Reopening the Electromagnetic Spectrum with Ultrawideband Radio for Aerospace

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Abstract — After 100 years of analog radio, it is time to look at the radio spectrum in a completely different way. Discrete, low-power pulses spread over many gigahertz allow us to manage spectrum by time, instead of frequency. Time Modulated Ultra-Wideband (TM-UWB) radio technology, implemented in Time Domain's PulsON™ chip, offers far-reaching impact for new tool sets for the aerospace industry. PulsON™ technology is based upon the precise correlation of discrete pulses transmitted across a 2 gigahertz or larger spectrum and processed in the time domain. This ultra-low power digital data stream can be used for voice, data, and video communications and new applications in geopositioning and precision radar surveillance. TM-UWB features ultra-low power, immunity to multipath (Rayleigh fading), spectrum sharing, virtual undetectability, and capacity for very high bandwidth and channelization.

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1. INTRODUCTION

Significant research on a new wireless medium, called Time Modulated Ultra-Wideband (TM-UWB) has now been reduced to practice, and results indicate a far-reaching impact for the aerospace industry. TM-UWB is based upon the precise correlation of discrete pulses transmitted across a 2+Gigahertz (GHz) spectrum and processed in the time domain. The result is an ultra-low power digital data stream that can be used for voice, data, and video communications as well as local positioning and precision radar.

The first century of radio technology was wedded to the sine wave. In turn, this restricted users to specific frequencies or bands centered on frequencies. This was a natural limitation of the electronics technologies that were available at the time. In 1976, the author started studying the possibility of using the radio spectrum in the time domain rather than the frequency domain. Time domain management employs a series of single waves or cyclets — in essence, clicks — at precise intervals rather than a continuing sine wave that is modulated. The position of the cyclet relative to the end of a preset interval determines the signal; a 0 if it arrives before the interval or a 1 if it arrives after. The timing of the intervals, and of the subintervals that offset the 0 and 1, can be varied to allow an almost infinite number of unique transmitters. This becomes possible only with the development of exceptionally fast, precise on-chip clocks.

Figure 1. Schematic depiction of continuous sine waves (left) and coded cyclets (right).

Time Domain Corporation has patented a range of TM-UWB technologies under the trade name PulsON™, a single word that goes to the heart of Time Domain's applications. PulsON™ technology enables hundreds of revolutionary products and opens up entirely new markets. The PulsON™ chip set is a wireless engine capable of enabling applications in communications, positioning and radar. Time Domain's first application-specific integrated circuits (ASICs) were fabricated a new silicon-germanium system utilizing state of the art technology for precisely slicing time to accurately position each coded pulse.

This new technique, which does not rely on traditional radio waves, offers solutions to some of the common drawbacks of current wireless systems, namely, ultra-low power, immunity to multipath (Rayleigh Fading), spectrum sharing, virtual undetectability, and capacity for very high bandwidth and channelization.

Billions of dollars are spent researching techniques to pass

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more data over limited RF bandwidth. The Internet has intensified consumer demand for high data rate links to the home and office. The FCC continues to sell or auction spectrum at huge costs to the providers, which are then passed on to the consumers. The spectrum is crowded and technologists are searching for ways to pack more information and channels into existing constrained spectrum. PulsON™ technology reopens the spectrum because its RF bandwidth is 1,000 times larger than any known commercial radio. PulsON™ technology requires no assigned spectrum because the transmissions are sent across an ultra-wideband at ultra-low power, too low to be distinguishable by other users of the spectrum or to interfere with others. Effectively, anyone picking up the transmissions will perceive them as white noise.

Traditional radio and radars transmit continuous sine waves which reflect off of objects, often canceling the very signals that were sent. This makes communications inside buildings particularly erratic and difficult. Because TM-UWB pulses are not continuous, its transmissions do not suffer from this cancellation effect. In fact, reflected signals can be added to increase the quality and robustness of the transmission. Further, TM-UWB offers transmission speeds that are orders of magnitude greater than technologies now being developed under the IEEE 802.11 standard as used in the ISM band (industrial, scientific, and medical applications).

Communications applications include aircraft-to-aircraft links for secure communications, real-time video links, and two-way data transmission, allowing ad-hoc networks in the sky. The members of the network can then share critical intelligence, whether it be flying conditions, terrain, aircraft performance, enemy information, etc. The free spectrum capabilities and high channelization expand the possibilities of communications available to pilots, flight crew, and ground operations.

The combination of almost limitless codes and ultra-low power also enable on-board wireless systems, reducing the wire count and allowing flexible re-instrumentation. The time-modulated pulses, which produce the data streams, are correlated in time, not frequency, making the receiver immune to the traditional multiple reflection problems that have prevented successful on-board wireless systems to date. Military operations and cell phone companies are often challenged by a lack of privacy and by electronic signatures that can be identified and tapped by others. PulsON™ radios pseudo-randomly transmit 10 million or more low-power monocycle pulses per second. Such transmissions are virtually indistinguishable from noise, making communications essentially undetectable.

To accomplish this process requires very low jitter electronics. In practice, it requires an overall jitter of less than 15 picoseconds and stable time bases on the order of several parts per million accuracy.

In addition to overcoming current wireless limitations, TM-UWB enables many new applications for wireless connectivity and diagnostic equipment in aerospace systems, not only in communication but also in geopositioning and precision radar surveillance.

Recent developments in chip fabrication have allowed the technology to be successfully reduced to a set of ASICs using the silicon germanium process pioneered by IBM. The chip sets have been incorporated into working prototypes for propagation and application testing and for various commercial uses. In June 1999, the Federal Communications Commission (FCC) approved a waiver of the Part 15 rules to allow the technology to be used in certain lifesaving applications. It is now believed by many that TM-UWB will likely become the next standard for wireless connectivity.

The progress of this technology is important to the aerospace industry, especially those involved in future designs. This paper will describe the status of this breakthrough technology and the enabling opportunities for its use in the aerospace and defense industry.

2. Principles

Time Domain's impulse radios have:

- Ultrashort duration pulses which yield ultrawide bandwidth signals,
- Extremely low power spectral densities,
- Center frequencies typically between 650 MHz and 5 GHz,
- Multi-mile ranges with sub-milliwatt average power levels (even with low gain antennas), and
- Excellent immunity to interference from other radio systems.

Time Domain has built several prototypes, the most recent being a full duplex 1.3 GHz system with an average output power of 250 microwatts and a variable data rate of either 39 kbps or 156.25 kbps. This radio has been tested to 1 km with omnidirectional antennas and to beyond 16 km with directional antennas.

Other prototypes have operated at data rates up to 5 Mbps and down to a few bits per second. One prototype was demonstrated to the U.S. Department of Defense and other governmental agencies, who determined that the signal could not be detected at ranges under 30 meters even when the transmission was being received 10 km away.

TM-UWB radios can qualify for type acceptance in the U.S. under the rules of Part 15 for unlicensed applications and can share spectrum without affecting conventional radio transmissions.

Widespread deployment of this technology is not currently permitted by the U.S. Federal Communications Commission

(FCC). However, the FCC is evaluating it and preparing to initiate a rulemaking on UWB technology. Time Domain operates under a waiver of existing rules for certain products using this technology.

Additionally, TM-UWB radios:

- Have exceptional multipath immunity,
- Are relatively simple and less costly than spread spectrum radios,
- Are expected to consume substantially less power than existing conventional radios, and
- Could be implemented as a two integrated circuit chip set with very few off-chip parts, when fabricated using advanced integrated circuit technologies.

Because of these characteristics Time Domain's technology is the optimal technology for a wide variety of aerospace applications, as we will expand in Part 3.

Technology Basics

Time Domain's TM-UWB transmitters emit ultrashort "Gaussian" monocycle pulses with a tightly controlled pulse-to-pulse interval. Time Domain has been working with pulse widths of between 1.50 and 0.20 nanoseconds (ns, billionths of a second) and pulse-to-pulse intervals of between 100 and 1,000 ns. These short monocycle pulses are inherently wideband. The system uses pulse position modulation. The pulse-to-pulse interval is varied on a pulse-by-pulse basis in accordance with two components: an information signal and a channel code. The impulse receiver directly converts the received radio frequency (RF) signal into a baseband digital or analog output signal. A front-end cross correlator coherently converts the electromagnetic pulse train to a baseband signal in one stage. There is no intermediate frequency stage, which greatly reduces complexity.

Gaussian Monocycle

The most basic element of Time Domain's TM-UWB radio technology is the practical implementation of a Gaussian monocycle. (Actual practice prevents the transmission of a perfect Gaussian monocycle. In the frequency domain, this results in a slight reduction in the signal's bandwidth.)

The monocycle is naturally a wide bandwidth signal, with the center frequency and the bandwidth completely dependent upon the pulse's width. In the time domain, the Gaussian monocycle is described mathematically by the first derivative of the Gaussian function (equation 1).

There is a direct relationship between the pulse's center frequency and its duration. The half power bandwidth is 116% of the center frequency and the pulse width specifies both the center frequency and bandwidth. In practice, the center frequency of a pulse is approximately the reciprocal of the pulse's length and the bandwidth is approximately equal to the center frequency. Thus, for a 0.5 ns pulse, the center frequency and the half power bandwidth are approximately 2 GHz.

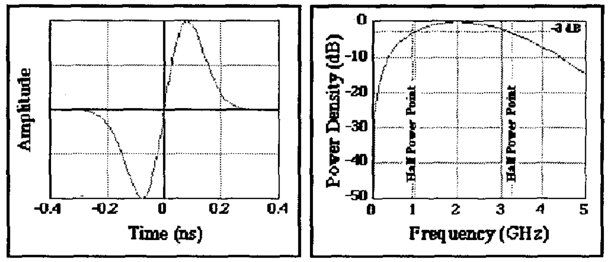

Figure 2. 2 GHz center frequency Gaussian monocycle in time and frequency domain.

A Pulse Train

Other TM-UWB systems use long sequences of pulses for communications, where Time Domain uses single pulses. Time Domain's prototypes have pulse repetition frequencies of between 1 and 10 million pulses per second (Mpps). In the frequency domain, this highly regular Gaussian pulse train produces energy spikes ("comb lines") at regular intervals; thus, the already low power is spread among the comb-lines. This pulse train carries no information and, because of the regularity of the energy spikes, might interfere with conventional radio systems at very short ranges. Impulse systems have very low duty cycles. In actual implementation the ac-

(a)
$$V(t, f_c, A) = 2\sqrt{e}\, A\, \pi\, t f_c e^{-2(\pi t f_c)^2}$$

(b)
$$V(f, f_c, A) = \frac{1}{2}\sqrt{\frac{2e}{\pi}}\,\frac{A}{f_c^2}\, e^{\frac{-1}{2}\left[\frac{f}{f_c}\right]^2}$$

(c)
$$\tau = 1/\pi f_c$$

A Peak amplitude of pulse

f_c Center frequency

t Time

τ Time between maximum and minimum amplitudes

Equations 1-3. Gaussian monocycle defined in the (a) time domain and (b) frequency domain; (c) relationship between pulse center frequency and duration.

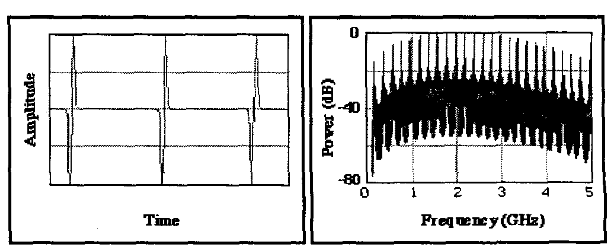

Figure 3. A pulse train in the time and frequency domains.

tual duty cycle is less than 1 percent (*i.e.*, the system is only transmitting less than 1 percent of the time).

Modulation

Additional processing is needed to modulate the pulse train, so the system can actually communicate information. Time Domain's systems use pulse position modulation as it allows the use of an optimal receiving matched filter technique. Time Domain's receivers use a cross correlator which gives the receiver the ability to find the signal well below the ambient noise level. The low duty cycle reduces the effects of nearby transmitters by 23 dB. Pulse integration provides additional code-division multiple access (CDMA) gain. The latter can be another 20 dB or greater in a voice communications system.

Pulse position modulation varies the precise timing of transmission of a pulse about the nominal position. For example, in a 10 Mpps system, pulses would be transmitted nominally

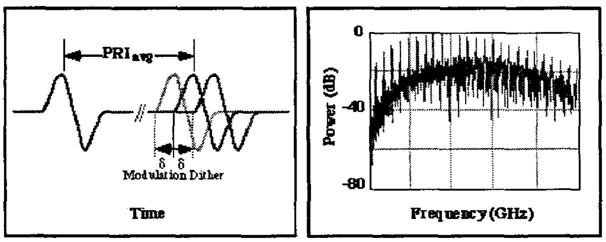

Figure 4. Pulse position modulation.

only once in each 100 ns window. In such a system a "0" digital bit might be represented by transmitting the pulse 100 picoseconds (ps) early and a "1" digital bit by transmitting the pulse 100 ps late. Pulse position modulation distributes the radio frequency energy more uniformly across the band (it smooths the spectrum of the signal), thus making the system less detectable. However, because information modulation only moves the pulses only a fractional part of a pulse width, this spectral smoothing impact is small.

Pseudorandom Noise Coding — Coding for Channelization

At this point any modulated pulse train looks like any other pulse train; it is not channelized. However, by shifting each pulse's actual transmission time over a large time frame in accordance with a code, one can channelize a pulse train. Time Domain applies a relatively large time offset (many nanoseconds) to each impulse. Time Domain uses "pseudorandom

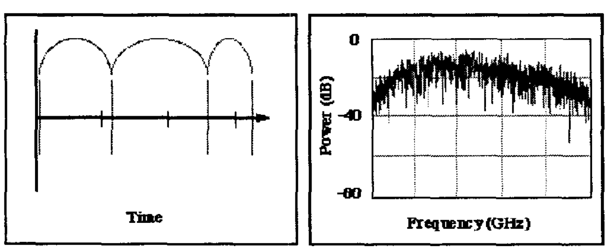

Figure 5. Pseudo-random noise coding.

noise" codes (PN codes) for this purpose. For multiple access, each user would have their own pseudorandom noise code sequence. Only a receiver operating with the same pseudorandom noise code sequence can decode the transmission.

In the frequency domain, this PN code makes Time Domain's signal appear like noise. As a result, anyone attempting to detect the presence of the signal would have to be very close to the transmitter and even then would have great difficulty decoding the transmission, thus providing secure communications. Adding encryption would provide additional security.

Besides channelization and energy smoothing, the pseudorandom noise coding also makes impulse radio highly resistant to interference from all radio communications systems, including other impulse radio transmitters. This is critical as all other signals within the band occupied by an impulse signal act as interference to the impulse radio. Since there are no unallocated 2+ GHz bands available for impulse systems, they must share spectrum with conventional systems without being adversely affected. The pseudorandom noise code helps impulse systems discriminate between the intended impulse transmission and transmissions from others.

Interference Resistance and Process Gain

Process gain is a measure of the radio's resistance to interference. TM-UWB radio has a huge processing gain. One definition of processing gain is the ratio of the bandwidth of the signal to the bandwidth of the information signal. For example, a conventional CDMA's spread spectrum system with a 8 kHz information bandwidth and a 1.25 MHz channel bandwidth yields a processing gain of 156 (22 dB). An impulse system transmitting the same 8 kHz information bandwidth and a 2 GHz channel bandwidth yields a processing gain of 250,000 or 54 dB.

Alternatively, the process gain for an impulse signal may be calculated from:

- The duty cycle of the transmission, e.g., a 1% duty cycle yields a process gain of 20 dB, an actual coding gain.
- The effect of integrating over multiple pulses to recover the information, e.g., integrating energy over 100 pulses to determine one digital bit yields a process gain of 20 dB.
- The total process gain is then 40 dB.

Thus, a 2 GHz / 10 Mpps link transmitting 8 kbps would have a process gain of 54 dB, because it has a 0.5 ns pulse width with a 100 ns pulse repetition interval = 0.5 percent duty cycle (23 dB) and 10 Mpps / 8,000 bps = 1250 pulses per bit (another 31 dB).

System Capacity

A theoretical analysis, by Professor R.A. Scholtz of the University of Southern California suggests that Time Domain's TM-UWB radio system could have thousands of voice channels per cell without special signal processing algorithms. Others have analyzed the system, and using more realistic assumptions, estimate the capacity to be between 200 and 1,000 simultaneous telephone conversations per base station, depending upon numerous environmental factors and also without special signal processing algorithms. Using a cellular architecture and standard radio engineering practices, Time Domain can achieve very high densities of simultaneous users.

Performance in the Real World

An early prototype built by Time Domain has an average radiated power of 450 microwatts. The center frequency is 675 MHz and smoothed by a pseudorandom code with 256 positions. The power spike just below 900 MHz is from two cellular base stations, one at about 400 meters distance, another about 1.6 km distance. The spikes between 360 MHz and 720 MHz are predominantly UHF television stations. The 720 MHz spike is a 2.2 megawatt EIRP channel 54 station approximately 11 km distant. Tests show that this technology causes only one-quarter the interference of laptop computers or other comparable electronic devices. Time Domain's non-military products are designed to meet Part 15B emission levels, the same as for most consumer electronics. (The "bumpiness" of the impulse spectral measurements reflects the impact of frequency domain multipath. Moving the receive antenna causes the location of nulls and peaks to move. This does not impact the performance of the impulse system. See "Multipath and Propagation" below.)

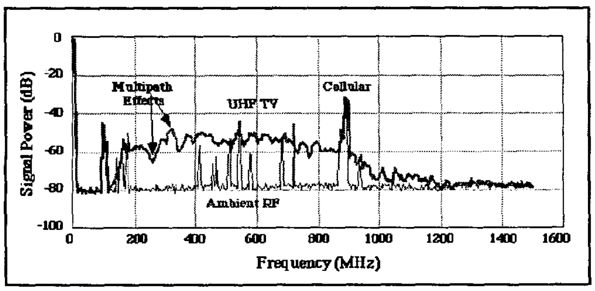

Figure 6. 675 MHz impulse signals at 3 meters (not adjusted to compensate for antenna performance.)

Time Domain also built a 1.3 GHz/2 Mpps prototype with an average output power of 33 μW. Peak power is approximately 200 times greater than average power. It is not the driver for local interference, and average power is the driver in the larger scenarios. The prototype's performance has been measured over two paths:

- With a 9.6 dBi transmit antenna buried in a highly conductive medium which had a total loss of 36 dB over a 6 cm path, Time Domain transmitted a 125 kbps pseudorandom bit stream an additional 4 meters through air to a 10 dBi receive antenna. The bit error rate was better than 0.5 x 10^{-5}. The demonstration took place in an office building.
- With the same experimental apparatus and the same location, the bit rate was lowered to 7.8 kbps and range was increased to 10 meters. The bit error rate was better than 10^{-6}.

In 1996, Time Domain engineers constructed a full duplex 1.3 GHz system operating at 5 Mpps. The system transmits at either 39 kbps or 156.25 kbps. The system has been tested successfully on long-range digital links exceeding 16 km and within buildings. Time Domain has also demonstrated an ultra-wideband video link.

The current state-of-the-art system, developed in 1997, is a 2 GHz, 10 megapulse/second system using 0.5 ns cycles, which positions the center frequency at 2 GHz. It has been successfully tested on a 10 km range. It will serve as the basis for a wide range of applications now being investigated and developed by Time Domain.

Multipath and Propagation

Multipath fading, the bane of sinusoidal systems, is less of a problem for TM-UWB systems than for conventional radio systems. Rayleigh fading, so noticeable in cellular communications, is a continuous wave phenomenon and not an impulse communications phenomenon. In order for multipath effects to occur in an impulse system, special conditions must persist. Either:

- The path length traveled by the multipath pulse must be less than the pulse width times the speed of light. For a 2 GHz pulse, that equals 0.15 meters or about 1/2 foot, i.e., [1/2 ns] x [300,000,000 meters/second]; or
- The multipath pulse travels a distance that equals the interval of time between pulses times the speed of light might interfere times an integral number with the next pulse. (For a 1 Mpps system that would be equal to traveling an extra 300, 600, 900, etc. meters.) However, because each individual pulse is subject to the pseudorandom dither, these pulses are decorrelated.

Pulses traveling between these intervals do not cause self-interference. Pulses traveling grazing paths create impulse radio multipath effects. Measurements were made in a single story office complex. The laboratory contained many feet of steel shelving, test equipment, and metal filing cabinets. One adjacent office space was occupied by a metal fabricating

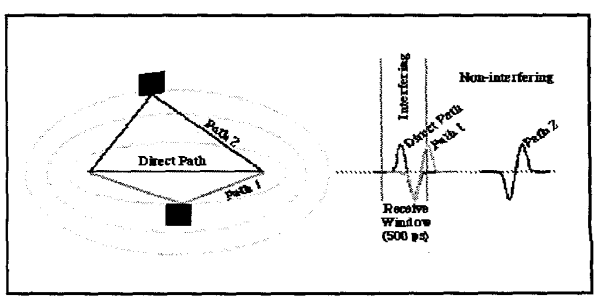

Figure 7. Multipath in an impulse system.

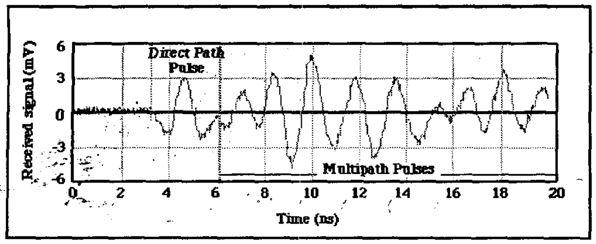

Figure 8. Time Domain measurement of 675 MHz impulse signal at 12 meters.

company. The other was occupied by a personal computer sales office along with that company's warehouse (using steel shelving). (Note: The receive antenna's characteristics convert the Gaussian monocycle into a "W" waveform.)

Key Components in Constructing a Time Domain System
Time Domain Corporation has expended significant resources to develop its impulse communications systems and determined that while all components must be very carefully designed, certain components determine the ultimate feasibility of producing impulse communication systems in mass quantities.

Time Base. Because this system uses picosecond deviations of the pulse position, an accurate clock is an absolutely necessity. Just a few years ago sufficiently accurate clocks were too expensive for consumer products. This is no longer true as technology has improved and new consumer products demand high performance clocks, *e.g.*, cellular telephones and consumer GPS receivers.

Acquisition and synchronization. Acquisition is accomplished by a sliding correlation of the incoming waveform. When correlation is detected, then the correlation locked loop takes over and locks the time base to the incoming waveform.

It is important to note that since the first units tested on a lab bench in the 1985 through the latest field tests, the transmitter and receiver have never been physically connected. Synchronization is achieved through low-jitter, fine-time resolution electronics.

Antenna. Most antennas are designed to operate over very narrow bandwidths. Time Domain Corporation has a small, effective broadband antenna. The dimensions for a 1.9 GHz center frequency Time Domain-patented antenna system would be about 5 x 7 x 0.7 cm.

PN codes. Codes must be orthogonal with respect to other codes as well as to themselves, i.e., there must be neither cross- nor auto-correlation. Additionally, the codes must smooth the energy distribution effectively and allow fast signal locking. There has been extensive research in the area of coding, which shows a large numbers of codes have the qualities required by Time Domain's TM-UWB system.

Simplicity
Time Domain's TM-UWB radios are much simpler to build than equivalently sophisticated conventional (narrowband) radios. The transmitter is a single transistor that operates in a digital mode — it flips from a "0" state to a "1" state. This transition produces a step waveform that can be easily filtered to produce a monocycle. Unlike conventional transmitters, it does not contain a linear power amplifier. This reduces cost and power consumption. The receiver is also simpler as it does not require IF stages. Unlike spread-spectrum receivers, the control loop operates at very low frequencies, which also saves cost and reduces power consumption.

Preliminary studies suggest the impulse transmitter and receiver front end can be built on a single chip. In addition to this chip a complete TM-UWB radio would include a time base and a microcontroller. Time Domain Corporation sees no impediments to producing an TM-UWB radio cordless telephone system for a retail price under $200.

3. Applications

TM-UWB technologies will find ready applications in a number of military, aviation, and space fields. The technology is so versatile that it enables many applications, most of which —like the laser in the early 1960s—cannot be perceived today. This list is by no means exhaustive since human innovation is endless (could the inventors of Great Britain's Home Chain early-warning radar during the Battle of Britain have foreseen radar's eventual use by baseball players?). Most of these applications derive from three major capabilities of TM-UWB:

- Precise positioning, including geopositioning,
- Secure communications, and
- Detailed imaging.

Dual-Use
Many TM-UWB applications can be considered as dual-use because they apply both to civil aviation (and other civilian areas) and the military.

Geopositioning. Current civilian systems using the Navstar-based Global Positioning System (GPS) receivers can locate objects to within 100 meters horizontal and 300 meters vertical (Standard Positioning Service, according to the U.S. Coast Guard). Reception can be fogged by signal multipathing in situations such as "urban canyons" or improved to within 1.5 meter or better by Differential GPS. The tiny, precise pulses used in the PulsON™ system can calculate the distances between reference points with a resolution of ±1 cm or better. Precision positioning capabilities in the sub-centimeter resolution will allow an aircraft to monitor its position relative to the position of other aircraft and the ground, providing safety and redundancy over current systems. TM-UWB would augment, rather than replace, GPS by providing precise relative positioning within the context of the geographic reference frame established by GPS. Real-time data from positioning sensors, radar, and GPS will allow an instrument landing even under inclement weather.

Security Access. The combination of positioning and intrusion alarming allows configurable systems for controlled access of humans to aircraft or certain locations in airports, such as baggage handling areas and food service trucks. The network would comprise PulsON™ transponders on moveable assets, and an array of fixed PulsON™ transponders. The location of each moveable unit would be determined by triangulating their positions within the mesh of fixed transponders. PulsON™ units could also be used as ground radar to ensure that untagged vehicles were located and monitored. In such a manner, large site intrusion and imaging security systems become possible.

Smart aerospace structures. Because aerospace structures are flexed throughout their lives, fatigue prediction becomes a major life assurance issue. A classic example is the long arc described by the wing tips of the B-52 Super Stratofortress during normal flight operations. At present, the extent and amount of flexing can only be estimated for a structure. TM-UWB transponders embedded within key points of structures could provide constant, real-time measurements without the need for wiring the entire structure with strain gauges or other instruments. A handful of master units located at well-defined points could measure the distance to each other and then to slave units located across the aircraft. This is enabled by the precise ranging capabilities of PulsON™ units. From this a living history of wing and fuselage flexure could be derived. This would help in predicting fatigue and failure (*e.g.*, is the wing flexing a little more than it used to, and under lighter loads?). Application of this technique during development could allow designers to improve designs to reduce loads and fatigue.

Computational fluid dynamics. Radio wavelengths that are refracted by air could be used to make tomographs of airflow over structures, either in the wind tunnel (predictive analyses) or in flight (refining analytical tools). Transceivers inside rocket engines also could provide visualization of fluid flow in combustion chambers. If the gas is radio transparent, it can be seeded with very small quantities of reflective ions that would act as fluid tracers (akin to iodine tracers in medical applications).

Military
Much of the history of warfare focuses on battles won by the side that was more certain of the enemy's location and strength, or could communicate between field units and commanders. TM-UWB offers tremendous potential to make the battlefield more dangerous for the other side. Two aspects were presaged in the science fiction thriller, *Aliens*, when Space Marines were equipped with helmet-mounted TV cameras that relayed field images back to a command post, and with handheld motion sensors that tracked the approach of alien predators. We aren't there yet, but Time Domain Corporation is developing the enabling technologies that could make this a reality in a few years.

Figure 9. U.S. Marine guards "civilians" during an urban warfare exercise on Mayberry Drive.

Urban Warfare. The U.S. Department of Defense anticipates the wars of the future increasingly will take the shape of small, intense conflicts with military personnel intermingled with civilian personnel within cities. DoD is investing in tactics and tools specifically for this field and to avoid the massive losses of life and assets such as Europe saw in World War II and even today in small ethnic conflicts. The soldier of the


Figure 10. U.S. Marines field testing Time Domain radio.

future will be increasingly dependent on advanced electronics system to keep himself and his team alive as they face new threats in the battlefield. In particular, soldiers will be equipped with laptop and palmtop computers and video systems that display data provided by unmanned aerial vehicles, command post databases, and comrades who are just around the corner. Such systems will be useless without secure communications that cannot be jammed.

First and foremost, TM-UWB's secure communications capabilities can provide a portable, flexible local area or wide-area network that moves with the battlefield. These easily set up wireless links for data and video transmission can give greater mobility to platoons and Tactical Operations Centers (TOCs). High bandwidth wireless links allow real-time video transmission and remote control instrumentation from unmanned aerial vehicles (UAVs) such as micro-aircraft for covert surveillance.

By virtue of its secure links and positive identification of authorized users, TM-UWB can also help mitigate the most tragic of battlefield events, injury or death by friendly fire. Soldier radios for squad-level operations that allow communications without traditional identification methods are being evaluated by the U.S. Marine Corps.

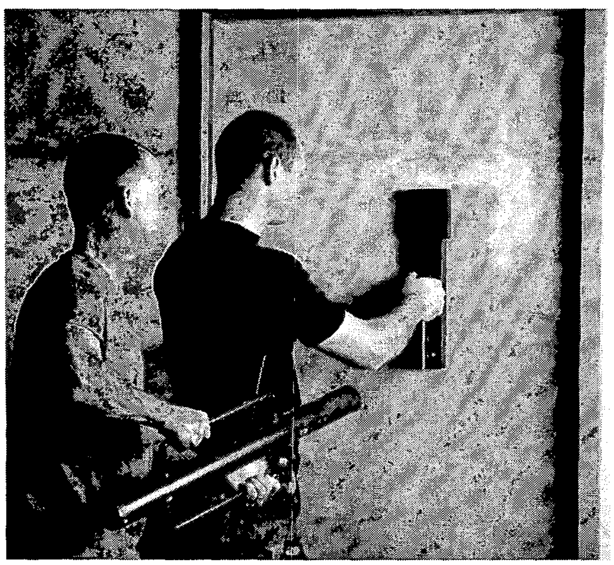

Figure 11. Handheld radar can detect movement of individuals on the other side of a wall or door.

Small, handheld TM-UWB in-building radar units would help squad leaders locate and assess threats as they search and secure buildings. Even the most advanced databases will not contain all relevant information about the structures that troops must clear in combat. Few things are more stressful than room-to-room combat where no one knows what's behind the next door. Through-wall imaging would assist troops in determining whether or not people were inside a room. As the system

Figure 12. Investigators sift through the debris of the Khobar Towers bombing in Dharan, Saudi Arabia.

advances and imaging is added to this unique design, troops would be able to tell whether the people were armed, thus allowing a ready distinction between combatants and civilians, and the location of arms caches. This would also help in locating survivors in bombed structures, thus speeding rescues in scenarios like the Khobar Towers bombing in 1996.

Finally, TM-UWB provides exceptional perimeter security potential. Its flexibility and low-cost would allow commanders to set up radar fences to augment traditional sentries. These could be placed farther away from a perimeter than would normally be prudent with humans, and could easily be left behind, in an emergency, with no fear that the enemy could use them because they would not have the correct codes.

Fire Control Radar. Despite advances in long-range missile interceptors, pilots often must hold fire until a potential tar-

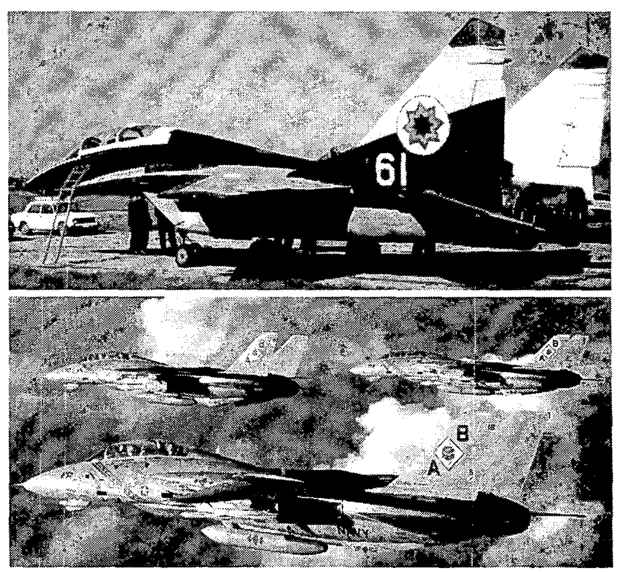

Figure 13. Similar designs of the MiG-29B (top) and F-14 Tomcat (bottom) can fool even trained eyes at a distance.

get is in visual range so they can confirm whether it is friend or foe or civilian noncombatant. Similarities in aircraft design — like the F-14 Tomcat, F-15 Eagle, and MiG-29, each having twin vertical stabilizers and twin engine nacelles around a center body — make this a challenge under the stress of combat. The fine resolution offered by TM-UWB offers the potential for radar imaging precise enough to distinguish specific features on aircraft/marine craft, bringing real-time intelligence to the battlefield. Not only would this identify enemy aircraft earlier in the game, it could also identify weapons loads and thus provide some hint of the aircraft's target or mission.

Arms Inspection. When imaging capabilities become available, TM-UWB internal radar will be able to look through conventional structures and quickly determine whether a structure warrants detailed inspection. Through-wall imaging would also be useful in searching for contraband that might be concealed inside double hulls of boats or bulk cargoes in law-enforcement or political quarantine situations.

Space

TM-UWB is adaptable to space applications ranging from precise joining of structures to exploration of the planets.

Rendezvous and Docking. Joining two multi-ton spacecraft in space is a delicate procedure than involves tremendous skill on the part of human pilots. Their workloads can be eased by employing three transceivers on each spacecraft. (One establishes distance; two establish alignment along only one axis; three fix the axes in all three dimensions.) This would allow calculation of precise relative position and alignment during their terminal docking phases. This could be most useful for automated docking systems and for assembly of large structures in space. Similar methods could be used in assembling large structures on Earth with low-cost (*i.e.*, disposable) transceivers built into structures. Stacking the major elements of the Space Shuttle boosters now employs surveying equipment. Transceivers might be embedded in the elements or attached to small, rigid fixtures on the exterior. This would allow calculation of the precise position and velocity of the hoisted body.

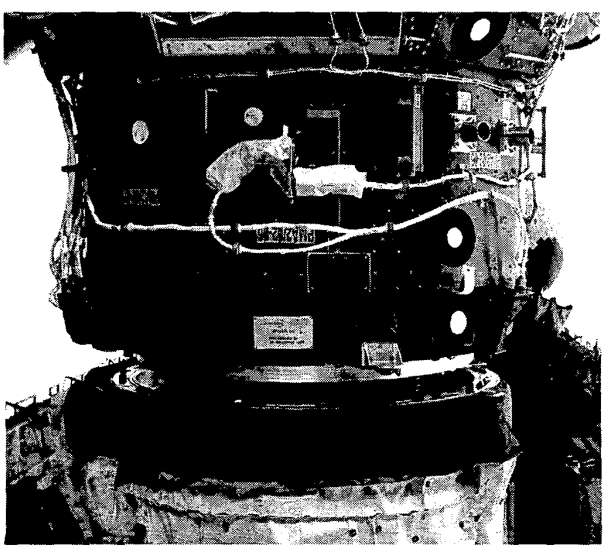

Figure 14. Space Shuttle *Atlantis* joins two modules of the International Space Station, a complex task demanding precision control.

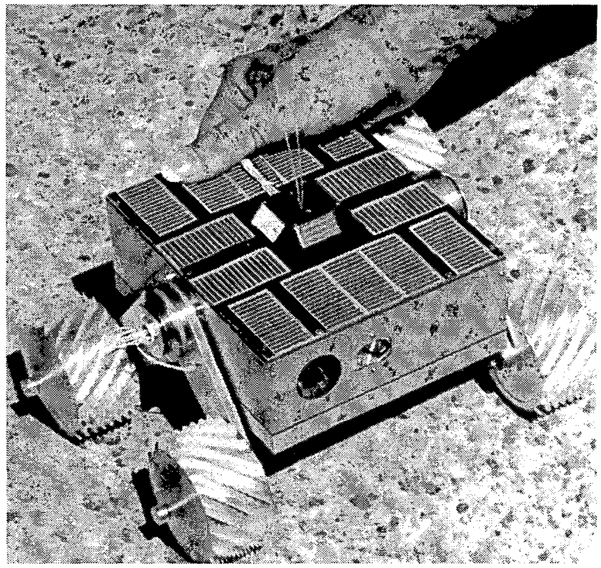

Figure 15. Microrovers planned for exploring asteroids could be enhanced by miniature, versatile sensors using TM-UWB technology.

Planetary exploration. The through-wall imaging capability of TM-UWB would be of immense value to surface explorations of other worlds where it is impractical to set up extensive drilling networks. TM-UWB imaging units could be installed on rovers of various sizes and provide images of the upper layers of soil as the craft move across a planet's surface. This would be especially helpful in detecting variations in density and structure, and in locating possible sources of water or water ice in subsurface soil. For advanced missions such as the proposed Proteus underwater vehicle that would explore Europa, TM-UWB's precision ranging capabilities would locate the most promising areas of thin ice for the drill unit to penetrate.

4. Conclusions

Time Domain Corporation's TM-UWB technologies offer tremendous applications potential to the commercial, aerospace, and defense communities. By using low-jitter electronics and precision clocks, TM-UWB provides precise range measurements to another object and to discrete features on that object. The coded cyclet technique, operating in the time domain and manipulated to appear as noise to any but the intended receiver, forms a secure line for transmitting sensitive information. The diagnostic, data transmission, and other capabilities will open the electromagnetic spectrum to wider use in aerospace, and will enable or simplify the use of radio in a range of uses that now require larger, more expensive, and less efficient systems.

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