200 tests were done, including:

- Transmitting high-detail breast cancer X-ray images to the Cleveland Clinic for review. Such telemedicine would allow specialists to get patient information from rural areas in seconds, where data transmission by phone lines would take hours.
- Collecting daily transaction details from automatic-teller machines for Huntington Bank.
- Nearly instantaneously relaying results of a jet engine simulation test on a supercomputer at Cleveland's Glenn Center to the Boeing Co. in Seattle and returning the Boeing engineers' adjustments of the test.
- Sending high-definition video from remote movie set locations to Sony's studio in California for editing and special effects so directors can quickly see the results.

In the wake of those successes, seven commercial satellite systems using Ka band are being readied. ACTS may not have spawned those projects by itself, Bauer said, but it certainly sped up the timetable.

NASA isn't planning a successor to the successful experimental satellite program, however. Although administrator Dan Goldin wants the space agency to return to its roots as the nation's research and development lab, some critics called the ACTS program "corporate welfare" that gave the satellite industry a government-aided advantage over competitors, including fiber-optics firms.

The political climate has changed. Now, "the satellite industry can support itself," Bauer said. "The role for government is not there anymore."

So in a month or so, ACTS will be parked in a safe orbit and eventually put to sleep, its solar panels shorted out, its fuel tanks exhausted. But it will have done its job.

As astronaut John Young, the Apollo 16 commander who walked on the moon, told an audience including Glenn Center staffers yesterday, "You can be very proud of ACTS. It's just the beginning. I can see people right now arguing about roaming charges on Mars."

ACTS final curtain call

FAR exceeding its planned 24-month mission, the Glenn-managed Advanced Communications Technology Satellite (ACTS) concluded its extensive experiments program on May 31 after 81 months of operations.

Launched in September 1993 as a partnership among NASA, industry, and academia, ACTS opened the door for U.S. satellite communications technology in demonstrating the use of the high frequency Ka-band (30/20 GHz). Until ACTS, this frequency was virtually unused—the majority of communication satellites used lower frequency bands called C- and Ku-bands. Exploring Ka-band technology was designed to relieve orbital crowding and demonstrate the first band of frequency wide enough to carry simultaneous services ranging from multiple voice, video, and data communications to computer connections at optical fiber data rates.

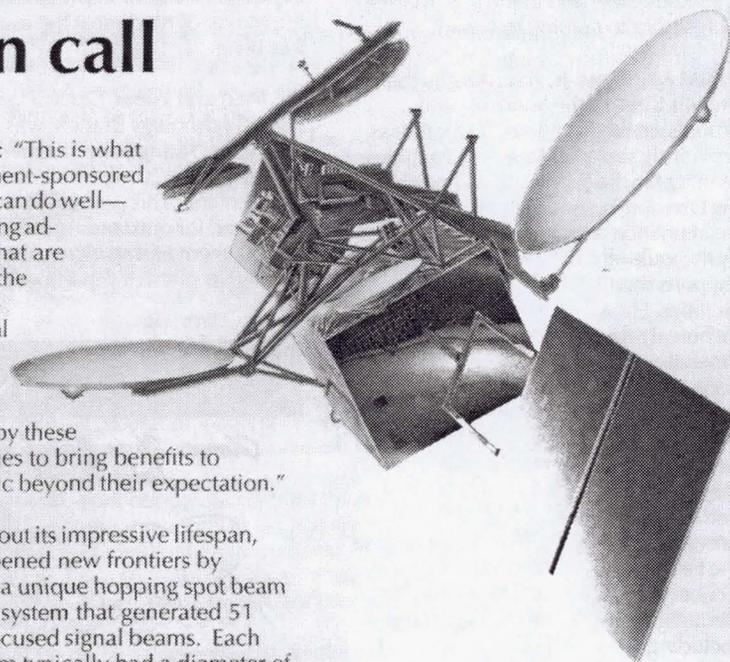
"The ACTS Experiments Program has been an outstanding research and development achievement that resulted in a unique operational capability for the Center and the Agency," said Center Director Donald J. Campbell.

NASA Administrator Daniel R. Goldin

affirmed: "This is what government-sponsored science can do well—pioneering advances that are beyond the scope of individual companies, but can be utilized by these companies to bring benefits to the public beyond their expectation."

Throughout its impressive lifespan, ACTS opened new frontiers by utilizing a unique hopping spot beam antenna system that generated 51 tightly focused signal beams. Each spot beam typically had a diameter of 150-200 miles and was able to "hop" from one location to the next, covering up to 40 locations in a millisecond. Concentrating satellite power in such a way permitted significantly smaller and less expensive Earth stations. In addition, the spot beam was better able to penetrate through rain and mitigate rain fade.

"The ACTS Experiments Program had the foresight to step beyond the conventional thinking and prove the technology needed for the future, as well as the present," said NASA



Associate Administrator for Space Flight Joseph H. Rothenberg.

CONTINUED ON PAGE 6

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 ACTS Telemedicine technology is spotlighted as the first in a series on biotechnology.

RETIREE SPOTLIGHT 9
 For retiree Harvey Schwartz, everything old is new again.

FEB AWARDS 12
 Six employees were honored by the Cleveland Federal Executive Board.

The ACTS Project is "one of Nation's most successful technology transfer programs impacting our daily lives, which promises economic advantage to our great country in the very competitive area of telecommunications."

—Congressman Dennis J. Kucinich (OH)



Technology that made a difference

CONTINUED FROM PAGE 1

The ACTS Experiments Program has achieved remarkable milestones with 103 experiments and numerous demonstrations involving over 200 diverse partners, paving the way for the next generation of communications satellites. It succeeded in areas as varied as advanced networking, medicine, education, defense, emergency response, maritime and aeronautical mobile communications, and science and astronomy.

"The timeliness of ACTS technologies could not have been better," said Robert Bauer, Glenn's ACTS project manager. "Had they arrived too early, few would have been ready to utilize the bandwidth being offered. Had they arrived too late, fiber may have completely shadowed the satellites' consideration in offering wideband services to diverse and remote locations."

In recognition of ACTS contributions, the first day of the sixth annual International Ka-Band Utilization Conference—held May 31-June 2 at The Renaissance Hotel, Tower City Center, Cleveland—was dedicated to ACTS. The day

included technical presentations and experimental results followed by an evening celebration and special program to commemorate the conclusion of the ACTS Experiments Program.

"The ACTS Conference was a fitting and likewise superbly conceived and executed tribute to ACTS, which demonstrated the same skill and dedication as the project itself," said Glenn Acting Deputy Director Gerald Barna. "I want to commend the entire team for their efforts!"

Over the years, Glenn's Space Communications Office has maintained primary responsibility for the ACTS Program. Notably, two prime contractors, Lockheed Martin (system operations) and COMSAT Laboratories (master control operators of the communications payload), made significant contributions to the program. Local contractors—Zin Technologies, Analex, and GTE Technology—have played valuable roles as well. ACTS successes have been recognized through numer-



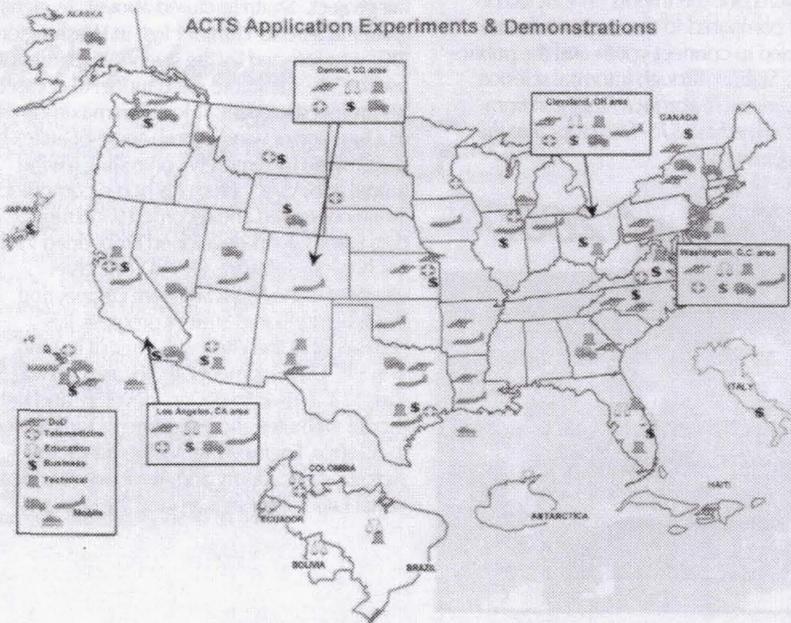
Ultra Small Aperture Terminals (USAT) are similar in size to today's direct broadcast television terminals and provide uplinks as fast as 1.5 Mbps and downlinks as fast as 45 Mbps.

ous awards including induction into the U.S. Space Foundation's Space Technology Hall of Fame in 1997, an R&D 100 Award in Significant Technology in 1995, and the prestigious Federal Technology Leadership Award in 1995.

Bauer explained that while the ACTS Experiments program has been shut down, the hardware has not been disabled. This month, the spacecraft will be moved to an orbital gravity potential well at 105.2 degrees West Longitude where it will be monitored for two months to ensure that it has settled into its final orbital slot. After the final location has been verified, the system will be "inerted," meaning that any remaining fuel will be expelled, the solar panels will be feathered, batteries will be shorted, and momentum wheels will be despun. ♦

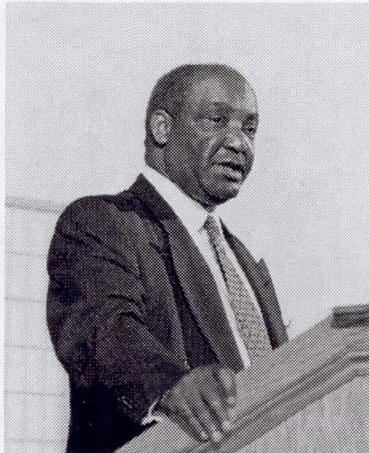
Portions of this article were written by Barbara Kakiris, public affairs specialist, Community & Media Relations Office.

This ACTS Spot Beam chart generates a system of 51 highly focused signal beams. Each spot has a diameter of 150-200 miles and has the ability to "hop" from one location to the next in milliseconds.



ACTS Conference 2000 Photos

Donald



Campbell

Frank



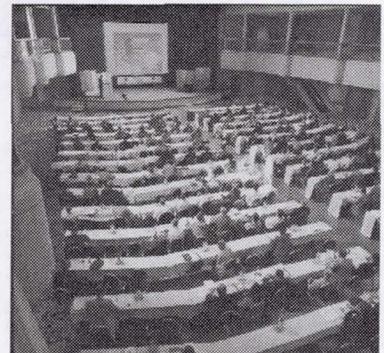
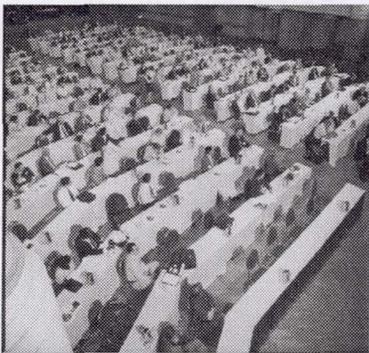
Gargione

Among the speakers who welcomed attendees were Donald Campbell, Director of NASA Glenn Research Center; Ohio Governor Robert Taft (whose phone call to the conference was over ACTS); Robert Bauer, ACTS Project Manager; Frank Gargione, a satellite industry consultant with Analex Corporation; and Franco Marconicchio of Agenzia Spaziale Italiana.

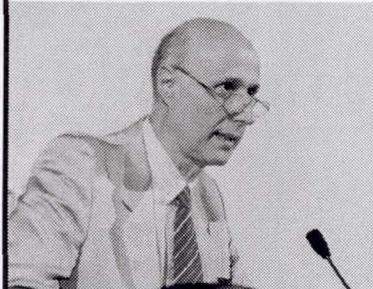
Robert



Bauer

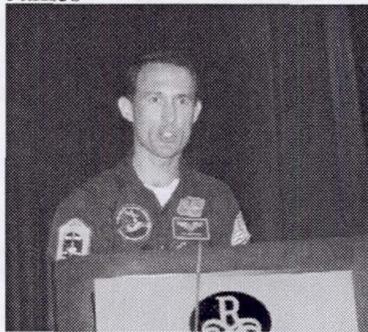


Franco



Marconicchio

James



Newman

John



Young

Astronaut James Newman, who as a mission specialist aboard STS-51 Discovery in 1993 helped launch the ACTS satellite, was the luncheon speaker. An added bonus was the unexpected appearance of astronaut John Young, a veteran of the Gemini, Apollo and Space Shuttle programs. In the photo on the right, Young chats with NASA Glenn engineer Don Hilderman.





The evening reception's featured speaker was Joe Rothenberg, NASA's Associate Administrator for Space Flight. Behind him at the podium in the above photo are the event's other speakers (from the left): Gerald Barna, acting Deputy Director of the NASA Glenn Research Center; Dr. Tom Brackey, Executive Director, Technical Operations for external affairs and Chief Scientist for internal technical matters at Hughes Space and Communications Company; Edward Fitzpatrick, Vice President of Hughes Network Systems; Jeffrey Grant, Vice President and Chief Technical Officer of Astrolink; and Edward Ashford, Corporate Development Unit Leader at SES-ASTRA.

Erv Edelman ably served as the evening's Master of Ceremonies.

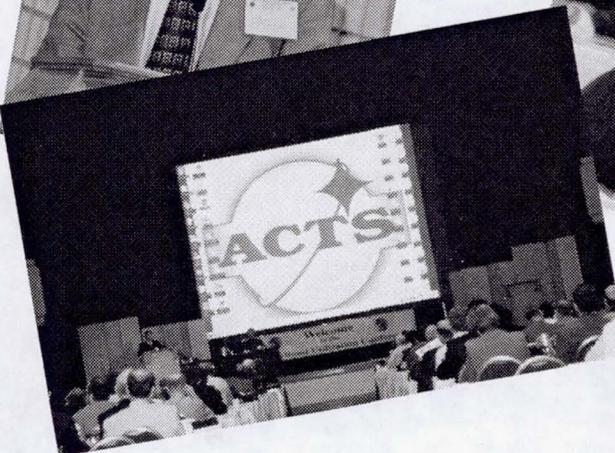
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Edelman









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