A LOW-MASS FARADAY CUP EXPERIMENT FOR THE SOLAR WIND

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ABSTRACT

Faraday cups have proven to be very reliable and accurate instruments capable of making 3-D velocity distribution measurements on spinning or 3-axis stabilized spacecraft. Faraday cup instrumentation continues to be appropriate for heliospheric missions. As an example, we have estimated the reductions in mass possible relative to the solar wind detection system we are about to fly on the WIND spacecraft. Through the use of technology we have developed or used at the MIT Center for Space Research but were not able to utilize for WIND: surface-mount packaging, field-programmable gate arrays, an optically-switched high voltage supply, and an integrated-circuit power converter, we estimate that the mass of the Faraday Cup system could be reduced from 5 kg to 1.8 kg. Further redesign of the electronics incorporating hybrid integrated circuits as well as a decrease in the sensor size, with a corresponding increase in measurement cycle time, could lead to a significantly lower mass for other mission applications.

Reduction in mass of the entire spacecraft-experiment system is critically dependent on early and continual collaborative efforts between the spacecraft engineers and the experimenters. Those efforts concern a range of issues from spacecraft structure to data systems to the spacecraft power voltage levels. Requirements for flight qualification affect use of newer, lighter electronics packaging and its implementation; the issue of quality assurance needs to be specifically addressed. Lower cost and reduced mass can best be achieved through the efforts of a relatively small group dedicated to the success of the mission. Such a group needs a fixed budget and greater control over quality assurance requirements, together with a reasonable oversight mechanism.

I. Introduction

Modulated-grid Faraday Cup sensors are useful for measurement of solar wind parameters because of several important properties. They measure the "reduced" velocity distribution of the plasma due to their inherent integration over velocities contained in a plane of differential thickness perpendicular to the axis of the sensor; they measure currents due to fluxes on a collector plate of low energy charged particles and are thus immune to radiation-induced counts in detectors using multiplier structures; and their wide field of view allows them to be used on 3-axis stabilized spacecraft as well as on spinning spacecraft without employing a scanning mechanism. Because they are not differential in angle, they require relatively low data rates; but, of course, for a given orientation they provide differential information in velocity space only along a direction perpendicular to the modulator grid.

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The modulated-grid Faraday cup has been a mainstay of space plasma measurements from 1961 [*Bonetti et al.*, 1963] to the present day. The basic technique, used by the space plasma physics group at MIT, consists of applying a time-varying, square wave potential to a grid within the cup and then synchronously detecting the corresponding modulated component of current on the collector plate due to particles within a known energy-per-charge window. Modulation of the current allows positive ions to be separated from electrons and both to be separated from the constant photo current produced by solar UV impinging on the collector plate, while synchronous detection allows for relatively large signal-to-noise ratios to be maintained over a large dynamic range ($\approx 10^5$). Other grids suppress production of secondary electrons from the collector plate [*Bridge et al.*, 1960; *Vasyliunas*, 1971].

The modulation technique was originally developed to measure the relatively weak solar wind signal in the presence of a strong photo-electron current background. To measure the supersonic solar wind, the sensor had to face into the sun, and the modulation of the retarding potential led to a simple, yet rugged design with excellent UV rejection.

Such sensors are best suited for measurements of supersonic ion distributions. They have also been used with success to measure moments of electron distributions in interplanetary space, and ion and electron distributions in planetary magnetosheaths and magnetospheres. Electrons can be measured only when the sensor is not pointed into the sun because the photoelectrons emitted from the modulator grid contribute an anomalous current signal.

The Voyager 2 measurement system (consisting of four modulated-grid Faraday cups) continues to provide data on the (now-cold) solar wind at nearly 40 AU, at proton densities less than $10^{-3}cm^{-3}$ [*Bridge et al.*, 1977; *Belcher et al.*, 1993] and thermal speeds less than 10 km/s. Currently, a Faraday Cup experiment is being readied for inclusion in the Solar Wind Experiment package on the WIND spacecraft.

II. The Faraday Cup on the WIND Spacecraft

In this talk we compare the mass and power requirements for the Faraday Cup system about to fly on the WIND spacecraft to those we estimate could be achieved with currently available technology. We do so to establish a checkpoint; further reductions are certainly possible for specific missions. We begin with a brief description of the Faraday Cup portion of the Solar Wind Experiment on the WIND spacecraft. Note that the technology actually used on WIND was dictated by Project requirements and strategies intended to reduce overall costs. In the second portion of the talk, we'll discuss the actual consequences of those strategies and suggest ways in which the management structure for future missions could be changed in order to save considerable mass and money.

Figure 1 shows a block diagram of a Faraday Cup sensor system. The multi-grid sensor modulates that portion of the incoming particle flux within an energy/charge range determined by the modulator voltage as described earlier. The ac portion of the current from a collector plate is passed to three range amplifiers. The output of each amplifier is synchronously detected and integrated for a preset number of cycles of the modulator waveform. The multiplexor then selects the highest gain output that is unsaturated and performs a logarithmic A/D conversion of that integrated voltage. The measurement process is repeated several times during a rotation of the spacecraft. The energy/charge "window" is then changed and the new window held for another spin. In this manner, the instrument sweeps through the energy/charge range from 150 to 8000 volts.

Figure 2 shows a block diagram of the SWE instrument and the portions related to the Faraday Cup detectors. The interface with the spacecraft is through the instrument's Data Processing Unit (DPU) which communicates with portions of the SWE instrument through Digital Interface Units.

Figure 3 shows the mass and power budgets for the portions of the SWE experiment that we estimate should be assigned to the Faraday Cup portion of the instrument. In addition, we show our estimates of the masses and powers for components that could be realistically achieved with the indicated changes in technology already used or developed at MIT.

Sensor: The sensor aperture and hence overall size is established by the expected fluxes of ions we wish to measure, the desired angular acceptance, and by the minimum currents we can measure with the current-sensitive measurement chain. Charged particle fluxes fall directly on the sensor's collector plate; no charge multiplication techniques are used because such devices generate counts due to incident sunlight. With the actual measurement system used on WIND, our minimum detectable current is $\approx 3\times10^{-13}$ amps using an integration time of 30 msec. The effective aperture of the sensor is 32 cm^2 taking into account the geometrical shadowing due to nine, 95% transmission, wire-mesh grids in the sensor. The minimum current corresponds to measuring 5×10^4 electron charges within the integration time. The thermal noise due to random currents in the input and feedback resistors of the preamplifiers is 1×10^{-13} amps.

Reduction in mass of the sensor itself depends on details of the mission: for WIND, the sensor was designed to have a flat angular response within a 45° half-angle cone. That goal was accomplished by using an appropriately-placed aperture with a diameter half that of the collector plate. Concern about time-varying sunlight glint from a boom required addition of a sunshade that reduced our acceptance to a 30° half-angle cone. Interplanetary missions which require the sensor to look only at a supersonic, high-Mach-number wind can employ a sensor with a narrower acceptance angle. In any case, the sensor mass can be reduced easily to ~300 grams without any change in aperture size, based on the mass of a sensor used on Voyager and reduction of the mass of the grid supports in the WIND design.

Measurement Chain: The WIND current-measurement system consists of two analog circuit boards, one for each half of the collector plate. Each holds a preamp, a bandpass filter, three op-amps in series, a synchronous detector and integrator for each op-amp, and a logarithmic A/D converter that is multiplexed to each of the three integrator outputs. In addition, there is a calibration system for injecting various currents into the measurement chain to check for possible changes in sensitivity over time. Each board and associated cabling has a mass of 300 grams. The appropriate control signals are produced on a third (digital) board which contains various latches and serves as the interface between an intermediate logic board and the central Data Processing Unit (DPU) for the experiment. We assign a net mass of 300 grams to each board and associated cabling plus ~400 grams for the box which holds the boards.

We suggest that the mass of such a measurement system could be reduced considerably by the use of surface-mounted ICs retaining the currently used, low-noise and low-offset-voltage, op-amp types. Two complete measurement chains will then fit on one board; in addition, we would use a common calibration circuit (though we lose redundancy).

The use of an entire board for digital control logic was dictated by the Project's concern for radiation hardness of microprocessors. The use of a set of digital logic in addition to the DPU was dictated by the duty cycle of the DPU: the Faraday cup required a continuous 200 Hz square wave and a similar wave form shifted in phase. The intermediate logic board between the DPU and our logic board was dictated by the multiple tasks carried on by the DPU which had to serve the equivalent of five independent experiments. In retrospect, we might have been able to use the DPU to perform many of the tasks done locally, but again the DPU itself was constrained by radiation dose requirements. We think that a realistic estimate for the measurement system weight could be 300 grams.

High voltage modulator: This section of the instrument produces a 200 Hz. square wave with a dc offset. The offset and square wave amplitude are separately controllable by digital words latched on the digital board. The modulator board also holds voltage monitors and a negative dc supply for the suppressor voltage. The net mass of this board is 900 grams. It was designed by the power supply section at GSFC.

We have developed and tested an engineering version of a much less massive modulator at MIT. It was not used because of development costs. (With the advantage of hindsight, it would have been a less expensive alternative.) We estimate the net mass of such a modulator to be 200 grams.

DPU: It is difficult to estimate the mass of the DPU assignable to the Faraday Cup portion of the experiment. The mass of the DPU is 1.9 kg (including the power converter @ 150g) but it serves five instruments. It requires a power of 2.2 watts. In addition there is an interface board with a mass of ~ 300 grams. We estimate that a dedicated DPU could be built with a mass of 500-600g. Much depends on the interface between that DPU and the spacecraft data system. Optical fiber interfaces provide freedom from ground loops and a net weight reduction. We estimate a reduced mass of 500-600g and a power of 1 watt.

An integrated DPU for all spacecraft experiments might provide a further mass and power savings. However, one must take care because such a DPU must of necessity be much more capable and such an arrangement might require an increase in cabling mass. More detailed studies on a specific spacecraft design would be required in order to assess whether such a more-integrated approach would really result in a net mass and power savings.

A common power converter for the entire spacecraft may provide substantial mass savings. The voltages supplied would be slightly reduced at each experiment in order to provide filtering and regulation. The advantages of such a common converter are that it can operate at higher efficiency since the overhead for individual, lower-power converters is taken only once and also there would not be a problem of synchronization of the individual converters.

Housing: On WIND, the mass of the boxes for the DPU, the Faraday Cup electronics, and the modulator are 1.3 kg. We would plan to house all elements in a single box with a 400g mass.

Summary: The net mass of the "Lite" instrument would be 1.8 kg. The net power would be less than 2.5 watts.

III. A Place in Future Missions

As we have just noted, the modulated-grid Faraday cup approach not only has a mature flight heritage and resilience but also, with work (i.e., further development funds for electronics) can be reduced in mass (and power) so as to accomplish major science goals on potential future missions that are constrained in spacecraft resources. This constraint will be encountered in the environment of "Lightsats" used in Earth-orbital applications, and on Discovery-class spacecraft used in planetary missions and/or deep-space missions with primarily space physics goals. For example, these sensors can be used to advantage in ionospheric environments with supersonic flows due to spacecraft motion. Unlike traditional retarding- potential analyzers, there is no "background level" set by photo- or secondary electrons; hence, the usable dynamic range can easily be extended to lower densities while maintaining the ability to make measurements at ionospheric peaks. The ability to concentrate measurements in a differential energy/charge window affords the opportunity to investigate lower flux species in the face of higher fluxes from a dominant ion. Applications include use in Earth's ionosphere (a "TIMED-like" Lightsat), or the upper atmosphere of a non-magnetic planet (Mars, Pluto, Venus and Titan are examples). In such cases, the mass and power can be further reduced for the relatively low ram energies encountered by an orbiting spacecraft.

Due to its inherent wide-angle response without need for a priori knowledge of the plasma flow direction, the Faraday cup is ideal for measuring the fluid properties of the solar wind on a fast time scale from either spinning or non-spinning spacecraft. This characteristic becomes increasingly important with increasing ratio of flow speed to characteristic thermal speed. A small instrument could conceivably be designed to obtained long-term (e.g., minutes) averages of solar wind fluid parameters on the Pluto Fast Flyby mission [*Staehle et al.*, 1992]. The averages could be stored and down-linked during periodic dumps of engineering data, maintaining a minimal use of spacecraft resources during cruise while making the maximum use of the cruise period for studying the outer heliosphere out to 30 AU during a different solar cycle phase than the Voyagers (M. Forman, private communication). In addition, because the heliographic longitude of that mission is similar to that of Voyager 1 and Voyager 2, such cruise science efforts could add enormously to our study of the radial evolution of the solar wind. Finally, by making use of tight spacecraft resources during a close occultation of Pluto (e.g., use power for a particle instrument during occultation when the light levels are too low to run the visible light camera), such instrumentation could be used to observe the interaction of Pluto's upper atmosphere with the solar wind [*Bagenal and McNutt*, 1989] in the same way that the solar wind experiment on Voyager 1 was used to observe the interaction of Titan's upper atmosphere with Saturn's flowing magnetospheric plasma [*Hartle et al.*, 1982].

A similar small instrument could also be implemented on a Solar Probe mission to make rapid measurements of solar wind properties [*Feldman et al.*, 1989]. Such an instrument could also play a significant role in solar wind and supersonic interstellar plasma measurements on a dedicated mission to the Very Local Interstellar Medium [*Holzer, et al.*, 1990].

Any spacecraft experiment has advantages and limitations that must be carefully weighed against science objectives, reliability, cost, mass and power budgets, and other mission-specific constraints. Although the modulated-grid Faraday Cup has limitations due to its electrostatic nature, it has a natural advantage in making rapid, reliable measurements of fluid properties of supersonically flowing and trans-sonic plasma. Developments in electronics, coupled with its inherently low data rate that can be further reduced with simple averaging and analysis algorithms, make it ideal for consideration on resource-constrained flights in planetary ionospheres and the interstellar medium. Modulated-grid Faraday Cups, acting alone or in tandem with other experiments, continue to have an important role to play in the exploration of the plasma environment in the solar system and beyond.

IV. The Need for a New Paradigm

Our experience on WIND has provided an education about existing management structures that stand in the way of achieving science goals in an efficient manner. The fault lies at all levels of the program. Therefore we would like to propose a return to the fundamental goals of doing science and training younger researchers in the most effective way possible. We can suggest the basic elements of such a program, but its development depends upon realizing that future resources will be very limited and that we all have to work together.

1) The management team needs to be small and to act with power. It should be headed by someone who understands that the goal is to do science. The head need not be a scientist, but it should be someone, as Dr. Forman said in her opening remarks for this meeting, "...with a passion to make the venture work." There should be opportunities for oversight by experienced scientists and engineers, but the Management Team needs authority to make decisions in a rapid manner and to carry out supporting studies. The Project Scientist should be a member of the team.

2) For lowest cost and minimum mass, the spacecraft and the experiments need to be developed together from the beginning in an intense, cooperative manner. The mechanical interfaces and the experiments themselves can then be integrated for an optimum design.

3) Centrally supplied utilities can reduce cost and mass. Japanese spacecraft have been using a central power converter and distributed dc voltages. Why can't we? We should consider using a central DPU with sufficient power to control the experiments and minimize distributed DPUs if that approach will reduce mass and power.

4) We must stop giving lip service to the idea of making experimenters responsibility for reliability of their experiments and really do it. At least on WIND and POLAR giving quality assurance to an outside contractor was problematic. There must be close cooperation between quality assurance people and the experimenters. Many Preferred Parts Lists are hopelessly out of date; the QA people are often inexperienced; costs are outrageous for qualification; and the final results of all that money and time are often piles of paper, specifications that are not relevant to the experiment's operation, and frankly an enormous waste. We need a few, good people not an army of woefully inexperienced workers. Note that commercial qualification requirements for temperature range and vibration for car radios are much tougher than for typical spacecraft (except for radiation). What does Hi-Rel really mean? Let us reconsider the usefulness of a mass buy. Recent experiences show that such a system has to be very well-organized to use its potential leverage.

5) The launch date should be not be a moving target.

6) The budget should be a fixed amount and realistic from the beginning. That effort requires a cooperative effort between NASA Headquarters and the Management Team. The Management Team should realize that its job is to help, not hector, the experimenters.

7) The universities should be seen as a source of "seed corn" for the Centers and Industry. It is tempting to use the larger resources of the Centers to build instruments based on detailed specifications of the university groups. Not only does this deprive the students and staff of the universities of the essential experience of constructing an experiment, but difficulties arise when those who conceive instruments and specify performance requirements are separated

from those doing the design and construction. This situation may also occur if a single instrument is divided into components built by different, separated groups, as was the case with our WIND experiment.

Close oversight as well as flexibility are hard to maintain when groups are physically separated. Even when interfaces are made as clean as possible, tradeoffs and solutions to difficult problems are achieved best when those concerned are in the same building and can talk on a daily basis. Creative energies are enhanced in small groups with a mix of expertise. It is very hard to make a system of distributed construction for a single, sophisticated experiment work well.

Extending those problems to the concept of building all experiments at a common facility makes it very unlikely that such a model can work unless the experiments are far from the cutting edge of science and technology.

The "culture" of how our business is done must be changed; its core must be small-scale, strong, centralized, competent management. Our feeling is that low-mass, reduced-cost missions require a real change in style of operation. If we want space science to continue and to flourish, we have to develop talent and we have to develop a lean, energetic style. We have talent in the Universities, Industry, and in the large Laboratories. We also have a middle-management level of well-meaning people who have lost sight of the purpose of our endeavor.

In spite of adverse funding realities, basic scientific research, itself an investment in the future, can only advance if sufficient investments are made with an eye toward future missions. In particular, the QA process for instruments and the space qualification process for custom electronics items, such as ASICs, must be changed to allow implementation of new technologies at reasonable cost. In addition, a program similar to PIDDP (Planetary Instrumentation Definition and Development Program) needs to be implemented for developing and refining space physics instrumentation including electronics-specific development, an item traditionally not covered by PIDDP.

V. Summary and Postscript

In this paper we have indicated how substantial reductions in mass and power could be made on an experiment soon to be launched. The reductions are achieved by straightforward changes using already existing or developed hardware and construction techniques. It is clear from the material presented at the meeting that more substantial changes in electronics mass are currently possible (the only exception being the high-voltage modulator which needs development effort for serious reduction in mass and volume).

We have commented upon the possible usage of modulated-grid Faraday Cup instruments in the context of several possible missions, all of which will only become reality if substantial reductions in instrument and spacecraft power and mass can be obtained. We suggest that substantial changes in management style are essential to achieve a well-balanced effort that makes best use of our nation's resources. With such changes, we can look forward to reaping a continuing harvest of new and exciting scientific results from the "upper atmosphere" to the edge of interstellar space.

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VI. References

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WIND SWE Faraday Cup Subsystem

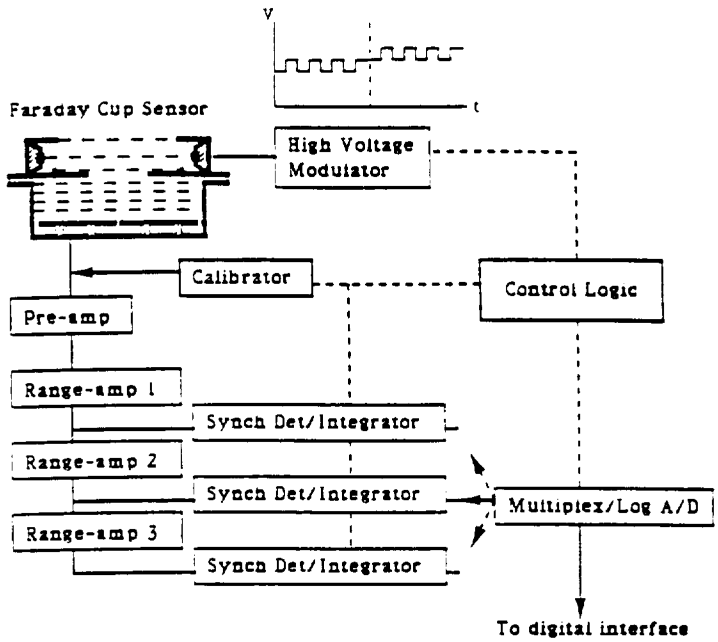

Figure 1.

WIND SWE INSTRUMENT

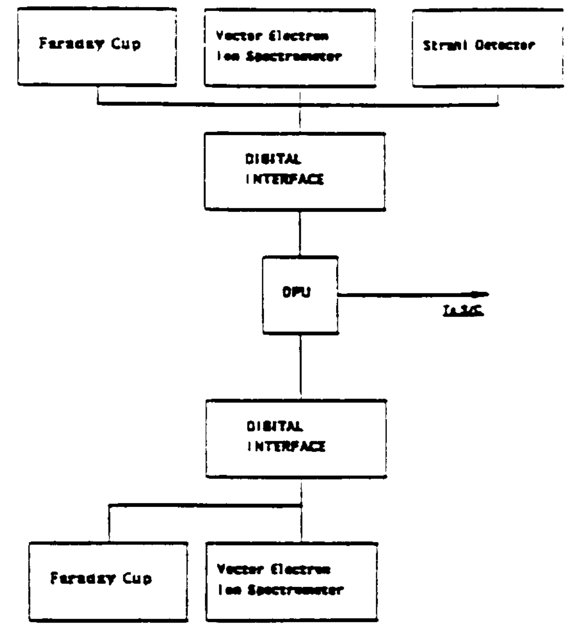

Figure 2.

COMPONENT	WIND	"LITE"	TECHNOLOGY
SENSOR	450g	300g	MISSION SPECIFIC GRID CONSTRUCTION VOYAGER
MEAS. SYS.	600g 1W	300g 1W	SURFACE MOUNT COMMON CALIB.
MODULATOR	900g 1.4W	200g 0.5W	NO TRANSFORMERS OPTICAL SWITCHES
DPU & DIGITAL	1.7kg 2.2W	500g <1W	ASICs LESS DISCRETE LOGIC (COMMON S/C DPU)
POWER	500g	<150g	HYBRID COMMON S/C DC
HOUSINGS	1.2kg	400g	ALL IN ONE BOX
TOTALS	5.4kg 4.6W	1.8kg 2.5W	

Figure 3. Mass and Power Budgets