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THE GPS BURST DETECTOR W-SENSOR

by

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ABSTRACT

The NAVSTAR satellites have two missions: navigation and nuclear detonation detection. The main objective of this paper is to describe one of the key elements of the Nuclear Detonation Detection System (NDS), the Burst Detector W-Sensor (BDW) that was developed for the Air Force Space and Missle Systems Center, its mission on GPS Block IIR, and how it utilizes GPS timing signals to precisely locate nuclear detonations (NUDET). The paper will also cover the interface to the Burst Detector Processor (BDP) which links the BDW to the ground station where the BDW is controlled and where data from multiple satellites are processed to determine the location of the NUDET. The Block IIR BDW is the culmination of a development program that has produced a state-of-the-art, space qualified digital receiver/processor that dissipates only 30 Watts, weighs 57 pounds, and has a 12"x14.2"x7.16" footprint. The paper will highlight several of the key multilayer printed circuit cards without which the required power, weight, size, and radiation requirements could not have been met. In addition, key functions of the system software will be covered. The paper will be concluded with a discussion of the high speed digital signal processing and algorithm used to determine the time-of-arrival (TOA) of the electromagnetic pulse (EMP) from the NUDET.

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1.0 W-SENSOR MISSION

The Burst Detector W-Sensor (BDW) is a special purpose receiver-processor that is part of the Nuclear Detonation (NUDET) Detection System (NDS) payload aboard each NAVSTAR Global Positioning System (GPS) satellite. The NDS mission is to provide survivable, worldwide NUDET surveillance and to verify compliance with the Limited Test Ban Treaty of August 5, 1963. Major components of the NDS are shown in Figure 1.

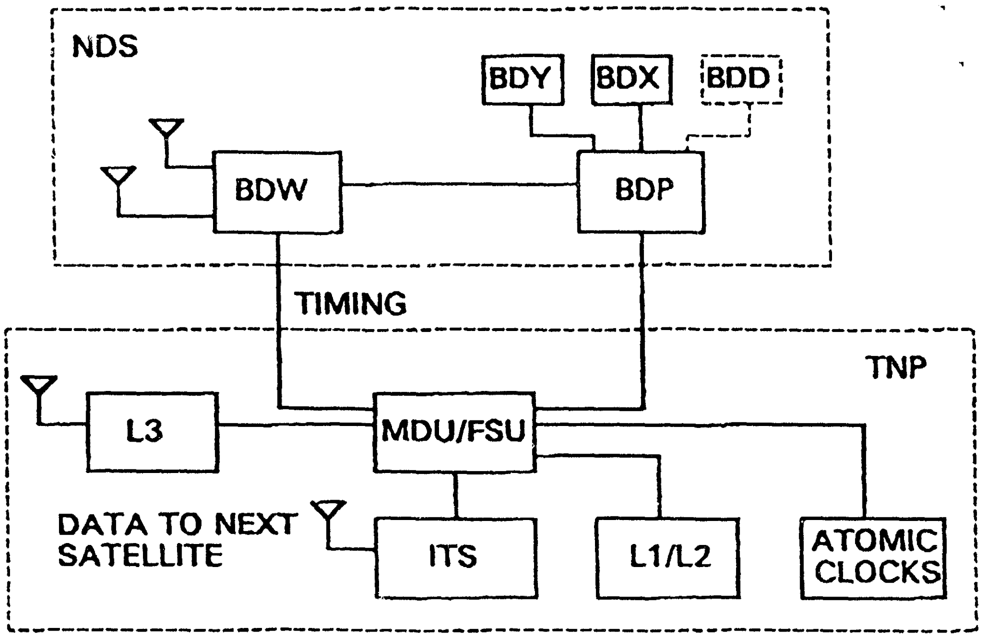

FIGURE 1: EXCEPT FOR TIMING SIGNALS, THE BDP CONTROLS THE BDW INTERFACE WITH THE TOTAL NAVIGATION PAYLOAD (TNP)

The NDS includes the BDW, the Burst Detector Optical Sensor (BDY), the Burst Detector X-Ray Sensor (BDX), and the Burst Detector Processor (BDP), which is the data processor and controller for the NDS subsystems. On certain space vehicles (SV), the BDX is replaced by a Burst Detector Dosimeter (BDD), which measures background radiation levels at the spacecraft.

The BDW mission is to characterize and accurately locate the source of the electromagnetic pulse (EMP) that is generated by the endoatmospheric NUDET event. Using separate antennas, the BDW monitors for EMP radiation in two frequency bands, the high band and the low band. Events that are detected by the BDW are correlated with BDY detected events by the BDP for positive confirmation since the BDY has a lower false alarm probability.

To maintain accuracy, the BDW receives timing signals (X1 epoch and 10.23MHz clock) directly from the TNP Mission Data Unit (MDU). These timing signals provide a reference for the BDW EMP time of arrival (TOA) processing. The TOA information from a particular satellite is used by the ground station, in concert with TOA information from three other satellites, to determine the precise location of the NUDET.

2.0 W-SENSOR FUNCTIONAL DESCRIPTION

Figure 2 provides a functional overview of the BDW. There are four main functional areas that will be covered: RF signal processing, digital signal processing and control, self test, and communications to and from the BDP.

2.1 RF Signal Processing

The RF subsystem consists of a redundant high band and a partially redundant low band. High band uses a single conversion architecture with a high side local oscillator and three 2MHz bandwidth IF channels, separated by 10.23MHz, that can be jointly tuned to sixteen frequency settings between 109 to 151MHz. The tuning process can be performed automatically, to tune away from interference, or manually using commands from the ground station. Low band includes two, 2MHz bandwidth channels that have fixed center frequencies of 53 and 74MHz.

The IF channel transfer functions are primarily determined by surface acoustic wave (SAW) filters with Gaussian responses for both high band and low band. Log detectors are used to convert the IF signals to baseband while minimizing delay variations over the wide dynamic range that the system is operated.

2.2 Digital Signal Processing And Control

The detected signals are sampled at 10.23MHz and digitized with 10 bit A/D converters for the high band channels and 8 bit A/D converters for the low band channels. The data from the high and low band A/D converters are transferred to the processor using application specific integrated circuits (ASIC) referred to as channel logic units (CLU). Identical CLUs are used for each of the five channels, three for high band and two for low band. The master CLUs of the high and low bands have additional logic enabled to control the concurrence logic for that band (discussed below), the high band local oscillator synthesizer, and the self test signal generators. A second type of ASIC, the processor support ASIC, is used to provide critical timing and control signals to the 1750A processor and associated memory. The digital hardware is fully redundant.

The BDW processor, programmed in Ada, periodically captures data for background noise level measurement and can set data capture detection thresholds for each of the five channels. In addition, detection thresholds can be set manually by command from the ground. Once a channel detection threshold has been exceeded, there is a mechanism to determine concurrence separately for each band during a timing window which is programmable by software. The concurrence logic generates an event interrupt to the processor if the selected one, two, or three channels in that band have triggered within the selected time period. The processor makes the final event declaration after determining whether the highest frequency channels triggered first since the EMP sweeps from high to

BURST DETECTOR W-SENSOR (BDW)

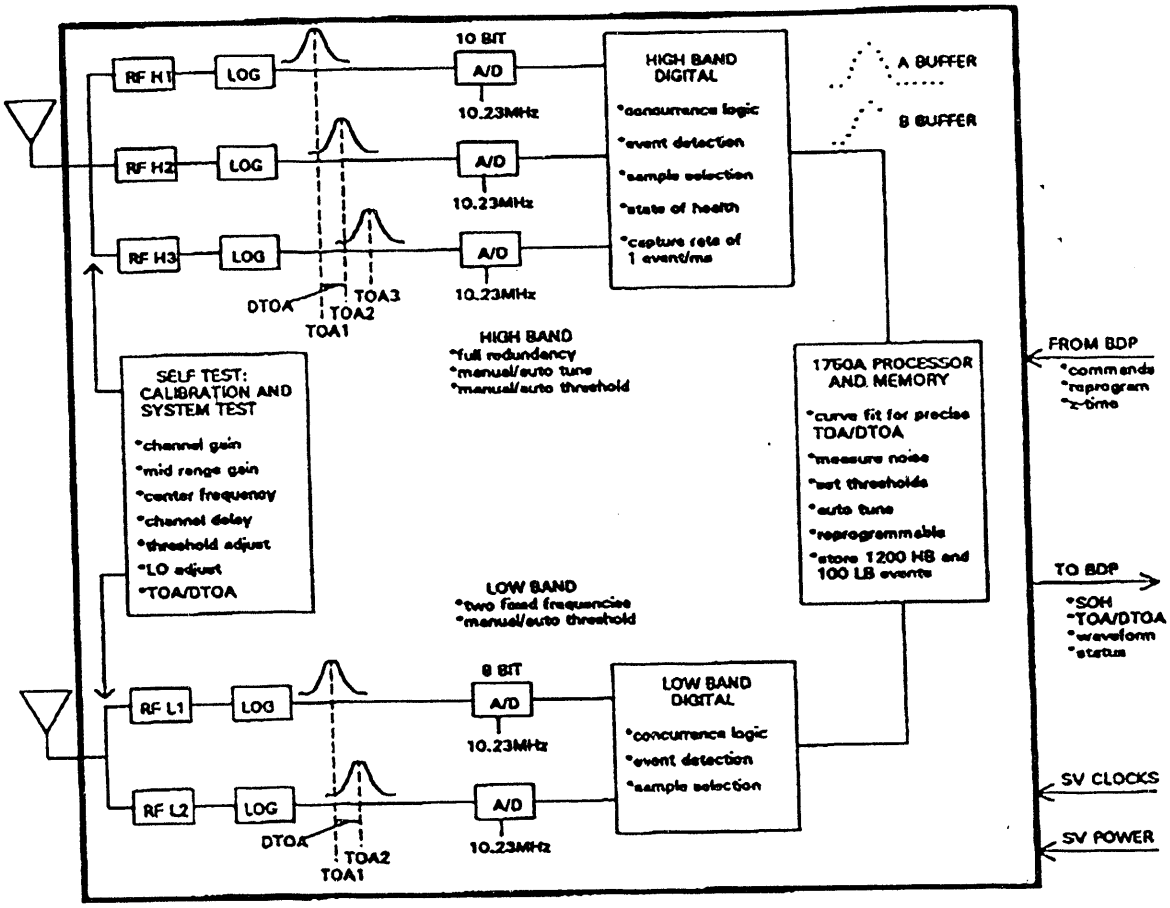

FIGURE 2: THE W-SENSOR COLLECTS NUDET DATA IN TWO FREQUENCY BANDS, USING A 1750A PROCESSOR FOR SYSTEM CONTROL AND COMPUTATION OF TOAs.

low in frequency. High and low band event processor interrupts are cleared by reading the time tag registers in the master CLUs. The value from the time tag register is used by the processor to synchronize the captured event to GPS time.

When an event has been detected, the processor reads the captured data and time tag from the CLU and transfers it to data memory. The channel is then re-armed for further event detection. "Sampled waveform" data, 100 samples, are provided by the A buffer for the first event in a sequence of events. Software formats the sampled waveform data for transmission to the BDP and selects the 20 sample data window for TOA processing. Subsequent sampled waveforms are taken as rapidly as possible after the raw data from the preceding event has been stored. For events in a burst of events for which sampled waveforms are not provided, 26 samples are captured by the B buffers for TOA processing. Logic in the CLU selects the appropriate 20 samples for TOA processing for these events. Sampled waveforms, TOAs, and DTOAs from the A and B buffer events are transmitted to the BDP for relay to the ground. As shown in Figure 2, a DTOA is the difference in TOA between two channels in the same band.

2.3 Self Test

Self test consists of "system test" and calibration. These functions are used as quick checks on the integrity of the system. Both system test and calibration are commanded independantly by the ground station.

System test injects a simulated EMP signal into the high band and an impulse into the low band to verify the operation of the system. The system test events are treated as real events but are flagged as test events. The simulated EMP is generated by driving a SAW device, which has a linear FM impulse response, with an impulse.

Calibration is a preprogrammed sequence of tests that is controlled by software. Internal pulse and signal generators are used to provide the necessary signals during calibration. The results of calibration are reported in the state of health and by the Calibration Status message and the delay calibration event messages. The tests include the following.

- Gain Adjustment - For each channel, a tone is inserted with known amplitude at the channel center frequency and the gain is adjusted until the proper A/D code level results.

- Midrange Gain - For each channel, a tone is inserted at the channel center frequency with a midrange level and the resulting A/D code level is reported.

- Center Frequency - For each channel, 11 evenly spaced tones are inserted across the 5MHz bandwidth and the center frequency is computed using the 11 point centroid method.

- Delay - An impulse is inserted into each band and the time delay is measured through each channel using the event processing software.

- Threshold Adjustability - The delay test is repeated with elevated channel thresholds and success is the absence of test events.

- Local Oscillator (LO) Adjustability - The LO setting is changed to (current LO + 8) modulo 16, and a tone is inserted in the center of the middle high band channel and the level is verified.

2.4 Communications To And From The BDP

The main communications link between the BDW and the BDP uses a universal synshronous/asynchronous receiver/transmitter (USART). Communications are asynchronous and even parity at 4843bps.

Types of communications from the BDW to the BDP include state of health (SOH) messages, event messages, status messages, and memory dumps. SOH messages are transmitted to the BDP every 6 seconds and contain the information shown in table 1. As shown, the SOH provides a comprehensive report of key system parameters on a continuing basis.

TABLE 1: State Of Health Information

FIELD	NUMBER OF ITEMS
Z-time	1
last SMC	32
noise monitoring period	5
avg. noise	5
false alarm counts	5
false trigger counts	5
CALIBRATION DATA	
gain values	5
A/D reading (gain)	5
center frequency	5
group delay	5
midrange gain	5
OTHER	
operational state (mode)	1
voltage sensors	3
temperature sensors	5
COMMAND VALUES	
ASIC control command	5
RF command	5
LO setting	1
last threshold setting	5
threshold offset from noise	5
SMC command ignored	3
TOTAL	111

Event messages are sent to the BDP when NUDETs are detected. They contain the TOA and DTOA values for the event as well as the sampled waveform data and other key identifying information needed by the ground station.

There are 15 status messages that the BDW can send to the BDP. They are used to report diagnostics status, memory errors, 1750A arithmetic errors, ASIC command errors, and Ada exceptions. They also report that the system is ready for an upload, that the processor has been restarted, or that failures occurred during a calibration. If a particular block of program or data memory needs to be evaluated, a memory dump can be requested.

The above BDW to BDP messages have proven useful during system integration in the lab and will provide insight into on-orbit system operation.

Types of communication from the BDP to the BDW include Serial Magnitude Commands (SMCs), uploads, and Z-time messages. SMCs are used to control system parameters from the ground, such as channel thresholds and concurrence, or manual or automatic tuning in the high band. System tests and calibrations can be commanded and various processor controls can be enabled.

Uploads are used to change the main program which is stored in EEPROM. Upload messages are sent to the BDW program RAM. When the upload is complete, the memory dump SMC is used to verify that the changes have been correctly made before the EEPROM is updated. When the upload has been verified, the BDW is restarted.

Z-time messages are sent from the BDP every 1.5 seconds to ensure that the BDW is synchronized with GPS time. The BDW monitors these messages and, if necessary, makes appropriate corrections to the BDW Z-time.

3.0 TOA PROCESSING

The TOA of a NUDET EMP that has traversed the ionosphere with respect to the BDW is defined as the time at which the channel's center frequency component arrives at the BDW input. The TOA measured by the BDW is reflected to the input by subtracting out the delay of the channel that was measured during delay calibration.

As mentioned in section 2.0 above, the transfer function of the channels is primarily determined by SAW filters with Gaussian responses. A Gaussian transfer function implies a Gaussian time response as well. Therefore, an EMP sweeping across a BDW channel will generate a Gaussian shaped time pulse at the log detector input where the peak of the pulse occurs at the center frequency of the channel. Taking the log of the Gaussian pulse results in a parabolic shaped time pulse at the log detector output. The parabolic pulse is digitized, the data set is windowed to remove unneeded data, and a parabolic curve fitting algorithm is applied to find the time that corresponds to the pulse peak which is the desired TOA. In addition, the amplitude of the peak is determined for signal quality estimates which use signal to noise ratio (SNR) as the metric.

3.1 Windowing Of Sampled Data

An initial window is used to select data for curve fitting that includes the peak sample, seventeen samples before the peak, and two samples after the peak. This window favors the samples on the leading edge of the pulse which contain more TOA information than the falling edge samples. The window is further restricted to reduce the use of noisy data by only including samples that have amplitudes above the channel threshold and greater than 15% of the peak amplitude. However, a minimum of four samples is maintained (one before the peak, the peak, and two after the peak) to ensure that the desired curve fitting accuracy is achieved.

3.2 Curve Fitting

The TOA and amplitude of the peak of the sampled event are found by fitting the data to a parabola using a least mean squares fit algorithm. The parabola to be fit is:

$$x = a_0 + a_1 t + a_2 t^2. \qquad (1)$$

The time at the peak value, i.e. the TOA, in terms of a_1 and a_2 is found from:

$$\frac{dx}{dt} = 0 = a_1 + 2a_2 t_{pk} \qquad (2)$$

$$t_{pk} = -a_1 / 2a_2 - d_0 \qquad (3)$$

where d_0 is the delay value from the delay calibration of the BDW channel. The amplitude at t_{pk} is found by solving the parabola at t_{pk}:

$$x(t_{pk}) = a_0 - a_1^2 / 4a_2 \qquad (4)$$

$$A_{pk} = 2.30258 e^{(a_0 - a_1^2/4a_2)}. \qquad (5)$$

The LMS algorithm requires that the value S be minimized:

$$S = \sum_i (a_0 + a_1 t_i + a_2 t_i^2 - y_i)^2. \qquad (6)$$

The sum is taken over the windowed data points and $t_i = nT$, n=sample number, T=sample period, and y_i=sampled data. The resulting simultaneous equations obtained from minimizing S are:

$$M_0 a_0 + M_1 a_1 + M_2 a_2 = W_0 \qquad (7)$$

$$M_1 a_0 + M_2 a_1 + M_3 a_2 = W_1 \qquad (8)$$

$$M_2 a_0 + M_3 a_1 + M_4 a_2 = W_2 \qquad (9)$$

where the moments M_i and W_k are defined as:

$$M_i = \sum_n (nT)^i y_n^2 \qquad (10)$$

$$W_k = \sum_n (nT)^k y_n^3. \qquad (11)$$

Each equation above has been weighted by the factor y_n^2, which has been found to improve accuracy. The simultaneous equations are solved using Cholesky's decomposition and the resulting values of a_0, a_1, and a_2 are used to determine the TOA (fine times) and amplitude for each channel. The TOA fine times are related to Z-time by use of the time tag, mentioned above, which is the number of 10.23MHz clock cycles from the X1 Epoch pulse until event detection. The BDP relates the time tag to Z-time. DTOAs are computed as the difference in TOAs between channels in the same band.

3.3 Ionospheric Effects On TOA Accuracy

As the EMP travels to the BDW receiver, it is dispersed due to the total electron content (TEC) of the ionosphere. As shown in Figure 3, pulse dispersion increases as TEC increases. A dispersed EMP that sweeps through the BDW band results in larger DTOAs and a less well defined peak in the received pulse of each BDW channel. The dispersed pulses yield less accurate curve fits leading to less accurate TOAs.

Another factor that effects TOA accuracy is the SNR at the input to the BDW. As the noise increases at the BDW input, SNR decreases, and the pulses become more ragged and harder to curve fit resulting in less accurate TOAs.

4.0 SUMMARY

The BDW is a low power, space qualified receiver/processor with a 99.9% reliability for 7.5 years in a radiation environment. The system can be reprogrammed from the ground and can provide precise TOAs from multiple nuclear detonations through a highly variable ionosphere. Utilization of the GPS crosslink allows worldwide coverage with a minimal response time. The key technical innovation involved implementing a high dynamic range receiver that can be tuned over a wide bandwidth while minimizing contributions to delay variability on the NUDET EMP signal.

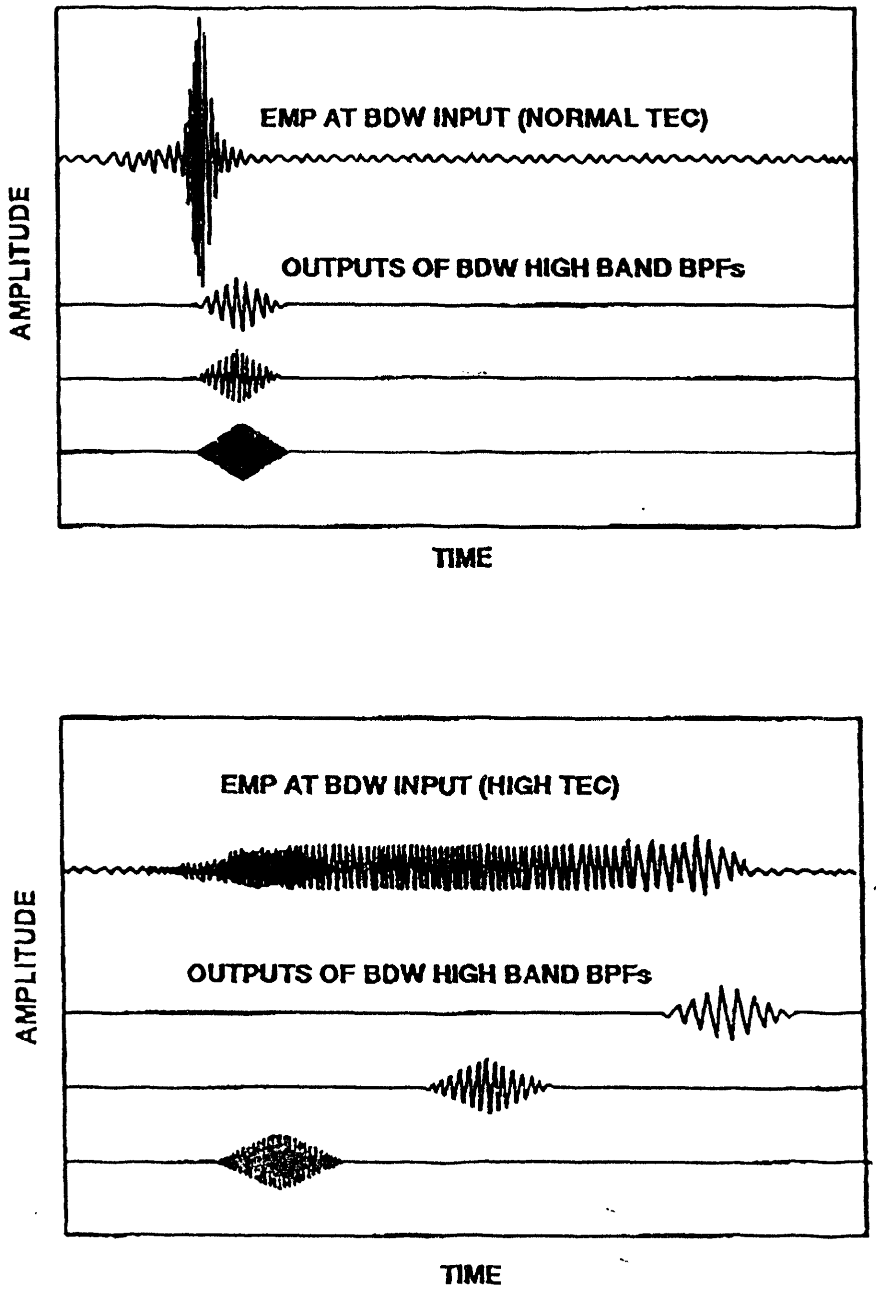

FIGURE 3: NUDET EMP DISPERSION IS PROPORTIONAL TO THE TOTAL ELECTRON CONTENT (TEC) OF THE IONOSPHERE

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