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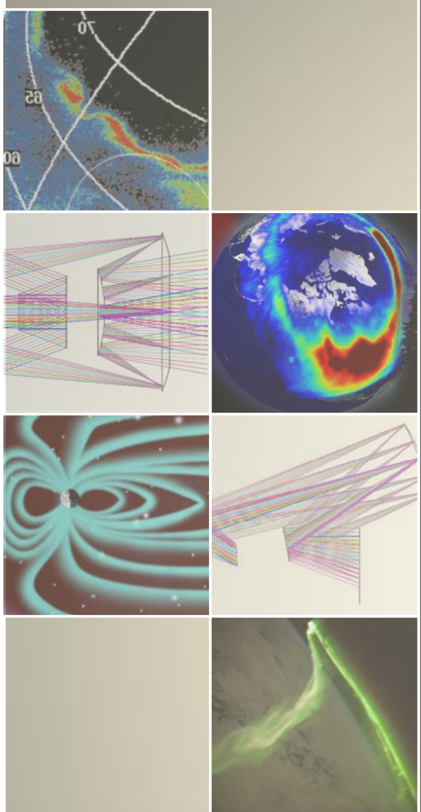

UVAMC Pre-Phase A Study FINAL REPORT

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Contents

Cover Images: (Top Left) Freja UofC, (Second Row Left) UVAMC Conceptual Design, (Second Row Right) Polar UVI, courtesy NASA, (Third Row Left) Magnetosphere, courtesy NASA, (Third Row Right) UVAMC Conceptual Design (Bottom) ISS Auroral Image, courtesy NASA.

1. Executive Summary

The UVAMC project was successful in addressing the science requirements and optical design of satellite borne auroral imaging for possible future missions. There were however, several changes that occurred over the course of the contract.

As we moved forward with the science requirements component of the SOW, it became clear that predetermining the science requirements in advance of knowing platform characteristics was counter-productive. We instead chose to take a broader approach and develop tools for deriving science requirements that are applicable to any scenario. This allows us to, in short order, develop a science targeted mission with concrete requirements that takes full advantage of the platform characteristics. These tools are presented in the UVAMC Science Requirements document (UVAMC.SR1.0001) and summarized in Sections 5 and 6 of this document.

Similarly for the conceptual design, we developed 45 optical designs and generic tools to assess an optical designs ability to address science requirements. This allows us to select a targeted design for any given set of science requirements and platform. We also developed a framework for design optimization to ensure maximum optical performance against the science objectives. This work is summarized in the Conceptual Design Document (UVAMC.DDD.0001) previously submitted to CSA.

Auroral spectral modeling was added to the UVAMC work through a contract to Computational Physics Inc. Model outputs provided by CPI played a key role in both science requirement derivation and instrument performance assessment. This work is discussed in the Science Requirements Document (UVAMC.SR1.0001) previously submitted to CSA.

A list of milestones and deliverables for this contract is shown in Section 3. This table is modified to include the status of each deliverable and the section in which is addressed.

2. Introduction

Auroral imaging is one of the most powerful experimental tools in space science. The aurora provides a two dimensional projection of plasma processes occurring in the near-Earth space environment and it the *only* tool that can provide continuous and consistent observations of these processes. Global auroral imaging has contributed to and/or driven major discoveries in geospace, such as details of day-side cusp dynamics and magnetospheric energy storage/release that had never before been seen at the system-level until Polar UVI snapped the first truly global images of the aurora.

Ultra-Violet Auroral Monitoring Cameras (UVAMC) is a project aimed at establishing a foundation for the next generation global auroral imager. Previous auroral missions were typically built to fit within tight financial, mass, volume budgets without a firm understanding of what the imager would deliver before they were commissioned. UVAMC will be an exception to this. Through UVAMC we have developed a “pathway to a conceptual design” based on the philosophy of matching instrument performance and science requirements. Starting from the science, UVAMC created tools to specify top-level requirements that address a broad range of science requirements (arguably for the first time for satellite borne auroral imaging). Top-level requirements can then be used to prescribe mission level requirements and constraints on imager design performance. Further, UVAMC developed quantitative tools to enable an end-to-end matching of design performance and mission requirements with a traceability framework to assess future trade studies. Without exaggeration, UVAMC tools are a leap forward in our ability to truly define targeted auroral imaging missions and understand the implications of design space trades.

In the following Sections we summarize the deliverable status and describe the work conducted under each work package.

3. Deliverables Summary

Milestones/Deliverables	Date Due	Document Reference
Final Report	Feb 1, 2012	------------------------
Quarterly Progress Reports	Quarterly	Not included in this report
University of Calgary KuaFu Meeting Presentations (included in quarterly reports)	Quarterly	Appendix C
UVAMC Science Requirements Document	January 31st 2012	UVAMC.SR1.0001 (previously submitted to CSA, not included in this report)
UVAMC Conceptual Design Document	January 31st 2012	UVAMC.DDD.0001 (previously submitted to CSA, not included in this report)

4. WP2100 Develop KuaFu Mission Level Science

The Kuafu mission was conceived of by Academician Chuanyi Tu (Peking University) and his colleagues in the Chinese Solar-Terrestrial research community. The original mission concept called for one L1 satellite providing Wind-type solar wind in situ and SOHO-type solar imaging observations as well as one MEO or LEO satellite providing unspecified space weather measurements. Kuafu, named for a character who in an ancient Chinese legend chased the Sun (until he died), was to be a "Sun to Mud" program, studying with one mission the complete space weather chain from Sun to Earth.

Following the March 2004 Sino-Canadian Space Science Symposium in Beijing, Chuanyi Tu approached the Canadian Ravens PI Eric Donovan to discuss whether Ravens (or Ravens-type) observations could replace the unspecified Earth orbiting mission component. The CSA Ravens concept study became the model for "Kuafu B" (Kaufu A being the solar probe), and formed the bulk of the text on Kuafu B submitted to the Chinese government for the Kuafu Assessment Study.

Kuafu B grew to include imaging (UVI, SI, ENA after Ravens; X-Ray and EUV) and in situ. The cost of Kuafu B became prohibitive, as did the complicated mix of international partnerships (China, Canada, UK, Ireland, Germany, France, Belgium, Norway, others), and was separated from Kuafu A (meaning the two could be launched separately. The Kuafu B community, led by Eric Donovan, Mark Lester, Pierre Rochus, Pontus Brandt, and Nikolai Ostgaard, agreed in a 2008 meeting in Montreal to carry forward with plans for a Ravens-type mission in parallel with Kuafu B.

Since that time a "Ravens Europe" proposal (including UVI instruments from Canada) has been submitted to ESA, but was rejected in the last cut of that competition. At the present time ESA is considering a scaled down version of Ravens (very light and simple payload including UVI imaging from an unspecified - but hopefully Canadian - source). KuaFu continues as a mission in consideration in China, with continued extensive international commitment to the mission if it goes forward. It is likely that if ESA were to fund Ravens Europe, it would become Kuafu B in partnership with China. It is critical that Canada maintain some level of commitment to these ongoing international activities, as it is very likely that the international community will eventually commit to a global imaging mission (under the banner of Ravens and/or Kuafu).

4.1 Frame work for a UVAMC instrument on Ravens Europe

The UVAMC team contributed an FUV imager design description to the Ravens Europe proposal based on one of the conceptual designs developed under WP 3200. This design was selected specifically for the platform characteristics of Ravens Europe (provided by Steve Millan and listed below) using the UVAMC tools for optical design selection. The description of the proposed instrument is included in Appendix B.

The relevant Ravens Europe mission parameters are;

- Orbital Configuration – 7 x 1.8Re (geocentric), 90^{o} inclination, 13.0h orbital period
- Spin rate of 2rpm
- Pointing Accuracy not specified
- Mass Allocation – 35kg
- Power Allocation – 35W (orbit averaged)
- Data Rate – 70kbs

The Ravens Europe proposal can be viewed online -
http://www2.le.ac.uk/departments/physics/research/rspp/missions/ravens/documentation/Ravens%20proposal.pdf

5. WP 2200 Explore UVAMC Science Objectives

Throughout the contract lifetime the number of science objectives explored by the UVAMC pre-phase A study steadily expanded as original objectives were explored and new areas of interest or relevance were discovered as they related to UVAMC. As we moved forward with the investigation of science requirements and the coupling to platform characteristics, it became clear that predetermining a set of concrete science objectives for the UVAMC project was counterproductive. Instead we chose to investigate a broad range of possible science targets and develop tools to assess (and or derive) appropriate platform characteristics. We therefore do not have a set of prioritized science objectives for the UVAMC project, rather specific studies of relevant science objectives and tools to generate prioritized mission specific science objectives based on mission characteristics. The science objectives specifically studied under UVAMC are;

- Determining the MLT localization of the tail-related wave activity in the optical aurora
- Understanding how the direction of the wave depends on its MLT position
- Determining characteristic values of the wave parameters (phase velocity, wavelength, growth rate, frequency, stationarity) at different substorm phases
- Determining what properties of tail plasma and geometry can be estimated based on the parameters of the auroral waves
- A quantitative analysis of energy release dynamics in the magnetotail
- Remote-sensing various types of plasma instabilities leading to auroral breakup
- Understanding auroral signatures of multiscale processes in the magnetosphere – ionosphere system.
- Atmospheric response to space weather; understanding auroral production of odd nitrogen and its effect on ozone depletion
- Investigation of the latitudinal alignment of discrete auroral forms and its relation with the processes in the magnetotail

All of these objectives were explored to a high degree and results pertaining to each of the objectives are detailed in the journal publications attached in Appendix A. UVAMC also generated a set of broader science themes which encompass all aspects of geospace science that are enabled and/or enhanced by auroral imaging. These themes include;

- Modes of Geospace
- Dayside Dynamics
- Space Weather Effects on the Earth's Atmosphere
- Evolution of Structure in Geospace, and
- Geospace Energy and Mass Budgets

Further, we developed a formal mechanism for producing mission level requirements based on the needs of the science objectives (coupled to work with WP3100). The development of this methodology involved; development of specific tools to quantify the behavior of the auroral system and coupling between measurement parameters, the derivation of basis set of top-level and mission-level science requirement parameters, determining the traceability of the top-level requirements to mission level parameters, and a thorough investigation of the effects of orbit and platform on the mission level parameters (see Section 6 for more details). This methodology is laid out in the science requirements document (UVAMC.SR1.0001) and feed directly into the UVAMC conceptual design work (WP3200).

6. WP 3100 UVAMC Measurement Requirements

6.1 UVAMC Measurement Requirement Derivation Tools

During the course of this contract numerous software tools were developed for analyzing physical constraints on UVAMC measurement requirements. These tools were used to analyze extended collections of high-resolution auroral images produced by POLAR UVI and IMAGE WIC. Images were processed using our numerical codes which allow us to measure spatial and temporal scales of discrete auroral forms under changeable geomagnetic conditions. The central goal of this research was to develop guidelines for optimizing the resolution and sensitivity of UVAMC cameras. We were able to derive coupling functions between temporal and spatial parameters of auroral emission regions to identify optimal requirement pairings for auroral imagers which provide sufficiently detailed small-scale information without oversampling.

We have found that for a given pixel size, there exists a lower time resolution limit representing the rate of change of the precipitating particles flux at this spatial scale below which the dynamics of the pixels cannot be fully resolved. Similarly, for a given sampling time, there is a spatial resolution constraint reflecting a characteristic size of short-living auroral features observed at this time scale. Both types of the resolution constraints are closely connecting with the brightness of the auroral region of interest and are therefore dependent on the sensitivity of the imager.

The UVAMC guidelines for temporal resolution, spatial resolution and detection threshold values contribute to a larger framework of measurement need derivation. Based on the needs of the science (in coordination with WP2200) we have developed a formalized requirements guideline that is presented in the Science Requirements Document (UVAMC.SR1.0001).

Tools developed under this work package have also been found to be extremely powerful in studying the structure and behavior of the auroral (and other) systems. We expect to see future impacts of these tools in terms of continued use in scientific studies and publications (on top of the 17 scientific publications listed in Appendix A).

6.2 UVAMC Modeled Auroral Spectrum Database

One of the key parameters contributing to an imager's ability to address science requirements is the choice of band pass and the subsequent requirements on filters. The only way to derive an appropriate band pass is with detailed knowledge of the auroral spectrum and an understanding of effects from different precipitating populations and possible signal contaminations. Under UVAMC, Computational Physics Inc. (CPI) conducted a number of auroral spectrum model computations to create a database relevant to satellite auroral observations. The model database consists of spectra computed for varying energies of electron and proton aurora, as well as models of solar Rayleigh scattering spectra. This database forms the backbone of a tool set that allows us to assess the suitability of band passes to address science questions and will contribute to on-orbit signal models of any future UVAMC mission. The UVAMC model database is described in the Science Requirements Document (UVAMC.SR1.0001) previously submitted to CSA.

6.3 Impact of Possible Future Mission Level Orbit Revisions

The UVAMC methodology for deriving mission level requirements provides a framework of traceability that will allows for quick assessment of the impact of mission level changes on science objectives. This process is laid out in the Science Requirements Document included in Appendix C, and was one of the primary drivers for generating the traceability framework under WP3100.

7. WP 3200 Identify UVAMC Candidate Designs

7.1 UVAMC Optical Designs

UVAMC has produced 45 candidate optical designs for satellite based auroral imaging, 23 of which we consider appropriate for further development. These designs are detailed in the Conceptual Design Document (UVAMC.DDD.0001).

7.2 Tools for Optical Design Selection

Tools to aid in the selection of an optical design given a satellite platform and science objectives are laid out in the Conceptual design document (UVAMC.DDD.0001) previously submitted to CSA. These tools also provide an assessment of the optimization of a given optical design relative to the measurement requirements and payload allocation limits. This information will be used in the optimization of any future UVAMC imager.

8. WP 4100 Identify Capabilities of Potential Industrial and Academic Partners

Through development of the conceptual designs in WP3200 various potential industrial and academic partners were identified. These include;

- System Design and Fabrication
  - COM DEV
  - MacDonald, Dettwiler and Associates
- Filter Design, Fabrication and Testing
  - Cascade Optics
  - Acton Optical
- Imager Intensifier
  - Photek (non-ITAR)

Specific products and/or services from any of these partners would depend on the nature of the component and the specifics of the mission.

9. Conclusions

The UVAMC project has produced 23 viable optical designs for satellite borne imagers, contributed to 17 scientific publications and one technical publication. Through UVAMC, the UofC team has built capacity in terms of developing UV imaging instruments that meet quantitative mission requirements and matching mission requirements to specific science objectives. We have created a framework for requirement derivation and tools to assess an optical designs ability to meet those requirements. Further we have built a database of auroral spectral outputs that can be used to derive and assess filtering needs and target spectral band based on science objectives. These tools are generic and will apply beyond the scope of the UVAMC contract. For example, the spectral database can be used in future mission development to derive an on-orbit signal model used to quantify signal-to-noise ratios and expected count levels.

Future work in this area should continue to develop capacity in terms of optical and instrument design, and spectral tools. We were only able to touch on spectral requirements within the framework of UVAMC. Future work should target the development of generic tools for on-orbit signal modeling and quantitative modeling of image formation within optical designs. For example, modeling of image distortion and stray light effects in final data products based on the characteristics of individual designs would be a powerful tool to have as the design process moves forward.

Although there is clearly much more work to be done, UVAMC has created a capacity and framework for auroral imaging mission design that we believe has not previously existed in the space science community.

Appendix A: Journal Publications

- Unick, C., E. Donovan, and E. Spanswick, Selection of FUV Auroral Imagers for Satellite Missions, to be submitted to Applied Optics, 2012
- Uritsky, V.M, E. Donovan and E. Spanswick, Multiscale transients in Earth's magnetosphere as a science target for an auroral imaging mission, *Journal of Geophysical Research – Space Physics*, in prep., 2012.
- Uritsky, V.M. and J. Davila, Multiscale emergence and submergence dynamics of solar magnetic structures, submitted to *Astrophysical J.*, 2011, arXiv:1111.5053v1 [astro-ph.SR].
- Knudsen, D. J., J. K. Burchill, E. F. Donovan, and V. M. Uritsky, Advection of magnetic energy as a source of power for auroral arcs, *Geophys. Res. Lett.*, doi:10.1029/2011GL049661, 2011.
- Liang, J., B. Ni, E. Spanswick, M. Kubyshkina, E. F. Donovan, V. M. Uritsky, R. M. Thorne, and V. Angelopoulos, Fast earthward flows, electron cyclotron harmonic waves, and diffuse auroras: Conjunctive observations and synthesized scenario, *Journal of Geophysical Research – Space Physics,* 116, doi:10.1029/2011JA017094, 2011.
- Pouquet, A., M.-E. Brachet, E. Lee, P. Mininni, D. Rosenberg, V. M. Uritsky, Lack of universality in MHD turbulence, and the possible emergence of a new paradigm?, *Proc. Int. Astronomical Union*, 271, p. 304-316, doi: 10.1017/S174392131101773X, 2011.
- Uritsky, V.M., J. Slavin, G. Khazanov, E. Donovan, S. Boardsen, B. Anderson, and H. Korth, Kinetic-scale magnetic turbulence and finite Larmor radius effects at Mercury, *Journal of Geophysical Research – Space Physics,* 116: A09236, doi: 10.1029/2011JA016744, 2011.
- Liu, W. W., L. F. Morales, V. M. Uritsky, and P. Charbonneau, Formation and disruption of current filaments in a flow-driven turbulent magnetosphere, *Journal of Geophysical Research – Space Physics*, 116: **A03213**, doi:10.1029/2010JA016020, 2011.
- Vallieres-Nollet, M.-A., P. Charbonneau, V.M. Uritsky, E. Donovan, and W. Liu, Dual scaling for self-organized critical models of the magnetosphere, *Journal of Geophysical Research – Space Physics*, 115: A12217, doi: :10.1029/2010JA015641, 2010.
- Uritsky, V.M., A. Pouquet, P. D. Rosenberg, D. Mininni, and E. F. Donovan, Structures in magnetohydrodynamic turbulence: Detection and scaling, *Physical Review E*, 82, 056326, doi: 10.1103/PhysRevE.82.056326, 2010.
- Uritsky, V.M., E. Donovan, T. Trondsen, D. Pineau, and B. V. Kozelov, Data-derived spatiotemporal resolution constraints for global auroral imagers, *Journal of Geophysical Research – Space Physics*, 115: A09205, doi:10.1029/2010JA015365, 2010.
- Liang, J., V. M. Uritsky, E. Donovan, B. Ni, E. Spanswick, T. Trondsen, J. Bonnell, A. Roux, U. Auster, and D. Larson, THEMIS observations of electron cyclotron harmonic emissions, ULF waves, and pulsating auroras, *Journal of Geophysical Research – Space Physics*, 115: A10235, doi:10.1029/2009JA015148, 2010.
- Klimas, A.J., V.M. Uritsky, and E. Donovan, Multiscale auroral emission statistics as evidence of turbulent reconnection in Earth's midtail plasma sheet, *Journal of Geophysical Research – Space Physics*, 115: A06202, doi:10.1029/2009JA014995, 2010.

- J. Wanliss and V.M. Uritsky, Understanding bursty behavior in mid-latitude geomagnetic activity, *Journal of Geophysical Research – Space Physics*, 115: A03215, doi:10.1029/2009JA014642, 2010.
- Uritsky, V.M., J. Liang, E. Donovan, E. Spanswick, D. Knudsen, W. Liu, J. Bonnell, and K.H. Glassmeier, Longitudinally propagating arc wave in the pre-onset optical aurora, *Geophysical Research Letters*, 36, L21103, 2009.
- Lovejoy, S. and 15 co-authors including V.M. Uritsky, Nonlinear geophysics: why we need it, *Eos*, 90(48), p. 455-456, 2009.
- Uritsky, V.M., J. Davila, and E.I. Jones, Coexistence of self-organized criticality and intermittent turbulence in the solar corona – reply to comment, *Physical Review Letters*, 103 (3): Art. 039502, 2009.
- Uritsky, V. M., E. Donovan, A. J. Klimas, and E. Spanswick, Collective dynamics of bursty particle precipitation initiating in the inner and outer plasma sheet, *Annales Geophysicae*, 27 (2): 745-753, 2009.

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Selection of FUV Auroral Imagers for Satellite Missions

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A survey of previously flown and recently designed FUV auroral imagers is presented in conjunction with selection criteria to optimize the potential scientific impact of future satellite based FUV auroral observations.

I. Introduction

The aurora is caused by electron and ion precipitation from the magnetosphere into the atmosphere, primarily into the ionosphere. The wavelength, geographical location, height, geometry, brightness, duration and motion of the aurora are directly related to phenomena occurring in the magnetosphere and it's interaction with the ionosphere. There is a great deal of physical information that can be derived from auroral images of the correct resolution and cadence in isolation, and even more in combination with in-situ measurements via particle and field measurements in the magnetosphere and/or ground based magnetometers, riometers or radars.

In the far ultraviolet (FUV) part of the electromagnetic spectrum there are several emissions that are relevant to particle interactions with the oxygen and nitrogen in the upper atmosphere, including the Lyman-Birge-Hopfield (LBH) band of excited molecular nitrogen that extends from around 1400 to 1900Å. Atmospheric absorption at these wavelengths is extremely efficient, which prevents ground observation, but also enables a characterization of the electron aurora. The shorter wavelengths in the LBH band, called LBH-s, are preferentially absorbed compared to the longer wavelengths, the LBH-l, which provides a means to estimate the depth in the atmosphere at which the emissions are occurring. The depth of the emissions is related to the characteristic energy of the electrons and the total intensity is related to the electron flux. With a pair of satellite born imagers, these two parameters can be derived from the images in a manner that is not continuously measureable by any other means with the same accuracy, cadence and geographic coverage.

The existing data sets of FUV images have been extremely useful to the scientific teams working in this field. However, these data sets are not continuous, they have breaks between images, and also come from single satellites which view the auroral region for a fraction of each orbit. The images can have field of view limitations as well that fail to record the entire auroral region at once. The physics that can be done with these data sets is nearing exhaustion and a new data set is needed without these gaps. The UVAMC study was undertaken to provide a way to select the optimum FUV imager design for any platform while meeting the desired science goals. The first part of the UVAMC study was to analyze the previous data sets to aid in the design process by identifying the relationships between the design parameters that would result in the maximum scientific return [Vadim]. Then the FUV imager designs described in this paper were approached with these targets in mind. Technological and platform constraints also play a role in what can be realized, therefore the final recommended imager selections form a matrix of designs specifically suited to the various possible missions.

II. FUV Imager Design

There are three basic parameters of the satellite orbit that are relevant to imaging the aurora; inclination, period and apogee/perigee height. Placing an auroral imager on a satellite with a polar orbit has the obvious advantage of guaranteed viewing the auroral region once per orbit. Tundra and Molniya orbits are well suited for imaging the auroral region as well because of the potential to align the apogee of the orbit over North America and view the entire auroral oval while the satellite is at apogee and moving slowly, therefore increasing the dwell time for imaging. Less attractive, yet still viable, orbits would have apogee over the northern hemisphere and have high inclinations, without the guarantee of having the apogee over the magnetic north pole.

The desire to capture the entire auroral oval in each image and the apogee height of the satellite are the factors that determine the minimum angular aperture of the imager. The field of view (FOV) of the imager should be sufficient to cover the auroral oval as soon at the satellite is positioned over the aurora. The Polar spacecraft had an apogee of approximately 9 RE and the 8° FOV of the UVI instrument could capture the entire oval from about 7 RE and higher. For an apogee height of about 7 RE, the FOV should be about 20° to be able to image the entire oval from less than 5 RE and higher. If the satellite is in a lower orbit, typically these would be LEO missions where the apogee would not exceed 2-3 RE, the FOV of the imager would need to be around 50° to capture the entire oval in each image.

Continuous (24 hour) imaging of the aurora is not possible with a single satellite. A constellation of at least 2 satellites is required for 24 hour monitoring of the auroral region (Northern Hemisphere only). The number of satellites required is a function of the individual satellite orbits. In general, though, complete imaging of the northern auroral oval can be accomplished with a constellation of two satellites (minimum) in high inclination orbits with image FOVs greater than 8°.

The ideal platform for imaging is a spin stabilized satellite that is maintaining Nadir pointing throughout the orbit. This is also among the most expensive type of platform to operate. Spinning platforms have been employed in the past for auroral imaging, noteably the Viking, Freja and IMAGE missions. Imaging the aurora from these spinning platforms meant that the image cadence was the same as the spin period, in the range of a few seconds to a couple of minutes, and there are gaps between the images when the earth is not in the field of view. Ideally, the image cadence would be chosen in concert with the ground resolution of the images to optimize the science potential of the mission, which can only be done precisely in the case of the spin stabilized platform.

The image cadence and ground resolution of the images should be chosen together to optimize the scientific utility of the data [Vadim]. Another competing limitation for data utility is the imager sensitivity, driven by the minimum resolvable brightness within the field of view [does Vadim have a publication on this yet???]. The values of these three imager parameters are not independent of one another if the designer is correctly optimizing the design. Within the constraints of the payload, including mass, size and power consumption, the optimum performance of the imager must be chosen to correspond to the scientific goals of the mission as discussed by [Vadim, etc.]. A variety of specific imager designs can be imagined that would achieve similar science goals given an arbitrary platform requirement with the only caveat being that the aurora is visible from the platform's orbit.

In order to achieve an acceptable exposure time for spinning platforms, the time delay integration (TDI) method of recording images is used. This process was used on the Viking and Freja missions and details of image formation are discussed in [Mende II]. In order to successfully build up a meaningful image with the minimum amount of image processing, one of the directions of the image capturing array must be aligned with the spin axis of the platform. Also, it is convenient to have an optical design that does not have distortion over the image field. This second condition is extremely difficult to achieve with an all reflective optical design that has a wide FOV, but the image distortion can be minimized through careful design. Increasing the field of view increases the amount of image distortion in optical designs, a 20° FOV can be almost distortion free but a 50° FOV imager will have significant distortion.

Light leakage from the sun is a major concern for image quality for both spinning and stabilized platforms. Primarily, the minimum angle between the bore-sight of the imager and the sun cannot be less than the half angle of the FOV otherwise the imager directly exposes the sun to the sensor and this may damage the instrument. If this is going to be the case, whether or not the imager is in position to acquire an image, a shutter mechanism (or a sun blocking arm) must be engaged to protect the sensor.

The secondary concern is illumination of the interior cavity of the imager and scattering that can contaminate the image. Baffling can be employed in this case to minimize the amount of light reaching the sensor from outside the field of view of the imager.

II. Technologies

The basic technological approach to designing far ultraviolet (FUV) auroral imagers has not changed and remains this way because the technological considerations are still the same as they have always been, specifically reflective optics due to large material absorption in transmissive optics and intensified CCD/CMOS arrays because of the low light levels captured by "small" imagers. UVAMC explores 3 and 4 mirror designs based on the Zukic [] thin film filtering method of removing the out-of-band light with an extinction of 10^{-10} relative to the in-band light. Two mirror designs, like the Viking based imagers, will not have this high extinction ratio, based on current filter capabilities, and will not be able to image FUV auroral emissions on the day side of the earth with the necessary sensitivity. However, these designs are included for comparison because they have been flown.

The restriction of using flight proven technologies, high technology readiness level(TRL) numbers, is less severe in a hypothetical survey such as UVAMC than it would be in a budget-limited, real-world situation. Even if the TRL of the existing intensfiers, for example, were to be ignored, the technology has some inherent size limitations based on how the technology works and cannot be reduced beyond a certain minimum level. Guessing where to draw the line when leaving room in the optical design for a custom intensifier photo-cathode is something that has to be done, but can be guided by the custom intensifier designs used in the IMAGE and Polar mission instruments. Radiation hardness of the electronics, including the intensifier and image recording device (CCD/CMOS), is another design consideration that is strongly dependant on the particulars of the mission and could change the imager design slightly due to increases in shielding for orbits that transit the Van Allen Belts or have long mission lifetimes. CMOS devices are rated higher than CCDs for radiation hardness.

III. Designs Available Prior to UVAMC

Prior to the inception of the UVAMC project the available designs for UV auroral imagers were taken from academic literature, as with Polar UVI, or based on previous imager designs, like the heritage of Freja and IMAGE WIC from the Viking design.

Literature sources for constructing imagers from all-reflecting optics include the OSA "Handbook of Optics"[] and designs by Korsch[] or Shafer[]. The relevant information in the OSA handbook is presented in Volume II, Chapter 18, in the graphs of "Field-of-view plots". For the purposes of this study, the designs that include refractive elements are disqualified due to the importance of low-loss designs and the relatively high absorption of transmissive optical elements in the wavelength region of interest. This condition combined with the requirements of a flat field and a two dimensional image reduce the number of design candidates from the OSA handbook with sufficient field of view for wide angle imagers, 20° or over, to zero. However, for applications requiring 10-20° field of view, the OSA handbook designs are marginal at best, but there are plenty of good designs described in this reference for a required FOV of 10° or less.

The designs in the "Handbook of Optics" are generally limited to less than 20° FOV except the designs attributed to Shafer. The Shafer designs in the Handbook are for strip images and have highly asymmetric image fields. Shafer's published designs from [ ] do not necessarily have this limitation, but the designs that are published are not shown in the correct manner to realize large, symmetric FOVs. A design loosely based on Shafer's design as pictured in the "Handbook of Optics" is included in this study with a 20° FOV and adequate spot size performance over the entire circular image.

The Polar UVI design is strongly based on one of the Korsch designs and has an FOV of 8°. This design can be extended to slightly higher FOV, around 15° [Korch 1991], without too much difficulty, but its performance rapidly degrades beyond that, as seen by the deliberate introduction of vignetting in the Korsch paper. An interesting feature of this design is the extremely low distortion of the image, a modified version of this basic design is included in this study with 10° FOV that would have no noticeable distortion over the entire field at very high resolution (spot size <25μm on a 25mm cathode), as well as an average spot size over the image plane that provides superior resolution when compared to the Korsch designs. These factors combine to make the design extremely useful for spinning satellite missions where the TDI method of image combining would require no extra image processing steps when shifting the image from column to column in the CCD as the spacecraft spins.

The Viking design [ ], later reworked for the Freja[ ] and IMAGE [ ] missions, is a two-mirror design, based on a Schwarzchild telescope, with a very large signal gathering power and large FOV, but has a curved image plane. The curved image plane is a feature common to many two-element reflective imagers and has repercussions on image uniformity and distortion while making intensifier design difficult. There is a slightly modified two-mirror Schwarzchild design that has a flat image plane, but has a much lower FOV at about 10° for a similar F/#, see the "Handbook of Optics". In regards to the Freja and IMAGE instruments, there was a window inserted between the secondary optic and the cathode to keep the high-voltage electronics in a dust-free environment. This window must be accounted for in the optical design since it will introduce significant aberations. The prescription of this window is not given in the publications from these missions, but looks like a low-power meniscus with the convex side toward the incident direction and a curvature that is very strong. It is not simply the presence of this window that causes concern for the optical performance of imagers based on this design, but the distance between the window and the cathode, knowing that the window materials have large chromatic dispersion in this wavelength region and MgF_2, with relatively low chromatic dispersion, has significant birefringence. The current technologies for intensifiers have the cathode deposited on the exit face of a planar window, which would not work for the curved field of these designs, but, it can be shown that using a low- power meniscus optic as the cathode substrate with excellent results for spot sizes on the cathode roughly one third the size of the other designs.

Another distinction to be made at this point is the design architecture of the Polar type imager compared to the Viking based designs, Polar belongs to the off-axis category and the Viking type designs are an on-axis design. All on-axis all-reflective imager designs will have an annular aperture somewhere in the optical path leading to what is referred to as an "obscured" design. It is possible to design an off-axis imager that is not obscured, and Polar used such a design, whether eliminating obscurations confers an advantage to such designs is not clear without comparing specific optimized designs.

A four-mirror off-axis 20° FOV design was proposed by Spann in [ ], which represents a significant increase in image quality and compactness over previous designs, as well as adding the advantageous suppression of out-of-band light inside the FOV of the imager. This design has the combination of two negative mirrors followed by two positive mirrors with the optical axis of the system concentric with the third mirror (also used as the system stop). It is possible to construct designs based on the work of Shafer that have different architectures but similar performance, as will be seen as part of the UVAMC work.

Of the various options that have been used before, the Polar UVI instrument marginally outperformed the IMAGE WIC instrument as can be seen in a side by side comparison, Table #.

Imager Parameter	Viking	Freja	IMAGE WIC	Polar UVI LBHL	Spann LBH
FOV (°)	20 x 25	22.4 x 30	17.2	8	20

Aperture Area (cm^2)	0.72	1.6	1.6	11.75	3.14
Integration Period (s)	1	0.37	6	37	20
Pixels	228 x 385	228 x 385	256 x 256	228 x 200	512 x 512
Available Photons at Aperture (R^{-1}) (Per Pixel)	0.1	0.11	1.0	13	2.3
Filter Throughput[a]	0.75[c]	0.75[c]	0.75	0.06	0.6
Available Photons at Photocathode (R^{-1}) (Per Pixel)	0.075	0.08	0.8	0.8	1.4
Nadir Resolution at 7RE (km)			44.5	25	26
Mass (kg)			4.1	15	6
Visible Rejection[a]			2.1×10^{-3}	4.2×10^{-4}	4.4×10^{-6}
Merit Function[b]			93	127	53,000

[a] Definition taken from Spann[]

[b] Merit function defined as the (Available Photons at the Photocathode)/(Mass * Visible Rejection)

[c] Values assumed to be the same as IMAGE WIC

Table #: Summary comparison of some existing instruments and the Spann design.

The proposed solution by Spann represents a significant advance in imager performance and meeting or exceeding this performance while also increasing the imager FOV is the goal of the UVAMC study.

IV. UVAMC

The UVAMC design candidates were identified by modeling various combinations of mirrors with Zemax and evaluating the spot size across the image plane for light incident from an object at infinity. The optical designs were constrained by the image diameter in the Zemax model, where either 25mm or 40mm was used as image diameter. These two values correspond to two of the available cathode diameters for commercially-available, flight-proven intensifier photo-cathodes, and these two sizes result in imager designs that are comparable in overall size and mass to the previously flown imagers. The other commonly available sizes are 18mm, 75mm and 150mm diameters, allowing for potentially smaller and larger designs if size or weight restrictions on potential platforms differ substantially from the legacy missions. Designs that are optimized for either 25mm or 40mm can be scaled linearly from one to the other, or can be scaled to the smaller and larger photo-cathodes. Also, it is possible to scale the image to use less of the active area of the photo-cathode, potentially reducing the image resolution, but enabling a smoother transition of the mass and size of the imager between the discrete sizes considering only the stock values of photo-cathode diameter.

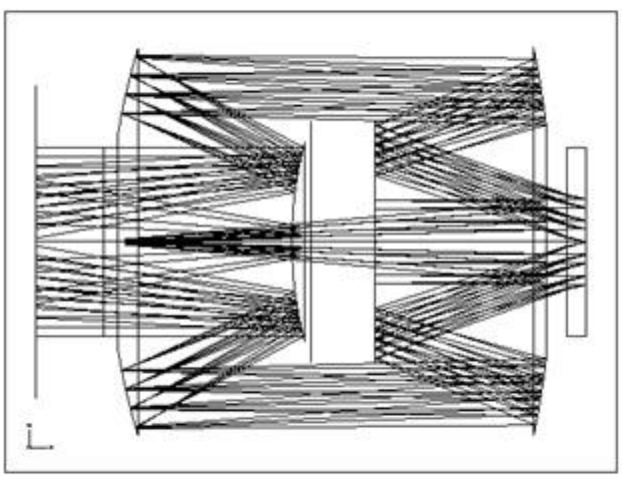
The base designs are also optimized assuming a 1024 x 1024 pixel sensor illuminated with a circular image, due to the circular footprint of the photo-cathodes. Pixel binning can be employed to increase the sensitivity of the imager when attempting to match the ground resolution, integration time and the minimum sensitivity. Therefore, some of the designs are optimized for a 1024 x 1024 pixel image, and some are optimized for 512 x 512 pixels.

IV. a) Four-Mirror On-Axis Designs

The four-mirror on-axis group of designs is the most versatile of all the designs studied for the UVAMC work. It consists of a central aperture illuminating a negatively powered primary mirror. The primary reflects the light to the secondary which is a toroidal, positive mirror that is positioned around the input aperture, as in an inverse Cassegrain. The tertiary mirror is a toroidal, positive mirror as well, and is used to allow correction of the image curvature of the overall imager. The final mirror has two designations, field correction and image relay. The quaternary mirror has little or no curvature, but uses strong high order aspheric coefficients to make small corrections to the system aberrations before relaying the light through the hole in the tertiary mirror and onto the photo-cathode at the image plane. The first three mirrors are aspheres with conic constants that vary from design to design.

This design enables the use of a 1024 x 1024 pixel sensor with single pixel resolution for any field of view less than 50°, when using a commercially available intensifier. If the intensifier were custom built to have a smaller outer case diameter for the same diameter of photo-cathode as the commercial models, then the maximum achievable single pixel FOV could be extended to around 55°. Image quality degrades rapidly for increased FOV and the best resolution achievable for a 60° FOV is 512 x 512 pixels.

Consider a comparison of a 20° design and a 48° design, as depicted with ray trace diagrams in FIGURE**. The rays enter from the left and are directed to a photocathode on the rear face of a window on the right. The image size is 25mm diameter in both cases, the size is quite different with the 20° design being much larger, yet the gathering power for the 48d design, 0.631sr cm^2, is only slightly less than the 20° design, 0.680sr cm^2. Both instruments are capable of single pixel resolution for narrow bandwidth filtering, about 10nm in the LBH wavelength region, but the 20° design will have superior performance for a larger bandwidths. If one were to increase the diameter of the 48° FOV imager photocathode to 40mm, the corresponding gathering power would significantly increase, by a factor of 2.56 to 1.615 sr cm2, while increasing the instrument size to approximately the same dimensions as the 20° FOV imager. The comparison made in [Spann] uses a figure of merit that includes the mass of the instrument by dividing the gathering power of the imager by the mass. Since the designs presented have not been carried through to include all the mechanical and electrical components, an estimate of the mass will have to suffice.



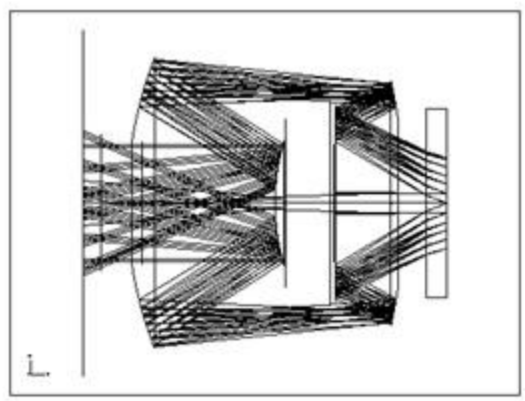


Figure #. Example ray traces of two designs, on the left is a 20° FOV design, on the right is a 48° FOV design. The rectangle on the right represents the cathode window of the intensifier which is the same size in both designs (height 55mm).

IV. b) Three-Mirror On-Axis Designs

Using the first three mirrors of the on-axis imager design discussed above to create a three-mirror imager requires that the detection electronics reside behind the primary mirror. This can lead to additional vignetting of the light passing from the secondary to tertiary mirrors. But, as mirrors in a FUV imager are lower efficiency than in visible imagers, this light loss may not be a significant impairment of the imager performance compared to using a fourth mirror. A variety of combinations of conics on the three mirrors can produce good, flat images at the image plane, trade-offs occur for gathering power of the imager versus size of the instrument.

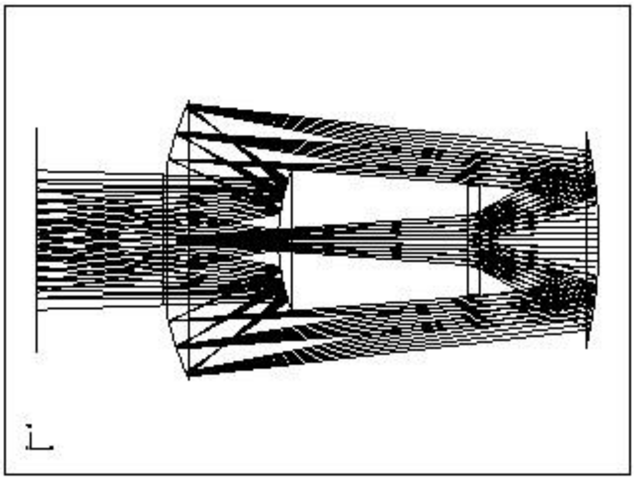


Figure #. Example ray traces of a three-mirror design with a 20° FOV. The rectangle toward the right represents the cathode window of the intensifier which is the same size in both designs (height 55mm).

The dimensions of the imager in FIGURE ### are roughly 22cm in length (mirror surface to mirror surface) and 15cm diameter, which is compact enough to yield a finished imager body with a mass of roughly 10kg. The rectangle in the figure represents the MgF_2 window on the intensifier and the remainder of the intensifier, the phosphor window, fiber taper, CCD and electronics would reside in the space between the primary mirror and the intensifier window. This assembly would have to be supported from the outside structure by three attached supports, this is commonly referred to as a spider. The spider slightly obscures the image, introduces a slight illumination non-uniformly, and contributes both additional scattering and diffraction. Increases in scattering and diffraction must be met with an overall improvement in sensitivity versus the mass of the imager to make these designs more desirable compared with off-axis designs. When considering the extreme minimum sensitivity required to image the aurora in the far ultraviolet and the modest resolution requirements, the on-axis designs become serious contenders for development.

The primary performance difference between a three-mirror and four-mirror on-axis design is the isolation provided by the filters to out of band light. The extra filter reflection for the four-mirror design may be required, especially if the desired sensitivity is low enough and the imager is being design to image the day-side of the earth. The range of FOV for the three-mirror on-axis variant is not as high as the four-mirror type because of the difficulty of getting a significant amount of light around the electronics as the spread in incident angles is increased. A limit of about 30° applies to the three-mirror on-axis imagers.

IV. a) Off-Axis Designs

Both of the four-mirror and three-mirror designs discussed above can be converted into off-axis variants by taking a small section of each mirror and a section of the image plane. These direct conversion off-axis imagers tend to be very inefficient compared to their on-axis parent designs and are restricted to roughly half the FOV. The potential saving that motivated the investigation of these types of imagers was in terms of the mass and volume of the devices. Maintaining the large gathering power with a relatively large FOV by sectioning the optics in this manner is not realizable.

A design loosely based on the off-axis four-mirror design by Shafer has very good resolution within a small package with an FOV of 20°, but suffers from low gathering power relative to its mass for a 25mm photocathode diameter intensifier. It is better than the converted designs described in the above paragraph, but the design so far has not reached a single pixel resolution for a 1024x1024 pixel CCD. The most advantageous characteristic of this design is the near telecentricity of the rays incident on the cathode window combined with the relatively high f/5.9 after the fourth mirror, making the effects of chromatic dispersion negligible over a reasonable range of wavelengths such as the LBH band. If the size of the intensifier is increased from 25mm to 40mm, this design becomes competitive with other off-axis four-mirror designs, like Spann's design, while maintaining similar dimensions, with a drawback of slightly lower resolution.

V. Comparison

The designs that have been flown provided the data sets that made the optimization of these future designs possible, including Spann's design, through the analysis described in [Vadim], which indicates that a 20s cadence and 20° FOV for an orbit similar to a Molniya orbit. In Table #, the parameters that most critically affect the utility of FUV auroral imagers are listed for two of the legacy designs, IMAGE WIC and Polar UVI (LBHL), and Spann's design as well as the two four-mirror UVAMC designs previously described. The new designs significantly out-perform the older designs as indicated by the values of the merit function shown in Table #.

Imager Parameter	IMAGE WIC	Polar UVI LBHL	Spann LBH	UVAMC 4-mirror On-Axis LBH	UVAMC 4-mirror On-Axis LBH
Nadir Resolution at 7RE (km)	44.5	25	26	26	21 @ 3RE
FOV (°)	17.2	8	20	20	48
Aperture Area (cm^2)	1.6	11.75	3.14	7.1	1.2
Integration Period (s)	6	37	20	20	20
Pixels	256 x 256	228 x 200	512 x 512	512 x 512	512 x 512
Available Photons at Aperture (R^{-1}) (Per Pixel)	1.0	13	2.3	5.4	4.9
Filter Throughput[a]	0.75	0.06	0.6	0.6[c]	0.6[c]
Available Photons at Photocathode (R^{-1}) (Per Pixel)	0.8	0.8	1.4	3.2	3.0
Mass (kg)	4.1	15	6	10	4.3
Visible Rejection[a]	2.1×10^{-3}	4.2×10^{-4}	4.4×10^{-6}	4.4×10^{-6} [c]	4.4×10^{-6} [c]
Merit Function[b]	93	127	53,000	77,900	157,000

[a] Definition taken from Spann[]

[b] Merit function defined as the (Available Photons at the Photocathode)/(Mass * Visible Rejection)

[c] Values assumed to be the same as the Spann design, uses the same filter technology

Table #: Summary comparison of some existing instruments, the Spann design and two UVAMC designs.

This merit function is different from Spann's "performance ratio" in that it calculates the ratio of the photons per pixel given a one Rayleigh source to the product of the mass an visible rejection. Again, the mass and visible rejection are strong indicators of the desirability of the design, but, with different pixel counts in the various instruments, the fair comparison of signal to noise ratio is dependent on the number of photons per pixel per integration period, as calculated by Torr, et.al., []. Submitting a lighter instrument design is an advantage when competing as a prospective secondary payload on an already approved mission and keeping within the range of 5 to 10kg per camera is going to be typical and won't heavily impact the merit function. The largest difference between the proposed solutions and the legacy designs is in the visible rejection, which will also have a great impact on the overall quality of the science that can be done with the images. The number of available photons must be kept up to level where at least one photon is available in the integration period per pixel for the minimum Rayleigh sensitivity of the imager. For example, with a desired sensitivity of 10R and a photocathode quantum efficiency of 10% (typical for FUV instruments), the 20° UVAMC imager will receive 3 or 4 photons on average in a 20 second integration period that result in a count in the detector.

Given that new designs will take advantage of the out of band isolation provided by the mirror filtering approach to imager design and the masses of instruments will vary by less than a factor of 2, the gathering power becomes an intelligent choice of a parameter used to compare the effectiveness of the variety of designs. Here, gathering power is defined as the product of the input aperture area and the solid angle of field of view, and is reduced by the "average" vignetting over the field of view for imager designs that have obscurations. This choice of comparison parameter can be bolstered because it is also independent of the filter absorption, out-of-band rejection and cathode efficiency, where technology improvements can make previously poor choices become viable alternatives to today's obvious winning design, such as improved isolation making a three-mirror design able to meet the requirements of a specific mission. Other influences for a specific choice of instrument will include input baffle size and internal scattering. Input baffle design is very dependent on mission and platform, a discussion of all the possibilities is beyond the scope of this paper. There are also some designs that have optical paths such that stray light scattered from the input baffle can be directly incident on the CCD, these designs have been disqualified from this survey. Some slightly more efficient variants of the included designs have this problem, primarily caused by increasing the input aperture without changing optics positions, which in turn requires larger apertures in internal baffles and optics opening up paths that were previously blocked. Increasing the gathering power is not an easy operation.

When approached with the possibility of designing an imager for a mission, the mass restriction of the imager will be arguably the most important limitation on the choice of design that can be employed for the mission. Thus, a design guide for making this important decision has been formulated that combines the gathering power and mass of the imager candidates and pictorially demonstrates the methods for altering the size of the candidate imager, hence it’s mass, to meet the specific mission requirements.

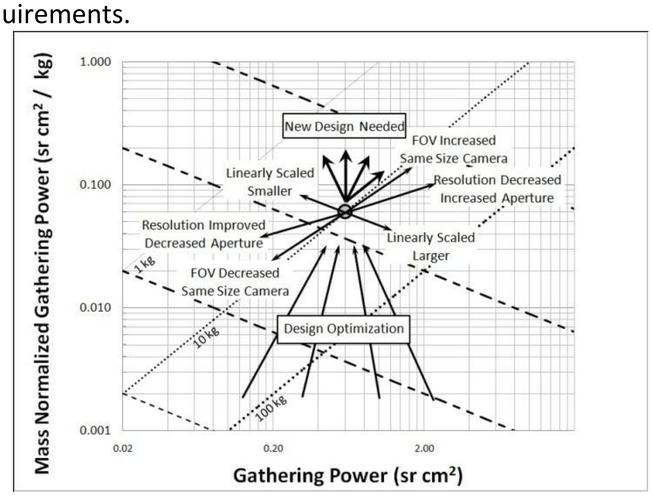
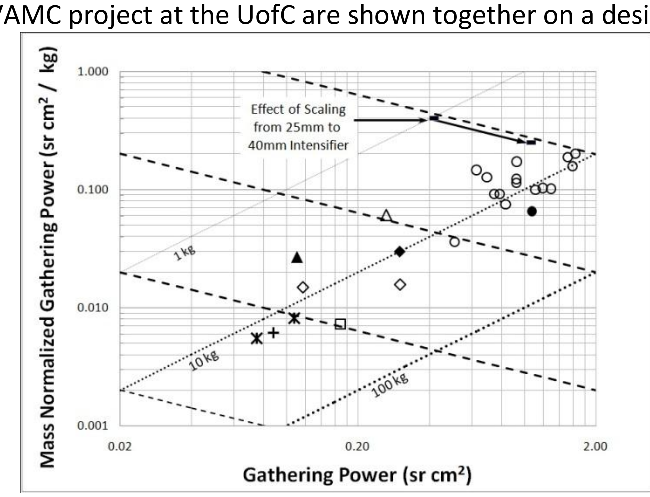


Figure #: Pictorial design guide diagram to aid in adjusting candidate designs based on gathering power and mass. The mass of the imager follows dotted lines that slope upward to the right. The dashed lines that slope downward to the right represent design trajectories that do not change the design, but involve scaling their dimensions.

In theory, one can select a design because it appears to be a good candidate for the imager mission. However, the design may not be exactly optimized based on the window covering the photocathode, which will introduce refraction variations over the image and refractive index dispersion over the wavelength band. Using a ray trace design software the basic design is optimized, that will place the design at the center point in the design guide diagram. From there, given the mass of the base design, one can either reduce or increase the mass by following the trajectory defined by the lines that slope downward to the right. From here, the FOV, resolution at the image plane and the aperture size (gathering power) are adjusted and the imager moves back and forth generally along trajectories parallel to the upward sloping lines of constant mass. The finished product will be the optimized version of the chosen candidate. Repeating this procedure for a variety of potential candidates will lead to a group of optimized designs that can be compared strictly on their end locations on the graph, those designs should have roughly the same mass, FOV and image resolution, but the best design will be the one furthest to the right because it will have a better signal to noise ratio for auroral features of a given intensity.

The legacy imagers, Spann's proposed design, and the designs undertaken as part of the CSA UVAMC project at the UofC are shown together on a design guide diagram in Figure #.



***** does not show polar, will replace

Figure #: The base designs for various imagers on the design diagram. WIC is the solid triangle, Freja "redesign" is the open triangle, POLAR is the solid square, Korsch like design is the open square, Spann's design is the solid diamond, Shafer like design is the open diamond, off-axis three-mirror designs are asterisks, off-axis four-mirror design is a plus sign, on-axis three-mirror design is a solid circle, and on-axis four-mirror designs are open circles. A demonstration of the effect of scaling from a 25mm photo-cathode to a 40mm photo-cathode is shown on this diagram as well.

The off-axis designs tend toward the left and downward direction in the diagram, meaning an overall less efficient design for the same mass as the on-axis designs that occupy the upper right side of the diagram. Exceptions are the IMAGE WIC imager and the Freja "redesign" that hover above the three and four-mirror variants of off-axis designs, primarily because they are two mirror designs that have lower mass for the same gathering power. Although it may seem clear by this demonstration in the design diagram that on-axis designs are preferred, the off-axis designs are thought to have better immunity to scattering and may require less restrictive input baffle designs compared to the on-axis varieties. Also, image quality is better for large bands of wavelengths for off-axis designs because they tend to have much higher f/# in the optical path immediately prior to the intensifier, refractive index dispersion in the intensifier window is less of a factor in this case. The Freja "redesign" came about by replacing the curved window in the Freja design with a thick intensifier window that is ground as a meniscus lens, the resulting improvement in image quality resulted in a much wider aperture for the same size of imager. To be fair to the Freja and Viking designs, the FUV filtering options available at the time did not allow for optimal system throughput, and the IMAGE mission flew the flight spare from Freja.

The three imager designs with the worst performance were off-axis variants that were derived from the on-axis designs as discussed previously. Additionally, most of the designs that are included in this study are for a 25mm diameter intensifier cathode, with the exception of the previously flown designs and a couple of 40mm diameter designs. The merit functions for the range of designs presented in the design diagram are tabulated with some other design details in Table #.

Number of Mirrors	Detector Diameter (mm)	FOV (°)	Aperture Area (cm^2)	Gathering Power (sr cm^2)	Mass Estimate (kg)	Estimated Isolation	Merit Function (2 x 2) [a]	Flat Field	On/Off Axis	Obs [b]	Binning Needed
2 [c]	10	22.4	2.2	0.263	4.3	2.1×10^{-3}	174	No	On	Yes	
3	25	201	11.3	1.08	16.5	9.6×10^{-5}	3590	Yes	On	Yes	
3	25	20	0.79	0.075	13.6	9.6×10^{-5}	304	Yes	Off	No	2 x 2
3	25	20	1.13	0.108	13.2	9.6×10^{-5}	449	Yes	Off	No	
3 [d]	25	10	7.07	0.169	23.4	9.6×10^{-5}	396	Yes	Off	No	
4	25	16	8.3	0.507	13.9	4.4×10^{-6}	38,600	Yes	On	Yes	
4	25	20	7.1	0.68	9.2	4.4×10^{-6}	77,900	Yes	On	Yes	
4	25	20	8.77	0.837	11.1	4.4×10^{-6}	79,700	Yes	On	Yes	
4	25	20	11.7	1.12	11.1	4.4×10^{-6}	106,000	Yes	On	Yes	2 x 2
4	25	20	13.5	1.29	12.8	4.4×10^{-6}	106,000	Yes	On	Yes	2 x 2
4	25	22	6.45	0.745	8.0	4.4×10^{-6}	98,400	Yes	On	Yes	
4	25	22	0.76	0.088	14.5	4.4×10^{-6}	6400	Yes	Off	No	
4	25	26	7.4	1.19	11.6	4.4×10^{-6}	109,000	Yes	On	Yes	
4	25	28	4.19	0.783	8.4	4.4×10^{-6}	98,600	Yes	On	Yes	
4	25	28	8.49	1.585	10.0	4.4×10^{-6}	168,000	Yes	On	Yes	
4	25	30	4.3	0.921	8.0	4.4×10^{-6}	122,000	Yes	On	Yes	
4	25	32	3.79	0.922	7.6	4.4×10^{-6}	129,000	Yes	On	Yes	
4	25	3	2.27	0.698	5.4	4.4 x	137,	Y	O	Y	

		6				10^{-6}	000	es	n	es	
4	25	44	2.04	0.931	5.4	4.4×10^{-6}	184,000	Yes	On	Yes	
4	25	48	1.16	0.631	4.3	4.4×10^{-6}	157,000	Yes	On	Yes	
4	25	20	1.23	0.117	7.9	4.4×10^{-6}	15,700	Yes	Off	No	2 x 2
4	40	20	3.14	0.3	19.2	4.4×10^{-6}	16,500	Yes	Off	No	2 x 2
4	40	55	2.14	1.52	8.0	4.4×10^{-6}	204,000	Yes	On	Yes	2 x 2
4	40	60	1.94	1.63	8.0	4.4×10^{-6}	220,000	Yes	On	Yes	2 x 2

[a] 2 x 2 binning is used in the calculation of the Merit Function in order to remain consistent with the previous calculations.

[b] Obs is short for obscured.

[c] This is the Freja redesign.

[d] This is the design that is based on the Polar UVI design.

Table #: Some important design information for the candidate designs selected for this paper. The mass is estimated for these designs and may not accurately reflect the mass of an actual imager, most likely they are over estimated and artificially reduce the merit function values.

Some of these designs are not useful for a single pixel application for a 1024 x 1024 pixel CCD and must be used in a binned mode, and others would require reduction of the resolution when the bandwidth of the source is increased to exceed about 10nm in the FUV region. Modifying the designs graphed and tabulated here can fulfill the requirements of specific missions with customized FOV and mass requirements within the range of values in the graph and table. To go beyond what is presented here would require increasing or decreasing the mass or compromising the image resolution as described.

There is another alternate design that could be considered for auroral imaging, the Wide Field Auroral Imager (WFAI) proposed by Bannister, et.al.[]. This imager has an FOV of 45.8° and a large gathering power, 1.0 sr cm^2 per the published numbers, but lacks resolution in the image plane. The authors claim that image resolution can be improved to the point where it becomes competitive, but there are no published accounts of this being accomplished. Also of concern is the lack of filtering and out-of-band isolation that impacts this design approach.

VI. Conclusions

Viable solutions exist for a range of FOV for satellite born auroral imagers that will cover the design space of a similar ground resolution (imager resolution) and temporal cadence from a variety of orbital heights. The exact resolution and cadence combination is chosen with respect to the science goals using the selection criteria outlined in [Vadim]. The allowed mass dictated by the platform forces the minimum sensitivity of the imager to be selected from the various designs through the gathering power design diagram. Table # provides a quick selection chart based on typical conditions of a prospective mission of 20-25km ground resolution and a 20s temporal cadence where the FOV is determined by the height of an imager of mass approximately 10kg as it passes over the auroral region.

Required FOV	Entire LBH band at once	Split LBH band into 2 or OI lines
Less than 10° FOV	Options are open	Options are open

10-16° FOV	Spann	Spann, Korsch / Polar Type
16-24° FOV	Spann	On-Axis 4 mirror UVAMC type
Greater than 24° FOV	On-Axis 4 mirror UVAMC type (With reduced resolution at high FOV)	On-Axis 4 mirror UVAMC type

Table #: The selection of the appropriate design is broken down by the required FOV.

If the cadence and resolution were to be reduced, the mass of the imager would have to increase accordingly to maintain the same sensitivity, or one could choose to live with the resulting loss in sensitivity.

There are a couple of advances in technology that could significantly benefit the performance of all of these devices. First, if there were to be a material developed that has low loss in the FUV wavelength band that could be used to make a transmission filter, such a device could be employed prior to the first mirror of the imager to reduce the amount of out-of-band signal entering the optical cavity of the instrument. A flat transmission filter placed at the input of the imager will not affect the optical design of the mirror elements since it only constitutes a lateral shift of rays and not a change in their angles which does not change the image for an infinite conjugate object. Second, the MgF_2 window on the intensifier could be replaced with LiF to remove the birefringence of the window without greatly increasing either the refractive index dispersion or the absorption in the FUV wavelength band.

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