INTELLIGENT INSTRUMENTS FOR THE SPACE PLASMA ENVIRONMENT

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ABSTRACT

The work of the Space Science Centre at the University of Sussex in the development of intelligent space plasma instruments is presented here. Previously the Centre has included various intelligent techniques within space instruments flown on a number of space missions. A neural network was included in the SPREE instruments flown on Shuttle flights STS-46 (1992), and STS-75 (1996). Fuzzy Logic control of telemetry compression and buffering was designed for the ELISMA instrument on MARS-96. Sussex pioneered the use of particle correlation via hardware and software processing as a means of studying plasma wave-particle interactions using particle detection pulses within particle sensors, (AMPTE UKS, CRRES, STS-46, STS-75, ESA Cluster II, and auroral sounding rockets). Large interacting arrays of microprocessors were employed to provide processing for the above activities (e.g. 20 separate processors were used within SPREE). Also fault-tolerant arrays of processors were designed for the MARS-96 ELISMA instrument. Current research at the Space Science Centre concentrates on the development of flexible space instruments compatible with on-board intelligence and on increased use of Field Programmable Gate Arrays, FPGA, for fast real-time implementations of dedicated complex algorithms. For example real-time plasma simulations of the spacecraft's plasma environment are being implemented in FPGA with local measurements used directly as input parameters. These simulations can then be used to optimise instantaneous instrument parameters and, most significantly, by comparing simulation results with actual measured parameters concentrate data transmission on phenomena whose physics is least understood.

1. ASPECTS OF INTELLIGENT INSTRUMENTS FLOWN TO DATE

1.1 Particle Correlation

Since 1979 simple microprocessors have been added to energetic particle detectors so that fast, detailed information that would otherwise not be transmitted to ground could be processed on-board. Sussex pioneered the use of particle correlation as a means of studying space plasma wave-particle interactions (Gough , 1998a, Gough et al, 2002). Prior to the application of particle correlators electron detection pulses were simply counted as a function of direction of arrival and energy or velocity to generate averaged electron distribution functions. The fastest time resolution provided was typically 0.1s, usually limited by the energy cycle stepping sequence of the instrument. However, it was realised that electron detection times could be measured to nanosecond accuracy within the instrument and those arrival times would contain information about any resonant waves that the particles had interacted with in the space plasma local to the spacecraft. Fast electronics combined with microprocessors enabled Auto-Correlation Functions, ACF, to be generated from the fast particle detection pulses to cover all of the expected wave frequencies up to 10's of MHz. ACF were accumulated typically over seconds before transmission to ground, partly because of limited telemetry capacity and partly to improve measurement statistics.

Particle correlators were flown on various auroral sounding rockets, AMPTE UKS, CRRES, STS-46, STS-75, and ESA Cluster II. The microprocessors involved were often only simple 8-bit microprocessors: National NSC800; radiation hardened Sandia 3000; and various Z80, 8031, 8051, etc. Despite the relative simplicity of application particle correlators furnished important new results about the nature of the interaction of natural auroral beams with the earth's ionosphere at auroral latitudes. Similarly man-made electron beams on Shuttle flights STS-46 and STS-75 were shown to interact with the ionosphere to generate a variety of waves from kHz to several MHz. Figure 1 illustrates some of the MHz electron modulations observed by particle correlators on STS-75 and highlights the ability to identify interacting wave type by observed dispersion, or variation of wave period with resonant electron velocity.

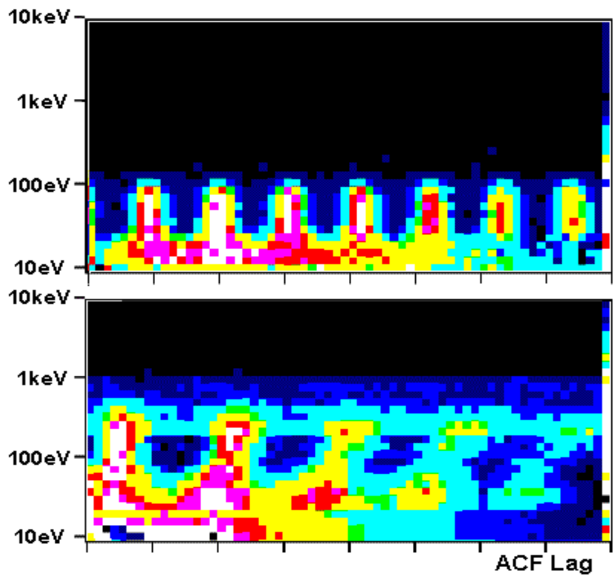

Figure 1. Wave particle interactions observed by 10MHz particle correlators on STS-75.
Electron ACFs with 64 lags of 50nS are plotted against 32 electron energy levels.
Upper plot - dispersionless modulations at electron gyrofrequency harmonics;
Lower Plot - dispersed modulations at frequencies corresponding to Bernstein waves.

1.2 On-Board Data Analysis by Neural Networks

The SPREE electron and ion instrument flown on STS-46 (1992) and STS-75 (1996) was a complex instrument with many outputs, including data types corresponding to both normal particle counting and also to a large dataset of particle correlation ACFs. SPREE generated over 20gigabytes of data that was stored for post-flight analysis in a modified Exabyte recorder inside the instrument located in the shuttle bay. Ideally, instrument modes should be controlled in real-time in response to the in-flight observations in order to optimise the science return. On these missions, however, the astronauts were scheduled with a high activity schedule that precluded their being able to monitor such a complex instrument. Also the continuous real-time telemetry available to SPREE was limited to only kilobit data rates. While this channel would enable the science investigators on the ground to monitor simple particle counting it would not provide a monitor of the ACF as this dataset was naturally the largest with at least one extra dimension (ACF time lag). Accordingly an Artificial Neural Network, ANN, (Gough, 1992) was included in the SPREE instruments for rapid ACF data analysis. A central 80C86 processor was already included to gather the results from the 18 individual ACF processors primarily to provide the function of formatting prior to recording on the Exabyte. By a simple software addition this processor was able to perform the ANN processing as a background task on the received 32 and 64 point ACF functions at a rate of 200 ACF functions per second. After suitable pre-flight supervised training of the ANN, each ACF was searched during the flight for 96 patterns in a time-domain pattern analysis. This search covered all possible frequencies of coherent wave modulation expected during DC electron beam emissions and also all possible electron radar return pulse pairs combinations expected during pulsed electron beam operations. The ANN consisted of 16 RAM neurons that each identified the most likely pattern while the output layer identified the single pattern with the highest vote. The final ANN output was simply the winning pattern number and its score, or significance. Figure 2 shows that the result of the on-board ANN analysis compares favourably with the subsequent post-flight analysis of the ACF by FFT.

On-board ANN in SPREE in fact first discovered by the particular scientific phenomenon illustrated in figure 2. These ion acoustic mode Cerenkov waves were found to be generated as the shuttle electron beam moving with the shuttle velocity across the earth's ionosphere exceeds the local ion acoustic velocity.

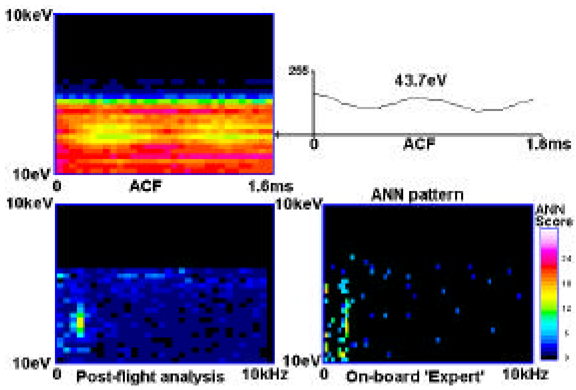

Figure 2. ANN discovered ion-acoustic mode Cerenkov wave phenomenon in the 10kHz electron correlator data. Real-time on-board ANN analysis is compared here with post-flight FFT analysis of the ACFs.

1.3 Fuzzy Logic Telemetry Control

A fuzzy logic system was developed to control the amount of instantaneous telemetry compression and buffering required for the various component instruments of the ELISMA wave instrument complex flown on MARS-96 (Monteiro et al, 1996).

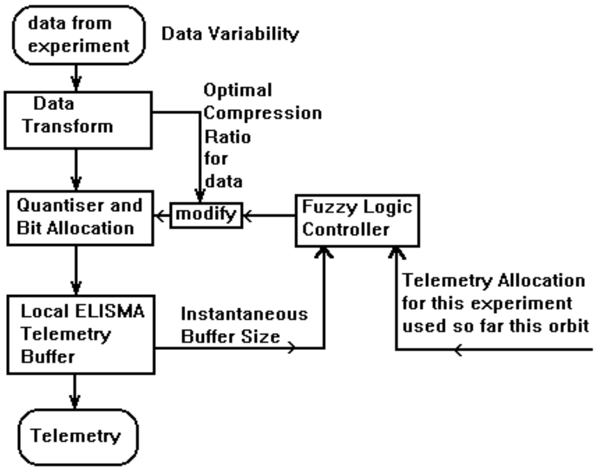

Figure 3. ELISMA telemetry compression ratio was controlled by on-board Fuzzy logic.

The overall data rate available for ELISMA was significantly less than the sum of the ideal data rates of the component instruments. A further data flow problem was caused by the necessity to sporadically buffer all data for significant periods when the available telemetry would be dedicated to the transmission of planetary pictures from the separate camera instrument. Figure 3 shows how the fuzzy logic algorithm continuously calculated the compression ratio for each instrument within the ELISMA complex. An ideal compression ratio was first derived for the data based on the instantaneous data variability obtained by the first stage of the compression process. Then, taking into account the available telemetry buffer and each instrument's use of its allocated data budget for that particular orbit the fuzzy logic modified this ideal compression ratio to obtain an overall optimum compression ratio for the prevailing circumstances.

1.4 Multi-Processor Arrays and Fault-Tolerance

1.4.1 SPREE. The large number of parallel computationally intensive processes involved in the above instruments has previously been implemented by arrays of processors. Often the functionality required naturally separates into separate parallel implementations of the processes. On SPREE some 12 eight bit microprocessors were used to implement 0-10kHz ACFs corresponding to 12 different electron and ion directions, and 6 hardwired fast special processors were used to implement the 0-10MHz ACFs corresponding to 6 different electron directions. Two sixteen-bit processors served all 18 ACF units - a total of 20 interacting processors. Such a combination provides redundancy to ensure sufficient scientific results in case of failures of individual ACF modules. Note that no failures or inter-processor communication faults were in fact observed during these two shuttle flights.

1.4.2 ELISMA. A fault-tolerant central processing unit was designed for the ELISMA wave instrument complex on MARS-96 using transputers. This used a combination of four processors, each with copies of all software processes to be run. Figure 4 shows that, in the event of failure of any one or more processors, the failed processor was bypassed by a switching of the links between processors. The fault-tolerant link switching was simply achieved in hardware with analogue switches and watchdog timers (Castro et al, 1991). After a failed processor is switched out the software processes required for the given instrument mode are then redistributed amongst the remaining hardware processors. Such autonomous fault-tolerant operation exhibits a graceful decay and is an essential requirement of planetary missions where the round-trip communication link takes >30minutes and a persistent failed state may lead to the instrument sustaining irrecoverable damage.

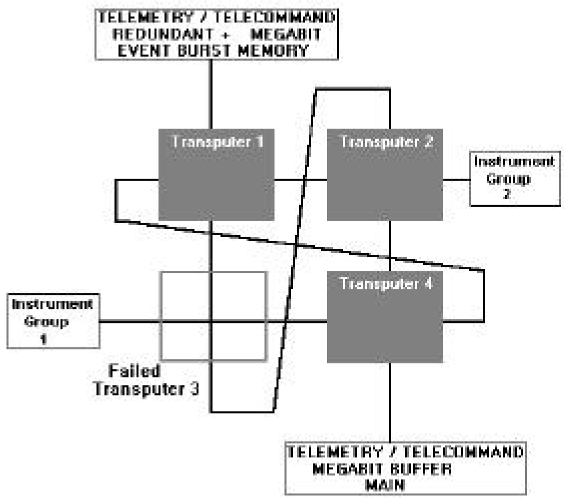

Figure 4. This fault-tolerant transputer array decays gracefully in response to processor failure by switching links to bypass failed processors and by redistributing the software processes amongst the remaining processors.

2. CURRENT INTELLIGENT INSTRUMENT DEVELOPMENT

2.1 Instrument Design for Flexibility

Prior to the use of on-board intelligence many instruments were of a 'point and click' variety with little real flexibility in mode of operation. In general it is a good design practice for instruments to have much extra flexibility in order to make efficient use of on-board intelligence. Instruments should be designed to cover a wider range of measurement parameter space and at higher resolutions than is apparently required from the pre-mission knowledge of the phenomena to be measured. Instruments need to have the ability to produce high quality data at rates higher than the data bandwidth allocated to them in the existing telemetry system. On-board intelligence can then be used to optimise the instrument measurement parameter space, optimise instrument resolution, and select the most scientifically valuable data for transmission. These activities ensure that the scientific return is maximised.

For example, in the above field of instruments involving particle detectors combined with particle correlators it makes sense to design a detector frontend such that it covers simultaneously many electron energies and directions, rather than stepping through energy space in a time sequence or relying on spacecraft rotation to complete the scan of directions. FPGA (see below) can then calculate a very large number of ACF functions in parallel and ANN can be used to select for transmission only those containing promising results. We are presently developing the CORES instrument (Corelating Electron Spectrograph) for inclusion on the Russian/Ukraine Obstranovka Instrument complex planned to fly on the International Space Station in spring 2004. As a spectrograph with a 360-degree field of view this instrument measures all energy-angles simultaneously, without stepping in energy. Associated FPGA can provide sufficient processing power to enable all energy angles to be studied via ACF. On-board intelligence then applies strong selection criteria to cut the data rate down to a realistic final value. FPGAs are also employed in the CORES sensor head to resolve in 2-D the energy and angle of each detected electron within 100nS.

2.2Field Programmable Gate Arrays

Current research at the Space Science Centre concentrates on the use of Field Programmable Gate Arrays, FPGA, for fast real-time implementations of dedicated complex algorithms within future space instruments (Bezerra et al, 2000a). FPGAs are ideal for implementations of particle correlators, supervised ANN like the one previously flown on STS-46/75, unsupervised ANN as discussed below, and general data compression algorithms. FPGA reliability is high since radiation hardened FPGAs are now available with high gate counts and also fault-tolerant techniques can be easily included within FPGAs to ensure algorithm integrity and continuous autonomous operation. For example, key processes can be copied in triplicate within an FPGA and a confident result derived by voting. Usually the level of fault tolerance that can be implemented in practice is limited by the ratio of FPGA effective capacity relative to capacity needed for the required functions.

2.3 Multi-Input Particle Correlation

In the field of space plasma multi-input particle correlators are being developed for future instruments with automatic analysis. For example, FPGAs will be used to simultaneously analyse over 100 outputs of the CORES instrument. Each output will have the following processes applied: normal count summation; high frequency ACF (10MHz); low frequency ACF (10kHz); extra low frequency ACF (150Hz); event recognition; and ANN pattern classification with scoring enabling selection of the most promising data for downlink.

An example of the processing speed-up provided by switching processing to FPGAs is illustrated by considering the 10kHz ACF functions that were previously implemented on SPREE within 8051 type microprocessors. This ACF function consisted of nested software loops involving many multiply-additions. By transferring this software function from a microprocessor to hardware FPGA implementation, the central function, which previously took 4096 clock cycles, could be completed in a one single FPGA cycle (Bezerra et al, 2000b). Furthermore this function only takes up a small fraction of the FPGA gate area.

2.4 Artificial Neural Networks

2.4.1 Supervised ANN have been developed for real-time compression of typical space plasma data. Typical plasma wave instrument spectra can be compressed on-board at reasonable ratios ~10:1 without any loss of scientific value (Reeder et al, 1996).

2.4.2 Unsupervised ANN have been traditionally used to classify data and identify new patterns and new classes of pattern. For example, the Associative List Memory, ALM, (Gough, 1997, 1998b) can rapidly process patterns of over 10^5 bits size and readily lends itself to FPGA implementation on-board space instruments. The data can be scanned in real-time to identify existing and new patterns or phenomena. Such information can then be used to make intelligent decisions on both instrument operation mode and selection of data for transmission.

2.4.3 Data Mining is a rapidly expanding application activity usually associated with ground-based databases. A typical example, the Whole Information System Expert, WISE, was developed at Sussex (Gough, 1993, Gough & Breuckner, 1995, Berry et al, 1996). This system combined pattern identification and classification of the features occurring in the different instrument datasets with identification and classification of the occurrence pattern of those features as a function of geomagnetic co-ordinates, space weather activity, and time. In this method of automatic data mining common phenomena can be identified across very different data types.

In principle these techniques are also applicable within the space instrument. By up-linking ancillary data, such as spacecraft location and geophysical activity, directly to the instrument processor and by expanded inter-experiment communication links, data mining techniques would further improve the instrument's knowledge of the importance of the present measurement. More appropriate decisions can then be taken concerning this instrument's, and other instrument's, measurement parameter space, downlink data rate, etc.

2.5 Real-Time Phenomena Simulation

FPGA can be used to implement complex space plasma simulations to achieve speeds comparable to clusters of large ground computers (Popoola, 2002). Therefore real-time plasma simulations of the spacecraft's plasma environment can be implemented in an on-board instrument FPGA with local instantaneous measurements of key plasma parameters used directly as input parameters. These simulations can then be used to predict other measurements for comparison with those actually being obtained. The simulation results can be used to optimise instrument parameters in real-time. Moreover, by comparing simulation predicted parameter values with actual measured parameters, data transmission can be concentrated on phenomena whose physics is least understood. Such a form of data selection provides the optimum compression and maximum scientific output.

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