Trends in Mobile Satellite Technology

Demand for sophisticated personal communication services has changed communications satellite design. Satellites have moved closer to the Earth to improve communication speed and enable personal communication services. But in so doing, they require more computing resources and more sophisticated protocols to handle intersatellite communications.

First-Generation Geos

Early satellite systems, such as Intelsat and Inmarsat, were designed primarily to support a small number of users at a high data rate (in the neighborhood of megabits per second). Their constellations (groups of satellites) typically consisted of one or more large, heavy satellites deployed in a geostationary orbit. At an altitude of 35,785 km, a geostationary orbit corresponds to one sidereal day at an inclination of zero degrees, placing it always at the equator. Thus the satellite appears to be stationary from the surface of the Earth, thereby providing continuous communications services over a given area. Assuming a minimum ground antenna elevation angle of 10 degrees, a single satellite in geostationary orbit can cover about 34 percent of the Earth's surface.

Basically, these first-generation satellites are repeaters, which translate the uplink frequency of a received waveform and reamplify it for downlink transmission. They employ bent-pipe transponders and basically handle only radio frequency waveforms, which means that systems engineers have focused only on layers 1 and 2 (the physical and data-link layers) of the OSI reference model.

Unfortunately, the altitude of a geostationary satellite results in a one-way, single-hop time delay of at least 0.25 seconds, caused by the speed-of-light transmission delay. Signal processing adds further delays, and the aggregate delay is called the communications propagation loss. Geostationary satellites, therefore, are less attractive for voice communication. The higher the satellite altitude,
the greater the delay, as Figure 1 shows. The plot in Figure 1a, derived from the equation shown, assumes an operating frequency of 2 GHz, the frequency range allocated to mobile satellite services. As the figure shows, the propagation loss is significantly higher for geostationary satellites than for low Earth orbit (LEO) satellites, which have an altitude of about 1,850 km or less.

Figure 1b shows the maximum achievable data rate as a function of satellite altitude, assuming the parameters shown. The figure compares three types of transmission antennas: 1- and 3-meter parabolic dishes and an omni, which is similar to a cellular antenna. As the figure shows, not only does the maximum achievable data rate decrease with satellite altitude, it also increases proportionally to the size of the transmit antenna.

Within five years, the minimum data rate required to support toll-quality voice communication is expected to drop to about 2,400 bps. If this is true, and if the omni is the only available transmit antenna for handheld, mobile communications, it becomes clear that satellites must move into the LEO range—geostationary satellites require prohibitively large antennas.

**NEXT-GENERATION LEOs**

The advent of personal communication services has created a demand for low-delay voice and data transmission systems capable of supporting many users. Thus, the philosophy governing satellite deployment is changing, and providers are moving away from deploying a few large geostationary satellites to deploying tens, even hundreds, of smaller lightweight satellites. Furthermore, the altitudes are either low (up to about 1,850 km) or medium (up to about 18,500 km).

These LEOs have satellite periods that range from about 1.5 to 10 hours. They also have high inclination angles to the Earth and so typically appear overhead only twice a day; thus they require more satellites per constellation to achieve continuous coverage. There are three basic types: nonvoice little LEOs, full-service big LEOs, and the newest, broadband LEOs.

**Little LEOs**

Recent technological advancements in antenna design, signal reception, and miniaturization have made feasible mobile communications systems that support 100- to 300-bps transmission. These little LEOs, which can operate at a frequency below 1 GHz, are therefore appropriate only for nonvoice, store-and-forward mobile satellite services.

Orbital Sciences Corporation’s OrbComm is an example. OrbComm is designed to provide full-time, global, two-way digital communications services: messaging, emergency alerts, position determination, and remote data collection. In space, OrbComm will consist of 36 satellites, each one weighing 85 pounds and designed to last for four years. (The final constellation architecture is still under development and may include only 26 satellites.) Space-to-ground communication is via VHF; 148-150.05 MHz for the uplink and 137-138 MHz for the downlink. OrbComm’s users will buy a handheld unit for between $100 and $500. The unit will be capable of transmitting at a burst rate of 2,400 bps and receiving at a burst rate of 4,800 bps, with an effective throughput of about 300 bps.

**Figure 1. Factors forcing communication satellites into lower orbits. (a) Propagation loss, as computed by the formula provided, where \( L_{fs} \) is the free space propagation loss, \( z \) is the user-to-satellite distance, \( f \) is the operating frequency, and \( c \) is the speed of light. (b) Maximum achievable data rate, assuming the parameters provided. Noise temperature reflects noise due to the thermal motion of electrons, galactic noise, interfering signals, and so on. Other link losses might be caused by multipath fading, rain, and atmospheric absorption.**

<table>
<thead>
<tr>
<th>Assumed parameters</th>
<th>Other link losses: 6 dB</th>
<th>Required signal-to-noise ratio: 10 dB</th>
<th>Link margin: 3 dB</th>
</tr>
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<tr>
<td>Transmit power: 1 W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna diameter: 0.33 M</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna noise temperature: 750 K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating frequency: 2 GHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Altitude (km)</td>
<td>0</td>
<td>9,250</td>
<td>18,500</td>
</tr>
<tr>
<td>Maximum data rate (Kbps)</td>
<td>100,000</td>
<td>10,000</td>
<td>1,000</td>
</tr>
<tr>
<td>3 m</td>
<td>1 m</td>
<td>omni</td>
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</tr>
</tbody>
</table>
Basically, OrbComm is a store-and-forward mailbox in the sky. Messages will be sent via OrbComm satellites to gateway stations on the Earth, which will either forward the message directly to the destination via leased lines or store it for access on demand. The satellites are very simple, small, and easily deployed (current expectations are that eight satellites will be deployed per launch, on Pegasus missiles). The effective throughput is low, but the global services OrbComm can support are much in demand.

In October 1994, the US Federal Communications Commission granted OrbComm a license to construct, launch, and operate a network of up to 36 LEO satellites—the first FCC license granted for a commercial LEO service. OCS launched the first two OrbComm satellites in April 1995, and is now offering limited services.

**Big LEOs**

The big LEOs include Motorola's Iridium, Loral and Qualcomm's Globalstar, and TRW's Odyssey.1,2 (Constellation Communication's Aries and Ellipsat's Ellipso are not described here because their level of technical and financial maturity is much lower than the three systems discussed below.) All these systems will provide the full range of mobile satellite services—voice and data—and operate between 1 and 3 GHz. The FCC awarded operational licenses for Iridium, Globalstar, and Odyssey in January 1995.

The big LEOs deploy more satellites, as economies of scale have reduced the impact of losing a single satellite. And in the case of Iridium, these are more complex satellites that perform more on-board processing: They not only translate a waveform's frequency and reamplify it before retransmission; they also process waveforms down to the bit level (the baseband), performing decoding, deinterleaving, demodulation, and so forth. As a result, these satellites can support a variety of packet-oriented services, including routing, flow control, and error detection and correction.

As Figure 2 illustrates, these networking services move satellite communications systems into higher layers of the OSI protocol model. Hence the effort to determine if new protocols are necessary to support these OSI layer 3 through 7 services.

**Iridium.** On-board processing is a major design feature of Iridium. Figure 3 shows the web of 66 LEO satellites, which will orbit in six equally divided planes, or rings, at an altitude of 785 km.

Motorola is aiming to be the first vendor to use some new techniques in a commercial satellite system: Iridium is the only big LEO that will try to circumvent the need to downlink voice and data traffic to intervening hub stations. To do so, Iridium will use satellite-to-satellite crosslinks. Each satellite will have four crosslinks: one forward within a plane, one backward within a plane, and two across planes. The crosslinks will operate at 25 M bps at between 22.55 and 23.55 GHz.

Iridium's on-board processing and satellite crosslink capability will allow it to be more flexible in how it
routes messages, at the expense of design complexity. For example, it may be a challenge to track Iridium satellites because the satellites in adjacent planes travel in opposite directions. These features also add weight: At 1,100 pounds, Iridium's satellites are heavier than Globalstar's, primarily because of the payload required for on-board processing and satellite crosslinks.

Each Iridium satellite enjoys the largest throughput of the three, at 3,840 full-duplex circuits. Note that per-satellite capacity is not cumulative, due to self-interference and beam overlap.

Iridium was scheduled to begin launching satellites, each of which has a mission life of five to 15 years, in November 1996. The launch was rescheduled for January 1997.

**Globalstar.** Loral Aerospace Corporation and Qualcomm are developing Globalstar, which consists of 48 LEO satellites at an altitude of 1,401 km and equally divided into eight orbital planes.

Like Odyssey, Globalstar will use traditional bent-pipe transponders instead of on-board processing. Each Globalstar satellite weighs about 704 pounds and has a capacity of 2,800 full-duplex circuits. The vendors plan to begin launching satellites, each of which has a mission life of between five and 15 years, in July 1997.

**Odyssey.** TRW's Odyssey comprises 12 MEO satellites at an altitude of 10,354 km and equally divided into 3 orbital planes. Because its satellites' altitudes are significantly higher, Odyssey requires fewer satellites to cover the globe. This was a major factor in TRW's decision to choose a MEO altitude, but this choice came at the expense of size: Each Odyssey satellite weighs 2,703 pounds. At higher altitudes, satellites need larger antennas as well as larger solar arrays and additional shielding to protect against increased radiation levels, all of which add weight.

Odyssey satellites have a capacity of 2,300 full-duplex circuits and have a mission life of between five and 15 years. They are expected to launch in late 1997.

**Multiple access**

As the sidebar "Battle for Access Standards" briefly describes, there are three basic ways to let multiple users share link capacity: frequency-division multiple access (FDMA), time-division multiple access (TDM A), and code-division multiple access (CDMA).

In FDMA systems, each user is assigned a unique center frequency within the operational bandwidth and multiple signals can simultaneously access the satellite amplifier. In a bent-pipe transponder configuration, the satellite translates the entire RF frequency spectrum to a downlink. To receive the signal, the ground station tunes to the proper band in the downlink spectrum. FDMA represents the simplest way to achieve multiple access, and the required systems technology and hardware are readily available.

The key limitation of using FDMA is the need to operate the satellite amplifier at approximately half its maximum output to avoid the generation of unwanted interference. In TDM A systems, all users transmit on the same frequency and each is assigned the total available bandwidth for a limited amount of time. Unused time regions between slot assignment—guard times—allow for some time uncertainty and act as buffers to reduce interference. TDM A systems segment time into frames, and each frame is further partitioned into assignable time slots. The frame structure repeats so that a fixed TDM A assignment constitutes one or more slots that periodically appear during each frame. Each transmitter sends its data in a burst, timed so as to arrive at the satellite transponder at the assigned time slot. This requires accurate timing and terminal-satellite distance data for all TDM A users. The major advantage of TDM A over FDMA is efficiency, because the satellite amplifier can be operated at maximum output power since only one carrier arrives at the satellite transponder at any given time.

In CDMA systems, all users transmit simultaneously and at the same frequency, with each being assigned a unique pseudo-random noise code. The data is first phase-modulated by a carrier and then the carrier is biphase-modulated with a pseudorandom noise code that is at a much higher rate than the data traffic. This generates a wide bandwidth, low-energy spread spectrum signal. Each user, in effect, behaves as a low-level interferer to each other user. The received signal is then "despread" by applying the same code to the received data stream. The maximum number of CDMA users is limited by their aggregate background noise level. CDMA systems suffer from the complexity associated with synchronizing the transmit and receive codes and from a limitation in the maximum number of users a given bandwidth can support.
munications CEO Craig McCaw and Microsoft Chairman and CEO Bill Gates. Teledesic plans to offer global fixed satellite service, meaning that the user is stationary, enabling the use of parabolic directional antennas for higher data rates.

The most interesting feature of Teledesic is that it does not plan to cater to the mobile communications market. Instead, it is positioning itself as AT&T did before the breakup—a wholesaler of communications capacity and bulk network capability, selling to retail telecommunications providers such as US West and Nynex. Teledesic has been called “real-time wireless bandwidth on demand,” the “global Internet,” and “AT&T in the sky.”

Figure 4 shows the space component of Teledesic, 840 satellites in a sun-synchronous altitude at 700 km. Its satellites will employ on-board processing techniques and support packet-switched asynchronous transfer mode (ATM) communications. Figure 5 shows the current architecture: Each satellite will have eight crosslinks supporting a nominal data rate of 155.2 Mbps with a maximum supportable data rate of 1.244 Gbps. The crosslink frequency band is 59-64 GHz. Connectivity with the ground is in the Ka frequency band, with 30 GHz (nominal) for the uplink and 20 GHz (nominal) for the downlink.

Teledesic's maximum achievable data rate to the ground is 1.244 Gbps, to both user terminals and gateways ("GigaLink" terminals). There is not much information available about Teledesic’s ground components. We do know that it will be compatible with ATM/Sonet technology and protocols under development and will interface with existing public and private networks.

Figure 4. Teledesic satellite constellation.

Figure 5. Proposed Teledesic architecture.
Within the context of this article, Teledesic is the best example of where satellite communication appears to be going. Specifically, it exploits services addressed by OSI layers 3 through 7. Other than Iridium, all the other systems are applying proven technology to new applications, with only limited use of services addressed by the higher OSI layers.

**SATELLITE NETWORKING**

There is little public information about the network protocols being developed for commercial systems. However, we can begin to appreciate the challenges they face by examining the work being done by the military and by civil organizations such as NASA and the Consultative Committee for Space Data Systems. CCSDS is the recognized international standards organization for space communications. It issues recommendations that can be subsequently approved by ISO as standards. CCSDS recommendations 701.0-B-2 allows both an optional layer 3 Internet service using the ISO 8473 connectionless network protocol and a special-purpose path service. Each of these two services allows the application layer to access the data-link layer without adding intervening functionality.

However, neither of these services can meet future mission requirements: They can’t efficiently support end-to-end networking, data protection, reliable delivery, and file handling. As a result, the US Department of Defense and NASA are undertaking the Space Communications Protocol Standards (SCPS) project, to develop more flexible higher layer protocol options for space communications.

SCPS, which is designed to extend existing capabilities, focuses on the end-to-end aspects of applications that (1) monitor and command space vehicles and their payloads and (2) return data to the Earth. However, it is expected that SCPS will also apply to satellite communications, where a space vehicle is used as a repeater with communication end points on the ground or in space.

SCPS will focus on online data communications functions at OSI layers 3 through 7. It is assumed that the protocols will operate over layer 2, the data-link layer, which provides services equivalent to those offered by existing CCSDS recommendations and military protocols (coding, framing, multiplexing packets, and so on).

Essentially, there are four types of space applications: telemetry (reporting status of equipment within the space vehicle); command (controlling the space vehicle or its payload); mission data (sending payload data to the ground); and the upload or dumping of programs and data tables to and from space vehicles.

**Space vehicle environment**

A space vehicle’s characteristics affect the communications protocols that can be used.

**Computing resources.** Space vehicles have only so much power, volume, and weight, so their processing capacity and online memory are limited. In general, only 0.15 to 4 M IPS and 0.15 to 4 M bytes are available for layer 3 through 7 protocols. Future restrictions on power, volume, and weight will be less severe, but processing capacity and online memory will continue to be more limited on a space vehicle than in ground systems. The available processing capacity available for layers 3 through 7 protocols is expected to be no more than 8 M IPS and online memory is expected to be no more than 8 M bytes.

**Communications architecture.** Most space vehicles now have a communications front end that interfaces with the data links and distributes data to other modules. In the future, we can expect a distributed communications architecture in which communication elements are connected via regular local area networks.

**Transmit power.** Currently, transmit power is relatively low, resulting in low-to-moderate data transmission rates. Advances in technology are expected that will allow the transmit power to increase, resulting in moderate-to-high data transmission rates.

**Network environment**

The characteristics of the space network environment have an impact on the communications protocols that would support space applications. This section addresses only the characteristics that affect layer 3 through 7 protocols.

**Connectivity.** Whereas geostationary space vehicles can be accessed continuously from the same point on Earth, LEOs are typically accessible on a periodic basis for only a few minutes at a time from the same point on Earth. Thus, systems consisting solely of LEO vehicles have a time-variant connectivity with the ground (each connectivity pattern lasts only a few minutes) where specific connectivity patterns are repeated periodically. With very few exceptions, there are no crosslinks in current space systems.

**Delays.** One-way delays between end points, due to propagation, are typically less than or equal to 0.125 second per space-ground link. Interleaving-deinterleaving of a space-ground link can significantly increase the one-way delay by an additional 0.25 to 0.50 second. One-way delays for crosslinks, due to propagation and interleaving-deinterleaving respectively, are expected to be less than for space-ground links.

**Errors.** Transmission errors are due to congestion, corruption, and link outages. Error rates due to corruption can be random or bursty. Currently, the random error rates visible by the network layer can fluctuate between $10^{-8}$ and $10^{-5}$. The burst error rates can be between $10^{-2}$ and $10^{-4}$. In the future, these rates are expected to improve by an order of magnitude.

**Link occupancy.** Currently, link occupancy is typically low-to-moderate in telemetry and control links.
Computer

and moderate-to-high in both mission data links and links carrying communications traffic between points on the ground. In the future, link occupancy is expected to stay the same because the increase in data traffic is expected to be proportionate to the increase in data transmission rate.

**SPACE PROTOCOLS**

Space protocols must meet four key requirements due to constraints within the space vehicle environment:

- They must support small programs. Implementations must use as little code as possible and use memory buffers efficiently to reduce online memory needs.
- They must allow uncomplicated programs. Simple finite state machines will reduce processing complexity.
- They should impose a low overhead. Their headers and trailers must be kept to a minimum size.
- They must support end-to-end communications. Individual addressing of each end system within each space vehicle will truly implement end-to-end communications.

In addition, to work in a network environment, the protocols must support:

- routing algorithms that both efficiently handle dynamically changing connectivity and maximize the probability of reaching the intended destinations within the required time;
- mechanisms to efficiently handle the combination of high delays and high error rates; and
- the suspension, resumption, and completion of large transactions in the presence of periodic short contact times separated by fairly long non-contact times.

The preferred solution to meeting the above requirements is to adopt existing terrestrial commercial standards without modifying them. If that is not feasible, then existing standards would be modified. If an existing standard would have to be changed extensively, then, and only then, a custom protocol would have to be developed.

**Existing standards**

There are two predominant protocol reference models for data communications: the OSI (Open Systems Interconnection) and Internet (which used to be called the DoD Reference Model). And there are two corresponding protocol suites: the OSI and Internet protocol suites. The standards in both of these suites are based on a set of assumptions about available resources and environment conditions that do not apply to space communications:

- Resources. Typical commercial communications are not highly constrained; nor are their end systems unequal in terms of processing power. In contrast, space-based resources are highly constrained. In addition, they are much more expensive, so typically the ground and space ends of the system are very unequal in terms of computing (processing and memory) resources.
- Environment. Commercial communications environments enjoy fairly stable connectivity and experience few errors, caused mostly by congestion. They also have a high bandwidth in local networks, and moderate bandwidth and delay in wide-area networks. In contrast, space communications have dynamic, intermittent connectivity; high and variable delays; restricted bandwidth; and high error rates due to congestion, corruption, and link outage.

<table>
<thead>
<tr>
<th>Functional category</th>
<th>OSI</th>
<th>IPS</th>
<th>Other</th>
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<tr>
<td>File handling</td>
<td>FTAM</td>
<td>FTP</td>
<td>SSFT</td>
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<tr>
<td>Transport</td>
<td>TP4, CLTP</td>
<td>TCP, UDP</td>
<td>XTP, NetBLT</td>
</tr>
<tr>
<td>Data protection</td>
<td>NLSP, TLSP</td>
<td>I-NLSP, IPv6</td>
<td>SP3, SP3'</td>
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<tr>
<td>Network</td>
<td>CLNP</td>
<td>IP, IPv6</td>
<td>BE, Path</td>
</tr>
</tbody>
</table>

Definitions:

- IPv6 = Internet Protocol version 6
- NetBLT = Network Block Transfer Protocol
- NLSP = Network Layer Security Protocol
- OSI = Open Systems Interconnection
- Path = CCSDS network protocol
- SP3 = Security Protocol at Layer 3
- SP3' = Low-overhead SP3
- SSFT = Space Station File Transfer Protocol
- TCP = Transmission Control Protocol
- TLSP = Transport Layer Security Protocol
- TP4 = Transport Protocol Class 4
- UDP = User Datagram Protocol
- BE = Brilliant Eyes custom network
- CCSDS = Consultative Committee on Space Data Systems
- CLNP = Connectionless Network Protocol
- CLTP = Connectionless Transport Protocol
- FTAM = File Transfer, Access, and Management Protocol
- I-NLSP = Internet Network Layer Security Protocol
- IP = Internet Protocol version 4
- IPS = Internet Protocol Suite
- IPv6 = Internet Protocol version 6
- NetBLT = Network Block Transfer Protocol
- NLSP = Network Layer Security Protocol
- OSI = Open Systems Interconnection
- Path = CCSDS network protocol
- SP3 = Security Protocol at Layer 3
- SP3' = Low-overhead SP3
- SSFT = Space Station File Transfer Protocol
- TCP = Transmission Control Protocol
- TLSP = Transport Layer Security Protocol
- TP4 = Transport Protocol Class 4
- UDP = User Datagram Protocol
- XTP = Express Transfer Protocol

Table 1 shows the existing standards that most closely match the protocol requirements. The SCPS project evaluated the functionality in each existing standard against the requirements to determine:

- if the functionality was required or could be easily omitted;
- if it would work in space or could be easily modified to work, and
- if it had been—or could be—efficiently implemented.

The SCPS project also identified missing functions. On the basis of this evaluation, they determined if a
standard could be adopted “as is” or could be adapted, or if a new standard had to be developed.

For example, SCPS considered four standards as the strongest transport candidates: Transport Protocol Class 4 (TP4) and Transmission Control Protocol (TCP) for connection-oriented operation, and Connectionless Transport Protocol (CLTP) and User Datagram Protocol (UDP) for connectionless operation. TP4 and CLTP are OSI standards; TCP and UDP are Internet standards and were selected as the baseline. The space characteristics inherent in satellite communications necessitated the following modifications to TCP/UDP:

- enhanced functions (a response to congestion should be different than a response to corruption),
- additional functions (including selective negative acknowledgment),
- mechanisms for the efficient use of bandwidth (header compression),
- memory conservation (support for minimal implementation size and efficient memory buffer handling), and
- mechanisms for the efficient handling of high delay and high error conditions (such as handling larger amounts of outstanding data).

Critical to the performance of TCP in the space environment is the use of a selective negative acknowledgment, which allows packets received out of sequence to be acknowledged individually. This function would increase throughput in environments that experience long delays.

**Proposed protocols**

On the basis of an assessment of existing standards, SCPS proposed protocols for space communications, as shown in Figure 6.

**File handling.** SCPS-FP will be interoperable with the existing FTP when the space enhancements (in italics below) are not invoked. It will offer

- operations on entire files,
- two-party file transfer,
- proxy file transfer,
- file-handling security,
- user-initiated interrupt and abort,
- operations on file records,
- recognition of system-detected interrupt notification,
- manual and automatic resumption after interrupt,
- integrity over operations on entire files, and
- integrity over operations on file records.

**Transport.** SCPS-TP will be interoperable with the existing TCP and UDP when the space enhancements (in italics) are not invoked. It will offer

- full delivery reliability,
- best-effort delivery reliability,
- minimal delivery reliability,
- multicasting,
- precedence handling,
- segmentation,
- operation over a wide range of network environment conditions,
- graceful closing of connections, and
- a different response to congestion and to corruption.

**Data protection.** SCPS-SP is a reduced-overhead version of SP3 and NLSP. It will offer

- access control,
- source authentication,
- command authentication,
- integrity, and
- confidentiality.
SCPS-NP, a custom protocol, can either be encapsulated by or translated into a commercial network protocol for ground distribution. It will offer:

- support for multicasting,
- support for multiple routing options,
- packet lifetime support via time stamps with automatic discard,
- separate reporting of congestion and corruption,
- support for precedence handling, and
- differentiation between real and test data.

The proposed protocols are undergoing specification generation, laboratory implementation and simulation, formal validation, and testing to ensure that they meet the requirements of civil and military space systems. They have been submitted to both the US government and CCSDS for approval as recognized standards. If successful, the result will be open global standards that stimulate vendors to produce commercial products.

The commercial space, military tactical, and wireless personal communications markets may also benefit from the technology of these space protocols because they have system and environment constraints in some cases similar to space communications.

Acknowledgment
We thank Lloyd Wood of the Centre for Satellite Engineering Research at the University of Surrey, UK, for permission to reproduce the satellite constellation images rendered using SaVi, the satellite visualization tool authored by Robert Thurman and Patrick Worfolk at the Geometry Center, University of Minnesota. (More on constellations at http://www.sat-net.com/L.Wood/constellations.)

References

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