A Comparison of Solar Wind Parameters from Experiments on the IMP 8 and Wind Spacecraft

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This paper compares solar wind speeds and densities derived from the MIT and LANL experiments on the IMP 8 spacecraft and from the MIT experiments on IMP 8 and the Wind spacecraft. The solar wind speeds determined by all three instruments agree within a few percent. In contrast, we find that the densities from the LANL IMP 8 experiment show a velocity dependence not seen in the comparison of densities from the two MIT experiments. The densities measured by the MIT IMP 8 experiment appear to be ~7% higher than the densities determined from the Wind solar wind experiment. The reason for that discrepancy is still under investigation.

INTRODUCTION

IMP 8, launched on October 26, 1973, is a spin-stabilized, Earth-orbiting spacecraft with its spin axis nearly perpendicular to the ecliptic plane. The Massachusetts Institute of Technology (MIT) solar wind instrument on the IMP 8 uses a Faraday Cup sensor which looks out in the equatorial plane of the spacecraft (see Figure 1a). The acceptance of the sensor is determined by a collimator in the front of the cup and a split collector plate at the rear of the cup which the solar wind particles strike. (The current produced by those particles is measured directly by an amplifier system and telemetered to Earth.) The collimator consists of a set of thin metal slats parallel to the spacecraft spin axis; they limit the acceptance angle for incoming particles to ±9.6° in the equatorial (azimuthal) plane. The acceptance in the meridional plane is broad and is determined by the overlap between the entrance aperture and the collector plate. Figure 1a also shows a sketch of the angular acceptance function of the sensor. As the spacecraft rotates, the flux of solar wind entering the sensor reaches a maximum at an azimuth angle where the sensor normal points as close as it can into the incoming flow; and the azimuthal flow direction of the wind can be determined from fluxes measured at and around that maximum. Since the collector plate is split parallel to the solar ecliptic, the meridional flow direction can be determined by comparing the relative flux striking the two halves of the collector plate.

The operation of the sensor itself is sketched in Figure 1b. A 1-kHz square wave voltage with a dc bias is applied to the "modulator" grid. As illustrated, if that voltage alternates between V_1 and V_2, positive ions with energies/charge between V_1 and V_2 will alternately pass through or be stopped by the modulator grid and will thus create a modulated component of current striking the collector plate. That modulated current is ac-coupled to a measurement chain in which it is synchronously detected and integrated on a capacitor while the spacecraft rotates through a specified range of azimuthal angles (a "sector"). At the end of an angular sector, the amount of integrated

Measurement Techniques in Space Plasmas: Particles
Geophysical Monograph 102

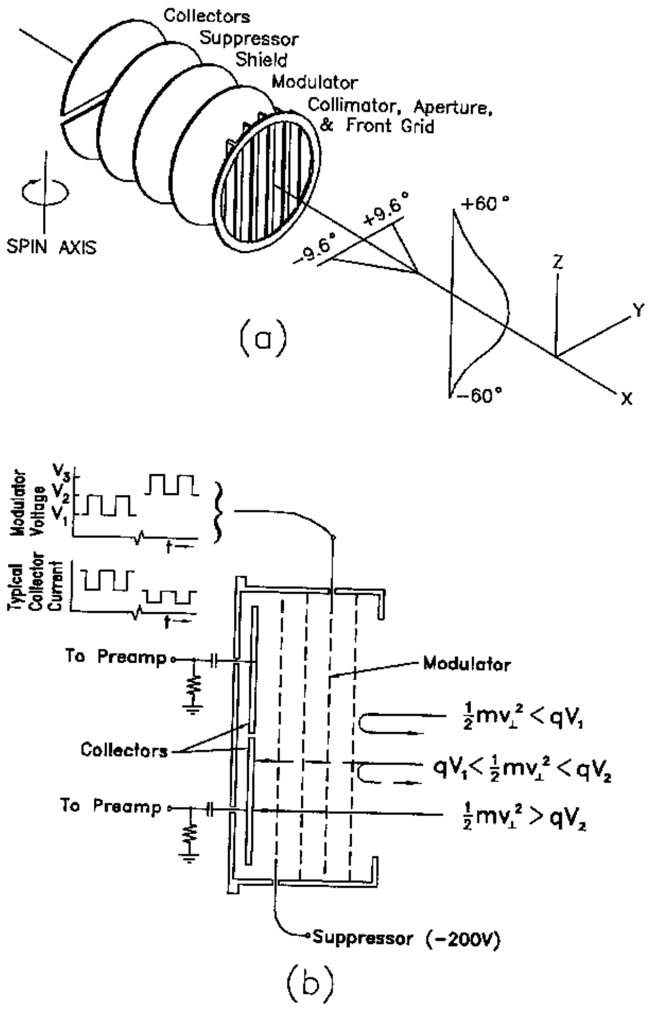

Figure 1. The MIT Faraday Cup instrument on IMP 8. a) A schematic view of the sensor and its collimator and split circular collector plate. The sensor's angular acceptance in the meridional and azimuthal directions is indicated. b) An illustration of the manner in which the energy/charge of the incoming particles is determined (see text).

current is determined by a logarithmic analog-to-digital (A/D) converter, and that result (corresponding to a specific modulation voltage "window" and angular sector) is stored for subsequent transmission to Earth. The modulation window is held fixed for a complete rotation of the spacecraft, then another set of voltages (V_2 and V_3) is selected and the process repeated. Secondary electrons from the collector plate are suppressed by applying a -200 V bias to a grid in front of the collector plate.

For ions, the energy/charge range from 60 to 6902 volts is covered by 24 logarithmically-spaced windows which typically slightly overlap each other; see Table 1. The windows have voltage widths proportional to their average voltage; thus each window modulates particles over a range of velocities relative to that defined by the average voltage where (Δvelocity) / velocity ≈ 0.1. Except for a "low-flux" mode (see below), the angular sectors used are eight 11.25° sectors centered on the Sun direction, followed by five 45° sectors and one 36.56° truncated sector (after which the voltages are changed) to complete the 360° rotation.

Table 1. Positive ion voltage[a] and velocity[b] levels for the MIT IMP 8 experiment.

Lower Voltage	Upper Voltage	Lower Velocity	Upper Velocity
55.3	11.4	97.9	108.6
68.1	13.9	108.7	120.4
83.6	17.0	120.5	133.4
102.5	21.1	133.3	147.8
126.6	26.0	148.2	164.2
155.0	32.0	163.9	181.8
190.0	39.3	181.4	201.3
234.7	48.4	201.7	223.7
280.6	59.4	220.2	244.9
353.9	73.2	247.6	274.7
437.0	90.1	275.2	305.2
531.3	110.4	303.3	336.6
658.7	135.5	337.9	374.6
812.8	166.0	375.5	416.0
995.1	203.7	415.4	460.4
1217.8	251.0	459.4	509.4
1502.2	309.5	510.2	565.8
1847.9	378.4	566.1	627.4
2265.8	466.7	626.6	694.9
2793.1	573.2	695.9	771.4
3435.8	704.5	771.9	855.5
4215.6	865.6	854.9	947.7
5182.7	1068.0	947.7	1051.0
6368.0	1304.0	1050.9	1164.6

[a] Voltages are given in volts.
[b] Velocities (km/s) are for normal incidence.

Various modes of operation of the instrument are employed: the "full-scan" (or acquisition) mode in which all 24 positive ion windows are used; a "tracking" mode, which selects a sequence of eight windows surrounding the window containing the peak current from the previous measurement; and a "low-flux" mode which also covers the full voltage and angular range but uses 45° sectors in the forward quadrant in order to increase the integrated currents. The "tracking" mode is the most frequently used mode of operation. It allows coverage of the full distribution function of interplanetary solar wind in a shorter time than would be necessary for the full-scan mode. Eight contiguous voltage windows are selected based on the previous measurement of the current distribution so that the peak current falls in the third lowest window. Eight windows allow coverage from the velocity corresponding to the lower edge of the lowest window chosen to 2.3 times that velocity. Ten spins of the spacecraft (~27 seconds) are required to complete a tracking-mode spectrum because electrons are also measured during two of the spins. Our discussion in this paper will be confined to the ion measurements.

The measurements are stored in a memory for transmission to the spacecraft data system. Unfortunately, half of that memory failed on May 18, 1974. After that date, only every other transmitted spectrum is useful for analysis; the resulting best time resolution is one spectrum every ~58 s, using the tracking mode. (The data from which solar wind proton parameters are determined typically come from three or four energy windows; the time required to take those data is 3-4 spacecraft rotations or ~8-11 seconds.)

ANALYSIS OF THE DATA

The analysis program on the ground must interpret the sector-averaged currents to obtain the basic plasma parameters of velocity, density, and thermal speed. The currents are quantized to a precision of ±2.2% by the A/D conversion system. The analysis program performs a nonlinear, least-squares fit [*Bevington*, 1969] of the sum of the sector currents in each energy/charge window to those expected from a convecting, isotropic Maxwellian velocity distribution function. The analysis program utilizes the geometrical response of the sensor, the behavior of the ions as they traverse the grids in the sensor, and the gain of the measurement system and its calibration. The purpose of this paper is to discuss instrumental factors which have an influence on the accuracy of the plasma parameters derived from that procedure.

CALIBRATIONS

Periodically, the MIT IMP 8 instrument goes into a "calibration" mode. Such calibrations were carried out approximately every two hours in the early years of the mission, but have had to be commanded manually since 1990. Due to concern for accidentally locking the instrument into the calibration mode, the manual command has been used only before Earth shadows after which the instrument mode is reset during the required power-on sequence.

Each current measurement chain is calibrated by injecting a pre-established series of currents produced by a ladder resistor network and a precision voltage source. Except for the lowest current levels ($<10^{-11}$ amps), the in-flight calibrations of the measurement chain have shown no significant change (<4.5%) over the life of the mission. The lowest current range began to show occasional decreases in sensitivity beginning on May 3, 1977; those decreases became more frequent and became permanent in 1981. The decreased sensitivity affects measurements of low flux densities ($<10^5$ particles cm^{-2} s^{-1}) corresponding to densities below 1 cm^{-3} at typical solar wind speeds.

The experiment's high voltages and reference voltages are also sampled during a calibration sequence. No detectable change in either the high voltage or reference levels has been noted.

COMPARISONS OF MEASUREMENTS USING DIFFERENT INSTRUMENTS

We have compared the solar wind parameters derived from the IMP 8 MIT instrument with those from the Los Alamos National Laboratory (LANL) instrument on the same spacecraft and with those obtained from the MIT Faraday Cup instrument on the Wind spacecraft. The LANL instrument is a curved-plate, electrostatic analyzer instrument that counts individual ions by counting pulses they produce in an electron multiplier system (see below). The Wind instrument is a Faraday Cup system with direct measurement of the incoming current as on IMP 8 [*Ogilvie et al.*, 1995]. (See *Vasyliunas* [1971] for a general discussion of space plasma measurements.)

In the supersonic solar wind, with its narrow velocity distribution function, the easiest parameter to measure is the solar wind speed. The speeds are determined by the high voltages applied to the sensors, and those voltages are well-known and well-calibrated. The flow directions depend on knowing the acceptance function and geometry of the sensors. The Faraday Cup acceptance is determined relatively easily; curved-plate analyzer sensor responses require more careful calibration. For a Faraday Cup looking out at an angle to the spin axis of a spacecraft, determination of the flow angle in the azimuthal direction depends on measuring the angular distribution of flux. Determination of flow angle perpendicular to the azimuthal plane depends on the ratio of fluxes on the two halves of the collector plate. There is a bias in our determination of the latter flow angle from IMP 8: the long-term average flow appears to come from ~1.7° South of the ecliptic. The reason for that bias is not understood, but it would take only an ~2% percent error in relative calibration of the two collector currents to cause such a bias. The gain change referred to earlier caused a bias of 5° in meridional flow angle, but that bias has been corrected for parameters now available from the NSSDC or MIT by calculating the meridional angle using only collector-plate current ratios when the measured flux exceeds the low flux limit given above. Because spectra having fluxes below that value are not published, this requirement eliminates them from the available parameter set.

Since the velocity is well-determined, accurate determination of the number density depends on knowing the flux of ions. That determination in turn depends on knowing the acceptance of the sensor in great detail as well as knowing the calibration of the measurement system (as discussed above) if the resulting current is measured directly. If the system counts individual charged particles, it is necessary to know the efficiency with which incoming particles are counted.

The IMP 8 LANL system counts secondary electrons created by ions striking a Be-Cu electrode. The electrons then enter an electron multiplier which generates a pulse for each incoming ion. In secondary-emission systems, the detection of an ion depends upon creating a large-enough pulse of secondaries to allow it to be counted. Such systems typically operate in a saturated mode with adjustable discriminator and/or bias levels to insure 100% counting efficiencies. Another factor that must be considered is that the efficiency for production of secondaries depends upon the species of incident ion as well as the energy with which it strikes the secondary emitter.

RESULTS

As expected, for all the comparisons the ion speeds agree well (see Figure 2a for the comparison between the two IMP 8 instruments and Figure 2b for the IMP(MIT)/Wind comparison).

The comparison of densities from the IMP 8 instruments (Figure 3a) indicates that the densities reported by the LANL instrument have a speed dependence; better agreement between the two instruments occurs for higher speed wind. A comparison of the densities as reported from the Faraday cup sensors on IMP 8 and Wind (Figure 3b) shows an ~10% offset but no dependence on solar wind speed. A possible explanation for the speed dependence exhibited by the LANL instrument is a lower efficiency for detection of the lower-speed ions.

The Wind/IMP comparisons in Figure 3b were done using Wind parameters based on 3-point fits to the current vs. energy/charge distribution (the "Key Parameters"). IMP 8 densities result from a nonlinear least-squares fitting procedure. Subsequent comparisons of the Wind 3-point parameters with those obtained using a full nonlinear fitting procedure show that the 3-point fits yield densities ~3% too low. Thus the nonlinear fit Wind densities are ~7% lower than those from IMP 8; there is no obvious speed dependence.

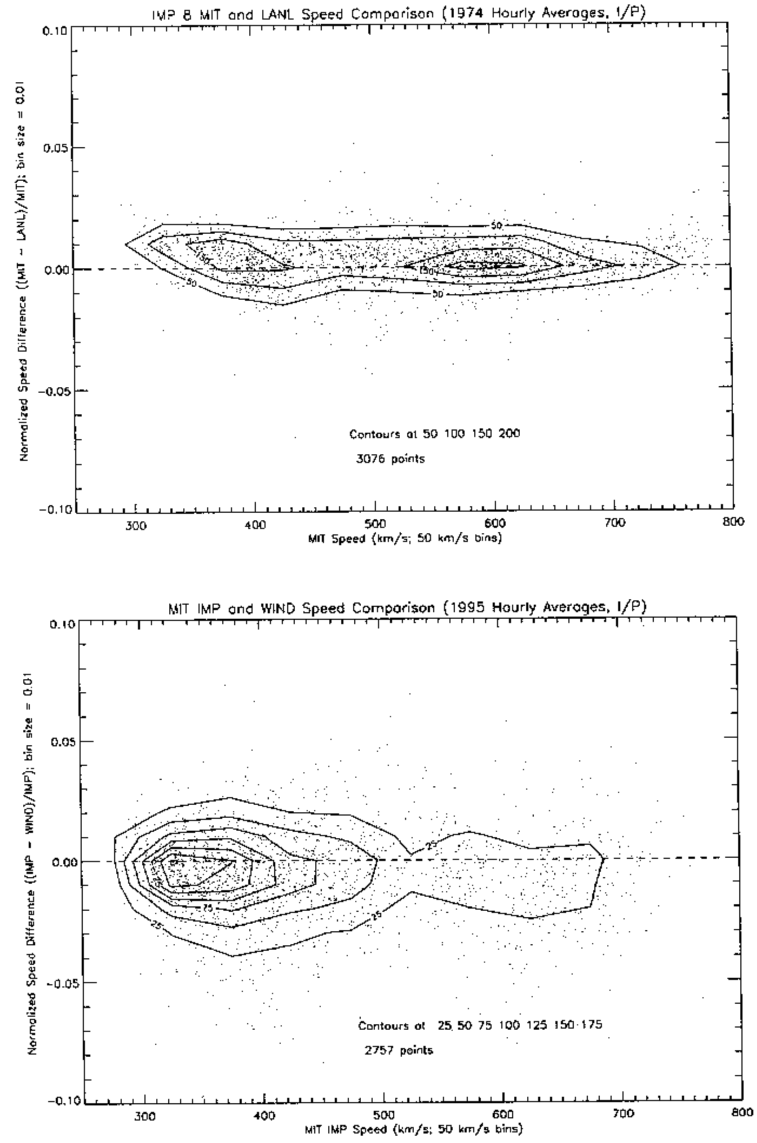

Figure 2. a) A comparison of the solar wind speeds determined from the MIT and LANL experiments on IMP 8. The speed differences reported by the two instruments are normalized by dividing by the speed determined by the MIT IMP 8 experiment. The data points are 1-hour averages of interplanetary data. The contours are drawn through bins containing the number of points indicated on the contour. b) A comparison of solar wind speeds determined by the MIT Faraday Cup experiments on IMP 8 and on Wind.

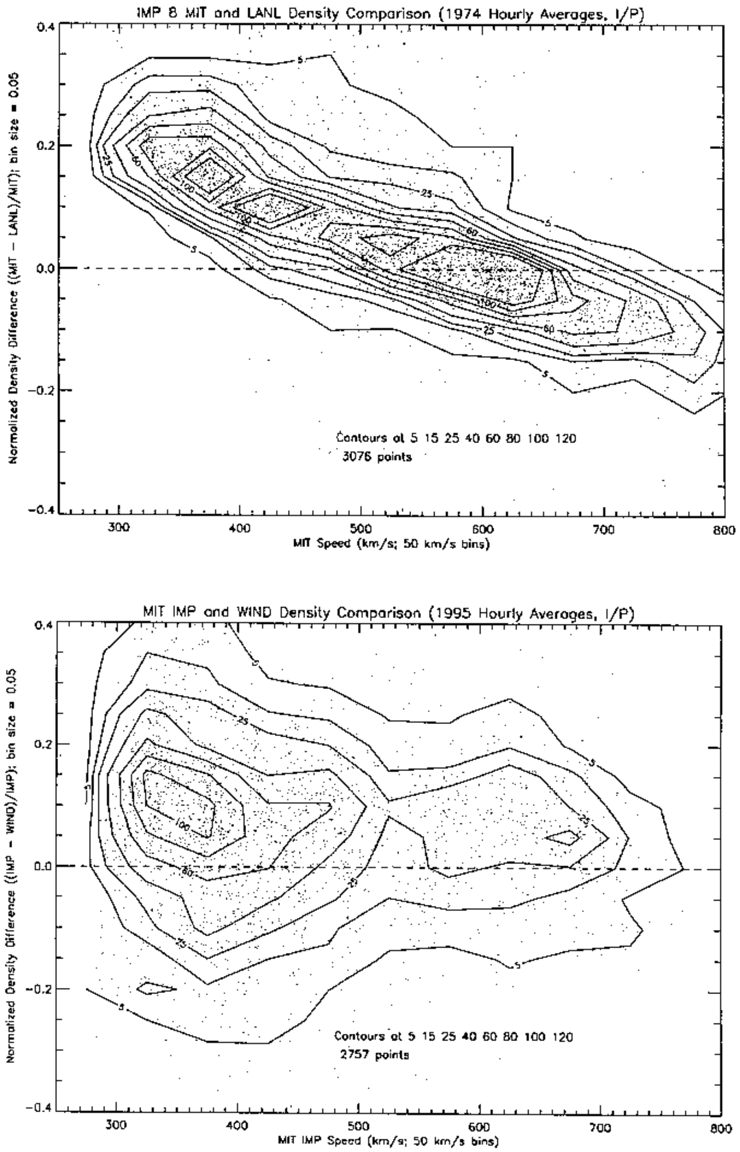

Figure 3. A comparison of the solar wind densities. a) Hourly-average densities determined from the MIT and LANL experiments on IMP 8 in 1974. Note that the density differences show a dependence on the speed of the solar wind. b) A comparison of hourly averages of densities from the MIT Faraday Cup experiments on IMP 8 and Wind in 1995. No adjustment for travel time of the solar wind between the spacecraft has been made. Although there is an ~10% offset between the reported densities (see text), there is no indication of a speed dependence.

DISCUSSION

The determinations of solar wind speed from Faraday Cup instruments or a curved-plate analyzer system are in good agreement. Determination of the absolute densities is a more difficult issue. *Petrinec and Russell* [1993] compared the MIT IMP 8 densities with those obtained from electron-based densities measured on ISEE 3. They drew two conclusions: 1) the MIT IMP 8 densities are ~20% too high in the velocity and temperature range in which they have the most measurements and 2) the (MIT IMP 8)/(ISEE 3) density ratio increases for lower solar wind temperatures. As discussed in detail below, we disagree with their conclusions (see the Comment [*Paularena and Lazarus*, 1994] and their Reply [*Petrinec and Russell*, 1994]). Note that the use of electron density measurements has an inherent difficulty at low temperatures due to spacecraft charging effects. *Scime et al.* [1994] discuss the specific problem of using electron densities not corrected for spacecraft charging.

The LANL/MIT IMP 8 density comparison presented here shows a dependence on the wind speed. *Russell and Petrinec* [1992] found a similar dependence. Knowing that the speed and temperature of the solar wind are correlated on the average (roughly constant Mach number flow), they came to the conclusion that the density differences were a function of solar wind temperature. In their study, they used MIT densities derived from 3-point rather than the more recent nonlinear analyses. We have explored the dependence of the density parameters by using model distributions as inputs to the nonlinear analysis code and have found no temperature or Mach number dependencies except for extreme, low- or high-Mach-number conditions.

Since comparison of densities from Faraday Cup instruments on IMP 8 and Wind show no such speed dependence and we know of no mechanisms by which the direct measurement of Faraday Cup current should depend on the speed of the wind, the comparisons suggest that the LANL instrument's detection efficiency is lower at lower wind speeds. A comparison of densities measured by the Faraday Cup instruments on IMP 8 and on Wind shows that the Wind densities are lower by ~7% (after correcting the 3-point density fits from Wind as discussed above).

Since the time of the Conference, we have gained additional confidence in the nonlinear fit densities reported from the Faraday Cup experiment on Wind: measurements by the WAVES experiment on Wind of the thermal noise radiated at the local plasma frequency, have yielded densities 2% higher on the average than those from the Faraday Cup; the standard deviation of the distribution was ~5% [*Maksimovic et al.*, 1996].

In summary, we interpret the comparisons presented here as follows: there may well be an ~7% overall overestimate of densities by the MIT IMP 8 experiment, but we find no evidence that its density determination is a function of temperature or velocity (except in extreme cases). We suggest that the densities determined by the

LANL instrument on IMP 8 do have a solar-wind-speed dependence.

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