JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 42, No. 2, March–April 2005

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed six manuscript pages and three figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Performance of Spread-Spectrum Communication for Satellite-Based Range Services

S. P. Kozaitis*
Florida Institute of Technology, Melbourne, Florida 32901

Nomenclature

A_L	=	vehicle inclination, rad
BW	=	bandwidth of pseudo-noise signal, Hz
E_b/N_c(rec)	=	received total energy per bit-to-noise density ratio, dB
E_b/N_c(req)	=	required total energy per bit-to-noise density ratio, dB
f	=	frequency, Hz
G_p	=	process gain, dB
H	=	altitude of satellite, m
M_L	=	link margin, dB
R	=	bandwidth of data, Hz
R_E	=	mean radius of Earth, 6371 km
R_V	=	altitude of launch vehicle from center of Earth, m
α	=	angle between vehicle axis and satellite, rad
β	=	angle between vehicle axis and its horizontal direction, rad
γ	=	angle between launch azimuth and satellite launch head line segment, rad
ε	=	angle between satellite and tangent of sphere at the vehicle altitude, rad
η	=	angle between satellite center of Earth line segment and vehicle–satellite line segment, rad
λ	=	angle between satellite center of Earth line segment and vehicle center of Earth line segment, rad
ρ	=	angle between satellite center of Earth line segment and vehicle tangent of sphere at normal at altitude of vehicle, rad

Introduction

ONE of the most crucial tasks of a communication system for launch vehicles is that of evaluating real-time tracking and telemetry data to provide command sequences for range safety.[1–3] Range safety is a collection of services that maintain the integrity of the launch system to avoid threats to human life. Many communication services with launch vehicles can tolerate outages, whereas range safety requires constant, reliable communication. Range safety communication systems receive inertial guidance and system health status data from the vehicle and transmit command data to the vehicle to invoke necessary action. For example, the flight of future vehicles may be controlled by their propulsion systems, thereby allowing for a controlled reentry. In addition, the range safety application may be expanded to include critical communication for vehicles from launch, orbit, and reentry. Therefore, ranges require a modern, reliable communication method to be useful.

The current method for providing range safety commands for U.S. ranges requires ground-based antenna systems to maintain an ultra-high frequency link with the launch vehicle. The link extent requires multiple downrange antenna systems. Associated with these systems are the operational expense, logistics, and technical complexity. New concepts for providing range safety have been investigated because of the costs associated with maintaining antenna systems, ground station horizon coverage limitations, and uhf frequency band crowding.

Space-based ranges may provide a more flexible, robust, and technologically advanced solution for range safety.[1,4–8] They offer increased reliability and global coverage, augmenting or eliminating the ground-based tracking systems currently used. In contrast to the current method for providing range safety, future communications systems are often based on digital spread-spectrum modulation. Spread spectrum is a digital modulation technique that separates signals by codes and transmits different signals in the same time and frequency space.[9] It is transmitted over a wide bandwidth, so that it provides an inherent degree of resistance to narrowband jamming and noise interference. However, little work has been done to evaluate the performance of a digital spread-spectrum communication system in a space-based range.

This Note determines the link characteristics of a digital spread-spectrum communication system between a launch vehicle and a space-based range during the launch phase. The launch phase represents one of the most critical times for communication with a launch vehicle. In contrast to a ground-based range, a vehicle at the launch head is typically farthest from a transmitter in a space-based range. This characteristic is unique to space-based ranges and is made more complicated due to the effects of rocket exhaust. There have been several studies on the effect of rocket exhaust on signal transmission.[10–19] However, most of these studies deal with analog ground-based transmission and cannot be directly applied to satellite-based spread-spectrum systems. Although we used the NASA Tracking and Data Relay Satellite System (TDRSS) as a specific example, our methodology is general and can be applied to a variety of satellites and geometries.

Our methodology includes the effect of attenuation due to rocket exhaust, the trajectory of a launch vehicle, and several parameters of the communication link such as signal-to-noise ratio (SNR), and data rate. As an example, we considered the use of the TDRSS geosynchronous satellite network for range safety services and provide results for a typical launch. In the next section, we briefly discuss spread-spectrum communication. Next, we discuss the attenuation due to rocket exhaust, followed by a discussion of the geometry involved. Finally, we use a specific launch profile to predict the performance of a communication system through the launch phase.

Received 24 January 2004; revision received 14 November 2004; accepted for publication 14 November 2004.

*Professor, Department of Electrical and Computer Engineering, 150 West University Boulevard; kozaitis@fit.edu.

Theory

Spread-Spectrum Communication

Spread-spectrum communication is currently used to provide reliable communications in a variety of commercial and military applications. It can be transmitted at low power, can be made difficult to jam by design, and can allow multiple users to occupy the same channel.[9] Signals are transmitted in the same time and frequency space and separated by codes, a process called code division multiple access. Direct sequence spread spectrum (DSSS) is probably the most widely recognized form of spread spectrum. The transmitted signal is spread over a bandwidth much wider than that required to send the actual data signal. At the receiving end, the signal is then despread by the same amount. In channels with narrowband noise or interference, increasing the transmitted signal bandwidth results in an increased probability that the received information will be correct. The process gain

$$G_p = \mathrm{BW}/R \tag{1}$$

provides increased system performance without requiring a high SNR.

The DSSS process is performed by effectively multiplying an rf carrier with a binary pseudonoise (PN) signal that is running at a much faster rate than the data. The signals generated in this manner appear noiselike in the frequency domain with a bandwidth equivalent to that of the PN signal BW. The wide bandwidth provided by the PN code may actually allow the signal power to drop below the background noise threshold without loss of information. Basically, the spread-spectrum system transmits a signal over a frequency that is much wider than the minimum bandwidth required for the signal. At the receiver, the signal, but not interference, is despread because of the unique code used.

The demodulation process correlates the incoming rf signal with the PN code used in the transmitter. Using the same PN code in the receiver as in the transmitter de-spreads the bandwidth of the received signal to that of the data stream at the input of the transmitter. The signal resulting from the same PN code is then filtered and demodulated, and the data are recovered. Signals encoded with different PN codes will generally not interfere because the codes are usually chosen to be uncorrelated.

Effect of Rocket Exhaust Plumes

Rocket exhaust has been known for some time to have a significant effect on communication to and from launch vehicles. This is primarily because rockets generate exhaust plasma clouds containing a high density of free electrons.[12,14] It has been found that the attenuation of a microwave signal by rocket exhaust plasma can be modeled as a diffraction problem, where the exhaust plasma is replaced by a diffracting object.[11,15] This model has shown to be useful, but it is only valid for relatively small angles from the vehicle axis. An improved model would allow for the effects of scattering at larger angles. Such an approach would allow the modeling of both diffraction and multipath fading.

Scattering

Modeling of rocket exhaust by a diffracting disk to determine the attenuation of a signal has been previously described.[11,15] We considered a conducting sphere to model an exhaust plume to include the effects of reflection at larger angles than those typically used with diffraction.[17] It has been shown that the scattered (diffracted) field in the forward direction of an obstacle does not depend on the detailed shape of the obstacle.[20] This phenomenon has been observed experimentally with a scale model of a rocket.[11] Therefore, the scattering by a sphere in the forward direction is a typical diffraction pattern, and our approach is consistent with previous results with respect to diffraction. The diffracted field due to rocket exhaust has been previously described.[15] In addition, a general solution describing the scattered field from a sphere at all points in space has been reported in detail.[17]

Geosynchronous Satellite Communications

Overview

We considered the use of TDRSS geosynchronous satellite system for a space-based range.[21,22] It consists of several satellites in geosynchronous orbits, a dedicated ground station, and a remote station. Two satellites form the nominal operational TDRSS service at 41° W and 174° W longitude with a ground station in New Mexico. There are at least four other satellites in the constellation that are not necessarily available for service and whose final locations are not presently known. The two available satellites provide near global coverage, excluding a small region at about 285° W longitude. A vehicle must maintain a 1200-km altitude for global coverage in this region. A third satellite operates at 285° W, with limited service with a ground station in Guam that could possibly provide global coverage.

Geometry

Figure 1 shows the geometry of the relationship between the vehicle and a satellite. The subsatellite point and vehicle are both on the surface of a sphere concentric about Earth, where the dark lines indicate arcs on the surface. Figure 2 shows the relevant relationships in the satellite–subsatellite–vehicle plane. The angle at the vehicle ε between a satellite and the tangent of the sphere can be found from[23]

$$\cos\varepsilon = \sin\eta/\sin\rho \tag{2}$$

where

$$\tan\eta = \sin\rho\sin\lambda/1 - \sin\rho\cos\lambda \tag{3}$$

$$\sin\rho = R_V/R_E + H \tag{4}$$

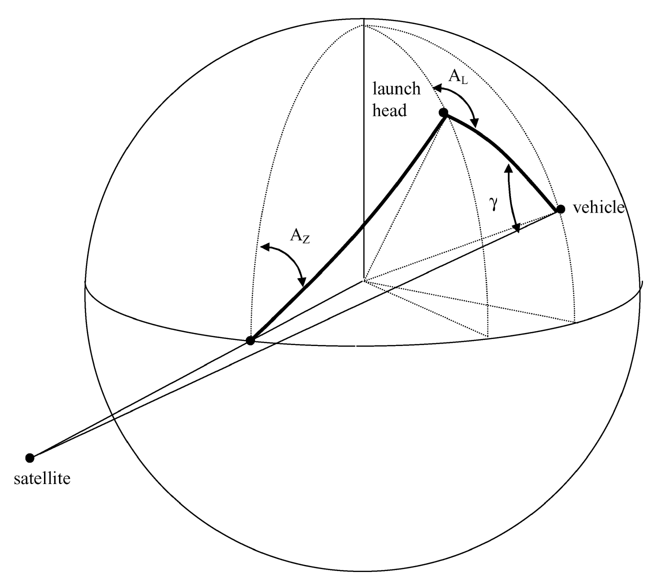

Fig. 1 Geometry of vehicle–satellite system.

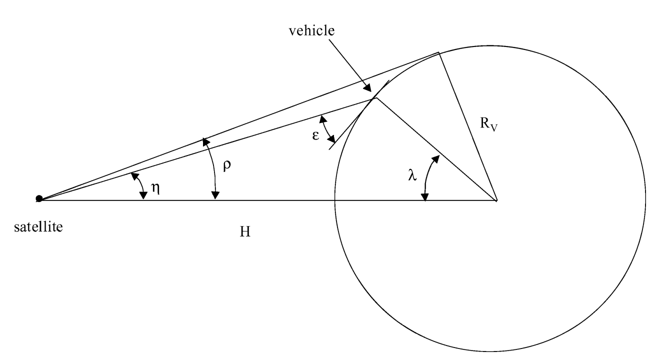

Fig. 2 Satellite–subsatellite–vehicle plane.

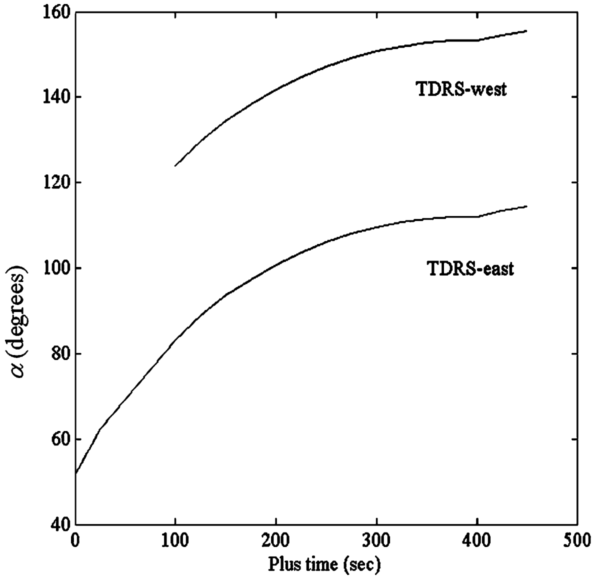

Fig. 3 Value of α as a function of time for STS-103 on a 90-deg launch azimuth.

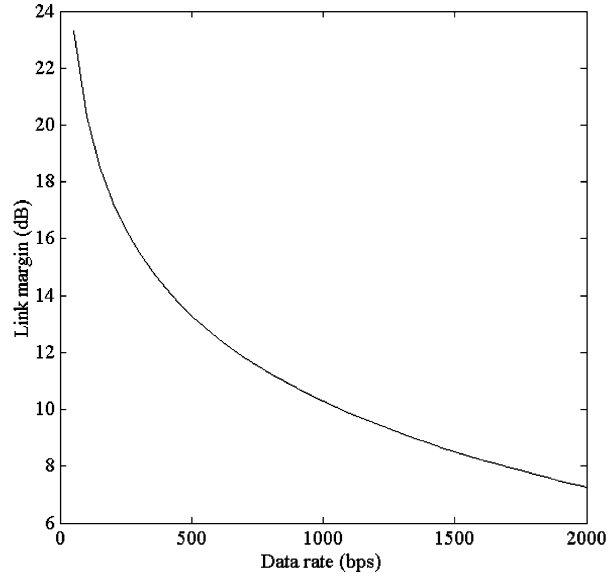

Fig. 4 Link margin as a function of data rate for E_b/N_0(req) = 5.1 dB.

For a vehicle traveling at an inclination of A_L, the angle between the launch azimuth and the satellite-launch head line segment can be written as

$$\gamma = \pi/2 + (\pi/2 - \varepsilon)\cos(A_L - \lambda) \tag{5}$$

The vehicle will be traveling along a trajectory where its vehicle axis makes an angle with the direction of inclination, depending on the vehicle's slope. Labeling the angle between the vehicle axis and the horizontal direction of the vehicle as β, we write the angle between the vehicle axis and the satellite at the vehicle axis as

$$\alpha = \gamma - \beta \tag{6}$$

As an example, we used the flight trajectory from a launch vehicle to find the value of α between the vehicle and the TDRSS satellites. We used the flight trajectory from space shuttle mission STS-103, on 20 December 1990, from NASA Kennedy Space Center, Florida, on a 90-deg launch azimuth. Using this trajectory, we calculated the values of α for both TDRSS satellites as shown in Fig. 3. Note that the TDRS-west satellite cannot support this mission at launch because the launch site is on the fringe of coverage and not usable in line of sight. However, the TDRSS support opportunities increase during the orbit insertion period. Therefore, values of α for the TDRS-west satellite are not shown when it is unavailable. The results show a similar pattern of angles increasing with time as the vehicle slopes more toward horizontal. In addition, the TDRS-west satellite has consistently larger angles than the TDRS-east satellite.

Simulation

We determined the link margin under ideal conditions as a function of data rate, then included the effect of rocket exhaust. A detailed link budget analysis of the TDRSS–vehicle (forward) link was previously performed.[1] The link margin can be written as

$$M_L = E_b/N_0(\text{rec}) + G_p - E_b/N_0(\text{req}) - \text{PL} \tag{7}$$

where each parameter in Eq. (7) is measured in decibels. We considered a carrier frequency of 2106.4 MHz that is a service available on each TDRS. The processing loss (PL) is due to various inefficiencies in the receiver and was taken to be 1.0 dB (Ref. 1). The value of E_b/N_c(rec) at 250 bps with the TDRSS operating in high-power mode was taken to be 21.4 dB, which was the value found in a previous study.[1] The required value of E_b/N_0 (req) depends on the bit-error rate (BER) that can be tolerated and the type of modulation used. We considered binary phase shift keying modulation in our study, which is commonly used and available with the TDRSS, and considered a BER $= 10^{-5}$. There are different methods to decode the data. A common practice uses convolutional encoding of data with a one-half code, Viterbi decoding with a constraint length of 7, and a 32-bit path memory, which gives E_b/N_0(req) $= 5.1$ dB (Refs. 1 and 9). Using the TDRS value for BW $= 6$ MHz in Eq. (1), and for a data rate of 250 bps, gives $G_p = 43.8$ dB. Therefore, Eq. (7) shows the static link margin to be 16.2 dB at 2106.4 MHz.

The link margin is dependent on data rate, BER, and modulation method. Using the aforementioned values, we determined the link margin from Eq. (7) as a function of bit rate as shown in Fig. 4. The results show that appreciable link margins can be achieved if the bit rate is low enough. For larger values of E_b/N_0(req), the data are shifted down by the corresponding amount and shifted up for smaller values of E_b/N_0(req).

For reliable communication, the link margin must be greater than a predetermined value for all times. To establish the link margin as a function of time, we first calculated the signal attenuation as a function of angle α. For small values of α, the attenuation will be due to multipath effects from reflection by the plume. In this case, we used an average symbol energy-to-interference ratio of one, with the phase uniformly distributed. Note that an additional 3 dB is required by the degraded channel to achieve the same performance as an unfaded channel.[24] For large values of α, the attenuation will be primarily due to diffraction. We used the same geometry as others,[25] specifically, a ratio plume center-to-receiver distance to a plume diameter of 2.8. The attenuation is a function of angle and is shown in Fig. 5 for the STS-103 mission. At small values of α, the attenuation is due to multipath effects; hence, the constant value. As the angle is increased, the source moves from the front of the vehicle to its rear, and the signal interacts more with the plume; therefore, attenuation increases. In general, the actual value of attenuation also depends on the propellant used; the large attenuation in Fig. 5 is due to the high aluminum content of the solid boosters.

The link margin may be determined as a function of time because the geometry of the launch vehicle is known as a function of time, just as the attenuation is a function of angle. Using the trajectory in Fig. 3 and an initial static link margin of 16 dB at a data rate of 250 bps from Fig. 4, we calculated the link margin as a function of time shown in Fig. 6. Because diffraction effects only occur at relatively large angles, the signal from the TDRS-east satellite was only affected by reflection and suffered a constant 3-dB attenuation. Because the TDRS-west satellite made relatively large angles with the vehicle, it suffered attenuation due to diffraction. Therefore, its link margin was attenuated more than the TDRS-east satellite. For this particular launch profile, one satellite would be able to

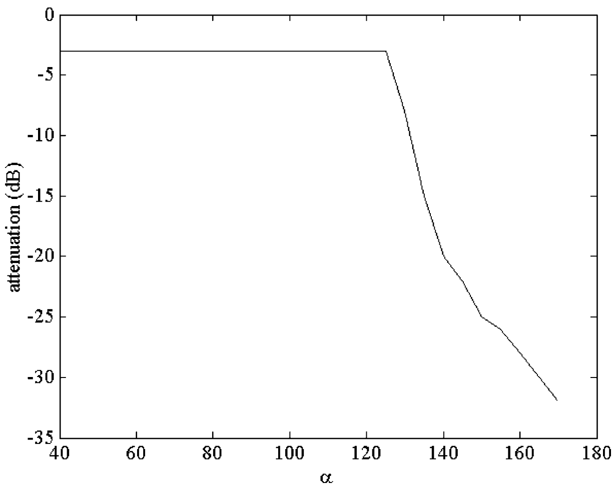

Fig. 5 Attenuation of link margin as a function of α due to rocket exhaust.

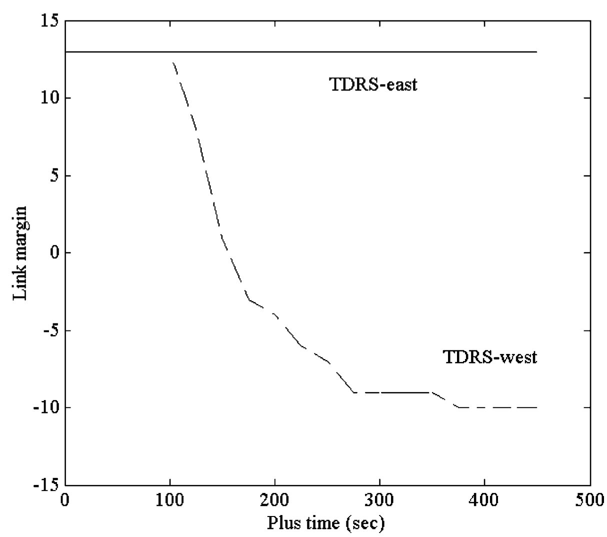

Fig. 6 Link margin as a function of time for STS-103 at 250 bps.

provide range safety services. For other launch profiles, the attenuation could be determined for a particular data rata, E_b/N_0(req), and propellant. The attenuation would determine whether range safety services could be provided or whether another satellite is needed to provide services.

The cost of implementing a space-based range can be high. The most practical solution is to consider satellites already available for service. Therefore, the launch and development of satellites can be avoided. Under this assumption, the cost of a space-based system is reduced to support services and equipment. Some ground services of space-based ranges are needed. They are, for example, data processing, weather forecasting, security, and command system tests. For ground-based systems, additional maintenance costs are needed to keep ground sites operational. The current method requires numerous ground sites to support range activities effectively. Agreements with different countries could change, causing an impact to current range operations. In addition, the range safety retention of UHF frequencies is uncertain. Another support frequency band may be needed that would significantly increase ground-based costs. Therefore, if a satellite network is considered an available asset, the cost of a space-based system is generally lower than that of a ground-based system.

Conclusions

By the use of our approach, the link margin for a particular vehicle launch profile, data rate, and signal-to-noise ratio can be determined. The features of a spread-spectrum communication link in a space-based range that contributed the most to the link margin of the received signal were the processing gain and bit rate. By adjustment of these factors, the link margin may be increased to an acceptable level. For a given satellite with a fixed processing gain, the bit rate can be lowered to increase the link margin. Given the TDRSS network and a launch azimuth of 90 deg from the east coast of the United States, a flight termination system with bit rates in the vicinity of 100–250 bps seems the most probable, with link margins in the vicinity of 13 dB. For this trajectory, we found that at least one of the two operational TDRSS satellites could provide flight termination.

Acknowledgment

The author acknowledges support from the American Society for Engineering Education/NASA Summer Faculty Research Program.

References

[1]Smith, J. A., Sobchak, T., and Walker, J., "NASA Space Network (SN) Support for Range Safety: Concept and Feasibility Study," NASA 450-RSOPSCON-SN, May 1998.

[2]Matsuoto, S., Suzuki, Y., Mugitani, T., and Kohtake, N., "H-IIA Rocket Range Safety—GPS Application," *Space Technology*, Vol. 21, No. 4, 2002, pp. 151–156.

[3]Sanchez, M., and Shome, P., "Accurate Range Safety Predictive Analysis Procedure for Launch Vehicles," *AIAA Guidance, Navigation, and Control Conference*, AIAA, Washington, DC, 1990, p. 902.

[4]Ulybyshev, Y., "Near-Polar Satellite Constellations for Continuous Global Coverage," *Journal of Spacecraft and Rockets*, Vol. 36, No. 1, 1999, pp. 92–99.

[5]Comstock, D. A., Christensen, C. B., Maryniak, G., and ten Cate, H., "Methodology for Cost–Benefit Analysis of Space Launch Infrastructure," *Journal of Spacecraft and Rockets*, Vol. 34, No. 2, 1997, pp. 246–251.

[6]Simpson, J., Denson, E., Valencia, L., and Birr, R., "Space-Based Communications," *Proceedings of the 40th Space Congress*, Canaveral Council of Technical Societies, Cape Canaveral, FL, 2003, pp. 63–71.

[7]Naus, B., Bocchino, C., Kardos, B., Lyle, J., Mason, G., Vaccaro, C., and Velez, B., "Command and Control Through Space-Based Systems," *Proceedings of the 35th Space Congress*, Canaveral Council of Technical Societies, Cape Canaveral, FL, 1997, pp. 21–29.

[8]Whelan, D. A., Filip, A., Koss, J. J., Kurien, T., and Pappas, G., "Global Space-Based Ground Surveillance: Mission Utility and Performance of Discoverer II," *IEEE Aerospace Conference Proceedings*, Vol. 5, Inst. of Electrical and Electronics Engineers, Piscataway, NJ, 2000, pp. 1–11.

[9]Rappaport, T. S., *Wireless Communications, Principles and Practice*, 2nd ed., Prentice–Hall, Upper Saddle River, NJ, 2002, p. 458.

[10]Baghdady, E. J., and Ely, O. P., "Effects of Exhaust Plasmas upon Signal Transmission to and from Rocket-Powered Vehicles," *Proceedings of the IEEE*, Vol. 54, No. 9, 1966, pp. 1134–1146.

[11]Golden, K. E., Taylor, E. C., and Vincete, F. A., "Diffraction by Rocket Exhausts," *IEEE Transactions on Antennas and Propagation*, Vol. AP-16, No. 5, 1968, pp. 614–616.

[12]Smoot, L. D., "Causes of Ionization in Rocket Exhausts," *Journal of Spacecraft and Rockets*, Vol. 12, No. 3, 1975, pp. 179–183.

[13]Bernhardt, P. A., "Changes in Electromagnetic Properties of the Upper Atmosphere Due to Rocket Effluents," *Journal of Spacecraft and Rockets*, Vol. 18, No. 3, 1975, pp. 248–253.

[14]Fredrick, R. A., Jr., Blevins, J. A., and Coleman, H. W., "Investigation of Microwave Attenuation Measurements in a Laboratory-Scale Rocket Motor Plume," *Journal of Spacecraft and Rockets*, Vol. 32, No. 5, 1985, pp. 923–925.

[15]Senol, A. J., and Romine, G. L., "Three-Dimensional Refraction/Diffraction of Electromagnetic Waves Through Rocket Exhaust Plumes," *Journal of Spacecraft and Rockets*, Vol. 23, No. 1, 1986, pp. 39–46.

[16]Lawrence, R., "Microwave Properties and Systems Overview," Rocket Motor Plume Technology, AGARD Lecture Series 188, 1993, pp. 5.1–5.33.

[17]Belov, I. F., Borovoy, V. Y., Gorelov, V. A., Kireev, A. Y., Korolev, A. S., and Stepanov, E. A., "Investigation of Remote Antenna Assembly for Radio Communication with Reentry Vehicle," *Journal of Spacecraft and Rockets*, Vol. 38, No. 2, 2001, pp. 249–256.

[18]Hwu, S. U., Loh, Y.-C., Johnson, L. A., and Panneton, R. J., "Solar Array Modeling for Space Station S-Band/Global Positioning System Communications Analysis," *Journal of Spacecraft and Rockets*, Vol. 40, No. 1, 2003, pp. 132, 133.

[19]Kim, J., and Tapley, B. D., "Simulation of Dual One-Way Ranging Measurements," *Journal of Spacecraft and Rockets*, Vol. 40, No. 3, 2003, pp. 419–425.

[20]Jackson, J. D., *Classical Electrodynamics*, Wiley, New York, 1975, p. 448.

[21]Brandel, D. L., Watson, W. A., and Weinberg, A., "NASA's Advanced Tracking and Data Relay Satellite System for the Years 2000 and Beyond," *Proceedings of the IEEE*, Vol. 78, No. 7, 1990, pp. 1141–1151.

[22]"TDRSS Training Manual," Rev. C, PCN-1, NASA JSC-ATS-TDRSS 21002, June 1999.

[23]Wertz, J. R., "Space Mission Geometry," *Space Mission Analysis and Design*, edited by W. J. Larson and J. R. Wertz, Microcosm, Torrance, CA, 1992, p. 108.

[24]Viterbi, A. J., *CDMA: Principles of Spread Spectrum Communication*, Addison Wesley, Longman, Reading, MA, 1995, p. 96.

[25]Bardina, J., and Rajkumar, T., "Intelligent Launch and Range Operations Virtual Test Bed (ILRO-VTB)," *Proceedings of the SPIE, Enabling Technologies for Simulation Science VII*, Vol. 5091, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 2003, pp. 141–148.

N. Gatsonis
Associate Editor