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Title: A SPACE-BASED CLASSIFICATION SYSTEM FOR RF TRANSIENTS

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A Space-based Classification System for RF Transients

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Abstract

The FORTE (Fast On-Orbit Recording of Transient Events) small satellite is scheduled for launch in mid 1995. The mission is to measure and classify VHF (30-300 MHz) electromagnetic pulses, primarily due to lightning, within a high noise environment dominated by continuous wave carriers such as TV and FM stations. The FORTE Event Classifier will use specialized hardware to implement signal processing and neural network algorithms that perform onboard classification of RF transients and carriers. Lightning events will also be characterized with optical data telemetered to the ground. A primary mission science goal is to develop a comprehensive understanding of the correlation between the optical flash and the VHF emissions from lightning. By combining FORTE measurements with ground measurements and/or active transmitters, other science issues can be addressed. Examples include the correlation of global precipitation rates with lightning flash rates and location, the effects of large scale structures within the ionosphere (such as traveling ionospheric disturbances and horizontal gradients in the total electron content) on the propagation of broad bandwidth RF signals, and various areas of lightning physics. Event classification is a key feature of the FORTE mission. Neural networks are promising candidates for this application. We describe the proposed FORTE Event Classifier flight system, which consists of a commercially available digital signal processing board and a custom board, and discuss work on signal processing and neural network algorithms.

FORTE Mission Overview

FORTE (Fast On-Orbit Recording of Transient Events) is a United States of America Department of Energy small satellite experiment scheduled for launch in mid 1995. The payload will measure VHF (30-300 MHz) electromagnetic pulses within a noise environment dominated by continuous wave carriers such as TV and FM stations. The Pegasus XL spacecraft will provide a circular, 68^{o} inclination, 800 km altitude orbit. A primary feature of this mission is the 10 m pseudo-log-periodic antenna coupled to state-of-the-art analog and A/D electronics.

Because lightning is expected to be the main source of electromagnetic transients in this frequency range, optical information will also be gathered to help characterize lightning events. The optical system consists of a high time resolution, low spatial resoultion photometer and a low time resolution, high spatial resolution CCD camera. Both RF and optical system data will be telemetered to ground for analysis.

The physical processes in lightning responsible for producing the optical and RF signatures are believed to be different. The relatively slow (10^{-6} s) optical flash is produced chiefly by the return stroke of the lightning process. The low frequency (few MHz) RF signature is also chiefly produced by the return stroke [Bruce and Golde, 1941; Lin et al., 1980]. The 30 to 300 MHz transients are believed to result from the lightning leader and intracloud processes [Rustan et al., 1980; Proctor, 1981]. These high frequencies correspond to timescales of $3x10^{-8}$ to $3x10^{-9}$ s and imply length scales of 10 m to 1 m (at the speed of light). Experimental observations of electron avalanche breakdown timescales in air [White, 1936; Wilson, 1936] roughly agree with these values. A primary FORTE mission science goal is to develop a comprehensive understanding of the correlation between the optical flash and the VHF emissions from lightning.

Space-based measurements of RF transients due to downward propagating lightning signals can be modeled by applying dispersive filtering (representative of ionospheric dispersion) to ground-based measurements of lightning. However, the positive potential difference between the ionosphere and the ground indicates a global electric circuit with charge transfer between cloudtop and ionosphere. Little is known about the characteristics of upward-traveling lightning. The FORTE mission will supply valuable RF and optical information on this exciting area of lightning physics.

Water transport is involved in charge transfer in the global electric circuit, although its exact role is not agreed upon, partially because correlated measurements of precipitation and lightning occurrence rates over areas exceeding mesoscale sizes are difficult to perform from ground stations. Small satellites such as FORTE offer an interesting platform for making these global correlation measurements.

Changes in the ionospheric total electron content (TEC) will produce variations in the amount of dispersion expected from a transient broadband RF source located below the ionosphere. Ground measurements of natural lightning sources will be augmented with controlled RF sources (active transmitters) and combined with FORTE data to study the effects of large scale structures such as traveling ionospheric disturbances and horizontal gradients in the total electron content within the ionosphere on the propagation of broad bandwidth RF signals.

Figure 1 shows some of the functional elements of FORTE. The trigger for the Data Acquisition System (DAS) can come from any of three sources: the RF section, the optical section, or the Flight Payload Controller (FPC) (for triggering at preset timed intervals). However, these triggering schemes still produce far more data out of the DAS than can reasonably be telemetered to ground. For example, a large lightning storm can fill the 108 MByte DAS memory in roughly 1 second. However, the DAS memory only gets downlinked once every 12 hours.

In order to reduce the total information telemetered to the ground, FORTE utilizes an advanced second level trigger called the Event Classifier. This Event Classifier incorporates special hardware for data preprocessing and neural network-based classification schemes. The Event Classifier is connected only to the FPC. The FPC routes commands to the Event Classifier over a serial link and sends DAS records over a high speed parallel link. The Event Classifier returns a record classification back to the FPC over the serial link.

FORTE Event Classifier Algorithms

The ionosphere reflects RF signals below a critical frequency that depends on the ionospheric TEC. This frequency is typically a few tens of Mhz for normal TECs. Frequencies above the critical frequency pass through the ionosphere and escape into space. Commercial television frequency bands are above the critical frequency. In order to maximize transmitted power, television broadcast antennas are usually aimed at the horizon. Thus, as the FORTE orbit pops over the various broadcast horizons, continuous TV carriers suddenly appear and disappear, resulting in continuous carriers that appear as transients. This effect is particularly strong over North America. The FORTE Event Classifier must distinguish any such events that manage to trigger the DAS.

There are also other man-made sources of RF transients that must be discriminated against by the Event Classifier. Short bursts of continuous wave carriers are produced by various communication and radar devices. Chirped radars also produce RF transients. These devices produce frequencies that ramp either up or down (typically linearly) in frequency over times approaching 10^{-6} s.

There are also natural sources of RF transients in space. Spacecraft discharges produce dispersionless broadband RF pulses with timescales shorter than 10^{-8} s. Terrestrial lightning is expected to be a much more copious source of RF transients in space. Lightning signatures can be modeled as wideband RF sources with timescales of order 10^{-8} to 10^{-9} s that pass through a dispersive filter, or ionosphere. Modeled waveforms of space-based measurements of lightning, chirped radar, and a short-lived continuous carrier are shown at the top of Figure 2. The extremely complex nature and associated difficulty of classification of these transients is evident.

It is also desirable to incorporate adaptability into operational systems. As the spacecraft passes from equatorial to polar regions, moves from sunlit to dark hemispheres, and passes over different land and ocean masses, the triggering and classification schemes need to change in order to maintain optimum performance. In addition, as the various RF and digital sections of the payload change with time (e.g., gains change), the classification scheme must adapt. Neural networks offer the exciting possibility of such adaptibility and robustness by incorporating onboard learning. Several such learning algorithms will be tried in the Event Classifier.

Previous work by Baumgart [1991] using data from a space-based RF payload element has demonstrated the feasibility of transient classification using neural network approaches [e.g., Pao, 1989]. The data consists of threshold triggered digital time series of broadband power levels at the spacecraft. After extracting peak amplitude, peak location, peak width (FWHM), and energy in each half of the record, they put these grouped features into a clustering algorithm. By adjusting the clustering vigilance parameter, a reasonable number of clusters were found. The records in each cluster were then examined visually and redundant clusters were combined. The resultant features and associated cluster values were then used to train a multilayer backpropagation neural network that exhibited 93% accuracy. This proven procedure is the baseline FORTE Event Classifier approach.

New approaches will also be tried in the Event Classifier. First, by performing joint frequency-time analysis, the various classes of RF transients can be more easily classified. This can be seen in the lower two panels of Figure 2, where the results of passing a sliding Fourier transform over the time series in the upper panels are shown. In the frequency vs. time representation, carriers show up as horizontal bands, chirped radars show up as slanted line segments, and spacecraft discharges (not shown) appear as vertical lines. Lightning and any other ionospherically dispersed signals form curves going from high to low frequency with increasing time. The curvature is a measure of the TEC that produced the dispersion.

After transformation into frequency-time space, the signals can be fed into a self-organizing map (SOM). As a preliminary step, we have trained an SOM network with 45 hand-selected samples of noise background, carriers, and signals (dispersed RF transients). Automatic selection of events using multiband power threshold crossings with causality constraints is currently being implemented. The training samples consist of the power in 17 frequency bins and 20 time bins, produced by sliding a 32 point FFT over the time series with 16 time steps per move. The 340 point records are fed into a 4x3 Kohonen layer implemented in the NeuralWare software package [NeuralWare, 1991] running on Sun platforms. The resulting clustering is shown in Table 1. These results are encouraging for SOM autoclassification of RF transients in space and will be tried in the Event Classifier.

The Event Classifier will have a variety of preprocessing and neural net options programmed onboard. Uplinked Event Classifier commands will consist of list sequences of function options, including peak detect and pulse width, pulse energy as a function of frequency, time integrated pulse energy, frequency vs. time conversion (sliding FFT, Hilbert transform, etc.), a clustering routine, a backpropagation algorithm, and a SOM. It will also be possible to uplink limited amounts of new code into Event Classifier temporary local memory.

Thus, existing as well as promising new ground-developed algorithms for classification of RF transients can be tested in space.

FORTE Event Classifier Hardware and Firmware

In order to implement space-based data preprocessing and neural network algorithms on digital time series records with communications to another computer via serial and parallel links, we have chosen to utilize existing Digital Signal Processing (DSP) technology. Neural network and fuzzy logic chip technologies can presently be purchased but their associated development systems and space flight characteristics are not mature. DSP systems have at least limited flight heritage and have complete off-the-shelf application development systems.

The DSP systems currently available must be augmented with radiation-hardened memory devices for use as the FORTE Event Classifier. The total mission radiation dose is less than 5 krad, but latchups must be non-destructive and have rates less than the average processing time per burst. The Event Classifier plan presented at this conference used an existing MIL-spec 6U VME board (produced by MIZAR, Inc. [MIZAR, 1993]) incorporating 4 Texas Instruments TMS320C40 DSP chips with 2 MBytes of RAM per DSP and 2 MBytes of global RAM shared among the DSPs (a total of 10 MBytes onboard), a JTAG port, a serial port, and 4 high-speed (200 MBytes/s) parallel ports. A second custom VME card housed radiation-hard (for the ~1 year mission lifetime) ROM for boot and program code and radiation-tolerant (~12 hour downlink to downlink timescale) EEPROM for temporary result storage. The proposed functional layout with weight and power estimates is given in Figure 3.

The Spectron SPOX operating system is a realtime DSP-based UNIX operating system [Spectron, 1991] with kernel sizes as small as 5 kBytes that was to slated be used to govern onboard processing. All code is written in C and TMS320C40 assembler and we planned to use the SPOX vector and matrix math libraries. In addition to processing serial command sequences, this firmware was to be responsible for processing 1 Hz state-of-health interrupts from the FPC. Processing times were estimated to be the order of 1 s per DAS record, well less than the mean time between latchup in this orbit. However, in the event of a latchup, the FPC interrupt will not be answered correctly and the Event Classifier power will be cycled for a restart by the FPC.

Initial program development on the MIZAR hardware was to be accomplished via JTAG interface. After the initial program development phase, communication via VME interface was to be implemented. The next step was to insert a local VME embedded controller emulating the FPC that communicates to the MIZAR board over the VME bus. The final step was to incorporate the serial and parallel links between the FPC emulator and the MIZAR board and test the MIZAR-custom memory board interface (also a high-speed parallel link will then Engineering approach.

Since the conference, the engineering plan has changed. Several components of the MIZAR board were found to be unsuitable for this mission. In particular, the TMS320C40 was found to have an unacceptably low latchup threshold (~6 MeV). As a result, we are now designing our own custom board to replace the MIZAR board. Because of the extremely short timelines involved, this new design is greatly descoped from the design presented at the conference. The new design will use a single TMS320C30 DSP chip (with a latchup threshold of 100 MeV) for computations and an Intel 8051 rad-hard microcontroller to decode commands and service the FPC interrupts. We will not be using the SPOX operating system but will use custom software instead. Weight, size, and interfaces are unchanged, but power consumption will be appreciably lower (less than 10 Watts).

Conclusions

The FORTE mission promises to provide exciting and fundamental new information on lightning and ionospheric physics. A key element of this combined RF and optical space-based experiment is an onboard Event Classifier. A variety of data preprocessing and adaptive neural network classification schemes will be tested on the payload using a combination of commercially available DSP and custom radiation-hardened technologies. Two separate classification schemes have been described for the difficult task of classifying space measurements of RF transients.

The FORTE Event Classifier described here represents a compromise between the desire to maximize functionality and ease of implementation versus the need to minimize spacecraft resources such as weight, power, and environmental tolerance. As in any engineering effort, many possible solutions exist. The approach chosen is the most state-of-the-art approach currently feasible given the fast mission schedule (launch in 1995).

Operational RF classification systems envisioned for future space missions may incorporate specialized neural network and fuzzy logic hardware as well as DSP-based feature extractors. While these advanced technologies are not currently flight-qualified, efforts are underway within the Department of Energy to ready them for flight. Multi-chip module and high density interconnect technologies are available for miniaturization of VME prototype systems, and software efforts on advanced training algorithms are underway. The solution to the space platform onboard decision problem is actively being pursued.

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Table Captions

Table 1. Results of SOM classification of 45 hand-selected frequency-time representations of RF noise background, carriers, and transients.

The left column is the winning Kohonen processor element, or category. The number displayed in each box is the number of records of a given class (vertical column) that were closest to the associated processor element. These results are encouraging for SOM autoclassification of RF transients in space.

Figure Captions

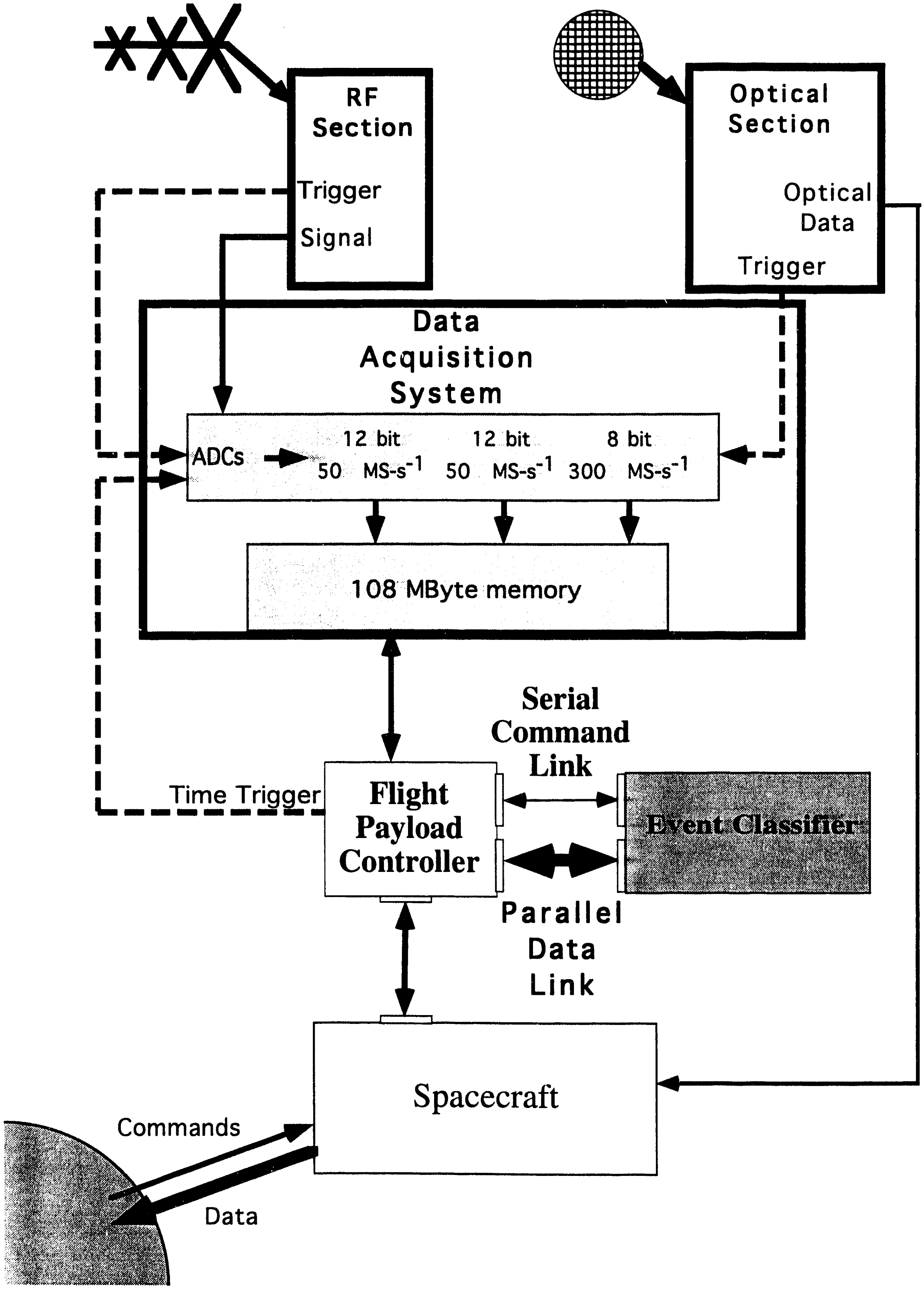
Figure 1. FORTE functional diagram. The Data Acquisition System can be triggered either by an RF trigger, an optical trigger, or at preset times by the Flight Payload Controller. The Flight Payload Controller routes commands (via serial link) and RF data records (via parallel link) to an Event Classifier. This Event Classifier uses special hardware to implement a combination of data preprocessing and neural network-based classification schemes to reduce the amount of RF data telemetered to the ground.

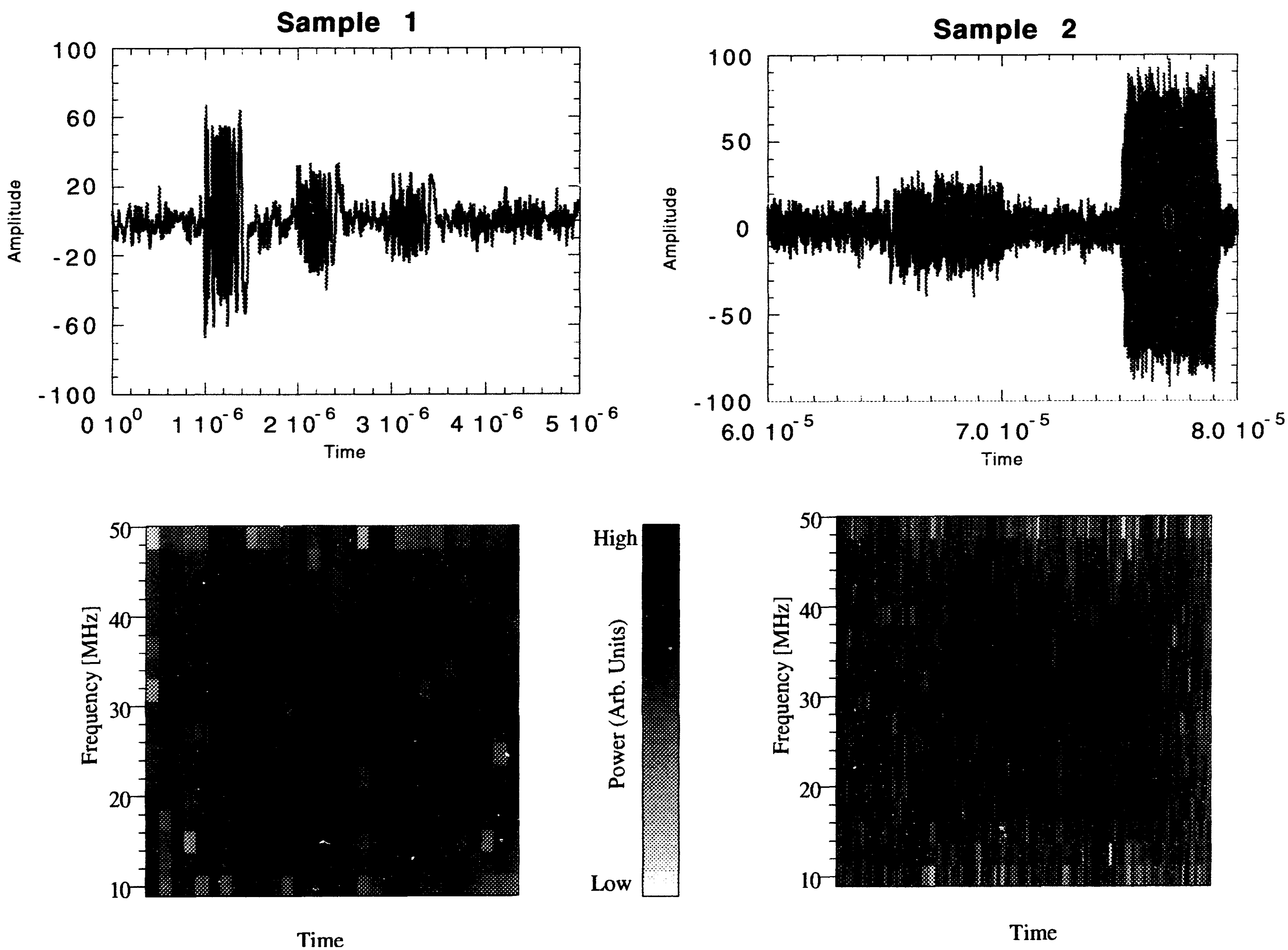
Figure 2. Top panels are waveforms predicted to be produced by the FORTE RF experiment. Amplitudes are in arbitrary units. The complex nature of the waveforms is evident. These transients have signal to noise ratios that may be significantly larger than those actually obtained during the mission. The bottom panels show the corresponding joint frequency-time spectrograms produced by sliding Fourier transforms. The three transients in the left panels represent a lightning source, while the right panels represent an upward chirped radar and a short continuous carrier burst. The frequency-time representation is clearly the better representation for humans to use in classifying these RF transients.

Figure 3. Functional layout of the FORTE Event Classifier as proposed at the time of the conference. It is comprised of a MIL-spec MIZAR quad-DSP board and a custom radiation-hardened memory board. Weight and power estimates are included. The Event Classifier is contained in a separate box and communicates only to the FPC via serial and parallel links. Due to unacceptable latchup charateristics,

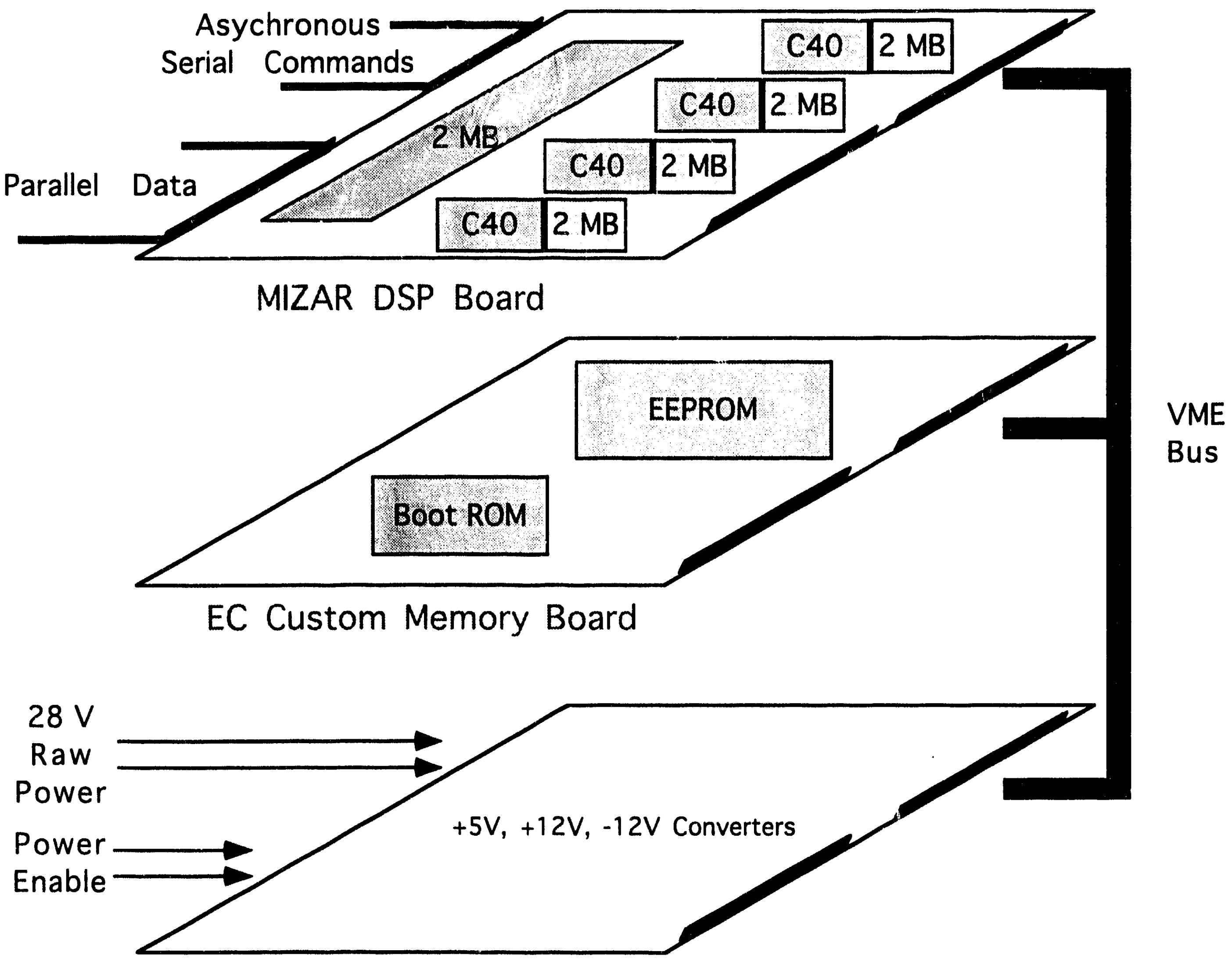
the MIZAR board has now been replaced by a custom board with a single TMS320C40 DSP processor and a microcontroller (see text).

FORTE FUNCTIONAL DIAGRAM




Sample 1
Amplitude
100
60
20
-20
-60
-100
0 10^0
1 10^-6
2 10^-6
3 10^-6
4 10^-6
5 10^-6
Time
Sample 2
Amplitude
100
50
0
-50
-100
6.0 10^-5
7.0 10^-5
8.0 10^-5
Time
Frequency [MHz]
50
40
30
20
10
Time
High
Power (Arb. Units)
Low
Frequency [MHz]
50
40
30
20
10
Time

FORTE EVENT CLASSIFIER



<u>Separate Event Classifier Box contains:</u>

2 6U VME Boards
Each board is 9.19" x 6.30" (233.5 mm x 160 mm)
Total area per board is 57.9 sq. in.

Estimated Weight: 2.5 kg (including box)

Power: 14.5 Watts operating (~1 second per event)
Need 5 V, +12 V, and -12V
1.0 Watt standby

Self-Organizing Map Results

45 samples → 8 clusters

PE	Background	Carriers	Signals	
1		5	1	6
2		1	2	3
4			1**	1
7	5	5		10
9	2	9	1?	12
10	1	1		2
11			1?	1
12		3	7	10
	8	24	13	45

Table 1

END

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