TRW BROADBAND PAYLOADS FOR THE EMERGING KA-BAND MARKET

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ABSTRACT

TRW initiated the Gen*Star processing payload development in 1995 to address demands for broadband satellite systems and services. The Gen*Star system objectives of profitable broadband connectivity with seamless interfaces to a terrestrial infrastructure imply highly reliable network nodes in space. To achieve these objectives, robust communications links and sophisticated onboard signal and data processing are required. The Gen*Star satellite payload provides those communication links and processing functions in a package suitable for launch into space, using technologies designed to operate for years in the space environment. The TRW Gen*Star payload development incorporated business analysis, network simulation and analysis, payload technologies, network operations, and terminal concepts. Since initiating the effort, TRW has completed simulations, a functional hardware prototype of the payload, and a complete engineering model payload. The end-to-end engineering model of a broadband payload operating at Ka-Band features engineering model hardware built to flight production standards and tested to flight environmental conditions. This presentation and paper will summarize features and capabilities of the TRW broadband engineering model payload and the payload test results.

DEVELOPMENT HISTORY

TRW has been developing complex space communications systems at Ka-Band for over two decades (Figure 1). Starting in the early 1980s, TRW developed the first onboard-processed, on-demand, multibeam digital communication payload for military satellite payloads. Using this experience, we have developed the technologies and design processes required for an onboard digital-processed payload. By the mid-1990s, we were developing our 3rd generation of highly reliable digital processing in space. The Astrolink payload hardware is a direct descendant of that hardware, as shown in Figure 1. At that time, the prospect of commercializing these technologies and processes was realized and we started a large research and development program. Beginning with business plan analysis, we performed system architecture studies and identified the high-leverage and enabling technologies. These technologies were then successfully developed over the next two years, including high-density microwave monolithic integrated circuit (MMIC) low noise amplifiers (LNAs), frequency converters, highly efficient digital signal processing algorithms, etc.

By the end of 1997, we had retired the technology risks involved in broadband digital payloads. However, the application of these technologies into a specific design that meets the challenges defined above still required proof. In early 1998, our research and development focus shifted to implementation of an end-to-end hardware functional prototype (HFP) of the system. The objective was to retire the remaining risks in one year. All these objectives were met.

Following this development, we proceeded with the development of flight payload design. High fidelity design verification model (DVM) units have been manufactured using

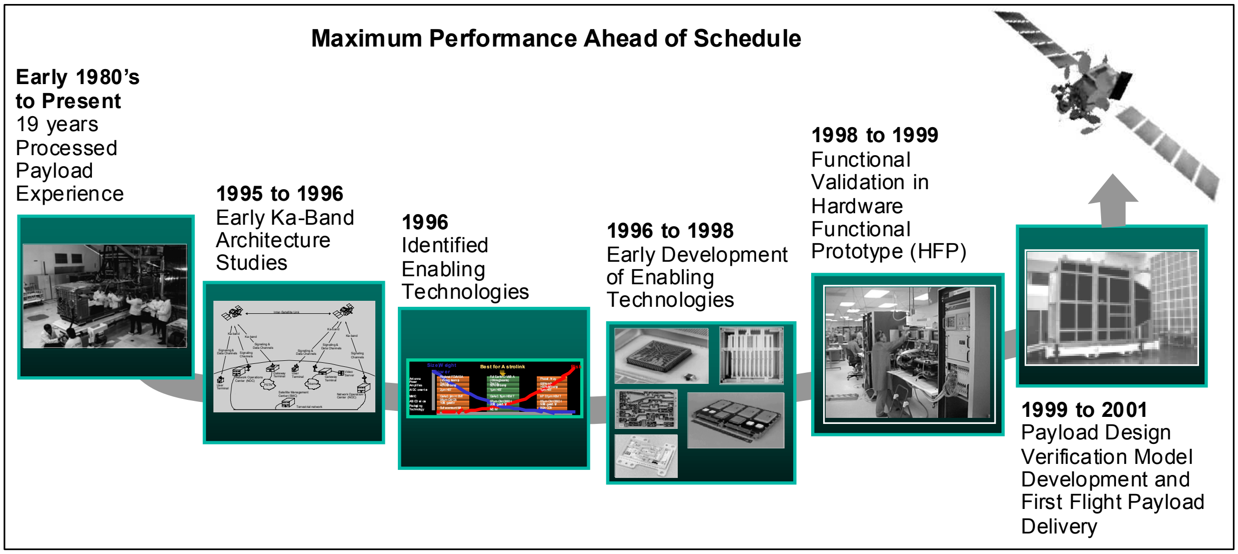


Figure 1. TRW Broadband Payload Heritage and Development

flight processes—integrated and are now in test. Results to-date demonstrated full functional capability, excellent correlation with performance predictions, and a low risk path to broadband payload solutions. Through this process we validated flight production techniques. Incorporation of design for testability concepts has enabled a reduction in overall cycle time.

REQUIREMENT SUMMARY

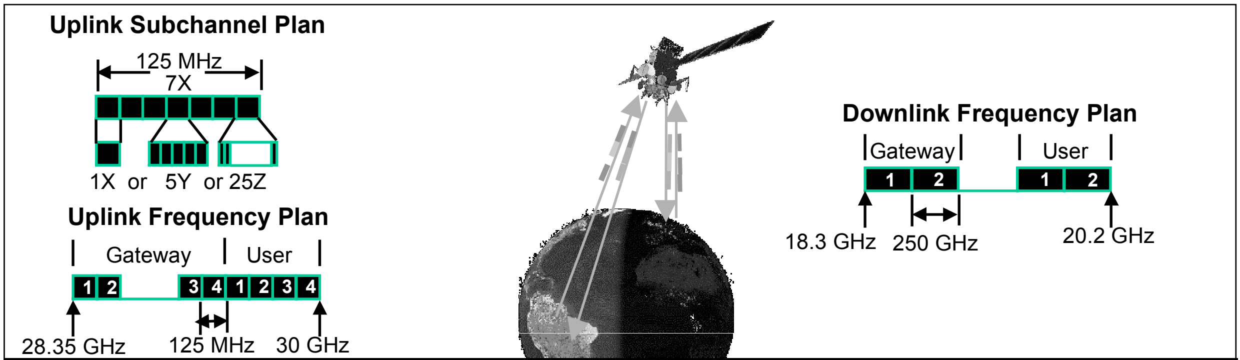
There are four categories of payload requirements for the Gen*Star system: (1) coverage, (2) uplink communication, (3) network functionality, and (4) downlink communications (see Figure 2).

The payload can provide coverage to densely packed ground cells. The Gen*Star payload has the flexibility to accommodate a wide range of cell locations distributed between user cells and gateway cells. User coverage cells have 4-way frequency reuse, i.e., each cell must support one-fourth total capacity of the frequency allocation. In addition, redundant uplink channels can be activated, providing additional uplink surge capacity in selected regions. Payload total capacity—after all overhead and coding are met—is up to 12 Gbps.

A series of design trades led to the selection of the uplink and downlink waveform for the Gen*Star broadband systems. The waveform has many features that enable excellent performance in broadband satellite systems.

For uplink communication, the payload must receive user and gateway signals in each ground cell, then channelize, demodulate, and decode the signals. The basic network protocol is based upon asynchronous transfer mode (ATM). ATM allows fixed uplink and downlink burst sizes to facilitate bandwidth assignments on the time division multiple access (TDMA) link, quality of service (QoS), and the encapsulation of various other protocols. The ATM protocol also facilitates interconnection with terrestrial networks. Three channel burst rates in the frequency division multiplex (FDM)/TDMA uplink structure enable the use of cost-effective terminals appropriate for each application. With a specified receive power for each channel rate, the decoded cell loss rate (CLR) must be less than 3×10^{-8}. The use of a common user terminal and gateway terminal transmission format simplifies system design.

The waveform incorporates pulse shaping to minimize self-interference and scrambling of both uplink and downlink data to prevent spectral emissions problems with repetitive data such as idle cell transmission. In the uplink frame where traffic is composed of short-duration TDMA bursts from multiple



Networking
- Full-matrix ATM cell switch provides point-to-point and multicast switching to any set of beams
- Supports over 10 million virtual path (VP) and virtual circuit (VC) connections
- 128,000 cell buffers and 16 priority levels per downlink channel support wide range of QoS
- Cell statistics collected for network optimization
- Buffer occupancy statistics collected for congestion control

User and Gateway Downlink Communication
- Single-carrier TDM QPSK format allows efficient TWT downlink amplifiers
- Stable 196.7 Msym/sec burst rate provides accurate frequency reference for terminals
- Powerful concatenated code enables minimal terminal size
- Adaptive convolutional code maximizes throughput and rain margin
- Common user and gateway format provides operational flexibility
- Downlink hops between two channels in 50/50, 67/33, 75/25, and 100/0 ratios

User and Gateway Uplink Communication
- FDM/TDMA QPSK format provides flexible transmission plan
- Three burst rates allow cost-effective terminal classes:
  - Z: 562 Ksym/sec (user)
  - Y: 2.81 Msym/sec (user)
  - X: 14.05 Msym/sec
- Powerful Reed-Solomon code provides reliable transmission:
  - CLR: $3x10^{-8}$
- Adaptive inner code maximizes throughput and rain margin
- Common user and gateway transmission format provides flexibility and simplifies system design
- High accuracy power/performance control

Coverage per Satellite
- Up to 80 coverage areas
- Up to 80 uplink/downlink channels provide user coverage
- Up to 80 uplink/downlink channels provide GW coverage
- Surge demodulations enable capacity to be concentrated into selected regions
- Payload capacity of up to 12 Gbps

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Figure 2. Gen*Star Payload Requirements Overview

users to the satellite, short 4-cell data blocks enable optimal allocation of bandwidth to user. In the downlink where a single data stream is sent to multiple users, longer data blocks with interleaving between the blocks is used to maximize code performance.

Uplink power and signal-to-noise metrics must be provided to enable terminals to perform uplink power control. Direct feedback from the payload enables greater power control accuracy and helps to minimize uplink interference.

The ATM switch must provide point-to-point, as well as multicast, connections between any of the cells, users, and gateways. It must support over 10 million connections, both virtual circuit (VC) and virtual path (VP). Multiple QoS types must be supported, including constant bit rate (CBR), realtime variable bit rate, non-realtime variable bit rate, and available bit rate (ABR), etc. Statistics are collected for network optimization, congestion control, fairness, and policing.

For downlink communications, the payload must encode and modulate each ATM switch output into a single TDM quadrature phase shift keyed (QPSK) signal shared by two beams for downlink transmission. The downlink signals must be transmitted at a specified power with strictly limited beam-to-beam interference. This downlink sharing allows capacity to flow dynamically to where it is demanded most.

PAYLOAD SIGNAL FLOW

A top-level payload block diagram is shown in Figure 3. The multibeam antennas receive uplink signals. The low noise amplifiers and downconverters are monolithic microwave integrated circuits and are packaged into a single integrated microwave assembly (IMA). The IMAs are mounted directly to the feeds.

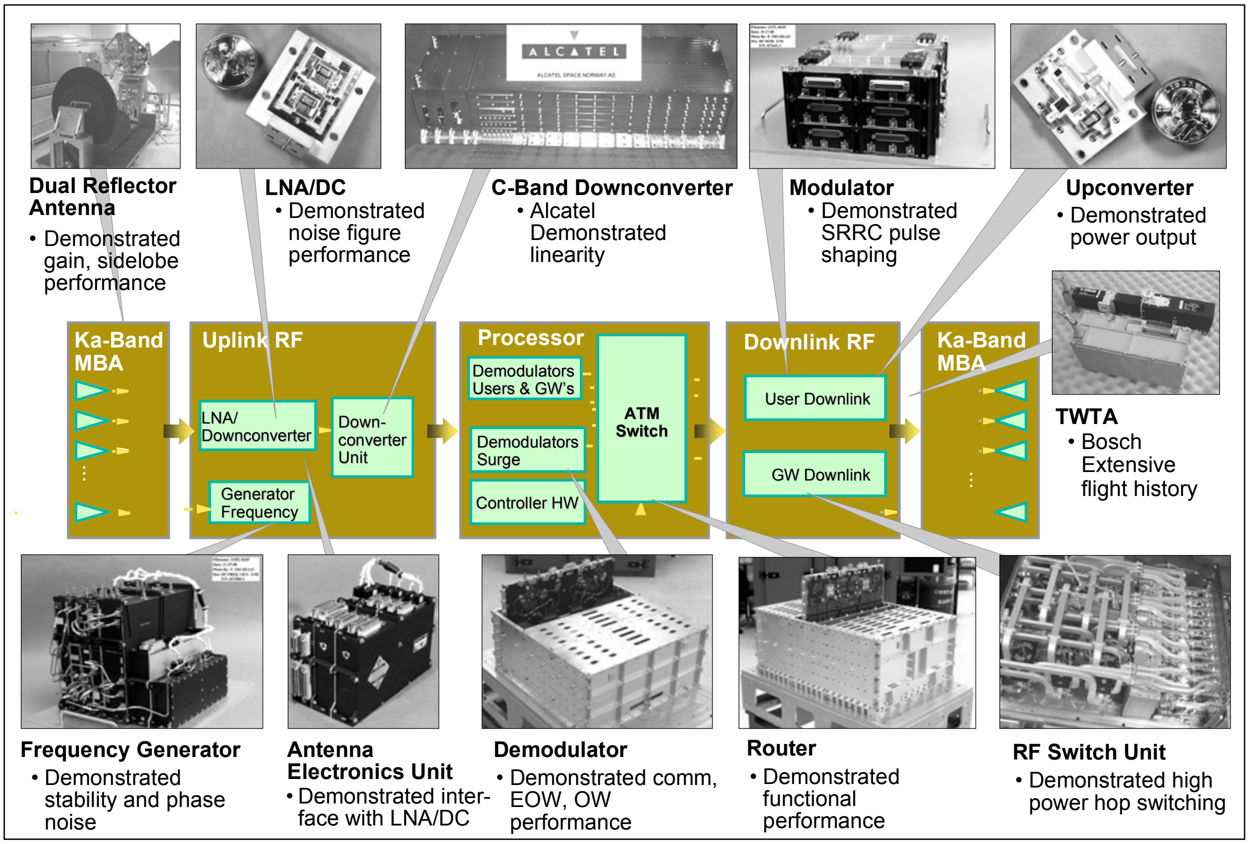

Figure 3. Payload Design Verification Model (DVM) Units

This allows a low frequency, low-loss, IF cable interface to the payload module, simplifying integration complexity and reducing weight. The IF signals are then downconverted to pseudo-baseband by the C-Band downconverter. This signal is input to the demodulators.

Demodulators immediately convert the signal to digital form. Digital samples are processed to select three different channel types. Each channel is demodulated and decoded. The demodulator outputs the data formatted into ATM cells for presentation to the broadband packet switch processor.

The broadband packet switch processor is composed of an ATM switch and an onboard computer for control. In support of ATM QoS, the switch design includes input fairness algorithms and significant downlink cell buffer capacity. Statistics are generated, packaged into ATM cells and routed to the network control center to facilitate traffic management.

Switch outputs are formatted and encoded for transmission, then modulated with QPSK square-root-raised cosine pulses. Upconversion via a single carrier per TWTA allows efficient transmission. The carriers are input to the antenna for transmission. In a further efficiency enhancement, the single carrier downlink signal can be timeshared between two beams.

PAYLOAD DEVELOPMENT STATUS

We have validated the Gen*Star system concepts in several stages. In 1999, we completed development and testing of a full end-to-end Gen*Star system testbed and the HFP, consisting of two full uplink and downlink channels and terminal emulators (Figure 4). The HFP was implemented hosting flight application-specific integrated circuit (ASIC) logic designs on field programmable gate arrays (FPGA). The approach facilitated design checkout and integration. The HFP demonstrated payload design functionality and performance, including uplink channelization,

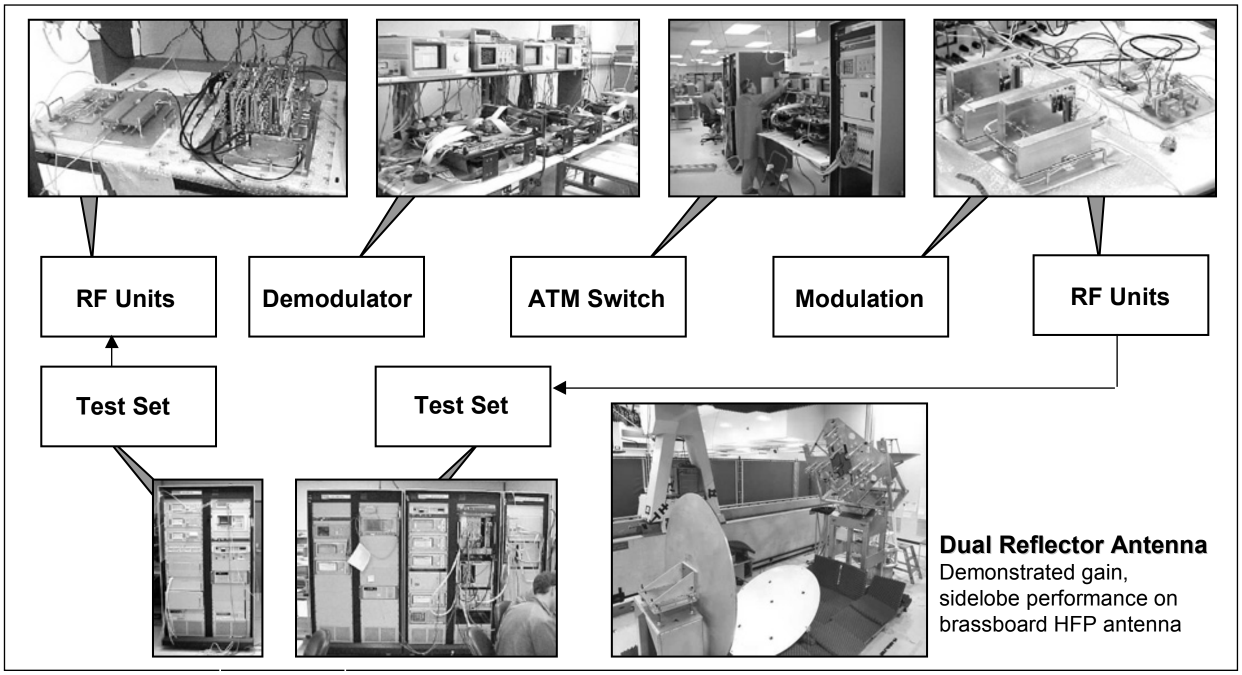

Figure 4. End-to-End Hardware Functional Prototype Testbed Demonstrated Payload/System

demodulation and decoding, cell routing, non-blocking ATM switch routing, downlink frame construction, and downlink modulation. In addition, payload test methods were developed in the HFP environment.

Along with this end-to-end electronics prototype, a brassboard antenna was developed. The selected antenna design was based on extensive design trades. Tests of the brassboard antenna correlate very well with analytical predictions to show outstanding gain and isolation performance across the entire Earth field-of-view (FOV).

After fully validating electrical design of the system using the HFP, the Gen*Star DVM payload was developed (Figure 5). DVM units, using flight parts and flight processes were built (Figure 3). Thorough design verification testing of the DVM units, including flight environmental screens, has been completed.

As a result of concurrent engineering, the unit designs take maximum advantage of design-for-manufacturing and design-for-test practices. The RF MMIC components are manufactured on an automated assembly line and achieve excellent performance without tuning. The digital boards are assembled on an automated line and incorporate extensive boundary scan and logic built-in-self-test (BIST) functions to facilitate checkout and detection of defective parts. The construction of the processor units enables replacement of a board without removal or disassembly of the unit from the satellite.

The DVM units were then integrated into a flight-like mechanical facsimile of the satellite structure to create a DVM payload. The DVM payload includes six full 125 MHz uplink channels and three full 250 MHz downlink channels. The DVM digital processors were built to full scale to enable unit thermal and vibration qualification. Each downlink channel serves two cells. The test equipment for the DVM payload is an extension of the HFP test equipment. Testing of the DVM payload is nearing completion as of this writing. Performance test results matched analytical performance predictions. Functional tests demonstrated successful routing of uplink ATM cells from the test set terminal emulator through all payload processing functions (downconversion, channelization,

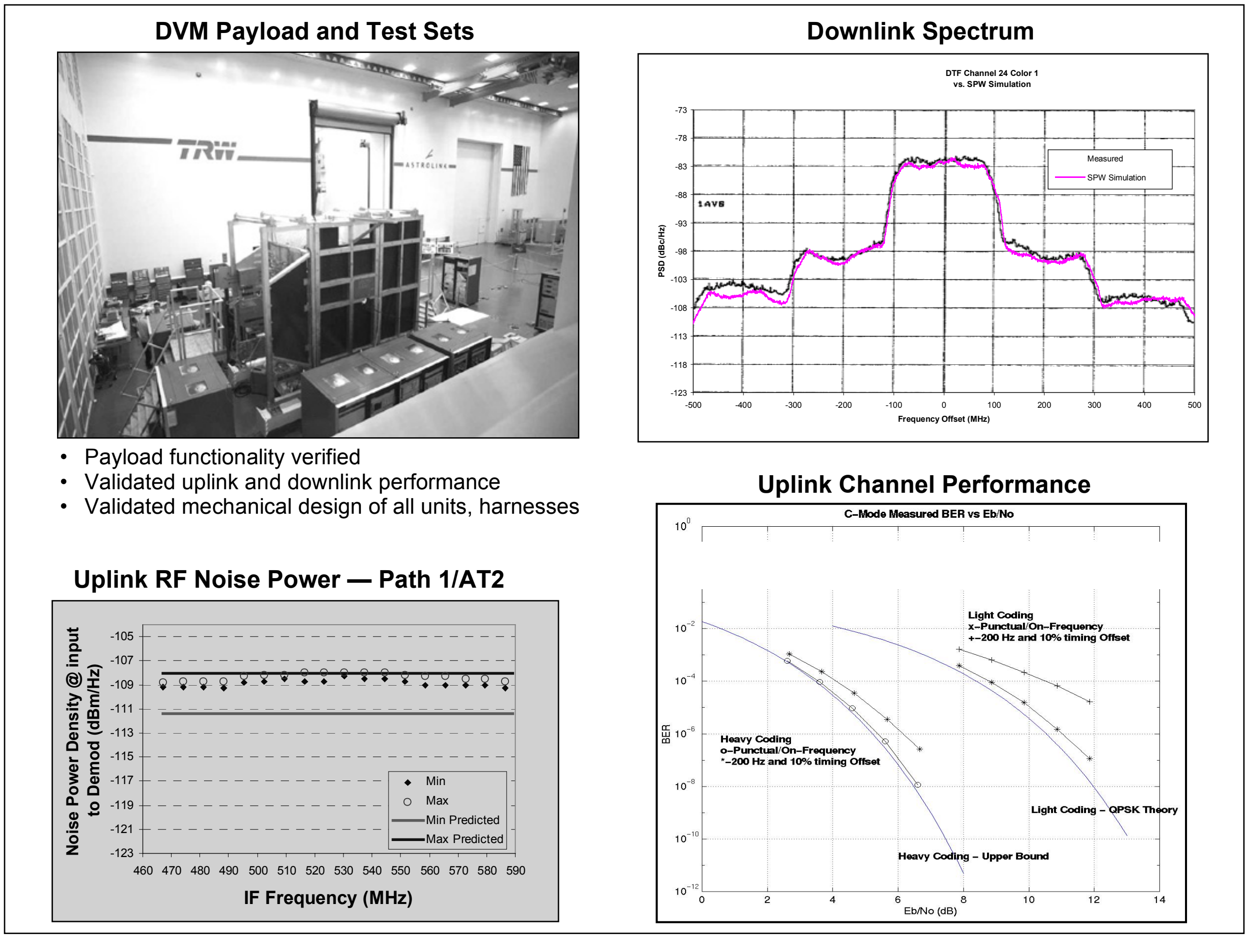

Figure 5. DVM Payload Integration Complete

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demodulation decoding at all three uplink subchannel rates, routing through ATM switch, modulation, upconversion, amplification and routing to the antenna) and back through the terminal emulator.

This DVM payload accomplished several major goals: (1) validation of the functional design of the payload, (2) validation of the payload performance, (3) validation of the payload manufacturing processes, and (4) validation of the mechanical design of the payload.

The DVM antenna was constructed in two phases. First, we upgraded the brassboard antenna with flight horns and reflectors. This DVM antenna was used for complete electrical characterization of the antenna design. Like the brassboard, test results show striking correlation with predictions and demonstrates the excellent gain and sidelobe performance required for high capacity broadband systems. The DVM antenna retired all risk related to the electrical performance of the antenna design.

To address the mechanical design, including the design of the full suite of four uplink and four downlink apertures, and the interface with the spacecraft bus, we developed an antenna interface simulator (AIS). The AIS consists of the core structure, one complete uplink aperture and one complete downlink aperture (Figure 6). This antenna has retired all risk related to the mechanical design of the antenna, including the manufacturing processes, the alignment processes, the pointing and the structural integrity of the antenna.

In summary the end-to-end payload design has been validated, first with the hardware functional prototype and also with the DVM

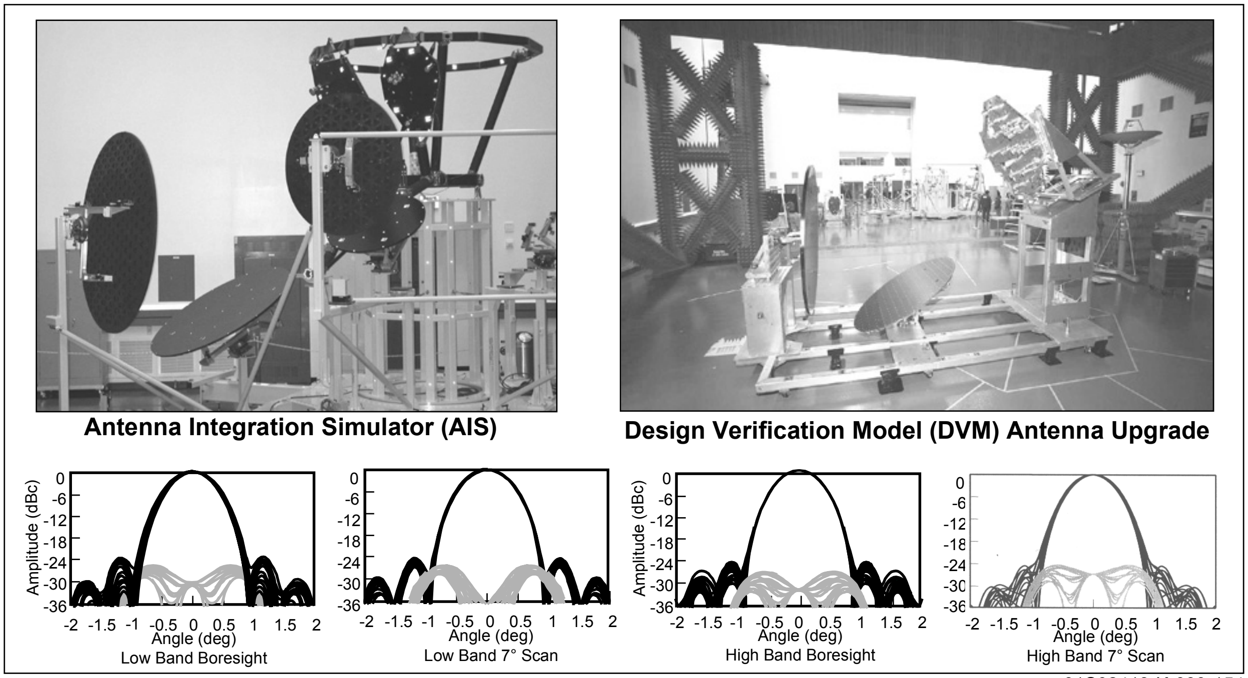


Figure 6. Antenna Integration Simulator and Design Verification Model

payload (Figure 7). The process and technologies developed for the Gen*Star broadband system has allowed us to reexamine some "myths" examined in the following section.

IMPACT OF GEN*STAR DEVELOPMENT ON PROCESSED PAYLOAD MYTHS

The Gen*Star payload development progress provides insight contradicting much of the conventional wisdom concerning the ability of

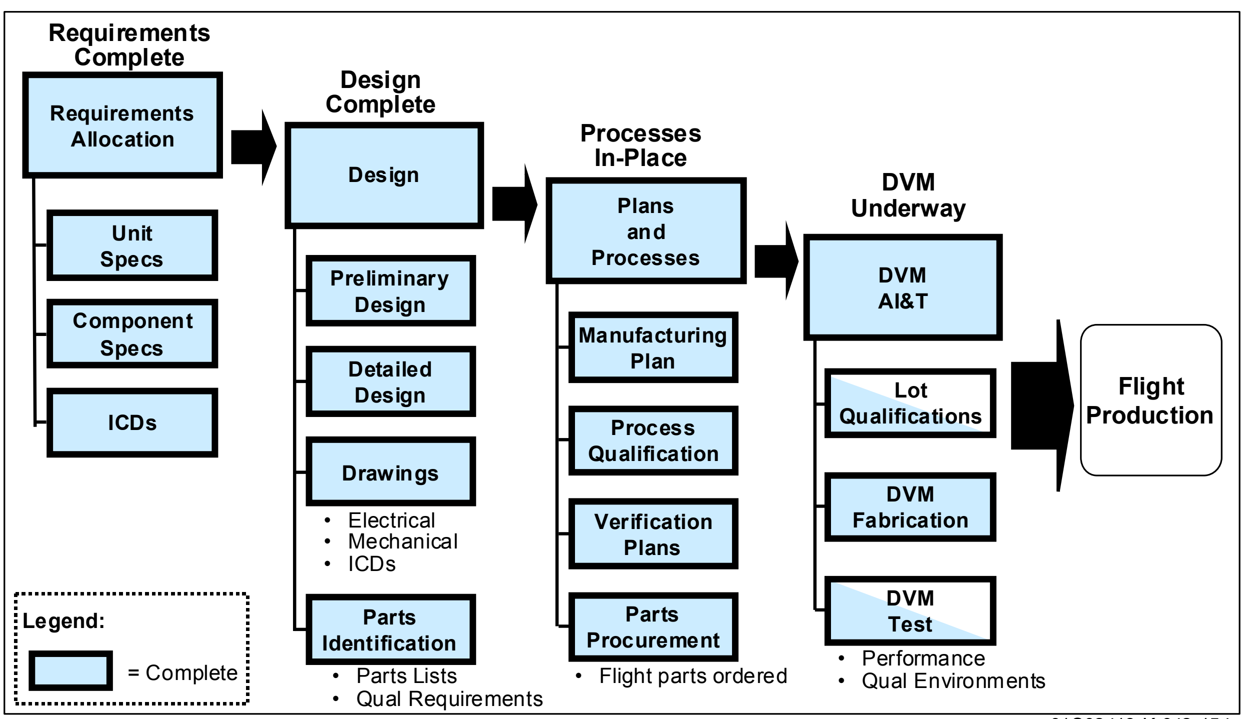


Figure 7. Payload Production Readiness Roadmap

processed, or regenerative, payloads to be competitive. These myths include:

Myth 1: **Processed Payloads Are Less Flexible—**Although the waveform is fixed, the ability to encapsulate any data over ATM permits efficient transport of voice, data, multimedia, or specific applications yet to be defined. If required, these services can be provided with guaranteed QoS agreements. The digital broadband packet switch processor permits any network topology, from point to point, hub and spoke, to full mesh connectivity. Furthermore, the topology can be evolved as the business plan changes during the lifetime of the satellite network. This flexibility can also be applied to network backup and restorability of service. A single on-orbit spare can backup multiple orbital slots in case of catastrophic

failure. The on-orbit spare can also be used to generate revenue until it is needed in its spare capacity. It is seen that while processing can reduce flexibility of the physical layer, it greatly increases flexibility of the network layer. Users care little about the what waveform their information is traveling over, but care a great deal about what services the network layer can support. Likewise, operators benefit by the greater deployment flexibility and restoration of service flexibility afforded by processing.

Myth 2: Processed Payloads Are More Costly and Take Longer to Field—The digital design incorporates BIST, which greatly simplifies hardware unit and payload level integration and test over the analog testing required for an IF switch. In addition, the modular design permits easy expansion and/or customization of the design configuration. This customization allows tailoring coverage and network mappings with minimum effort resulting in lower overall cost and schedule for constellations of more than one satellite where the coverage and network map varies from one orbital slot to another. By reducing spare satellites and launches required for a constellation, overall life cycle costs are greatly reduced.

Myth 3: Processed Payloads Are Riskier to Field—Modern design practices make digital design faster than analog design, and has enabled building of a flight-like DVM payload in a time span comparable to bent pipe payloads. The BIST allows faster and more thorough verification of the design. Being digital, it will perform throughout its life, over temperature, etc., just as it does when new. Integrated fault management systems improve reliability and ability to recover from faults.

Myth 4: Processed Payloads Are Prohibitive Impacts to Spacecraft Weight and Power—The processor switch permits multiplexing multiple signals destined for a downlink beam to be multiplexed into a single high-rate data stream. This single channel per carrier signal can be transmitted using a high-efficiency saturated TWTA at a much lower DC power consumption than the equivalent multi-channel signal through a TWTA, which is backed-off in power. Additionally, this single carrier operation is more bandwidth-efficient (no need for internal guard bands) compensating for the packet overhead. Furthermore, total payload weight can be reduced by designing the digital broadband packet switch processor to multiplex traffic from multiple beams into a single downlink signal that is hopped between multiple beams. This sharing of transmit hardware across multiple ground beams greatly improves the weight efficiency of processed payloads.

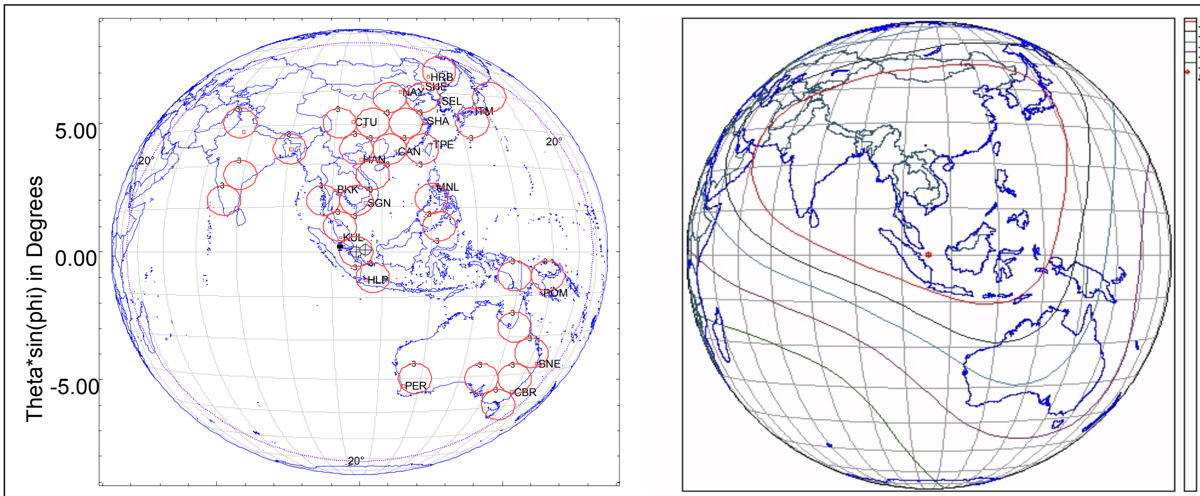
OTHER GEN*STAR FEATURES

The Gen*Star Payload Applies to Bent-Pipe Systems. The TRW Gen*Star payload elements can be configured in high performance bent-pipe configuration as well. The performance advantages of the Gen*Star antenna apply directly to this alternate configuration. The high performance MMIC LNA/downconverter mounted with the antenna feed offers optimum satellite gain/temperature (G/T) with the benefits of signal routing, filtering and conditioning at a convenient IF frequency.

Extension of Gen*Star to C-Band and Ku-Band Broadband Satellite Networks. The benefits of spot beam antenna coverage and onboard processing can also be applied at C-Band and Ku-Band. The same onboard processors used at Ka-Band can be used in these frequency bands. The spot beam antenna coverage is achieved through multibeam antenna designs adapted to use at these frequency bands. These advances in satellites coverage can been achieved while supporting legacy networks, adding new network capabilities enabled by the improved technologies.

As in Ka-Band, use of multibeam antenna designs to produce spot beam coverage increases system capacity through frequency reuse. Frequency reuse values greater than 10 are possible with this technology, resulting in dramatic increases in revenue-producing capacity. Additionally, satellite power resources are used more efficiently with spot beams by dedicating coverage to the high revenue producing areas. Partition of services to provide local content delivery is also obtained through the use of spot beams. Thus, content is only delivered to the revenue producing customers and not entire regions. Another benefit is that coverage can be tailored to support geo-political concerns such as regulatory requirements in very straightforward manner. Figure 8 demonstrates the multibeam advantage.

Use of multibeam antennas at these frequencies also produces several benefits in communication link performance. Use of spot beams implies that the antenna gain is very much higher than seen in conventional C- and Ku-Band systems. These means that higher effective isotropic radiated power (EIRP) and G/T can be readily obtained. With higher EIRP and G/T, the satellites can easily support higher data rates. Indeed, downlink data rates greater than 100 Mbps are easily supported. This truly brings broadband communication capability to these networks. An additional



Multi-Beam Coverage | **Single Wide Area Coverage Beam**

- More than ten times capacity
- Higher effective system bandwidth

$$\text{Effective bandwidth} = \frac{(\text{number of cells}) \times (\text{allocated bandwidth})}{\text{Frequency reuse factor}}$$

Example: 50-beam system using dual polarization

$$\text{Effective bandwidth} = \frac{(50 \times 2)\,(500\,\text{MHz})}{4} = 12.5\ \text{GHz}$$

Equivalent number of 36 MHz transponders ≈ 12.5 GHz/40 MHz = 310

Figure 8. Higher Capacity Through Frequency Reuse 01S02418-K-040A-R1-154

advantage of the higher gain satellite antennas is that Earth terminals can use smaller antennas and lower transmit powers to achieve higher data rates. For example, a C-Band earth terminal with a 1.8-m antenna and a 4-watt transmit power can support a 4-Mbps uplink. This can only be achieved with much larger Earth terminals in conventional systems.

Using the satellite network improvements described above means multimedia broadband services similar to the developing Ka-Band systems can be provided at C-Band and Ku-Band. These advanced networks are especially well adapted to support both mesh and star network capabilities. With the addition of onboard processing that includes routing, full peer-to-peer (mesh) connectivity is obtained. Thus, fully interconnected broadband multimedia networks can be achieved in regions where the propagation conditions such as those seen in high rain-rate tropical areas prohibit practical deployment of Ka-Band systems. In addition, onboard routing permits interconnectivity between cells serviced with different frequency bands.

A solid systems engineering competency is required to bring these critical technologies to fruition, particularly for use in broadband satellite networks. Systems engineering used in developing broadband Ka-Band satellite networks have resulted in technologies directly applicable to other frequencies. Two products that are critical technologies to the emerging Ka-Band market are high performance antennas designed for use at Ka-Band and C-Band (shown in Figure 9) and onboard processing technologies.

SUMMARY

Construction and launch of the first Gen*Star payload application, Astrolink, is well underway. The high degree of maturity and excellent demonstrated performance of the Gen*Star payload enables low risk, early service initiation. Successful technology developments in high-density electronics enable high capacity at low risk. Finally, the end-to-end payload design has been validated, first with the hardware functional prototype and now with the DVM payload. The DVM payload is manufactured using full flight processes, validating the high throughput manufacturing techniques needed for these multiple beam satellite systems. The technologies developed for the Gen*Star broadband system apply to other broadband architectures, including bent-pipe architectures and systems operating in alternate frequency bands.

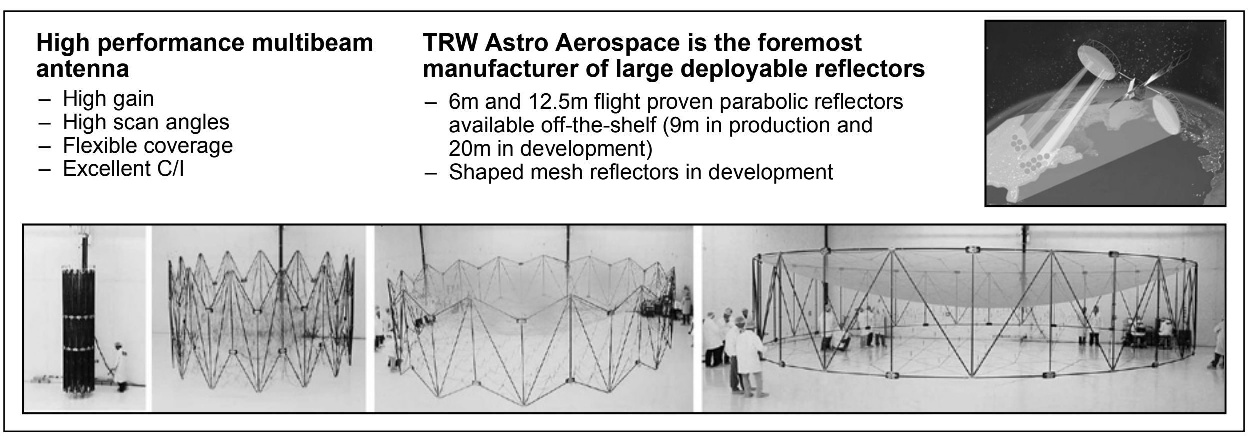


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Figure 9. High Performance Antennas