Abstract. A wide-field zenith-looking telescope operating in a mode similar to time-delay-integration (TDI) or drift scan imaging can perform an infrared sky survey without active pointing control, but it requires a high-speed, low-noise infrared detector. Operating from a hosted payload platform on the International Space Station (ISS), the Emu space telescope employs the paradigm-changing properties of the Leonardo SAPHIRA electron avalanche photodiode array to provide powerful new observations of cool stars at the critical water absorption wavelength (1.4 μm) largely inaccessible to ground-based telescopes due to the Earth’s own atmosphere.

Cool stars, especially those of spectral-type M, are important probes across contemporary astrophysics, from the formation history of the Galaxy to the formation of rocky exoplanets. Main sequence M-dwarf stars are the most abundant stars in the Galaxy and evolved M-giant stars are some of the most distant stars that can be individually observed. The Emu sky survey will deliver critical stellar properties of these cool stars by inferring oxygen abundances via measurement of the water absorption band strength at 1.4 μm. Here, we present the TDI-like imaging capability of Emu mission, its science objectives, instrument details, and simulation results.

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1 Introduction

Even though M-dwarfs are the most abundant stars in our Galaxy, relatively little is known about their make-up (i.e., their abundance patterns of elements heavier than hydrogen and helium) because of their intrinsic faintness, cool temperatures ($T_{\text{eff}} \lesssim 4000$ K), and complex atmospheres. Their low photospheric temperatures result in a stellar spectrum that contains overlapping atomic and molecular absorption, making meaningful measurement of bulk stellar metallicity challenging—let alone key elemental abundance patterns. This complexity makes for a
highly degenerate problem, rendering it difficult to uniquely determine a set of stellar parameters to describe a given star, something routinely done for Solar-type stars. In such cool stars properties such as temperature ($T_{\text{eff}}$), the bulk metallicity ($[\text{M/H}]$), and elemental abundances such as $[\text{O/H}]$ and $[\text{C/H}]$ all prominently affect the large-scale shape of the observed spectrum and greatly complicate the use of traditional analysis techniques.

Most of the dominant molecular absorbers in cool atmospheres contain oxygen [e.g., TiO in the optical; H$_2$O and CO in the near-infrared (NIR)] where, in chemical equilibrium conditions, the amount of oxygen-free to form such molecules is sensitive to the carbon abundance through the formation of energetically favorable CO.\textsuperscript{2,3} The observational consequence of this is that both oxygen and carbon—elements difficult to measure on their own—have an out-sized impact on the shape of a spectrum and greatly affect the ability to reliably measure stellar metallicity.\textsuperscript{4}

The ability to reliably measure oxygen would thus aid in resolving this degeneracy and help to unlock the chemistry of the most common kind of star. To this end, one particular wavelength region of interest (ROI) is the H$_2$O band at 1.4 $\mu$m. Unfortunately, this region is exceedingly challenging to observe from the ground due to moisture in our atmosphere.\textsuperscript{5} However, space-based observations show tremendous promise in opening this unique window into the physics of stellar atmospheres of cool stars.

The International Space Station (ISS) provides a unique platform to perform life, physical, Earth, and space science research and technology development. The ISS, being a science platform, provides all of the resources that a scientific instrument would expect from an Earth-like laboratory, such as power, cooling, data, and communication needs. The ISS external payload platform provides a new opportunity to realize space missions extraordinarily fast and of low cost in comparison to traditional research conducted on-board the ISS. It provides the flexibility to be replaced with different instruments or, in some cases, brought back to the Earth. The experiments on these platforms can fit into short-term funding cycles available on national and multinational levels. External payload accommodations are available on the “Expedite the Processing of Experiments to the Space Station” (ExPRESS) Logistics Carrier (ELC), “Japanese Experiment Module-Exposed Facility,” (JEM-EF) and the “Columbus-External Payload Facility” (Columbus-EPF) of the ISS.\textsuperscript{6} The commercially available external platforms for small payloads include NanoRacks External Platform\textsuperscript{7} (operational from 2016) attached to JEM and Bartolomeo platform\textsuperscript{8} attached to Columbus Module, which is operated by Airbus Defence and Space. Emu leverages these emerging cost-effective and reduced mission risk platforms to perform the infrared sky survey, along with key detector technology demonstration in space.

The Emu mission will undertake its NIR sky survey in a band centered on 1.4 $\mu$m (Emu $W$-band or $W_3$) as well as in $J$ band (for cross-calibration) as a method of estimating oxygen abundance in the atmospheres of cool stars down to a magnitude $m_{\text{eff}}$ (AB) $\leq 12.5$. Emu is a compact wide-field photometer destined for a 6-month mission on the exterior of the ISS. The Emu payload conforms to a 6U CubeSat form factor and employs “noise-free” SAPHIRA infrared detector array\textsuperscript{9} and will perform time-delay-integration (TDI) such as imaging from the ISS.\textsuperscript{10} The ISS presents a platform for a survey instrument, due to its precessing orbit. It follows that a high-speed imager with a 1.2-deg diagonal field of view (FOV) toward the zenith can map the sky without active pointing. Therefore, it demands that stars do not traverse more than one pixel per readout, to avoid smearing. These frames are then shifted, aligned, and stacked to produce a continuous strip with an effective exposure time equivalent to the full transit time of the array. Emu will also demonstrate the NIR TDI-like imaging capability of SAPHIRA in space, which can play a crucial role in future missions such as GaiaNIR.\textsuperscript{11-13} Emu is in the early phase of development and the conceptual design of the instrument has been completed (at the time of writing). The launch has not been finalized yet, and we are exploring different opportunities to fly this mission. Critical hardware and subsystems for the mission are being developed and validated.

### 1.1 TDI-Like Imaging

TDI or “drift scan” imaging is an electronic scan technique, based on the concept of the accumulation of cumulative exposures of the same object as it is moving across the FOV.\textsuperscript{14} One of the major telescope facilities that use the TDI imaging technique is the Sloan Digital Sky Survey.
such as GALAH16 and APOGEE17 but, despite their prevalence, most of these are not M-dwarfs. Stars with measured metallicities and elemental abundances in massive spectroscopic surveys, such as GALAH16 and APOGEE17, have been critical components of stellar and Galactic astrophysics for many decades now. There are now many hundreds of thousands of stars with measured metallicities and elemental abundances in massive spectroscopic surveys such as GALAH16 and APOGEE17, but, despite their prevalence, most of these are not M-dwarfs. Indeed, GALAH has a temperature cut around \( T_{\text{eff}} \approx 4000 \text{ K} \). The band is affected by non-LTE and inhomogeneities in solar-type and cooler stars, while the extremely weak forbidden lines [OI] at 0.6300 and 0.6363 \( \mu \text{m} \) require high sensitivity and high-resolution spectroscopy to separate them from the forest of transitions associated with other elements and is not practical in M stars.

The strongest water absorption feature in the coolest (<3000 K) stars is at 2.7 \( \mu \text{m} \). Observation at this wavelength is challenging due to the high thermal background. The strongest absorption feature that can be readily accessed is between the astronomical \( J \) and \( H \)-band windows at 1.4 \( \mu \text{m} \). Its measurement from the ground is challenging due to the dominance, and rapid variability, of the water absorption column in the Earth’s atmosphere and the wide FOV required to provide sufficient reference stars for a differential calibration. Space-based observations are therefore desired. The \( W_{\text{K}} \)-band center is at 1.4 \( \mu \text{m} \) with a bandwidth of 0.15 \( \mu \text{m} \). The band is strongest in the atmospheres of the coolest stars \( (T_{\text{eff}} = 2700 \text{ K}) \) is adopted as a functional limit based on currently available model atmosphere data) and weakest in warmer stars (with \( T_{\text{eff}} = 4000 \text{ K} \) adopted as the functional upper limits for cool stars). The band strength is also dependent on the relative abundance of heavy elements in the star. Emu will measure the water
abundance by comparing the observed flux of stars in the Emu $W_E$-filter to the expected flux predicted based on broad-band photometric values available in the literature.

The Emu $W_E$-band provides an improved indicator of the underlying oxygen abundance than other broad-band filters (which blends complex metallicity signatures) as the dominant molecular absorber at 1.4 $\mu$m is H$_2$O. Compare this to the optical, where there is a larger contribution from a much greater range of sources: from atoms, as well as molecules such as oxides (e.g., TiO, VO, ZrO) and hydrides (e.g., MgH, CaH, SiH), which all contribute to the complex metallicity and abundance signatures. Two example synthetic spectra are shown in Fig. 1, showing the variation in the water absorption strength for two temperature and metal abundance levels. The synthetic spectrum of a warm (shown in blue, effective temperature, $T_{\text{eff}} = 3600$ K) low-metallicity M-star is shown compared with a cooler star with higher metallicity (shown in red). The Emu $W_E$-filter band, indicated by the green lines, straddles the strong water absorption band in both cool stars, but with significantly more absorption in the higher metallicity source. O is fully condensed into H$_2$O in dwarf stars at solar metallicity 3000 K or in giant stars at 2000 K. For near dwarfs with $T_{\text{eff}}$ below 3300 K, the depth of water features are therefore more of a measure of [O/H] than $T_{\text{eff}}$. A representative Earth’s atmospheric transmission spectrum (infrared spectra of the atmospheric transmission above Mauna Kea) is also shown, as well as the canonical and widely used $J$ and $H$ band astronomical filters. The water absorption in the Earth’s atmosphere hinders these observations from being performed with ground-based telescopes. A full statistical analysis using all available photometric data will of course underpin the measurement of stellar abundance using the $W_E$-band. However, a simple color–color diagram (photometric intensity ratios in different filter bands) demonstrates the power of our unique Emu $W_E$-band for determining stellar atmospheric abundance (Fig. 2) across a wider range of stellar parameters. A star’s location in the color–color space made available by the $W_E$-band provides a probe of the atmospheric water content, and hence oxygen abundance, free from the degeneracies associated with other broad-band filters alone. Photometric accuracy at the 3%

![Fig. 1](image-url)
level (SNR ≥ 30) will provide powerful empirical evidence for the metal abundance of the coolest stars. For warmer atmospheres and higher metallicities, the brighter sources (with 1% photometric errors) from the Emu survey will be used. Emu will provide critical empirical evidence of the validity of the state-of-the-art models, which have significant uncertainty at high metallicities and for the warmer stars.

3 Instrument Overview

Emu is a 6U form factor payload to be hosted on the ISS. The instrument layout of Emu is shown in Fig. 3.

The optical system is a compact Cassegrain telescope, with a re-imaged pupil and it will occupy 2U space. The integrated detector cooler assembly (IDCA) system contains the cold baffle, detector, and Stirling cooler. The IDCA will fit in a 1U unit. The IDCA holds the filters which are required to achieve the desired passband and as well as thermal requirements. A further 0.5U is required for the ANU “Rosella” detector readout electronics system. Rosella is a modular and compact readout electronics system to read out the SAPHIRA detector. In the baseline design, a further 2U is set aside for a commercially available off-the-shelf data mass storage system. The different instrument parameters are shown in Table 1. The drifts scan survey approach, enabled by the low readout noise of the SAPHIRA detector at a high frame rate, removes the mass and complexity associated with a conventional pointing-and-tracking telescope. The telescope’s primary mirror will be baffled and sufficient thermal blocking is achieved in the cold section of the instrument. The SAPHIRA detector will be cooled to 80 K (in principle SAPHIRA can be operated at a higher temperature, but this will cause an increase in the dark

![Fig. 2](image-url) A synthetic color–color diagram shows the ability of the Emu $W_E$-band photometry (the data product from our all-sky survey) to measure stellar metallicity. Tracks show the zero-age stellar main sequence for cool-stars ($2700 \leq T_{\text{eff}} \leq 4000$ K, in steps of 100 K) at the indicated [Fe/H] metallicity with all elemental ratios such as [O/Fe] fixed to solar values. Note how the use of a $J$–$W$ color enables the separation of the stars into distinct metallicity sequences, demonstrating the power of the Emu $W_E$-band. The $i$–$K_s$ color on the $X$-axis is a proxy for stellar temperature (with some dependence on [Fe/H]), with the $J$–$W$ color plotted on the $Y$-axis being primarily sensitive to [Fe/H].
current\textsuperscript{12}), and while this aspect of the project presents a significant design challenge, the power consumption and waste heat dissipation necessary are within the scope of capabilities provided by our preferred host platform on the ISS. The direction of flight will be along the short axis of the detector (256 pixels) and the transverse field will be along the long axis (320 pixels). Along with the $W_E$-band imaging, Emu will also undertake a sky survey in the $J$-band for cross-calibration of data. The simultaneous $W_E$ and $J$-band imaging is achieved by placing two separate $W_E$ and $J$ filters before the focal plane. The filters will be placed such that they will be perpendicular to the direction of flight, which would allow scanning the same portion of the sky in both bands. $J$ and $W_E$-band will occupy 60 and 180 pixels with an intermediate dead band of 16 pixels necessary for mounting the filters at the focal plane ($\sim0.4$ mm gap between filters). The mission will operate for 6 months on the ISS with the majority of data recorded with on-board storage for sample return, due to communication bandwidth restrictions. We will be able to downlink $\sim1\%$ of this data for calibration purposes.

4 ISS Platform and Jitter

The ISS is maintained in a nearly circular orbit with an average altitude of 400 km, at an inclination of $\sim51.6$ deg to Earth’s equator. The orbital period of ISS is $\sim92.68$ min, with $\sim15.54$ orbits per day.\textsuperscript{6} Emu will perform the NIR sky survey between $+51.6$ deg and $-51.6$ deg declination during its 6 months of operation and thus would scan $\sim78\%$ of the total sky.

To understand the effect on image quality of Emu, due to ISS jitter, we have simulated a random vibration profile from the power spectral density (PSD) data available from the External Payloads Proposer’s Guide to the ISS.\textsuperscript{6} This corresponds to around 30 microradians in both axes of the focal plane and less than one Emu pixel ($10''$). The ISS platform PSD and the random vibrations (in Emu pixel scale) derived from the PSD are shown in Fig. 4. One of the missions that performed the characterization of the ISS vibration environment is the Optical Payload for Lasercomm Science (OPALS).\textsuperscript{33} OPALS is a technology demonstration for laser communication aboard the ISS, and it has been utilized for different extended missions after its primary mission. From this experiment, the ISS jitter has been estimated to be in 20 to 30 microradians range.\textsuperscript{34} This is in agreement with the derived jitter from the ISS PSD data. Thus, the ISS jitter will not be a critical noise source in the Emu data and just be within the tolerance ($\text{FWHM} = 20''$). Also, the jitter does not introduce significant rotational issues in the data; but does introduce a significant global translation between frames. We can freeze out the vibration frame to frame (because of fast frame readout), but they do have an impact on

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Fig. 3 The Emu conceptual model is shown. The optical elements, including the cold detector assembly and thermal management system, occupy a volume equivalent to 3U. A further 1U is required for the control system electronics. In the baseline design, a further 2U is set aside for a data mass storage system.
Table 1 The Emu instrument specifications are shown here. The optimum pixel size for the Emu sky survey is 10′. A FWHM of 2 pixels is considered to satisfy the Nyquist sampling and this will result in a spatial resolution of 20′ for Emu. Emu uses a low readout noise SAPHIRA detector to enable TDI-like imaging capability. SAPHIRA will be operated in a CDS readout mode resulting in a science frame rate of 25 Hz. In this mode, a non-destructive readout (NDR) reset and exposure frame will be taken, which will result in a 50-Hz NDR frame rate. Emu will fit in a 6U volume and it can achieve a sensitivity around $m_H(AB) \sim 12.5$ in H band with an SNR of 10.

| Instrument NIR imager |
|-----------------------|
| Imaging mode TDI-like |
| FOV 0.71 deg $\times$ 0.89 deg |
| Aperture size 83 mm $\times$ 83 mm |
| Central obstruction $\sim$12.5% |
| Equivalent circular aperture diameter 93.65 mm |
| Effective area $\sim$60 cm$^2$ |
| Focal length 495 mm |
| Operating bands $W_E$ (1.34 to 1.5 $\mu$m) and $J$ (1.17 to 1.33 $\mu$m) |
| Detector SAPHIRA eAPD from Leonardo MW Ltd. |
| Array size 320 $\times$ 256 |
| Spatial resolution FWHM = 20′ (2 pixels) |
| Frame rate 25 Hz CDS, (50 Hz NDR) |
| Number of field transits 256 |
| Effective exposure time $\sim$7.2 s (in $W_E$-band) and $\sim$2.4 s (in $J$-band) |
| Limiting magnitude (single orbit) $m_H(AB) \leq 12.5$ in H-band (with SNR =10) |
| Weight $\leq$ 8 kg |
| Dimension ($L \times W \times H$) 300 $\times$ 200 $\times$ 100 mm (6U form factor) |
| Power $< 50$ W |

Fig. 4 (a) ISS platform PSD. (b) Random vibrations in Emu pixel scale. Note the ISS jitter is less than one Emu pixel scale and thus it will not be a critical noise source in the Emu data output.
the image trajectory across multiple frames of the data. Cross-correlation between successive frames will be performed to shift and stack multiple frames (details in Sec. 5).

5 Instrument Performance Estimates

Traditionally, TDI uses a CCD technology by shifting the electrical charge across the detector at the same velocity as the object image to avoid blurring. The analog of this for CMOS technology such as SAPHIRA is taking images at a high enough frame-rate and poststacking them to produce effectively long exposures. The conventional CMOS cannot work in TDI mode, because of the high readout noise at a fast frame rate. However, the low electronic noise of the SAPHIRA detector allows the camera to read out images at the same rate that stars transit the image pixel (25 Hz). A series of images is recorded as the sky crosses the static (with respect to the Space Station) telescope FOV. The images are then aligned (using integer pixel shifts) in postprocessing and stacked to give a composite image. The exposure time of each frame is chosen to match the time taken for a star to traverse one pixel on the detector, such that the next exposure will see the same image but with everything shifted by one whole column. The frame rate is set by the drift speed, which is \( \sim 233 \, \text{s}^{-1} \) for the ISS in a 400-km LEO.

The exposure time per individual integration is then calculated from the pixel size, \( S_{\text{pix}} \), (in units of arc seconds) and drift speed, \( R_p \):

\[
\tau_{\text{exp}} = \frac{S_{\text{pix}}}{R_p}.
\]

The frame rate is given as

\[
\text{Frame rate} = \frac{1}{\tau_{\text{exp}}}.
\]

The frame rate for a 10'' pixel based on Eq. (2) is 23.3 Hz. For simplicity, for the Emu baseline design, we have considered 25 Hz frame rate.

The full effective exposure time is then a function of the number of pixels along the flight path of the platform, \( N_x \):

\[
\tau_{\text{eff}} = N_x \tau_{\text{exp}}.
\]

A simulation has been performed to recreate the effects of the SAPHIRA detector, ROSELLA electronics, optical elements, background noises, ISS vibrations, TDI-like imaging, and stars. The different input parameters to simulate Emu mission data are shown in Table 2. The simulation input parameters provide high flexibility and would allow simulating similar TDI-like mission (for example, GaiaNIR mission—see Sec. 13 for more details).

The thermal background at the focal plane is another input parameter which is discussed in Sec. 11. Orbital and spacecraft platform parameters for the simulation consist of the angular speed of the ISS and the data on vibrations on the ISS external platform (discussed in Sec. 4). To simulate the star-field, we have used the 2MASS star catalog data.\(^{27}\)

The different processing steps and logical flow of the simulator is schematically shown as a flowchart in Fig. 22 (see Appendix). The SAPHIRA operates on correlated double sample (CDS) readout mode over the full array with a resulting science framerate of \( \sim 25 \) Hz. In this process, nondestructive readout zero (NDR0) frame or reset frame will be generated followed by an exposed frame or nondestructive readout one (NDR1) frame. Each of these frames requires two readouts (one after reset and one after exposure) that are differenced to produce a CDS science image.

To simulate the vibrations on the ISS external platform, a random vibration profile is generated as mentioned in Sec. 4, and it is then added to the trajectory. Based on the resulted trajectory coordinates, an ROI is selected from the 2MASS star catalog.\(^{27}\) From this ROI, the stellar coordinates and magnitude data are extracted for stars that would fall in the Emu FOV. To add
these selected stars to the frame, a coordinate transformation is applied to convert the world coordinates to pixel coordinates.

In this simulation 2MASS, $J$, and $H$ band magnitudes are used to simulate the flux of stars. The 2MASS $J$ and $H$-band Vega-based magnitudes are converted to the AB system as

$$M_{AB} = J - 0.91,$$

$$M_{AB} = H - 1.39,$$

where $M_{AB}$ is defined in SI unit as

$$M_{AB} = -2.5 \log_{10}(f_{\nu}) - 56.10 \ f_{\nu} \text{ in W m}^{-2} \text{ Hz}^{-1}.$$

The energy of the photons that the telescope received can be expressed as a function of the flux spectral density $f_{\nu}$. For the purpose of simulation, we approximated a flat spectrum in the corresponding wavelength band. By dividing this energy by the energy of a photon $h\nu_{\text{eff}}$, we can obtain the number of photons collected by the telescope for one star as a function of $f_{\nu}$, and then, as a function of $m_{AB}$:

$$N_{\gamma} = \frac{E_{W}}{E_{\gamma}} = \frac{1}{h\nu_{\text{eff}}} \int_{\nu_1}^{\nu_2} f_{\nu} \Delta \nu \Delta T = \frac{1}{h\nu_{\text{eff}}} f_{\nu} \Delta \nu \Delta T,$$

where $A$ is the telescope’s collecting area, $\Delta \nu$ is the spectral bandwidth of observation, $T$ is the exposure time. By substituting the $f_{\nu}$ expression from Eq. (6) in Eq. (7), we obtain

$$N_{\gamma} = \frac{1}{h\nu_{\text{eff}}} A \Delta \nu T 10^{-\frac{m_{AB} + 56.10}{2.5}}.$$

Using Eq. (8), the number of photons corresponding to each star is calculated. A null flux map frame is generated and each star is added as a Poisson distribution. The thermal background photons are also added as Poisson distribution to this flux map.
To find the relative shift between frames due to the vibrations on the ISS external platform, a cross-correlation between successive frames is performed. The offset obtained from this cross-correlation is used to correct for the relative shift between the frames. These $W_E$-band and $J$-band frames are then shifted (each pixel by one column, based on the TDI technique), aligned, and co-added separately to produce a continuous strip with an effective exposure of the time taken for a target to cross the entire array. A weight map is also created in parallel corresponding to the number of shifts to correct the exposure gradient. The shift and the co-added frame are then divided with this white map to create the strip of the Emu star-field. An example of a single exposure simulated frame (with $J$ and $W_E$ bands) is shown in Fig. 5. A simulated sky strip that Emu will deliver in $W_E$ and $J$ bands are shown in Figs. 6 and 7, respectively.

To understand the sensitivity of the simulated data, we ran a source extractor algorithm on the simulated image. The source extractor algorithm extracts the flux value and signal-to-noise ratio (SNR) of each star in the simulated star-field. The extracted stars from the simulation are

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**Fig. 5** An example of Emu single frame with exposure time $\sim$0.04 s using the 2MASS catalog at the Galactic anticenter. Here, the blue, green, and red box represent $J$, $W_E$ bands, and dead space between the bands, respectively.

**Fig. 6** The image shown is an Emu $W_E$-band data simulation based on the current Emu baseline design and the 2MASS $H$-band input catalogue (extrapolated to the 1.4 $\mu$m Emu $W_E$-band). This image was produced by shift and stacking $\sim$1200 frames, over one orbit pass at mid-latitude. The effective exposure time is individual pixel exposure time (0.04 s) $\times$ number of pixels in $W_E$-band (180) = 7.2 s.
then cross-matched with the stars in the 2MASS catalog, to understand the sensitivity of the simulated star-field. Figure 8 shows the SNR of each star in the simulated sky strip. To estimate \( m_{AB} \approx 12.4 \) (\( H \)-band) and \( m_{AB} \approx 12.6 \) (\( J \)-band) can be detected with an SNR of 10 with the Emu sky survey. The simulation shows that we can achieve the necessary sensitivity without a pointing and tracking system, by performing TDI from the ISS platform.

5.1 Cosmic Ray Event Rate

To understand the cosmic ray (CR) events experienced by Emu we have used the data from the Wide Field Camera 3 infrared channel (WFC3/IR) on the Hubble Space Telescope. The WFC3 IR detector is a HgCdTe 1024 × 1024 array, with 18-μm pixels. As per the WFC3 instrument handbook, the WFC3/IR camera has a CR event rate of 5 events/s/camera. The WFC3/IR detector area is 3.39 cm\(^2\) and this corresponds to 0.68 events/s/cm\(^2\). For SAPHIRA, the detector area is 0.472 cm\(^2\). And this will result in a CR event rate of 0.32 events/s for Emu. At 25 frames/s frame rate, this corresponds to 0.012 events/frames. This implies that the CR event rate has a little direct impact on Emu observations. However, the tolerance of SAPHIRA to such
events is as yet unknown (indeed this is an important technical demonstration goal of the Emu mission), as are the implications for the control system electronics.

6 Optimum Pixel Size for the Mission

For the Emu mission, a critical mission parameter is the selection of pixel size. A larger pixel size provides a wider FOV for a detector with a fixed number of pixels as well as leads to a greater TDI crossing time (hence increased integration time). This is important for sensitivity and frame to frame alignment. However, larger pixel size would also increase the potential for source confusion (multiple sources in a single pixel). The optimum pixel size is depending upon the field alignment requirement for the single frame as well the confusion limit of the co-added frames.

To perform alignment between different frames, it is required that every single frame has three or more guide stars detected to a significant level. The point spread function (PSF) of the final stack of the image (PSF_{Out}) should be blurred by no more than 10% of the input PSF (PSF_{In}) for an individual frame.

Centroid error in terms of full width half maximum (FWHM) and SNR can be expressed as

\[ \sigma(\text{centroid error}) = \frac{\text{FWHM}}{\text{SNR}}, \]

and FWHM is

\[ \text{FWHM} = 2.35 \times \sigma(\text{PSF}_{\text{In}}). \]

So centroid error can be expressed as

\[ \sigma(\text{centroid error}) = 2.35 \times \frac{\sigma(\text{PSF}_{\text{In}})}{\text{SNR}}, \tag{9} \]

The output PSF would be 110% of input PSF and it can be expressed in terms of its standard deviation (\(\sigma\)) as

\[ \sigma(\text{PSF}_{\text{Out}})^2 = 1.1 \times \sigma(\text{PSF}_{\text{In}})^2. \]

And also

\[ \sigma(\text{PSF}_{\text{Out}})^2 = \sigma(\text{PSF}_{\text{In}})^2 + \sigma(\text{centroid error})^2, \]

i.e.,

\[ \sigma(\text{centroid error})^2 = (1.1^2 - 1) \times \sigma(\text{PSF}_{\text{In}})^2. \tag{10} \]

By substituting Eq. (9) in Eq. (10), we will get

\[ \text{SNR} \sim 5. \]

From this analysis, it can be estimated that an SNR of \(\geq 5\sigma\) is required to limit the output PSF blur to less than 10% of input PSF.

This implies guide stars’ magnitude in every single frame should be at least 10 mag (2MASS \(H\) (Vega)). So to Nyquist sample the image inputs, the FWHM is assumed as two pixels. To understand the best pixel size approximate for Emu, we have assumed a fiducial reference mission with three different pixels sizes, such as 5, 10, and 20 arcsec. To estimate the optimum pixel size for the mission, the stellar density was derived empirically from representative fields at the Galactic anti-center and the Galactic pole as extremely high and low density cases. The Galactic center has a highly crowded stellar field, and the effect of source confusion is high compared to other regions of the sky.\(^\text{40}\) To reduce the effect of source confusion, we chose a sky field in the Galactic anticenter instead of the Galactic center. The stellar density estimated using 2MASS catalog data\(^\text{27}\) at the Galactic-anticenter and the Galactic north pole is shown in Fig. 9. The
fiducial reference values such as the Emu pixel size and photometric aperture size (twice of FWHM) are also shown.

From the stellar density information, the Poisson probability of more than three stars in the FOV was estimated and it is shown in Fig. 10. It can be concluded that a pixel size greater than or equal to 10″ is required to satisfy the minimum three stars per frame condition for alignment purposes. To estimate the confusion limit, the Poisson probability of more than one star in the photometric aperture was derived and this is shown in Fig. 11. From Figs. 10 and 11, it can be concluded that a pixel size of $\sim10^0$ would be optimal for the Emu mission (when constrained to a single SAPHIRA focal plane array).

7 SAPHIRA Electron Avalanche Photodiode Detector

The Emu mission concept was developed based on the groundbreaking sensitivity of the SAPHIRA detector from Leonardo MW Ltd. The SAPHIRA adds an eAPD region below a traditional HgCdTe absorption layer, as part of a hybridized assembly with a CMOS readout integrated circuit with 32 parallel readout channels, each supporting a pixel rate of up to 10 MHz. The array has $320 \times 25624$ μm pixels. The detector is sensitive to a nominal wavelength range of...
0.8 to 3.5 μm, with the effective quantum efficiency in the range 2.5 to 3.5 μm depending on the selected avalanche gain. A quantum efficiency of >60% has been demonstrated for the SAPHIRA in Emu’s wavelength band. The avalanche gain is tunable via manipulation of bias voltages and provides a near-noise-free signal gain of up to several hundreds. This linear signal amplification results in an effective readout noise contribution of ≤1 electron per pixel per CDS image pair. This near-zero readout noise regime is critical to implementing the TDI-like observation mode for the Emu mission.

An avalanche gain of 45 was chosen for Emu to obtain a system readout noise ≤1e−. Increasing the gain would reduce the dynamic range of the system. Emu’s bright magnitude limit is 4.5mH (AB) and this is basically set by the gain choice of 45. The gain can be controlled by setting the readout electronics reset voltage; thus, the different modes of operation with different gain (thus different dynamic ranges) are possible.

SAPHIRA detectors are already used in ground-based astronomical instruments for fast wavefront sensing and fringe tracking applications, but their utility in space applications is yet to be exploited. Specifically, their suitability for high-speed and/or photon-starved applications has profound implications for space-based NIR instruments, including TDI-like surveys of the sky from a low earth orbit platform. This removes the need for a complex fully steerable (pointing and tracking) telescope that would add significant cost and risk to the project. This principle can also be applied to NIR and short-wave infrared remote sensing Earth Observation applications.

The SAPHIRA detector has also undergone radiation testing, with a gamma and proton radiation campaign by the European Space Agency (ESA) showing no permanent damage to the device. A fully integrated SAPHIRA focal plane built at ANU is shown in Fig. 12. One of the goals of the Emu mission is to advance the SAPHIRA detector and ANU “Rosella” control electronics to technology readiness level 9 (TRL9). The use of the ISS as the orbital platform circumvents many of the engineering risks associated with small space missions as it removes the need for a full free-flying satellite bus and offers features such as active cooling and payload return.

**8 Rosella Detector Control Electronics**

Rosella is a high-performance detector controller for space, developed by ANU to address the lack of space-compatible pixel digitization options for science grade optical sensors, which typically have no on-board analog-to-digital converters (ADCs).
The Rosella system is compact and easily reconfigurable for a wide range of visible and IR CMOS detectors including the Leonardo SAPHIRA and Teledyne HxRG family of infrared arrays. The Rosella architecture (Fig. 13) features a preamplifier board, bias board, video board, and a timing board based on a field programmable gate array (FPGA). The preamplifier board provides early amplification of the detector output signals very close to their origin, reducing the influence of electrical noise induced further down the signal chain. The bias board generates accurate and stable DC voltages for the detector, including the SAPHIRA’s variable avalanche gain bias.

The video boards host 32 ADC channels for digitizing the incoming pixel stream. These devices are selected for low noise performance. The timing board manages the entire system, including bias configurations, clock pattern generation, ADC triggering, image processing, and communication with an external host computer through one of several standard protocols (e.g., Ethernet). Although the Emu mission requires a 50-Hz frame rate, the Rosella controller has been designed with high-resolution Earth Observation missions in mind, with frame rates approaching 1 kHz. A breadboard prototype of Rosella (Fig. 14) has been successfully demonstrated on-sky at the ANU 2.3 m Telescope.

Rosella’s final version will occupy a volume of ~0.5 U, comprising a connector-less printed circuit board (PCB) assembly based on rigid-flex technology. Each rigid PCB section features an outer thermal conduction region that interfaces with an aluminum wall that forms a contiguous
and enclosed board stack by folding the flex circuit sections. The enclosure also provides light-tightness for payloads sensitive to infrared emission (thermal “glow”). Figure 15 shows a “FlatSat” engineering model of Rosella and a mock-up of the PCB and enclosure assembly.

9 Integrated Detector Cooler Assembly

The IDCA system contains the cold optics, detector, cooling system, and mount. It is required to maintain the detector and cold optics at specified temperatures to meet the instrument performance requirements. The IDCA layout is shown in Fig. 16.

The assembly must also make provisions for trapping volatile contamination to avoid degradation of the performance of the cold optics and detector. The operating temperature requirement for the SAPHIRA detector is 80 K, and this will be provided by a miniature split-Stirling cooler UP8497/01 from Thales Cryogenics. There is no Dewar, so the Stirling may work only when Emu is in a vacuum. This means Emu can be operated only under an external vacuum. Almost one hundred electrical wires (thin narrow tracks of the flexible cable) are coming from the 80 K zone to the detector control electronics operating at approximately room temperature. The regenerator with the cold finger is a part of the Stirling cooler. The detector (80 K) and the cold baffle (~200 K) are mechanically held only by the cold finger and do not touch any other constructions. The rigid-flex PCB includes the thin flexible cable (with four wings) and connects electrically SAPHIRA with the pre-amplifier PCB. The thin flexible cable has low thermoconductivity so the total heat load to the cold finger’s tip is within our miniature Stirling’s possibility...
to lift heat. The metal cold baffle is a truncated four-side pyramid glued to the rim of the SAPHIRA package. At the tip of the cold finger, there are detector, cold baffle, cold filter, and mounts. The rest of the Emu subsystems will operate at room temperature. The total mass of this assembly is around 10 g. We have performed vibration tests with a dummy cold finger and dummy mass to be sure that the cold finger of our Stirling is strong enough not to crack during launch vibrations. These vibration tests have been performed at the National Space Test Facility, at the Mount Stromlo Campus of the Australian National University (ANU). The qualification test was based on General Environmental Verification Specification (GEVS) standard and yielded compliant results. The inner truncated four-side pyramid (metal) holds the cold filter and the Teflon tube. This pyramid is glued to the SAPHIRA's rim and gets cold from it. The outer pyramid’s base (metal) is glued to the base of the inner one.

10 Optics

Emu optics have been designed such that they will have control over the thermal background and will block the unwanted radiations from all directions, except for light passing through the telescope pupil. This is achieved by re-imaging the telescope’s input pupil at an intermediate pupil plane cold stop. A cold aperture placed in this pupil image will block all the unwanted radiation not coming through the telescope. A set of four relay lenses (antireflection coated) are used to reimage the pupil to the cold stop and subsequently focus the light rays on the detector focal plane. A cold filter along with a science filter close to the detector focal plane will provide the necessary transmission and suppression for Emu. A deuterated potassium dihydrogen phosphate (DKDP)-based filter is used as a cold filter to block long-wavelength thermal emission (see Sec. 11 for details). A ray trace of the optical system is shown in Fig. 17.

The entrance aperture of the optical system is an 83 × 83 mm and the system focal length is 495 mm, yielding a plate scale of 10′/pixel (at the 24 μm pixel pitch of the SAPHIRA eAPD detector). The diagonal FoV is ∼1.2 deg (Fig. 18). The mirrors will be made from low thermal expansion Zerodur material and will be coated with gold for maximum reflectivity at 1.4 μm. The field lenses are of zinc selenide (ZnSe) and zinc sulfide (ZnS) materials. The spatial resolution requirement of the system is 2 pixels FWHM. The distortion of the optical system is less

Fig. 16 IDCA and cold baffle concept layout.
than 0.1%. The axial length of the optical system is around 190 mm, and this restriction is imposed by the 2U volume requirement on the optical unit. The throughput requirement of the optical system is $\sim 80\%$.

11 Thermal Emission Analysis

Emu will be operating in $W_E$ and $J$ bands, and it will be sensitive to the thermal emission from other parts of the instrument. This can be further complicated by two factors: the use of the SAPHIRA detector which has significant long-wavelength quantum efficiency in some modes of operation; and, the likely high telescope operating temperature ($\leq 50^\circ C$). This results in a careful balance of operating requirements for the Emu system. We have developed a thermal model to understand the various contribution of thermal noise to the detector plane.

The SAPHIRA eAPD detector was originally developed for high-speed wavefront sensing with adaptive optics systems. An application in which dark current is not a major concern due to the high frame rate. While device characteristic has improved in later implementation of the
Leonardo eAPD detector family, the SAPHIRA detector available to the Emu project in the early phase has a relatively high dark current of \( \sim 21 \, e^{-} \, s^{-1} \) or \( \sim 1 \) electron per Emu frame (for the flight version we will use SAPHIRA with lower dark current \( \sim 8.4 \, e^{-} \, s^{-1} \)). So for the thermal analysis, a worst-case scenario of dark \( \sim 21 \, e^{-} \, s^{-1} \) current is assumed. This sets a fiducial reference against which to develop the allowable thermal background noise budget for Emu. It is comparable to the assumed effective readout noise of \( \approx 1 \) electron per pixel derived from selecting an avalanche gain setting that maintains sufficient dynamic range while still suppressing intrinsic readout noise.

The thermal model for Emu assumes an uncooled telescope structure at an equilibrium reference temperate of 50°C. The combined warm optical train is assumed to have an effective emissivity of \( \epsilon \leq 0.15 \), based on commercial grade infrared gold coatings for the two telescope mirrors and antireflection coatings on each surface of the four lens elements. Science and short-pass blocking filters are cooled to 150 K resulting in negligible thermal emission in the \( J \) and \( W_{E} \) bands. There is an additional contribution (assumed unit emissivity) from the central obstruction which occupies 12.5% of the pupil in the current configuration. The current optical design includes baffling for the central obstruction in the cold stop structure, ensuring a lower emission temperature for this component. This component is also cooled to 150 K and hence is also negligible when fully masked. The thermal background provides a hard lower limit on the thermal background (with equilibrium temperature and effective emissivity dictated by external design considerations for Emu).

The Emu optical design includes an intermediate pupil image and associated optical stop. As discussed earlier in Sec. 9 and Fig. 16, this cold stop is part of the cooled detector cold baffle and hence blocks thermal radiation from outside the telescope pupil reaching the detector. The cold stop modeled to achieve an equilibrium temperature of 200 K. It remains undecided as to whether the cold stop will be provided with occluding structure to mask the central obstruction, as the performance gain would be marginal due to the current analysis.

A cold short-pass filter is required to block long-wavelength thermal emission (from the detector enclosure and from any low transmission red leak associated with the science filters). The design of conventional interference filters for this role can be challenging due to the possibility of the same transmission overtones the filter is designed to suppress in the primary science filter. A common practice in infrared instrumentation has been to use the crystalline material DKDP. DKDP has high short-wavelength transmission, and fine-tuning the level of deuteration, functionally zero transmission beyond 2.5 \( \mu \)m can be achieved with compromised performance in the transition region 1.8 to 2.5 \( \mu \)m, see Fig. 19 (DKDP filter transmission measurement shown here was done at the ANU Research School of Physics using the FTIR spectrophotmeter in vacuum mode). The DKDP filter will be mounted close to the detector (bonded to the detector carrier plate) to provide wide angle suppression of thermal emission. This optical arrangement is predicted to result in a thermal background of \( \leq 7.5 \, e^{-} \, s^{-1} \) per pixel, of \( \approx 0.3 \) e\(^{-}\) per Emu frame at

![Fig. 19](image_url) The measured DKDP filter transmission profile. It has high short-wavelength transmission and has good suppression beyond 2.5 \( \mu \)m, which is required to realize Emu pass bands.
25 Hz, with the dominant source of thermal background being the direct thermal emission from the optical system in the longer wavelength Emu W$_{E}$-band. This will require experimental verification as it remains a critical performance risk for the Emu system sensitivity.

12 Observation Strategy

The ISS provides a platform for the Emu payload to perform sky surveys in the water absorption band. A relatively wide field zenith-looking telescope with TDI capability can perform the near IR sky survey without active pointing. The detector clock has to be synchronized with the transit speed of ISS. There is a significant field overlap (≈74%) between observations in adjacent orbits. This would enable to shift and stack multiple orbits of data, thereby increasing the sensitivity of the final data product. The field overlap is shown in Fig. 20, and the arrow indicates the moving direction of ISS.

Emu’s commissioning begins soon after Emu is mounted on the ISS platform. The duration of the commissioning period is 4 weeks and it will generate raw data of 7.5 TB. In the first week of commissioning, Emu outgasses itself and the detector will not be operated. All data during this period will be downloaded. In the next 3 weeks, the normal operation will start. The main science operation will begin after the commissioning period. The total data generated during this period will be around 55 TB and with at least one additional data downlink session/week, 0.3% of the data can be downlinked. Emu will perform the astronomical observations only in the dark portion of the ISS orbit. In the default mode, it will acquire images at 50 Hz NDR (25 Hz CDS pairs) and will store the data in the onboard solid-state memory. The raw data rate of Emu is 66 Mbits/s and this corresponds to >300 GB/day. The available downlink rate is around 1 Mbits/s and with only one uplink/downlink session per week available, for 8 h. Emu has an onboard storage module with 60 TB of solid-state memory, to store the data corresponding to 6 months of operation. With the available downlink capability, we will be able to downlink only 1% of this data to Earth for the purpose of quality control and monitoring. The solid-state memory will be returned to Earth for postprocessing when Emu’s 6-month mission is completed.

13 TDI-Like Imaging in the Context of GaiaNIR Mission

GaiaNIR is a new all-sky near IR astrometry mission under consideration by the ESA as a part of its Voyage 2050 future science mission program. One of the significant technical challenges for GaiaNIR is the requirement for low noise NIR detectors which can perform TDI-like imaging.11

![Fig. 20](image-url) The field overlap between successive orbits is shown. The green box corresponds to the FOV in initial orbit and red boxes corresponds to the FOV in the successive orbits with 0.5 s time difference.
Emu will be performing a TDI-like NIR sky survey using the Leonardo SAPHIRA eAPD 320 X 256 detector array. Leonardo MW Ltd. is developing large format 2K × 2K eAPD detector arrays and could be a potential detector for the GaiaNIR mission. The metallicity information derived from the proposed Emu $W_E$-band filter will be useful in interpreting the GaiaNIR data; since no onboard spectroscopy is planned in the latter mission. The Emu simulation suite as outlined in Sec. 5, has been modified, to present TDI-like imaging simulations relevant to the GaiaNIR mission concept. A single 2K × 2K detector, with a pixel sampling scale 0.3″ per pixel and an exposure time of 3.75 ms per frame is assumed for this simulation. The simulation in Fig. 21 is not an actual representative of a the GaiaIR mission, but it shows that the Emu simulation can be modified by changing the input parameters to analyze the sensitivity of TDI-like GAIA NIR mission based on low noise SAPHIRA like eAPD detector arrays.

**Fig. 21** The image shown is a simulation for GaiaNIR like mission based on TDI concept. Star field at the Galactic-anticenter was simulated based on the 2MASS H-band input catalogue. Also shown is the simulated GaiaNIR concept simulation signal-to-noise model.

14 Summary

TDI-like imaging has great potential for NIR observations from space, and this is possible with the low-readout noise and high-speed SAPHIRA detectors. Emu is a proposed mission on the ISS and will demonstrate this key capability in space along with performing an infrared sky survey in a $W_E$-band at 1.4 $\mu$m, inaccessible from the ground. The Emu survey will provide a unique new photometric measurement which, when properly combined in a statistical sense with the full suite of contemporary data, will allow a wide range of questions in stellar atmospheric research to be addressed. The measurement of the critical oxygen-to-hydrogen abundance of both dwarf and giant cool-stars (as probed by their water absorption band) will provide critical new empirical constraints to state-of-the-art astrophysical models. It has the potential to advance not only our observational understanding of the chemodynamical evolution of our Galaxy through the study of its coolest—and most common—stars and their planets but will also facilitate the development of state-of-the-art stellar atmosphere models. Combined with the revolutionary
data released from missions such as the ESA’s Gaia survey, this work enables the powerful development of stellar atmosphere modeling. Also, this mission will be the first in-orbit demonstration of SAPHIRA, elevating its space-readiness to TRL9 along with our Rosella readout electronics. The Emu $W_E$-band survey mission will be the first science program to demonstrate the power of these new devices for astronomy and science in general. The Emu mission passed its Conceptual Design Review in May 2019 and prototyping of critical and high-risk systems is under way.

15 Appendix

A flow chart outlining different processing steps involved in the TDI-like sky field simulator is shown in Fig. 22.

![Flowchart of Emu simulation](image)

**Fig. 22** Flowchart of Emu simulation.

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