Applied Technology Institute (ATIcourses.com)

Stay Current In Your Field • Broaden Your Knowledge • Increase Productivity

349 Berkshire Drive • Riva, Maryland 21140
888-501-2100 • 410-956-8805
Website: www.ATIcourses.com • Email: ATI@ATIcourses.com

Boost Your Skills With ATIcourses.com!

ATI Provides Training In:

- Acoustic, Noise & Sonar Engineering
- Communications and Networking
- Engineering & Data Analysis
- Information Technology
- Radar, Missiles & Combat Systems
- Remote Sensing
- Signal Processing
- Space, Satellite & Aerospace Engineering
- Systems Engineering & Professional Development

Check Our Schedule & Register Today!

The Applied Technology Institute (ATIcourses.com) specializes in training programs for technical professionals. Our courses keep you current in state-of-the-art technology that is essential to keep your company on the cutting edge in today's highly competitive marketplace. Since 1984, ATI has earned the trust of training departments nationwide, and has presented On-site training at the major Navy, Air Force and NASA centers, and for a large number of contractors. Our training increases effectiveness and productivity.

Learn From The Proven Best!

Via Satellite, October, 1998

Earth Station High Power Amplifiers

KPA, TWTA, or SSPA?

by Robert A. Nelson

The high power amplifier (HPA) in an earth station facility provides the RF carrier power to the input terminals of the antenna that, when combined with the antenna gain, yields the equivalent isotropic radiated power (EIRP) required for the uplink to the satellite. The waveguide loss between the HPA and the antenna must be accounted for in the calculation of the EIRP.

The output power typically may be a few watts for a single data channel, around a hundred watts or less for a low capacity system, or several kilowatts for high capacity traffic.

The choice of amplifier is highly dependent on its application, the cost of installation and long term operation, and many other factors. This article will summarize the technologies, describe their important characteristics, and identify some issues important to understanding their differences and relative merits.

TYPES OF AMPLIFIERS

Earth station terminals for satellite communication use high power amplifiers designed primarily for operation in the Fixed Satellite Service (FSS) at C-band (6 GHz), military and scientific communications at X-band (8 GHz), fixed and mobile services at Ku-band (14 GHz), the Direct Broadcast Service (DBS) in the DBS portion of Ku-band (18 GHz), and military applications in the EHF/Q-band (45 GHz). Other frequency bands include those allocated for the emerging broadband satellite services in Ka-band (30 GHz) and V-band (50 GHz). Generally, the frequency used for the earth-to-space uplink is higher than the frequency for the space-to-earth downlink within a given band.

An earth station HPA can be one of three types: a klystron power amplifier (KPA), a traveling wave tube amplifier (TWTA), or a solid state power amplifier (SSPA). The KPA and TWTA achieve amplification by modulating the flow of electrons through a vacuum tube. Solid state power amplifiers use gallium arsenide (GaAs) field effect transistors (FETs) that are configured using power combining techniques. The klystron is a narrowband, high power device, while TWTAs and SSPAs have wide bandwidths and operate over a range of low, medium, and high powers.

The principal technical parameters characterizing an amplifier are its frequency, bandwidth, output power, gain, linearity, efficiency, and reliability. Size, weight, cabinet design, ease of maintenance, and safety are additional considerations. Cost factors include the cost of installation and the long term cost of ownership.

KPAs are normally used for high power narrowband transmission to specific satellite transponders, typically for television program transmission and distribution. TWTAs and SSPAs are used for wideband applications or where frequency agility is required.

Originally, TWTAs provided high power but with poor efficiency and reliability. Compared to a KPA, these disadvantages were regarded as necessary penalties for wide bandwidth. SSPAs first became available about 20 years ago. They were restricted to low power systems requiring only a few watts, such as small earth stations transmitting a few telephone channels.

Within the past decade, however, TWTA and SSPA technologies have both advanced considerably. Today there is vigorous competition between these two technologies for wideband systems.

KPA

The klystron power amplifier (KPA) is a narrowband device capable of providing high power and high gain with relatively high efficiency and stability. The bandwidth is about 45 MHz at C-band and about 80 MHz at Ku-band. Thus a separate KPA is usually required for each satellite transponder.

In a klystron tube an electron beam is formed by accelerating electrons emitted from a heated cathode through a positive potential difference. The electrons enter a series of cavities, typically five in number, which are tuned around the operating frequency and are connected by cylindrical "drift tubes".

In the input cavity the electrons are velocity-modulated by a time-varying electromagnetic field produced by the input radio frequency (RF) signal. The distribution in velocities results in a density modulation further down the tube as the electrons are bunched into clusters when higher velocity electrons catch up with slower electrons in the drift tubes.

Optimum bunching of electrons occurs in the output cavity. Large RF currents are generated in the cavity wall by the density-modulated beam, thereby generating an amplified RF output signal. The energy of the spent electron beam is dissipated as heat in the collector.

The intermediate cavities are used to optimize the saturated power, gain, and bandwidth characteristics. Additional bunching of electrons is provided, yielding higher gain.

The gain is typically 15 dB per cavity, so that a five-cavity klystron can provide a total gain of about 75 dB if synchronously tuned. However, by "stagger tuning" the individual cavities to slightly different frequencies, the bandwidth can be increased with a reduction in gain. A typical gain is on the order of 45 dB.

For a cavity device like a klystron, the bandwidth is a fixed percentage of the frequency of operation. The bandwidth is proportional to the frequency and inversely proportional to the Q (quality) factor, which is defined as 2π times the ratio of the energy stored and the average energy lost in one cycle. Thus at C-band (6 GHz), a typical bandwidth is 45 MHz. But at Ku-band (14 GHz) the bandwidth is about 80 MHz. These bandwidths are well suited for C-band and Ku-band satellite transponders. By adding a sixth, filter cavity the KPA bandwidth can be doubled. Thus 80 MHz KPAs are also available at C-band.

Klystrons can be made with "extended interaction" circuits in one or more cavities that increase the bandwidth substantially. This technology can provide a bandwidth of 400 MHz at 30 GHz. Output powers up to 1 kW can also be achieved at different bandwidths.

Although the bandwidth is relatively small, a conventional klystron can be mechanically tuned over a wide frequency range. A klystron can be capacitively or inductively tuned. All satcom klystrons are inductively tuned because of better efficiency and repeatability. The inductance is varied by moving a wall in the cavity (sliding short).

The output power of a KPA is about 3 kW at C-band and 2 kW at Ku-band. The lowest power KPA offered for commercial satellite communications is around 1 kW, although for certain applications powers under 1 kW are available.

TWTA

The traveling wave tube amplifier (TWTA) consists of the traveling wave tube (TWT) itself and the power supply. The TWT can have either a helix or coupled-cavity design.

The TWT is a broadband device with a bandwidth capability of about an octave, which easily covers the 500 MHz bandwidth typical of satellites in the FSS. It also covers the typical 800 MHz DBS bandwidth requirement, as well as even broader bandwidths in Ka-band and higher bands.

The TWT, like the klystron, is an example of a device based on modulating the flow of electrons in a linear beam, but differs from the klystron by the continuous interaction of the electrons with the RF field over the full length of the tube instead of within the gaps of a few resonant cavities.

The TWT has a heritage of over half a century. The original concept was proposed in 1944 by Rudolf Kompfner, who investigated experimental laboratory microwave tubes while working for the British Admiralty during World War II.

The first practical TWT was developed at the Bell Telephone Laboratories in 1945 by John Pierce and L.M. Field. Bell Labs was interested in the technology for its possible application to communication. By the early 1960s, the TWT was adapted for use in satellite power amplifiers in the Telstar program.

In a TWT, amplification is attained by causing a high density electron beam to interact with an electromagnetic wave that travels along a "slow-wave structure", which usually takes the form of a helical coil. A helix is the widest bandwidth structure available. The electrons are emitted from a heated cathode and are accelerated by a positive voltage applied to an aperture that forms the anode. The electrons are absorbed in a collector at the end of the tube.

The RF signal is applied to the helix. Although the signal travels at nearly the speed of light, its phase velocity along the axis of the tube is much slower because of the longer path in the helix, as determined by the pitch and diameter of the coil, and is nearly equal to the velocity of the electrons. For example, if the electrons are accelerated by a 3,000 volt potential difference on the anode, the speed of the electrons is about one tenth the speed of light. Thus the length of the helix wire should be about ten times the axial length of the tube to bring about synchronism between the RF traveling wave and the electron beam.

The electrons interact with the traveling wave and form clusters that replicate the RF waveform. Midway down the tube, an attenuator, called a "sever", absorbs the RF signal and prevents feedback, which would result in self-oscillation. On the other side of the attenuator, the electromagnetic field of the electron clusters induces a waveform in the helix having the same time-dependence as the original signal but with much higher energy, resulting in amplification. The gain is typically on the order of 40 to 60 dB.

The beam-forming optics are critical parts of the tube. To minimize heat dissipation caused by electrons striking the helix, the beam must be highly focused and the transmission from one end of the tube to the other must be close to 100 percent. When the electrons reach the end of the tube, they impact with the walls of the collector, where most of the heat is generated.

The efficiency of the tube can be improved by applying a negative potential to the collector, which retards the electron beam as the electrons enter it. A collector designed to operate in this way is called a "depressed collector". Less energy is converted to heat as the electron beam impinges on the collector, and consequently less energy is lost as thermal waste.

However, the distribution of electron energies is not uniform. In a multi-stage depressed collector, high energy electrons are directed to stages with high retarding fields and low energy electrons are directed to stages with low retarding fields. This configuration improves the efficiency further, but with greater complexity.

Another means of achieving greater efficiency is through improving beam synchronization. As the electrons travel along the tube and interact with the RF signal, they give up energy and lose velocity. Thus with an ordinary helix, they tend to fall behind the signal. This problem can be mitigated by brute force by increasing the accelerating potential but at the expense of degrading the TWT linearity.

A more elegant method is through the use of a tapered helix, in which the pitch of the helix decreases along the tube. The signal velocity is thus retarded to compensate for beam slowing. The selection of optimum helix configurations has been made possible through advanced computer modeling techniques.

Another type of TWT is a coupled-cavity device, used for high power applications. In this case a series of cavity sections are connected to form the slow-wave structure and is similar to the klystron in this respect. However, in the klystron the cavities are independent, while in the TWT the cavities are coupled by a slot in the wall of each cavity.

The output power of a helix TWTA at C-band ranges from a few watts to about 3 kW, while power levels of 10 kW can be attained with coupled-cavity TWTAs. Helix TWTAs at Ku-band have less power, with a maximum power of around 700 W.

Higher frequency TWTAs are also

available, including those at Ka-band (20 - 30 GHz) and V-band (40 - 50 GHz) where new broadband satellite services are under development. However, because the market is not well established, there are fewer manufacturers of tubes at these frequencies.

The dimensions of the slow-wave structure -- whether a helix, a coupled cavity, or any other type -- are determined by the frequency of operation. The product of wavelength and frequency is equal to the speed of light, so that as the frequency increases the wavelength decreases. The dimensions are proportional to the wavelength. Thus the structure dimensions are approximately inversely proportional to frequency. It is much more difficult to satisfy the criteria for operation at high frequencies such as Ka-band or V-band than at C-band or Ku-band.

The gain of a TWTA can be from 45 dB to 75 dB, depending on the number of active wavelengths in the helix circuit.

SSPA

A solid state power amplifier (SSPA) uses a gallium arsenide (GaAs) metallic semiconductor field effect transistor (FET) as the amplifier gain element. The field effect transistor is a voltage-controlled, unipolar device that conducts only majority carriers and has good thermal stability. In contrast, an ordinary junction transistor is a current-controlled bipolar device, in which both minority and majority carriers participate in conducting an electrical current, and can be thermally unstable. Gallium arsenide FETs can operate at higher frequencies than silicon devices, but the power output is limited by the poor thermal conductivity and lower breakdown voltage.

The maximum continuous output power of a single microwave FET can be from a few watts to several tens of watts. The limiting factor is the generation of heat. At the thermal limit the maximum power is theoretically inversely proportional to the square of the frequency. Thus in the present state of the art, a typical GaAs FET at C-band might have a maximum output power of between 30 W and 45 W, while at Ku-band it is 15 W.

Transistors are combined to form modules. For example, a C-band module containing twelve FETs might be configured with four FETs in parallel in a power-combining output stage, preceded by an intermediate stage with two FETs in parallel and six driver stages in series with one FET per stage. Each FET has a gain of about 8 dB, so that in this case there are eight stages of amplification with a total gain, including losses, of about 60 dB or a factor of 1,000,000. If each of the four FETs in the final stage had an output power of 30 W, the total output power would be 120 W. With a gain of 60 dB, the input power to the first stage would be 0.12 mW.

Higher powers are obtained by assembling modules using standard power combining techniques. The modules are connected in parallel by waveguide elements, such as hybrids or magic tees, to obtain the required total output power. However, the number of parallel modules is limited by combination losses.

SSPAs are readily available with rated powers up to about 500 W at C-band or 100 W at Ku-band.

A new solid state technology is the microwave monolithic integrated circuit (MMIC). This device combines active FETs with passive circuit elements that are deposited on a chip in a single process. The maximum power of a single MMIC is about 20 W at C-band and about 5 W at Ku-band. The total power can be increased by the combination of several MMICs in a series-parallel assembly, but is limited by combination losses which increase as the frequency increases.

Low power MMICs are sometimes used as gain stages to drive high power devices. MMICs can provide higher gain with less space and complexity than discrete low power FETs.

LINEARITY

An important characteristic of any HPA is its linearity. This property is a measure of how well the transfer characteristic of output power vs. input power follows a straight line.

In practice, HPAs are inherently nonlinear devices. Nonlinearity means that the output power is not simply proportional to the input power. Instead, as shown in the figure, the graph representing the output power as a function of input power is more nearly represented by a third order polynomial than by a straight line. Thus there is a region of approximate linearity beyond which the graph curves downward and reaches a plateau.

The output power at this plateau is called the "saturated power" (PS). The saturated power is the maximum power that can be generated. The point of inflection on the curve that is 1 dB below the linear extrapolation is called the "1 dB compression point" (P1).

The transfer characteristic for an SSPA approaches saturation within about 1 dB of the 1 dB compression point, whereas for a TWTA or KPA it bends more gradually, reaching saturation about 3 dB above this point. Therefore, an SSPA has superior linearity to that of a TWTA or KPA over the full range of operation to saturation. However, below the 1 dB compression point, the linearities are similar.

The physical effect of nonlinearity is the generation of harmonics of the fundamental carrier frequency. High frequency harmonics can be eliminated by filtering. For example, at C-band the second harmonic is at 12 GHz and the third harmonic is at 18 GHz, which are well out of band.

For single channel per carrier (SCPC) frequency division multiple access (FDMA) systems, nonlinearity causes intermodulation interference among neighboring channels. The principal source of interference is the third order intermodulation (IM3) product, which comes from the cubic term in the polynomial representation of the transfer characterstic. This contribution to the nonlinearity generates frequencies formed by mixing the second harmonic of one carrier with the fundamental of another. Thus given two carriers with frequencies *f1* and *f2*, the intermodulation products will have frequencies 2 *f2* - *f1* and 2 *f1* - *f2*, which are the same as the frequencies of adjacent channels if they are equally spaced, and cause unacceptable levels of interference. The figure of merit is the so-called two-tone "third order intercept point" (IP3), where the graph of the intermodulation power intercepts the graph of linear gain.

In this case, the HPA must have a "back off" (BO) to operate at a power (P) in a region that is sufficiently linear where the intermodulation products are within acceptable limits as specified by the maximum carrier to interference power ratio (D3). This ratio may be estimated from the third order intercept and the single carrier ouput power by the relation D3 = 2 (IP3 - P).

Intermodulation interference does not exist if only one carrier occupies the entire bandwidth of the HPA, such as a single 36 MHz analog FM video channel in a KPA or multiple wideband digital time division multiple access (TDMA) channels in a TWTA or SSPA. At any given instant the carrier occupies the full bandwidth of the HPA and there are no neighboring channels with which to interfere. In this case, an HPA can be run at full saturated power.

RATED POWER

The comparison between TWTA and SSPA output power ratings has been obscured by differences in traditional measures of output power. For a TWTA, the rated power is the saturated power, because TWTAs operate at this power for single carrier applications. On the other hand, for an SSPA the rated power is the 1 dB compression point. The "advertised" power of an SSPA is sometimes the saturated power, which is about 1 dB higher. No standards for equal comparison exist in the industry.

Another issue is the distinction between the output power of the TWT and the power at the TWTA output flange, which is about 0.5 to 0.7 dB lower. Allowance must also be made for tube aging. The power delivered to the output flange must be used in system planning. For example, a TWTA with a rated power of 400 W at saturation would actually deliver about 350 W to the antenna waveguide.

For multiple carrier operation, backoff is always referenced with respect to the rated power. A typical output backoff for a TWTA would be about 6 or 7 dB (with respect to saturation). Since every 3 dB corresponds to a factor of 2, a 6 dB backoff would deliver only one-fourth of the rated power. At the same intermodulation specification, an SSPA would require about 2 or 3 dB of backoff (with respect to 1 dB compression), delivering about half the rated power. Thus, as noted by TWTA industry representative Stephan Van Fleteren in *Satellite Online Magazine*, 6 dB of backoff in a TWTA would be roughly equivalent to 3 dB of backoff in an SSPA for the same 1 dB compression point.

For example, in SCPC FDMA applications a C-band TWTA rated at 400 W at saturation would have a practical output power of less than 100 W. On the other hand, an SSPA rated at 175 W at 1 dB compression (or 200 W at saturation) would have a similar practical output power. Therefore, in this situation, an SSPA rated at 175 W would be operationally equivalent to a TWTA rated at 400 W. They would each provide about - 25 dBc separation for two-tone, third order intermodulation performance, which is a standard figure of merit for earth station operation (where dBc refers to the level in decibels of the spurious intermodulation product relative to the carrier).

The same TWTA would have twice the useful power if combined with a linearizer. A linearizer is a network of solid state components that increases gain and phase lead as the input power increases, thus compensating for the gain reduction and phase lag as the TWT approaches saturation. The linearizer reduces the intermodulation level. The output backoff can be reduced by about 3 dB, thereby doubling the output power. Therefore, with a linearizer the traffic capacity could be doubled; alternatively, for a given capacity the required TWTA saturated power could be halved.

If only a single carrier is present, such as in digital TDMA systems, then no backoff is required at all. In this case, the 400 W TWTA without a linearizer would have four times the useful power compared to multicarrier FDMA operation.

In the presence of rain fade, the KPA and TWTA have about 3 dB more margin than an SSPA for extra power when nominally operating in the linear region. There is a tradeoff between increased intermodulation interference and rain attenuation and noise that can be exploited with automatic power control.

EFFICIENCY

The efficiency may be defined as the ratio of the useful output power and the required prime power consumption. Values may differ with different definitions of output power. It is thus best to completely specify the conditions under which the efficiency is calculated. The efficiency depends on the output power and the frequency of operation. A few examples may be illustrative.

In single carrier operation, a typical C-band TWTA rated at 75 W at saturation delivers 70 W to the output flange and has a required prime power consumption of about 350 W. The efficiency is thus 70/350 = 20 percent. A C-band TWTA rated at 400 W delivers 350 W to the flange and requires about 1300 W for an efficiency of 27 percent, and a Ku-band 500 W TWTA delivers 450 W and requires 1900 W for an efficiency of 24 percent. TWTA efficiency has steadily increased, in part due to the development of depressed collector technology and improvements in beam focusing and synchronization.

A representative C-band 100 W SSPA at saturation requires a power of 700 W with an efficiency of about 14 percent. At Ku-band, a typical 100 W SSPA has a power requirement of 1000 W for an efficiency of about 10 percent.

At Ka-band current off-the-shelf TWTA performance is 125 W with a typical efficiency of 20 percent. Current SSPA performance is less than 2 W at about 2 percent efficiency.

As another example, in multiple carrier operation a Ku-band TWTA rated at 125 W at saturation would deliver about 100 W at the output flange. With 6 dB of backoff, the useful power would be 25 W. The maximum prime power consumption would be about 650 W, but in this mode the input power would be about 500 W. The efficiency is thus 5 percent.

This unit would be operationally equivalent to an SSPA rated at 50 W at 1 dB compression, yielding 25 W of useful power with 3 dB of backoff. The prime power consumption would be approximately 550 W, so the efficiency is about 5 percent.

For the SSPA the power consumption stays the same, regardless of backoff and resulting output power. Until about 10 years ago, this was also true for TWTAs. With multistage depressed collector technology, however, the required input power drops monotonically with output power, albeit not proportionately. Thus in this example, the efficiency of the TWTA is comparable to that of the SSPA.

The efficiency of a KPA is about 40 percent, which is relatively high compared to TWTAs and SSPAs.

RELIABILITY

Reliability is an important consideration in the design of a satellite communication system.

The overall reliability of a TWTA is affected by the failure rates of both the TWT and the power supply. The life-limiting factor of a TWT is cathode depletion. When SSPAs were introduced 20 years ago, TWTs used "B" type cathodes with a relatively short design life of less than 25,000 hours. These are dispenser cathodes made from porous tungsten and filled with metallic compounds of barium, calcium, and aluminum. The operating temperature is about 1000 °C.

Today TWTs employ "M" type cathodes with a design life of over 100,000 hours. These cathodes have a surface layer of osmium, which due to the lower work function enhances electron emission and allows a lower temperature to extend life. The TWT mean time before failure (MTBF) has also improved significantly, from approximately 8,000 hours to approximately 40,000 hours.

The overall TWTA reliability must include the MTBF of the high voltage power supply. The power supplies are susceptible to arcing if they become contaminated. Advances in power supply reliability have in part been the result of a large market for high voltage power supply circuit components with attendant high production and improved quality control. Components used in TWTAs are also used extensively in the consumer product industries to manufacture power supplies for microwave ovens, copiers, and electronic equipment.

SSPAs are not subject to any known life limiting factors. They do not degrade with time, they use low voltage power supplies that are reliable and safe to operate, and they are not affected by vibration. However, SSPAs are sensitive to voltage spikes and fluctuations in temperature.

In redudant 1:1 configurations, the standby SSPA can be inhibited to save power with no penalty in switchover time if the primary SSPA fails. On the other hand, TWTAs have a long warmup time, which requires that the spare be kept in a ready-to-transmit state, consuming full power.

SSPA manufacturers state that SSPAs have a MTBF ten times better than a TWTA's. Additionally, high power SSPAs with multiple FETs in the output stage will continue to operate in the event of a FET failure, although at reduced power.

So far, no authoritative study has been performed on the failure histories of earth station high power amplifiers. The principal data come from studies performed on space-borne satellite power amplifiers. A study of 2400 amplifiers onboard over 70 commercial satellites was reported by R. Strauss in the *International Journal of Satellite Communications* in 1993. Surprisingly, it was concluded that C-band TWTAs had about 33 percent better reliability than C-band SSPAs, while the reliability of Ku-band TWTAs was about the same as that of C-band SSPAs.

The KPA is the most reliable amplifier of all. It has a proven field MTBF of approximately 100,000 hours, or eight years average life.

SUMMARY

There is increasing competition between TWTA and SSPA technologies in C-band and Ku-band. SSPAs compete effectively with TWTAs in efficiency and cost for rated powers up to around 250 W in C-band and 50 W in Ku-band. In these bands TWTAs have several competitive advantages over solid state at higher power levels.

The performance of SSPAs is optimized at lower power levels, where their characteristics include better linearity, lower cost of ownership, and improved safety because of lower voltages. Ease of maintenance is also a consideration, but replacement of the RF module cannot be done easily in the field.

As the power increases, the size and weight of the equipment must increase because of the need for heat sinks. Cooling is accomplished by either conduction or forced air systems.

At high frequencies, TWTAs dominate for high power wideband applications, especially in Ku-band and beyond. At Ka-band and V-band their advantages may become overwhelming. Present wideband amplifiers at Ka-band are all TWTAs. At this time SSPAs are not economically feasible in the DBS band or in Ka-band.

It is often stated that a lower power SSPA can replace a higher power TWTA in multiple carrier FDMA operation due to its superior linearity. However, the comparison may be misleading because of differences in definitions of rated power. In addition, if a linearizer is added, a TWTA will approach the performance of solid state but at higher cost.

When comparing backoffs, power outputs, and efficiencies, the different measures of rated power and any losses in the HPA must be taken into account. The issue of backoff becomes moot for single carrier operation, such as digital TDMA systems, where backoff is not required and the maximum saturated power can be fully utilized.

KPAs have high efficiency and are generally economical to operate. Traditionally, the klystron power amplifier has been a workhorse in the satellite communication industry. For narrowband systems with fixed frequency assignments, especially for television broadcasting, they remain an attractive alternative. The demand continues to grow and contemplated advances in design will further strengthen their role.

Dr. Robert A. Nelson, P.E., is president of Satellite Engineering Research Corporation, a satellite engineering consulting firm in Bethesda, MD, and is Technical Editor of *Via Satellite*.