5/32

2001024814

514270

16P

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

By Richard J. Krawczyk
NASA-Glenn Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
Phone: 216-433-3539
E-mail: r.j.krawczyk@grc.nasa.gov

Louis R. Ignaczak
NASA-Glenn Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

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 +/-0.025 ° 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 5.0x10e-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.

7.0 References

1. G. Bussaca, R. McCann, P. Mullen, "900 MHz Bandwidth 30 GHz Center Frequency Low Noise Receiver," in *ACTS Results Conf.*, Cleveland, OH, Sept. 1995.

2. S. Mentler, J Logrando, "The ACTS Traveling Wave Tube Amplifier," in *ACTS Results Conf.*, Cleveland, OH, Sept. 1995.

3. R. Acosta, "ACTS Multibeam Antenna Analysis and on-orbit Performance," in 2nd *Ka-band Utilization Conf.*, Florence, Italy, Sept. 1996.

4 R. Krawczyk, F. Gargione, "Performance of ACTS as a Ka-band Test Bed," in 5th *Ka-band Utilization Conf.*, Taormina, Italy, Oct. 1999

5 R. Acosta, S. Johnson, "Six years of ACTS Technology Verification Experiment Program Results," in 5th *Ka-band Utilization Conf.*, Taormina, Italy, Oct. 1999

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

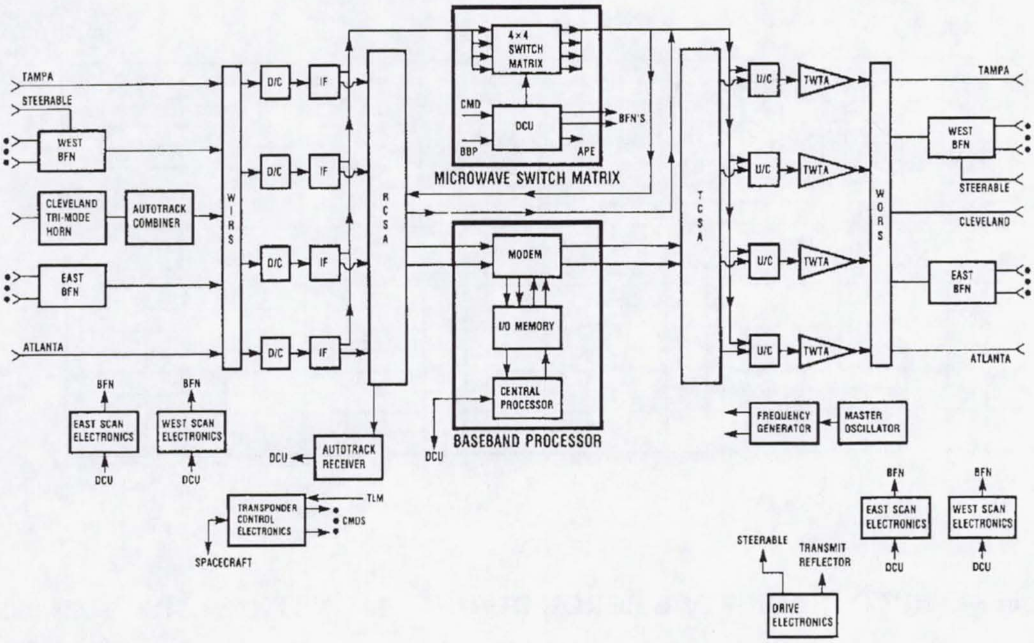


Figure 2. AUTOTRACK PITCH AND ROLL ERROR (TOP) AND SIGNAL STRENGTH

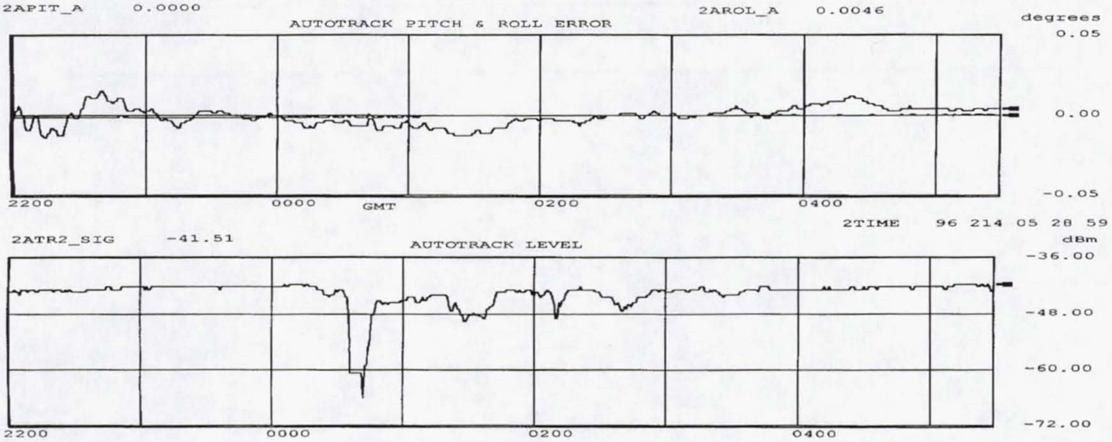


Figure 3. YAW ERROR (TOP) AND AUTOTRACK ROLL ERROR AT 0.8° INCLINATION

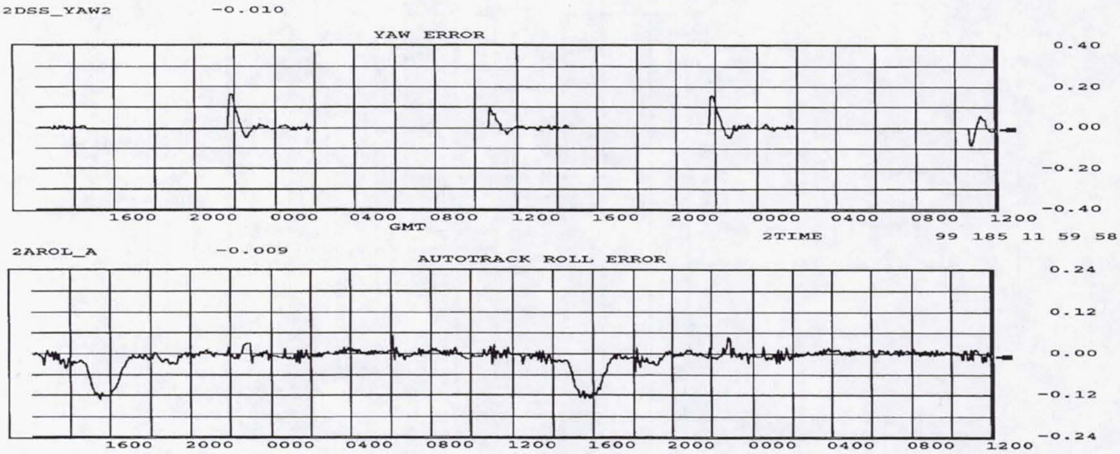
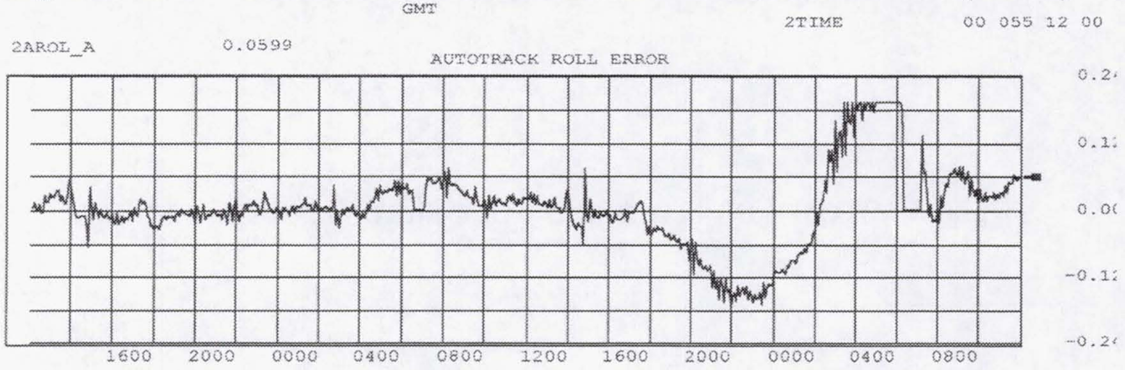


Figure 4. AUTOTRACK ROLL ERROR DURING MAGNETIC STORM (2/24/00)



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

Glenn Research Center

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

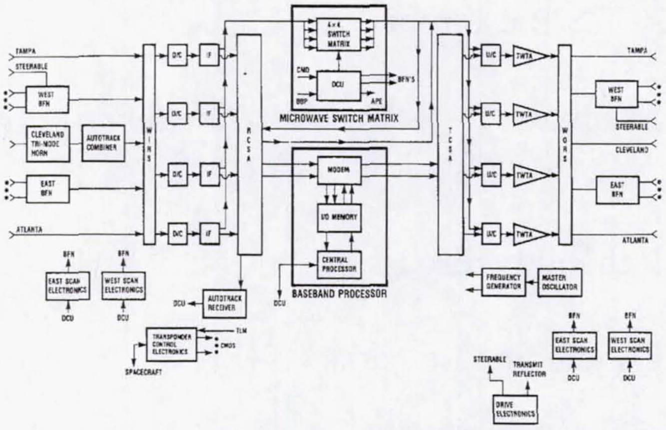
- Objectives: Demonstrate, verify and characterize technology for comsats and evaluation of Ka band systems.
  Provide a reliable GEO experimental testbed.

- Original 2-year mission extended twice to take advantage of excellent performance of hardware.

Glenn Research Center

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.

Glenn Research Center

Successful Ka-Band Comsat Technology

30 GHz Low Noise Receivers

- Four LNRs. HEMT LNA with3.8 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.

Glenn Research Center

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.

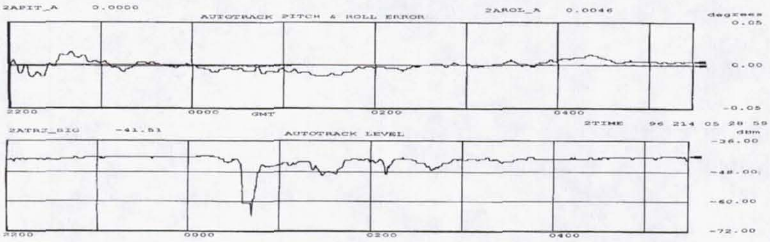
- One meter steerable beam reflector (SBA) has enabled links, from Antarctica to Arctic Circle, to fixed, airborne and shipboard terminals. Manual peaking can assure users of max signal - point by shaft position telemetry plus command step count.

Glenn Research Center

Attitude Control for Spot Beams

Attitude Determination

- Narrow spot beams require more precise pitch/roll pointing (+/-0.025°).
- 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.

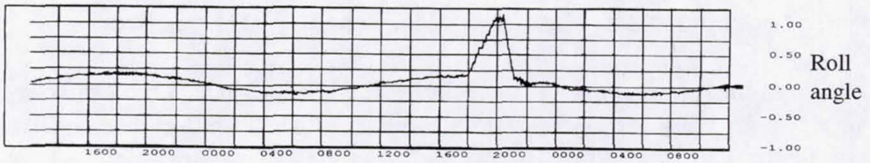
- Yaw requirement (+/-0.15°) implemented by sun sensors and yaw estimator. This method can be operator intensive to regain estimator convergence during geomagnetic storms.

Glenn Research Center

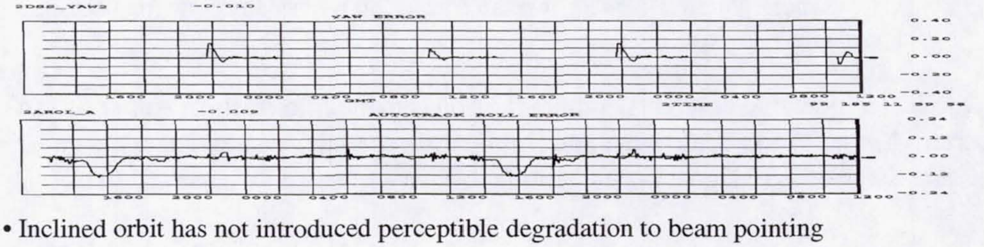
Attitude Control for Spot Beams

Attitude Control

- Excellent pitch control (<0.01°) 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

Glenn Research Center

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.

Glenn Research Center

Providing a Reliable Experimental Comsat

Reliability Modeling

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

	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

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

Glenn Research Center

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.

Glenn Research Center

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