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Swarm – An Earth Observation Mission investigating Geospace

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Abstract

The *Swarm* mission was selected as the 5th mission in ESA's Earth Explorer Programme in 2004. This mission aims at measuring the Earth's magnetic field with unprecedented accuracy. This will be done by a constellation of three satellites, where two will fly at lower altitude, measuring the gradient of the magnetic field, and one satellite will fly at higher altitude. The measured magnetic field is the sum of many contributions including both magnetic fields and currents in the Earth's interior and electrical currents in Geospace. In order to separate all these sources electric field and plasma measurements will also be made to complement the primary magnetic field measurements. Together these will allow the deduction of information on a series of solid earth processes responsible for the creation of the fields measured. The completeness of the measurements on each satellite and the constellation aspect, however, implies simultaneous observations of a unique set of important electrodynamical parameters crucial for the understanding of the physical processes in Geospace, which are an important part of the objectives of the International Living With a Star Programme, ILWS. In this paper an overview of the *Swarm* science objectives, the mission concept, the scientific instrumentation, and the expected contribution to the ILWS programme will be summarized.

Keywords: Geomagnetic field; Electric field; Satellite constellation; Earth observation; Magnetosphere; Ionosphere

1. Introduction

In 1999 the International Union of Geodesy and Geophysics (IUGG) adopted a resolution proposed by the International Association of Geomagnetism and Aeronomy (IAGA) in order to encourage the research of geopotential fields over one decade, making use of the new satellite opportunities that would become available. This effort, the International Decade of Geopotential Field Research, started in 1999 with the launch of the Ørsted satellite and initiated a new era of intensely focussed geomagnetic research, paralleled only by the activity generated by the MAGSAT mission some twenty years earlier. This activity has evolved to the present day due to the launch in 2000 of two additional magnetic mapping satellites CHAMP and SAC-C, which all have delivered high-precision geomagnetic data during the first years of this decade.

However, these three missions were conceived as single-satellite missions. Although some of the primary instruments were similar, they all had additional different instrumentation, spacecraft designs and orbits. The science results obtained from these missions demonstrate that the main limiting factor in the accuracy of present geomagnetic field models is the continuously varying contributions from external currents. Single-satellite missions are therefore not able to take advantage of the impressive instrument improvement, which has been achieved during the last couple of years. Multiple satellite missions measuring simultaneously over different regions of the Earth offer the only

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way to take full advantage of this new generation of instruments. At the same time magnetic field measurements are important for Space Weather applications. Results of combining Ørsted, CHAMP and SAC-C observations from a few suitable periods indicate the great potential of a constellation.

Another limiting factor regarding the advance of geomagnetic research concerns the requirement for measurements during a full solar cycle. This is needed to properly distinguish between solar activity and secular variation effects.

Scientists in the various geomagnetic research disciplines are exploring the available data with increasingly sophisticated methods. But continued scientific progress calls for an interdisciplinary approach based on the development of new tools to deal with all the various contributions, from the magnetosphere to the deep core, in a comprehensive way. Only by such an approach we can hope to synthesise various scientific issues into a coherent and unified picture of the coupled Sun–Earth system.

The *Swarm* mission is based on the mission proposal in response to the ESA Earth Observation Programme call for Opportunity Mission proposals in 2001. The proposal was co-written and submitted by a team lead by Eigil Friis-Christensen, Hermann Lühr, and Gauthier Hulot (Friis-Christensen et al., 2002). Out of 25 full proposals *Swarm* was selected as one of the three mission candidates chosen for feasibility study. The Phase-A studies were finalised by early 2004 and formed the basis for the final mission selection (ESA SP-1279(6), 2004). In May 2004 the *Swarm* mission was selected as the fifth Earth Explorer Mission in ESA's Living Planet Programme to be launched in 2010. Fig. 1 shows the spacecraft designs proposed by the industrial consortia in Phase A.

The geomagnetic field is one of the primary factors controlling the impact on the Earth's environment of solar variations. Due to its focused goal and complete instrumentation to pursue this goal the *Swarm* mission therefore fits well into the research programme of the International Living with a Star (ILWS) program. ILWS was formed to stimulate, strengthen, and coordinate space research to understand the governing processes in the connected Sun-Earth system viewed as an integrated entity. The steering committee of the ILWS programme consists of members from the Canadian, Russian, Japanese, European, and American space agencies. Its Ionosphere–Thermosphere task group identified *Swarm* as an ILWS priority at a meeting held at Nice, France in April of 2003.

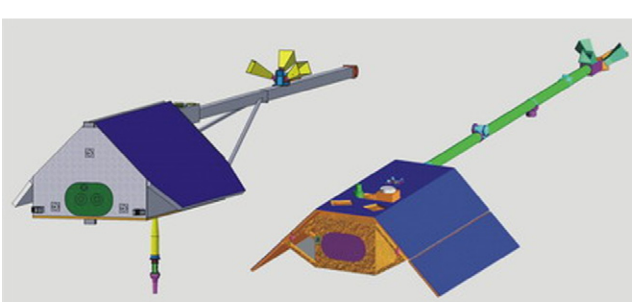

Fig. 1. Spacecraft designs proposed by the industrial consortia in Phase A.

2. Science objectives

The objective of the *Swarm* mission is to provide the best ever survey of the geomagnetic field and its temporal evolution, in order to gain new insights into the Earth system by improving our understanding of the Earth's interior and the Geospace environment including the Sun–Earth connection processes.

The *Swarm* mission will provide the first global representation of the geomagnetic field variations on time scales from an hour to several years. The more challenging part is, however, to separate the contributions from the various sources. *Swarm* will simultaneously obtain a space–time characterisation of both the internal field sources in the Earth and the ionospheric–magnetospheric current systems.

The primary research objectives of the mission are:

- studies of core dynamics, geodynamo processes, and core-mantle interaction,
- mapping of the lithospheric magnetisation and its geological interpretation,
- determination of the 3-D electrical conductivity of the mantle,
- investigation of electric currents flowing in the magnetosphere and ionosphere.

In addition to the above sources, the ocean currents produce a contribution to the measured magnetic field. But the magnetic field is not only used as evidence of the evolution of the planet, it also exerts a very direct control on the dynamics of the ionised and neutral particles in the upper atmosphere, and has possibly even some influence on the lower atmosphere. This leads to the identification of the secondary research objectives:

- identify the ocean circulation by it magnetic signature,
- quantify the magnetic forcing of the upper atmosphere.

Analysis of the *Swarm* data will largely improve existing and provide new models of the near-Earth magnetic field of high resolution and authenticity as compared to a single-satellite mission. This will bring the prospects of investigating new features of the Earth's interior.

2.1. Core dynamics and geodynamo processes

Ørsted and CHAMP have recently demonstrated the capability of satellite missions to increase the spatial resolution of secular-variation models. *Swarm* will further improve models of the core field and its secular variation by ensuring long-term space observations with an even better spatial resolution. New science opportunities will include more detailed core surface flow models, which can be used to investigate torsional oscillations and core-mantle interactions as well as the possible relationship to magnetic jerks. Combining existing Ørsted, CHAMP and future *Swarm* observations will more generally allow to investigate any magnetohydrodynamic phenomena affecting the core on sub-annual to decadal scales, down to length scales of about 1000 km. *Swarm* will provide models that include details on small-scale structures, which will allow to identify the important scientific issue of the role of diffusion. Another fundamental problem, which will be possible to address with improved data, is the identification of the wave motion in the core and the impact on model constraints regarding the toroidal magnetic field at the top of the core. Finally, by making it possible to access the detailed evolution of the field at the core surface over a significant time period, data assimilation approaches could be used to predict the future behaviour of the Earth's magnetic field, and of the South Atlantic Anomaly in particular.

2.2. Lithospheric magnetisation

The previous satellite missions have provided impressive results about the magnetisation of the crust and uppermost mantle and their geodynamic implications, but the resolution has been rather insufficient to image the entire crust, and there remains a spectral "hole" between spherical harmonic degrees 60 and 150, corresponding to the middle crust. Degrees higher than 150, corresponding mainly to the upper crust, are accessible from high-quality airborne surveys. The higher resolution provided by the *Swarm* satellites, in combination with more comprehensive approaches provided by means of aeromagnetic surveys, will allow for global compilations of lithospheric fields at scales from 5–3000 km. The increased resolution of the *Swarm* satellites will allow, for the first time, the identification from satellite altitude of the oceanic magnetic stripes corresponding to periods of reversing magnetic polarity. Such a global mapping is important because the sparse data coverage in the southern oceans has been a severe limitation regarding our understanding of plate tectonics in the oceanic lithosphere. In addition, the north–south trending magnetic anomaly stripes are among the along-track features, which are difficult to extract from a single polar-orbiting satellite. The unique *Swarm* constellation with a small East–West separation of two of the satellites will contribute significantly to overcome this difficulty (Olsen et al., 2004).

2.3. 3-D electrical conductivity of the mantle

The secondary magnetic fields due to the electric currents in the mantle induced by the time-varying field caused by currents in the ionosphere and magnetosphere are influenced by the large-scale spatial variations and 3-D structures in upper mantle electrical conductivity. Due to the sparse and inhomogeneous distribution of geomagnetic observatories, with only few in oceanic regions, a true global picture of mantle conductivity can only be obtained from space (Olsen, 1999; Constable and Constable, 2004). Accurate mapping of the 3-D electrical conductivity structure of the deep Earth requires better spatial data coverage and improved estimates of the electrical response of the mantle at long periods. This is not possible with single satellite data. Magnetic data from satellites in a constellation as proposed in the *Swarm* mission will provide the necessary simultaneous observations over different regions. Since the conductivity is dependent on the composition and temperature the resulting models will provide new information about the physical properties and dynamics of the mantle.

2.4. Magnetospheric and ionospheric current systems

Studies of the Earth's interior are limited by the effect on the magnetic field models of the contribution from currents in the ionosphere and magnetosphere. Even during magnetically quiet conditions, there is a systematic effect due to these sources. Recently, much progress has been done in modelling Earth's core field and its secular variation simultaneously with ionospheric and magnetospheric contributions in a comprehensive approach by means of a joint inversion of ground-based and satellite magnetic field measurements (Sabaka et al., 2002; Sabaka et al., 2004). Simultaneous measurements at different latitudes and local times as foreseen with the *Swarm* mission will allow better separation of internal and external sources, thereby improving geomagnetic field models (Olsen et al., 2004).

In addition to the benefit of internal field research, a better description of the external magnetic field contributions is of direct interest to the science objectives of ILWS. These contributions come from magnetospheric and ionospheric currents, some of which cause poloidal magnetic fields and others cause toroidal ones. Due to their dynamics the latter are very difficult to characterise from a single satellite. But, with a constellation it will be possible to distinguish between these two types of fields. The local time distribution of simultaneous data will foster the development of new methods of co-estimating the internal and external contributions (Olsen et al., 2004). Such methods can also take advantage of complementary data acquired by other planned (space environment) missions and ground based research facilities in the polar regions.

The *Swarm* mission can be regarded as a complement to ESA's Cluster mission. Whereas the Cluster mission is designed to measure the processes deep in or at the boundary of the magnetosphere, the *Swarm* constellation of spacecraft will allow, for the first time, the unique determination of the near-Earth field aligned currents, which connect various regions of the magnetosphere with the ionosphere. At auroral latitudes solar wind-magnetosphere interaction is causing strong ionospheric currents, as for example seen during geomagnetic storms and substorms. At mid- and low-latitude the ionospheric currents are driven primarily by high-altitude wind systems. The specific instrumentation with combined electric and magnetic field measurements as well as in situ plasma density measurements, and the specifically designed constellation of the *Swarm* mission will significantly increase our understanding of the upper atmosphere dynamics.

The structure of the ionospheric phenomena such as the mid-latitude trough and the low-latitude Appleton anomaly can be mapped using the plasma density measurements. On the other hand, the plasma density significantly perturbs the local magnetic field measurement through the diamagnetic effect, and this effect has to be taken into account in magnetic field modeling (Lühr et al., 2003). Density variation in the neutral upper atmosphere are believed to occur in response to Joule heating in the ionosphere (Lühr et al., 2004). By combining air drag observations with electric and magnetic field measurements, the physical mechanism causing the density variation can be elucidated.

The *Swarm* electric field measurements will contribute to scientific studies related to ILWS in two ways. First, it will significantly improve measurements of the main geomagnetic field. The geomagnetic field is the dominant terrestrial feature determining the interaction of the solar wind and near-earth space, and accurate characterization of its state and evolution is vital to an understanding of solar-terrestrial interactions. Electrical currents in the ionosphere produce magnetic perturbations at *Swarm*'s orbit that are comparable to or larger than fields originating inside the earth's crust and mantle. Since these currents are proportional to E, E-field measurements allow them to be characterized, and their effects taken into account to support high-precision measurements of the internally-generated geomagnetic field.

Secondly, *Swarm*'s measurements of ionospheric electric and magnetic "noise" will provide the most precise and comprehensive view ever of electromagnetic energy exchange between the magnetosphere, ionosphere and upper neutral atmosphere. *Swarm* will measure the electromagnetic Poynting vector $\mathbf{E}\times\mathbf{H}$ to a resolution of 1 mW/m^2, and at spatial scales from $\sim$1 km to global. Together with the fields themselves, this important parameter can be used to study phenomena as diverse as auroral arc formation and dissipation, gravity wave coupling of atmospheric regions, field-line resonances, neutral wind dynamos, plasma instabilities, traveling ionospheric disturbances, and sub-auroral ion drifts. Ultimately, these are all manifestations of the massive flow of energy that originates from the sun, passing through and into our space and atmospheric environments.

3. Mission concept

Single-satellite magnetic missions do not allow taking full scientific advantage of currently obtainable instrument precision because the sequential data sampling results in an inadequate capability of separating the contributions from various sources. In principle, the field modelling algorithms require a well-distributed global and instantaneous data set. Since this is not feasible, temporal variations occurring during the sampling process have to be accounted for in a proper way. A major difficulty in this respect is the fact that internal sources are Earth-fixed, while external contributions are ordered primarily in a local time frame. In a polar orbit a single satellite can obtain a reasonably dense sampling of the internal field components within a few days, but it fails to provide an adequate spatial coverage of the external contributions, because of the slow orbital precession through local time. Designing a mission with several spacecraft simultaneously orbiting the Earth at different local times will solve this problem.

The scientific return for each of the research objectives can be considerably enhanced when optimised spacecraft constellations are obtainable. An important task is to find an orbit configuration, which is a viable compromise for all objectives. The selected constellation reflects an attempt to optimise the primary research objectives: the investigation of the core magnetic field and its secular variation, the mapping of the lithospheric magnetisation with high resolution, and the determination of mantle conductivity.

This actually implies that the effects of the remaining sources should be either modelled or reduced. From the research objectives it follows that the orbit inclination shall be near polar, primarily to obtain a good global coverage. The research objectives demand that the unsampled areas around the poles should be kept small, to obtain complete maps of the magnetic field contributions. On the other hand, orbits right across the poles (90° inclination) are not favoured, since they result in a fixed synchronisation of the local time and season for the orbit. In this case scanning all local times will take one year. This would prohibit a distinction between signatures corresponding to the two different effects.

For core field modelling the larger scales are of importance. Improved results are obtained when the orbital planes of the spacecraft are separated by 3–9 h in local time. This allows for an adequate sampling of internal and external field contributions. This is also desirable for deriving the 3-D conductivity of the mantle since this relates to the interaction between the fields (Olsen et al., 2004).

For improving the resolution of lithospheric magnetisation mapping, the satellites should fly at low altitudes. The selected altitude ranges should, however, be compatible with a multi-year mission lifetime. Once the minimum possible altitude is selected, further improvement in the retrieval of the high-degree magnetic anomalies field can be achieved, by considering gradients in the inversion algorithm, in addition to the full magnetic field readings. Optimal spacecraft separations for deriving the gradients are dependent on signal spectrum and instrument resolution. An additional consideration is the definition of the smallest scales that should be resolved during the mission. A spacecraft separation in longitude between 1° and 2° has shown to optimal. A further advantage is that signals from large-scale external contributions that predominantly change in North-South direction are suppressed by the gradient method applied in the East-West direction (Olsen et al., 2004).

Two satellites flying side-by-side closely spaced in the East–West direction is also a favourable constellation for the determination of ionospheric currents. The estimation of field-aligned currents, for example, will be based on the curl-B technique (Vennerstrøm et al., 2004). At auroral latitudes, where these field-aligned currents are most prominent, field lines are almost vertical. It is proposed to use measurements taken almost simultaneously i.e. within 10 sec at the four corners of a rectangle to calculate the radial current density. The *Swarm* constellation will allow, for the first time, a unique determination of these very important coupling currents, routing the energy input from the solar wind into the upper atmosphere.

With a constellation of satellites the response of the upper atmosphere to influences from outside can be traced with increased accuracy. The multi-point measurements also taken at different altitudes allow the determination of the shape of thermospheric density structures or ionospheric plasma enhancements. In addition, the propagation direction and velocity of such features can be obtained. All these items are necessary pieces for a systematic understanding of the atmosphere.

The identified three-satellite orbit constellation that can be achieved through a single launch comprises the following parameters (see Fig. 2):

- One pair of satellites (*Swarm* A + B) flying side-by-side in near-polar, circular orbits with an initial altitude and inclination of 450 km and 87.4°, respectively. The east–west separation between the satellites shall be between 1 and 1.5° in longitude, and the maximal differential delay in orbit shall be approximately 10 sec.
- One higher satellite (*Swarm* C) in a circular orbit with 86.8° inclination at an initial altitude of 530 km with right ascension of the ascending node close to that of the two other satellites.

4. Instrumentation

The payload complement of the *Swarm* satellites consists of core instruments, which are required for a precise determination of the ambient magnetic field and of auxiliary-type instruments, which are needed for a better separation of the various field sources and for the detection of effects related to geomagnetic activity.

Measuring the vector components of the magnetic field with an absolute accuracy requires the combination of readings from three instruments: A scalar magnetometer, a vector magnetometer, and a stellar compass to provide the attitude of the vector magnetometer with the required accuracy. Only if the performances of all three instruments are matched an optimal result is achieved. We therefore treat them as a single package.

High-quality instruments for such packages have been developed in the context of the Ørsted and CHAMP missions and are readily available for *Swarm*. The desired accuracy of the magnetic field products is significantly higher than that of existing missions. This demands precise attitude transfer to the vector magnetometer and a magnetically clean or controlled environment. Furthermore, a continuous record of precise orbit information is needed for the interpretation of the data, which can be obtained from a high-quality GNSS receiver.

In order to improve the determination of the contribution to the magnetic field from currents in the ionosphere, the payload includes an instrument to measure the electric field. Plasma density measurements are also included since the plasma density significantly perturbs the local magnetic field measurement through the diamagnetic effect, and this effect has to be taken into account in magnetic field modeling (Lühr et al., 2003).

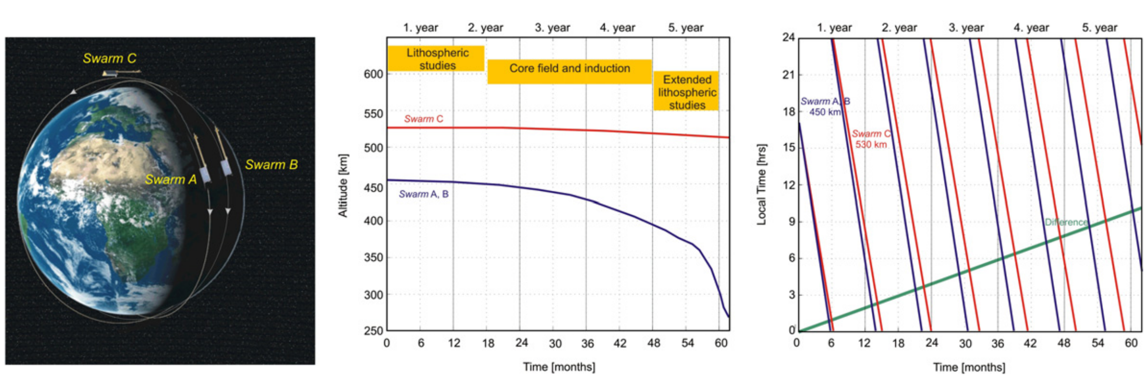

Fig. 2. Impression of the proposed three satellite constellation (left) and mission scenario. Change in altitude versus time (centre) Local time evolution for the satellites in the two orbital planes (right).

Density variation in the neutral upper atmosphere are believed to occur in response to Joule heating in the ionosphere (Lühr et al., 2004). Combining air drag with electric and magnetic field measurements will contribute to the elucidation of the physical mechanism causing the density variation. The air drag, needed for deriving the thermospheric density, can be obtained from observing the non-gravitational forces. Suitable instruments i.e. tri-axial accelerometers are presently used in gravity missions. Precise orbit information is needed for calibration purposes and for complementing the air drag obtained from an accelerometer at long wavelengths.

The overall accuracies of the data products at level 1b for the various quantities can be summarized for each single satellite (ESA SP-1279(6), 2004):

- magnetic field magnitude: 0.15 nT 1σ-accuracy for signal up to 20 km wavelength, with a stability in time accurate to 0.05 nT per 3 months for the slow variations,
- magnetic field vector: 0.5 nT 1σ-accuracy for signal up to 2 km wavelength, with a stability in time accurate to 0.5 nT per year for the slow variations,
- electric field vector: 1.5 mV/m 1σ-accuracy for signal up to 20 km wavelength, with a stability in time accurate to 0.5 mV/m per month for slow variations,
- electron density: 0.5×1010 m-3 RMS precision for signal up to 20 km wavelength,
- air drag: 1.75×10-8 m s-2 1σ-accuracy for signal up to 200 km wavelength in all directions.

The level of performance reached by currently available space instruments is already fairly high. For the *Swarm* mission it is anticipated to basically rely on instrument performances, as they have been experienced with Ørsted and CHAMP. However, higher accuracy demands are put on the final data products, based on the experiences gained from the existing missions. The improved quality of the derived information is expected to rely on coordinated measurements at the dedicated spacing provided by the controlled constellation of spacecraft. An important requirement regarding the *Swarm* mission is thus that the complement of all spacecrafts is treated as a single system. This implies that all readings from the three satellites must be directly comparable. A desirable mission target would be to achieve the overall mission requirements listed above on *Swarm* system level. Such a performance would contribute to improve our knowledge significantly in several areas of geomagnetism.

As a minimum, each of the spacecraft should perform as good as existing magnetic field missions. In particular, if the direct comparability between the different spacecraft is no longer available, e.g. due to instrument problems, the value of the constellation concept could reduce, depending on the instrument.

For most of the instruments the actual provider has not been selected yet, since this will depend on the result of the selection of the industrial proposals that will be submitted in response to the current ESA ITT.

But for the electric field instruments on *Swarm* the case is different. According to an agreement with ESA these instruments will be provided by the Canadian Space Agency. The Canadian Electric Field Instrument (CEFI) will determine ionospheric electric fields in the plane perpendicular to the magnetic field, with a time resolution of 16 samples/s and a 2-σ accuracy of 5 mV/m. The CEFI will also deliver measurements of ion density, ion and electron temperature, spacecraft potential, H^+ and O^+ mass concentrations, and ion distribution functions.

The CEFI's basic measurement is of 2-D images of the ionospheric ion distribution function. Distribution images are formed using a concentric pair of hemispherical electrostatic grids situated inside a cylindrical sensor head, shown in Fig. 3. The incoming distribution in dispersed in radius according to its constituent energies. This technique was first used on the Freja satellite's Cold Plasma Analzyer (Whalen et al., 1994). The detector consists of microchannel plates, a phosphor screen, and a CCD camera that images the phosphor with ~3000 pixels.

Fig. 4 shows a simulated detector image typical of what will be measured on *Swarm*. Oxygen ions and protons separate into two sub-distributions, owing to the different ram kinetic energies as seen in the satellite frame. The first moment (position) of the O+ sub-distribution (at right) provides a sensitive measure of 2-D ion drift velocity, the 2nd moment estimates ion temperature, and the relative intensities of the two sub-distributions measure ion composition. The *Swarm* CEFI will have two orthogonal sensors to provide a full, 3-D ion drift vector, with a redundant

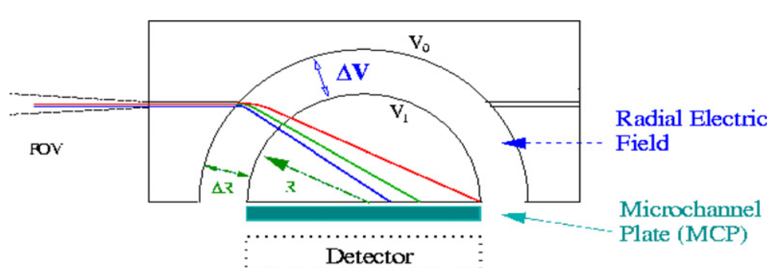

Fig. 3. The CEFI's electrostatic focusing system. An inward-directed radial electric field accelerates very-low-energy ions (blue) toward the center of the detector, with higher energy ions (red corresponding to 20 eV) landing at larger radii.

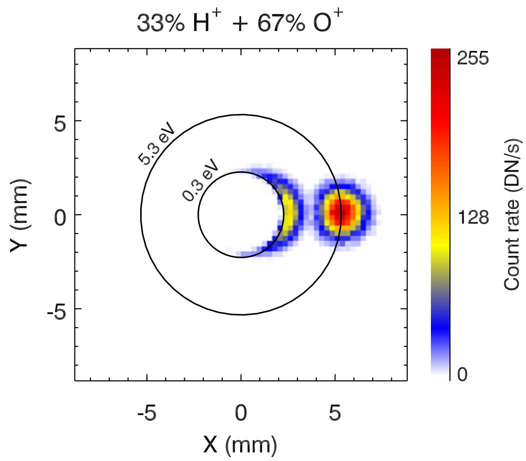

Fig. 4. Simulated CEFI image with plasma drift of 7.6 km/s in the payload frame. Figure courtesy of JK Burchill.

measurement of ram velocity. Electron density and temperature will be derived from a separate Langmuir probe measurement. The ability of the CEFI design concept to determine electric fields with the sufficient accuracy has been established by direct comparison with electric field double probe experiments on sub-orbital sounding rockets (Knudsen et al., 2003; Burchill, 2003).

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