# A Ka-band Hybrid Ground/Space Communications Network for LEOs Provides Ad Hoc On Demand Access to Mission Data and Agile Space Operations

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**This paper details the design of a hybrid communications network usable by LEO satellites, developed in partnership with NASA under the Communication Services Project. The key attributes of this network are discussed, as well as advancements beyond the existing state of the art. The first underlying network is a traditional, high-rate LEO-ground solution, operating at the EESS Ka-band. The second underlying network is a new, LEO-GEO relay system utilizing high-capacity Ka-band GEO satellites. The design of a specialized user terminal, necessary to access the hybrid network, is described. Applications of the network are discussed in terms of tradeoffs between operating costs and the latency between data collection and delivery to Earth, and are compared to other generic types of space communications networks. Finally, test and verification plans for the hybrid network, including on-orbit demonstrations using LEO space vehicles, are described.**

## I. Introduction

The communication link with a spacecraft greatly affects the designs and operational concepts of satellite missions today. Satellite designers must generally make a trade-off between the amount of time that the satellite is in contact with ground and the total cost of communications system (including space and ground segments) employed. For example, traditional S- and X-band satellite communications limit both the contact time and link speed in current missions, limiting both the volume and timeliness of the data they can transport. Most satellites operating with S-/X-band networks communicate with the ground once or twice per orbit. This is often provided at higher latitudes but can also be done at various other locations around the globe. This provides limited opportunities to command the spacecraft, issue tasking, re-plan mission parameters, transfer mission data to the ground, react to current events to redirect tasking, or react to space vehicle anomalies to accelerate recovery and resumption of mission operations. Certain missions, such as those with optical payloads, can benefit from real-time operational data, such as cloud cover information. Providing more frequent satellite communication is an operationally useful endeavor, which can enhance the efficiency of spacecraft operations, improve the end-user experience, and increase the value and relevance of mission data collected by satellites. Besides contact time and frequency, the aggregate volume of communications can also be improved. Current X-band missions often operate in the 50-500 Mbps communication range. With the advent of higher resolution sensors, more data is being generated in a shorter period of time, and the archaic paradigm of store and forward is no longer acceptable or beneficial to the mission provider or end customer. In order to solve these problems, a hybrid network composed of multiple communications networks is proposed and discussed.

## II. Hybrid Network Overview

A hybrid space access network takes multiple, independent underlying communications networks which provide access to the user and seamlessly routes data, commands, and telemetry across any of the networks in a dynamic fashion. These different networks may each provide varying characteristics allowing individual users to customize their communication profiles depending on their mission requirements. Combining these individual networks, each with various advantages and disadvantages, in an optimum way can provide an overall network that is more operationally useful than the sum of its constituent parts. In addition, the hybrid network increases resilience against outages or contention in the individual underlying networks.

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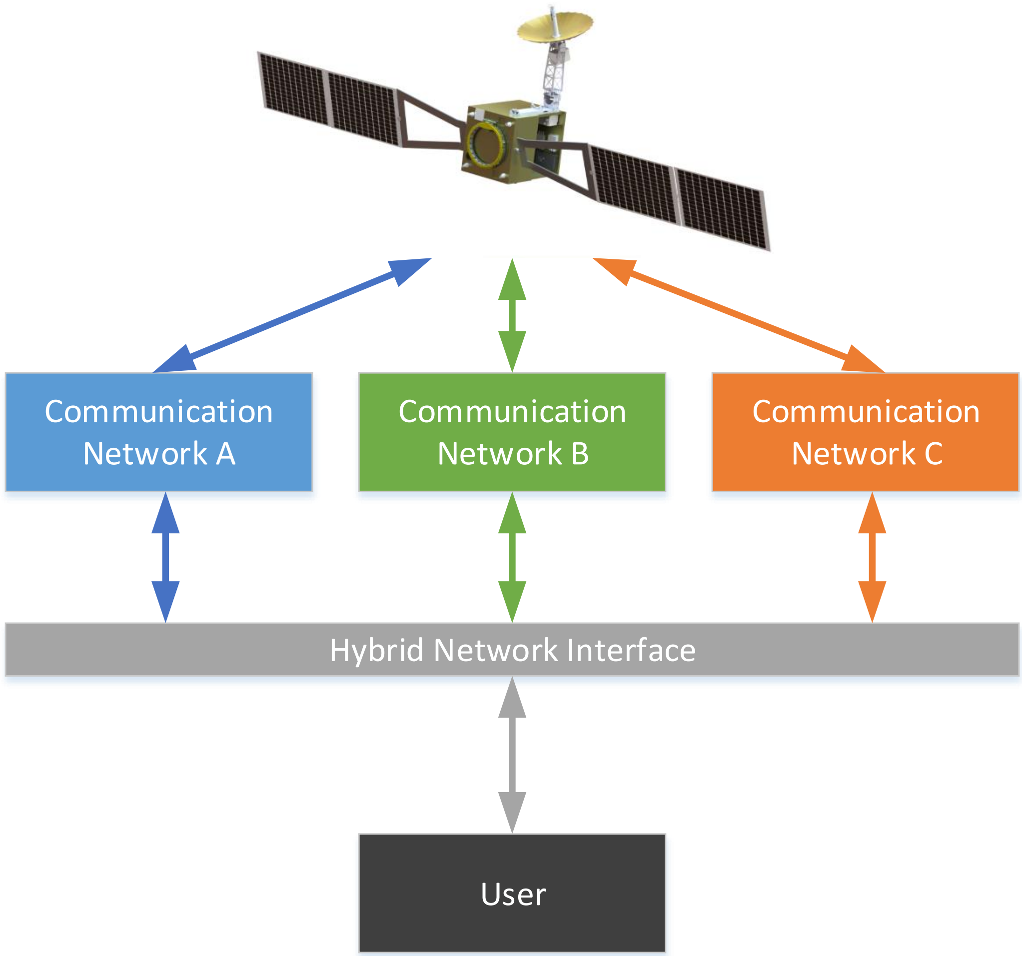


**Figure 1: Generic Hybrid Network Diagram**

The notional concept of a hybrid network is shown in the above diagram. In this example, three different networks (A, B, and C) are made into a usable hybrid network through the hybrid network interface. This is a critical enabling technology, allowing the user to seamlessly communicate through all networks. Hybrid networks are currently utilized for satellite communications in a limited sense, mainly in the context of using multiple ground system networks. For example, a satellite operator may use an internally owned and operated antenna along with external services from a ground antenna operator. New space communications networks that operate with varying technologies in different orbital regimes offer an opportunity to create more advanced hybrid networks that offer new benefits and mission capabilities to the end user.

While these could include a variety of communication links, including RF and free-space optical (FSO) links in LEO, MEO, and GEO orbital regimes, this paper proposes a hybrid network composed of a global ground-based antenna network (LEO-to-ground link) and an RF space relay (SR) network using geostationary satellites (LEO-to-GEO link). The following section describes each network in more detail.

## III. Description of Networks

The two individual communication networks that were used to model the hybrid network are described in the following sections.

### A. LEO-Ground Network

Viasat's Real-Time Earth (RTE) Service is a commercial service for control, operation, data collection, and data delivery for satellites from Low Earth Orbit (LEO) to Geostationary Earth Orbit (GEO). This service is a scalable solution that provides highly reliable and secure delivery of payload data as well as telemetry, tracking, and command (TT&C) capabilities for diverse satellite missions. RTE ground stations operate in S-band (uplink and downlink), X-band (downlink) and Ka-band (downlink), with the ability to operate simultaneously in multiple bands. A Ka-band link budget for one of the RTE ground sites is shown in Figure 4.

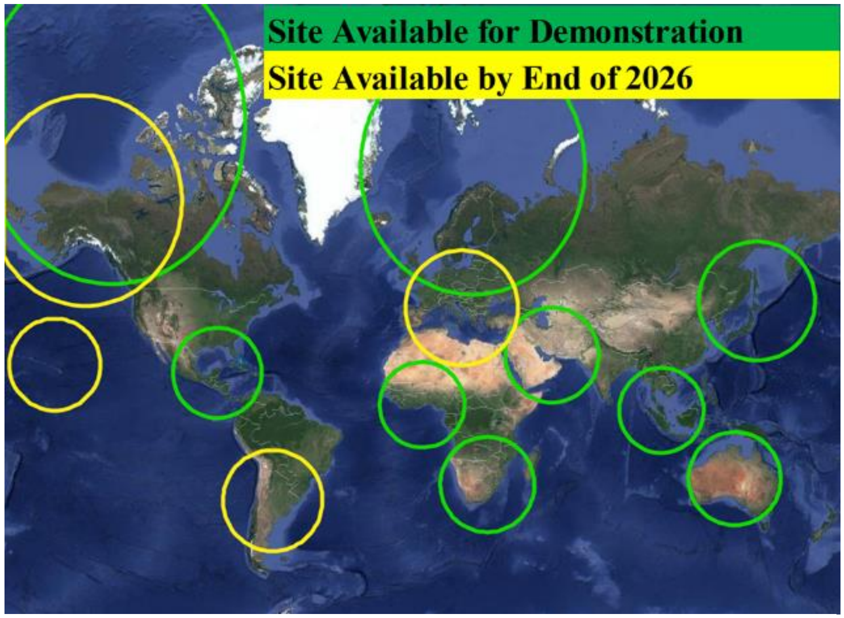


**Figure 2: Strategically located RTE sites and associated coverage area provide enhanced mission assurance.**

Viasat's Real-Time Earth service (RTE), shown in Figure 2, is an innovative approach to providing ground station service. RTE is a commercial network which leverages the major investments Viasat has made into virtualization and IP cloud based technologies for our award winning broadband Internet services. The result is a worldwide private network of interconnected ground stations, each of which uses common ground station equipment to support different satellites on a pass by pass basis.

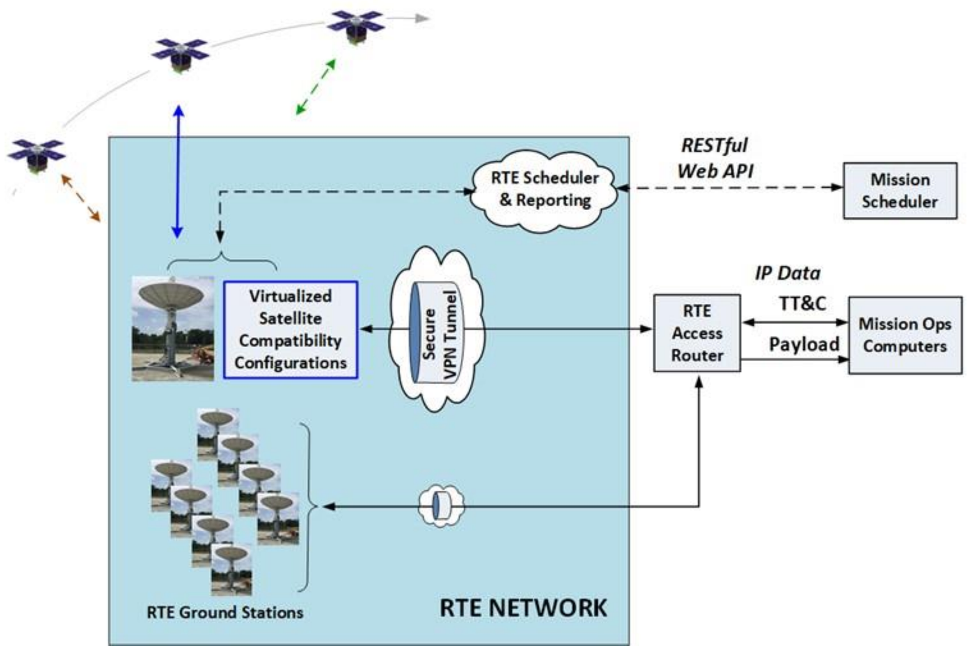


**Figure 3: RTE Network**

This innovative approach to ground station service includes the following features which differ from services of traditional ground stations.

- All RTE ground stations include software-based modems and packet processors containing virtualized configurations with different satellite protocols, which are combined into a single set of ground station equipment. This equipment is automatically reconfigured for compatibility with the next scheduled satellite on a pass-by-pass basis. This eliminates the need to install any equipment on RTE ground stations.

- One single common interface point for to connect into the RTE private network for TT&C messages and access to payload data for all RTE ground stations. A separate, single common interface point to schedule passes on all of the available antennas in the RTE network. This eliminates the need to manage multiple, separate terrestrial circuits to individual ground stations.

- All RTE ground stations make scheduling of antennas and access to data available on a 7x24 basis using machine-to-machine communications. Antennas are automatically reconfigured on a pass-by-pass basis without need of human intervention. The ground stations are remotely monitored on 7x24 basis. This enables unmanned ground stations and eliminates the hassles for the customer associated with human interaction across global time zones.

- All data is in Internet Protocol (IP) data format which assures compatibility with todays latest and tomorrow's future technology. This provides a future proof platform to the customer and eliminates the need for the customer to support legacy protocols.

- The global reach of the Internet combined with secure VPN technology provides the customer easy access to a worldwide network of ground stations with assured security for their data.

| Elevation Angle | deg | 5 | 10 | 15 | 20 | 90 |
|---|---|---|---|---|---|---|
| Satellite EIRP | dBW | 36.93 | 36.93 | 36.93 | 36.93 | 36.93 |
| Satellite Frequency | MHz | 26250 | 26250 | 26250 | 26250 | 26250 |
| Slant Range | km | 2075.4 | 1693.5 | 1406.6 | 1192.4 | 500.0 |
| Path Loss | dB/m2 | 187.2 | 185.4 | 183.8 | 182.4 | 174.8 |
| Availability | % | 98.0 | 98.0 | 98.0 | 98.0 | 98.0 |
| Rain Rate | mm/hr | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Total Atmospheric Loss | dB | 30.3 | 17.3 | 12.7 | 10.3 | 7.9 |
| Total Path Loss | dB | 217.5 | 202.7 | 196.5 | 192.6 | 182.7 |
| Polarization Loss | dB | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Received Isotropic Power | dBWi | -182.0 | -167.3 | -161.0 | -157.2 | -147.2 |
| Antenna Gain | dBi | 61.2 | 61.2 | 61.2 | 61.2 | 61.2 |
| Antenna Noise Temperature | K | 160.0 | 106.0 | 81.9 | 67.6 | 36.3 |
| System Gain at LNA | dB | 60.4 | 60.4 | 60.4 | 60.4 | 60.4 |
| System Noise Temp at LNA | K | 352.9 | 308.0 | 287.9 | 276.1 | 250.0 |
| G/T | dB/K | 32.9 | 33.4 | 33.7 | 33.9 | 34.2 |
| Received C/No | dB-Hz | 79.5 | 94.7 | 101.3 | 105.3 | 115.6 |
| Received Es/No | dB | -8.3 | 6.9 | 13.5 | 17.5 | 27.8 |
| DVB-S2 Mode | | N/A | Mode 13 | Mode 23 | Mode 28 | Mode 28 |
| Threshold Es/No | dB | N/A | 6.62 | 13.13 | 16.05 | 16.05 |
| Bits/Symbol | # | 0 | 1.98 | 3.57 | 4.45 | 4.45 |
| Bit Rate | Mbps | 0 | 990 | 1785 | 2225 | 2225 |

**Figure 4: LEO-Ground Link Budget**

### B. LEO-GEO Network

Viasat is nearing launch of our next generation geosynchronous (GEO) global satellite network (ViaSat-3), a constellation consisting of three high capacity Ka-band satellites, designed to provide global secure broadband coverage to residential, enterprise and government customers. Each satellite in the network provides 1+ Tbps of total capacity, with the flexibility to dynamically assign capacity on demand, in a geo-temporal fashion. ViaSat-3 class satellites will utilize small spot beams.

The first satellite is planned to cover the Americas. The second is set to cover EMEA — Europe, the Middle East, and Africa. The third is planned to cover Asia-Pacific (APAC). Once in place, the three satellites are expected to provide near global coverage for land, air, and sea.

In addition to terrestrial fixed and mobility users each satellite includes coverage for any LEO orbit up to an altitude of 1000 km, including the underserved Polar Regions. Each GEO satellite can simultaneously serve hundreds of Low Earth Orbit (LEO) satellites on-demand or continuously.

As a space relay network, ViaSat-3 is a natural complement to direct to earth services to demonstrate the utility of integrating heterogenous networks into a cohesive larger hybrid network. The ViaSat-3 space relay network allows for bidirectional ad hoc, on demand, connectivity for LEOs for telmetry, command, tasking, and data dissemination. No a priori scheduling is required. Furthermore, each LEO user is given a dedicated steerable beam, only needing to transition when moving to the coverage area of a different GEO relay satellite.

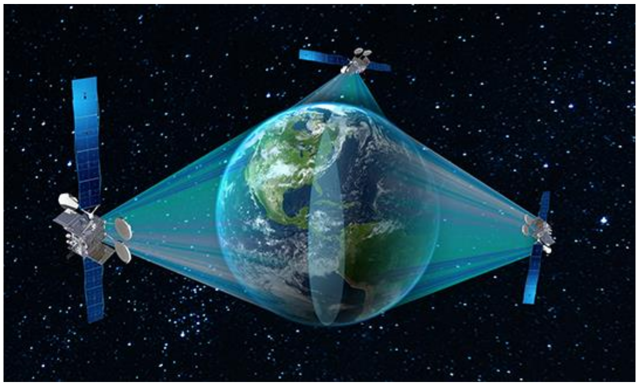

**Figure 5: The ViaSat-3 initial constellation supports global service for terrestrial and LEO customers.**

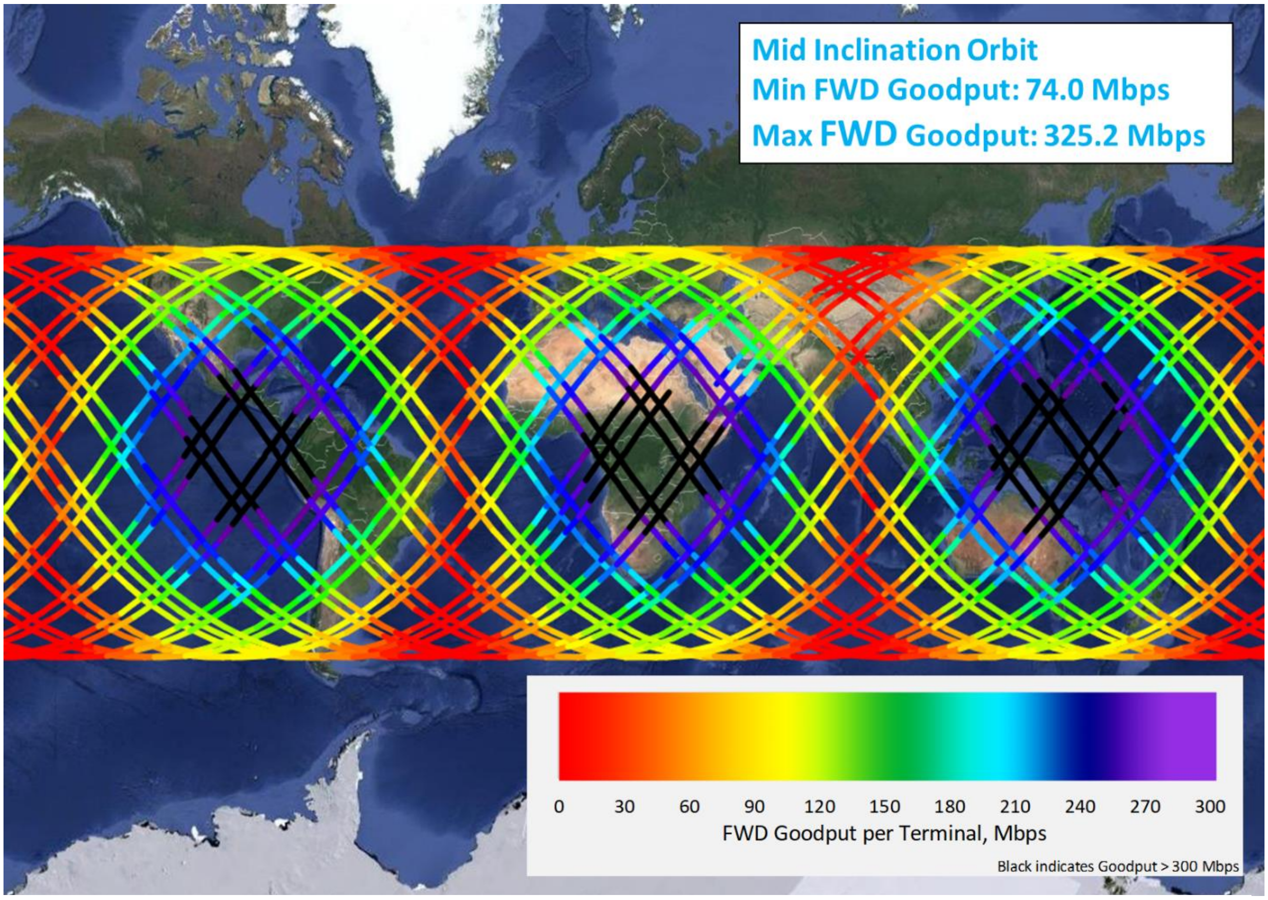


**Figure 6: Analysis of the ViaSat-3 space relay capability shows that it provides an ad hoc on demand interactive capability peaking at 325 Mbps of forward link goodput.**

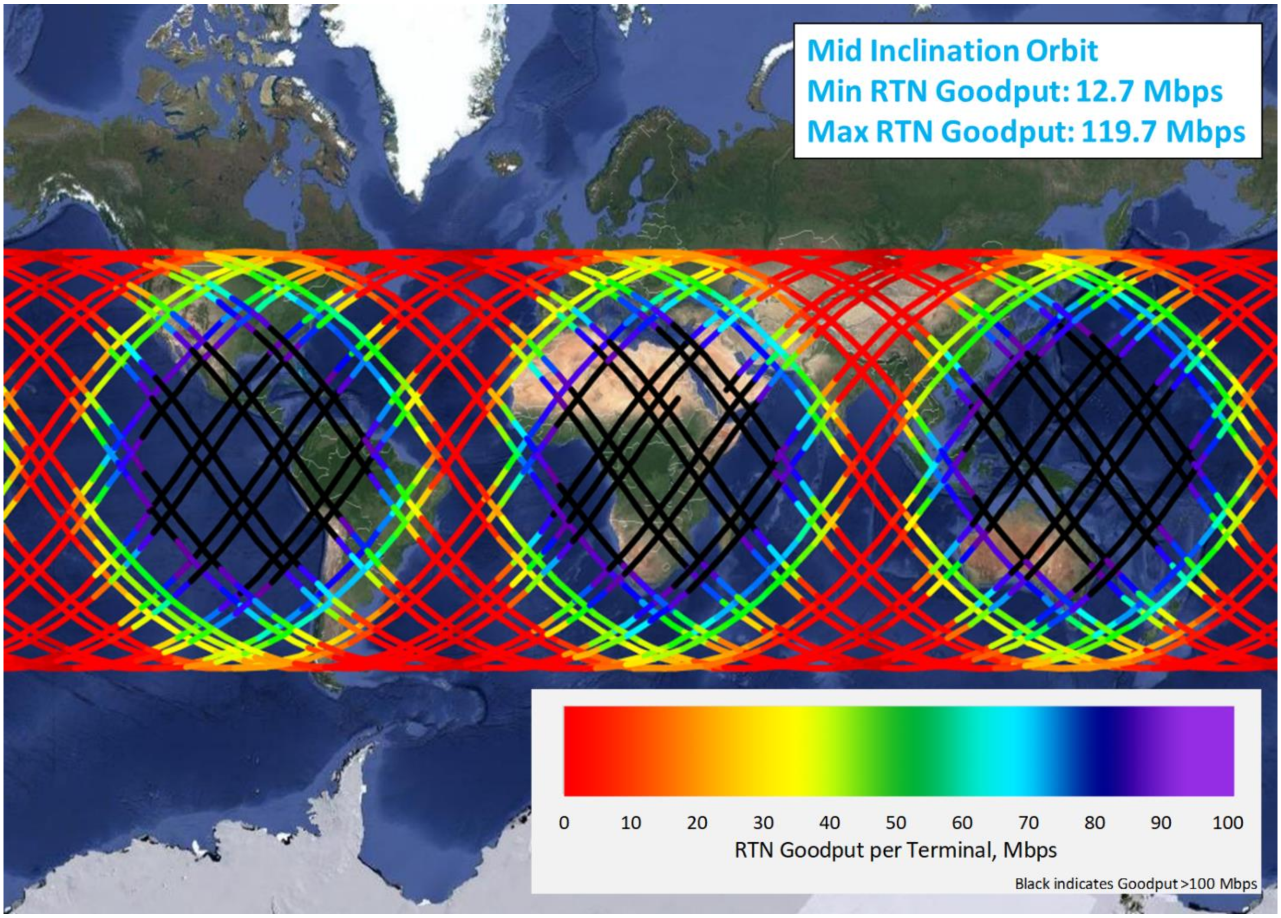


**Figure 7: Analysis of the ViaSat-3 space relay capability shows that it provides an ad hoc on demand interactive capability peaking at 120 Mbps of return link goodput.**

The two figures above show an analysis of the instantaneous goodput (defined as throughput with all overhead removed) for a typical mid inclination LEO orbit at 500 km altitude for both the forward link (ground to Space Vehicle) and the return link (Space Vehicle to ground). There is an inverse relationship between the angle between the GEO subsatellite point and the LEO position and the data rate. When the angle between the GEO subsatellite point and the LEO is small, the data rates are at the highest. Likewise, when the angle between the GEO subsatellite point and the LEO increases the data rate decreases.

| SV | Ant. (cm) | Instantaneous Goodput (Mbps) | | | | | | Aggregate Data Volume | | | | | Average Latency | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | | FWD | | RTN | | FWD | | RTN | | DTE | SR | DTE |
| | | MIN | MAX | MIN | MAX | MIN | MAX | GB Per Orbit | GB Per Day | GB Per Orbit | GB Per Day | TB Per Day | ETE (ms) | ETE (min) |
| Mid Inclination | 70 | 86.7 | 445.9 | 74.0 | 325.8 | 12.7 | 120.1 | 125.0 | 1956.3 | 42.7 | 668.5 | 8.0 | 279.6 | 21.9 |

**Figure 8: Data rates and aggregate volumes for the ViaSat-3 space relay network and the Viasat Real Time Earth network.**

## IV. Applications and Networks Comparison

Hybrid networks are ideal for operators with needs for both real-time data relay and large data-volume file transfer. Many operators require an uninterrupted connection to their spacecraft for both command and control and for delivery of time-critical mission data from the vehicle. Many of the same satellites also generate large volumes of data and must downlink this data to Earth within a useful time period. While it is possible to address both needs with a single network type, the advantages of hybrid networks become clear when lifecycle cost is taken into account, as shown in Figure 9.

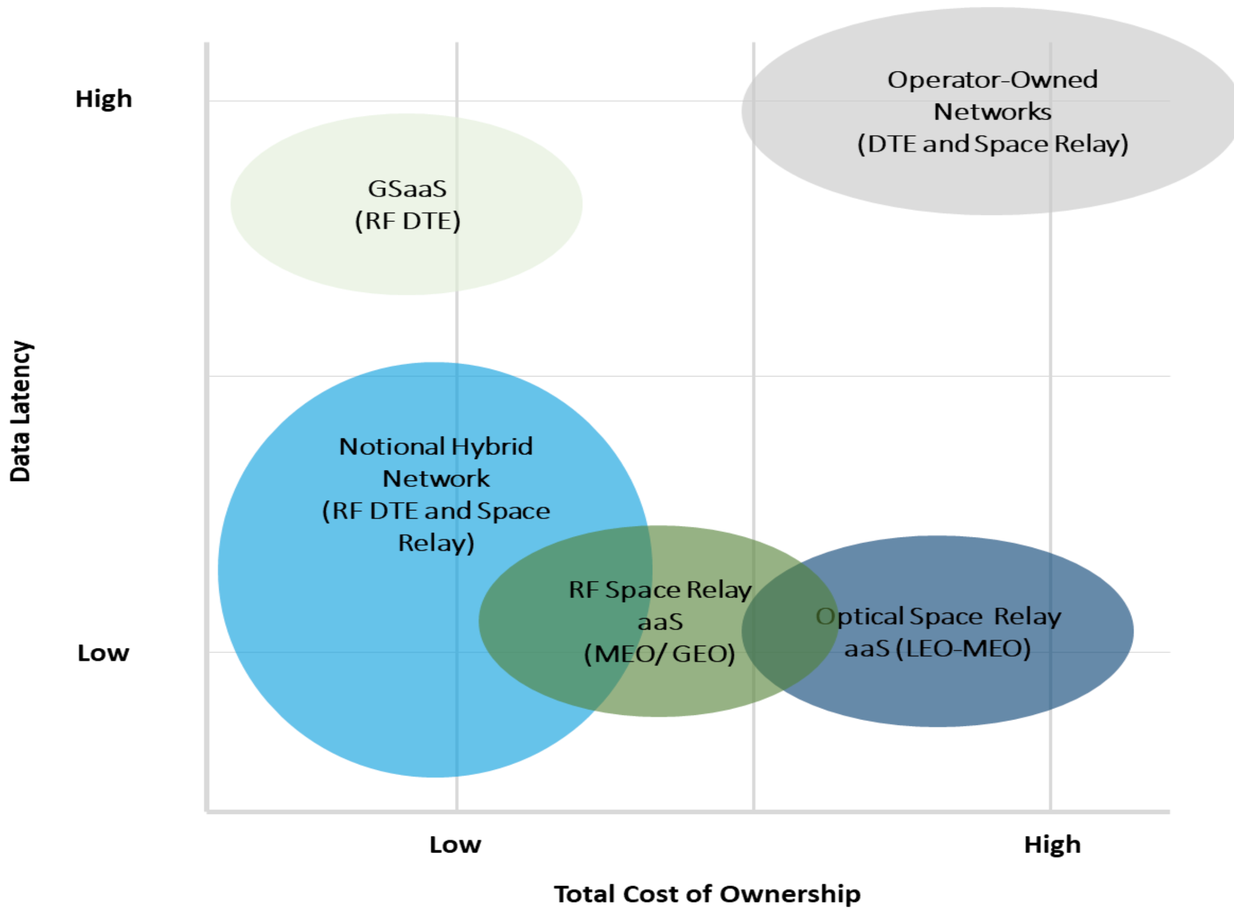


**Figure 9: Comparison of space-ground communications networks**

Figure 9 compares various space-ground communications networks using two metrics: data latency, defined as the time elapsed between the collection of mission data by the satellite and its transport to the ground, and total cost of ownership, which is defined as all of the costs incurred by the operator to deploy (if necessary) and use the communications network for the life of the satellite. Several network types are considered, including variations that employ either RF or optical transport modes:

- Operator-owned networks: a direct-to-Earth (DTE) or space relay communications network, wholly owned and operated by the satellite operator, including all space and ground hardware and software
- Ground-segment-as-a-service: access to a network of multiple terrestrial antennas provided to the satellite operator on a leased or on-demand basis, for a fee
- Space relay as-a-service: access to a space network via satellite crosslinks (LEO-LEO, LEO-GEO, etc.) provided to the satellite operator on a leased or on-demand basis, for a fee

- Notional hybrid network: this represents the hybrid network described in Section III, which consists of direct-to-Earth and space relay networks provided on-demand, for a fee

As Figure 9 illustrates, operator-owned networks (whether ground- or space-based) provide the operator with maximum control over their communications network, but come at the highest total cost of ownership, and suffer from high data latency unless very expensive networks are deployed. Historically, operator-owned networks with low data latency have only been deployed by sovereign nations (ex. TDRSS). However, ground-segment-as-a-service (GSaaS) offerings dramatically reduce the lifecycle costs to the satellite operator by providing access to a shared network of antennas, while also providing a useful drop in data latency, since most GSaaS networks have many more antennas globally than operator-owned ground networks. Space relay as-a-service networks feature even lower data latency, but are also more expensive to access than GSaaS networks, due to the high cost of launching relay assets to space (even when those costs are shared amongst multiple space relay users).

The proposed hybrid network architecture offers low data latency and low total cost of ownership. This is because the hybrid network allows operators to choose which of the underlying networks are used to transport data to and from the satellite. When low data latency is desired, low-latency networks (such as space relay networks) can be employed to efficiently process time-critical data. When low-priority data must be moved across the network in a cost-effective manner, operators can choose lower-cost networks (such as GSaaS networks) with higher data latency but lower operating costs. Therefore, operators have the ability to continually optimize the tradeoff between data latency and cost.

A critical advantage of hybrid networks is that this tradeoff often can be made by the satellite operator in near-real-time, whereas for all of the other networks in Figure 9, the data latency and cost trade must often be fixed at the time the network architecture is defined, which generally occurs months to years before the satellite is launched.

Finally, a hybrid network architecture achieves compounding resilience and availability through integrating multiple networks. Achieving many 9's of availability in any individual network becomes increasingly more difficult and cost prohibitive. However, integrating multiple networks together is cost efficient and achieves impressive overall availability without any of the individual networks being particularly available. For example, if the hybrid network consists of 2 networks each with a modest 90% availability, then the overall network availability achieves 99.00% as shown in the table below. When doing the same with 4 networks, 4 nines of availability is achieved with each network being only 90% available. For missions requiring high availability, resilience, or frequent access an integrated network of multiple underlying communications paths is an excellent way to achieve it.

| Number of Hybrid Member Networks | Individual Network Availability | Overall Hybrid Network Availability |
|---|---|---|
| 2 | 90.00% | 99.00% |
| 4 | 90.00% | 99.99% |

**Figure 10: Integrating hybrid networks dramatically increases overall availability**

## V. Spacecraft User Terminal

The enabling payload technology to achieve access to the hybrid network is one or more space qualified communications terminals that are compatible in frequency, bandwidth, waveform, and power with each of the member networks. This can be achieved via multiple terminals or a combined terminal. There are trades associated with either approach depending on mission objectives and requirements. A combined terminal is a more efficient SWaP solution, but limits access to a single network, and is more costly due to NRE to integrate multiple hybrid network capabilities. On the other hand, integrating multiple existing terminals increases onto a space vehicle requires more SWaP. But it also provides simultaneous access to multiple networks with the ability to achieve aggregate higher data rates to reduce latency for large data files or data volumes. This approach also can maintain communications during critical times in the event of an outage in one of the member networks.

Viasat's approach to developing a hybrid network user terminal includes both approaches to the terminal, namely utilizing multiple terminals to expedite hybrid network access, as well as enhancing the baseline space terminal to include additional frequency bands and waveforms in an integrated package.

Viasat is currently developing a Space Terminal (ST) compatible with the ViaSat-3 GEO relay network to be coupled with a direct to earth (DTE) terminal for hybrid network access on LEO space vehicles. The ST is modular for flexibility in SV integration and for compatibility with a variety of spacecraft. It's divided into 3 modules, which we describe in the following paragraphs.

The Space Terminal under development is built around our unique System in a Package (SiP) design. The high-level design of this terminal is shown in Figure 11**Error! Reference source not found.**. The SiP package includes a fully programmable radio from baseband (GigE Ethernet) to RF. The RF Module is capable of transmission and reception in the FSS Ka-Band (17.7 to 20.2, 27.5 to 30.0 GHz), MIL-Ka-Band (20.2 to 21.2, 30.0 to 31.0 GHz), and will include the EESS Ka-Band (25.5 to 27.0 GHz) as a future capability.

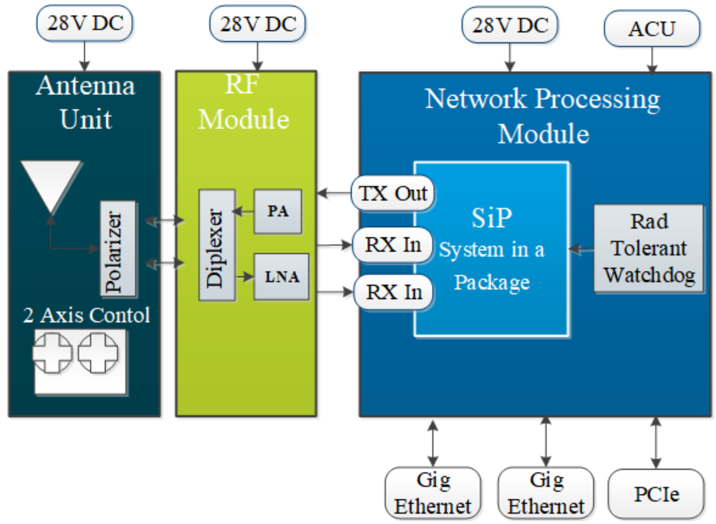


**Figure 11: The Space Terminal is designed around our System in a Package programmable Ka-Band core, with application specific RF/Antenna modules and radiation tolerant design.**

The Network Processing Module (NPM) includes the SiP and a watchdog Master Control Unit to allow reset in the case of a Single Event Upset (SEU), enhancing the radiation tolerance of the design. The software-selectable personality of the SiP can be selected to support either SR or DTE configuration, allowing for a common NPM design. The RF module, which has been evaluated in benchtop operation, can support SR or DTE functions.

The SWaP estimates for the standard terminal, occupies < 1380 cubic inches (stowed), weighs < 22 pounds and consumes between 100 and 150 W.

At least one terminal must be utilized for SR service and one for DTE service if simultaneous operation is required. If the CONOPS allows, a single terminal can be shared between the services. Multiple terminals can be bonded to a single antenna system to increase throughput on a single platform. Also note that platforms that require make-before-break connectivity with the ViaSat-3 satellite system will require two SR terminals so that the rising target satellite can be acquired prior to releasing the setting satellite. Future development of a multi-beam phased array antenna will alleviate the requirement for two terminals.

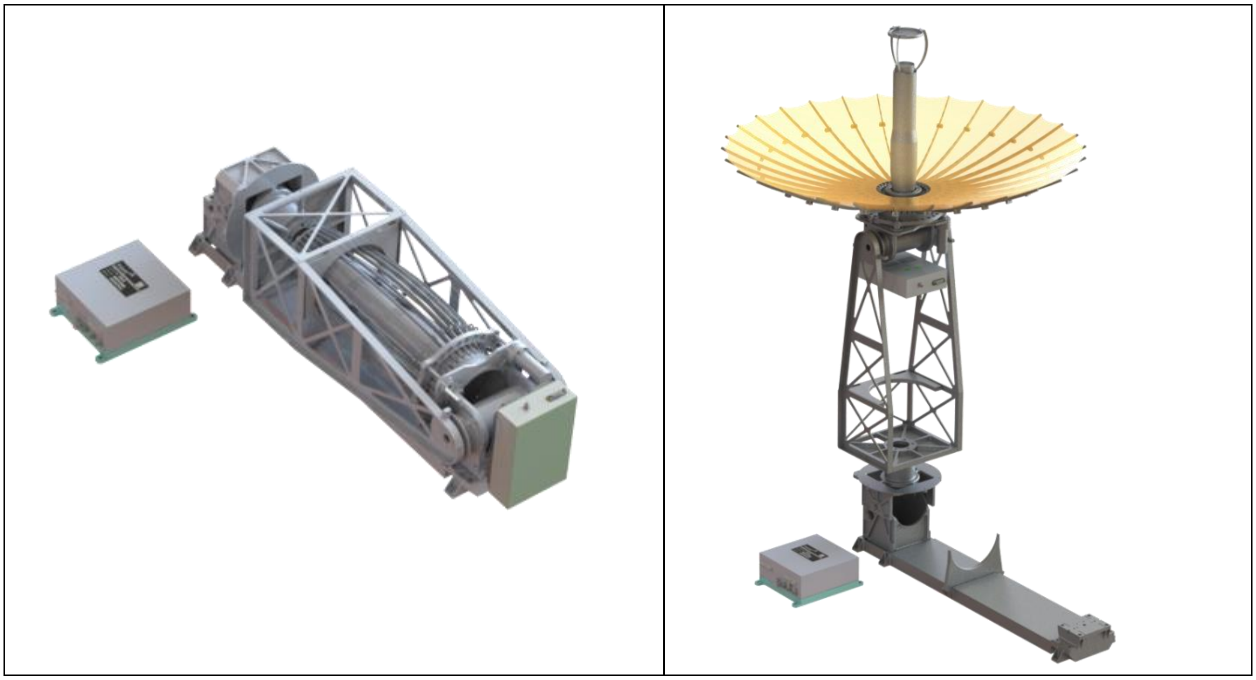

**Figure 12: Space Terminal stowed and deployed configuration**

## VI. Test and Demonstration Plan Leading to Commercial Services

Viasat is taking a phased integration and demonstration approach to achieving the hybrid network in order to reduce risk for customer adoption as an operational service. As part of the initial proof of concept phases, we are developing a full end to end model of the hybrid network inclusive of several demonstration space vehicles. For each demonstration SV, or Design Reference Mission (DRM), we are developing the full mission and simulating it within STK SOLIS. The simulations and resulting Technical Performance Measures will be used to inform and design on orbit experiments, demonstrations, and CONOPS.

The outputs from the simulation stage will help inform the on orbit demonstration planning and execution processes, showin in Figure 13. Viasat's demonstration concept consists of validating the two primary transport networks, ViaSat-3 Space Relay and Direct-to-Earth, integrated through agile software defined networking that serves as the backbone of the hybrid service. For the demonstration, Viasat will plan, integrate, test, and demonstrate a representative CONOPs for assessing the security, performance, and availability.

The demonstration will test the performance of the terminals integrated onto a customer satellite. The demonstration will include terrestrial and cloud-based routing using SDN to a Mission Operations Center (MOC) Meet-Me-Point. Finally, the demonstration will introduce our mission management and monitoring portals to support operator utility and agile operations.

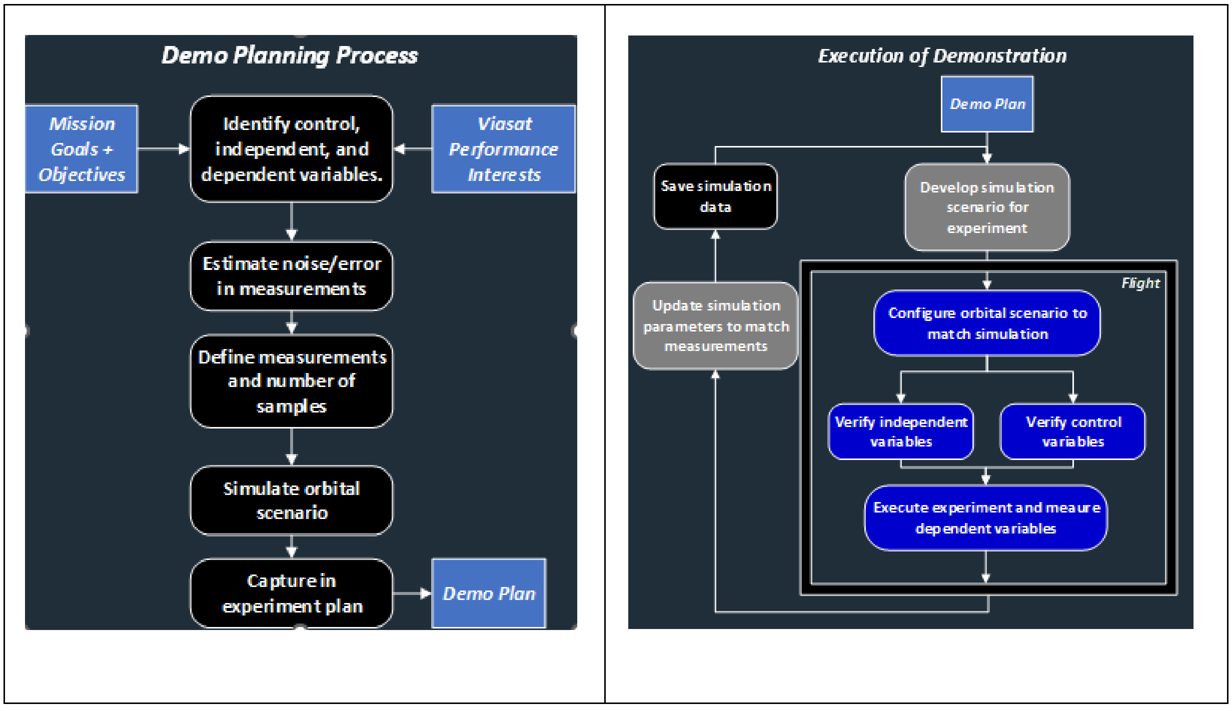


**Figure 13: Viasat is using an iterative phased simulation and demonstration approach to prove out the seamless hybrid service**

Our risk reduction validation events feature four key technology demonstrations while supporting candidate customer CONOPs. Each of the technology demonstrations are designed to reduce risk and provide opportunities to provide an assessment of performance and system compatibility with candidate customer applications. This will provide an opportunity to assess the performance of the hybrid transport network, terminal hardware, and APIs for system interoperability with Mission Operation Center (MOC) systems. The four technology demonstrations include:

1. Demonstration of the space terminal hardware with the SR network. This will include a ground-based validation of the performance and network transport to the MOC Meet-Me-Point. This will use flight representative hardware to ensure network compatibility and provide initial performance estimates under different network loading scenarios.
2. Demonstration of the APIs and portals used to support service management and monitoring. Viasat will demonstrate a remote operators' ability to schedule and manage connectivity services. Additionally, the demonstration will include health and status of the hybrid terminals, ground network, and terrestrial pathways.
3. Demonstration of real-time cyber detection and monitoring capabilities using Viasat's CSOC and threat detection performance. Viasat will provide an assessment of the threat reporting and mitigation capabilities and the results of our ongoing penetration testing performed on the overall hybrid network
4. Demonstration of the DTE service with MOC interoperability. This will allow ground network validation for simulating traffic flows from the DTE gateway sites to the MOC network access points. This portion of the technology demonstration will include a waveform validation using network simulations.

The service construct for the hybrid network combines the SR and DTE key capabilities. Orbiters operating to serve a wide range of applications (commercial space stations, science missions, Earth observation, surveillance, RADAR and others), outfitted with a Space Terminal, seamlessly route data through the SR and DTE paths based on agile routing policies that are centrally orchestrated. This intelligent orchestration allows for flexible traffic flow optimization to provide assured communications for any user platform, while accounting for link resource opportunity in real-time.

To integrate the SR and DTE networks, data is aggregated on the ground via a cloud-based architecture that uses SDN orchestrators to manage the Quality of Service (QoS) of the individual links. The terrestrial side of the network includes customer Virtual Private Clouds (VPC), the Viasat Enterprise Management System which provides back-office services, management plane for service scheduling, and a machine-to-machine NASA MOC interface. Backhaul to customer Mission Operations Centers is realized via SDN. Additionally, Viasat can set up IP tunnels through the internet to MOC Meet-Me-Points.

Once the routing policies are set, the on-board SDN capability and cloud-based terrestrial architecture combine to render a network that is seamless and agnostic to the data path taken. This, in turn, enhances reliability through access to multiple service networks (SR/DTE), and includes our Cybersecurity Operations Center (CSOC) services and capabilities. Reliability is also enhanced with the network's ability to flexibly concentrate capacity to meet Service Level Agreements (SLAs) (on a per-user basis). The features will include:

- Resilient software defined networking for high availability
- Built-in IA architecture and end-to-end cyber security monitoring and protections
- Access to multiple networks without requiring a priori coordination (e.g. for VS-3, users can authenticate and login to the network without advanced planning)
- SR Network capabilities include real-time mitigation of EMI interference
- Remote operations for service management and network monitoring of a suite of terminals.

Viasat has developed the hybrid network service concept in parallel with our DTE and SR networks, including engagements with a range of potential and existing customers to understand needs and pain points to design a system that meets the communications needs of LEO mission operators.

## VII. Conclusion

Recently, commercial Earth observation satellite operators have clearly demonstrated the value of timely delivery of observation data from LEO to the ground. While existing communications networks present a number of challenges and costs to reducing data latency from LEO, a hybrid network that takes advantage of both space relay and direct-to-Earth transport paths can minimize these obstacles. As the proposed hybrid network is developed, actual use cases will be tested and data collected to demonstrate the relative performance of this network compared to existing network architectures. Other future areas for study include integration of additional networks into a single user terminal, as well as the use of new antenna technologies (such as phased arrays) that extend hybrid networking to new classes of space users.

## Acknowledgments

The authors would like to thank NASA for their support and investment in accelerating the development of the hybrid network service.