An Ultra Wideband Communications Link for Unmanned Vehicle Applications

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Abstract

Covert communications links are highly desirable for unmanned vehicle applications in which the presence, and hence location, of the vehicle must not be compromised by the long range detection of electromagnetic emissions radiated from the platform. In addition, an anti-jam (AJ) command and control uplink is critical to the survivability of unmanned aerial vehicles in either hostile or high electromagnetic interference (EMI) environments.

Ultra wideband (UWB) technology, well-known for its ground penetrating radar applications, has been demonstrated to possess both low probability of intercept and detection (LPI/D) as well as AJ features when properly deployed in a communications system design. Such waveforms provide an unique form of spread spectrum communications utilizing extremely short duration pulses (typically 1-2 nanoseconds) and low average power levels (typically only a few microwatts). UWB systems are also characterized by their low cost, all-digital design, small size, and light weight making them ideally suited to unmanned vehicle applications.

This paper describes the design and performance characteristics of recently developed UWB transceivers which can be used for the LPI/D transmission of digital voice, data and high resolution video imagery.

Introduction

UWB transmissions have been defined by the DARPA Panel on Ultra-Wideband Radar as "..any radar whose fractional bandwidth is greater than 0.25 regardless of the center frequency or the signal time-bandwidth product."[1] The current use of UWB in high resolution ground penetrating radar (GPR) applications is well known[2]. More recently, UWB technology has been applied to the design of high resolution LPI/D radar altimetry and collision avoidance systems.[3] Over the last ten years, however, ultra wideband (UWB) techniques have also been successfully applied to LPI/D communications systems.

Ultra wideband (UWB) signals, much like conventional spread spectrum waveforms, minimize transmission intercepts from unintended receivers by generating negligible amounts of energy within an intercept receiver's acquisition bandwidth. However, unlike either direct sequence (DS) or frequency hopping (FH) spread spectrum (SS), the spread bandwidth for UWB waveforms is generated *directly* and not by modulation with a separate spreading sequence such as a PN code or hopping pattern. Thus, UWB is essentially a time-domain concept in which an extremely short RF pulse generates a very wide instantaneous bandwidth signal because of the direct Fourier transform relationship between time and frequency. From the Uncertainty Principle[4], it can be shown that the time-bandwidth product of such signals satisfies the relationship

$$\frac{\left(\int_{-\infty}^{\infty} x(t)dt\right)^2}{\int_{-\infty}^{\infty} x^2(t)dt} \bullet \frac{1}{2} \frac{\int_{-\infty}^{\infty} \left|X(\omega)\right|^2 d\omega}{\left|X(0)\right|^2} \equiv \Delta T \bullet \Delta W = \pi$$

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[1] *Assessment of Ultra-Wideband (UWB) Technology,* Report R-6280, prepared by OSD/DARPA UWB Radar Review Panel, July 13, 1990.

[2] Owen, T.E., ed., Journal of Applied Geophysics (Special Issues) Vol. 33, No. 3/4, Ground Penetrating Radar, 1995.

[3] Fontana, R.J., H.C. Koppier and R.W.T. Mulloy, *A Low Cost Ultra Wideband (UWB) Radar Altimeter,* **AUVSI '96 Proceedings**, July 15-19, 1996, pp. 297-301.

[4] Liu. C.L. and J.W.S. Liu, **Linear Systems Analysis**, McGraw-Hill, NY, 1975, Chapter 8.

where x(t) and X(ω) are Fourier transform pairs. Thus, an ultra wideband signal has a very small time-bandwidth product, with processing gain achieved by time-gating the receiver to match the pulse duration. For the type of detector used (cf. below), the shorter this time-gate, the smaller the resultant noise variance and, hence, the larger the resultant output signal-to-noise ratio. Conversely, conventional spread spectrum waveforms exhibit significantly larger time-bandwidth products (several hundred to many thousand), with processing gain achieved through correlation techniques.

From the perspective of spectral occupancy, UWB fractional bandwidths – which typically exceed 25% independent of modulation rate – are significantly larger than typical DS- or FH-SS bandwidths. As an example, a UWB voice transmission at L-band has been demonstrated with an instantaneous bandwidth exceeding 500 MHz (cf. Figure 1); while a DS-SS waveform with a large 40 dB of processing gain would have a bandwidth of only 50 MHz using an equivalent 5 kHz information bandwidth.

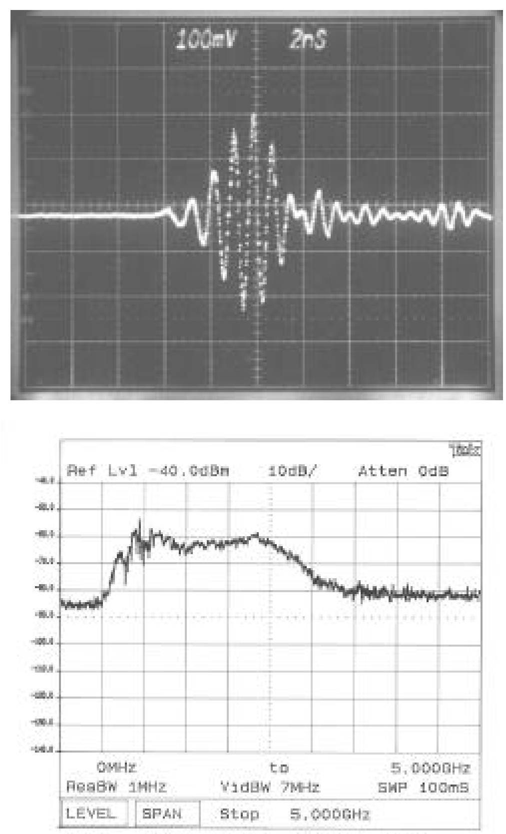


Figure 1. L-band UWB Pulse and Power Spectral Density.

The LPI/D performance of a UWB signal occurs since the majority of intercept receivers cannot respond to such short duration pulses. In the case of a wideband radiometer, whose bandwidth is tailored to that of the UWB signal, the detection performance is limited because of the extremely low average power density of a UWB signal.

As an example, a conventional narrowband radio such as a cellular phone generates between 0.1 and 3W of continuous power in a 30 kHz bandwidth resulting in an instantaneous power density of from 3.3 to 100 μW/Hz. For a Part 15 spread spectrum device having a 1W power output and a minimum 500 kHz bandwidth (e.g., spreading gain of 20 dB for a typical voice channel), a power density of 2 μW/Hz is obtained. For a 1W peak power UWB system having a 2 ns pulsewidth and 128 kb/s data rate, the *peak* power density is only 2 nW/Hz, with an average power density of 0.5 pW/Hz!

Anti-jam performance of the UWB receiver derives from its ability to respond to the leading edge of the received pulse; which, when combined with time-gating, provides a type of noise-blanking which has been shown to be very effective in the presence of in-band CW or barrage noise jamming.

Finally, the simplicity of a UWB system, together with the high level of circuit commonality between communications and radar applications, make it a very attractive candidate from a cost/performance perspective (cf. Figure 2).

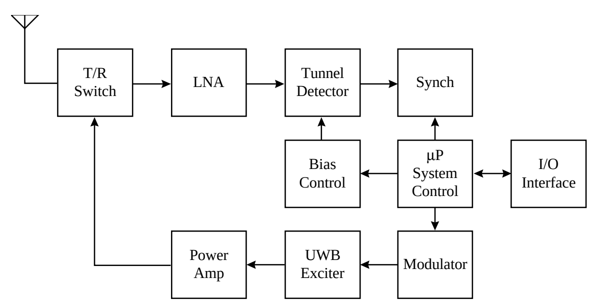


Figure 2. UWB Communications System Block Diagram.

As observed in Figure 2, the RF/microwave circuitry for a UWB system is minimal – requiring no frequency synthesizers, up/down-converters, image rejection filters, etc. Thus, frequency adaptive designs are readily achieved in which the only changes required are in the antenna and low noise amplifier. The vast majority of the design is digital, further lending to a low cost and small size package.

In summary, the primary advantages of UWB communications systems include:

a. Extremely low probability of intercept and detection (LPI/D);
b. High anti-jam immunity;
c. Frequency diversity with minimal hardware modifications;
d. Commonality of signal generation and processing architectures for both radar and communications applications; and,
e. Low cost components and assembly -- nearly “all digital” electronics with minimal RF/microwave circuitry.

Communications Performance

The detection of extremely short, subnanosecond to nanosecond duration, pulses requires the use of highly specialized detectors. Most conventional microwave detectors are typically designed for significantly wider pulsewidth or CW operation. For many applications where price, size and reliability are critical parameters, simple threshold detectors have been utilized with substantial success.

A tunnel diode, properly biased to operate as a charge sensitive detector, has proven to be very reliable in the detection of UWB transients. When the accumulated charge across its terminals exceeds a given threshold, the tunnel diode “fires” and effectively latches its output. By gating the detector to be sensitive *only* during the pulse duration, one can obtain a receiver operating characteristic which provides for highly reliable single pulse detection.

A novel DSP-based UWB receiver processor which utilizes a charge sensitive tunnel diode detector for single pulse UWB detection is shown below in Figure 3. This UWB receiver/processor is capable of single pulse UWB detection with a sensitivity of -78 dBm (in a 400 MHz bandwidth with a system noise figure of 2.5 dB) at a bit error rate of 10^{-3}. This corresponds to a peak signal-to-noise ratio of approximately +7.3 dB.

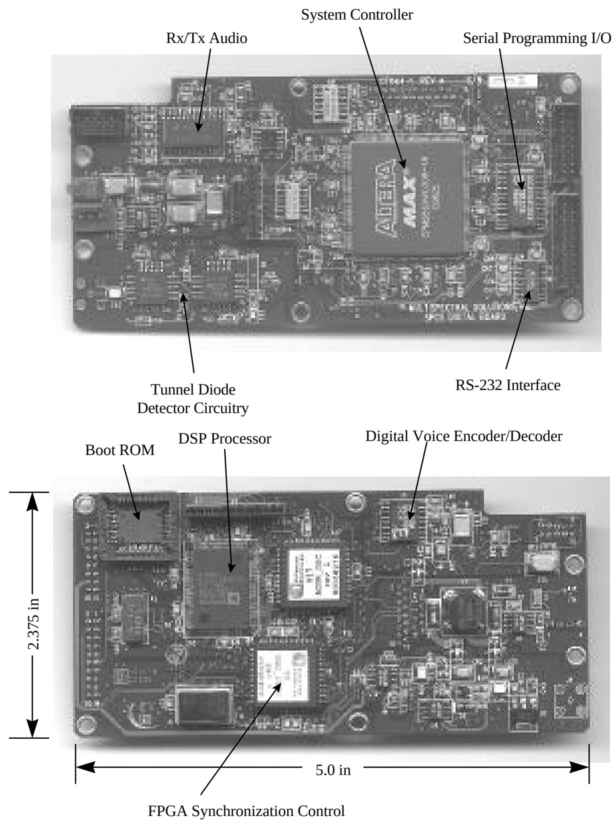


Figure 3. UWB Receiver Processor (Front and Back Views).

A current UWB transmitter design is shown in Figure 4.

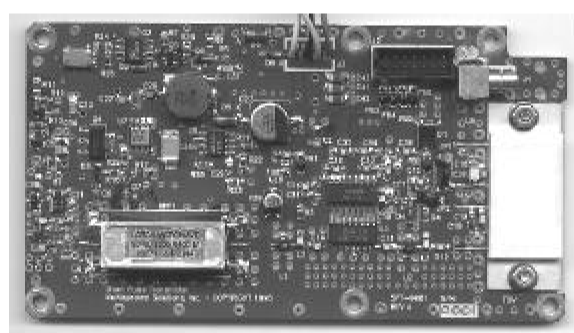
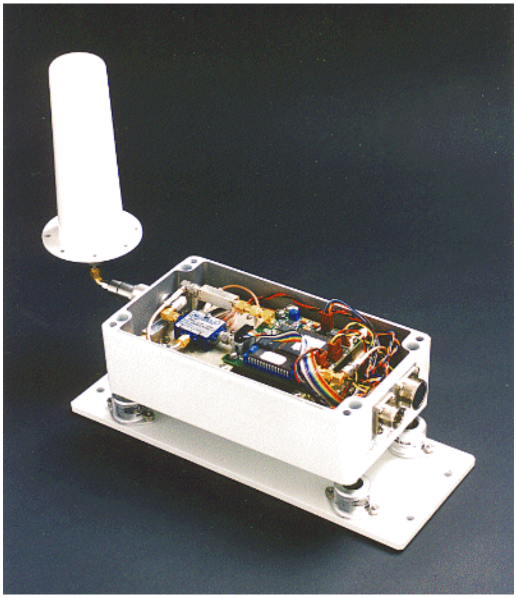


Figure 4. L-band UWB Transmitter.

Figures 5 and 6 illustrate several recently developed UWB systems using single pulse UWB detectors. Field test performance results with these systems are discussed in further detail below.



(a) UWB Packet Radio

- Size: 9 x 4 $^{3}/_{4}$ x 3 $^{1}/_{8}$ in
- Weight: 66.8 oz
  - Ruggedized waterproof housing for SOF high speed boat applications
- Performance:
  - Half duplex 9600 baud
  - GPS relay and RS-232 data
  - LPI/D with 33% fractional BW
  - Multi-user packet protocol
  - Frequency Adaptive
  - Range (demonstrated)
    - 3.7 miles over water
    - 50+ miles line-of-sight

(b) UWB Packet Radio Performance Parameters

Figure 5. UWB Packet Radio

(a) UWB Voice/Data Handheld Radios

- Size: 7 $^{7}/_{8}$ x 2 $^{3}/_{8}$ x 2 $^{1}/_{2}$ in
- Weight: 39.2 oz
- Power:
  - Rx 3.8W full duplex
  - Tx 0.5W (16 kB) to 6.2W (128 kB)
- Performance:
  - Full duplex 128 kB/s
  - Voice/data modes
  - LPI/D with 33% fractional BW
  - Fully reprogrammable
  - Range
    - 1 km design goal (with low profile antennas)
    - Multiple mile performance with higher gain antennas

(b) UWB Handheld Performance Parameters

Figure 6. UWB Voice/Data Handheld Radios.

Field Test Results

A number of field tests were performed with the UWB transceivers illustrated in Figures 5 and 6. Propagation with the ruggedized UWB packet radios, Figure 5(a), was evaluated in a series of tests performed at low antenna grazing angles over both water and land at the Naval Air Warfare Center's Chesapeake Test Range in Patuxent (PAX) River, MD; as well as line-of-sight in mountaintop-to-ground tests in the Catoctin Mountains outside of Frederick, MD. For these tests, a variety of wideband, nondispersive gain antennas was used.

The PAX River tests with the UWB packet radios dramatically illustrated the effects of multipath cancellation at extremely low grazing angles. For two antennas at heights h_1 and h_2 separated by distance D, the differential path length between direct and reflected (off the surface) wavefronts is given approximately by

$$\Delta \approx 2h_1h_2/D.$$

As an example, for two antennas 6 feet off the ground, the path differential at a range of 1 mile is approximately 0.16 *inches*, resulting in a time delay of roughly 14 ps between direct and reflected paths. Since the reflection coefficient is approximately -1, significant signal cancellation occurs, even for a subnanosecond UWB pulse. It can be shown[5] that, under such multipath conditions, the received signal strength follows an R^4-dependency with range. Thus, link margins for communications to and from unmanned ground vehicles, for example, must take into account multipath cancellation effects even for short pulse UWB signals.

The 1W UWB packet radio range performance closely tracked the theoretical R^4-dependency as shown in the following figure.

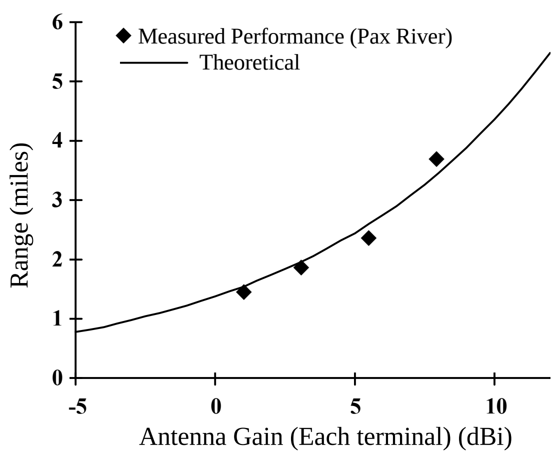


Figure 7. Measured and Theoretical Performance of UWB Packet Radios in Multipath Propagation.

These experiments confirmed both the R^4-law behavior as well as the 6dB/octave height dependency. Doubling the height of the antennas at *both* transmitter and receiver sites resulted in an effective doubling of the communications range.

[5] Siwiak, K., **Radiowave Propagation and Antennas for Personal Communications**, Artech House, Boston, MA, 1995, Chapter 6.

By way of comparison, Figure 8 illustrates the theoretical performance for the same radio (1W peak) in a line-of-sight environment; e.g., ground-to-UAV applications. Experiments performed in the Catoctin Mountains verified the LOS range calculations to beyond 20 miles with a 1W system, and 50 miles with a 10W system, both with +8 dBi cavity-backed wideband dipole antennas.

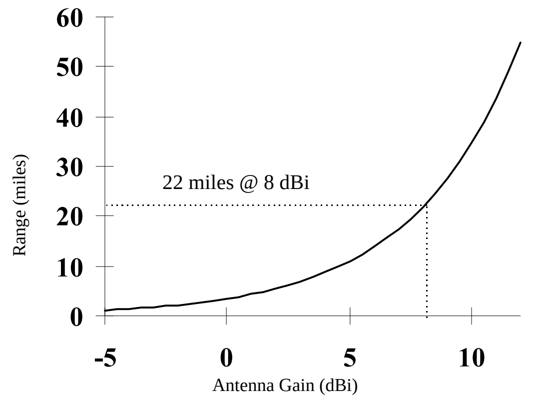


Figure 8. Theoretical Performance of 1W UWB Packet Radios in Line-of-Sight Propagation.

The handheld UWB voice/data transceivers (Figure 6(a) were also evaluated over water and land at various locations in MD and VA using low profile UWB antennas. These experiments also confirmed the same R^2 and R^4-dependencies.

With a 2W peak UWB output, the handheld radios were usable (with the -1 dBi wideband whip antennas) to effective ranges of greater than 2 km. Line-of-sight tests have not yet been performed with these radios; however, it is expected that these results would be comparable to those achieved with the packet radios. For increased range, higher peak powers can of course be utilized.

Currently, MSSI is developing UWB communications systems having operational frequencies ranging from L-band (approximately 1.5 GHz center frequency) to C-band (5.6 GHz center frequency). L-band operational frequencies were used in the UWB mobile packet radios, UWB handheld transceivers and in UWB high resolution radar altimeters[3]. The higher C-band frequencies are being used on several new programs involving high speed video and command & control links, as well as a new series of high resolution UWB radar altimeters.

Conclusions

Ultra wideband (UWB) communications systems have been operational for over 10 years. Recent advances in UWB receiver technology have permitted the single pulse detection of extremely low level UWB signals using the unique properties of the microwave tunnel diode. The ability of the tunnel to trigger on the pulse leading edge permits anti-jam operation in the presence of strong in-band pulse or barrage noise jamming.

The performance of two recently developed UWB transceivers – the first a UWB packet radio designed for covert SOF boat-to-boat transmissions, and the second a UWB voice/data handheld transceiver – were discussed. It was observed that UWB transmissions are affected by multipath cancellation under geometries in which low grazing angles are encountered. Experimental data verified the predicted R^4 range dependency in multipath and the R^2-dependency under LOS conditions.

Multispectral Solutions, Inc. (MSSI) is currently involved in the development of UWB communications and radar equipment for a wide variety of applications (Figures 9 and 10).

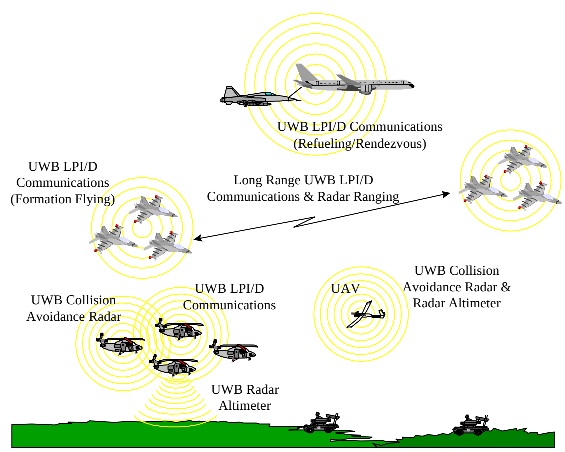


Figure 9. UWB Communications and Radar Applications (I).

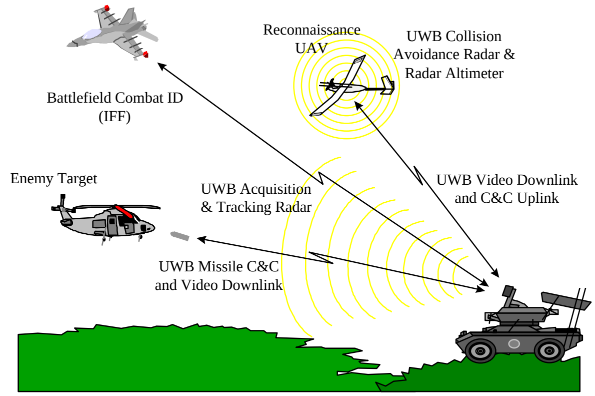


Figure 10. UWB Communications and Radar Applications (II).

These applications include: inter- and intra-flight voice/data communications, UAV command & control and video relay, high resolution radar altimetry, and shock-hardened gun-launched UAV and missile video applications. UWB communications systems are proving to offer high performance in terms of covertness, size, cost and reliability.