Development of a Radiation Hardened 2 GHz Acquisition System for Space

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Abstract—This paper presents Southwest Research Institute's radiation hardened digital oscilloscope tailored for space applications. The Waveform Capture System (WCS) was designed as a data acquisition system for a time of flight instrument on the European Rosetta cometary mission. The WCS is a radiation hardened low power, single board solution, providing 11 bits of accuracy, sub-nanosecond resolution, and complete command and data handling. This paper details the design and evolution of the WCS, as well as presenting results from recent testing of the engineering qualification module (EQM) with the time of flight instrument.

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1. INTRODUCTION

Recent years have seen a dramatic increase in space based mass spectrometry. Recently launched mass spectrometer instruments include the Plasma Experiment for Planetary Exploration (PEPE), Cassini Plasma Experiment (CAPS), and Thermal Ion Dynamics Experiment (TIDE). The European Space Agency's Rosetta mission includes several mass spectrometers providing a unique opportunity for large scale, multi-year *in situ* study of the structure of a comet. One of the instruments dedicated to the study of the volatile components of the cometary coma is the ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) instrument. The Waveform Capture System (WCS) is one of the primary data acquisition systems for the ROSINA RTOF (Reflectron Time of Flight) [1] instrument.

Time of flight systems are based on the principle that the flight time of a particle is proportional to the particles mass per charge. In the ROSINA RTOF, the cometary ions enter one end of the time of flight tube, traverse through the system and arrive at a detector, in this case a microchannel plate (MCP).

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Acquisition of the MCP data requires a high degree of accuracy, both in time and amplitude. This level of accuracy is required due to the nature of the scientific measurements. A discussion of how these measurements relate to the design of the WCS follows.

2. REQUIREMENTS

The design and performance requirements of the WCS reflect the rigorous and ambitious scientific objectives of the ROSINA RTOF instrument and Rosetta mission as a whole. The design of the WCS calls for a full data acquisition system, integrating both command and data handling functions as well as data acquisition onto a single circuit board. The individual design and performance requirements of the WCS are summarized below in Table 1.

Table 1. Performance Requirements for WCS

Performance Constraints	
Time Resolution	<2.0 nanoseconds
Maximum Extractor Rate	10KHz, programmable
Acquisition Window	64 microseconds
Conversion Accuracy	10 bits
Serial Command / Housekeeping	Programmable
Time for Full Spectral Acquisition	2 seconds
Data Downlink Rate	125 KHz
Physical Constraints	
Radiation	<15 Krad
Mass	<500 grams
Power	<8 watts average
Operation Temperature Range	-30 °C to +60 °C

An example of how the scientific requirements translate into engineering constraints is the measurement of isotopic ratios in the coma of the comet. Accurate determination of these ratios requires a high degree of temporal resolution (on the order of 0.5 to 2 nsecs), as well as a wide dynamic range (i.e. 4 to 6 orders of magnitude). Traditional space data acquisition systems, such as Time to Digital

Converters (TDC's), provide excellent time resolution, but typically only a limited dynamic range. The WCS is unique in the respect that it provides not only time resolution comparable to the performance of TDC systems, but also a considerably wider dynamic range.

Southwest Research Institute's design for the WCS has evolved over the last 2 years from initial concept to the delivery of the engineering qualification module. We begin the discussion of the design of the WCS with review of the original design work.

3. WCS EVOLUTION

In the initial conceptual stages of the WCS, an evaluation was made of the current state of the art in sampling technology and their application to a high reliability, space targeted system. The limits imposed by the operational environment (i.e. limited power, mass, extreme temperature, and radiation) proved to pose numerous problems for current sampling techniques. A unique sampling method would have to be derived to satisfy the performance goals and operational constraints.

Initial work on the design of the WCS began in the fall of 1997. The first generation of the WCS was based on a time domain sampling technique for repetitive waveforms.
Figure 1 shows the original sampling concept. A high speed ramp with a period equal to the waveform to be sampled was generated, along with a much slower ramp function. The two ramp functions were compared with a high speed comparator, resulting in the ramp crossings generating the trigger pulses for successive time sampling of the waveform.

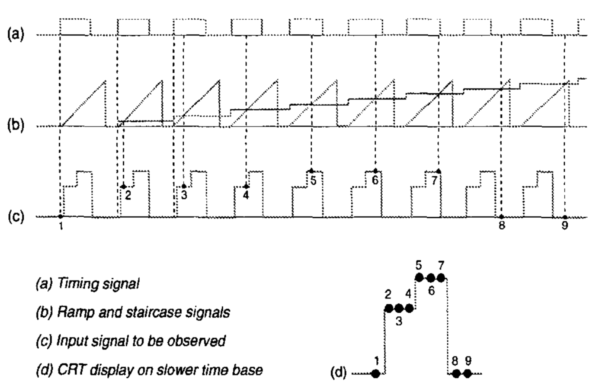

Figure 1. Ramp / Comparator Sampling

Based on this initial approach, a breadboard proof of concept design was produced. The breadboard unit contained a number of separate circuit boards implementing the functions of each subsystem. Subsequent successful testing of the breadboard led to the design and development of a laboratory prototype, merging the separate elements into a single printed circuit board solution.

After significant testing of the laboratory prototype a number of limitations of the ramp sample system were discovered. The integration of the separate analog circuit boards from the breadboard unit, with a full command and data handling system into a single module introduced noise into the system. The ramp crossing method has a high susceptibility to noise, which translates into a loss of both amplitude and time resolution.

Following these tests, a redesign study began to determine a more robust system for sampling. The sampling technique that was finally selected is based on a time domain multiple-pass, delayed sampling method.

4. MULTI – PASS SAMPLING

The multi-pass delayed sampling method acquires the spectra through repetitive sampling of the incoming waveform. The sampling is controlled through a set of delay lines providing a sampling stepsize of 500 picoseconds.

The sampling begins by driving an extractor pulse to the ion optics, which launches stored ions toward the MCP. The ions strike the MCP, delayed by a time of flight equivalent to their m/q (mass / charge). The MCP output is fed directly to the WCS and amplified for sampling and data conversion.

The multi-pass delayed sampling uses a set of two delay lines to control the individual sampling. The first delay line, the wide step delay line, provides a programmable delay with steps of 125 nanoseconds. The second delay line, the fine step delay line, provides another programmable delay, with steps of 500 picoseconds.

Actual sampling of the flight time is broken into 8 discreet time slices. These slices cover a full 64 microsecond range in 8 microsecond blocks. Each extractor firing causes one sample to be taken from each of the eight time slices. After sampling a given time slice, the sample delay for that slice is incremented by a programmable amount (minimum of 500 picoseconds). This, in effect, steps the sampling of the time of flight data over each 8usec window. Figure 2 below illustrates the function of the individual time slices in the multi-pass concept.

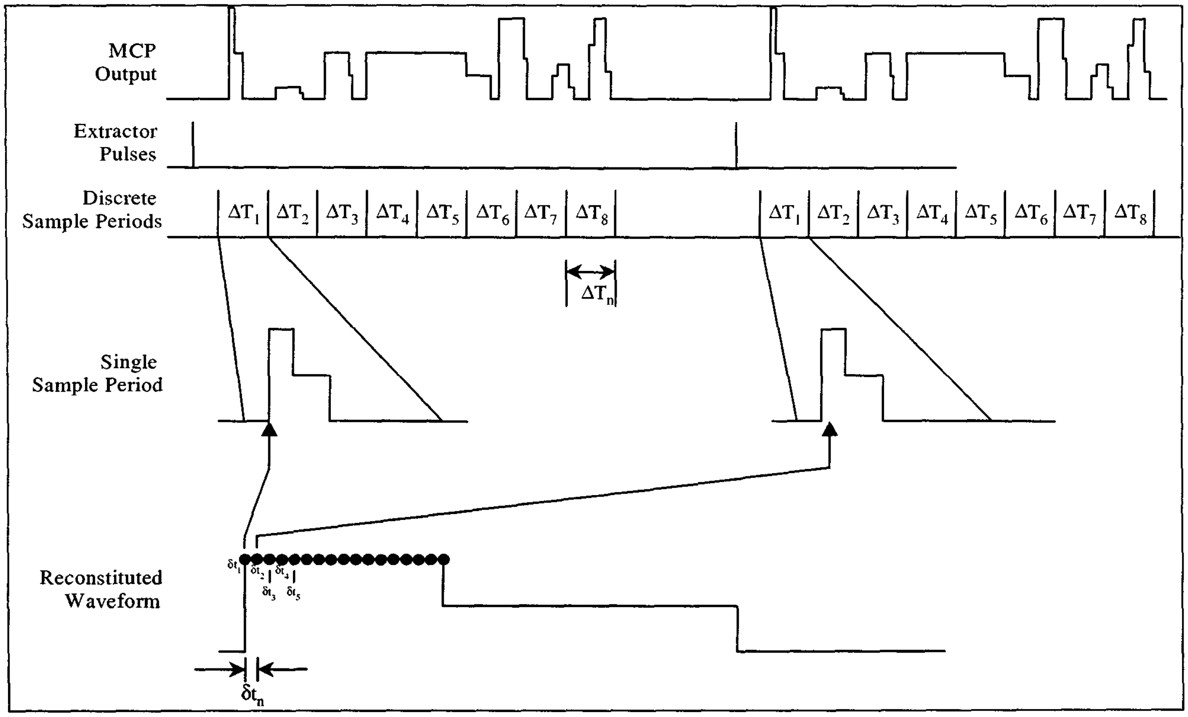

Figure 2. Multi-Pass Sampling

The notation used above in Figure 2 is continued throughout this paper to denote the sampling structure as well as the individual samples. Each individual time slice is designated ΔT_1 through ΔT_8, while individual samples within each time slice are referenced as δt_1 through δt_{16000}. Any of the 128000 possible samples can be referenced by its time slice (ΔT_i), and its sample delay (δt_j), as $\Delta T_i \delta t_j$.

5. Sampling Flexibility

The WCS expands the multi-pass concept by incorporating an extremely flexible sampling system. This sampling flexibility allows the WCS to acquire spectral ranges by manipulating individual time slice characteristics.

In the WCS full spectrum mode, the entire 64 microsecond time of flight spectrum is recorded with 500 picoseconds of accuracy. The calculation for the time required to acquire the full spectrum is shown below in (1).

$$t_{acquisition} = 8\frac{samples}{extractor} \bullet \frac{1}{T_{extractor}} \bullet N_{samples} \tag{1}$$

The fastest extraction rate the WCS supports is 10KHz (i.e. $T_{extractor}$ = 100 microseconds). Plugging the extraction rate, along with the 128,000 samples taken in full spectrum mode into (1), the time required to acquire the full spectrum is 1.6 seconds. This length of time is short enough to obtain a large amount of spectral information for the ROSINA RTOF. However, some scientific measurements intended for the ROSINA RTOF require more periodic sampling to measure shorter duration phenomenon.

To support these short term measurements, the WCS provides the ability to individually and independently set the location and width of the data to be taken in each time slice. By optimizing the starting points and ending points of each time slice for scientifically significant regions, the actual number of data samples taken can be dramatically reduced.

As an example, consider Table 2 below, which illustrates a possible configuration of the time slices. This configuration not only manipulates the sampling windows within each time slice, but also the sampling step size. Note: All time entries are in microseconds.

Table 2. Example Time Segment Parameters

Time Slice	Start (usec)	Stop (usec)	Step Size (usec)
1	0	200	0.5
2	8000	8800	2
3	16500	16700	0.5
4	31000	31200	0.5
5	35000	38200	8
6	40000	40400	1
7	49000	49200	0.5
8	58000	58200	0.5

The time slice parameters shown above control the position and number of samples to be collected in each time slice. The table configuration collects 400 samples for each of the time slices. The number of samples is given by (2).

$$\#samples = \frac{(stop - start)}{stepsize} \qquad (2)$$

The data acquired using Table 2 takes 5 milliseconds. This is a dramatic reduction from the 1.6 seconds required for the full spectrum mode. From a scientific standpoint, this provides the ability to collect rapid statistical data in quickly changing areas, (i.e. "zoom" in on individual mass peaks).

In addition to the programmability of each time slice, the WCS also provide the ability to position the overall 64 microsecond sampling window up to 500 microseconds out in time. This allows the WCS to acquire spectral data covering a large time of flight range, which translates into the ability to acquire spectral data for the higher masses (beyond mass 500).

6. Detailed Design

A block diagram of the WCS is shown below in Figure 3. From the block diagram, 3 major subsystems are apparent: high speed sampling circuitry, command and data handling, and the communications interface. The design methodology for each subsystem will be explored in this section.

High Speed Sampling Logic

As previously discussed, ions are released into the time of flight system by firing the extractor circuit, the trigger of which is controlled by the WCS. Once the ions are released, they traverse the time of flight tube, arriving at the detector after a flight time proportional to their mass. The detector output is fed directly into the WCS where it is conditioned, processed, and sampled by the high speed sampling circuitry. The sampling circuitry itself is composed of several major blocks: initial amplification, sampling pulse control, diode bridge sampling, analog to digital conversion, and sample discharge.

Once the signal from the detector reaches the WCS it is fed through an RF amplifier, providing 10dB of signal gain. The use of an initial amplification stage significantly improves the overall signal to noise ratio. The output of this amplifier is fed as the input to the diode bridge for sampling. The actual sampling control for the bridge is based on the multi-pass delayed sampling, described previously. The bulk of this control logic, as well as a programmable 125 nanosecond step delay line is implemented in a single field programmable gate array (FPGA). Figure 4 provides a more detailed look at the logic needed to provide the timing for a single time slice.

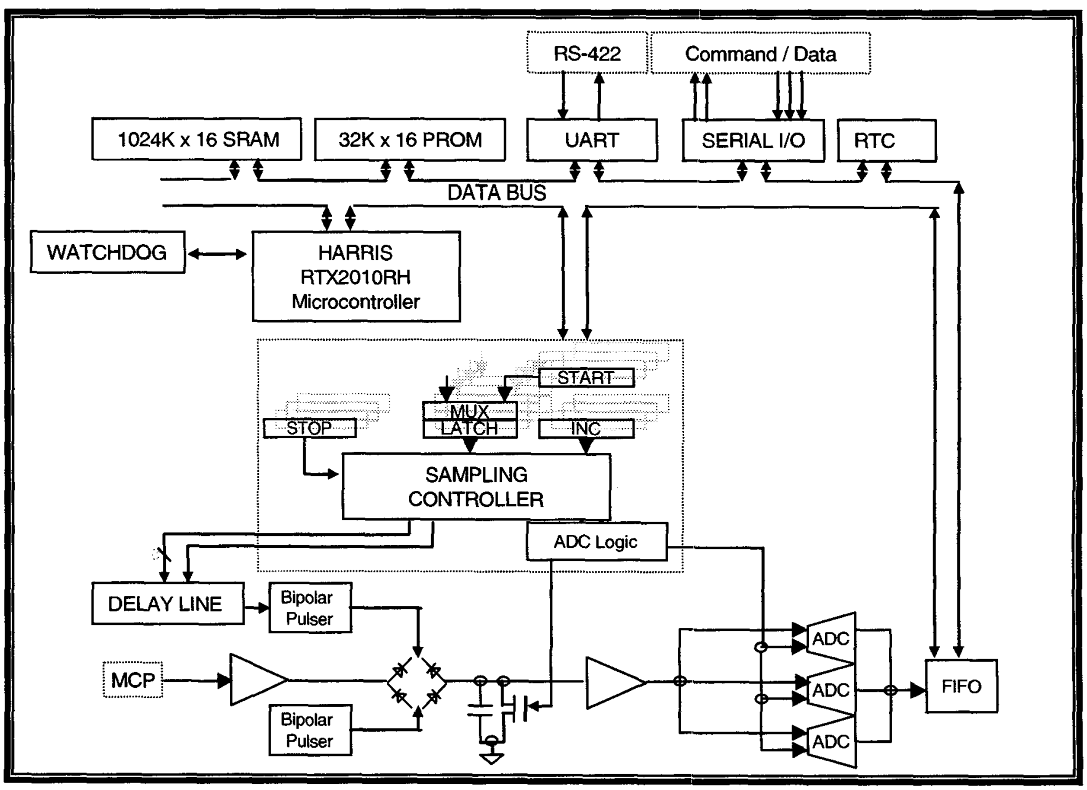

Figure 3. WCS Block Diagram

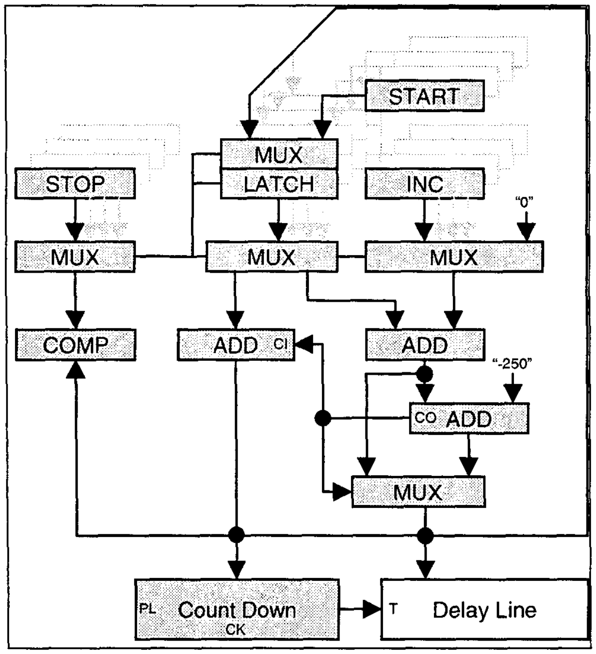

Figure 4. Slice Control Implementation

The control for each time slice is implemented as a set of start / stop and increment registers. The active time slice is specified through external logic, with the selection of the slice begin accomplished by the multiplexers shown. For a given time slice, the increment value is added to the start register contents, and stored into an accumulator. The accumulator is compared with the value of the stop register. If the result is less than the stop value, the result is split into two portions. One contains the number of 125 nanosecond steps in the result, the other contains the remainder. The remainder portion is fed to a discreet programmable delay line, external to the FPGA, as the delay amount in 500 picosecond steps. The 125 nanosecond steps become the count value for programmable delay line, internal to the FPGA. The delay line is implemented as a count down timer, shown in Figure 4. The output of the delay line feeds the input of the external programmable delay line. If the accumulator value was greater or equal to the stop register contents, then the accumulator is reloaded with the original start register value.

Once the appropriate delay value is determined, the sampling pulse is sent through the delay lines, which provides the correct timing and triggers the sampling circuitry.

This process is repeated for each time slice every extraction cycle. The net effect is a fully programmable, continuous sampling of the incoming waveform.

Upon generating the sampling control signal, the output of the sampling logic is fed circuitry referred to as the bipolar pulse generators. The bipolar pulse generators produce extremely narrow (500 picosecond) pulses that are designed to trigger the diode bridge, sampling the input waveform. This triggering / sampling occurs 8 times per extractor cycle firing, i.e. once per time slice. The final samples are held on the sample and hold capacitor

The output of the sampling bridge feeds a set of gain amplifiers, which provide the final sampled waveform to a set of 3 time multiplexed radiation hardened 100KHz analog to digital converters. The use of multiple converters is required to collect samples closely spaced in time, due to the conversion times of the 100 KHz ADC's. As higher frequency, lower power, radiation hardened converters become available, the number of A/D converters can be reduced, thus reducing the required power.

Special care must be taken in calibrating the individual converters to avoid offset and gain differences between the three A/D's.

The converted samples are stored in a FIFO for processing by the onboard command and data handling system. Storing the samples in a FIFO provides a number of advantages in data processing. The most significant of which is the ability for processing the past extraction samples concurrently with storing new data. The FIFO allows the processor to accumulate and store the samples using the full extractor cycle (100 microseconds, at the fastest rate). Without the FIFO, the processor would be forced to accumulate and store the samples in the dead time between extractors. This would severely load the processing resources and force the use of higher clock rates, increasing overall power consumption.

Once the samples have been converted and stored to the FIFO, the initial sample must be discharged from the storage capacitor. A FET switch is used for discharging the capacitor to ground. Recent testing has demonstrated that extensive care must be taken in the control and selection of the FET. One of the main drawbacks of the use of a FET switch is the coupling of the gate voltage to the source or drain voltage. This coupling takes the form of both high frequency noise as well as an overall increase in the current. [2]. By carefully choosing the FET based on response time and capacitance, and providing a filtered and conditioned gate voltage, the noise coupling can be significantly reduced.

Command / Data Handling Subsystem

The command / data handling subsystem of the WCS provides for complete acquisition control, command decode and execution via the serial command channel, housekeeping reporting, data storage and data transmission, as well as error checking and status monitoring.

The WCS implements a full command and data handing subsystem. The core of the system is the Harris

Semiconductor RTX2010RH, a radiation hardened 16 bit microcontroller, operating at 12 MHz. Supporting the RTX is 32K x 16 of radiation hardened PROM, 1024 x 16 of radiation shielded SRAM, as well as two field programmable gate array's (FPGA's). The WCS also supports 32K x 16 of socketted FLASH memory to aid in software development, which can be replaced with radiation hardened PROM.

The Harris RTX2010RH processor is a fully radiation hardened processor, capable to 300 Krad (Si). The overall processor architecture represents a FORTH engine tailored for computationally intensive tasks. The 16 bit processor provides single cycle execution, three 16 bit timers / counters, two on chip 256 word stacks, as well as support for traditional DSP functions such as multiply-accumulate, barrel shifting, etc.

The FPGA's provide additional peripherals to the processor, including: Watchdog timer, real time clock, interrupt controller, and a programmable clock generator.

The bulk of the operational software for the WCS is implemented in 'C'. Computational intensive routines, such as the data acquisition functions are implemented using the RTX assembly language, which is based heavily on the FORTH programming language. The WCS software is modifiable in flight, allowing new code to be uploaded as needed.

To best support the ROSINA time of flight instrument, the WCS operational software has been designed to serve as the final flight software for the system. The software is structured to support the various scientific goals by providing: multiple stored sampling configurations, sample co-adding, calibration functions, and post acquisition signal processing.

Communications Subsystem

The WCS provides serial communication interfaces for commanding and downlinking data. The command interface provides a time multiplexed command and housekeeping serial channel, while a separate serial channel is provided for data downlinking.

The data format used for the downlink data is CCSDS (Consultative Committee for Space Data Systems) source packets [3]. This format allows the data to be packetized into a well known, international data format, providing a large degree of flexibility and standardization.

The command and data channels for the ROSINA instrument are operated at 125KHz, with the clocks provided externally in both cases.

In addition to the command / housekeeping and data channels, a standard 38400 baud, RS-422 UART is provided. The UART provides additional support for further software development, and greatly improves the overall system testability.

Table 3 below provides a summary of the subsystems implemented in the WCS.

Table 3. WCS SubSystem breakdown

SubSystem	Description
High Speed Sampling Logic	1. 10KHZ to 2.5GHz RF Amplifier 2. High speed sampling bridge 3. Fast Extraction Drivers (100 psec rise time) 4. Three Time multiplexed ADC's 5. Programmable Extractor Rate 6. Programmable Sampling Start / Stop / Increment 7. Programmable delay lines – 0.5nsec and 125nsec
Command / Data Handling	1. Harris RTX2010RH rad hard microcontroller 2. 32K x 8 rad hard ROM 3. 1024 x 16 rad shielded SRAM 4. Real Time Clock / Watchdog Timer 5. Interrupt Controller.
Communication	1. Independent serial data / command channels 2. Time multiplexed command / housekeeping channel 3. RS-422 UART (38400 Baud)

8. Radiation Tolerance

Radiation hardening of the WCS is accomplished through selection of radiation hardened, qualified, or tested components. Overall, the WCS is functional to 100 Krad's (TID). Table 4 below indicates the radiation characteristics of each major subsystem and the corresponding part implementations.

Table 4. Subsystem Implementation

Subsystem	Part Selection	Vendor
Processor	Rad-Hard Microcontroller	Harris
Memory – ROM	Radiation Hardened PROM	Lockheed Martin
Memory – SRAM	Radiation Packaged SRAM	Space Electronics
Communications subsystem	Radiation Packaged FPGA	Space Electronics
Acquisition Controller	Radiation Packaged FPGA	Space Electronics
Analog to Digital Conversion	Radiation Packaged ADC's	Space Electronics
Glue Logic	Radiation Tolerant process	National Semiconductor

RF Amplification	Radiation Tolerant Process	Stellex Microwave
Analog Processing	Radiation Tested	Analog Devices

8. RESULTS

Figure 5 below shows the engineering qualification module (EQM) of the WCS. The EQM weighs 435 grams, consumes approximately 8 watts of power, and has been fully qualified over the temperature range of –40 °C to +70 °C.

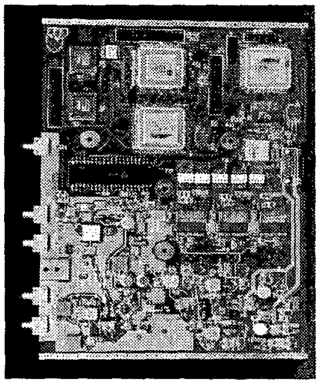

Figure 5. WCS Engineering Qualification Module

The WCS EQM has recently been delivered to the University of Bern, in Switzerland for integration with the EQM of the ROSINA RTOF. The results of these tests have been very successful. Figure 6 below illustrates the performance of the WCS with the laboratory prototype of the ROSINA time of flight system. The peak shown corresponds to an Argon 40 peak (width of 20nsec) obtained with a single pass through the spectrum (i.e. no spectral averaging). The horizontal axis shows the time of flight, while the vertical axis represents raw A/D conversion result (un-correlated).

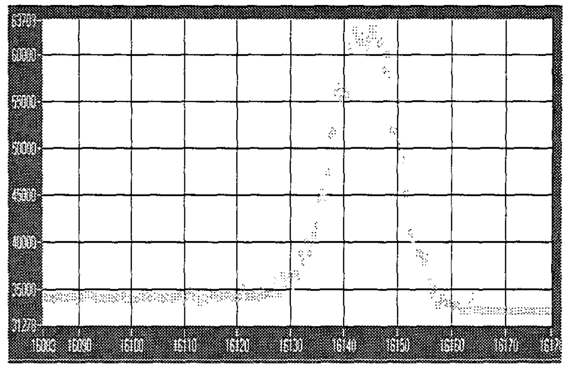

Figure 6. Argon 40 Spectrum

One of the major scientific objectives of the ROSINA RTOF instruments is the accurate determination of isotopic ratios in the comet's coma. Figure 7 and Figure 8 below compare the performance of the WCS verses the performance of a commercial 1.5 GHz digital storage oscilloscope. The data shown is a Xenon spectrum. The WCS data was acquired with a single pass through the spectrum with no averaging, while the oscilloscope data shown has been averaged 1,000 times. As can be seen from these figures, the WCS does an excellent job acquiring the various xenon isotopes with a performance that is comparable to the digital oscilloscope. It should be noted that both the horizontal and vertical axis between these two graphs represent raw, uncorrelated values and are included as a point of reference only.

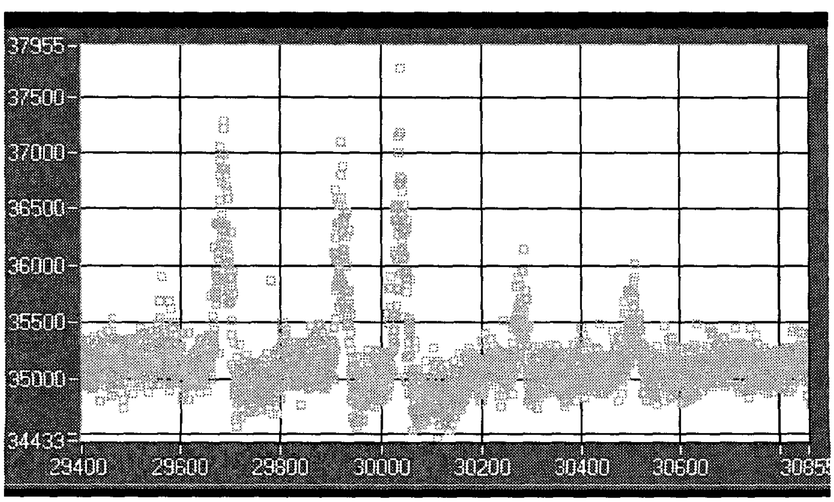

Figure 7. WCS Data - Xenon Spectrum

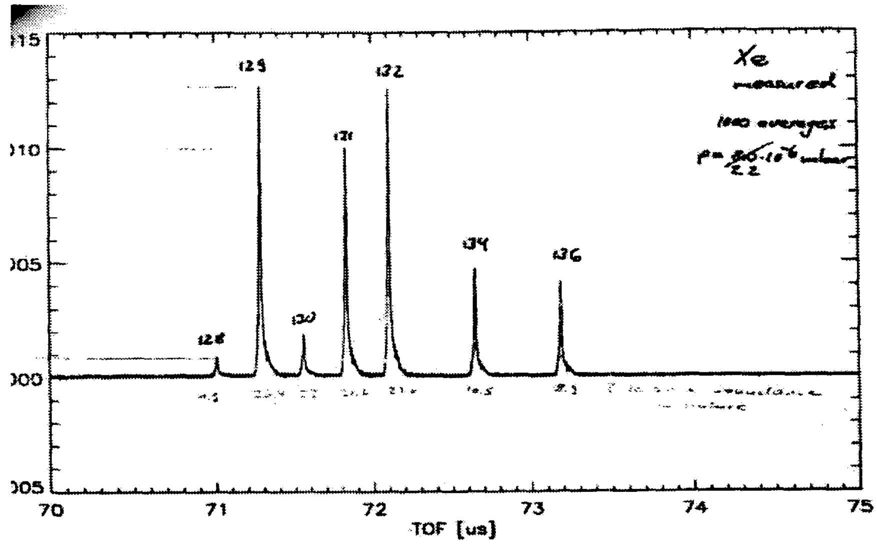

Figure 8. Digital Oscilloscope - Xenon Spectrum

Additional tests have been performed at SwRI as well as in Switzerland characterizing the overall performance, both in time and amplitude. The results of these tests are still under analysis, but initial results indicate the WCS provides 11 bits of sample accuracy, with a time jitter on the order of 200-300 picoseconds.

9. Future WCS Activities

As mentioned, the WCS is currently undergoing integration in Europe with the engineering qualification module of the ROSINA RTOF instrument. Detailed testing of the fully integrated instrument is underway and will continue through the first few months of 2000. These tests will verify the accuracy, stability, and commandability of the WCS.

Production of the flight WCS units will begin in May 2000, with a delivery date for final integration with the flight instrument of early August, 2000. Additionally, the WCS is currently baselined into a number of other SwRI mass spectronomy experiments.

10. Conclusion

In this paper we have presented the Waveform Capture System (WCS), a 2 GHz sampling system tailored for space applications. The WCS provides a complete data acquisition system featuring 11 bits of sample accuracy, coupled with 500 picoseconds of time resolution. The WCS contains an extremely flexible sampling system, providing full configurability, which can be tailored for specific scientific goals (i.e. iosotpic ratio determination, long statistical dwells, etc.). Initial test results demonstrated the ability of the WCS to accurately collect scientific data from the prototype time of flight system. The WCS presents an innovative, and high performance, data acquisition system tailored for the rigors of space operation.

11. References

[1] Stefan Scherer, *Design of a high performance Reflectron Time-of-Flight mass spectrometer for space applications*, PhD dissertation, University of Bern, Switzerland, 1999.

[2] Paul Horowitz and Winfield Hill, *The Art of Electronics*, Cambridge: Cambridge University Press, 1989.

[3] Consultative Committee for Space Data Systems, *Telemetry, Summary of Concept and Rationale*, CCSDS 100.0-G-1, Green Book, 1987

Buddy Walls *is a research engineer with Southwest Research Institute. Prior to joining SwRI, Mr Walls worked on low bit rate speech coding as part of the recent Department of Defense Digital Voice Processing Consortium study. Since joining SwRI, he has developed custom hardware for the IMAGE, QuikSCAT, Coriolis and ROSETTA satellite missions, as well as the CAPER sounding rocket program. In addition to his hardware design, Mr. Walls has produced embedded software for the SwRI integrated GPS control computer, ROSINA WCS, as well as the QuikSCAT satellite program. Mr. Walls is currently serving as deputy program manager for the ROSINA WCS program. Mr. Walls has a bachelors and masters degree in electrical engineering from Oklahoma State University.*

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Dr. J. H. Waite *is the Director of the Space Science Department in the Instrumentation and Space Research Division at SwRI. While at SwRI, Dr. Waite has served as Team Leader for the Cassini Ion and Neutral Mass Spectrometer investigations, and co-investigator in two planetary observing programs with HST. Dr. Waite is currently serving as a co-investigator on the ROSINA instrument. Prior to coming to SwRI, Dr. Waite was a research scientist at NASA's Marshall Space Flight Center. Dr. Waite is a member of the American Geophysical Union, and a former editor of the AGU letter journal, Geophyiscal Research Letters. Dr. Waite received his bachelors in physics at the University of Alabama, and masters and PhD in physics from the University of Michigan.*

Mike Pilcher *joined Southwest Research Institute's Communications Engineering Department as an engineer in 1998. He designed analog electronics for the ROSINA WCS as well as analog and digital electronics for the Instantaneous Personal Protection System. He has assisted internal research in the areas of radar and antenna modeling. Mr. Pilcher received his bachelors in electrical engineering from Rose-Hulman Institute of Technology and is currently pursuing a masters from the University of Texas in San Antonio.*