PrimeTime Positioning

Using Broadcast TV Signals to Fill in GPS Acquisition Gaps

Max Martone and Jon Metzler, Rosum Corp.

TELEVISION. IT FEATURES PROMINENTLY IN OUR LIVING ROOMS AND IN OUR DAILY LIVES. IT INFORMS us, educates us, and entertains us. And now, thanks to a development at Rosum Corp. in Mountain View, California, TV will also position us. Researchers have devised a way to use terrestrial TV signals, both analog and digital, to determine positions. In a similar fashion to how GPS works, a special receiver can extract timing information from received TV signals to produce pseudoranges and, with additional transmitter clock offset information from a server, can determine the horizontal coordinates of the receiver. And since TV signals are quite strong, positions can be obtained inside buildings where conventional GPS and often assisted GPS does not work. In this month's column, we examine TV positioning. Authors from Rosum Corp. describe how the technique works, both standalone and in conjunction with GPS, discuss its advantages and limitations, and how the technique might provide added security for the global position, navigation, and timing infrastructure in these uncertain times. — R.B.L.

The market for integrated positioning and navigation systems is dominated by systems using GPS receivers as their primary positioning technology. However, one major limitation of GPS is that uninterrupted satellite reception is not possible in many situations. Densely populated areas and radio-frequency-signal shadowed environments such as urban centers generally do not allow proper operation of GPS — yet it is these environments where most assets of human and material value exist.

While network-assisted GPS (A-GPS) can extend the operational range of classic autonomous GPS, in some situations its efficacy and reach are insufficient. There is a clear need for a cost-effective system that sustains performance indoors and in urban canyons. Furthermore, GPS itself is susceptible to jamming and other man-made interference. A solution that is distributed and robust to jamming is desired.

We advocate the use of broadcast TV signals as an augmentation to, or substitute for, GPS-based solutions. The core idea is to exploit the existing commercial broadcast TV infrastructure to obtain ranging information anywhere GPS solutions are not able to provide acceptable performance.

GPS generally provides global outdoor coverage, but its shortcomings in urban and indoor environments mean its effective real population coverage or "man-hour coverage" is quite low. If defined in terms of contribution to an economy, urban centers or even heavily urbanized states typically have outsized importance. Our TV-positioning technique can be enacted as a standalone approach or be used in conjunction with ranging information from GPS satellites (hybrid positioning). In this article we provide an overview of the distinctive features of the technology, future advances, and technology applications.

New Positioning Channel

The basis of the technology lies in the innovative concept of using unmodified commercial broadcast TV signals for positioning. TV signals are broadband signals with a bandwidth of 6 MHz to 8 MHz — much wider than the primary lobe of the civil GPS C/A-code, thereby permitting higher-accuracy tracking. TV signals are at lower and more-diverse frequencies and are much higher in power, making them optimal for indoor and urban reception. They were designed for the purpose of indoor reception. TV picture information is not demodulated in our system.

TV signals occupy nearly half of the spectrum between 30 MHz and 1 GHz. Our company has implemented a first-generation system that exploits Advanced Television Systems Committee (ATSC) digital and National Television System Committee (NTSC) analog TV signals and is functional across North America, parts of South America, and South Korea.

We are also in the process of developing solutions for the (coded) orthogonal frequency-division multiplexing ((C)OFDM) digital broadcast standards such as Japan's Integrated Services Digital Broadcasting – Terrestrial (ISDB-T) and Europe's Digital Video Broadcasting – Terrestrial (DVB-T) and – Handheld (mobile) devices (DVB-H) standards, as well as legacy analog standards such as Phase-Alternating Line (PAL) and Séquentiel couleur avec mémoire (SECAM), used in Europe and the Middle East.

How It Works

The system concept is depicted in **Figure 1** (page 54). The ATSC digital TV signal is an 8-ary vestigial sideband (VSB) signal at a symbol rate of approximately 10.76 MHz and a corresponding data rate of approximately 19.28 megabits per second (Mbps).

The basic synchronization feature that is exploited by the technology is the synchronization field (field sync), which is a special segment made of a pseudorandom noise (PN)-code of length 511 and three additional PN-codes of length 63. Additionally, each 828-symbol segment is preceded by a four-symbol binary pattern that acts as a segment synchronization sequence.

NTSC analog signals have several synchronization features as well, such as horizontal and vertical synchronization pulses. At present, our technology primarily exploits a waveform called the Ghost Canceling Reference (GCR).

The basic ATSC and NTSC synchronization signals provide periodic waveforms with ideal code wavelength. While the ATSC field sync repeats approximately every 24 milliseconds, the NTSC GCR waveform repeats approximately every 16 milliseconds.

Technology Trio. Our technology comprises three parts: the mobile device, such as a mobile phone, equipped with a TV tuner and a baseband TV measurement module that receives TV signals and calculates pseudoranges; a location server for calculation of position; and a regional monitor unit that measures certain clock characteristics of TV signals and sends time correction data to the location server.

A communication channel is required between the TV measurement module and location server, and between the regional monitor unit and location server. Currently, commonly available cellular standards such as the Short Message Service (SMS) and the General Packet Radio Service (GPRS) are used to send pseudoranges from the TV measurement module to the location server; other Internet Protocol (IP) channels such as Single Carrier Radio Transmission Technology (1xRTT) over code-division multiple access (CDMA) networks or tactical communications channels may easily be used.

Clock correction data is sent from the regional monitor unit to the location server over the Internet.

The regional monitor unit and TV measurement module measure the same TV signals, which are typically exploitable at a range of 50 to 100 kilometers from the transmitter depending on terrain. Regional monitor units are sited at surveyed locations and are equipped with a stable clock source (GPS), which enables accurate timing measurements and the creation of aiding information. Three regional monitor units typically are deployed in each metropolitan service area. This arrangement provides ample system redundancy and enables verification of transmitter wave-form centers. However, we have supported city-wide demonstrations based on a single deployed regional monitor.

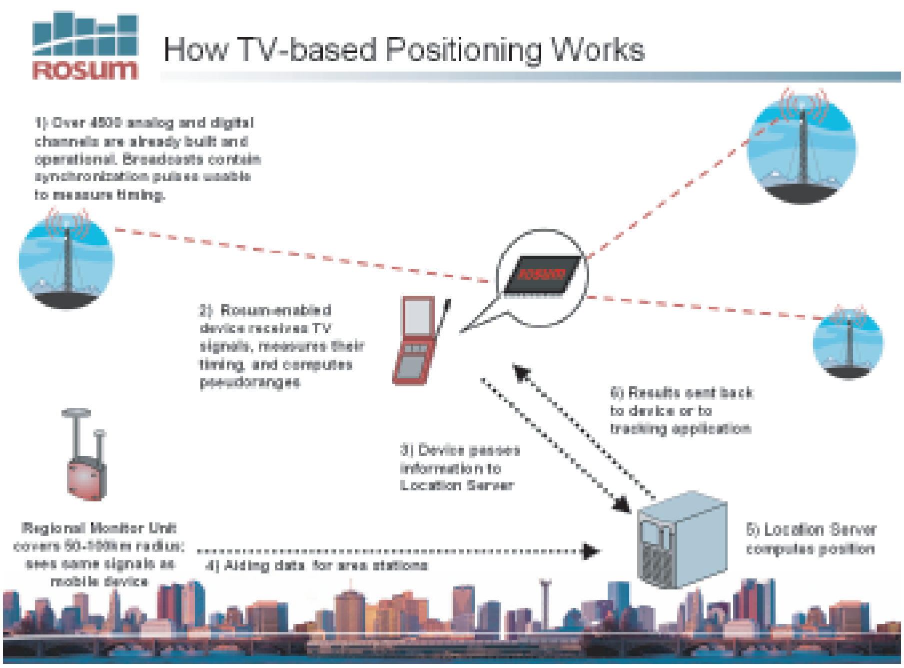
Figure 2 shows messaging flow in our system. The user devices (TV measurement modules) generate a "Dynamic Aid Request," which is satisfied by the "Server Dynamic Aid Response." The Dynamic Aid Response message contains regional monitor unit measurements for that particular geographical area. The user device replies with a "Position Fix Request" message. The "Position Fix Response" message contains timing measurements that allow the positioning algorithm in the user device to assemble pseudoranges much like a GPS receiver does.

The basic double-difference equation for TV-positioning is as follows:

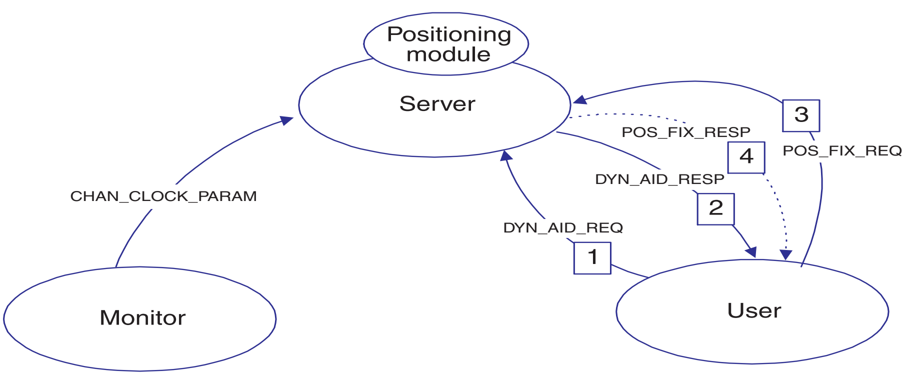
$$\delta\hat{\rho}_{i,j} = \delta R_U[i,j] + \delta b_U[i,j] - \delta B[i,j] + \delta\eta_{i,j} + \delta\eta_{P,i,j}$$

where:

- $\delta\hat{\rho}_{i,j}$ is the differenced pseudorange measurement properly computed by means of integer ambiguity removal from timing measurements performed at the user and at the monitor relative to the channel pair *i,j*,
- $\delta R_U[i,j]$ is defined as the difference between $R_{U,i}$ and $R_{U,j}$,
- $\delta b_U[i,j]$ is the channel pair user receiver clock error,
- $\delta B[i,j]$ is the channel pair TV transmitter clock error,
- $\delta\eta_{i,j}$ is the Gaussian time of arrival meas-



▲ **Figure 1** Overview of Rosum system architecture.



▲ **Figure 2** Message flow in the Rosum system.

urement error caused by thermal noise,

- $\delta\eta_{P,i,j}$ is the differenced measurement bias caused by multipath propagation.

The network of monitor stations enables an estimate of the corrections necessary to remove (or significantly reduce) the errors related to clock effects. On the other hand, proprietary signal processing techniques deal with multipath and by proper coherent integration with Gaussian noise.

Error Mitigation

This section explains two major error sources encountered in TV-based positioning: transmitter clock instability and multipath.

Transmitter Clock Instability. TV transmitters typically are equipped with clock-reference oscillators that cannot match the quality of GPS satellite clocks. The random fluctuations or deviations in oscillators can often be characterized by certain power law spectra. The various noise types that afflict a generic oscillator are white-noise phase modulation, flicker-noise phase modulation, white-noise frequency modulation, flicker-noise frequency modulation, and random-walk frequency modulation. In practice however, and within limits, much simpler models can be used than one based on all of these noise types.

A first order parameterization of the TV transmitter clock behavior defines a single parameter fractional clock rate offset (FCRO) defined as FCRO $\Delta f/f$, where Δf is the frequency offset at a particular time epoch from the clocking signal nominal frequency f.

The FCRO characterizes the real rate of repetition of the Field Synchronization Sequence for ATSC (or the GCR for NTSC) with respect to the nominal one and so it defines the most-important deterministic portion of a clock behavior over a short time interval. The regional monitor unit observes and models this behavior, and forwards it to the location server as correction data for use in position calculations.

Multipath Mitigation. Multipath-prone environments such as urban centers where GPS and A-GPS have difficulty have been our primary focus to date. Indeed, resolution of multipath in these environments is arguably one of the most significant achievements.

The selection of broadcast TV signals for use in a positioning system as a GPS complement or substitute was in large part due to their wide bandwidth and frequency diversity, which offer superior multipath mitigation attributes. This is an arena where traditional GPS methodologies do not provide much value. In harsh multipath environments, the strongest arriving signal may be reflected off a nearby structure whereas the line-of-sight signal may have passed through building materials and other assets before reaching the user. Our company has developed and patented proprietary methods for extracting the true line-of-sight signals.

Hybridization With GPS

We have developed methods to combine TV and GPS pseudoranges for hybrid positioning. The purpose of this advancement is to develop a composite system that will work in almost all situations including those where one of the two systems would not work as a standalone system.

The two signal sources are highly complementary in that TV transmitters are well-correlated with urban environments where GPS performance is weakest. Conversely, in more austere environments where there are fewer TV transmitters, GPS signals are likely plentiful. In total, there are more than 2,800 transmitters broadcasting on more than 4,500 channels, and about 1,600 digital channels, at present in the United States.

For its initial implementation, our company partnered with another to develop a TV and GPS hybrid fleet management device. The device will be available in production volumes in early 2006; we are supporting field trials for select partners.

GPS Pseudoranges. The GPS segment of the user device produces pseudoranges at the server as

$$\hat{\rho}_{GPS,i} = Ru_{GPS,i} + b_{GPS} - B_{GPS,i} + I_i + E_i$$
$$i = 1, 2, \ldots, M_{GPS}$$

where

- $\hat{\rho}_{GPS,i}$ is the pseudorange measurement obtained from the GPS receiver and properly timed with the TV segment,
- $Ru_{GPS,i}$ is the range to the ith satellite,
- b_{GPS} is the GPS receiver clock offset from GPS Time,
- $B_{i;GPS}$ is GPS transmitter clock offset from GPS Time,
- I_i is the ionospheric error,
- E_i is the tropospheric error,
- M_{GPS} is the number of visible GPS satellites.

The GPS pseudorange measurement can be obtained from a traditional autonomous GPS receiver or from an A-GPS receiver. In particular, it is important to emphasize the fact that the TV segment can resolve coarse user time independently of GPS, so the GPS integer ambiguity on A-GPS code phases can be easily and reliably resolved without resorting to known A-GPS time-transfer techniques that are susceptible to network latency.

After pseudorange correction, the simplest method to solve for position using a mix of TV and GPS ranging measurements is to collapse the two sets of observation equations into a single matrix equation, exploiting the fact that TV pseudorange differences are substantially "time-independent."

The linearized equations are

$$\begin{bmatrix} \Delta\delta\rho_{TV} \\ \Delta\rho_{GPS} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{TV} & \boldsymbol{0} \\ \boldsymbol{A}_{GPS} & \boldsymbol{1} \end{bmatrix} \Delta\boldsymbol{x}$$

where $\Delta\boldsymbol{x} = [\Delta X, \Delta Y, \Delta b_{GPS}]^T$ are perturbations in the user (X, Y) coordinates and the GPS receiver clock offset, b_{GPS}; while $\Delta\delta\rho_{TV}$ and $\Delta\rho_{GPS}$ are the corresponding TV and GPS pseudorange perturbations. The equations are solved using some specific variations of the classical maximum likelihood approach. Nonlinear channel fault isolation and detection are merged into a nonlinear procedure that manages to extract the TV/GPS measurements that can generate the best predictable error.

Going Global

Both Europe and Japan have adopted a multicarrier waveform of the OFDM type for digital TV broadcasting. But both the European standard DVB-T and the Japanese ISDB-T digital broadcast TV standards do not embed time-domain reference patterns. Even though pilot signals are embedded in the frequency domain representation of the waveforms, the time-frequency resolution of such pilots is not robust to clock variation effects caused by receiver and transmitter local oscillator instability.

Multicarrier techniques transmit data by dividing the stream into several parallel bit streams. Each of the subchannels has a much lower bit rate and is modulated onto a different carrier. OFDM is a special case of multicarrier modulation with equally spaced subcarriers and overlapping spectra. The OFDM time-domain waveforms are chosen such that mutual orthogonality is ensured in the frequency domain. Time dispersion is easily handled by such systems because the substreams are essentially free of intersymbol interference (ISI). To force the ISI-free nature of the waveform all wideband OFDM systems are circularly prefixed.

Both the European DVB and ISDB-T systems inject a "cyclic prefix" in the OFDM symbol that introduces significant signal redundant information. This is an extremely valuable feature in TV-positioning. The duration of the cyclic prefix depends on the expected severity of the multipath, but in any event can be, by specification, 1/4, 1/8, 1/16, or 1/32 of the full OFDM symbol. This means that technically a significant portion of the signal (in fact 1/32, 1/16, 1/8, or 1/4) can be used for ranging and accurate positioning without any significant implementation complexity or risk.

This observation is well understood studying the ambiguity function of a cyclically prefixed OFDM signal. The ambiguity function is a well known tool of radar theory. Basically the ambiguity function defines the capability of any arbitrary waveform to resolve in time and in frequency multipath propagation. Proper coherent integration can be achieved when the waveform is periodically transmitted. This periodic repetition can be exploited to improve the multipath rejection capability of the scheme. The correlation properties of the basic OFDM symbol improve as the integration period increases. This is a unique feature of an OFDM signal. The basic waveform is periodically injected but it randomly varies from symbol to symbol achieving an almost ideal time-frequency behavior.

There is significant integration gain to be had even if the reference waveform is noisy, but of course that gain is not as large as the gain that one would have if the cyclic prefix was perfectly known. The cyclic prefix will always be noisy, because it is extracted from the received signal. The post correlation signal-to-noise ratio increases because the matching waveform is fixed and the noise random, and due to the randomness of the reference waveform.

We have developed a technique to discriminate time delay from a multicarrier waveform to the maximum extent allowed by the bandwidth of the TV signal. An OFDM signal is completely flat in-band presenting an almost perfect spectrum utilization, while the pulse shape is relatively smooth. While the good properties of OFDM have been widely recognized in the communications community, we observe positioning applications can also take advantage of OFDM.

Intermediate processing steps common to all OFDM receivers reveal the inherent advantage of OFDM for positioning applications: an OFDM system with a large number of carriers is very close to a bandlimited Gaussian process with the net result that for ranging purposes OFDM is an almost optimal waveform Since the cyclic prefix itself changes from symbol to symbol, the novel correlation method gains a spectacularly random pseudo-random noise sequence with excellent correlation properties.

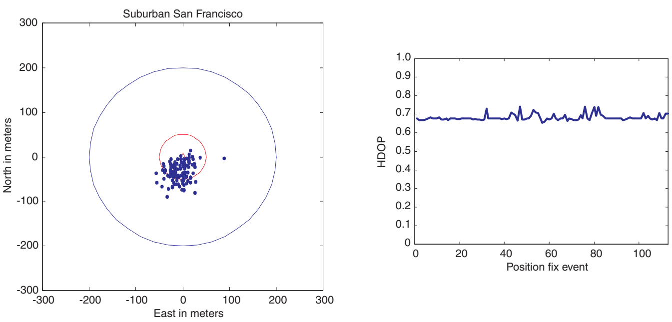
Field Test Results

We have conducted extensive field tests of standalone TV-positioning and hybrid positioning performance.

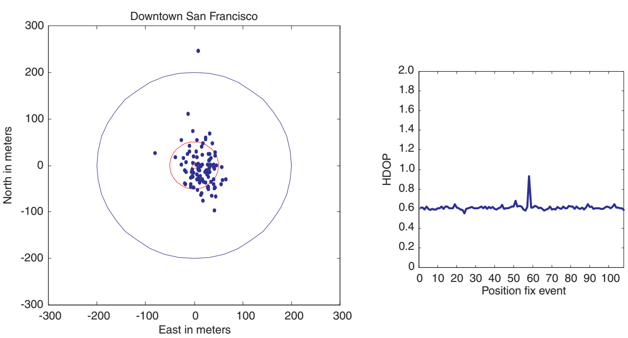
Standalone TV Positioning. Figure 3 shows test results from comparative testing with GPS-based devices conducted in the financial district of San Francisco. Devices were placed side-by-side on a café counter in an urban canyon environment. The circles in the figure with radii of 50 and 150 meters represent the accuracy specifications for the Federal Communications Commission's Wireless E9-1-1 regulations for cellular handsets: position fixes should be within 50 meters 67 percent of the time, and 150 meters 95 percent of the time. These results demonstrate the value of TV-based positioning. This specific location is known to be a challenge for all GPS receivers, both standalone and assisted.

▲ **Figure 3** Side-by-side comparison testing with GPS and A-GPS in urban canyons.

In testing conducted one floor underground, in the San Francisco Bay Area Rapid Transit (BART) subway system below Market Street in San Francisco's financial district, the median position error was 48.3 meters while the 67th and 95th percentile values were 58.2 meters and 95.4 meters, respectively. An A-GPS device generated no position fixes. The multipath nature of this particular environment creates a challenge that is overcome by the specific signal process-



▲ **Figure 4** Results of test near San Jose, California.



▲ **Figure 5** Results of test in downtown San Francisco.

ing solutions employed in our application-specific integrated chip.

We conducted a test in an open-sky environment with line-of-sight to TV transmitters, and placed the receiver in an environment without multipath, so as to show an "apples-to-apples" comparison with GPS outdoor performance. The median position error was 4.7 meters while the 67th and 95th percentile values were 4.9 meters and 13.6 meters, respectively. Performance is shown to be comparable to that of GPS. In the tests discussed, all results shown are raw, discrete position fixes using only TV signals. Fixes have not been averaged or "snapped" to roads or landmarks.

TV + GPS Hybrid. An extensive campaign of field measurements has been performed in the San Francisco Bay area for TV-based positioning that is augmented with a GPS receiver. **Figure 4** shows the positioning results from a test in a suburban area near San Jose, California, were all within about 100 meters of the true position. The horizontal dilution of precision (HDOP) was less than 0.7 for the duration of the test. The radii of the circles in the figure are 50 meters and 200 meters. The HDOP remains good during the entire positioning event, which is typical in a suburban environment

In another test in the dense urban canyon environment of downtown San Francisco (see **Figure 5**), performance was degraded by multipath. Nevertheless, almost all fixes were within 100 meters of the true position while HDOP remained around 0.6 with a brief excursion to 0.9.

The fixes for these tests were generated with an interval of approximately 10 seconds to 30 seconds depending of the latency of the communication link.

Further Advances

As shown above, the TV-positioning system architecture currently comprises three components, and uses a server-based positioning model in which the user device is essentially a timing measurement device. The presence of the regional monitor unit is required since TV station clocks are typically unsynchronized either to each other or a common time reference such as GPS.

On-device autonomous positioning is achievable in two ways. The aiding data that is currently sent to the server could be pushed to the device, either over a communications channel or over the airwaves.

The device would receive this aiding data and autonomously position itself. The second model involves synchronizing TV channels to a common reference time. We have explored this using locally deployable low-power pseudo TV transmitters synchronized to GPS Time. Autonomous device-based positioning is also possible this way.

Synchronizing all TV channels would make this possible on a metro-wide scale or even a national scale. This could be achieved by using off the shelf equipment such as a GPS-disciplined clock. We have estimated the cost of doing so with rubidium clocks at approximately $22.5 million for the about 4,500 channels in the United States. This cost compares to the estimated $400 million spent annually on GPS upkeep. Using an ovenized quartz oscillator disciplined by GPS would cost about $13.5 million.

The Defense Advanced Research Projects Agency and others have recognized that the susceptibility of GPS to jamming represents a threat to national security.

In December 2004, President Bush issued a Presidential Decision Directive recognizing GPS as critical national infrastructure as well as GPS's inherent vulnerabilities, and mandating the search for terrestrial complements to GPS. TV positioning is one such realistic option.

Conclusions

With its first-generation chipset, TV-based positioning technology in standalone and GPS hybrid settings has demonstrated advantages over existing systems by providing accuracy and availability in environments where GPS-based solutions are challenged or ineffective. ⊕

Manufacturers

Rosum's (Mountain View, California) *Rosum TV Measurement Model (RTMM)*, *Regional Monitor Unit*, and *Rosum Location Server* comprise the broadcast TV signal solution. **Trimble** (Sunnyvale, California) is a partner in the TV/GPS hybrid signal acquisition solution.

DR. MAX MARTONE is the chief architect of the TV-positioning system at Rosum Corp. in Mountain View, California. He received an M.S.E.E. at George Washington University and the Doctor in Electronic Engineering degree at the University of Rome ("La Sapienza"), Italy. He has served as a consultant for L3-Communications, BAE Systems, Cubic, DRS and other defense-related companies, with expertise is in advanced wireless communications, digital signal processing and geolocation.

JON METZLER is the director of business development at Rosum. He is a graduate of the M.B.A./M.A.–Asian Studies program at the University of California at Berkeley, and is an advisor to the UC–Berkeley Management of Technology Program.

"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by **RICHARD LANGLEY** of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments and topic suggestions. To contact him, see the "Columnists" section on page 6 of this issue.

Further Reading

For further details on Rosum's TV-positioning technology, see

"Is a Next Generation Positioning Technology Necessary?" by M. Rabinowitz and J.J. Spilker, Jr., a white paper available for download from the Rosum Web site: <http://www.rosum.com/RosumCorpWhitePaper_Is_A_Next_Generation_Positioning_Technology_Necessary.pdf>

"The Rosum Television Positioning Technology" by M. Rabinowitz and J.J. Spilker, Jr., in *Proceedings of the 59th Annual Meeting of The Institute of Navigation*, Albuquerque, New Mexico, June 23–25, 2003, pp. 528-541.

"A New Positioning System Using Television Synchronization Signals" by M. Rabinowitz and J.J. Spilker, Jr., in *IEEE Transactions on Broadcasting*, Vol. 51, No. 1, March 2005, pp. 51–61.

For a discussion on extracting timing information from OFDM signals, see

"ML Estimation of Time and Frequency Offset in OFDM Signals" by J.J. van de Beek, M. Sandell, and P.O. Börjesson in *IEEE Transactions on Signal Processing*, Vol. 45, No. 7, July 1997, pp. 1800–1805.

For details on GPS signal acquisition, processing, and error analysis, see

Global Positioning System: Theory and Applications, Vol. I, edited by B.W. Parkinson and J.J. Spilker, Jr., published by the American Institute of Aeronautics and Astronautics, Inc., Washington, D.C., 1996.

For details of the new U.S. policy on GPS and related technologies, see

"U.S. Space-based Positioning, Navigation, and Timing Policy," a fact sheet issued by the Whitehouse Office of Science and Technology, December 15, 2004. An on-line version is available: <http://www.ostp.gov/html/FactSheetSPACE-BASEDPOSITIONINGNAVIGATIONTIMING.pdf>