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THE FAR ULTRAVIOLET (FUV) AURORAL IMAGER FOR THE INNER MAGNETOSPHERIC IMAGER (IMI) MISSION: OPTIONS

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Introduction

The change from an intermediate class mission (cost ceiling of $300 million) to a solar-terrestrial probe class mission (cost ceiling of $150 million) will require some major changes in the configuration of the IMI mission. One option being considered is to move to a small spin-stabilized spacecraft (with no despun platform) which could be launched with a smaller Taurus or Conestoga class booster. Such a change in spacecraft type would not present any fundamental problems (other than restrictions on mass and power) for the He^+ 304 Å plasmasphere imager, the high and low energy neutral atom imagers, and the geocoronal imager, but would present a challenge for the FUV auroral imager since the original plan called for this instrument to operate from a despun platform. Since the FUV instrument is part of the core payload it cannot be dropped from the instrument complement without jeopardizing the science goals of the mission. A way must be found to keep this instrument and to allow it to accomplish most, if not all, of its science objectives. One of the subjects discussed here are options for building an FUV instrument for a spinning spacecraft. Since a number of spinning spacecraft have carried auroral imagers, a range of techniques exists. In addition, the option of flying the FUV imager on a separate micro-satellite launched with the main IMI spacecraft or with a separate pegasus launch, has been considered and will be discussed here.

Instrument Requirements

In order to accomplish its mission, and be at least current with the state of the art in auroral imaging, the FUV auroral imager will need to have the following characteristics (as identified by the science working group for the original baseline design):

1. A large field-of-view of $30° \times 30°$.
2. A small angular resolution of $0.03° \times 0.03°$.
3. Ability to obtain separate images of the auroral oval at 1304 Å, 1356 Å and in the LBH band (1200–1800 Å).
4. High time resolution; image repetition rate of one minute or less.

Despinning the Image

If the FUV imager is carried on a spinning spacecraft then one task it must perform is the despinning of the image. Several auroral imaging instruments have flown on spinning spacecraft in the past which have performed the despinning task in three different ways. These include (1) the Scanning Auroral Imager (SAI) which flew on the DE 1 spacecraft[3]. This instrument used the spacecraft's rotation to scan a small instantaneous field-of-view (0.32°) across the sky in one dimension. Scanning in the perpendicular direction was accomplished by a movable mirror. This technique gave long image construction times (12 min) and short image exposure times (4 ms). (2) The second technique was used on the V5 instrument flown on the Swedish Viking satellite. This instrument had a large instantaneous field-of-view ($20° \times 25°$) through which the image would sweep each spacecraft rotation[1]. To compensate for rotation the accumulated charge in the CCD rows were stepped across the detector at the same rate the image swept across the field-of-view[6]. With this system an image was obtained each spacecraft rotation (20 s) with an exposure time of 1.2 s. (3) The third technique was used by the ATV instrument flown on the Japanese satellite EXOS-D (Akebono). This instrument used a despun mirror, which spun opposite to the direction the spacecraft was spinning, to compensate for image motion[7].

Telescopes

One way to get the large total field-of-view that the FUV instrument will need is to build it up from successive scans as was done by the SAI instrument which flew on DE 1. The alternative is to use an optical system with a large instantaneous field-of-view. There exists a number of space flown (or soon to be flown) telescope designs which have large instantaneous fields-of-views. These include: (1) the VIKING V5 Instrument[1] which is an inverse Cassegrain, Burch-type with a field-of-view of $20° \times 25°$, a focal length of 22.4 mm (f/1) and an angular resolution of $0.077° \times 0.077°$; (2) the NUVIEWS Astronomical Instrument[2,10] which is a three mirror anastigmat (TMA) off axis imager with a $20° \times 40°$ field-of-view, a focal length of 90 mm (f/3) and an angular resolution of 0.058°; and (3) the POLAR VIS Earth Camera[1] which is also a three mirror anastigmat (TMA) off-axis system with a $20° \times 20°$ field-of-view with an angular resolution of 0.08°.

Among this list the NUVIEWS telescope comes closest to meeting the requirements for the FUV instrument. As originally designed the NUVIEWS instrument had a $40° \times 40°$ field-of-view. Down sizing to a telescope with a $30° \times 30°$ field-of-view would not present a problem. It would have the added benefit of increasing the angular resolution (to less than 0.058°) and reducing various aberrations (spherical, coma, astigmatism) which affect image quality and resolution.

Filtering The Image

All instruments designed to image the aurora in the VUV have had to filter the incoming light so as to remove scattered sunlight in the visible and near ultraviolet. The SAI instrument on DE 1, the V5 instrument on VIKING, the ATV instrument on EXOS-D, and the VIS Earth Camera on POLAR all use fairly broadband (150–500 Å FWHM) filters which would be inadequate for the FUV instrument on IMI. The filtering system to be used on the POLAR UVI instrument was designed for spectral resolution close to the IMI requirements. It is based on the use of specifically designed multilayer reflection and transmission filters[9]. Each of the five filters is a small optical system with three flat mirrors and a transmission filter. The band widths of the five filters are: 1304 – 30 Å, 1356 – 50 Å, LBHs – 80 Å, LBHl – 90 Å, and Solar Spectrum – 100 Å [8]. The FUVIM instrument proposed for the IMAP small explorer[5] would use a diffraction grating, in place of transmission filters, to spectrally separate the incoming light. Since FUVIM will be a line scanning instrument it will be an imaging diffractometer. The position of the diffraction grating (moved by a stepper motor) will determine which part of the spectrum, from the imaged slit, falls on the detector. With the characteristics of the diffraction grating (3600 lines/mm, blaze angle of 13.5°), the internal geometry of the instrument, and the size of the detector, FUVIM will have a FWHM passband of 34 Å at any desired wavelength.

Detectors

Imagers which do single pixel or line imaging (such as the SAI instrument on DE 1) can use simple detectors that do not require special cooling. Imagers which do instantaneous two-dimensional imaging require more sophisticated detectors. There are two basic types which can be used. One involves an image intensifier coupled to a charge coupled device (CCD) and the other involves a microchannel plate (mcp) connected to a position sensitive anode. The CCD based detector is the detector of choice because the mcp/anode detector is a single event detector. That is it counts one photon at a time and while the anode electronics is reading out the results of one photon event it cannot see another which might arrive in the mean time. The total number of counts per second which such a detector can see before performance is degraded depends then on the speed of the anode readout electronics. Current performance for these detectors is low enough so that will be saturated by auroral VUV light intensities. CCD detectors do not have this problem since each pixel in the array can count photons independent of whether the other pixels are also currently counting photons.

Instrument Sensitivity

One of the most important criteria for measuring an imaging instrument's performance is its sensitivity S. S can be expressed thus: $S = (F/4\pi)Ar^n F_r \Omega_p T_g Q_e C_m T_e$ where F is the flux of photons (photons/cm^2/s), 4π is the number of steradians in a full sphere, A is the aperture area of the imager, r is the reflectivity of the mirrors in the optical system, n is the number of such mirrors, F_r is the filter response, Ω_p is the solid angle of the pixel, T_g is the transmission of the detector's glass window, Q_e is the quantum efficiency of the photocathode material, C_m is the collection efficiency of the microchannel plate, and T_e is the exposure time. The units of S are counts/kR/pixel/Ip where kR is kiloRayleighs and Ip is the integration period. S will depend on the wavelength of the photons since r, F_r, T_g, and Q_e are all wavelength dependent. As an example of the use of this equation the SAI derived instrument planned for the MARIE mission had the following values for each factor (at 1304 Å): $A = 20.3$ cm^2, $r = 0.95$, $n = 4$, $F_r = 0.3$, $\Omega_p = 1.9 \times 10^{-5}$ st, $T_g = 0.95$, $Q_e = 0.13$ electrons/photon, $C_m = 0.85$, and $T_e = 0.004$ s. With a flux of 1 kiloRayleigh ($F = 10^9$ photons/cm^2/s) $S = 3.2$ counts/kR/pixel/Ip. This sensitivity is small enough that some of the weaker, but important, signals would not be seen by this instrument. The main thing that can be done to increase S is to increase the exposure time T_e but this value can't be larger than the desired time resolution. Another thing that can be done is to increase Ω_p but this action degrades the angular resolution of the instrument which is undesirable. Achieving high sensitivity is always a trade-off with achieving small angular and temporal resolution.

Possible Configurations for an FUV Auroral Imager

Option 1. The first option for the IMI FUV auroral imager would be to use the Far UltraViolet Imaging Monochromator (FUVIM) as proposed for the IMAP small explorer, as it is. Advantages of using the FUVIM instrument are: (1) it is small, has a low mass, small power need, and low data rate; (2) the design has over twenty years of flight heritage; (3) the FUVIM uses detectors which do not require special cooling; (4) FUVIM can also perform the task of geocoronal imaging; and (5) it does not place extreme requirements on the spin axis stability of the spacecraft. Disadvantages of this option include: (1) the angular resolution is not very small being $0.25° \times 0.25°$; and (2) it may lack the sensitivity to produce images with statistically significant count levels for the 1356 Å and LBH images.

Option 2. For the second option one could use four or five VIKING V5 cameras where each camera is optimized for a desired wavelength. The transmission filter at the front entrance and the reflection filter coatings applied to the two mirrors in each camera would be designed after the Zukic method[9]. During one minute of elapsed time images of the aurora at each of four or five passbands (1216 Å, 1304 Å, 1356 Å, 1400-1600 Å, and 1600-1800 Å) could be obtained with an exposure time of 4 s (assuming an instrument field-of-view of $25° \times 25°$). For the weaker features longer exposure times could be used without sacrificing one minute, or shorter, time resolution for the stronger features. Estimates of the sensitivity of each camera using a CsI photocathode and the angular resolution of the V5 instrument give values of 150 (1304 Å), 274 (1356 Å), 223 (1500 Å), and 100 (1700 Å) counts/kR/pixel/Ip. There also appears to sufficient out of band rejection to separate these four features from hydrogen Lyman-α although the 1356 Å feature will be partially contaminated by 1304 Å radiation.

Advantages of this approach include: (1) small total instrument mass ≤ 20 kg; (2) the basic camera design has about 4–5 years of flight heritage; (3) the instrument could perform the task of geocoronal imaging; (4) This instrument could obtain all of the separate auroral images, at different wavelengths, simultaneously; and (5) image motion is compensated for by electronic scanning, eliminating the need for moving mirrors. Disadvantages of this option include: (1) the angular resolution ($0.076° \times 0.076°$) is larger then the IMI requirements; (2) the original V5 camera design had problems with stray light which may persist; (3) using the full temporal and spectral resolution which this instrument concept could provide would require a fairly large data rate; (4) additional cooling for the detectors would be needed; and (5) the spacecraft spin axis would be required to remain stable to about 0.08°/min.

Option 3. For this option one could use a single imaging head with an optical system based on the NUVIEWS telescope modified to have a $30° \times 30°$ field-of-view, with an angular resolution of $0.03° \times 0.03°$ (or as close to that as possible). The instrument would stair out the side of the IMI spacecraft (perpendicular to the spacecraft's spin axis) and use electronic sweeping of the CCD array to provide longer integration times of about 5 s in a one minute period. The filter system would be that designed for the POLAR UVI instrument with the possible inclusion of a filter designed for hydrogen Lyman-α at 1216 Å. In operation this camera could sum images gained in successive revolutions until the one minute period was reached or sufficient counts had been obtained. The detector would be an image intensifier/CCD combination using a large format CCD array (1000×1000 pixels). Estimates of the sensitivity of such an instrument, based on the POLAR UVI sensitivities scaled for the shorter integration time, are: 27 (1304 Å), 46 (1356 Å), 76 (1500 Å), and 24 (1700 Å) counts/kR/pixel/Ip.

Advantages of this approach include: (1) small total instrument mass ~ 22 kg; (2) this instrument could perform the task of geocoronal imaging; and (3) image motion is compensated for by electronic scanning, eliminating the need for moving mirrors. Disadvantages of this option include: (1) the angular resolution may not reach the IMI goal (it would at least be $0.05° \times 0.05°$); (2) the design may not have sufficient sensitivity; (3) the CCD detectors would need to be cooled to at least $-55°$ C; and (4) a stable spacecraft spin axis is required (0.05°/min).

Option 4. In this design one could use the imager described in option 3 above, but instead of seating the instrument so that it looked out the side of the spacecraft perpendicular to the spin axis, it is positioned so that it looks out one end of the spacecraft parallel to the spin axis and into a despun mirror tilted at 45° to stair continuously at the earth. This would allow much longer integration times, and increase the instrument sensitivity. Estimates of such sensitivities, based on the POLAR UVI values with a 30 s integration time are: 163 (1304 Å), 277 (1356 Å), 456 (1500 Å), and 144

(1700 Å) counts/kR/pixel/Ip. (These sensitivities assume a $0.03° \times 0.03°$ angular resolution, an aperture size, mirror reflectivity, filter response and detector response of the POLAR UVI instrument.) These sensitivities would allow the possibility of achieving the IMI goals of angular resolution and temporal resolution for the FUV instrument.

Disadvantages of this option include: (1) the angular resolution may not reach the IMI goal (it would at least be $0.05° \times 0.05°$); (2) the despun mirror would add complexity and cost to the instrument design, (3) the design would not allow the possibility of geocoronal imaging; (4) the CCD detectors would need to be cooled to at least $-55°$ C; and (5) a stable spacecraft spin axis would be required (0.08°/min).

Option 5. This last option would take the instrument from option 3 and place it on a nadir viewing three-axis stabilized micro-satellite. This approach would provide the high sensitivities of option 4 without the need for the complexity of a despun mirror. There would also be no need for electronic scanning of the image for motion compensation. It may also eliminate some of the pressure on the resources of the spinning satellite portion of IMI. The added complexity of a second spacecraft would have to be evaluated carefully to see if it was worth these potential gains.

Advantages of this approach include: (1) much higher sensitivities would be possible, comparable to those in option 4; and (2) the instrument would be simpler, since it would not need a despun mirror. Disadvantages of this option include: (1) the angular resolution may not reach the IMI goal (it would at least be $0.05° \times 0.05°$); (2) the micro-sat might not be able to provide the pointing stability, accuracy or knowledge without excessive cost; (3) adding a second spacecraft would add to the overall management and operations cost of the mission; and (4) the CCD detectors would need to be cooled to at least $-55°$ C.

From this list of options one can conclude that an FUV like instrument can be carried on a small spinning spacecraft. Options 4 and 5 illustrate ways that such an instrument could meet, or come close to meeting the IMI requirements. If option 4 or 5 is ruled out because of cost or some other factor then fall back positions exist which are still fairly attractive. They would however, require the sacrifice of some of the original goals for the IMI FUV instrument.

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