eMAS: Enhancements to The MODIS Airborne Simulator

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***Abstract*— The Enhanced MODIS Airborne Simulator (eMAS) is an ARRA funded upgrade of the MODIS Airborne Simulator (MAS) at the NASA Ames Airborne Sensor Facility (ASF). It is divided into two efforts: one aims to replace the MAS thermal and mid-wave IR spectrometers (ports 3 and 4) with a cooled optics bench (eMAS-COB) housing cryogenic optics and stops; the second will implement hyperspectral Offner spectrometers (eMAS-HS), to complement the MAS solar reflected bands (ports 1 and 2). The goal of both updates to ASF's workhorse instrument is to provide continuity of historical capabilities provided by MAS on current and future high altitude platforms. Additionally, the enhancements are intended to increase stability of the instrument during high altitude flight conditions and decrease calibration uncertainty.**

I. eMAS Spectrometer Heritage

The MAS spectrometer has been gathering earth science remote sensing data from the NASA ER-2 superpods since 1995 [1]. Originally, MAS was conceived as a test platform for collecting data sets to inform the band selection and algorithm development for the MODIS instruments before the launch of the TERRA and AQUA satellites [2]. The ER-2's ability to fly above 95% of the atmosphere [3] makes it a unique asset that can "simulate" an orbital perspective above the atmosphere, coupled with the ability to return the instrument to earth. Since the launch of the MODIS instruments in 1999 and 2002, MAS has continued to serve as an airborne complement to those orbital sensors. On an ER-2 at 20 km altitude, MAS offers 50 m spatial resolution, 50 spectral bands from visible to thermal infrared, and greater operational flexibility with respect to flight times, locations, and accompanying instruments than satellites with fixed orbits. This gives mission planners flexibility when selecting companion instruments such as lidars [4], FTIRs [5], and other earth and solar radiometers to achieve a mission's particular objective.

Flexible deployment and frequent return to earth present their own challenges however, particularly when the MAS instrument deploys from tropical locations to high altitude and back. In such cases the instrument experiences decades of temperature and humidity changes in a single 8-hour mission. The nature of its design - broad spectral coverage (0.400-14.5 μm) and wide field of view (nearly 86 degrees) viewed through one fore-optic (to ensure virtually perfect spectral co-registration) - requires that it operate in the unpressurized area of the superpod, without a window. The environmental stresses on the instrument create challenges in calibration and stability that the satellite-borne instruments do not face.

MODIS and MAS are now over a decade old, and a new generation of earth remote sensing instruments is in the design or final-assembly stages. Some of these instruments, such as VIIRS, owe obvious heritage to the basic MODIS cross-track scanner configuration [6]. A newer class of instruments utilize concentric spectrometer designs to achieve a higher solar reflected spectral resolution than MODIS, e.g., HyspIRI [7]. Additionally, many next-generation instruments emphasize lower radiometric calibration uncertainties.

As the options for instrument design grow and mature, so do the options for high altitude platforms on which to deploy the instruments. In the past, the manned ER-2 and WB-57 were the only options for top- of-the-atmosphere imaging spectrometer missions above 18 km. NASA's recent test flights of its new Global Hawk UAVs present a long duration, unmanned option for mission planners with a different kind of operational flexibility [8]. A Global Hawk mission could begin and end from its base at Dryden Flight Research Center, reach most locations from the Pacific Rim to the mid-Atlantic, and return to Dryden within one 30-hour mission. The cryogenic thermal IR systems in MAS were not originally designed to meet the long duration requirements of UAV missions.

The enhancements to MAS (eMAS), now in the fabrication phase, reflect advances in both sensor and aircraft technology. The eMAS efforts will provide continuity of suborbital MODIS-like data sets on current and future high altitude platforms with improved performance. The enhanced MAS project is divided into two parallel efforts: eMAS-HS, a separate hyperspectral pushbroom system, and eMAS-COB, a replacement thermal spectrometer module on a cooled optics bench to be retrofitted to the current MAS scanner.

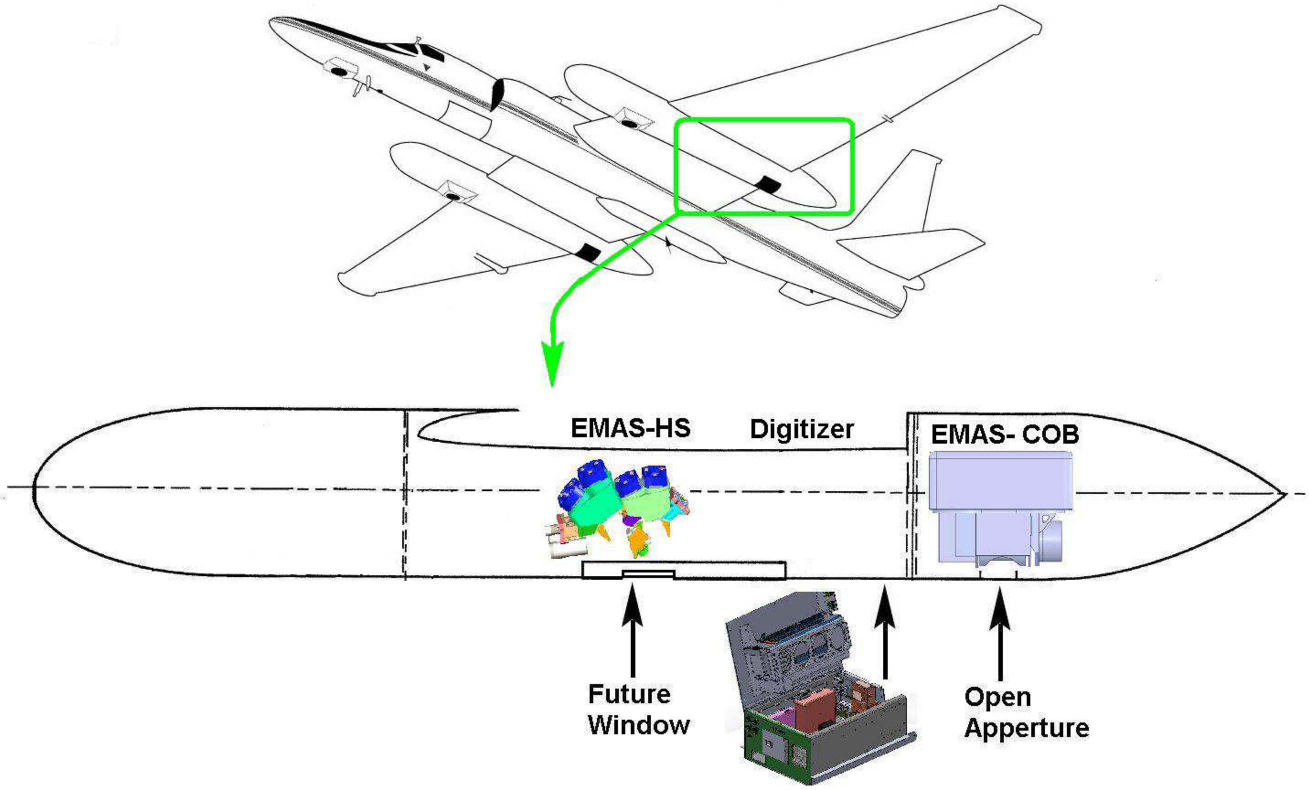

Figure 1. Schematic of the ER-2 superpod. The eMAS-HS will be situated over a window in the pressurized midbody of the superpod. The eMAS-COB will be integrated with the existing scanner system, which installs in the unpressurized tailcone and views through an open port.

II. eMAS-HS

The goal of the eMAS-HS effort is to fabricate a pushbroom hyperspectral imager to complement the eMAS scanner. The eMAS-HS will inhabit a pressurized area forward of the eMAS scanner, viewing the scene from behind a window. The EMAS-HS will view a 50 degree subset of the same cross track scene as the eMAS scanner, which has a much higher FOV (85.92 degrees) than a pushbroom system could typically achieve. Due to its more benign environment and ability to ingest in-flight sources, the eMAS-HS will add value to eMAS missions with its more robust calibration and validation performance for cross-calibrating the legacy scanner bands in ports 1 and 2. Additionally, the higher spectral and spatial resolution inherent in a hyperspectral design will allow scientists to test application of different wavebands to models that could identify important spectral bands for future instruments.

Of primary importance in the eMAS-HS is the ability to carry a ground calibration to the high altitude environment with low uncertainty. Also important is to maintain stable performance over the 30 hour Global Hawk flight time. Finally, the ability to ingest light from a stability source to validate flight performance in comparison to the ground calibration lab performance is another goal of the program.

A more detailed discussion of the eMAS-HS design and performance has been presented elsewhere [9]. Briefly, the instrument consists of SWIR and VNIR offner spectrometers that share a common entrance slit through a dichroic splitter. The slit is illuminated by a four mirror anastigmatic telescope with a very wide field of view, 50 degrees. TheVNIR spectrometer uses all spherical surfaces to create a 1-to-1 dispersed image of the slit on the visible focal plane array. The SWIR spectrometer performs a slight de-magnification in order to co-register its 30 μm pixels to the 32 μm VNIR spectrometer pixels. This departure from the symmetry of a classic Offner relay introduces aberrations; these are corrected by an aspheric surface in the first mirror of the SWIR spectrometer.

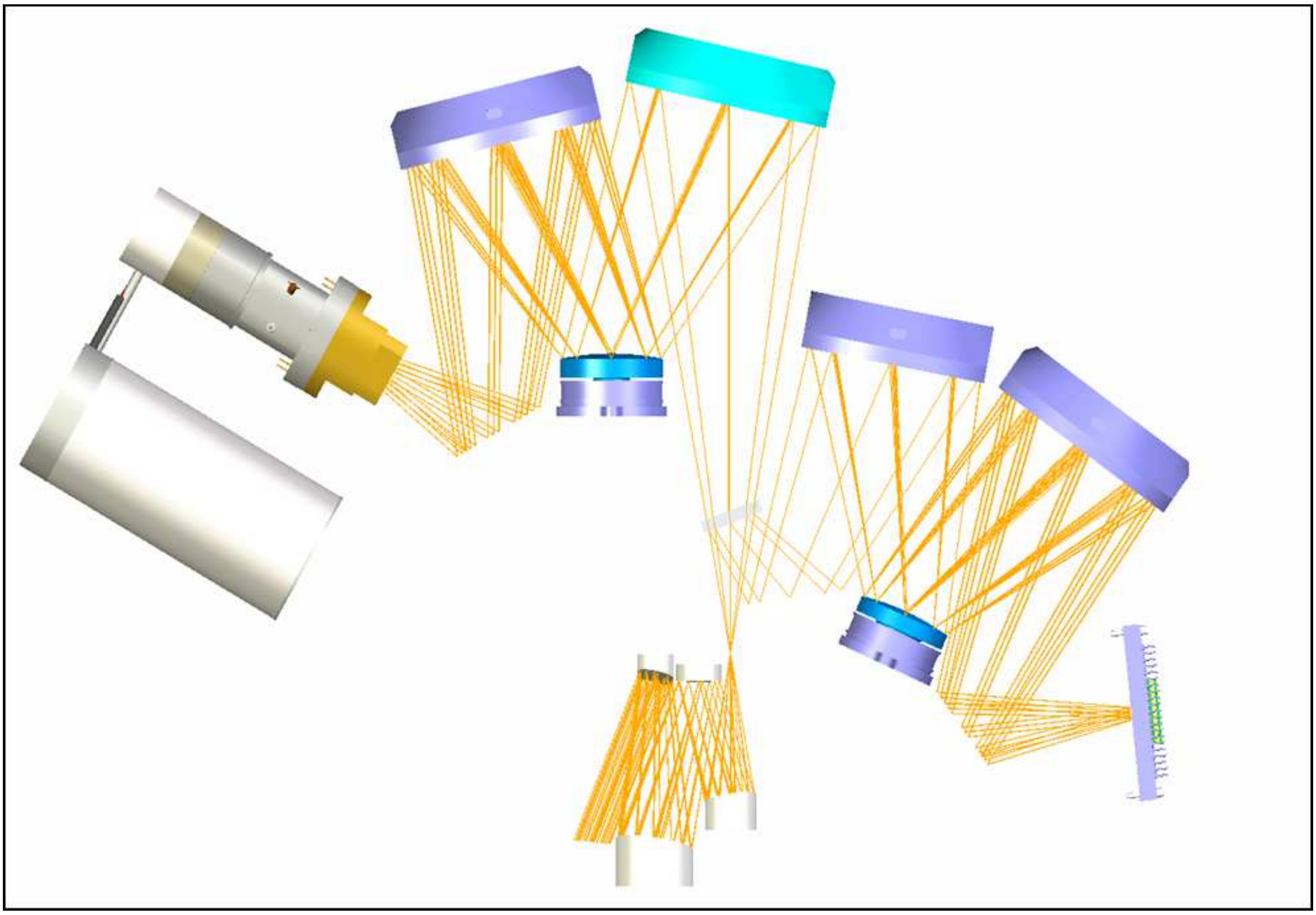

Figure 2. Solid model view of the eMAS-HS with ray trace superimposed to illustrate the optical design. The SWIR spectrometer and IDCA/FPA are in the top-left, the VNIR spectrometer and FPA are on the right.

A. eMAS-HS Telescope

Although eMAS-HS will cover a smaller cross-track FOV than the scan angle of the companion scanner instrument, it will have an exceptionally wide FOV for a 380-2400 nm pushbroom spectrometer. This is due to the aggressive design of the 4-mirror anastigmatic telescope, operating at $f/2.8$. Other wide band, wide field-of-view Offner spectrometers have been designed with three [10] or as few as two [11] aspheric mirrors in the telescope, but they have different requirements. In general these instruments project a curved field of view on the ground, and remove the several pixel curvatures in the scene with post-processing rectification. eMAS-HS is required to co-register its field of view with the flat eMAS-scanner field of view to within a binned pixel. Across the 50 degree wide field of view, the four mirror design exhibits cross-track ground sample distortion that is less than a quarter binned pixel (8 μm).

B. eMAS-HS SWIR Focalplane Array

The focalplane array used in the SWIR spectrometer is noteworthy. It is a hybrid focal plane array with back-illuminated HgCdTe detectors. This detector material offers very high and flat quantum efficiency across the SWIR band. The hybrid FPA comes from the vendor packaged in its IDCA with clocking and drive electronics, making a COTS camera system ready for spectrometer integration. This camera system is designed specifically for hyperspectral imaging rather than staring array imaging. The geometry of the FPA and pixels are suited for one dimension of dispersion. Typically, a science grade hybrid FPA might have a square geometry; such an array would not be fully utilized in an offner type hyperspectral imager which tends to have higher resolution in the spatial dimension than the dispersed dimension.

The readout IC bonded to the detectors also has hyperspectral-specific features. An advantage that a MODIS, VIIRS or MAS style scanning array has over a hyperspectral imager is that each detector band can have its gain tuned based on the dynamic range of the in-band scene radiance and the A/D converter. Usually a hyperspectral imager's detectors are multiplexed through the same A/D converter and the gain for a given band may be set sub-optimally because an out of band region with more radiance or sensitivity must not saturate. The eMAS-HS FPA clocking selects a large or small electron well depth on a row by row basis. For spectral bands that coincide with an atmospheric absorption, the scene radiance might be much lower than in a close-by neighboring band. Rows associated with atmospheric window bands might be best served by the lower gain setting, darker regions that correspond to absorptions would benefit from the higher gain setting.

$f/\#$	$f/2.8$
field-of-view	$\pm 25°$
ground projection distortion	0.25 pixel
spatial resolution	832 spatial samples
spectral resolution	10 nm
VNIR spectral bands	256×2.5nm
SWIR spectral bands	140×10nm
VNIR magnification	1:1
SWIR magnification	32:30

Table 1. eMAS-HS summary of first order properties.

C. eMAS-HS Environmetal Isolation and Stability Monitoring

An important requirement of the eMAS-HS is to carry a stable calibration into the high atmosphere reliably, and keep track of its stability over a long flight potentially up to 30 hours. The eMAS-HS instrument will be installed in the pressurized forward section of the same ER-2 superpod that carries the eMAS-scanner. Although pressurized, at 20 km (65000 ft) this compartment sees 34.5 kPa (5 PSI) pressure, about equivalent to 9 km altitude, and about 0 to -10 C temperatures [3]. To further stabilize the instrument it will be packaged in its own pressure box that will include fans and heater elements to bring the internal temperature to sea level regimes. The pressure box window will have a flexible bellows with an o-ring flange that extends down to an open port in the skin of the superpod hatch.

The system level stability of the spectrometers will be tracked by occasionally viewing a stable broadband source, the radiometric stability monitor (RSM). The RSM consists of a QTH lamp with an elliptical reflector that focuses the light into the end of a hollow tube with high specular reflectance. In typical illumination applications, this type of mixing rod produces a uniform light source at the opposite end [12]. In contrast, the RSM will have a longitudinal slit that the light will escape from. At the opposite end from the lamp, a TE-cooled, two-color detector (silicon and InGaAs) will monitor the VNIR and SWIR irradiance in the mixing tube. The mixing tube and its reference slit will be behind the scene slit in the pressurized housing. A moving fold mirror will select between the scene slit with light from the telescope or light from the RSM.

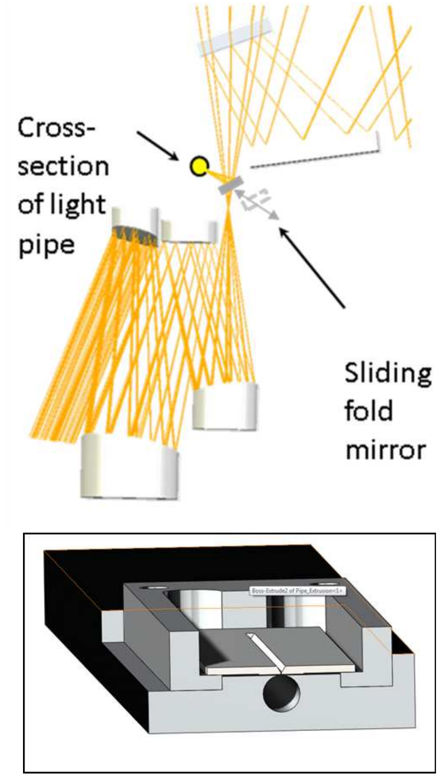

Figure 3. Schematic design for the RSM.

D. eMAS-HS Electronics

The solar reflected eMAS-scanner ports 1 and 2 share an entrance pupil and field stop with thermal ports 3 and 4 by using dichroic splitters after the telescope to feed the separate instruments with essentially perfect spectral band registration. A disadvantage of the separate fore-optic for eMAS-HS is that exact registration with the scanner is not possible. Furthermore, the geometry of the eMAS-HS scanline will be different from that of the eMAS scanner due to the nature of pushbroom vs. scanned IFOV instruments. The optics for a pushbroom imager cannot achieve the wide field of view and low distortion of the scanned system so it necessarily images a sub-sample of the scanner's cross-track FOV. To synchronize acquisition of each scan line from the two instruments, the eMAS-HS electronics are designed to receive frame triggers from the eMAS-scanner.

The eMAS-HS embedded control PC and software also provide a "UAV mode" which allows way-point triggered, programmed or remote telemetry control. The current MAS system is designed for the ER-2 pilot to start and stop acquisition manually from a switch panel in the cockpit. In future missions, the eMAS-HS embedded computer will be capable of remote control and data streaming with NASDAT, the ethernet-basednetworked downlink and telemetry environment developed for NASA's Global Hawk by ASF.

III. eMAS-COB

The eMAS-COB effort enhances the performance in the thermal infrared bands of the instrument by replacing the existing ports 3 and 4 with an enclosed cryogenic optical box. The goals of the improvements are again to increase flight calibration stability and signal to noise ratio. These goals will be achieved by reducing and stabilizing thermal expansion variance and backgrounds sensed by the instrument due to its own self-emission. Sealing spectrometer optics from condensing environments will further increase stability. The main strategy to effect this stabilization and background mitigation is to cool, isolate, and stabilize the thermal IR parts of the instrument in a cryo-vacuum enclosure.

A. eMAS-COB Cryogenic Optics Bench

The MAS design is essentially a confocal parabolic, centrally-obscured telescope that feeds a series of grating spectrometers by way of dichroic splitters. Ideally, the exit pupil of the telescope would match the entrance pupil of each spectrometer's imaging optics. In fact, the simple design of the telescope and the need for working distance to place the dichroic folds prevents the ideal design. The longer than ideal standoff of the telescope exit pupil from the spectrometer's perspective means that a significant portion of the spectrometer's field of view is not just the scene energy coming from the telescope but the interior of the spectrometer housing itself. In the thermal IR ports, this leads to substantial signal from self-emissions that change with the temperature of the spectrometer housing during a flight. The generic approach to stop down a thermal IR instrument is to apply a cold stop, usually close enough to the detector to be cooled by the same cold finger. This method is not applicable to a grating spectrometer where the image of the telescope field stop is dispersed in one dimension.

To reduce system noise due to these self-emissions, the eMAS-COB internalizes as much of the optics as possible into the cryogenically cooled compartment with a radiation shield and a long stand-off cold stop. The optics are now mounted on a mechanically cooled optical bench. In the LWIR port 4, this includes the MWIR/LWIR dichroic splitter, the beam folding mirrors and gratings, the 5-element achromatic lens and the order-sorting filter and FPA. By effectively pushing the cryogenic cooling from near the detector array out in front of the grating, dispersion does not prevent use of a cold stop to limit radiance to scene energy from the telescope's exit pupil.

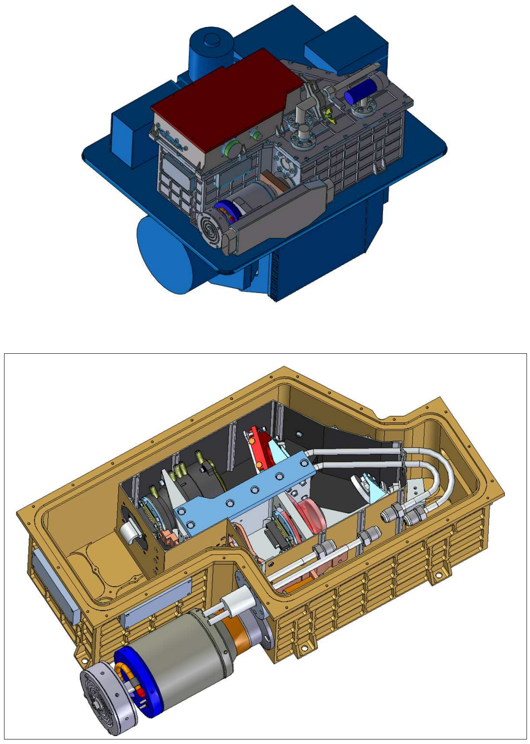

Figure 4. Solid model of the eMAS-COB. Top: integrated with the scanner; bottom: vacuum and cold shield lids removed.

The schedule and funds available did not allow for an MWIR port 3 spectrometer. Instead the most important 3.7 μm band was selected as the sole MWIR channel in a filter radiometer configuration. The eMAS-COB MWIR port 3 has been designed specifically for the option to easily upgrade to a spectrometer by swapping in a lens, grating and detector array. The achromatic lens and grating/FPA design for an MWIR spectrometer upgrade have been completed under this contract and confirmed to fit with minimal adjustment. Other options for MWIR port 3 upgrades are under consideration, such as a dual gain radiometer for simultaneous background and fire-mapping missions.

B. eMAS-COB Distortion Corrected Focalplane Array

The distinctive PC-HgCdTe focalplane array has a unique geometry that reduces spectral cross-talk and maximizes signal-to-noise by conforming to the distortion in the optical system. The imager optics and rear telescoparabola relay a nearly 1:1 image of the telescope field stop onto the detectors. In the current MAS port 4, "spectral smile" from these optics leads to twisted and skewed scene IFOV images at the focal plane. In the current MAS instrument, the corners of one bands' image bleed over into the neighboring detector, increasing optical cross talk.

Furthermore, detectors at the edge of the field are displaced significantly from the line where the middle bands fall, making it impossible to maximize clocking and position alignment for maximum ensquared energy for both paraxial and wide field detector bands. In eMAS, the FPA is designed to mitigate the effects of this distortion. The detector for a given band is simply displaced and tilted to the location where its energy falls. In this way the lens design is optimized for the other aberrations without much concern for spectral smile.

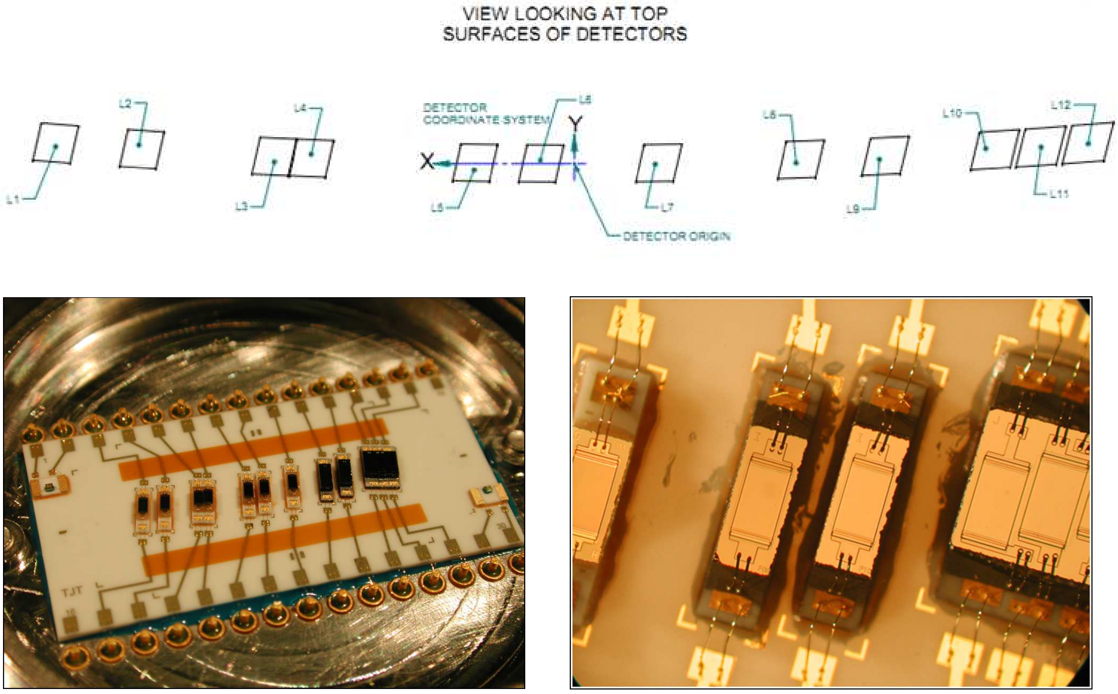

Figure 5. eMAS-COB FPA design corrected for distortion to improve ensquared energy and reduce spectral cross-talk. Top: eMAS-COB FPA coordinate system, below: final FPA before integration in the LWIR FPA assembly, and close up of detectors L7-L11.

The Port 4 spectrometer design for eMAS, unlike the current MAS system, covers more than one diffraction order, approximately 6.5-14 μm. One of the requirements for eMAS was to pick up a new band at 6.7 μm for atmospheric sounding. The current MAS employs a linear variable band-pass filter as a moving cold stop for the port 4 detector array. Without the LVF, the system would saturate on its own broadband self emission. This LVF is expensive, difficult to source replacements for, and sensitive to alignment adjustment. In eMAS-COB, there is no need for a narrow bandpass filter for each detector because the cold optics reduce the self-emission background. Instead, a simpler two coating bandpass filter is used for order sorting.

Band	Center Wavelength (μm)	FWHM (μm)
M1	3.646	0.183
L1	6.715	0.253
L2	7.325	0.260
L3	8.280	0.264
L4	8.550	0.264
L5	9.730	0.262
L6	10.200	0.261
L7	11.030	0.260
L8	12.020	0.258
L9	12.600	0.255
L10	13.335	0.263
L11	13.635	0.259
L12	13.935	0.253

Table 2. Predicted bandpass performance for eMAS-COB IR channels.

The wide bandpass of port 4 leads to another problem: the type of PC-HgCdTe detectors sensitive to 14 um light have poorer detectivity at the shorter wavelengths. In particular, the 6.7 um band will be starved for photons since it coincides with an atmospheric CO_2 absorption. Since the detectors are discrete, the solution was to source three different HgCdTe chemistries with different band gaps tuned to three spectral sub-regions. The option to use photovoltaic HgCdTe detectors at the shorter wavelengths was considered, but rejected due to the complexity this would bring to the FPA and amplifier design and limits in funding and schedule.

IV. Conclusion

The eMAS enhancements to the MAS spectrometer have been funded by The American Recovery and Reinvestment Act. Most of the subsystems in the eMAS upgrade are provided by private contractors many of them small, growing, high technology businesses. The final delivery and acceptance of the components is scheduled for February 2012. The enhancements will upgrade the instrument for longer duration UAV platforms, increase performance with state of the art technology, and improve instrument calibration stability during high altitude missions.

V. Aknowledgments

This program has been made possible by ARRA stimulus funding. The subcontractor building the eMAS-HS are lead by Brandywine Photonics, who designed the spectrometers and provide system engineering and architecture.

The prime eMAS-COB subcontractor is Space Dynamics Laboratory, a Utah State University UARC. SDL performed all optical and mechanical design and fabrication of the COB. Teledyne Judson Technologies worked closely with SDL to make the custom focalplane array design.

Program, science, and technical oversite expertise has been provided by the Space Science and Engineering Center at the University of Wisconsin-Madison and the EOS Project Science Office at Goddard Space Flight Center.

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