# Development and Demonstration of a Wideband RF User Terminal for Roaming between Ka-band Relay Satellite Networks

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## Abstract

The National Aeronautics and Space Administration (NASA) has provided low-latency communication relay services to science and exploration spacecraft for nearly four decades with the Tracking and Data Relay Satellite System (TDRSS). Through NASA's Communications Services Project (CSP), the agency is pursuing a transition away from dedicated government-owned communication relay satellites and infrastructure in favour of commercially provided satellite communication (SATCOM) services. Many of these SATCOM services are offered in the K/Ka-band covering spectrum allocated to commercial, military, and civilian space operations. While these services were intended to provide broadband connectivity for terrestrial, maritime, and aviation customers, many can be tailored to support orbiting spacecraft. By introducing commercial SATCOM providers, NASA intends to create an interoperable network of networks which will enable missions to roam between multiple service providers. A key enabling technology needed for this vision is a multi-frequency (wideband), multi-waveform user terminal which can seamlessly roam between multiple providers. This paper discusses the development and ground demonstration of a new wideband RF user terminal prototype designed to roam across multiple networks over the Ka-band, allowing ubiquitous service, resiliency, and flexibility for the user.

## 1. Introduction

As the commercial satellite communications (SATCOM) industry continues to develop communication services and infrastructure in near-Earth orbit, NASA is actively pursuing commercially-led satellite communications for future missions. This position is consistent with the United States National Space Policy [1] which guides agencies to pursue transferring routine space functions to the commercial space sector where beneficial and cost effective. These new commercial services are intended to complement NASA's Tracking and Data Relay Satellite System (TDRSS) and eventually replace it as the existing satellites reach their designed service lifetime in the 2030's. As NASA reduces the number of new TDRSS customer commitments, this represents a major transition for the agency and drives the need for operational commercial services [2].

A key to realizing this transition is the expansion of commercial SATCOM services from their typical terrestrial broadband market to supporting space-based users. Earlier studies by NASA, including a Request for Information (RFI) [3] and Broad Agency Announcement (BAA) Space Relay Partnership and Services Study [4,5] analysed the current state of the commercial SATCOM market and its readiness to support NASA missions. Based on the information received and under the framework of US National Space Policy [1], the Commercial Services Project (CSP) [6] was established with the goal of stimulating the commercial market to develop the capabilities needed to provide SATCOM services to NASA, as well as the broader commercial space-based user market.

Though these activities have identified several potential spectrum solutions across the L-, S-, Ku-, Ka-, and optical bands that could be utilized as future potential commercial service offerings, it was identified early on that Ka-band provides an optimal spectrum solution across existing and future planned SATCOM services. Furthermore, Ka-band has advantages from the standpoint of a single, low size, weight, and power (SWaP) communications payload for the mission spacecraft [3-5]. In the Ka-band, existing NASA services occupy the 22.55-23.55 GHz receive and 25.25-27.5 GHz transmit bands; current and future commercial Ka-band services occupy the 17.7-20.2 GHz receive and 27.5-30 GHz transmit bands; and DoD services occupy the 20.2-21.2 GHz receive and 30-31 GHz transmit bands. Therefore, a single communications payload that can operate over the 17.7-23.55 GHz receive and 25.25-31 GHz transmit bands and provide dynamic waveform switching represents the foundational hardware for a wideband RF user terminal that can achieve interoperable communications services within this future envisioned architecture.

Benefits of this approach will allow future NASA mission users in near-Earth orbit the flexibility to continue to utilize NASA's TDRSS services while adoption of commercial SATCOM services gradually takes place over the next decade. In this paper, we describe the objectives of the Wideband RF User Terminal, key subsystem and waveform development activities, system performance characteristics, and the results of ground-based demonstrations of the terminal operating across both NASA and commercial SATCOM networks.

## 2. Purpose and Approach

At the NASA Glenn Research Center, the Wideband RF Project is developing a prototype Ka-band user terminal to support NASA's transition to commercial SATCOM services. The purpose of this development is to demonstrate connectivity to NASA, commercial, and DoD relay satellites from a single user terminal which can seamlessly roam between services, as illustrated in Fig 1. Since current space-qualified terminals are not wideband, the objective of this development is to develop the necessary wideband components and integrate with commercially available product lines towards the realization of a flight terminal. Initially the terminal will be demonstrated with a series of ground-based experiments, followed by a potential flight experiment.

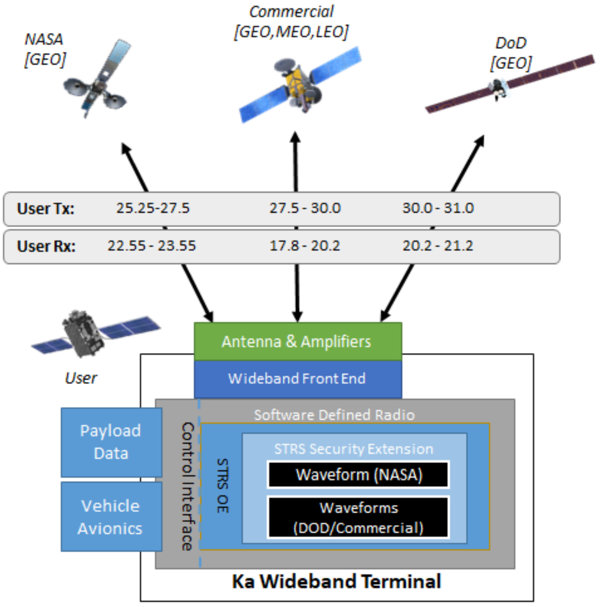

Fig. 1 – Ka-band Wideband Terminal Concept

Enabling long term sustainable service is also an objective of the wideband terminal, especially when considering science missions like Hubble which have been in operation for over three decades. A wideband terminal will enable missions to span multiple service providers, avoiding vendor lock-in and reducing the risk of paying more than the market price. Future missions will also benefit from the flexibility and resiliency provided by multiple services. The mission would be able to decide the best service to use at any given moment, accounting for differences in Quality of Service (QoS), latency, cost, and performance.

Achieving interoperability with multiple service providers will be challenging and may require customized waveform software for each provider. A software-defined radio (SDR) approach is envisioned to allow the terminal to host each provider's unique waveform. Currently, NASA works with international space agencies through the Consultative Committee for Space Data Systems (CCSDS) to develop common standards for cross-support and interoperability, however, these standards are not adopted by commercial SATCOM providers. The purpose of the Wideband RF terminal is to provide a method of interoperability by enabling roaming across multiple providers, even without common waveforms and standards [2].

## 3. Wideband Terminal Specifications

The proposed high-level specifications for the wideband terminal are listed in Table 1. The operational frequency bands cover the desired K/Ka-band allocations previously discussed. A bandwidth of 500 MHz was selected for both transmit and receive bands based on known commercial service bandwidths. The antenna gain to system noise temperature (G/Tsys) ratio, and Effective Isotropic Radiated Power (EIRP) were selected based on link budgets for reasonable performance over relay satellites in LEO, MEO, and GEO orbits. Power and mass are estimated requirements based on known available or anticipated hardware, and consistent with existing Ka-band terminals. Finally, the specifications reflect known performance requirements (e.g. axial ratio) to be compatible with existing military satellite communication (MILSATCOM) standards. Temperature and life requirements are tied to the expected operational use of the hardware.

Table 1 - Terminal Performance

| Parameter | Value |
|---|---|
| Frequency Bands | 17.7 -23.55 GHz Receive<br>25.25 – 31 GHz Transmit |
| Bandwidth | 500 MHz |
| Antenna | ≤1 meter |
| Axial Ratio | 1.5 dB Rx, 1 dB Tx |
| Polarization | Selectable RHCP/LHCP |
| EIRP | >50 dBW |
| G/Tsys | > 12 dB/K |
| Power | <150 W (active) |
| Mass | <15 kg |
| Temperature | -25 C to +55 C operational |
| Life | 15 year |
| Radiation | 100 kRad |
| EMC | MIL-STD-461F |

## 4. Wideband Terminal Development

The Wideband RF User terminal consists of a software-defined modem, a wideband frequency converter, and wideband RF front end, as shown in Fig 2. This configuration is notional and can be customized to accommodate a range of antenna types and pointing methods (body pointed vs gimbal) depending on mission needs. The selection of high-power amplifier (HPA) output power and location of the low noise amplifier (LNA) can also be customized as needed.

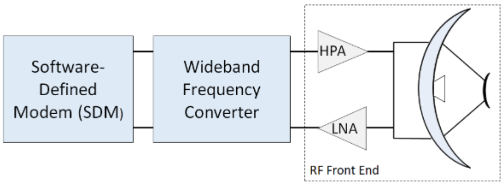

Fig. 2 – Wideband Terminal Components

Each of the subsystems is described in greater detail in the subsections below, including additional information on the waveform applications developed for the modem as well as embedded control software for managing the platform.

### 4.1. *Wideband RF Feed and Antenna Subsystem*

The ground-based demonstration uses a 1-meter Cassegrain reflector with a wideband dual-polarized feed assembly, as shown in Fig. 3. While the reflector was a standard off-the-shelf item, the wideband feed was custom developed by the vender per the specifications in Table 1. The feed uses standard WR-34/WR-42 waveguide sizes for ease of integration with other RF components while offering selectable right- and left-hand circular polarization (RHCP/LHCP) needed for the various providers. The antenna subsystem met the axial ratio requirement and achieved <1dB for almost the entire receive band in addition to the transmit band. Fig. 4 shows that the overall antenna and feed subsystem achieves a flat gain response over the desired ~6 GHz in both transmit and receive for both polarizations. The dish is specified to be capable of handling up to 50 W of RF power or greater. The as-built performance measurements of the antenna and feed assembly exceeded the minimum requirements and demonstrated a single assembly capable of meeting the wideband requirements.

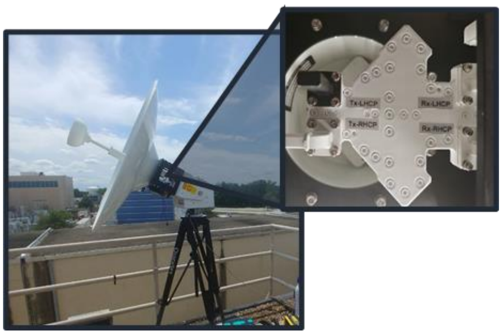

Fig. 3 - Antenna subsystem highlighting dual polarization wideband feed assembly

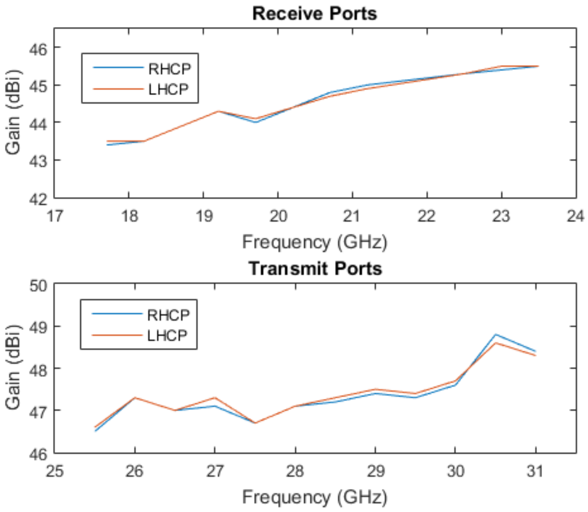

Fig. 4 - Antenna gain for transmit and receive for RHCP and LHCP ports.

### 4.2. *High-Power Amplifier*

When selecting the high-power amplifier (HPA), no commercial solution was identified that covered the entire wideband frequency range at the desired output power of 10-20 W. A Gallium Nitride (GaN) monolithic microwave integrated circuit (MMIC)-based amplifier covering 27 GHz – 31 GHz was selected, allowing full coverage of commercial and military bands and partial TDRSS coverage. As shown in Figure 8, the output power at 25.5 GHz is significantly reduced, but still approaches 10 W. Based on this market assessment further development is needed for space-qualifiable solid state power amplifiers (SSPAs) that can support a wideband terminal architecture. This work was initiated as part of the project and on-going at this time.

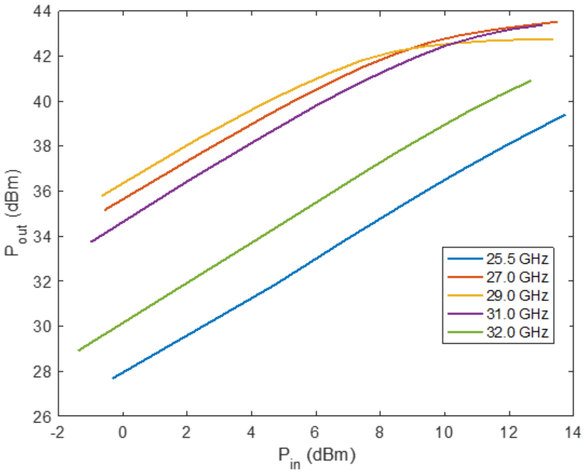

Fig. 5 - Measured gain compression of the high-power amplifier at select center frequencies

### 4.3. *Wideband Frequency Converter*

To communicate over the full 17.7 to 31 GHz, a wideband frequency converter is required. The wideband converter consists of separate up- and down-converters, each with an Intermediate Frequency (IF) of 1.5 GHz and the ability to tune over a relatively broad operating range (~6 GHz). Requirements were derived with L3Harris Technologies and design trades were performed on approaches compatible with the L3Harris µSDR platform. Both single and double conversion options were investigated, and the resulting wideband converter was simulated in Keysight Technologies' SystemVue software. A two-stage up/down-conversion architecture featuring switched RF filter banks was selected to reduce filter requirements and for improved interference and spurious signal rejection.

A notional block diagram of these subsystems is shown in Fig. 6. From this initial design, several modifications to the final constructed architecture occurred as a result of differences between stated performance in component data sheets and actual measured performance of received parts, but functionally, the architectures are equivalent.

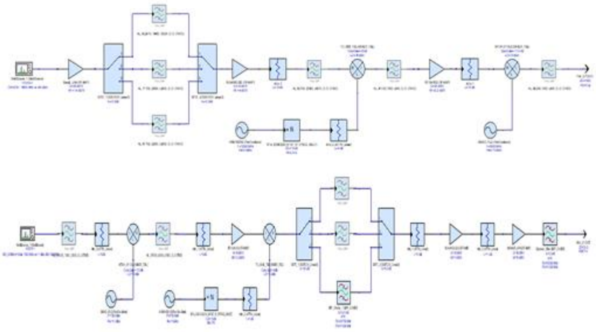

Fig. 6 - Block diagrams of the wideband downconverter (top) and upconverter (bottom) designs.

For the ground demonstration, a prototype converter was built using connectorized components and is shown in the photograph in Fig. 7. A common 10/100 MHz reference signal provided phase lock for all LO components. A graphical user interface (GUI) was developed to automatically control the switch positions and frequency synthesizers for the desired center frequency.

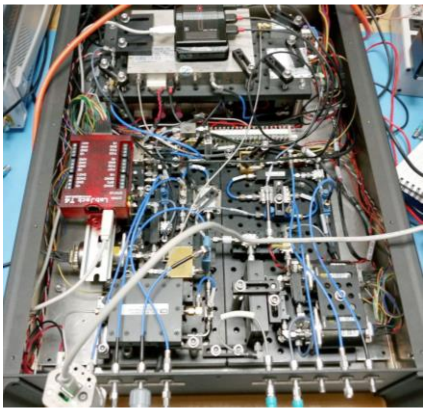

Fig. 7 - Photograph of prototype wideband frequency converter assembly.

Initial performance characterization of the converter was captured to demonstrate compatibility with the military standard for interoperability of superhigh frequency satellite communication terminals [7]. Figs. 8–10 show performance data of the upconverter segment. In Fig. 8, the full passband of the upconverter is shown. This plot was generated by transmitting a 1.5 GHz IF tone and sweeping the tuneable LO to generate the full range of output transmit frequencies. In addition, the switched filter bank was toggled in order to cover passband conditions across the full 25.25-31 GHz band. Fig. 9 is a plot of the output of the upconverter (after the final high-power amplifier stage) across the MIL Ka-band, showing that the spurious emissions limit of -60 dBc is met. Fig. 10 provides the phase noise characteristics of the upconverter assembly, also showing that phase noise requirements for transmit operations in the MIL Ka-band is achieved [7].

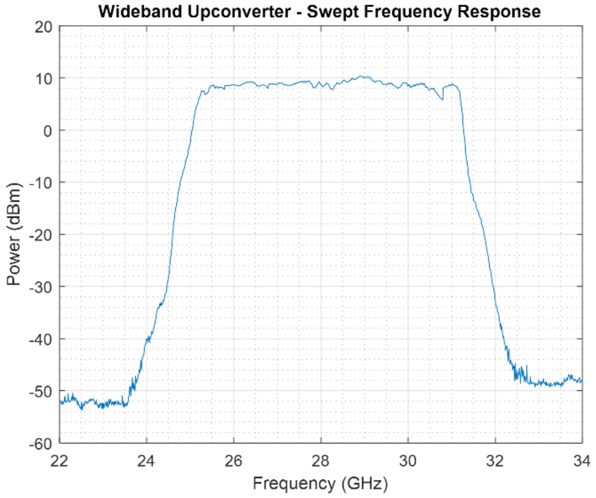

Fig. 8 - Swept frequency response of wideband upconverter full passband covering 25.25-31 GHz transmit band

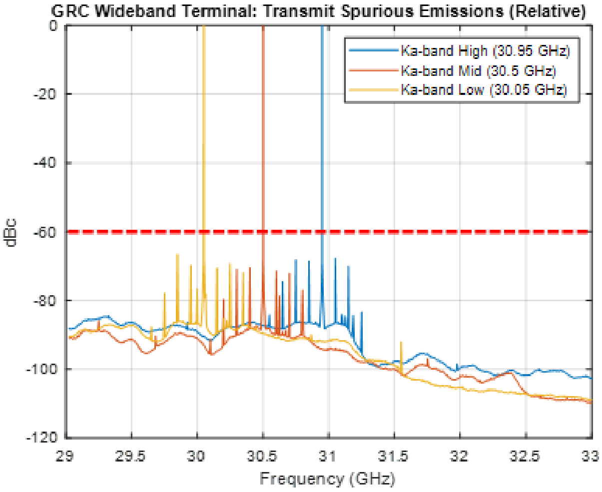

Fig. 9 - Spurious emissions of wideband upconverter chain as measured across 30-31 GHz military Ka band, indicating emissions fall below NTIA requirement of -60 dBc.

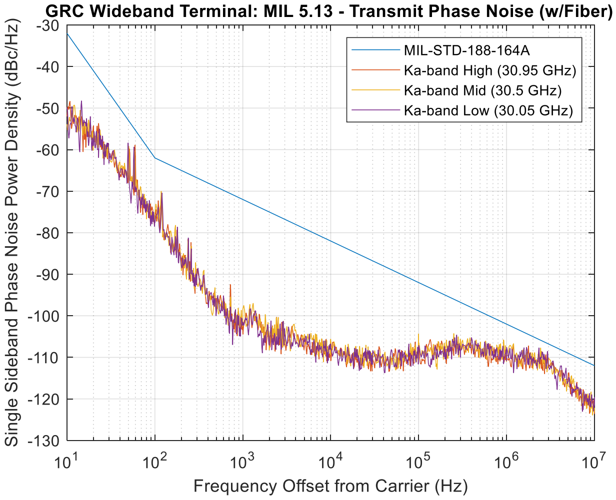

Fig. 10 - Transmit phase noise performance of wideband upconverter as measured across 30-31 GHz military Ka-band. Performance clearly meets transmit phase noise mask [7].

### 4.4. *Software-Defined Modem*

Baseband signal processing is performed on the μSDR, a software-defined modem developed by L3Harris Technologies [8]. Through reprogramming the device’s field programmable gate arrays (FPGAs) custom transceiver designs can be deployed on the platform, even while the terminal is on orbit. The platform, used on over 100 operational satellites including the Iridium NEXT constellation, offers sufficient instantaneous bandwidth and processing power to support NASA-developed high-rate modem applications. Several key modem specifications are provided in the table below.

Table 2 – Modem Specifications

| Parameter | Value |
|---|---|
| Mass | < 1kg |
| Form Factor | 3U SpaceVPX |
| IF Bandwidth | 750 MHz (Tx/Rx) |
| Channels | 2 Rx, 1 Tx |
| Reliability | 0.995 success (3 year) LEO |
| Power | 35 W (typical) |
| On-board Processing | 450 GFLOPS |

### 4.5. *Waveform Applications*

The μSDR platform is capable of loading new waveforms on-the-fly. For this project, multiple waveforms from the Space Telecommunications Radio System (STRS) repository [9] were adapted and improved to support operations with TDRSS and commercial SATCOM providers. STRS is a software defined radio standard developed by NASA [10]. The TDRSS-compatible waveform consists of a gigabit-class multi-mode transmitter capable of high spectral efficiency modulation and encoding, and a medium-rate BPSK/QPSK receiver with Viterbi-based convolutional decoding. For commercial network compatibility, a DVB-S2 compliant transmitter from the STRS waveform repository was combined with a DVB-S2 compliant receiver IP Core purchased from Creonic GmbH. The waveform applications and their capabilities are summarized in Table 3.

Table 3 - Waveform Application Summary

| | High-Rate Bandwidth-Efficient | DVB-S2 Transmitter | DVB-S2/S2X Receiver | PSK Receiver |
|---|---|---|---|---|
| Modulation | GMSK, BPSK, OQPSK, 4/8/16-PSK, 16-QAM, 16/32-APSK | 4/8-PSK, 16/32-APSK | 4/8-PSK, 16/32/64/128 /256-APSK | BPSK,QPSK |
| Data-rate (Tunable) | 333.33 Mbaud (1.67 Gbps un-coded) | 16 Mbaud (66.5 Mbps) | 62 Mbaud (~250 Mbps) | 7.8 Mbaud, (Extensible to 62.5 Mbps) |
| Pulse-Shape Filter | SRRC, RC, α = 0.1 -> 1.0 | SRRC, α = 0.2 -> 0.35 | SRRC, α = 0.05 -> 0.35 | Low-pass |
| Forward Error Correction | LDPC 1/2, 2/3, 4/5, 7/8, Parallel Rate ½ Conv | BCH / LDPC 1/4 to 8/9, Short Frames | DVB-S2XShort / Normal | Rate ½ Conv (Viterbi) |

Further enhancements were added at the encapsulation and networking layers for the DVB-S2 transceiver waveform to support network-level demonstration and testing. Specifically, support for Generic Stream Encapsulation (GSE) from the European Telecommunications Standards Institute (ETSI) TS 102 606 standard was added. In addition to GSE, several modifications were made to the waveform to accommodate unique, non-standard, behavior of commercial DVB-S2 modems that were not designed to fully operate with other providers’ modems. For example, one commercial modem implemented custom values of the Protocol Type field within the GSE header, requiring modifications in the software-defined modem to indicate encapsulation of IPv4 traffic.

### 4.6. *Platform Management*

The platform is managed by an STRS operating environment (OE) which is responsible for monitoring and controlling the waveform applications. The STRS OE is connected via SpaceWire to a single board computer (SBC) running an interactive, command-line utility provided by L3Harris. An "strs" command was integrated into this utility in order to interact with the OE applications and call STRS methods from the outside world. This SBC also provides a SpaceWire-network bridge that is used for telemetry distribution. An STRS application running on the platform continuously polls various waveform data and STRS properties and exports this telemetry to the SBC via the L3Harris SpaceWire Service. The SBC then publishes these packets to subscribers on the local network. A graphical user interface was implemented to display and plot a real-time view of this telemetry for performance monitoring during experiments, and a logging utility was also used to save the full telemetry stream to disk for postprocessing. Along with these current capabilities, future STRS application development is planned to further improve the automation of platform and waveform management in support of service roaming experiments.

## 5. Demonstration Concept of Operations

While working with commercial service providers a concept of operations was developed to capture how a wideband terminal would operate as part of a network of networks. Based on this a series of ground demonstrations were identified. The test configuration for these ground demonstrations is shown in Fig. 11. The wideband terminal as described in Section 4 was located at NASA GRC in Cleveland, Ohio. The terminal was placed on a roof-top location with line-of-sight to TDRSS, Inmarsat’s I5 satellite, and the O3b constellation. Bi-directional communication was established with each service over Ka-band through the relay satellite to the respective ground station. Bi-directional network data connections with each provider were established linking back to the GRC Mission Operation Center (MOC) to allow for full Forward and Return traffic between the terminal and the MOC. For NASA’s TDRSS, testing windows were scheduled as needed using unused TDRSS time for short durations (typically <1 hour). Commercial services were procured for a minimum of one week with the service available for testing 24 hours per day over the period of service.

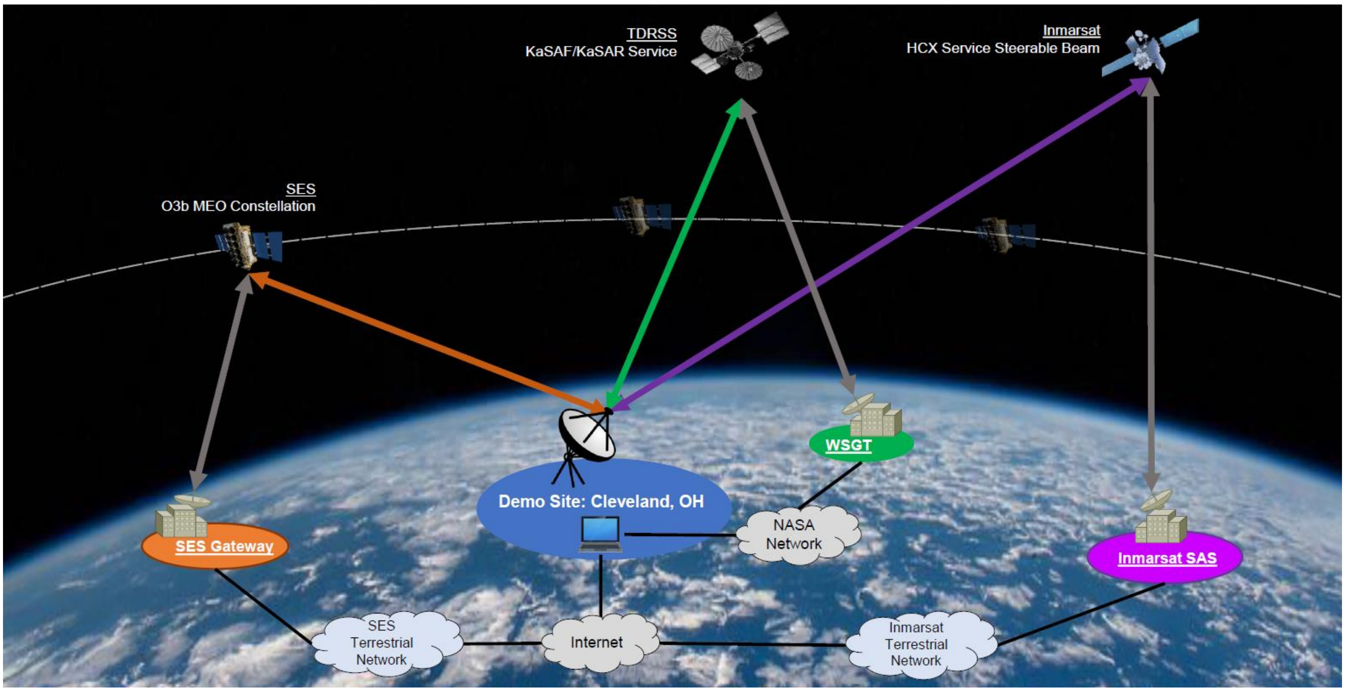

Fig. 11 - Ground demonstration test configuration illustrating RF and network connections for NASA's TDRSS, Inmarsat's Global Xpress steerable beam service, and SES's O3b constellation

## 6. Demonstration Results

The Wideband RF terminal was demonstrated over several weeks of testing with NASA's TDRSS, Inmarsat's Global Xpress, and SES's O3b networks. These networks were selected based on their diverse orbits (MEO, GEO), spectrum coverage (commercial, civilian, and military) and their potential to service future user spacecraft. Four separate test campaigns were conducted, each lasting 1-2 weeks. The primary objective of the testing was to demonstrate end-to-end connectivity with each network using the wideband terminal, while assessing physical, link, and network layer compatibility as well as overall system performance.

The demonstration included several secondary objectives focused on 1) advanced waveform features, 2) emulating a LEO spacecraft, and 3) roaming experiments between multiple services. Advanced waveform features include demonstrating on-the-fly reconfiguration of modulation and coding (MODCOD) and optimizing performance with non-linear channels. Emulating the orbital dynamics of a LEO spacecraft such as Doppler, and path loss variation are key for demonstrating the feasibility of expanding the commercial services to space-based users. In the following sections some preliminary results are presented. Additional testing is on-going, and further analysis and reporting is expected.

### *6.1. Return Link Performance*

While most testing was conducted at the nominal committed information rate (CIR) with the service provider, the minimum and maximum achievable rates were also determined experimentally. A subset of the modes tested for each of the services is provided in Table 4, highlighting the nominal and maximum data-rate modes. The highest rate was NASA's TDRSS which achieved nearly 540 Mbps over the 225 MHz channel. Using the DVB-S2 waveform provided a substantial improvement over the standard TDRSS waveform which ran at 150 Mbps using Offset QPSK with a rate ½ convolutional code. Both commercial services were capable of >100 Mbps using 8-PSK modulation and a Low Density Parity Check (LDPC) code. To accommodate high-order modulations such as 32-APSK, the amplifier output was backed off by at least 3 dB from maximum saturated output (Psat).

Table 4 – Return Link Performance Summary

| | Mod. | FEC | Symbol Rate | Info Rate (Mbps) | Rx Es/No (dB) |
|---|---|---|---|---|---|
| TDRSS | OQPSK | Rate 1/2 | 150M | 150 | n/a |
| TDRSS w/DVB-S2 | 8-PSK | LDPC 9/10 | 200M | 535.8 | 12.8 |
| Inmarsat | 8-PSK | LDPC 3/5 | 70M | 124.6 | 6.1 |
| Inmarsat | 16-APSK | LDPC 3/4 | 15M | 41.42 | 12.3 |
| O3b | 8-PSK | LDPC 3/4 | 70M | 145.45 | 9.5 |
| O3b | 32-APSK | LDPC 8/9 | 20M | 83.2 | 16.3 |

Note that the values in Table 4 are dependent on several factors and higher rates may be achievable. The tests were conducted with different constraints for each service provider, including allocated bandwidth, weather impairments, and permitted user terminal EIRP. A larger user terminal antenna (0.7 vs 1-meter) was also installed part way through the test campaign.

While the maximum rates were limited by either bandwidth or EIRP, the minimum data-rates were limited by the service provider's receiver. The minimum supported data-rate was 122.6 kbps over Inmarsat's Global Xpress, while TDRSS's high-rate DVB-S2 receiver only supported 2.45 Mbps. It should be noted that the user terminal was responsible for lowering the EIRP to comply with power flux density (PFD) restrictions over the commercial services.

### 6.2. *Forward Link Performance*

In a similar manner to the Return Link, the Forward Link performance was evaluated over the commercial services. While a Forward Link was established with TDRSS, it was not the focus of any extensive characterization in this test. The maximum Forward Link rates is summarized in Table 5 for the commercial services. Both achieved near 150 Mbps or greater and were a substantial improvement over the 25 Mbps maximum with TDRSS.

Table 5 – Forward Link Performance Summary

| | Mod. | FEC | Symbol Rate | Info Rate (Mbps) | Received Es/No (dB) |
|---|---|---|---|---|---|
| Inmarsat | 8-PSK | LDPC 5/6 | 59M | 146 | 6.4 |
| O3b | 16-APSK | LDPC 2/3 | 80M | 200.4 | 16.3 |

Regarding minimum data-rates on the Forward Link, both commercial service providers were able to support 49 kbps using QPSK with a LDPC rate ¼ code. The lower bound was determined by the 100 kbaud symbol rate limit of the DVB-S2 modulator. To comply with power flux density regulations, the Forward Link EIRP of the relay satellite was reduced accordingly. Due to the inherent Doppler with each MEO relay satellite, the lowest symbol rate modes would not acquire unless the received frequency was within an acceptable range. Doppler pre-compensation was provided by an RF channel emulator prior to the receiver at the user terminal to enable these low-rate modes. In the future, this function will be moved into the waveform application.

Even lower data-rates may be possible by using the Very-Low Signal-to-Noise (VL-SNR) modes added in the DVB-S2X standard, however, it was noted that none of the commercial DVB-S2 modems currently support these modes.

### 6.3. *Network Connectivity*

For both the commercial SATCOM services, bi-directional Internet Protocol (IP)-compatible network traffic was established over the RF link as well as the terrestrial connection between the Mission Operations Center and the service provider. An example network configuration diagram is shown in Fig. 12. To demonstrate connectivity, basic networking tests such as pings using the Internet Control Message Protocol (ICMP) were run with public Internet servers, as well as bidirectional User Datagram Protocol (UDP) data between the Wideband RF User Terminal and the MOC at NASA GRC. The network connectivity tests were successful for both commercial services and provide the framework for future networking experiments.

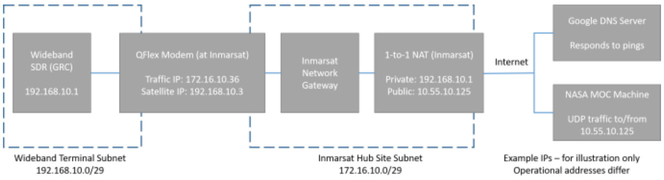

Fig. 12 – Representative Network Diagram

### 6.4. *Adaptive / Variable Coding and Modulation*

Adaptive Coding and Modulation (ACM) automatically selects the ideal MODCOD based on the received signal-to-noise (SNR) ratio and desired link margin. Commercial DVB-S2 modems support ACM, however, it is typically implemented using proprietary in-band signaling between modems built by the same manufacturer. By introducing a software defined modem, this complicates support for unique features such as ACM. Implementation of ACM over commercial networks is desired but may require further coordination with service providers and modem vendors.

Despite this limitation, variable coding and modulation (VCM) was demonstrated over each of the services. In VCM, the MODCODs follow a pre-determined sequence and can adjust for known variations in the SNR such as path loss. An example VCM test sequence is shown in Fig. 12, showing seamless transition between MODCODs and the resulting change in user data-rate.

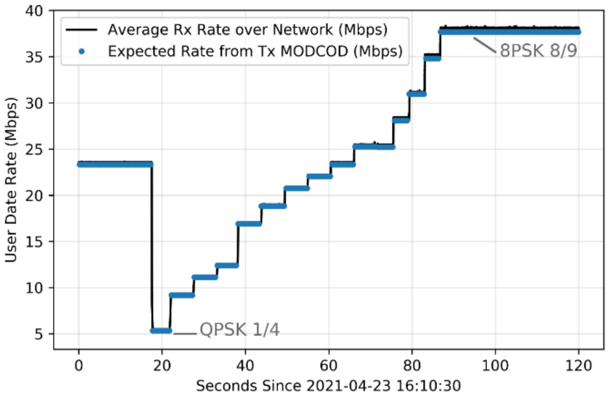

Fig. 13 – Example VCM test sequence over NASA's TDRSS

### 6.5. *Doppler Emulation of LEO Spacecraft*

While the testing was conducted from the ground at NASA GRC, realistic channel impairments (e.g. Doppler, path loss) were emulated over the link to provide confidence that the service would function with a spacecraft in LEO. The channel impairments were introduced with a RF channel emulator (Keysight PropSim F64) at the user terminal, for both the Forward and Return Links. For GEO relay satellites, the emulated LEO spacecraft Doppler was directly added to the link, while for MEO satellites the natural Doppler was mathematically subtracted such that the resulting residual Doppler would be equivalent to tracking a LEO spacecraft.

The focus of the LEO emulation test was to determine if the modems were capable of handling the additional Doppler. As an example, Fig. 14 compares the performance of two different DVB-S2 modems available in the Return Link for the Inmarsat test. Modem 1 was provided by Inmarsat, while Modem 2 was an additional commercial modem provided by NASA for comparison. As the Doppler exceeds 600 kHz, Modem 2 lost acquisition, as indicated by the gap in the reported frequency offset. This highlights the need for the proper modem selection and/or Doppler compensation to accommodate future space-based users.

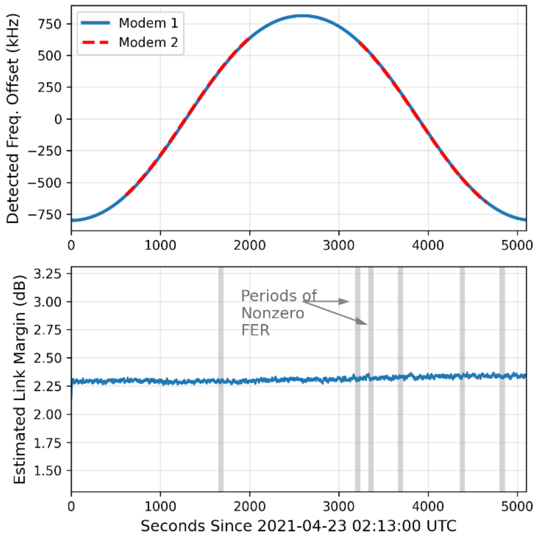

Fig. 14 - Example Doppler profile over Inmarsat emulating LEO spacecraft.

### *6.6. Roaming*

The ability to switch between services in real-time was demonstrated as part of this test campaign. As shown in Fig. 15, service was switched from the commercial service provider over to a scheduled TDRSS event, and then back to the commercial service. The process to switching services involved 1) disabling the HPA to prevent interference, 2) switching waveform for the new service 3) commanding antenna to track new relay satellite, 4) configuring the wideband frequency converter, and finally 5) enabling HPA and verifying that the service is operational. The terminal was able to successfully roam from TDRSS to Global Xpress with <30 sec downtime using mostly manual controls. Future work will include automating this process to make the handoffs more seamless.

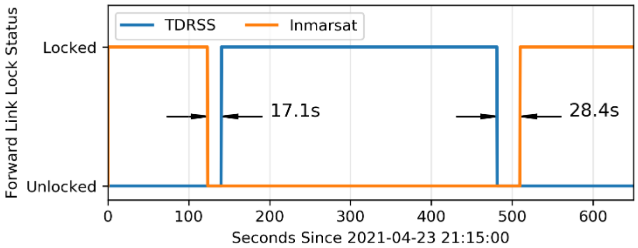

Fig. 15 - Example Forward Link roaming transition between TRDSS and Inmarsat

## 7. Conclusion

The development and basic functions of the Wideband RF User Terminal prototype have been demonstrated with the ground-based experiment as presented in the paper. Future work will include enhancement of the terminal functions to include intelligent automation and security, working with various LEO/MEO/GEO constellations service providers for broader compatibility with commercial service networks, and continued formulation of potential flight demonstrations. The Wideband RF User Terminal is at a sufficiently high technology readiness level that direct commercialization of flight-qualified version could be realized within 3-5 years. Lessons-learned from ground-based and flight-based wideband experiments will help and support smooth transition of NASA near-Earth missions to rely and exclusively use of commercial communication services.

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