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GALAGO-1: A COMPACT DAY-NIGHT BAND PATHFINDER

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1. Introduction

The National Oceanic and Atmospheric Administration (NOAA) Satellite Observing System Architecture (NSOSA) study (NOAA/NESDIS, 2018) proposed several future architecture concepts to fulfill Low Earth Orbit (LEO)-based observing requirements currently supported in part by the Joint Polar Satellite System (JPSS) Visible Infrared Imaging Radiometer Suite (VIIRS) instrument. These architectures include flying VIIRS as a standalone instrument, disaggregating VIIRS capability across a number of platforms, or relying on partner satellite missions (e.g. EUMETSAT) for imagery data. The disaggregated alternatives can enhance the architecture flexibility and adaptability. However, lower cost alternatives must be realized for these to be viable options for Near Constant Contrast (NCC) Imagery Environmental Data Record (EDR), achieved by the VIIRS Day-Night Band (DNB), and which was elevated to a Key Performance Parameter (KPP) after the launch of Suomi-NPP. SmallSat formfactors may enable this lower cost paradigm.

2. Strategic Objectives

This Phase A Pathfinder program seeks to design and mature technologies for a compact, low-cost (e.g., SmallSat-hosted), adaptable, low-light visible/near-infrared sensor, capable of meeting or exceeding the sensing, coverage, and spatial/temporal resolution performance requirements of the currently-specified VIIRS-DNB associated KPP as part of NOAA's future LEO satellite observing system architecture.

The Galago-1 Pathfinder program objectives support NSOSA strategic objectives for weather imaging and regional forecasting at higher latitudes (if not globally), while maintaining VIIRS-DNB data availability with lower cost, flexible, disaggregated capability.

DNB mission areas, generally, align with NOAA NESDIS and National Weather Service Weather Ready Nation mission service areas of routine and severe weather, environmental modeling prediction, aviation weather, fire prediction, and hurricane / tropical storms.

3. Requirements

The NOAA Forecasting Office in Alaska currently relies on the DNB imagery to "turn night into day," which requires Arctic nighttime coverage. The imagery is used to detect clouds, sea ice, shipping vessels, city lights, and fishing lights at night, during the day, and at the sensor-performance-stressing terminator crossing. Additional applications in lower latitudes may include the ability to detect low level clouds for maritime applications, and nighttime hurricane imagery for track and intensity predictions.

The existing KPP for the DNB mission requires the Near Constant Contrast (NCC) imagery environmentadata record (EDR) for latitudes greater that 60deg N in the Alaskan region, with an 87-minute data latency (US DOC, 2014). This is achieved on VIIRS from an 824-km sun-synchronous orbit, with a 1330 local time of ascending node (LTAN). This KPP and associated constellation configuration will serve as the baseline for design purposes, except in the coverage KPP; the trade study will look to sensor concepts that can provide global coverage.

Additional mission-level requirements, per discussion with NOAA, include a four-month operational threshold with an objective one-year on orbit operation, and a low-cost, compact sensor design capable of rapid insertion into an architecture.

The Galago-1 Pathfinder concept is to meet the current VIIRS-DNB on-orbit performance as presented in (Liao, 2014). However, the sensor design trade space will look at several options that maintain sensitivity and dynamic range but consider relaxation of the Horizontal Spatial Resolution (HSR) and swath width. The rationale here is that the HSR and swath width drive the single-sensor complexity and its size, weight, and power (SWAP). Overall coverage will be met by combinations of multiple sensors on a platform and the number of platforms.

The design, to maintain adaptability and be "bus agnostic," will drive toward interfaces that minimize integration complexity.

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4. Technical Trades

To understand the sensor trades and their associated motivations, it is useful to briefly describe the VIIRS DNB sensor: The DNB is part of the rotating telescope that services all of the spectral bands of the VIIRS sensor. It is a "whiskbroom scanner" with a rather small number of detector elements in each of the bands. The telescope line-of-sight (LOS) is scanned from horizon to horizon (a total of 116 degrees or +/- 56 degrees about the nadir point) by rotating the telescope in a direction orthogonal to the direction of platform motion, hereafter referred to as the "track" direction. An entire telescope rotation takes 1.8 seconds with 31% of this time covering the image 112-degree image swath. An internal mirror mechanism cancels the effective forward track motion during each scan. Owing to the small number of detector elements that are scanned in parallel, the field-of-view of the telescope is quite small (about one degree). However, the rate of telescope rotation, and hence the rate of detector scanning, is quite high due to the combination of this small FOV and the sensor orbital motion in the track direction. Consequently, the telescope aperture is large (i.e. 19 cm). The DNB detection is enabled by a visible scanning time-delay-and-integrate (TDI) charge-couple-device (CCD) focal plane located at an appropriate focal position within the telescope optical path. The high LOS scan rate described above results in an exceptionally high CCD pixel scan rate (260,000 pixels/sec) in the TDI section of the device before analog charge-packet aggregation occurs. Such aggregations are implemented in 32 steps from nadir to the edge-of-scan and are different between the scan and track directions to maintain a relatively constant horizontal spatial resolution (HSR) over the 56-degree field-of-regard. All these features make this high line rate TDI CCD wholly unique and expensive for the DNB application.

Stand-alone, disaggregated sensor concepts, capable of accomplishing the DNB mission but which are lower in cost and complexity, are highly desired. Several approaches are possible.

This first of these is a modification of the existing whiskbroom DNB approach, wherein the scanning TDI CCD would be much longer in the track direction thereby slowing down the CCD line rate in the scan direction. The LOS mechanism would be a two-sided rotating mirror. The lower CCD line rate might allow for a more standard CCD to be used; it is not clear whether such a device could support analog charge-packet aggregation that is unique in the along and cross-scan directions to affect a constant HSR. The rotating flat will exacerbate the sensitivity of the sensor to stray light. The negatives of a complicated scanning mechanism and the high voltages needed to operate the CCD remain. Note that CCDs generate analog video, so a separate signal processor is needed to convert the pixel video into a digital format. If the aggregation is not possible with a more standard TDI CCD then the aggregation function would have to be done in the digital domain and sample noise effects would impact sensor sensitivity.

A pushbroom sensor approach eliminates the scanning mechanism entirely, however now a large field-of-view is necessary perpendicular to the track direction, with a large visible FPA. For this case the track and scan direction are the same. The 112-degree field-of-view (FOV) is too large to be serviced by a single sensor hence this FOV would be broken down into multiple sensors each with a reduced FOV and a smaller FPA. The required line rate of the FPA would be substantially reduced. TDI CCD technology could be applied and would assure high sensitivity, however variable aggregation along the cross-scan dimension of a CCD would not be possible – this is something that would have be done digitally in a processor. As described above, the CCD analog video would first needed to be converted to digital format.

An alternative pushbroom approach would be to consider a non-CCD solution, namely the use of CMOS FPA technology that has on-chip analog to digital conversion. Such devices dissipate much lower power and eliminate the need for a processor that converts analog pixel video to a digital format. These devices typically come in a large two-dimensional format with very small pixels, limited in dynamic range, but with very low noise and low dark current. The cost of such CMOS FPAs is exceptionally low, and these devices are readily available if the standard formats can be used. At least two of these devices have been qualified for space use by appropriate radiation testing. The approach would be to design the DNB pushbroom sensor concept around one or more available CMOS FPA formats and use digital processing to affect the pixel summation in the cross-track, cross-scan direction needed to maintain HSR.

A preliminary study was completed that resulted in two sensor designs, capable of the DNB sensitivity and constant HSR with appropriate digital binning in the cross-scan/cross-track direction. The numbers of pixels in the scan/track direction far exceeded what was needed from a sensitivity viewpoint. However, these devices have very high gain (and hence low noise) but limited dynamic range at the pixel level. To implement the needed wide dynamic range (quarter moon to full daylight illumination or a factor of 10^7) a mask would be placed over the CMOS FPA rendering distinct gain regions (probably two or three) along the track/scan direction. Neutral density filters would be used to implement the lower gain regions. For the case of terminator crossings, the separation between these regions would need to be enough to avoid electrical crosstalk between the high gain and low gain regions of the CMOS FPA.

5. Identified CMOS FPA Technologies

Based on preliminary work, two candidates were chosen for the investigation of a digital CMOS-based pushbroom sensor: Case A used the CMV50000, a 7920 x 6004 format with 4.6-micron x 4.6-micron pixels. Case B used the BAE LTN4625A, a 4608 x 2592 format with 5.5 micron by 5.5-micron pixels.

Through sensitivity and MTF analysis, it was determined that each could meet the DNB performance from a 12U CubeSat using a two-headed optical system. The Case A assembly used 6 total FPAs, 3 per optical head, and Case B would use 8, 4 per optical head. Each telescope had a 55.4° Field of View (FOV). Case B, in this configuration, can only cover 95% the FOV. Straylight was not yet fully considered for these configurations, and remains a critical risk for the program. Additional commercially available FPAs will be analyzed as the study progresses.

6. Risks, Future Work

A number of risks are to be mitigated as design work progresses. Notably, additional FPA characterization efforts involving lab testing will be undertaken to understand the dynamic range of the sensor, and assess for electrical crosstalk and straylight saturation effects. Additionally, the compact optical design will prove aggressive due to the wide FOV and high MTF requirements.

The optical FOV is extremely challenging in such a design particularly given the HSR requirements. Follow-on work will look at a reduced field-of-view with a modular “building-block” design approach. A feasible single baseline sensor will be developed in more detail wherein multiples of said sensor would be used on a single platform to implement a 112-degree field-of-view (three or four) or used in a proliferated approach (i.e. multiple smallsats, CubeSats, etc.) each with a FOV less than the 112-degree discussed above. Since each of these schemes could involve this single baseline DNB CMOS pushbroom sensor concept being pointed in a different cross-scan/cross-track direction, the binning needed to assure a constant HSR would require unique processing for each pointing case. The digital processor to accomplish this would be programmable, meaning the sensor hardware would remain the same.

Additional discussion of ongoing and future efforts is presented here. Other design considerations to be addressed include but are not limited to: restricted bandwidth to ground requiring onboard processing, driven by the data latency requirement; contamination control, which adds handling cost and complexity; host jitter environments for rideshare options, which impacts image stability.

6.1 FPA characterization

Managing the dynamic range during terminator crossings using the CMOS FPA design construct discussed above can only be verified by empirical measurement. Hence one of the planned activities is to characterize one or more of the CMOS FPAs mentioned in Section 5 for electrical crosstalk under the conditions of optical overload consistent with irradiance ranges that span the two sides of the terminator.

6.2 Sensor Calibration

Because Galago-1 will be a smallsat payload, or part of a suite of instruments, onboard calibration is likely out of scope; onboard calibrators add mission complexity and additional SWAP. Vicarious methods will instead be considered, including lunar and stellar calibration, terminator imaging for daytime, evening and nighttime operational setting ratio calculations, deep-space imaging for offset determination, and uniform scene imaging for non-uniformity corrections.

Pre-launch calibration will be conducted in the Aerospace Calibration Facility. The Facility has been used for several Aerospace sensor prototyping efforts, including the operational CUbesat MULtispectral Optical System (CUMULOS) (Pack, 2017).

6.3 Interface Definition

With the effort to be “bus agnostic” and maintain lower cost, sensor-to-spacecraft interfaces will be closely analyzed as design work progresses. These interfaces will be driven by the sensor design and its requirements, including restrictions on pointing stability, thermal control, and straylight. Electronics, power, and data handling interfaces will also be defined to assure mission success. These interfaces are to be designed such that the sensor can integrate with a variety of spacecraft with little to no modification if possible. This will enable adherence to a flexible architecture with the capability to insert new technologies as they become available.

6.4 Optical Design

After design requirements and first order imaging parameters have been set, a detailed optical lens and baffle design will follow. Appropriate glass materials will be included in the design to ensure that the concept will perform at the required wavelength bandwidth of operation. The design will also include passive athermalization if necessary. Material quality and cleanliness requirements needed to perform at a terminator crossing will also be determined. This finalized design will be assessed for manufacturability and an initial tolerance analysis will be conducted. Expected design performance using optimal tolerances for the as-built design will be evaluated against MTF imaging requirements. Notable Deliverables include custom finalized design, manufacturability and tolerance report including expected performance.

The optical design will take into account stray light mitigation, which is a critical consideration for achieving performance requirements in the DNB, particularly for radiometric calibration and maximizing the contrast of the imagery. This is most important near the terminator where bright daytime scenes can scatter light into the night side imagery. In particular, given the operational use of the NCC imagery in the Alaskan region, straylight impacts at the Northern terminator crossing must be minimized.

7. Conclusion

The Galago-1 Pathfinder Prototype will enable NOAA's future LEO earth observing system need for DNB capability. This will be achieved through a modular, pushbroom sensor, capable of integrating with smallsats. The sensor will have: no moving parts; a restricted optical FOV to allow for a feasible and manufacturable optical design; readily available, lower cost 2D CMOS imaging FPAs to avoid expensive, custom FPA designs; no obsolete CCD technology requiring high amplitude analog clocking; a fixed optical design with FPA pixel binning and variable frame rate operation to allow flexible instrument pointing with the fixed HSR constraint over the FOV; unique sunshade implementation driven by pointing angle choice to mitigate straylight concerns.

This modular design can be viewed as a "building block" for a flexible architecture, using either a single sensor per platform across multiple satellites for a highly disaggregated approach, or multiple sensors on a single platform to cover a wider FOV and provide desired coverage from one satellite.

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