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Development of a Gimballed, Dual Frequency, Space-Based, Microwave Antenna for Volume Production

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Abstract

A dual-frequency, two-axis Gimballed, Microwave Antenna (GMA) has been developed by COM DEV and Motorola for commercial satellites. The need for volume production of over three hundred antennas at a rate of four per week, a compressed development schedule, and the commercial nature of the effort necessitated a paradigm shift to an "overall" cost-driven design approach. The translation of these demands into antenna requirements, a description of the resulting GMA design, and examples of development issues are detailed herein.

Introduction

The GMA is a gimballed, dual reflector, microwave antenna designed for use on commercial satellites. Each satellite contains four GMAs, which support communication links with Earth-based tracking terminals. The total number of GMAs to be supplied is greater than 320, including qualification models and spares, with a peak production rate of four units per week.

By mass production standards, neither the production quantity nor the rate is large, but by satellite equipment manufacturing standards — the primary business of the co-developers — these requirements were a quantum leap. The requirement for high-rate bulk production was just one of many development challenges for the design team. Other challenges included traditional gimballed antenna specifications — low mass, launch vibration, and pointing accuracy — as well as a short (one-year) development cycle, and low, fixed cost. How these requirements were met and the lessons learned during the development of the GMA are the focus of this paper.

Development of the GMA (Figure 1) is complete. All design issues have been resolved, and the GMA successfully passed qualification testing in July, 1995. Production shipsets have been delivered. Qualification and early production results compare favorably with specified requirements and analytical predictions.

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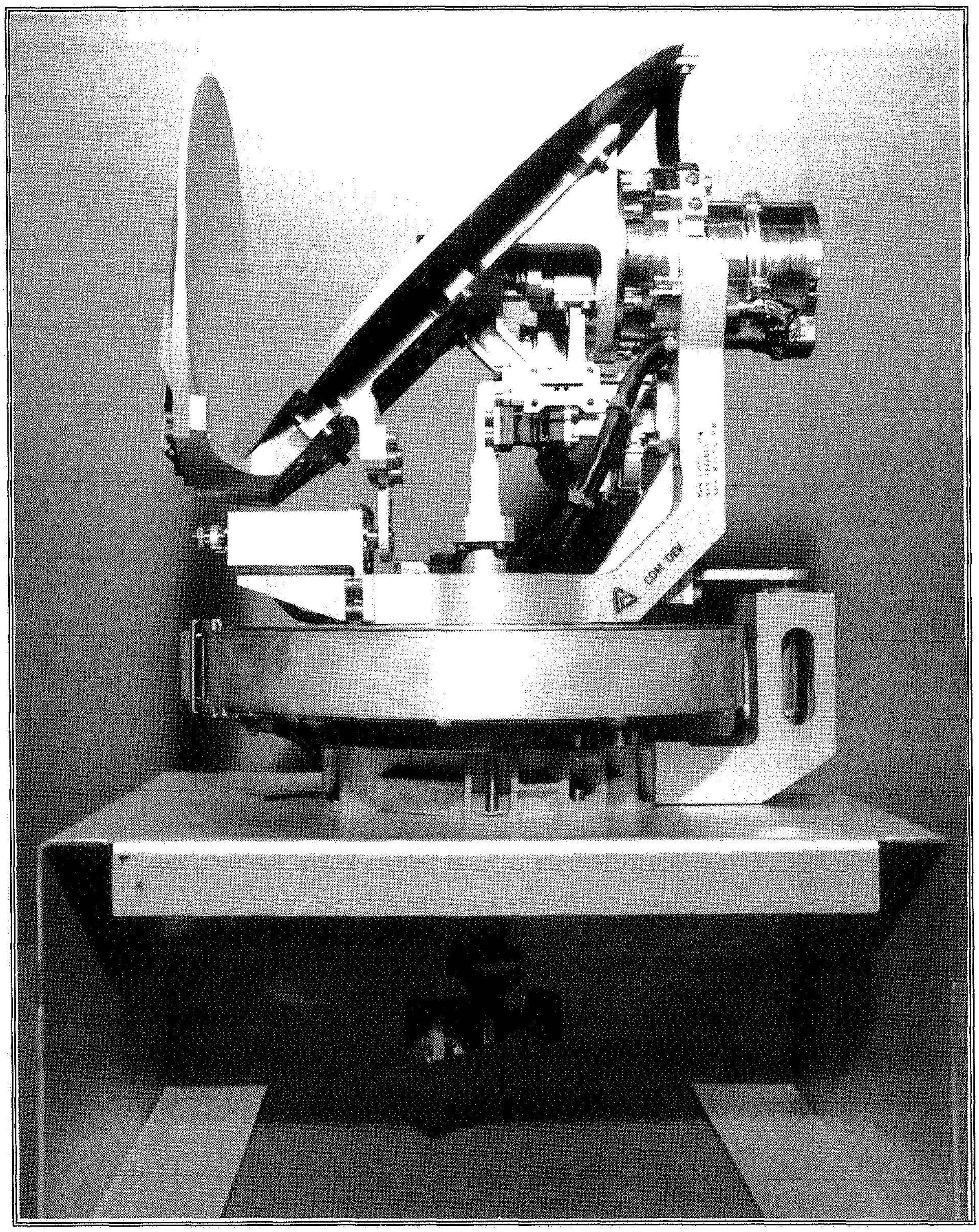

Figure 1
Gimballed Microwave Antenna (GMA)

Requirements and Capabilities

The design requirements of the GMA, along with its capabilities and analytical predictions, are presented in Table 1.

Table 1
GMA Requirements vs. Capabilities and Predictions

PARAMETER	REQUIREMENT	QUAL AND PRODUCTION UNIT CAPABILITIES[1]	ANALYTICAL PREDICTIONS
Dual Freq. wave	20 GHz/30 GHz (Tx/Rx)	Comply	Comply
Positioning Accuracy	≤ 0.60°	Max = 0.4° Mean = 0.3°	0.51°[2]
Range of Motion	AZ: ±185°; EL: +27° to 90°	Comply by Test	Comply
Angular Rate	AZ: 15°/sec max EL: 6°/sec max	Comply by Test	Comply
Step Size	.047°	Comply by Test	Comply
Motion Envelope	26.9 D X 31.1 H (cm)	Comply by Test	Comply
Lifetime Excursions	5.9 x 10^5	Comply by Test	Comply
Mass	5.44 kg (12.0 lbm)	5.23 kg (11.54 lbm)	5.28 kg (11.65 lbm)
Rotational Mass	EL: 1.04 kg AZ: 2.54 kg	Comply by Design	EL: .94 kg AZ: 2.46 kg
Random Vibration	12.4 Grms	Comply by Test	Comply
Sine Vibration	5 G's From 5 Hz to 100 Hz	Comply by Test	Comply
Stowed Resonant Frequency	≥ 100 Hz	102 Hz; Q=7 (X-axis) 120 Hz; Q=6 (Y-axis)	108 Hz; Q=20 140 Hz; Q=15
Pyro Shock	1000 G peak	Comply by Test	Failure
Thermal Extremes: Operating	-40°C to +76°C; Low Temp Controlled by Heaters	Verified in TVAC Testing	Comply
Thermal Cycles	1020 Cycles: -50°C to +85°C	Comply by Test	Comply

Design Description

The GMA is a dual reflector microwave antenna driven by an elevation over azimuth gimbal system, the general layout of which is shown in Figure 2. An RF rotary joint and a flat-ribbon cable wrap are integral to the azimuth rotary actuator and pass microwave signals, power, and telemetry across the azimuth axis. The dual reflector antenna design was chosen for its compactness, and it eliminates the need for an elevation axis RF rotary joint. Paraffin actuator launch locks provide restraint of motion about the azimuth and elevation axes during launch. GMA thermal control is primarily passive, though flexible Kapton heaters are used to maintain actuator temperatures above their low-end operating extremes.

GMA azimuth motion is provided by a rotary actuator supplied by Honeywell Satellite Systems Operation (HSSO). This actuator is a three-phase, 3.75° stepper motor with integral 80:1 harmonic drive gear reduction, thus yielding a nominal 0.047° output step increment. The actuator output bearing set was sized to react expected launch loads of 283 N-m (2500 in-lbf) in bending and 4450 N (1000 lbf) in shear, while the titanium housing material was chosen to match the coefficient of thermal expansion (CTE) of the steel bearing set. A built-in, incremental encoder attached to the motor, when combined with an output shaft reference switch signal, provides both step count and actuator zero location to the GMA controller unit aboard the Space Vehicle (SV).

[1] Based on nine samples (one qual and eight production units)
[2] 3σ estimate

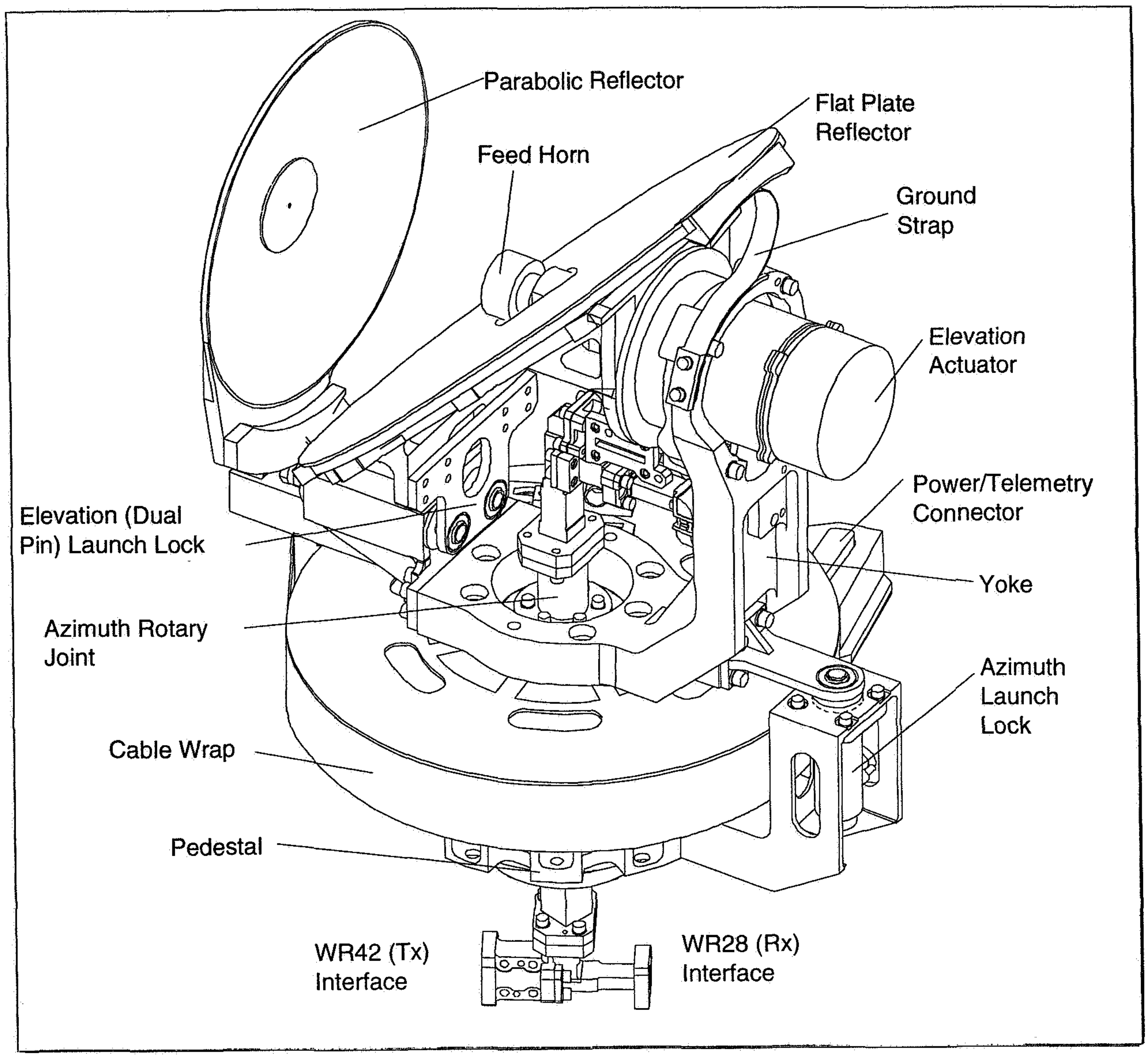

Figure 2
GMA Layout

To provide a transmit and receive signal path across the azimuth axis, the rotary actuator incorporates a circular waveguide along its centerline. Early teaming of mechanical and RF engineers was essential to define the interfaces between the rotary actuator and the RF signal processing components (Figure 3). The circular waveguide concept was chosen for its low signal power loss across the interface, but it required tight runout tolerances. After the concept was selected, the rotating and static components of the RF path were immediately fabricated and tested to verify performance assumptions.

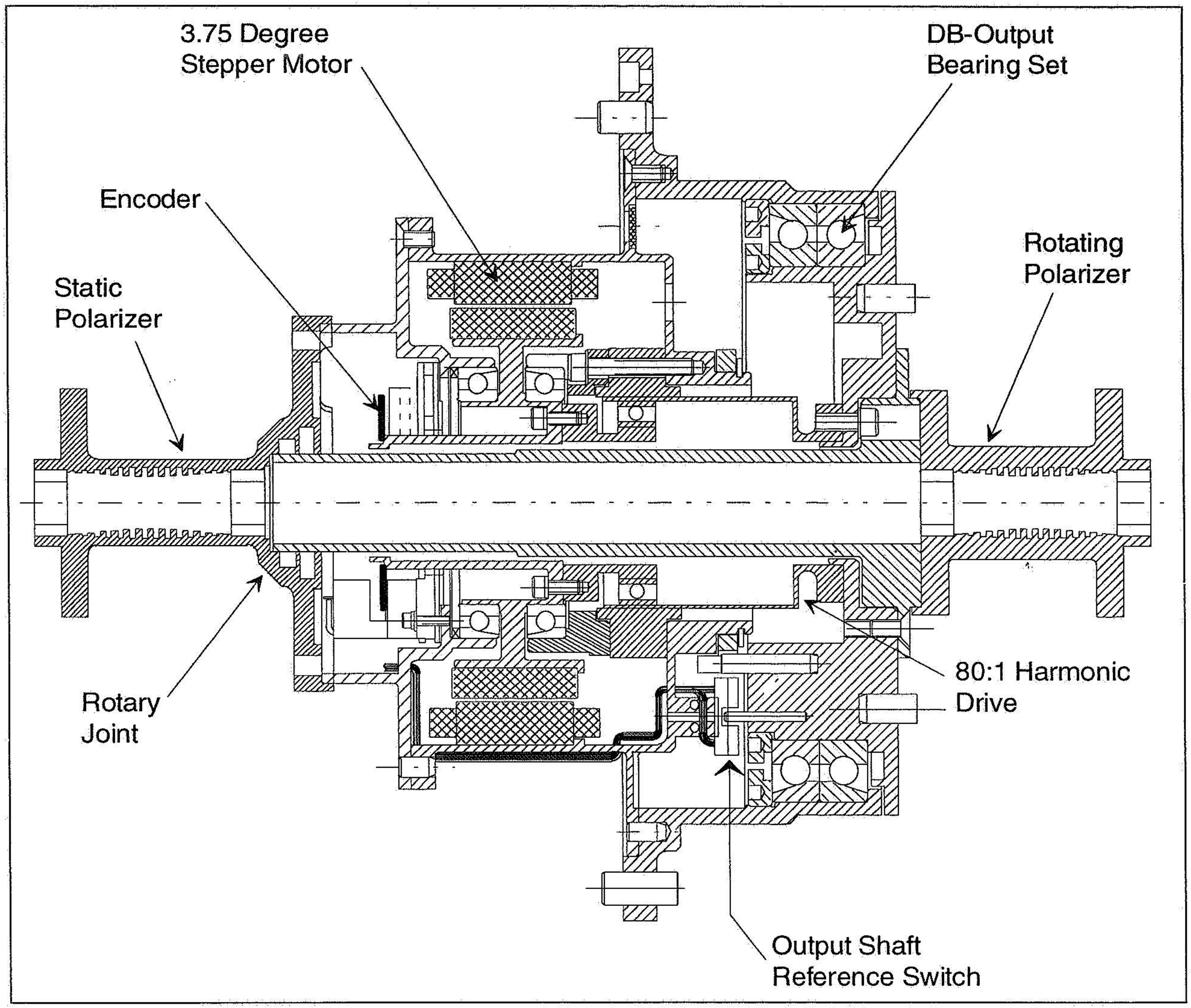

Figure 3
Azimuth Actuator/Rotary Joint Cross Section

Directly attached to the azimuth actuator is a cable wrap mechanism[3] which controls the motion of a 19-conductor flat-ribbon cable throughout the full 370° range of azimuth motion. The critical design feature of this mechanism is low drag torque over the operating temperature range (-40°C to +76°C). This low drag torque minimizes actuator pointing errors caused by torsional loading of the harmonic drive. Drag torque and life tests were completed early in the program to reduce risk.

The design of the azimuth actuator had to be closely coordinated between four companies in only a four-month design cycle: COM DEV defined launch loads, mass, power, pointing error, and waveguide requirements; HSSO provided detailed actuator

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[3] Supplied as part of the azimuth rotary acuator by HSSO.

design; and Motorola and the SV bus supplier defined vehicle loads and component placement and designed the composite panel and interface to which the rotary actuator mounts.

The stator portion of the azimuth actuator is mounted to a machined titanium pedestal to raise the GMA off the SV panel enough to assure a clear field of view (FOV) for the antenna. The rotor side of the actuator is attached to an aluminum yoke which provides structural support and alignment for the elevation axis antenna components. Yoke and pedestal material selection was finalized only after completion of a detailed thermal distortion analysis of the actuator bearings. When considering use of dissimilar materials in a mechanism assembly, it is important to assure bearing performance is not adversely affected by CTE mismatch.

The GMA yoke supports the elevation actuator, antenna feedhorn, and associated RF signal paths. The elevation rotary actuator is identical to the azimuth rotary actuator in construction, except it is smaller due to lower launch loads and has no requirement for an integral RF waveguide. A more detailed description of the design of both these actuators is provided by Koehler [1].

The feedhorn of the GMA is mounted in a stationary position on the yoke, while the flat plate and parabolic reflectors are mounted to the rotor side of the elevation actuator, and thus become the rotational portion of the antenna in elevation. This configuration eliminates the need for a rotary joint through the elevation axis which, in turn, reduces the part count, cost, complexity, and mass of the assembly. The flat plate and parabolic reflectors are weight-relieved aluminum machinings with a sulfuric-acid anodized finish. The 7075-T73 aluminum was chosen over more exotic, lower mass materials for low cost and availability, and the surface finish was chosen as a compromise between thermal, RF, and cost performance.

GMA pointing accuracy was specified to be within 0.60° of target. This accuracy had to be achieved after consideration of machined part tolerances, thermal distortion, and beam squint. Early conceptual studies concluded that the two antenna reflectors needed to be joined by a common structure so that they could be precisely aligned and rotated together about the elevation axis. This design, though volume- and RF performance-efficient, was essentially a cantilevered load suspended from the elevation rotary actuator and led to a requirement for a mechanism to offload the actuator during launch. The resulting elevation axis launch lock mechanism employs a dual-pin arrangement, using a High Output Paraffin (HOP) actuator[4] together with a secondary pin, joined by a tie bar (Figure 4). The secondary pin slides on Karon®[5]-lined, low-friction bushings, and the two pins engage Karon®-lined spherical bearings on the reflector support bracket. The spherical bearings were chosen to allow the mechanism the freedom to disengage when small misalignments are present in the assembly. The mechanism was analyzed to assure a deployment margin of at least

[4] Supplied by Starsys Research Corporation, Boulder, CO
[5] Karon® is a registered trademark of Kamatics, Inc., Bloomingfield, CT

50% when worst-case actuation forces were compared to the worst-case combination of friction forces.

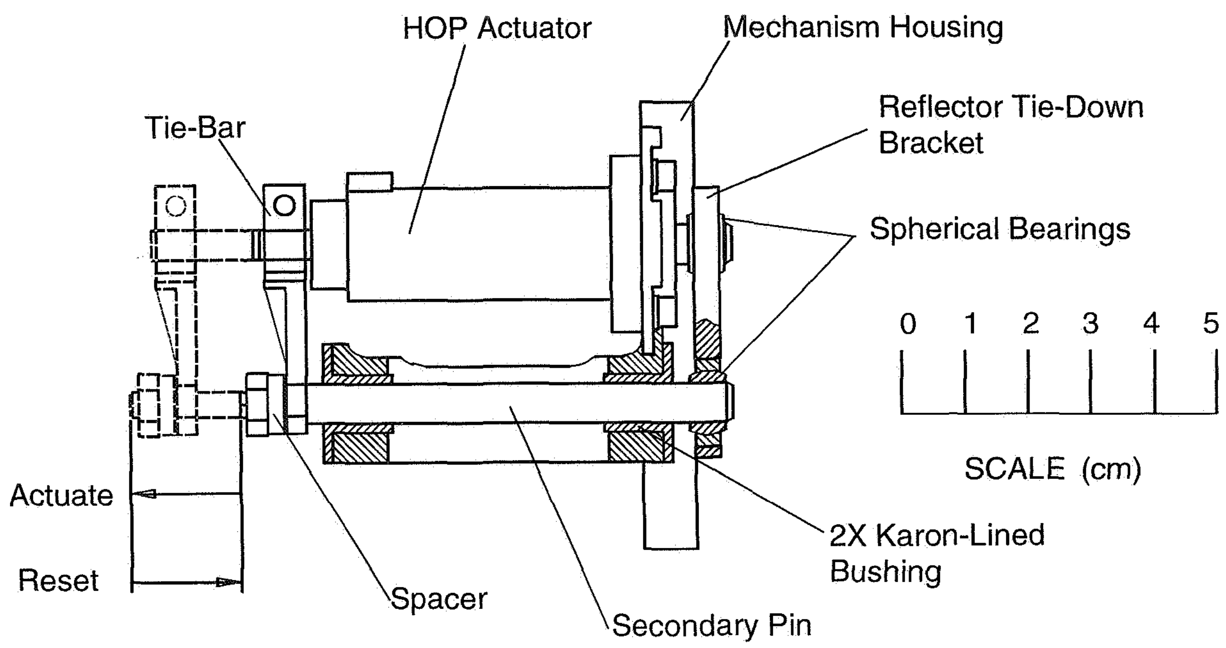

Figure 4
Elevation Axis Dual-Pin Launch Lock Mechanism

Rotation of the GMA about the azimuth axis is prevented during launch by the azimuth launch lock, which employs a similar HOP actuator to that used in the elevation axis launch lock, but does not require a second pin.

Another important consideration in designing the GMA gimbal mechanism was electrical grounding across the rotational axes. This requirement arises from the need to bleed off charges that accumulate on the reflector surfaces in space. Rotary actuator output bearings are not suitable grounding paths for this purpose. The azimuth axis uses cable wrap conductors to provide the necessary electrical continuity, whereas the elevation axis required a ground strap to connect the flat reflector to the yoke, thus bypassing the elevation axis rotary actuator. The flat reflector rotates 63° in elevation relative to the yoke; therefore, the ground strap must allow for this rotation. Other ground strap requirements were (1) high flexibility to minimize drag torque; (2) shape retention during handling and launch vibration; (3) ability to survive 750,000 motion cycles; and (4) capability to withstand the external and thermal environments. After considerable testing, a 0.05-mm-thick beryllium copper strap with a black oxide finish was chosen for this purpose.

Design For Volume Production

The unique aspect of the GMA spacecraft mechanism design was the requirement to design for volume production and to "Design to Unit Production Cost (DTUPC)." In this aspect, the development task took on a more commercial flavor and set it apart from the previous experience of the co-developers. Some of the design decisions that were necessitated as a result of these unique requirements are highlighted below.

Antenna Configuration

The initial GMA concept was a more traditional horn and lens design, chosen for its excellent RF parameters (Figure 5). Considerable effort was put into this design before realizing it was extremely complex, its expected cost was well over production targets, and there were significant technical issues. There were material problems with the lens (Atomic Oxygen, CTE mismatch with the horn, grounding), rotational inertia and overall mass specifications could not be met, and the assembly could not meet its volume envelope. Therefore, the design team re-opened the trade space and re-addressed the GMA design, based on manufacturability and DTUPC concepts.

Out of this joint buyer/seller re-design effort came the dual reflector design, a more compact design that allowed the GMA to meet its envelope requirements. Overall mass was lowered by 0.59 kg (1.3 lbm), thus allowing the assembly to meet its specification, CG was lowered by 1.3 cm, which lowered structural loads, and the mass imbalance of the lens was removed, thereby allowing the GMA to meet its rotational inertia specifications. These reductions made internal loads smaller, thus making launch lock design easier and cutting structural mass further. Finally, the assembly part count was reduced by half (including the removal of an elevation rotary joint which was 10% of the expected production cost), thereby increasing reliability and decreasing complexity. The slightly less efficient antenna design was offset by the decreased feed loss due to removal of the elevation rotary joint, so the only expense associated with the benefits of the dual reflector design was the addition of a pedestal to raise the assembly phase center for clear FOV.

Rotary Actuators

The GMAs are not the only antennas that COM DEV and Motorola supply for commercial satellites. The four GMAs constitute just part of a K-Band antenna suite which contains two other gimballed antenna assemblies that are quite different from the GMA design. Design of actuators, optimized for each individual gimballed antenna assembly in the K-Band antenna suite, would have required a total of four unique actuator designs. An early program decision was made, based on DTUPC/economy of scale principles, to standardize all gimballed antenna actuator designs, thus reducing the number of actuator designs needed to two.

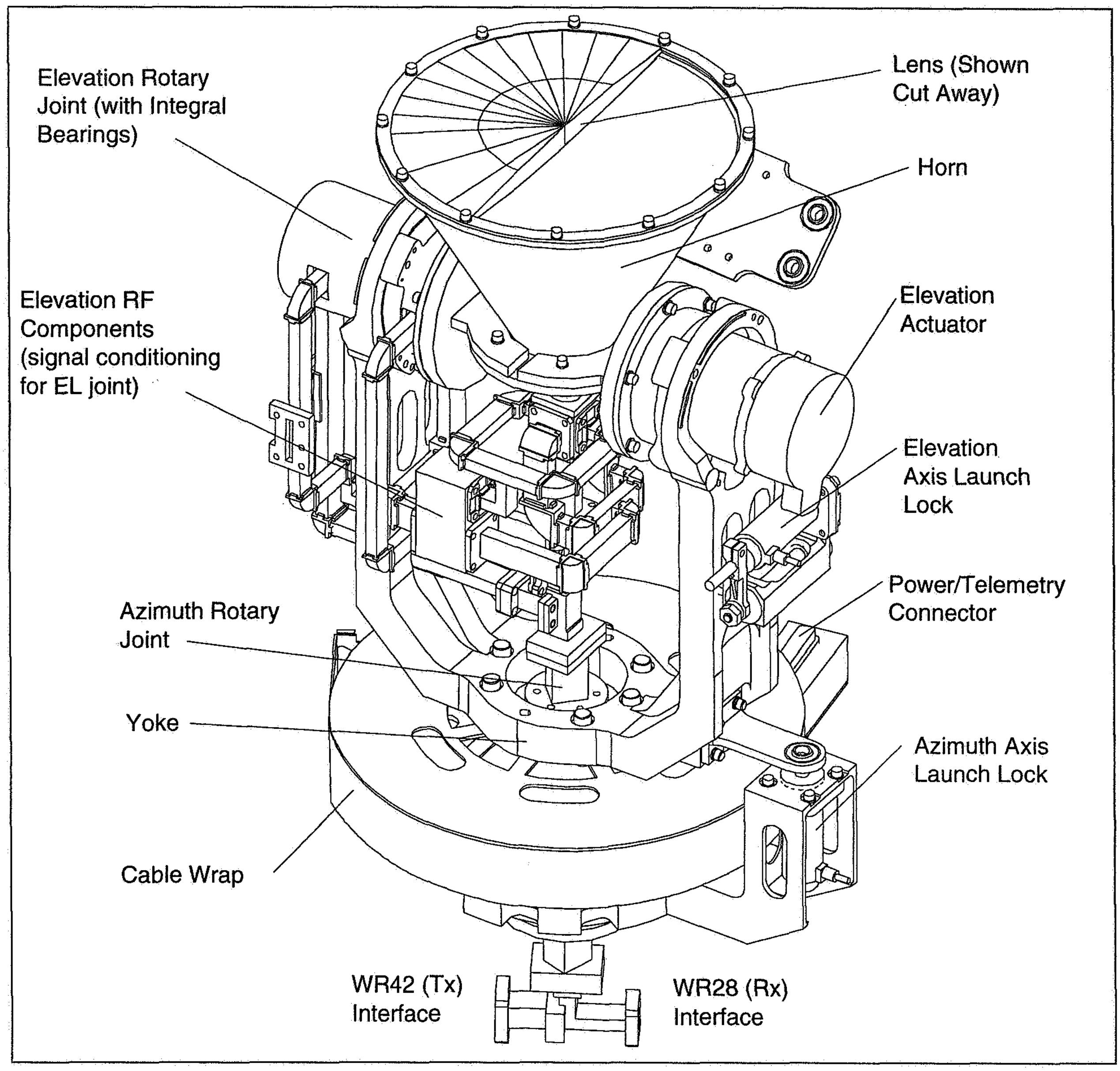

Figure 5
Initial GMA Horn and Lens Design

The use of common actuators made for a more challenging design phase, since actuator designs had to account for differences in the launch loads, waveguide dimensions, and hard stop positions of the various antenna assemblies. Possibly some volume and mass optimization were lost; however, the cost and complexity savings, as well as the tooling and overhead savings, far outweighed any losses.

Launch Locks

Launch locks were designed integral to the GMA instead of including them as a separate structure on the SV, thus avoiding the associated additional harnessing, alignment problems, and higher volume. In addition, it cut assembly time and part stocking overhead at the SV level, as well as simplifying GMA testing and transporting.

The same commonality principle used in the rotary actuator design was used in the launch lock design. Each gimballed antenna assembly (six total, including GMAs) in the K-Band antenna suite needed two launch locks — a production total of 960 over the program life — so the economic benefit of standardizing launch lock designs was obvious. Design of launch locks, optimized for each gimballed antenna assembly, would have required four unique designs. Rather than use four unique designs, all efforts were made to provide a single design. In the end, however, two distinct launch lock designs had to be used: a single-pin design used in the bulk of applications, including restraint of the GMA azimuth axis, and a dual-pin design necessary to offload the GMA elevation components. The impact of accommodating two distinct launch lock designs was minimized by using the same spherical bearing in both designs and only slightly modifying the HOP actuator for use in the dual-pin design. Only one part within the HOP actuator was changed — the actuator pin was extended through the back of the actuator (Figure 4); therefore, subcontract costs were minimized.

The GMA launch locks were designed to be simple, reliable, and resettable. The HOP actuators were chosen based on these requirements, and they generate no shock on deployment. Both the azimuth and elevation launch locks were designed to be reset after actuation by using spring-loaded tools that either push (elevation dual pin) or pull (azimuth) the HOP actuators back to their locked positions. The provision to actuate and quickly reset the launch locks at both the antenna and SV level was necessary to meet both GMA and SV test cycle time requirements. Verification of flight hardware by performing multiple actuation/reset cycles during ground testing helps assure reliable on-orbit deployment. Shock-free antenna deployment helped avoid costly design and testing cycles and had the additional benefit of not requiring the handling and safety overhead associated with pyrotechnic actuators.

Cable Wrap Mechanism

The initial concept of the cable wrap mechanism design was based on wiring that met all military specifications for shielding and for separation of signal and power lines. The design was unacceptable from cost, volume, and mass standpoints. At this point, the design team did something that was a standard practice on the program: we got a supplier involved in the design. A cable vendor[6] was invited to a joint review of the design. After both reviewing the design and determining the actual requirements, the design was changed to make use of a commercial product. The final wiring configuration is based on a 19-conductor, flat-ribbon cable with internal shielding between the power lines and the encoder lines. An external shield is added using aluminized Mylar film, contacts are gang-crimped to the ends of the cable, and the contacts are batch-soldered to spaceflight connectors. All processes are highly automated, and the vendor now supplies the cable for the cable wrap mechanism as a drop-in, pre-tested assembly.

[6] W.L. Gore & Associates, Inc.

By leveraging the knowledge of a supplier and careful review of the program technical requirements, cable wrap mechanism cabling costs were reduced nearly ten-fold, assembly time was substantially decreased, and a 0.45-kg mass savings was realized.

Manufacturability

The GMA gimbals consist of not only the azimuth and elevation rotary actuators, but also precision machined parts, such as the pedestal, yoke, and antenna support brackets. These machined parts have a large influence on the pointing accuracy of the antenna and are manufactured in quantities of 200 to 300 pieces. The use of shimming at component interfaces to assure that the pointing accuracy of any antenna would meet specification was not permitted. Therefore, the emphasis was on selecting machining tolerances that were realistic, economic, and could be controlled through statistical process control (SPC) at the machine shop level. This philosophy of manufacturing (i.e., SPC of machined parts and no shimming) had a direct impact on the next aspect of volume production — assembly.

Assembly

The GMA design had to assure an assembly time that allowed delivery of four GMAs per week. Therefore, the assembly design was based on the following key points:

- *No Shimming Permitted*: There was simply not enough time in the production schedule to test for pointing accuracy, to disassemble, to adjust by shimming, then to retest.
- *Fully Interchangeable Parts*: Use of match drilling and pinning of parts to increase alignment accuracy was not permitted. The flexibility of allowing any rotary actuator or machined part to be used in any antenna assembly greatly increases production flow and cuts part tracking overhead.
- *Alignment features for ease of assembly*: Although the antenna gimbals are precision assemblies, the alignment of a rotary actuator to a pedestal or yoke is simply a matter of mating alignment features on one part to reciprocal features on the other part. This places minimal burden on assembly personnel, both in terms of time and elimination of alignment errors.
- *Minimal Staking*: Staking of parts was nearly eliminated, thus cutting costly assembly time and the even longer cure times during which the assembly is unavailable for further processing. This also reduces the "as required" parts count, and, therefore, assembly variation.

Test

The time required for verification testing of each antenna was minimized through design features and testing philosophies, such as:

- *1g Holding Capability*: Rotary actuators were designed to provide unpowered detent torques large enough to maintain the antenna elements in a fixed position, regardless of antenna orientation, during ground testing. Thus, no cumbersome 1g negation devices were required.
- *Antenna Test Range Automation*: Pointing accuracy of a gimballed antenna is verified on an antenna test range. The time required to take measurements and process data is excessive, and accounts for a major portion of the GMA

acceptance test cycle. Range availability is also an issue because of the quantity of antennas which must be processed through the range during peak production. Therefore, this process has been streamlined by automating test range operations. Antenna pattern measurement and data reduction have been automated through the use of newly developed software, thereby significantly cutting test cycle time.

- *Built-in Test Ports*: RF test couplers were designed into the RF signal paths of the GMA and located for ease of access at both the antenna and SV levels. This allows for rapid test connection and end-to-end test of the SV-level RF path without cumbersome antenna-to-antenna interrogation of the system. A minimal mass penalty is paid for flying the test couplers with the GMA, but this is more than offset by minimized test set-up time and complexity.

SV Level Assembly

Speed of assembly at the SV level is essential to achieve a peak delivery rate of one SV per week. The following features were added to the GMA to optimize SV level integration time:

- *Captive Mounting Bolts*: GMA mounting bolts are locking bolts that are captive in the pedestal. Captivity in the pedestal reduces bolt installation time and removes the possibility of bolt dropping/finding time. Locking elements in the bolts remove the need for bolt staking.
- *Single Interface Connector*: All electrical signals, excluding antenna microwave signals, enter the GMA through a single multi-pin DD interface connector. This simple interface cuts assembly time and is standard throughout the system.

The total time for GMA integration onto the SV is just 11.0 minutes and requires no further adjustment after installation.

Testing/Results

The GMA successfully passed qualification testing in July, 1995. Test results correlated well with analytical predictions (Table 1).

One minor problem was encountered during the testing: the initial version of the elevation axis ground strap failed during random vibration testing. This initial design was a 0.05-mm-thick pure copper strap with a black oxide finish that was already being considered for change because it tore easily during assembly. The ground strap material was then changed to beryllium copper (BeCu), which was more durable and survived a re-qualification vibration test. The BeCu version of the ground strap was then subjected to a 750,000 motion-cycle life test, which it passed.

Conclusion and Keys to Success

Development of the Gimballed, Microwave Antenna (GMA) was highly successful. The end result was a reliable, low-cost, high-performance, gimballed satellite antenna designed from a commercial, "overall cost" standpoint which allowed for volume production at the antenna assembly facility and high-rate installation and test at the satellite level. This commercial, low-cycle time, bulk volume perspective was a paradigm shift for the contractors, who were from low volume DOD/Space backgrounds, so the development was not without difficulties. However, with these difficulties came lessons, a sample of which follow:

- *Use design heritage.* There will be enough wheels to invent.
- *Build many prototypes, especially of moving assemblies, and build them early on.* 3D models do not catch all problems. An engineering model GMA rotated into an adjacent box during SV subassembly range testing, much to our surprise. This should have been caught by the 3D model, but as the design task progressed, modelling responsibility was transferred to people less and less familiar with the design concept. Rotational operation of the GMA was not communicated accurately to the new designers; hence, the interference was not detected, thus leading to re-design which could have been prevented by building an earlier prototype.
- *Design special test equipment (STE) with an eye on all levels of assembly*: Make sure STE that might be used at higher levels of assembly is designed considering ease of access at higher levels of assembly. All launch lock resetting and optical verification tools were designed to fit both at the GMA assembly level and at the SV level. However, on another antenna assembly in the K-Band antenna suite, ease of access for a reset tool was not considered, and a new tool had to be immediately developed for use in a cramped space.
- *Account for changing requirements up front.* Requirement generation and hardware development always overlap somewhat, thus creating shifting, and entirely new, requirements during the design phase. Design in extra margin, design for easy modifications, and set aside costs for the inevitable changes.
- *Political/Cultural issues are the hardest to overcome* when jointly developing with multiple contractors. Cultural differences include
  - Direct vs. Indirect Investors
  - Military vs. Commercial Attitudes (Risk Taking)
  - Large vs. Small Corporations (Resources)
  - U.S. vs. Non-U.S. (ITAR, Customs, etc.)
  - Teaming vs. "Us Against Them"

  To lessen the impact of cultural differences, create a cross-contractor team, at least at the technical level.
- *Nail down design and analytical responsibilities early to avoid arguments (about cost/resources) and delays later.* In the rush to get the GMA subcontract signed, responsibility for the GMA orbital thermal modelling was not delineated. In addition, the specification was vague. When the scope of the effort became clear, work on thermal modelling came to a halt. Many extended phone conferences were held, airline seats filled, and meetings attended. All of these efforts could have been avoided by taking the extra time to clear up "gray" areas in the contract and specification early on.
- *Synchronize work of co-contractors and suppliers. When a team member gets ahead, the design is driven by factors other than optimal product outcome.*

Rotary actuator design progressed much more rapidly than did the antenna or SV designs. Actuator envelopes were created by the actuator developer, piece part drawings were released and housings machined, all before design of the structure was complete. When the structure design was nearing completion, it was clear that either the actuator would have to change or the structure would not be optimum. An acceptable compromise was reached, but this would not have been necessary had work been better synchronized.

- *Contractor incompatibilities hinder the design process.* The different CAD systems, geographic locations, and communication systems of the various subcontractors made the design process less efficient. 3D modelling was used at only two of the four main players, so models could not be easily swapped, thus resulting in duplication of effort. Pagers were profuse at some subcontractors and virtually non-existent at others, while email, which proved to be a great time zone equalizer, was not available at one location.
- *Do not ignore small issues. Small issues become big problems later on.* The shielding concept of the actuator wires was a known issue. The desired shielding resulted in a wiring bundle that did not fit within the available routing volume. Though the desired shielding was relayed to the supplier, it was never requested in the specification, so no changes were made. Both sides thought they were getting what they wanted. When initial actuators were delivered without the shielding, the small problem transformed into a large problem. This problem was quickly solved by calling the technical team together and working the issue but could have been avoided by better communication.
- *Early supplier involvement creates better products at lower cost* by taking advantage of experts' design and capability knowledge.
- *Define interfaces as quickly as possible.* Pass on prospective changes as quickly as possible. This allows the design team to find a solution while the contractual issues are resolved as a side issue.
- *Develop a team.* "Design-in-a-vacuum" costs. Poorly communicated requirements cause huge problems. It may not seem worth it, but formalized meetings, or a process to communicate to the entire team, will solve problems more expediently and optimally. However, this requires all players' commitment to the best technical solution.

Acknowledgments

We would like to thank our numerous colleagues at COM DEV and Motorola for contributing to the work described in this paper. We would also like to acknowledge the management of Motorola and COM DEV for their support and encouragement and Industry Canada for partial funding of the program at COM DEV.

References

1. Koehler, David R. "Low-cost, High-reliability Rotary Actuator for a Space Satellite." Ninth Annual AIAA/USU Conference on Small Satellites, Space Dynamics Laboratory/Utah State University, Logan, UT, September 19, 1995.