Basic Calibration Procedures for CAPS data

Included below are basic procedures for calculating a calibration parameter for each type of CAPS data in the CAPS archive volume COCAPS_1nnn. As noted, some values included in the equations are preliminary and will be updated as data validation by the team proceeds. In addition to updated procedures, a separate CAPS volume (COCAPS_2xxx) will be generated that will contain calibrated data files (contents TBD).

General Electron and Ion Mass Spectrometers (ELS and IMS):

For the CAPS electron and ion mass spectrometers, measured number of counts (C_{sijk}) from a single species, s, at energy step i, elevation j, and azimuth k, is related to phase space density of that species (f_{sijk}) by

$$f_{sijk} = \frac{C_{sijk} m_s^2}{2\tau \varepsilon_{sij} G_{ij} q_s^2 e^2 E_i^2} \quad \text{(Equation 1)}$$

where m_s is the mass of the particle, τ is the integration time, ε_{sij} is a detection efficiency, G_{ij} is a geometric factor, q is the charge of the particle (in units of electron charge), e is the electron charge, and E_i is the energy (in eV) at the center of the pass band for step i.

This phase space density is an average over the sensor's energy and angular pass band. In the warm plasma limit, this can be assumed to be the phase space density at the center of the pass band. This is accurate to the extent that the phase space density varies slowly (linearly) across the pass band. If this is not the case, there is no direct or assumption-independent to calculate phase space density.

Before applying the above equation, counts should be corrected for cross-talk, dead time, and background subtracted. For data obtained after August 24 at 00:00:00, 2003 background subtraction for IMS data may use energy step 63 of each energy sweep, where 0 V are applied to the ESA to make a measurement of penetrating radiation. Some details of these procedures are described below. In some cases, the process is much more complex, situation-dependent and not described in this document.

Electron Spectrometer (ELS) Data:

Calibration Parameter

f_{ijk}= Phase space density [s^3m^{-6}]

E_i = See ELS_ENERGY_ARRAY.TAB for the energy corresponding to each of the 63 energy steps in a sweep [eV]

m_e = Mass of an electron (kg). $m_e = 9.11000\text{x}10^{-31}$ kg

q_e = Electron charge = -1

e = Charge of an electron (coulombs). e = $1.602\text{x}10^{-19}$

τ = Accumulation time [s]. τ = 0.0234375

$\varepsilon_{eij}G_{ij}$ = Geometric factor [m^2str eV/eV]. Geometric factors for ELS are given in a matrix whose entries correspond to each elevation & energy combination. The matrix is in a comma-separated format with each of the 63 rows representing an energy step and containing 8 columns/elevations. The data is in the file ELS_GEOM_FACTOR.TAB. Additionally, the geometric factor includes efficiency and resolution.

ELS Data Corrections

Data are corrected for summing vs. averaging done during the in-flight collapse, deadtime correction, and MCP level below calibrated level.

1) Before August 26, 2003, in cases where the full ELS dataset could not be telemeterd, the ELS dataset was collapsed by averaging. Starting in December 2003, commanding was added to make it possible to either average or sum the data when collapsing. A flag is located in the ELS data file ("Collapse flag") to indicate whether collapses are done by summing or averaging. For telemetry modes involving collapsing in either energy or azimuth, if the "Collapse flag" indicates summing was being done, the data is averaged to re-instate the best possible time resolution, which is 2-seconds. When the data is averaged in-flight, the values are repeated to fill out the full, standard array size (8 EL x 63 E/Q x 16 Azimuths).

2) All data are corrected for deadtime (1.05 μs for ELS). For data starting in December 2003, in-flight deadtime correction was performed. Prior to this date, the deadtime correction must be performed retrospectively on the telemetered data. This will not be 100% accurate for data products that have been averaged in energy or elevation. If dead-time correction was done in flight, it can be calculated as follows:

   $$\text{Corrected\_value} = \text{raw\_value} / (1.0 - (\text{raw\_value} * 4.48\times10^{-5}))$$

   In the ELS data product table, the "Collapse flag" gives information regarding whether in-flight deadtime correction was enabled.

3) The correction for MCP level below the calibrated level is determined by choosing the appropriate gain_scale factor. The procedure for doing this is to determine which MCP level the instrument was set to by using the "ELS_MCP_ADJ" parameter in the ANC data product. Conversion is as follows:

   $$\text{MCPvalue} = \text{ELS\_MCP\_ADJ} / 58.73$$

   Take the MCPvalue and use that value to look up the gain_scale factor in the following array:

MCP value	Gain scale factor
40 and below	0.00
41	0.00115235
42	0.00115235
43	0.0224406
44	0.181708
45	0.529355
46	0.837943

47	1.00000

This array will be updated as the MCP gain level is adjusted and in-flight calibrations indicate a change is needed. If a subsequent change occurs, it will be indicated in the "ELS_MCP_ADJ" parameter.

With all these 3 pieces of information, C_{ijk} is calculated using the following equation:

$$C_{ijk} = \text{Corrected\_value} / \text{gain\_scale}$$

Calibration Parameter Limitations

1) The data has not been corrected for spacecraft potential. The process used to develop the correction algorithm is complex, depends on several factors, and is not yet fully understood.
2) Geometric factors were measured at 6 selected electron energies during ground calibration at Mullard Space Science Laboratories. These values were interpolated over the whole ELS sweep range to give the array of geometric factor values for each of the 63 ELS energy steps and each of the 8 anodes. ELS calibrations are being preformed in-flight and we expect to update the geometric factor as new information becomes available.

Ion Mass Spectrometer (IMS) Data:

IMS Singles data (SNG):

Calibration Parameter

C_{sijk} = counts from species s
f_{sijk} = phase space density of species s [s^3m^{-6}]
τ = IMS accumulation interval = 0.0546875 s
E_i = energy of level i (eV). See IMS_SWEEP_TABLE_0_V3.TAB for the 63 energy steps used.
m_s = Mass of ion species s (kg). $m_p = 1.6726\text{x}10^{-27}$ kg
q_s = Ion charge (in units of electron charge)
e = Charge of an electron (coulombs). $e = 1.602\text{x}10^{-19}$ C
G_{ij} = geometric factor of detector (elevation) i and energy step j = 1.5008×10^{-7} m^2sr eV/eV NOTE: This is currently assumed to be energy and elevation independent.
ε_{si} = detection efficiency for species s at energy E_i
= (foil transmission)(dome grid trans)(MCP grid trans)(start efficiency)(probability that at least one start electron is created at the foil)
= (0.66)(0.65)(0.9)(0.69)(0.6)
= 0.160
the detector efficiency is currently the same for every species.
NOTE: the detector efficiency and geometric factor are subject to revision pending ongoing data validation.

Singles data does not inherently differentiate between ion species. In a multi-species plasma, the inverted and modified form of equation 1 is

$$C_{ijk} = \sum_s \frac{2\tau\varepsilon_{sij} G_{ij} q_s^2 e^2 E_i^2}{m_s^2} f_{sijk} \quad \text{(Equation 2)}$$

Determining phase space density for each species, or using the measured counts to calculate moments (density, flow velocity, etc.) requires the use of additional data (e.g. simultaneous IMS TOF spectra) and/or assumptions. For example, if phase space density is calculated assuming all ions are protons, and the results used to calculate density, the result will actually be $<(q/m)^{1/2}> n_i$ and may be corrected for an assumed mean charge-to-mass ratio. Another approach we currently use is to assume the plasma is composed of hydrogen (H+) and a generic water group species (W+). In this case, we attribute all counts below four times the H+ corotation energy to hydrogen, and all counts above this energy to W+.

IMS ion data (ION):

IMS ION data are energy-elevation-azimuth spectra similar to the SNG data and are converted to phase space density in the same manner. Rather than being all start events (and therefore measuring the flux of all ions, regardless of species), the ION data are calculated from TOF spectra and an on-spacecraft deconvolution. This, ideally, produces energy-elevation-azimuth spectra of selected species.

Calibration parameter

With one exception, all calibration parameters for ION data are the same as those for SNG data. The efficiency for ION includes the neutral and positive foil yields (nominally 0.9 and 0.1) and the probability of a stop detection (0.65) As a result
$\varepsilon_{ST} = \varepsilon_{SNG} * 0.9 * 0.65 = 0.0936$
$\varepsilon_{LEF} = \varepsilon_{SNG} * 0.1 * 0.65 = 0.0104$

These efficiencies are very approximate since the true yields and probabilities of stop detection are energy and species dependent. These values will be replaced when more comprehensive values are available.

Note that the parameter “SAM ion number” in the ION data identifies the species, whether it was derived from ST or LEF spectra, and what group table (deconvolution parameters) were used in the on-spacecraft calculations. The ion number is
mass * 1000 + charge * 100 + <2 digit ID number for group table>
Where mass is in AMU and charge is in units of the electron charge. Group table ID numbers are even for ST-derived species and odd for LEF-derived ones. For example, an ion number of 4202 is He^{++} (mass=4, charge=2) from a ST group table. Additional information about naming can be found in ION_and_GroupTable_naming.doc in the CALIB directory. Using the parameter “Sam Ion number”, the choice to use the ST or LEF flux equation can be determined. In addition, by using the “Sam Ion number”, the mass of the ion can be determined (and hence the ion i).

IMS time-of-flight (TOF) data:

Calibration parameter

Conversion of TOF data from counts to relative abundance of various ion species is best performed by fitting the energy/time-of-flight spectra to a linear sum of model peaks. This is complicated by the fact that efficiency and yields are often a strong function of energy and species. A full library of model spectra is in development, but is not sufficiently advanced for distribution as part of the CAPS archive.

Species identification may be preformed location of peaks and applying the following formulas:

Straight-through (ST) neutral peaks (from ions which exit the entrance foil with a neutral charge):

$$M = (E+q*\Phi) * [(0.102\pm0.002) + (0.001488 \pm 2x10^{-6}) * TOF]^2$$

Linear electric field (LEF) peaks (from singly-charged ions which exit the entrance foil as singly-charged ions):

$$M = [(0.123\pm0.001) + (0.003503 \pm 3x10^{-6}) * TOF]^2$$

Where TOF is the time-of-flight bin, out of the instrument's full, 1-2048 bin range, M is the ion mass in AMU, E is the ion's energy (external to the instrument) in keV, q is the ion's charge (external to the instrument) in units of electron charge, and Φ is the IMS post-acceleration voltage, normally 14.6 kV.

The TOF spectra may also contain the following additional peaks, which do not have simple, analytic expressions for the peak locations: Straight-through (ST) negative peaks (from ions which exit the entrance foil with a negative charge), ST higher-charge peaks (from ions which exit the entrance foil with a positive charge greater than one), an LEF echo in ST spectra (i.e. a ST peak at the same time-of-flight as a stronger LEF peak) and several other types of low-amplitude secondary or ghost peaks.

IMS Calibration Parameter Limitations

1) Singles data does not inherently differentiate between ion species. The use of singles data in a multi-species plasma is described above.
2) Between June 19^{th} 21:52:04, 2004 and July 12^{th} 17:37:42, 2004 the on-spacecraft deconvolution used to calculate ION data was based on calibrations of the IMS prototype. There were systematic differences between prototype and flight IMS spectra (peak locations and shapes) which were not corrected for. As a result, the ION data from this period may not have been correctly deconvolved.
3) Since September 20^{th} 15:30:25, 2004 the on-spacecraft deconvolution used to calculate ION data has used an identity matrix, and is simply returning counts between specified TOF bins.

4) Time-of-flight data are a sum over all angles sampled in a 256-s or 512-s period (depending on instrument mode.) This is not a uniform sampling of 4π sr and some species may be over- or under-represented in this sample.
5) Several calibration values should rigorously be energy or elevation dependent. We provide single values which assume this is not the case, and further analysis of pre-launch and in-flight calibrations is in progress.
6) There is some evidence of cross-talk between elevations in SNG and ION data products. Appropriate methods of removing this are under development.
7) Before August 28th 13:44:51, 2001, in cases where the full IMS datasets could not be telemeterd, the IMS datasets were collapsed by averaging. Starting in August 28th 13:44:51, 2001, data were collapsed by summing.
8) Data should be corrected for deadtime, however IMS data generally exhibit a non-linear behavior which is not simply described by the standard equation

Corrected_value= raw_value/ (1.0 – A*raw_value)

As a result, counts above ~1000 counts per sample should be treated with caution.

Ion Beam Spectrometer (IBS) Data:

IBS data can be arranged into arrays of counts N_{raw} as a function of fan 1, 2, or 3, particle energy-per-charge e/q, and measurement time t as follows. Raw counts N_{raw}(fan,e/q,t) need first to be dead-time-corrected.

$$N_{DTCorr} = \left(\frac{\frac{N_{raw}}{\tau}}{1 - \frac{N_{raw}}{\tau}\tau_D} \right) \tau$$

In the above expression τ_D is the IBS dead time (see IBS Key Calibrations Parameter table below) and N_{DTCorr} are dead-time corrected counts. Each IBS detector records counts from particles that directly impact that detector. In addition, each IBS detector responds occasionally to particles that impact one of the other IBS detectors. We refer to this effect as cross-talk, and a correction can be applied to minimize the effect of cross-talk. To apply the correction, take the counts in each of the 3 fans accumulated at the same time t_i and energy/charge step e_i/q, and treat it as a simple 3-component vector. Multiply that vector by the cross-talk-correction matrix **β** (see IBS Key Calibrations Parameter table below**)** as shown below.

$$\begin{pmatrix} N(fan1, e_i/q, t_i) \\ N(fan2, e_i/q, t_i) \\ N(fan3, e_i/q, t_i) \end{pmatrix} = \begin{pmatrix} \beta_{11} & \beta_{12} & \beta_{13} \\ \beta_{21} & \beta_{22} & \beta_{23} \\ \beta_{31} & \beta_{32} & \beta_{33} \end{pmatrix} \begin{pmatrix} N_{DTCorr}(fan1, e_i/q, t_i) \\ N_{DTCorr}(fan2, e_i/q, t_i) \\ N_{DTCorr}(fan3, e_i/q, t_i) \end{pmatrix}$$

<u>IBS Particle Flux</u>

The IBS detectors were designed to measure directed beams of charged particles rather than particles with distributions that are quasi-isotropic. In the following discussion, we assume that the particle distribution producing counts in the IBS detectors is a beam distribution in energy-angle space, and that the thermal width of the particle beam is very much smaller than 150°, roughly the field of view in the "plane of a fan". We assume the thermal width of the beam extends beyond the field of view in the direction perpendicular to the plane of a fan.

With counts corrected for dead-time and cross-talk, particle flux J ($cm^{-2}sec^{-1}$) can be determined. Were an IBS fan response flat across the field of view, calculating flux would be straightforward. However, as is typical for this type of analyzer, the effective response area A varies with the angle of beam entry into the fan. In general, determining the particle flux requires knowledge of the particle beam direction. Without determining the beam direction, we can only get a particle flux lower limit. The effective response area is maximum A_O (table) near the center of the fan field of view (i.e. beam entry normal to an analyzer aperture). The lower-limit particle flux J_O in a given fan at time t_i and energy-per-charge step e_i/q is given simply by:

$$J_O = \frac{N(fan_i, e_i/q, t_i)}{A_O \tau} \quad \left(cm^{-2}\sec^{-1}\right)$$

This lower-limit flux J_O is the same as the actual flux J in the case where a beam enters near the center of a fan. When a beam enters a fan at an angle θ away from fan center, the flux is found as follows:

$$J = \frac{N(fan_i, e_i/q, t_i)}{w(\theta) A_O \tau} \quad \left(cm^{-2}\sec^{-1}\right)$$

In the above expression w(θ) is a weighting function and θ is the angle of a beam relative to the center of a given fan. A lookup table of w(θ) values is provided (see IBS Key Calibrations Parameter table below).

Beam Flow Direction:

In order to find the flow direction, IBS requires that the CAPS actuator is sweeping the fans' fields of view across a charged particle beam. The flow direction can be determined if at least 2 of the 3 fans detect a peak flux as a function of actuator sweep angle. The procedure is as follows. First, one must determine α_1, α_2, and α_3 the actuator angles for which a peak flux was detected in fans 1, 2, and 3 respectively as the actuator sweeps across the incoming beam. We define the following vectors, which are normal to the IBS fan-planes at the time the beam was detected by each fan.

$$\hat{n}_1 = (-\cos(30^\circ)\cos(\alpha_1), \cos(30^\circ)\sin(\alpha_1), -\sin(30^\circ))$$
$$\hat{n}_2 = (\cos(\alpha_2), \sin(\alpha_2), 0)$$
$$\hat{n}_3 = (-\cos(-30^\circ)\cos(\alpha_3), \cos(-30^\circ)\sin(\alpha_3), -\sin(-30^\circ))$$

If only 2 fans detect the beam, then only 2 of the above vectors can be evaluated. The flow direction is found in turn by taking cross products between pairs of these vectors.

$$\hat{d}_{12} = \hat{n}_1 \times \hat{n}_2 / |\hat{n}_1 \times \hat{n}_2|$$
$$\hat{d}_{23} = \hat{n}_2 \times \hat{n}_3 / |\hat{n}_2 \times \hat{n}_3|$$
$$\hat{d}_{13} = \hat{n}_1 \times \hat{n}_3 / |\hat{n}_1 \times \hat{n}_3|$$

If all three of the IBS fans detected a beam, then the flow direction can be evaluated using each of the 3 expressions shown above. The results for all 3 should be similar. If only two of the IBS fans detect the beam, then the flow direction can only be found by 1 of the 3 expressions above. Once the flow direction is found, then the angle θ_i of beam into a detector can be found as follows.

$$\theta_1 = \arccos\left[(\sin(\alpha_1), \cos(\alpha_1), 0) \bullet \hat{d}\right]\left(\frac{-d_z}{|d_z|}\right)$$
$$\theta_2 = \arccos\left[(\sin(\alpha_2), \cos(\alpha_2), 0) \bullet \hat{d}\right]\left(\frac{-d_z}{|d_z|}\right)$$
$$\theta_3 = \arccos\left[(\sin(\alpha_3), \cos(\alpha_3), 0) \bullet \hat{d}\right]\left(-\frac{d_z}{|d_z|}\right)$$

The values of θ_I so determined can be used to find the effective area weighting function $w(\theta)$ from the table.

TABLE: IBS Key Calibration Parameters

April 29,2005

Integration time	τ	0.0068359375 seconds
Effective area	A_O	0.34 cm^2
Dead time	τ_D	0.86 microseconds

Cross talk correction matrix (unit-less)

β_{11}= 1.02575
β_{12}= -0.143420
β_{13}= -0.0385874
β_{21}= -0.135635,
β_{22}= 1.02600
β_{23}= -0.0406647

β_{31}= -0.136521
β_{32}= -0.135645
β_{33}= 1.01217

NOTE: the cross talk correction matrix provided here is valid for counts below 300. Above 300 counts, its reliability is uncertain because of cross-talk. We believe that a more sophisticated cross-talk correction will be appropriate for IBS counts greater than 300, but it remains to be developed.

Effective area weighting factor (unit-less)

θ	w(θ)
-75.0	0.00000
-72.0	0.00425
-69.0	0.01558
-66.0	0.02974
-63.0	0.05595
-60.0	0.08428
-57.0	0.10694
-54.0	0.12465
-51.0	0.11331
-48.0	0.11261
-45.0	0.10340
-42.0	0.10836
-39.0	0.14731
-36.0	0.13314
-33.0	0.16360
-30.0	0.17847
-27.0	0.23371
-24.0	0.29462
-21.0	0.36969
-18.0	0.47380
-15.0	0.60340
-12.0	0.74717
-9.0	0.86331
-6.0	0.92564
-3.0	1.00000
0.0	0.97026
3.0	0.97167
6.0	0.95821
9.0	0.81161
12.0	0.62606
15.0	0.49221
18.0	0.36827
21.0	0.23938

24.0	0.17422
27.0	0.12677
30.0	0.07649
33.0	0.04249
36.0	0.02762
39.0	0.02266
42.0	0.02974
45.0	0.02479
48.0	0.04249
51.0	0.04887
54.0	0.04603
57.0	0.06020
60.0	0.06657
63.0	0.06586
66.0	0.06374
69.0	0.04249
72.0	0.03895
75.0	0.02550