RAMS: A Miniature Ram Angle and Magnetic Field Sensor for Picosat Attitude Estimation

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Abstract

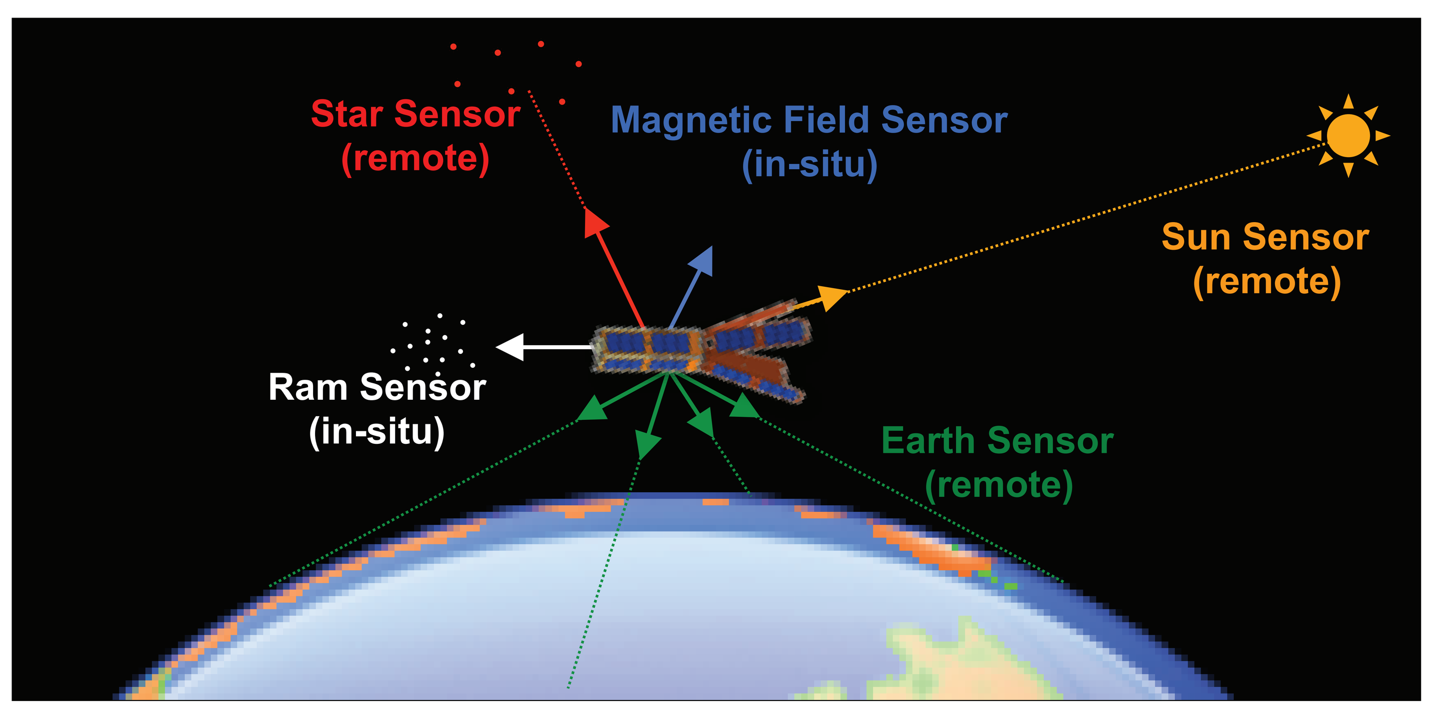
The popular and well-established concepts for satellite attitude sensing, including Earth horizon sensing, Sun sensing, geomagnetic field sensing, and star sensing have had almost no new revolutionary additions in decades. In this paper we introduce a new attitude sensing concept and prototype miniature sensor called RAMS (Ram Angle and Magnetic field Sensor). This novel instrument directly measures the in-situ 2-axis ram direction of a LEO satellite by collecting the incoming thermospheric flow field through a wide field of view entrance aperture, ionizing the neutral molecules in a thermionic cathode chamber, adjusting the kinetic energy of the charged molecules in an electric field, and measuring their impingement location in two coordinate axes on a quad detector. Coupled with its own built-in magnetometer, RAMS provides an estimate of the satellite's 3-axis attitude relative to the local orbit frame regardless of roll angle or sunlight conditions as long as the ram direction is within the field of regard of the entrance aperture. If available, an external Sun sensor can be utilized in place of the magnetometer during daylight conditions. As a by-product of interest to the space weather community, the sensor also provides an estimate of the in-situ cross track winds and density of the thermospheric neutrals.

The RAMS sensor head has a mass of 23 g, occupies a volume of 22.5 cubic cm, and an expected power draw of ~0.5 W. The measurements consist of the two angles (α, β) defining the ram vector **R** relative to the x-axis of the sensor frame, and the components (Bx, By, Bz) of the local geomagnetic field vector **B** from the built-in magnetometer. The measured ram direction represents a vector addition of the satellite velocity vector **V** and the total wind vector **W**, which consists primarily of the co-rotational winds and the horizontal thermospheric winds. We will describe in detail the sensor components and software modules necessary for estimating the horizontal wind angle and the satellite attitude from the instrument measurements. Additionally, we will provide both high-fidelity simulations and ground calibration from a flight RAMS unit highlighting its potential for sub-degree attitude estimation in a light-weight, low-volume, low-power, and low-cost package compatible with the extreme limitations of CubeSat-class missions.

The RAMS sensor is manifested on STPSat-5 satellite as a secondary payload. The launch target is Q4FY16 and the objective for RAMS is to verify functionality of the sensor on-orbit by comparing with stellar aspect solutions from the STP-Sat-5 star camera.

Motivation

- The vast majority of LEO satellites are Earth-pointing with a forward-looking nose.
- There are currently four attitude sensor options available for LEO satellites.



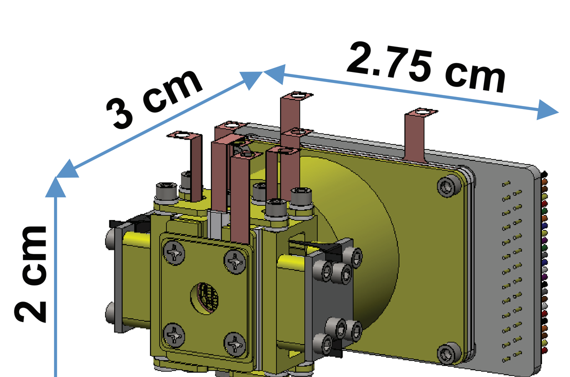
- RAMS offers a novel in-situ attitude sensor capable of measuring a fundamental quantity inherent to every Earth-pointing satellite…the ram direction
  - The ram direction is observable continuously (unlike the Sun direction)
  - The ram direction is observable regardless of roll angle (unlike the Earth direction)
- Develop and test a PicoSat-compatible attitude sensor based on sensing the RAM direction via a neutral wind measurement and coupling that with a magnetometer measurement to provide continuous attitude knowledge relative to the local orbit frame.
- In the process we monitor a good set of Space Weather measurements!

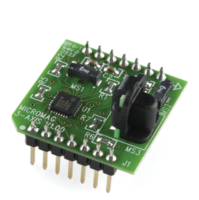
Objective

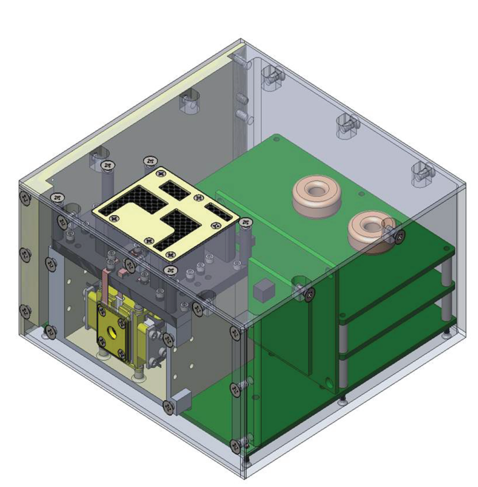
Develop and test a PicoSat-compatible attitude sensor based on sensing the RAM direction via a neutral wind measurement and coupling that with a magnetometer measurement to provide continuous attitude knowledge relative to the local orbit frame. Intent is to demonstrate operational utility of data satellite with a star camera for validation and then demonstrate active control from a CubeSat.

Approach

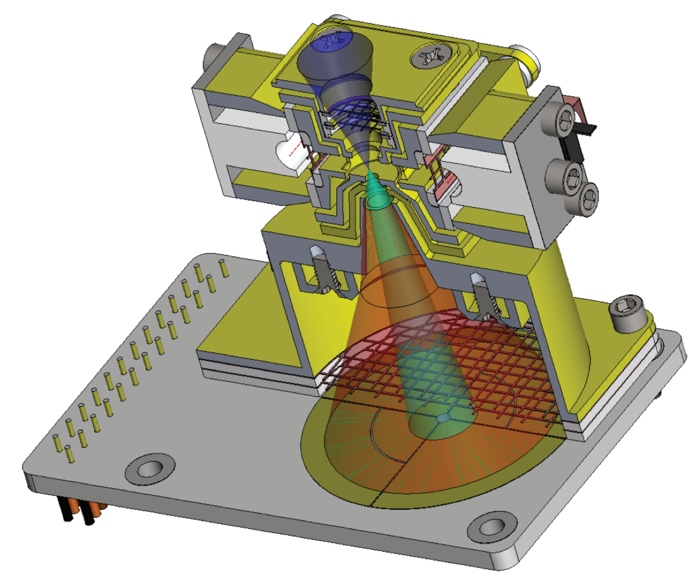
RAMS uses a small magnetometer combined with a quad-collector geometry with incidence axis aligned to a rigid satellite reference to obtain the centroid of the neutral an ion flux distributions with respect to the satellite velocity **V**. This method provides estimates of the neutral wind and ion-drift components perpendicular to **V**. Splitting two of the quad anodes makes it possible to also estimate the neutral and ion temperatures. Finally, the total collected currents of the ionized neutrals and the incident ions give the neutral and ion densities.



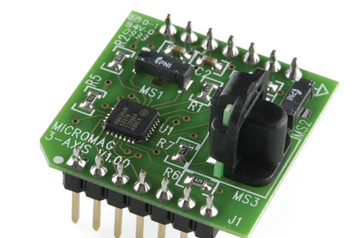




RAMS Integrated Components



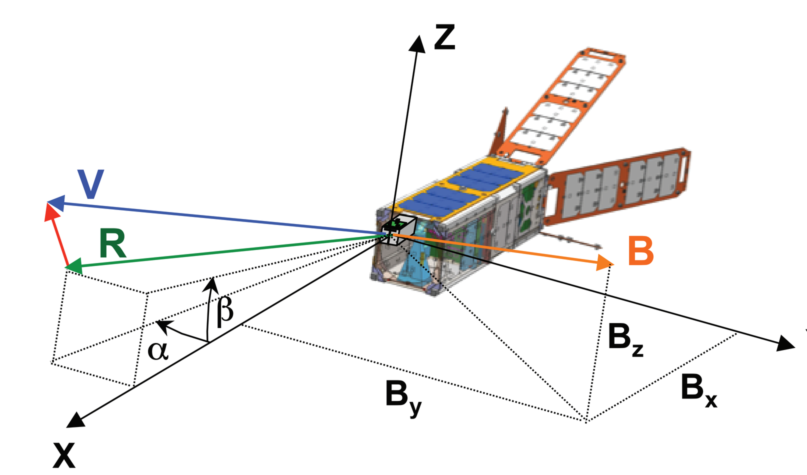
Spectrometer

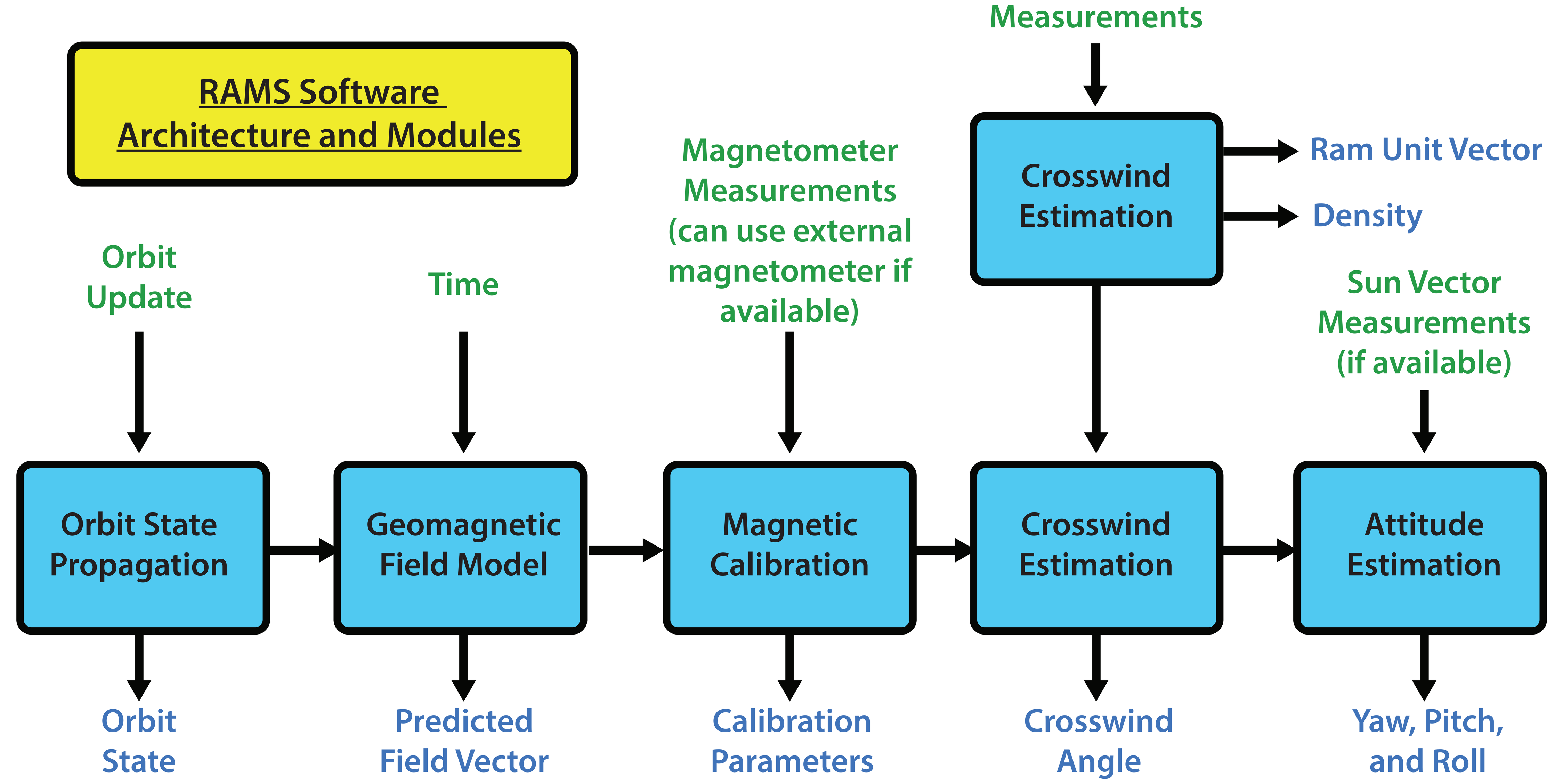


Magnetometer
PNI RM3100

RAMS Measurements (α, β, B_x, B_y, B_z)

R = ram vector
B = magnetic field vector
V = satellite velocity vector
W = thermospheric wind vector
$\theta = (\alpha^2 + \beta^2)^{1/2}$ for small α and β

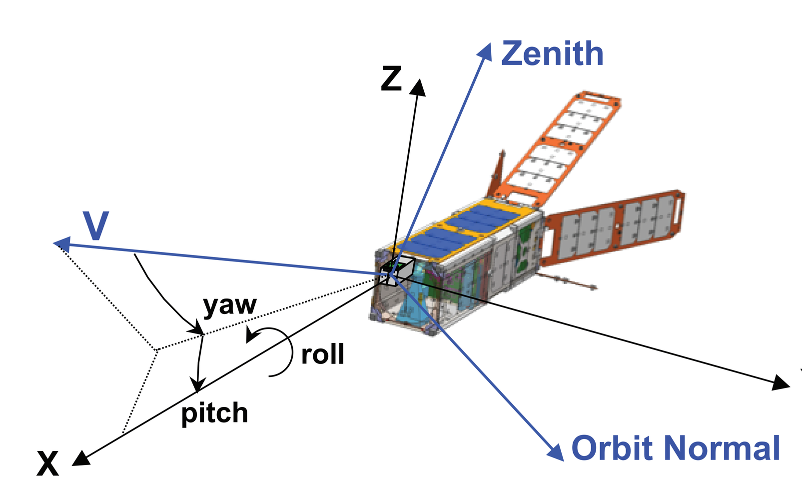




Measurements Capabilities

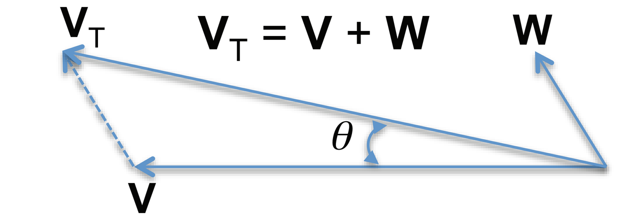
Parameter	Range	Resolution	Accuracy	
W_{perp}	1-1000 m/s	0.5 m/s	± 0.5 m/s	Neutral
T_n*	500-5000 K	50 K	± 50 K	Neutral
n_n**	10^2-10^{10} cm^{-3}	10 bit	± 30%	Neutral
Vi_{perp}	1-1000 m/s	0.5 m/s	± 0.5 m/s	Ion
T_i	500-5000 K	50 K	± 50 K	Ion
n_i	10-10^7 cm^{-3}	10 bit	± 3%***	Ion
Ram angle****	± 10 deg	±0.05 deg	±0.5 deg	
B	±800 μTesla	26 nT	20 nT	

* based on modeled relative composition, e.g., O, N_2, He…
** Ion source sensitivity ~0.1/mA adjustable electron beam.
*** Based on laboratory electrometer calibration.
**** @ 400 km



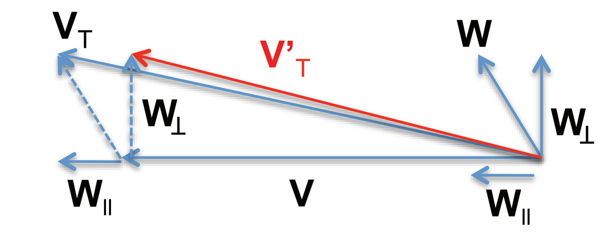
The total velocity vector V_T is defined here as the ram direction, and it is entirely due to the wind vector **W** and the satellite velocity **V**:

$$V_T = V + W$$



Decomposing **W** into components parallel and perpendicular to **V** shows the error incurred when the magnitude of V_T is unknown:

$$W = W_{\parallel} + W_{\perp}$$



$$\tan\theta = \frac{W_{\perp}}{V + W_{\parallel}}$$

where θ is the angle measured in the quad-collector

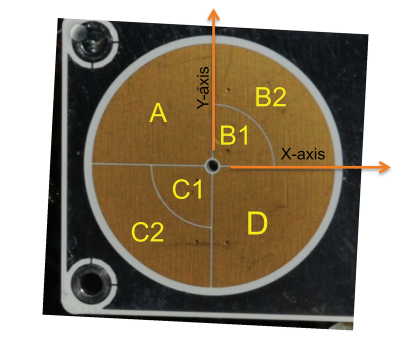
Since $W_\parallel$ is not known, $W_\perp$ is estimated from

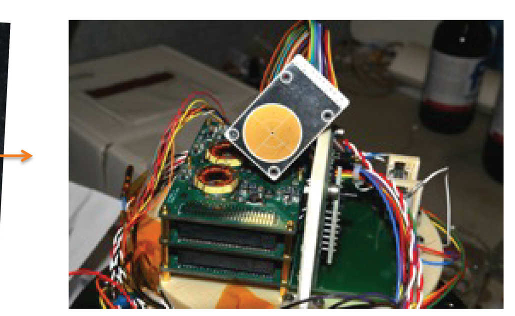
$$\tan\theta' = \frac{W_{\perp}}{V}$$

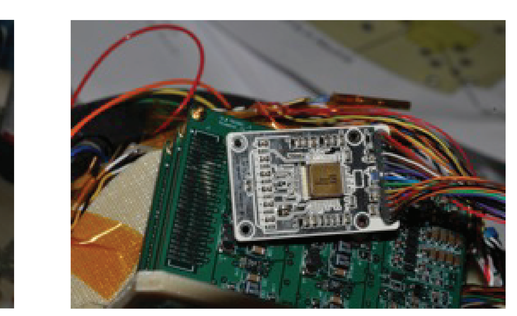
Which corresponds to a fictitous V'_T (red vector in diagram) with an error directly proportional to the magnitude of $W_\parallel$

$$\varepsilon_{W\perp} = W_{\parallel}\tan\theta \cong \frac{W_{\perp}}{V} W_{\parallel}$$

Ion enter a ram-pointing aperture subtend a cone half-angle of less than 10 degrees at the quad-collector. The four quadrants (A, B, C, D) have segments B and C further divided into B1, B2 and C1, C2.







Ram direction is computed from collected currents to give the X-Y position of teh centroid.

X position = $(I_B+I_D)/(I_A+I_C)-1$
Y position = $(I_A+I_B)/(I_C+I_D)-1$
where $I_B = I_{B1} + I_{B2}$ and $I_C = I_{C1}+I_{C2}$

The beam half width (w), which provides a measure of temperature, follows from:
$w = (K_B+1)^{1/2} I_{B1}$ where $K_B = I_{B2}/I_{B1}$ a ratio of measured currents.

The RAMS electrometer has aresolution of 0.01% corresponding to a theoretical Δθ resolution of better than 0.005 deg. Once combined with the magnetometer data and processed we expect measurable angles of a few tenths of a degree or better.

Neutral and ion densities may be derived from the RAMS data.

The RAMS apeture has an area, a, of 0.008 cm^2.

The ion source ionization effiency (ξ)is 10% of the ionizing electron beam current, I_e, from the cathode. Total neutral density, n, is obtained from the current of ionized neutrals:

$$n = I_n/(q_e \xi V a)$$

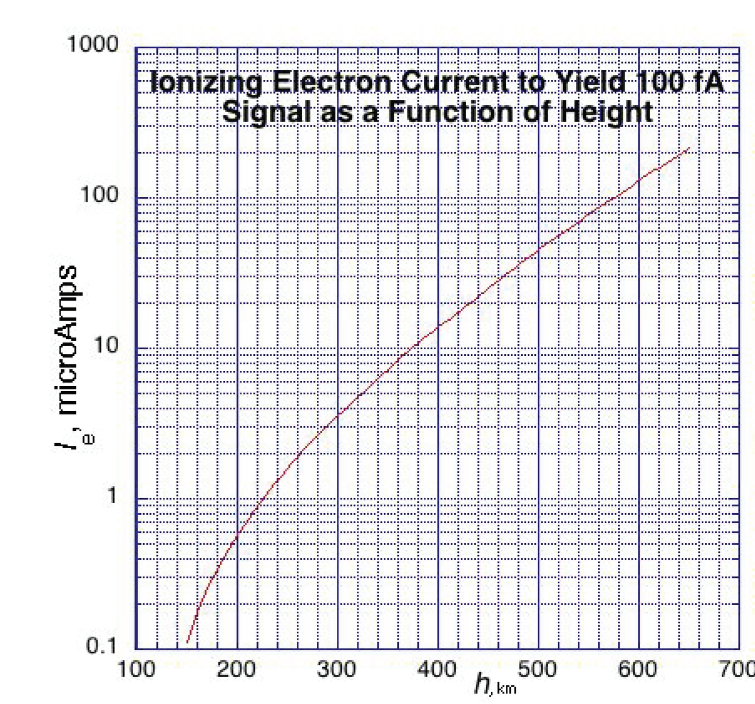
Neutral density sensitivity is controlled by adjusting I_e by up to a few milliAmps.

Ion density is given by:

$$n_i = I_i/(q_e V a)$$

where V is the spacecraft velocity and q_e is 1.6E-19 C

Calibration of the ion current in the RAMS electrometer yield accuracies of 3% for n_i.



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