Design of an Imaging Infrared Spectrometer Using Compact Dyson Lenses

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Abstract

We describe a concept for a new imaging spectrometer operating in the mid-wave and long-wave infrared. The instrument would be proposed as an upgrade to The Aerospace Corporation's Broadband Array Spectrometer System (BASS), a 2.9-14 micron sensor currently in use on the Advanced Electro-Optical System (AEOS) 3.67 meter telescope. The primary tasks of the instrument would be to generate precise spectrophotometry of stars, and to characterize resident space objects. The core of the design features two ultra compact spectrographic modules, each utilizing a concentric Dyson lens and concave diffraction grating. We will describe the considerable advantages that result from the design as well as the implementation of the instrument on the AEOS telescope and similar facilities.

Introduction

The Air Force Maui Optical and Supercomputing (AMOS) sites' Advanced Electro-Optic System telescope (AEOS) is currently hosting The Aerospace Corporation's Broadband Array Spectrometer System (BASS) [1,2,3,4,5,6]. The BASS instrument is a high sensitivity MWIR and LWIR non-imaging spectrometer operating at low spectral resolution (R~ 100) and moderately fast focal ratio (F/3). BASS provides nearly continuous wavelength coverage from 2.9-14 microns, using two prism-based spectrometers to disperse an image of the pupil on its two 58 element linear arrays. BASS has a proven capability to obtain spectroradiometric measurements of high accuracy, and its primary mission at AMOS is to provide such observations for the radiometric calibration of the SBIRS sensor. Despite the continuing utility of the BASS spectrometer, a number of aspects of the sensor have been identified where improvements could enhance its radiometric performance. These include: increased spectral resolution, over-sampling of the spectrum, an enlarged field of view, and a long-slit capability. These improvements can be realized by using two-dimensional focal planes to improve observing efficiency and to provide enhanced hyperspectral capability. An upgraded sensor designed toward spectroradiometric performance that incorporates these enhancements is now in the concept and design phase. Unlike the original BASS sensor, its successor would be an imaging spectrometer based on a design using concentric Dyson lenses and concave gratings as the dispersion elements. The instrument will herein be referred to as a Dyson spectrometer. The Aerospace Corporation is currently building a Dyson spectrometer for another application which is scheduled for first light in the fall of 2007.

General Instrument Description

Fig 1 depicts the conceptual layout of the new sensor. The instrument would be positioned at the nasmyth feed used by the current BASS sensor. The primary components in the optical path include transfer optics, a kmirror, a collimator-expansion box, MWIR and LWIR spectrometers, and a visible camera for guiding. The spectrometers would be housed in a cryostat that operates below 10ºK. The field of view of the system would be defined by the spectrometer's entrance slit, about 4.5 x 60 arc seconds. The following is a conceptual description of the sensor's major subassemblies with a brief discussion of the trade space involved in each. We close with a description of a workable spectrometer system based on the Dyson form.

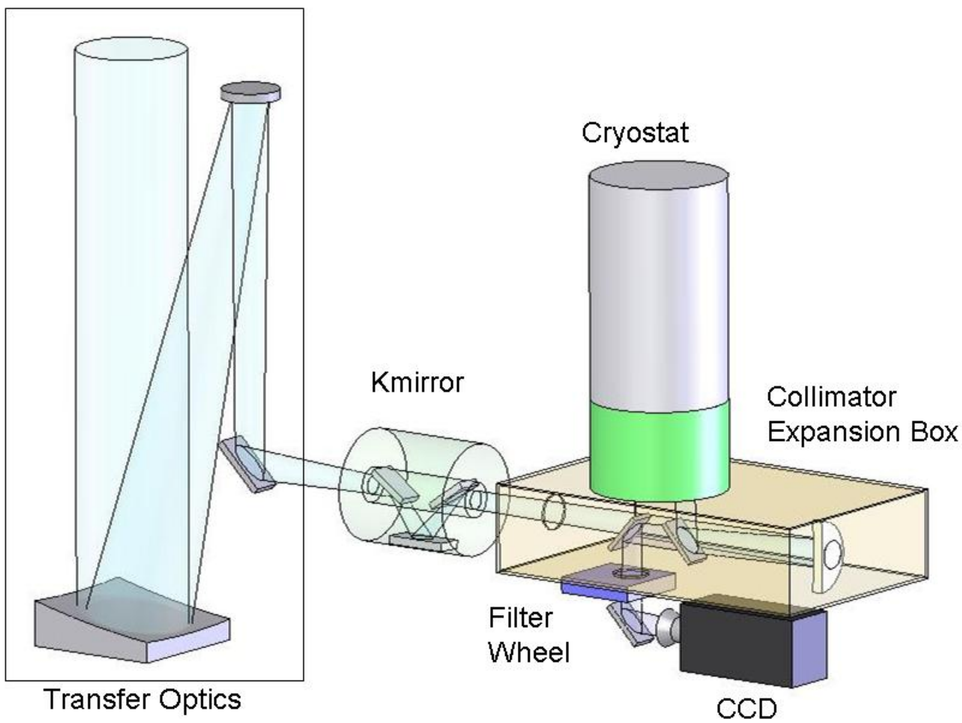

Fig 1 depicts the beam path for the new sensor

Transfer optics

The optical path incorporates the existing two-mirror transfer optics installed on the AEOS 3.65m telescope in 2006. This reflective optical system features an off-axis parabolic mirror and a hyperbolic secondary. It intercepts the telescopes F/200 beam between the M4 and M5 mirrors and produces an F/32 image plane accessible by the BASS sensor. This final focal ratio was dictated by compatibility with the Cassegrain feed of the Infrared Telescope Facility (IRTF) on Mauna Kea where the BASS sensor also operates. The image scale for the resultant optical feed is about 1.7 arc seconds/mm. The transfer optics can provide up to a 60 arc second field allowing for observations of resident space objects as well as planets and most other extended objects. The transfer optics and spectrometers would be mounted on the existing precision rail assembly that allows the system to be accurately placed into the beam for observation.

Kmirror-Field rotation

The nasmyth feed on an alt-azimuth telescope such at AEOS produces field rotation as a function of the telescope elevation angle. Operationally, the BASS sensor uses the chopping function of the telescope's secondary mirror to facilitate background subtraction. For the new system, chopping the image along the axis of the slit doubles the observation efficiency of the current BASS sensor. Thus, the object and its chopped image need be oriented along the image of the slit length. For slow moving point sources, such as stellar objects, it should be possible to use dual-axis control of the secondary mirror chopping function to maintain object alignment within the slit. Because the elevations for stellar objects are known, accurate control of the secondary mirror should permit operation without the addition of a Kmirror assembly and the increased background signal it would introduce. However some observations benefit from the flexibility to rotate the spatial field. The imaging capability of the new spectrometers would make it possible to produce a 2D image of an extended object provided that the slit image can be favorably oriented and scanned across the field to produce the desired geometry. Such a capability requires the addition of a Kmirror and its control system. We propose studying the placement of a Kmirror assembly prior to the image plane of the transfer optics in the F/32 beam. Inclusion of the Kmirror assembly into the cold cryostat would dramatically increase the size and thermal loads of the cryostat and would be undesirable. Command and control of the Kmirror rotation axis could be obtained from the AEOS system directly since the telescope elevation is known in real time and would be the only parameter needed for adjustment. A proper kinematic mount would permit translation of the Kmirror assembly into the beam if required.

Collimator-expansion box

Collimation of the field would be accomplished using reflective optics to provide an achromatic pupil image accessible by the spectrometers and the visible guide camera. The unit would contain a short-pass beam splitter which reflects wavelengths longward of 2.9 μm through a port located on the top surface of the box and into the cryostat that houses the MWIR and LWIR spectrometers. The shorter wavelengths would be directed through a port on the bottom surface for use in the guide camera system. The box has room to allow for future growth. The addition of spectrometers operating from UV through the SWIR are envisioned to augment the remote sensing capability of the new system. The described geometry also produces an easily accessible pupil image which facilitates alignment of the sensor to the telescope system.

Cryostat-cooling

Achieving high signal to noise ratios and reducing the thermal background requires operational temperatures at or below 10K. All of the optical components from the Lyot stop to the FPA would be operated at this temperature. There are really only two practical methods of cooling to such temperatures, cryocoolers or liquid cryogens (LHe). The merits of each type of cooling method affect construction and operation of the sensor as well as logistical support. For this sensor, portability would be a key consideration due to operation of the instrument on the AEOS and the IRTF telescopes as well as occasional use for field and laboratory experiments. Liquid cryogenic dewars are fairly simple in design and provide a very stable operating environment for the FPA and spectrometers. Our current systems use liquid cryogens and achieve hold times (between fills) of approximately 40 hours. The downside of this path would be the procurement of the liquids and their transport to the facility. Cryocooler systems would be an attractive alternative but present a different set of requirements. Although cryocoolers need no re-supply, they are power intensive and produce a significant amount of waste heat which must be directed away from the vicinity of the telescope to mitigate the effect on seeing. Vibration caused by these systems may increase noise contribution as well in the form of microphonics. Additionally, the cooler system would negatively affect the portability of the sensor. The final decision on the cooling method will be made during the study phase of this design; it minimally affects the discussion here.

Tracking camera-Filter wheel

The current plan would be to use an existing CCD imager to provide the guiding capability for the new system. The visible component of the beam would be transmitted through the beam splitter in the collimator box and folded down through a port towards the tracking camera. This configuration has the advantage of monitoring the field rotation should the Kmirror be in use. A filter wheel placed in the beam, as in the current configuration, permits the use of narrow band filters for certain science applications and allows for greater control of the image brightness at the CCD.

Dyson Spectrometer - FPA considerations

The design of imaging spectrometers and indeed all imaging instruments, is dictated in practice by the available detector materials and formats. Only two materials, HgCdTe and extrinsic silicon (e.g. Si:As BIB), have been developed into workable focal plane arrays for the LWIR band. The physical characteristics of arrays likely to be used are summarized in Table 1.

Table 1: Candidate detector arrays

Detector	Format	Pixel Pitch (µm)	Dispersion (mm)	Slit Length (mm)	Operating Temp (K)
HgCdTe	256 × 256	40	10.24	10.24	40
HgCdTe	256 × 512	40	10.24	20.48	40
Si:As	128 × 128	75	9.6	9.6	10
Si:As	256 × 256	50	12.8	12.8	10
Si:As	160 × 640	40	6.4	25.6	10
In:Sb	256 x 256	30	7.68	7.68	<40

Although they are more challenging to cool, we favor the Si:As BIB focal planes for their superior uniformity and operability (low number of "bad" pixels) compared to LWIR HgCdTe. For the purpose of this discussion we propose to baseline a Si:As FPA in the 128 x 128 pixel, 75µm format for both channels.

Dyson Spectrometer – History

Dyson [7] first demonstrated that a simple concentric arrangement of a plano convex lens and concave mirror, as shown if Fig 2, would be free of all Seidel aberrations at the design wavelength and center of a field imaged at 1:1 magnification. Mertz [8] later proposed that the Dyson principle could form the basis for a very high throughput spectrometer. More recently, Mouroulis and Green [9] considered Dyson designs for visible spectrometry. However more attention and development has gone into the Offner form and derivatives [9,10], which are also based on concentric principles and have some competitive advantages for systems with more modest f/ratios.

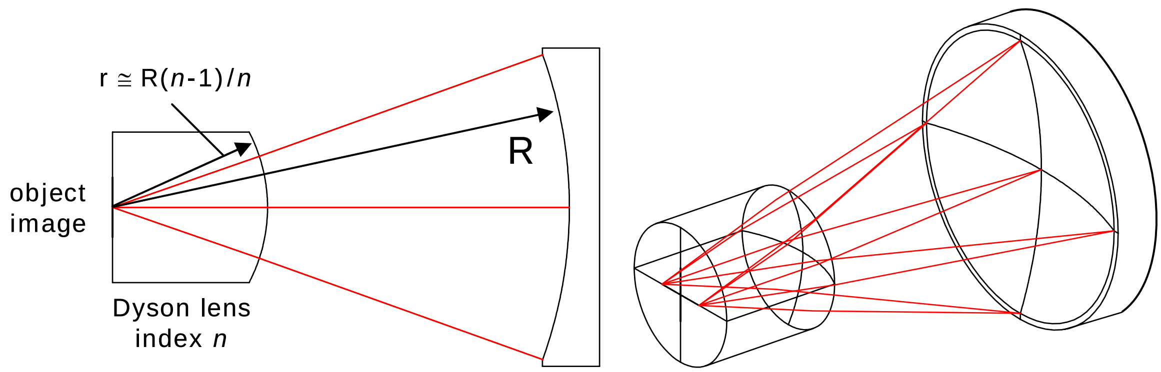

Fig 2. Basic Dyson geometry.

Dyson Spectrometer – A working design

To make the spectrometer usable, the object and image planes require relief from the Dyson lens to allow for slit and FPA placement. Spherical aberration is the principal driver keeping the image surface close to the rear surface of the Dyson lens. For a given system, the geometric spot size increases linearly with the image plane relief and also as the cube of the f/ratio as the throughput is increased. At F/1, image quality is unacceptable with only a few hundred microns of relief, not enough to be useful. The grating is a pupil in the Dyson form, and spherical aberration resulting from introducing focal plane relief can be corrected with a radially symmetric aspheric profile on the diffraction grating. However, a radial aspheric, while possible in principle in a diamond machined grating, complicates the tool motion and potentially introduces high spatial frequency irregularity in the surface. (This would not necessarily be the case with a holographic grating.) The addition of a near zero-power ZnSe corrector between the Dyson lens and the grating permits placement of an aspheric surface near the pupil preserving a spherical form for the grating. This dramatically improves geometric aberrations and allows for relief of the object and image planes resulting in a workable design. The units would be very compact allowing for both MW and LW spectrometers and their reimaging optics to fit inside a cryostat volume smaller than the current BASS sensor. Inclusion of the reimager into the cryostat permits its use as a stand-alone hyper-spectral imager for laboratory use and field experiments and facilitates the internal alignment.

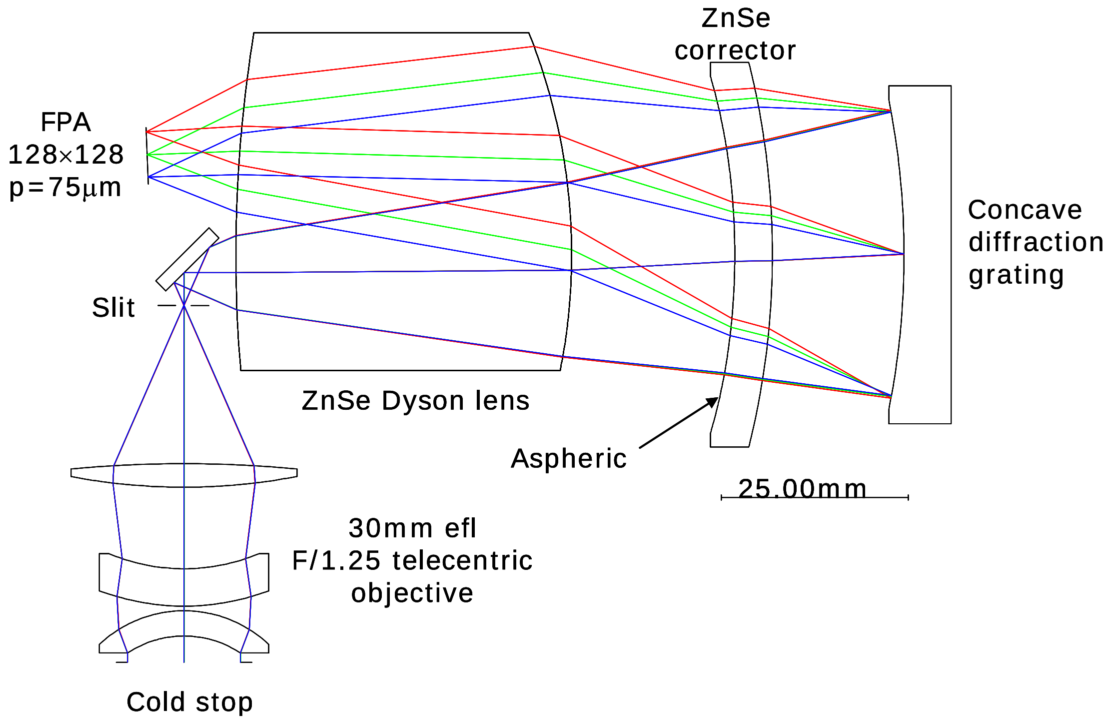

Fig 3: A refractive objective can be incorporated inside the cryostat to make a self-contained imaging unit. In this case, the 30mm efl yields a 2.5mrad IFOV for the 75µm pixel. The objective must be telecentric to provide proper input to the Dyson spectrometer.

Seeing conditions at the AOES site can be quite variable from night-to-night [11]; this negatively affects the precision of stellar photometry. The 2mm circular field stop (~ 3 arc seconds) in the current BASS sensor is marginally adequate for capturing all of the energy from a star when the seeing degrades much beyond an arc second. This happens frequently due to winds or with objects observed beyond a few air masses. To mitigate this, the imaging capability of the new spectrometers would use a slit with an effective width and length of 2.6mm and 35mm respectively. The result would be a field 4.5 x 60 arc second; using the maximum field available from the transfer optics. The baseline parameters for the spectrometers are as follows:

Bandpass	Resolving Power	Field (arc seconds)	FPA	F/#
LWIR 7.8 – 14um	R=160	4.5 x 60	128^2 75um pitch Material Si:As	1.25
MWIR 2.9 – 5.5um	R=160	4.5 x 60	128^2 75um pitch Material Si:As	1.25

As depicted in fig 4, the imaging performance would be significantly smaller than a pixel across the spectral band and field. The future potential to upgrade to a higher performance (smaller pitch) FPA would allow greater over sampling of the spectrum. This should have a positive affect on the radiometric performance for those spectral channels that are located near atmospheric absorption features.

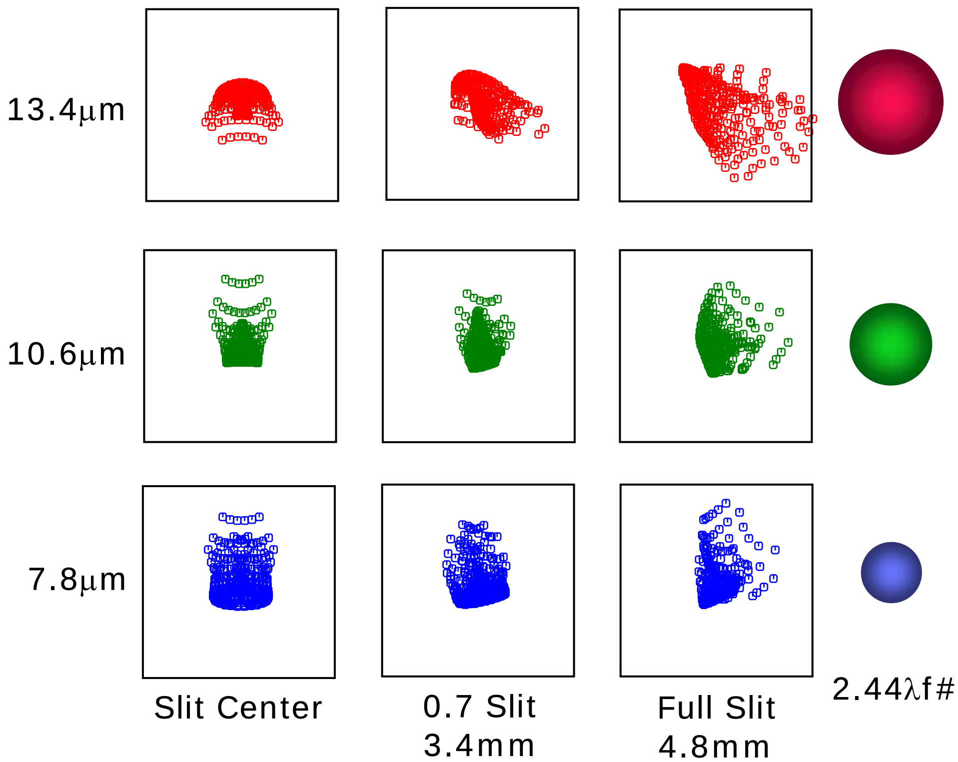

Fig 4. Geometric spot diagrams for the combined f/1.25 ZnSe spectrometer and objective system in Fig 10. Squares are one pixel (75μm). Diffraction point spread functions (2.44λf#) are 23-41μm, depending on wavelength.

Conclusions

We have presented the general architecture of a replacement instrument for the BASS sensor. The conceptual layout and form of the subassemblies are well within reach. The functionality of an operational Dyson spectrometer will be evaluated this fall for another program and lessons learned will be applied to this sensor. Final system design parameters will be adjusted during the study phase and will be reported in a future paper.

Acknowledgements

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