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CASSINI RADIO AND PLASMA WAVE INVESTIGATION: DATA COMPRESSION AND SCIENTIFIC APPLICATIONS

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The Radio and Plasma Wave Science (RPWS) experiment being built for the Cassini spacecraft will study a wide range of plasma and radio wave phenomena in the magnetosphere of Saturn and will also make valuable measurements during the cruise phase and at other encounters. A feature of data from wave receivers is the capability of producing vastly more data than the spacecraft telemetry link is capable of transmitting back to the Earth. Thus, techniques of on-board data compression and data reduction are important. The RPWS instrument has one processor dedicated to data compression tasks.

1. INTRODUCTION

The Radio and Plasma Wave Science (RPWS) instrument is a set of radio receivers onboard the Cassini spacecraft designed to study naturally emitted radio and plasma waves from Saturn's magnetosphere and atmosphere. At present, most of our understanding of the radio, plasma and magnetic environment of Saturn has come from the measurements during the flyby of the Voyager 1 and 2 spacecraft. These measurements indicate that the Kronian, or Saturn's, magnetosphere is the source of a wide range of trapped and freely propagating radio emissions which will be studied in more detail by the Cassini RPWS instrument. This paper does not attempt to be comprehensive but presents specific examples of emissions to illustrate onboard data compression.

Radio waves are generated in the magnetospheres of five planets; Earth, Jupiter, Saturn, Neptune and Uranus, and are important in the remote-sensing of magnetic structures of the giant planets. The generation of these waves is of astrophysical interest. Plasma waves are important to the understanding of many energy and momentum transfer processes by providing effects analogous to collisions in un-ionised gases. Langmuir probe and sounder techniques will be used in the study of plasma processes and, in particular, in some ionospheric studies around Titan.

The team for the RPWS investigation is given in Table 1 where their main technical responsibilities are also outlined.

2. SCIENTIFIC OBJECTIVES

The first *in situ* observations of radio and plasma waves at Saturn were by Gurnett *et al* [1] and Warwick *et al* [2]. They showed a variety of phenomena, some of which are targets for detailed study by RPWS.

The radio wave measurements of RPWS will concentrate on the Saturn kilometric radiation (SKR). The generation mechanism for this emission is generally considered to be the cyclotron maser mechanism [3] which yields intense emissions in the right-hand polarized extraordinary mode at frequencies near the local electron cyclotron frequency. The radiations come from the dayside auroral zone, on field lines which are close to the dayside plasma cusps [4]. The intensity is strongly modulated at Saturn's internal rotational period [5] and has other modulations which are asssociated with variations in the solar wind dynamic pressure and the orbital position of Dione. The SKR may be associated with the "spokes" in the rings and does show fine structure which was not resolved adequately by Voyager. At frequencies below those of SKR other radio emissions have been observed [1] which are thought to have been caused by mode conversion from electrostatic waves at half-integral harmonics of the electron cyclotron frequency and may come from near Rhea, Dione and Tethys. The radio continuum radiation has a low frequency cut-off [6] which will yield an electron number density profile of the outer magnetosphere of Saturn. Saturnian Electrostatic Discharges (SED's) were originally detected by Voyager and should easily be observed by the RPWS. These unusual signals appeared as intense, broadbanded bursty emissions and are believed to be created by atmospheric lightning discharges [7]. The emission low frequency limit can be used to estimate the ionospheric plasma density.

The plasma wave environment of Saturn is rich with a wide variety of phenomena [8]. Some specific questions for RPWS are; what types of plasma waves are associated with gas emissions from Titan, the rings and the icy satellites; how are newly-injected ions thermalized; which wave-particle interactions cause the loss of radiation belt particles; what waves are involved in the aurora; do plasma waves accelerate charged particles in the magnetosphere and what waves exist in the magnetotail and polar regions of Saturn's magnetosphere which were not visited by Voyager? Many of these questions are of a physical importance and can be studied best at Saturn where the gas and dust environment is unique.

Low energy plasma measurements will be made by RPWS using the Langmuir probe and sounder instruments. The plasma density can also be inferred from the ambient plasma wave data.

TABLE 1: *RPWS Investigators and their key technical responsibilities.*

RPWS Investigator	Institution (Country)	Main Technical Contribution
D.A.Gurnett (P.I.) W.S. Kurth (Deputy P.I.)	Univ. Iowa (USA)	Electric pre-amplifiers, Data processing unit, Medium frequency receiver, low frequency channel receiver, Wideband receiver
K.Goetz P.Kellogg	Univ. Minnesota (USA)	
M.D.Desch W.M.Farrell M.L.Kaiser	NASA/GSFC (USA)	Electric antenna
F.Genova C.C.Harvey A.Lecacheux P.Zarka	Meudon (France)	High frequency receiver, Sounder
P.Canu N.Cornilleau-Wehrlin P.Louarn A.Roux	CRPE/CNET (France)	Sounder, Magnetic antennae
G.Gustafsson J.-E.Wahlund	Uppsala (Sweden)	Langmuir probes
H.O.Rucker	Graz (Austria)	
L.J.C.Woolliscroft	Univ. Sheffield (UK)	Data compression

These data will be used collectively to determine the ionospheric profiles of Titan and for studies of Saturn's magnetosphere. Small scale fluctuations will yield an understanding of turbulence induced by the complicated interactions of Titan, Saturn and the solar wind and perhaps show soliton-like density structures in auroral field-aligned current regions.

The micron-sized dust environment of Saturn is probably caused by micrometeoroid impacts on the rings and the icy satellites. These dust particles are important; they can be a source of gas and plasma, they can absorb energetic particles and, as charged bodies, they electrically interact with the ambient plasma creating a dusty plasma. When dust hits the spacecraft, a small cloud of plasma is generated which can be detected by the RPWS electric antenna. Questions to be studied include the mass and spatial distribution of the particles in the Saturn system and hence their role in plasma processes.

On the way to Saturn, RPWS will make measurements of solar generated phenomena, such as type III solar radio bursts and waves from interplanetary shocks. These observations will take place at a different time in the solar cycle compared to those previously made and could also be combined with simultaneous observations by Voyager, Galileo and Ulysses (provided that those spacecraft continue to function) to give a better understanding of spatial and temporal structures in the solar wind. Interplanetary dust will also be studied.

The planned asteroid fly-by may be too distant for local plasma wave measurements but weak radio emissions and dust particles may be detected.

The Jupiter encounter will provide the opportunity for multi-spacecraft measurements (with Galileo) and hence direction finding on radio wave source regions. New regions of the magnetotail of Jupiter should be visited by Cassini. Specifically, the RPWS will be able to monitor the freely escaping Jovian decametric, hectometric, kilometric and continuum radio components over long time periods. Such observations will indicate the time variability of the Jovian auroral region and Io torus.

3. RPWS INSTRUMENT

The RPWS instrument, [9], was proposed to NASA and the selected instrument is used as the basis for this paper. It is likely that the instrument flown will have evolved from the selected baseline. The block diagram of this baseline instrument is shown in fig. 1. The relationship between this figure and the scientific objectives can be inferred from fig. 2 (a,b) which shows best estimates, based on previous measurements, of the various signals to be detected around Saturn. The planned dynamic range will be some 100 dB and should thus encompass all the major scientific signals of interest. These levels are also suitable for studies in the solar wind and at other bodies on the way to Saturn. Not explicitely shown in these figures is the Langmuir probe which will provide the number density of thermal electrons together with electron temperatures. The Langmuir probe and the wideband receiver will also be used to detect small dust impacts. The data processing unit will include one processor module which is dedicated to data compression and similar application tasks.

The Cassini Data Compression Processor uses a CMOS 8085 radiation hard processor. The 8085 is used in a somewhat expanded configuration which uses an address latch to give a full 16-bit address bus. The clock is 2.0 MHz (TBC) received from the BIU (TBC). Reset is initiated by an internal power-on circuit or by command from either the High Rate Processor or the Low Rate Processor.

The compression processing unit contains 64K of 8 bit read/write memory and 2k of 8 bit read-only memory. Communication uses a CMOS 81C55 I/O chip which contains 22 bits parallel I/O and a 14-bit programmable counter. An 8-bit bus oriented port is used for high speed communication with either the High Rate or the Low Rate Processor.

4. RPWS DATA COMPRESSION

It is easy to show that data compression by factors of a million

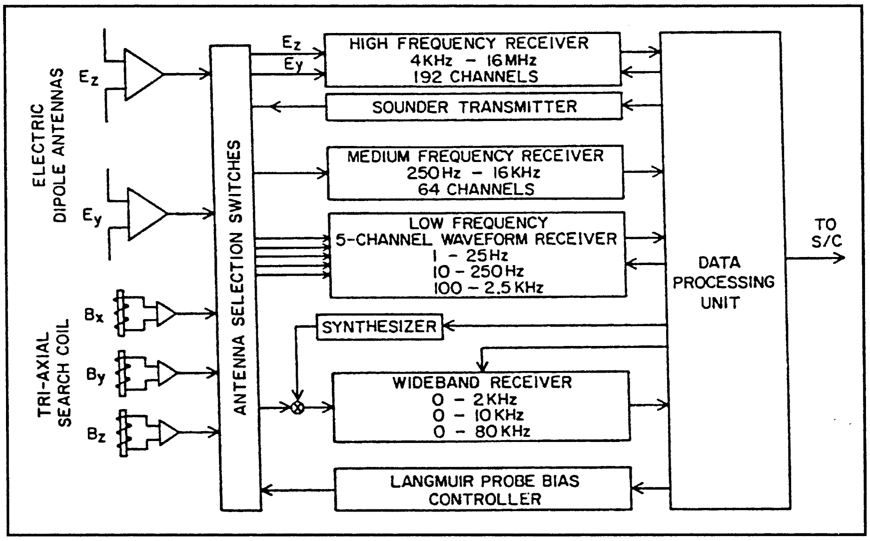

Fig. 1 The RPWS functional block diagram.

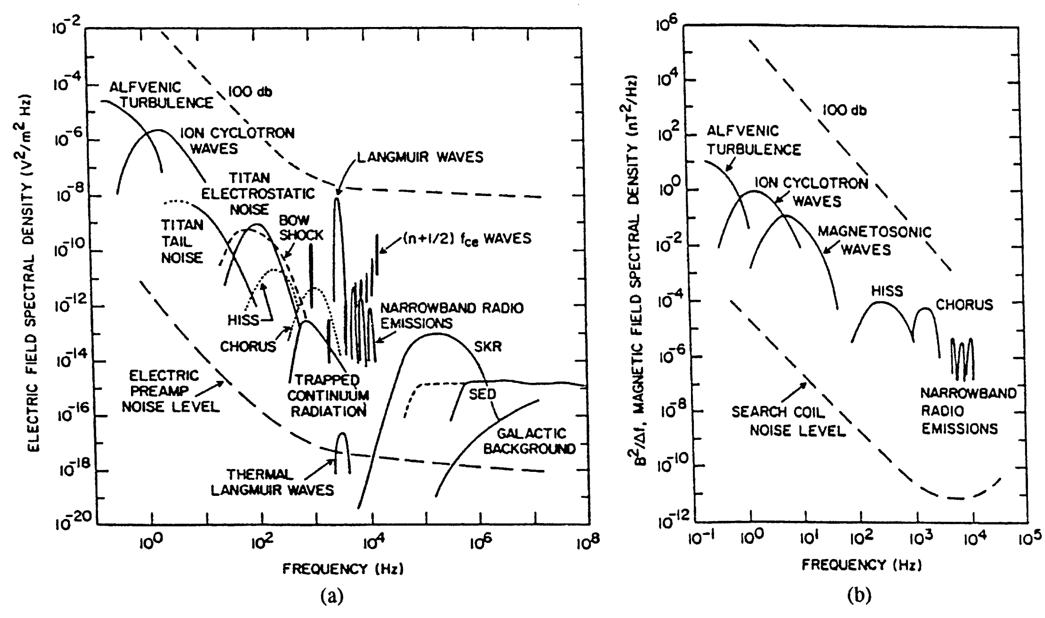

Fig. 2 Noise levels for (a) electric fields and (b) magnetic fields which can be expected around Saturn plotted against frequency. The electric field measurement levels assume an effective dipole antenna length of 20 m.

or more is needed to ensure that all the data which the RPWS transducers (antennas and probes) produce is sent to Earth. This is not possible. Traditional wave instruments have used hardware data compression and selection in determining their signal processing block diagram. This tends to be rather inflexible and it is hard to cover the wide range of phenomena which RPWS anticipates measuring. So RPWS is being designed so that the hardware is capable of producing data at a rate above that which is allocated by the on-board data handling system and telemetry. Software compression will be used together with instrument mode selection from Earth.

The RPWS low-rate modes have data returning at the rate of either 1, 2 or 4 kbps. The 'normal' low rate mode is the 1 kbps rate. The data will be packetized, with a typical packet containing about 76 bytes of header (i.e., time, pointers, etc.) and about 1024 bytes of science data. Although the exact details of the packet structure are not presently known, it is assumed that multiple data sources of varying output rates are embedded within. Further, these different sources can be either in a compressed or uncompressed form. For ground testing and for use during test operations it is desirable to be able to turn off the data compressor and return data in its uncompromised format. A modular structure which allows data to be processed without compression will also increase the reliability of the RPWS instrument in space. Table 2 shows the proposed nominal bit rate for the different instruments comprising the RPWS experi-

TABLE 2: *Approximate data rates from RPWS low rate instruments.*

High Frequency Receiver (HFR)	450 bps
5-Channel Waveform Receiver (WFR)	360 bps
Sweep Frequency Receiver (SFR)	56 bps
Digital Spectrum Analyser (DSA)	96 bps
Dust Detector	10 bps
Langmuir Probe	100-200 bps

ment. Clearly, the HFR, WFR, and Langmuir probe have the larger sample spaces, thus compression of data from these particular instruments will be most beneficial.

In contrast, the high-rate mode returns data at a faster rate, between 10 and about 400 kbps. In the past (e.g., Voyager Plasma Wave Experiment), the high-rate mode was reserved for the wide-band (WB) waveform receiver, this sampling voltage as a function of time, V(t). These data then undergo spectral analysis on the ground. On Cassini, it is anticipated that WB data and packets containing other instrument samples will be returned via this mode. The WB waveform receiver samples at a frequency a little above the Nyquist frequency (to allow for real filter effects). Data compression will allow more samples to be returned in a given time interval, effectively increasing the receiver bandwidth. For example, if a 5 to 1 compression scheme is used for the WB instrument, the compressed data in the 10 kHz band has the same sample space as all the uncompressed data in the 2 kHz band. Consequently, the mode having a higher bandwidth can be used with compression. Clearly, data compression has a direct impact on the performance of this particular receiver. For other parts of RPWS the effect of compression can be to improve the temporal resolution of the measurements.

There are various techniques for data compression which are being evaluated for the RPWS instrument. They can be classified roughly as follows:-

4.1 Lossless compression techniques

Zero information loss compression reduces the redundancy in the data stream to achieve a data compression. This form of compression is known by many different names: zero entropy compression implying that increasing entropy is associated with increasing disorder, noiseless compression because no noise is introduced, lossless compression because there is no information loss and compaction because the data are made more compact without changing them.

4.2 Information loss techniques

At first sight it might be felt that compression which allows some loss of information would be scientifically un-acceptable. But we remember that the absence of data compression implies an information loss as well with high resolution features missing from the dataset. It can be argued that this is not too bad a problem since we are familiar with the instrumental limits, but, by the same argument, we can become familiar with the limitations caused by some data compression information loss. It is possible to make the information loss well-understood or well-controlled. For example, with wave receivers, a requantization of the values to a lower resolution might be acceptable in certain applications such as the creation of a frequency versus time radio spectrogramme. However, such requantization may not be acceptable in other applications such as wave-normal calculations.

Figure 3 shows an example of an information loss technique known as adaptive delta modulation (ADM). The algorithm being applied is one originally created by Song *et al* [10]. The top curve shows the actual data from the Voyager-2 PRA experiment during the spacecraft encounter with Neptune. The lower curve shows the reconstructed data following compression to 2 bits per sample *via* Song *et al's* process. From the figure we note that there is reasonably good correspondence between the actual and ADM time series.

4.3 Transform techniques

Various techniques exist which apply a mathematical transform to the data as a part of a compression scheme. This transform may be a Fourier transform (more frequently the FFT algorithm is used) or, for example, a Hadamard transform. The actual transform process does not normally provide any compression. Neither does it, in general, cause any information loss. The reason to apply a transform is that, in transform space the data can be put into a form in which some subsequent simple compression strategy will be effective. The subsequent compression may, of course, then be either a zero information loss or an information loss algorithm. One difficulty with this approach is that it requires careful analysis to evaluate the effect of any information loss of the transformed variables in the compression stage.

Figure 4 shows an example of compression using a transformation. The actual Voyager-2 PRA measurements shown in the top curve were transformed using a fast Walsh-Hadamard transform (WHT). As previously mentioned, the transformation itself does not compress the data. However, compression results from processing the transform coefficients. For the case shown in the figure, the coefficients were requantized to just six levels based upon their statistical average value and standard deviation. These requantized coefficients were then efficiently packed using run-length coding. This combination results in a compression down to 2 bits per sample. As is evident in the figure, there are some minor distortions in the WHT time series that result from the requantization process.

4.4 On-board analysis techniques.

It can be argued that the main reason for on-board analysis of the data is purely to do with data compression. There are, however, reasons why on-board analysis may have additional value; closed loop servo control (to hold a probe close to space potential) and event recognition to trigger a different mode of instrument operation are two examples.

5. DISCUSSION

The RPWS experiment will make comprehensive measurements on the radio and plasma wave environment of Saturn. Data compression and selection will be used to enhance the range of measurements. There are paradoxes to be considered in the design of space instrumentation - if the characteristics of the parameters being measured are known sufficiently for a sure design, then these parameters may not be scientifically the most exciting. To express this another way, it is the unexpected measurements which may be the most important. The RPWS approach is to have a flexible instrument and to use it in a way that will allow some exploratory measurements. A further

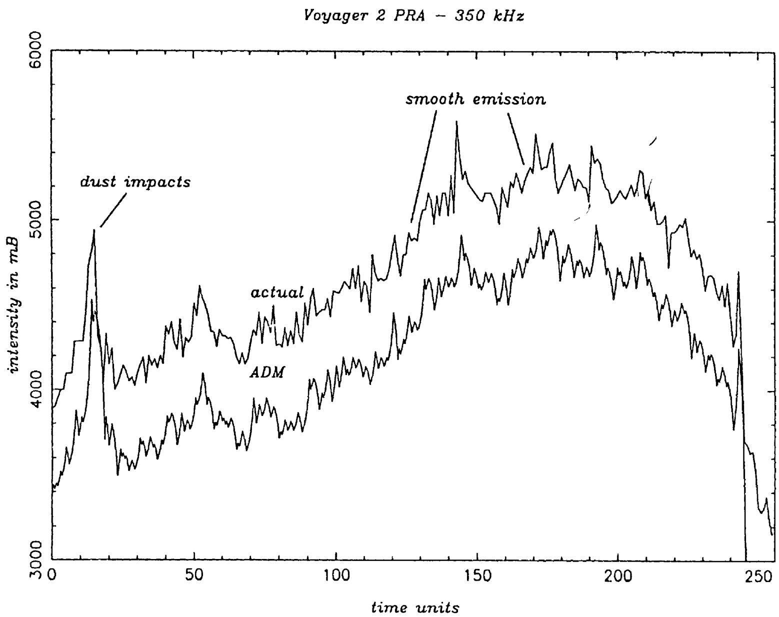

Fig. 3 Voyager-2 PRA data compressed using ADM algorithm (lower line) and original data (upper line).

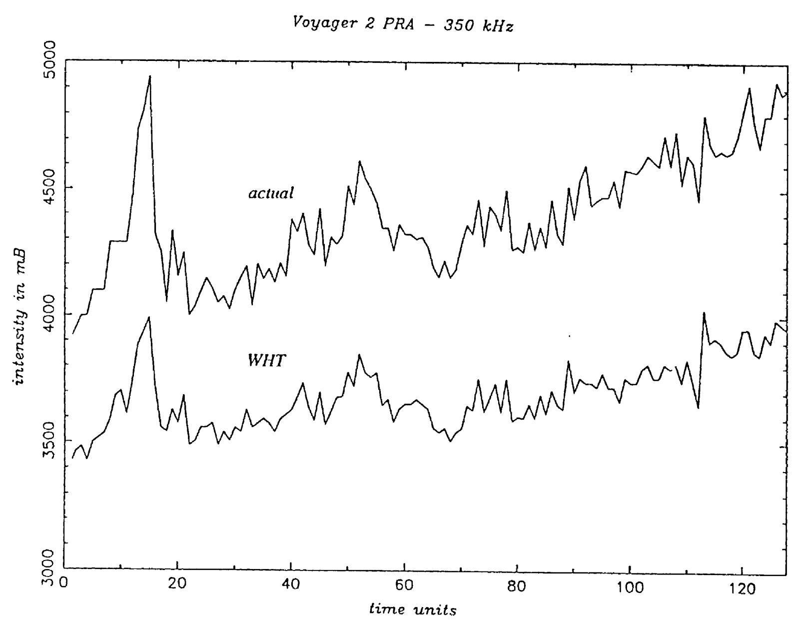

Fig. 4 Voyager-2 data (upper line) and after WHT transformation and requantization (lower line).

paradox concerns data compression. The most effective algorithms involve some loss of information. The RPWS approach is to ensure that all data selected have a well characterized accuracy.

It should be noted that to take advantage of data compression the instrument hardware must be capable of generating data at rates which are greater than can be handled directly by the Cassini data handling system (i.e., telemetry). This implies an early decision to adopt some compression or, if compression were to fail, make compromises with instrument operation to return to the nominal bit rate.

6. ACKNOWLEDGEMENTS

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