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ABSTRACT

While optical and radio transient surveys have enjoyed a renaissance over the past decade, the dynamic infrared sky remains virtually unexplored from the ground. The infrared is a powerful tool for probing transient events in dusty regions that have high optical extinction, and for detecting the coolest of stars that are bright only at these wavelengths. The fundamental roadblocks in studying the infrared time-domain have been the overwhelmingly bright sky background (250 times brighter than optical) and the narrow field-of-view of infrared cameras (largest is VISTA at 0.6 sq deg). To address these challenges, Palomar Gattini-IR is currently under construction at Palomar Observatory and we propose a further low risk, economical, and agile instrument to be located at

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Siding Spring Observatory, as well as further instruments which will be located at the high polar regions to take advantage of the low thermal sky emission, particularly in the 2.5 micron region.

Keywords: Gattini-IR, DREAMS, infrared, all-sky survey, Antarctica, polar regions, Siding Spring Observatory, Palomar Observatory

1. INTRODUCTION

The field of astronomy is enjoying a revolution in expanded opportunities thanks to the advent of more accessible technology. The speed, scope, and ambitions of observing programs have seen dramatic breakthroughs, enabled by nimble all-sky monitoring systems. Single static images have been replaced by rapid, continual observations, allowing astronomers to scan and target dramatic but short-lived events or subtle, varying signals that might have been missed before. The significance of capturing these transient sources is perhaps best exemplified by the discovery of the acceleration of the expansion of the Universe,[1] a result that led to the 2011 Nobel Prize in Physics. In 2017, the Nobel prize in Physics again focussed on the transient Universe when the international Advanced LIGO collaboration announced the first observation of gravitational waves (GW).[2] This facility went on to detect a nearby neutron star (NS) merger with the fortunate orientation to pinpoint its location with relative ease. Observations of this cataclysmic event at infrared wavelengths proved that such events are the forges in the Universe that produce elements such as gold and platinum. Gravitational wave telescopes are at the forefront of enabling next-generation astronomical facilities alongside current optical, radio, and neutrino detection facilities.

By comparison with the optical regime, the transient infrared sky still remains virtually unexplored. Infrared light is a powerful tool for probing transient events in dusty regions that are impenetrable to optical telescopes, as well as for detecting the coolest of stars that emit most of their light in the infrared. Despite the value in pursuing observations in the infrared, until recently, the fundamental roadblocks to studying the infrared sky have been the blindingly bright sky background and the narrow field-of-view of infrared cameras. Infrared transient surveyors and all-sky survey telescopes would greatly assist in the search for infrared counterparts to multi-messenger astrophysical events while also complementing other existing and upcoming surveys, including SkyMapper, the Large Synoptic Survey Telescope (LSST), and the Zwicky Transient Facility (ZTF).

We are planning a sequence of three increasingly ambitious all-sky surveys in the near-infrared (NIR). In order to increase the overall sky coverage and reduce the initial outlay and deployment time, different versions of all-sky infrared surveys will be constructed. Palomar Gattini-IR is currently under construction at the California Institute of Technology (Caltech) for deployment at Palomar Observatory, California, USA; the Dynamic REd All-sky Monitoring Survey (DREAMS) is currently under development for deployment at Siding Spring Observatory, New South Wales, Australia; and there are further plans to deploy other versions, currently known as Turbo Gattini-IR, in the polar regions.

Figure 1 shows the Manua Kea Observatories (MKO) filter specifications which are currently the standard photometric system in the NIR. Beginning with Palomar Gattini-IR with a single J-band filter, increasing to Y, J, and H filters for DREAMS, and further increasing to Y, J, H, and $\mathrm{K_{DARK}}$ for Turbo Gattini-IR, these survey telescopes will systematically cover the entire NIR. Turbo Gattini-IR will use the $\mathrm{K_{DARK}}$ filter instead of the Ks filter shown in Figure 1; $\mathrm{K_{DARK}}$ is a filter specifically used at Antarctic locations, centered around 2.3µm, which takes into account specific site conditions relevant to polar regions.

Each of these different telescopes with different filters, different locations, and different survey speeds will cover a wide range of different time scales and a large sky coverage.

2. SCIENCE CASES

An infrared transient and all-sky surveyor will open up areas of transient related science that are currently unable to be explored by current facilities. Optical and radio instruments are blind to transients that are either self-obscured or located in dusty regions (e.g., molecular clouds, dense starburst regions). There is also now a class of explosive transients, known as SPRITEs (eSPecially Red Intermediate Luminosity Transient Events)[4] which do not have optical counterparts. We also know that a large fraction of luminous stars are self-obscured as they

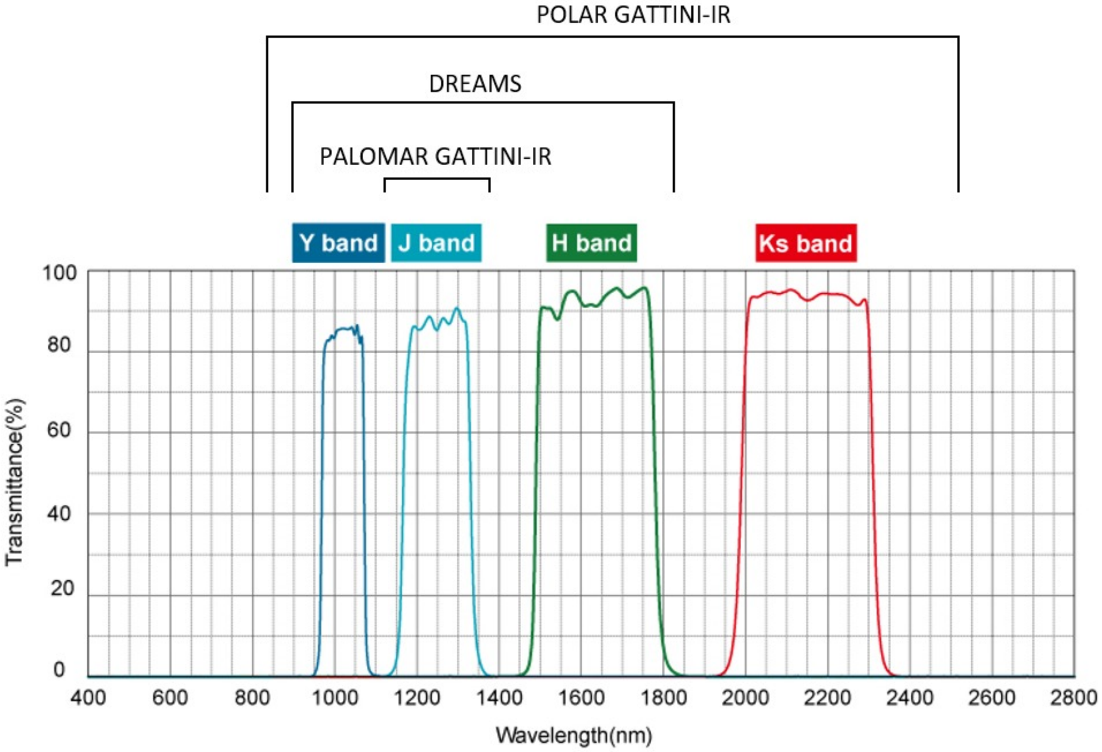


Figure 1: Near-infrared Maunakea Observatories filters, showing the different filters that will be used; modified version of Asahi Spectra filters.[3]

are intrinsically unstable due to radiation pressure and/or copious mass-loss and circumstellar dust formation. Moreover, opacity calculations[5] suggest that the spectra of electromagnetic counterparts to gravitational wave sources such as neutron star mergers peak in the infrared.

Each infrared all-sky and transient surveyor provides distinct advantages which lead to wide and varied science cases. We give brief details on three science cases below, and list a further 20 that our collaborators have proposed, ranging from solar system objects to high ($z \sim 7$) redshifts.

2.1 Multi-messenger Astrophysics

Recent discoveries of both gravitational waves and electromagnetic radiation from a neutron star merger marked the dawn of a new era in multi-messenger astrophysics.[6] GW170817 lit up the entire electromagnetic spectrum, spanning gamma-rays to radio, and for the first time, we saw possible evidence of r-process nucleosynthesis, the process by which half the elements in the periodic table heavier than iron are synthesized. Heavy elements span atomic mass numbers between 60 and 250 with several elements filling the electronic d- and f-shells. Owing to the large number of line transitions, the opacity is very high and the emission from their radioactive decay gets shifted out of the optical bands and into the infrared (IR) bands.[7] Therefore, the key to understanding the nucleosynthesis is in characterising the IR data.

This first discovery opens up many questions for future discoveries to answer. Are NS-NS mergers the only sites of r-process nucleosynthesis? Do NS-NS mergers produce heavy elements in the same relative ratio as seen in the solar neighbourhood? Are the heaviest elements in the third r-process peak synthesised, such as gold and platinum? Which elements are synthesized when a NS merges with a stellar mass black hole (BH)?

Most current models predict that the bright optical emission seen will be hostage to several parameters as illustrated in Figure 2.[7] They predict that the optical emission will be suppressed if: (1) the mass ratio is large

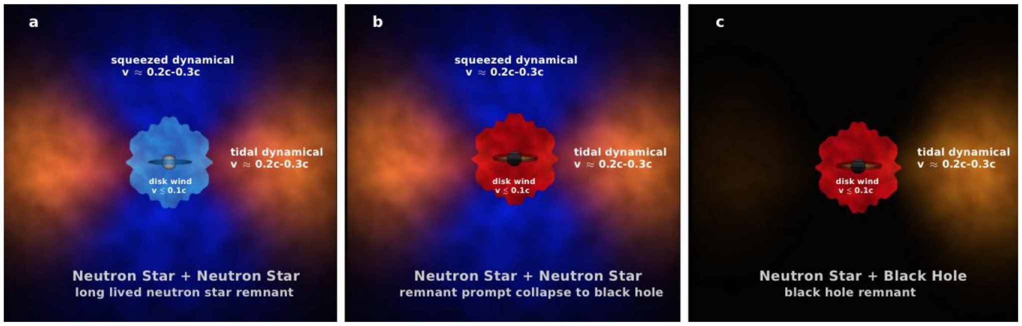


Figure 2: Schematic depicting electromagnetic counterparts to NS mergers, with heavy r-process IR emission (red) and light r-process UV/optical emission (blue). Isotropic emission in the IR would be more likely to be observed than orientated UV/optical emission.[7]

as in NS-BH mergers, or (2) the viewing angle is more equatorial, or (3) the velocities are lower, or (4) the opacity is higher, or (5) the remnant lifetime of the hyper-massive NS is relatively short.

Even if optical emission is present, it decays on day timescales. On the other hand, bright infrared emission from radioactive decay of heavy elements is expected to be ubiquitous and independent of geometry, opacity, remnant lifetime, and mass ratio.[7] NS-BH mergers are predicted to have even more ejecta mass and hence, even more luminosity, in the infrared than NS-NS mergers. Moreover, the IR emission decays on week timescales. Thus, a systematic search for the electromagnetic counterpart to the full sample of NS-NS and NS-BH mergers can only effectively be undertaken in the infrared.

The major roadblock in undertaking a systematic multi-messenger census is the lack of wide-field IR survey capability that matches the scale of the coarse GW localizations (tens of square degrees with three advanced GW interferometers). Our infrared instruments are designed to provide the capability to detect the infrared counterparts to these events.

2.2 RR Lyrae Stars

During the epoch of assembly of large disk galaxies, the turbulent velocity of the gas in the disks was falling with time, as first the thick disk formed 10 to 12 Gyr ago, and then the thin disk presumably began to form as the turbulent velocity became lower.[8] RR Lyrae (RRL) variable stars are ideal for probing the dynamics and chemical properties at this epoch of disk assembly (redshifts $z = 0.8$ to 3) as they are very old stars (8 to 13 Gyr), and their characteristic light curves make them easy to recognise against the background of younger disk stars at low Galactic latitudes.

Old RRL stars have been found in small numbers in the thin and thick disk, but have not yet been used as probes of the early phase of disk formation due to the difficulty in observing such a large area at infrared wavelengths. The extinction from dust in the plane of the Galaxy is low at 1.65 µm (0.17A(V)). The light curve amplitudes for the common RRL variables are about 0.3 magnitudes, with periods mostly between 0.4 to 0.8 days, which, when combined with the low extinction, makes them easy to detect. Thus in the infrared we will find RRL stars in the old thin disk and thick disk out to distances of at least 5 kpc.

2.3 Fast Radio Bursts

A new class of millisecond-duration radio transients, termed fast radio bursts (FRBs), has been discovered,[9] but the cause of the bursts is unknown. FRB radio dispersion measures (i.e., frequency-dependent arrival time) and sky distribution strongly indicate extragalactic origins out to high redshift.[10] FRB dispersion measures can be used as a powerful tool to probe and measure the ionised baryons in the intergalactic medium out to high redshift and to understand compact source physics producing such immense energies. To date, no shorter-wavelength FRB counterpart has been found in conventional follow up programs, as they are expected to evolve very quickly.

The Deeper, Wider, Faster (DWF) program[11] coordinates a new proactive approach that enables the detection of fast transients with millisecond-to-hours durations and resolves previous obstacles to FRB counterpart detection. DWF uses over 40 telescopes worldwide and in space to perform simultaneous fast cadenced, wide-field, multi-wavelength observations and real-time supercomputer data processing for fast identification and follow-up. However, there is a gap in this coverage due to the lack of wide-field infrared telescopes and our telescopes will provide a key capability to search for FRB counterparts and fast transients, as many are predicted to be most luminous in the infrared. Another benefit of wide-field infrared instruments is that FRB fields are often located near the Galactic plane, as they piggy-back surveys searching for pulsars that are located there, meaning that the FRB fields are largely impenetrable at optical wavelengths.

2.4 Additional Science Cases

These surveys will also enable further science cases that will allow us to answer a multitude of questions. This is a non-exhaustive list and it is expected that other yet as unknown questions will also be answered.

- Albedo determination of Near Earth Objects
- Long term monitoring of Miras & AGB stars
- Cepheid Variables in the Disk and Bulge
- Mass Loss in Wolf Rayet Carbon Stars
- Brown Dwarf Weather and Companions
- Detecting flares on M dwarf stars
- Detection of post-transient compact binaries
- Low surface brightness detection in NIR
- Outflows and jets from super-Eddington BHs and NSs
- Testing Shock-Dust mechanism in Novae
- Stellar Mergers and Common Envelope Transients
- Obscured outbursts of luminous blue variables
- e-capture Supernovae from extreme AGBs
- Stellar mass black holes from failed Supernovae
- Obscured Supernovae and cosmic star formation rate
- Infrared-Radio Synergies
- Cosmology with Type Ia Supernovae
- Superluminous Supernovae to high redshift (to $z \sim 1$)
- Quasar Variability in the infrared
- High redshift Quasar detection (z=7 to 9)
- High energy neutrino follow up (IceCube data search)

Table 1: Palomar Gattini-IR Specification

Palomar Gattini-IR	
Telescope Aperture	300mm
Telescope F/ratio	1.44
Field of view	25 sq. degrees
Filter	2MASS J Band
Detector type	Teledyne Hawaii 2RG
Pixels per array	2048x2048
Pixel Size	18 µm
Plate scale	8.59 arcsec
Survey depth	16.4 M_{AB}
Survey speed	24 hours

3. PALOMAR GATTINI-IR

Palomar Gattini-IR[12] is an ultra-wide field infrared telescope that will be located at the historic Palomar Observatory. This instrument has an aperture size of 300mm and a capture field of 25 square degrees; the full specifications of Palomar Gattini-IR are shown in Table 1. The system operates in the J band, at a wavelength of 1.25 µm, where the near-infrared sky is darkest from this temperate location.

3.1 Current Status

The telescope mount, the 10Micron GM3000 HPS, that will be used for Palomar Gattini-IR has been delivered; the survey scheduling software and fully robotic operations have been successfully tested using an optical camera. Figure 3a shows the tracking mount with a simulated payload, while Figure 3b shows the the tracking mount, levelling mount, and pier.

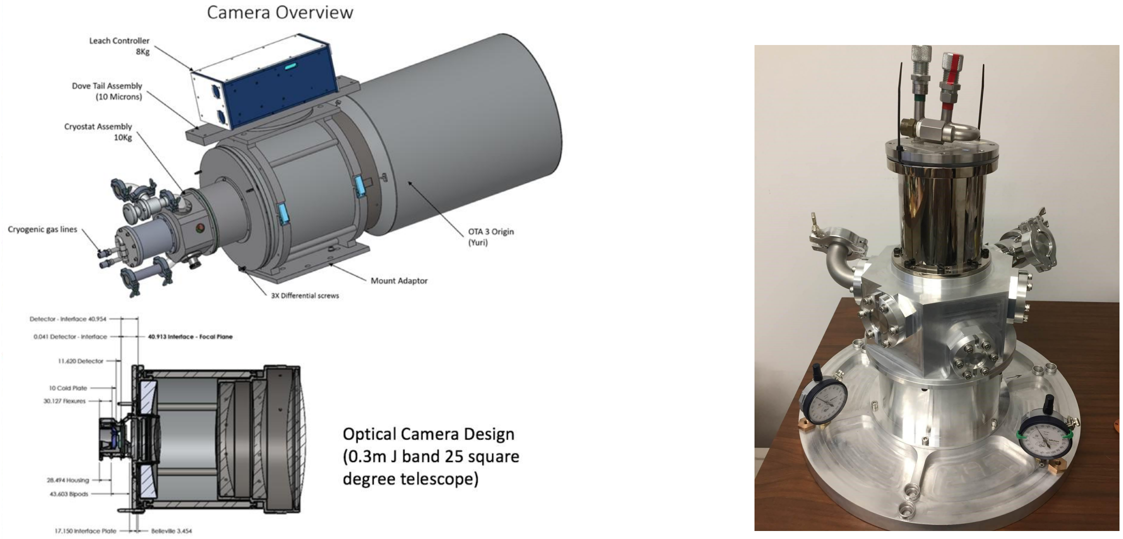
The optical telescope assembly (OTA) has been delivered by Telescope Engineering and integrated with the GM3000 mount, this setup was tested on sky from the roof of the Cahill Centre for Astronomy and Astrophysics at Caltech with an optical camera.

A 3D model of the infrared detector, cryostat, and optical telescope assembly is shown in Figure 4a and an image of the assembled cryostat is shown in Figure 4b; the cryostat has been cooled and pressure was successfully maintained.

(a) Telescope mount with a simulated payload.

(b) Telescope mount.

Figure 3: Palomar Gattini-IR telescope mount



(a) Mechanical schematic of the cryostat and OTA for Palomar Gattini-IR.

(b) Cryostat.

Figure 4: Palomar Gattini-IR cryostat

The development of the data reduction pipeline (DRP) for Palomar Gattini-IR is ongoing, the final pipeline will provide an automated image processing pipeline, image differencing, and an automated transient source identification.

4. DREAMS

The Dynamic REd All-sky Monitoring Survey (DREAMS) is a fully automated, 0.5m aperture, Y (1µm), J (1.25µm), and H (1.65µm) band custom designed telescope and camera combination. The telescope will be housed in the UNSW Automated Patrol Telescope building at Siding Spring Observatory. DREAMS consists of the following components as shown in Figure 5 (i) an optical telescope assembly; (ii) a six-channel infrared camera module; and (iii) a tracking mount, pier, and levelling support. The facility also includes automation hardware and software that is based on heritage from other systems and a sophisticated data reduction pipeline. The DREAMS optical design produces sub-pixel imaging performance across its entire field. Each of the six channels images a slightly different patch of sky, and has a configurable Y, J, and H band filter, offering maximum configurability at low cost. The precision of broadband IR photometry with current technology depends on photon statistics. The 2MASS JHK point source survey provides an ideal network of photometric and astrometric stars for the DREAMS wide-field instrument.

Table 2 details the current specifications of DREAMS, the baseline survey for DREAMS covers the entire accessible Southern Sky (15,000 square degrees) over three nights at 1.65 µm. The survey speed refers to the amount of time required to cover the visible sky at any instant.

4.1 Design

4.1.1 Optical Telescope Assembly

The optical design of DREAMS, shown in Figure 6, consists of a 0.5m telescope with primary hyperboloid (M1) and aspheric secondary (M2) and two spherical corrector lenses (L1/L2). Each camera relay contains 9 lenses (RL1-RL9), two interchangeable filters and the detector vacuum window, and converts the F/5 telescope beam to the required F/2 beam onto the detector. The optical design produces constant illumination across the six channels and allows each set of filters for each camera relay to be changed independently.

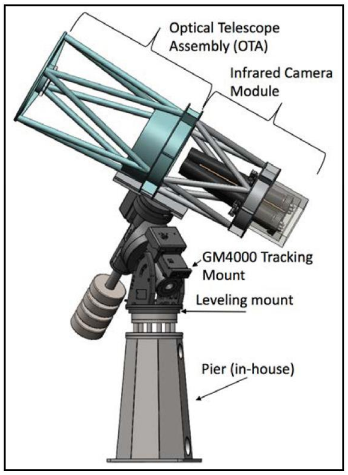


Figure 5: DREAMS

Table 2: DREAMS Specification

DREAMS	
Telescope Aperture	500mm
Telescope F/ratio	2.0
Field of view	3.75 sq. degrees
Filter	Y, J, H Band
Detector type	6x Princeton SCICAM InGaAs
Pixels per array	1280x1024
Pixel Size	12 µm
Plate scale	2.48 arcsec
Survey depth	17.8 MAB
Survey speed	24.7 hours

4.1.2 Detector

DREAMS will use 6x Princeton SCICAM1280 Indium Gallium Arsenide (InGaAs) units, shown in Figure 7; the SCICAM1280 InGaAs unit from Princeton Infrared Technologies is an off-the-shelf unit with an in-built cooling system, controller, and software for a fraction of the cost of traditionally used Mercury-Cadmium-Telluride (HgCdTe) arrays. InGaAs cameras are traditionally not selected for astronomical projects due to their higher read noise, however for the case of the F/2 DREAMS, the sky noise in every pixel is sufficiently large that the

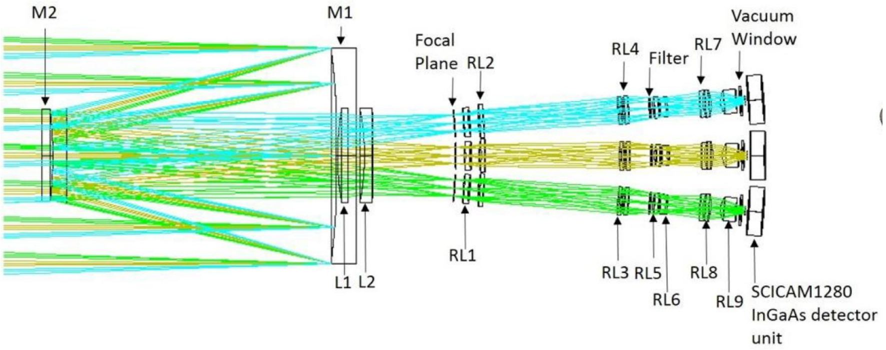


Figure 6: Optical design of DREAMS.

Figure 7: Princeton 1280SCICAM InGaAs Science Camera.

higher read noise detector unit can be implemented with no degradation in performance. Recent test observations made with an InGaAs prototype astronomical camera have shown that they are capable of delivering sky-photon limited noise performance.[13] These InGaAs detectors are suitable for use for observations to just under 1.7µm in the H band, which is shorter than the atmospheric window however they still provide a sufficient window for the science cases.

Combining these off-the-shelf detectors with the unique design of the optical telescope assembly ensures that DREAMS will be able to achieve the required performance without cryogenic housings and additional controllers, that are required for HgCdTe arrays, thus decreasing the overall complexity of DREAMS.

4.1.3 Telescope Mount

DREAMS requires a tracking mount with a minimal reconfiguration time given that infrared detector arrays can be read out in milliseconds, while the speed of the tracking mount implies that DREAMS can outperform other large telescopes when scanning the sky in the infrared. Figure 8 is an example of a custom mount produced by Optical Mechanics, Inc (OMI) that is similar to the mount that will be used for DREAMS and provides a two second reconfiguration time, which corresponds to a dead time of only 10%.

4.1.4 Data Reduction Pipeline

The DREAMS data reduction pipeline (DRP) is a critical component of the facility and will be a robust, high fidelity data reduction pipeline that maximizes the science potential of DREAMS. The DRP will consist of two main components, a real-time transient detection pipeline and a legacy image archive and light curve archive with precision photometry.

The real-time transient detection pipeline will have the following components: (i) de-trending including dark subtraction and flat-fielding,(ii) optimal background subtraction implementing a double pass, (iii) astrometric solution with respect to GAIA, and precise stacking of dithered frames, (iv) photometric solution relative to the 2MASS catalogue, (v) co-addition of high-quality images to construct references, (vi) image differencing using

Figure 8: Custom tracking mount by Optical Mechanics, Inc

the mathematically optimal ZOGY[14] algorithm, (vii) transient source identification and aperture photometry on the difference image, (viii) machine learning to distinguish between detector artefacts and astrophysical sources, and (ix) a database and web portal to organize follow-up of sources by various panchromatic telescopes around the world.

The legacy archive will serve the following products with an interactive user interface, (i) raw images, (ii) reduced images with end-of-night calibration products, (iii) deep, weighted, stacked images at each location, and (iv) light curves with precise relative and absolute photometry enabling various avenues of science.

4.2 Comparison

The specifications and performance of DREAMS, as shown in Table 2, combined with the different aspects listed above means that DREAMS will provide a capable infrared transient and all-sky surveyor which is capable of outperforming any previous infrared survey; Table 3 and Figure 9 show the performance of DREAMS in comparison to other infrared surveys.

Table 3: Comparison of infrared surveys.

Survey	Field of view	Telescope aperture	Location	Survey Speed
	sq degrees	m		sq degrees / hr
DREAMS	3.75	0.5	Siding Spring (Australia)	336
2MASS	0.02	1.3	Cerro Tololo (Chile)	36
UKIRT WFCAM	0.2	3.8	Mauna Kea (Hawaii)	26
VISTA VIRCAM	0.6	4.1	Cerro Paranal (Chile)	18
CFHT WIRCAM	0.13	4	Mauna Kea (Hawaii)	17
AST3-NIR (KISS)	0.08	0.5	Dome A (Antarctica)	16

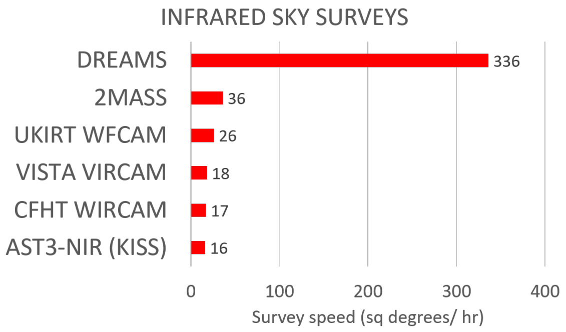


Figure 9: Comparison of infrared survey speeds.

5. POLAR REGIONS

Turbo Gattini-IR is a proposed instrument that would take advantage of the colder atmosphere at a polar location such as Ellesmere Island in the High Arctic, or the South Pole station in Antarctica, where the atmospheric thermal emission is shifted red-ward enough to reveal a very low sky background at 2.4µm. The current design of Turbo Gattini-IR is shown in Figure 10, and initial specifications are shown in Table 4, the design incorporates 4 x 0.5m identical aperture barrels to greatly increase the field of view of the instrument to 100 square degrees at a lower cost.

In comparison to another near-infrared southern hemisphere survey, the VISTA Hemisphere Survey (VHS), which took 600 hours to survey an area of 18,000 square degrees down to $20\mathrm{M}_{\mathrm{AB}}$, Turbo Gattini-IR will be capable of surveying an area of 15,000 square degrees down to $23.4\mathrm{M}_{\mathrm{AB}}$ in 2 hours.

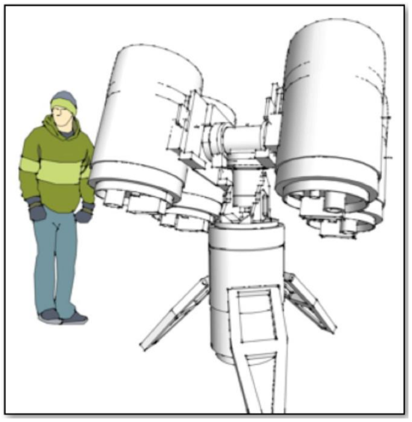


Figure 10: Turbo Gattini-IR

Table 4: Turbo Gattini-IR Specification

Turbo Gattini-IR	
Telescope Aperture	4x 500mm
Telescope F/ratio	2.0
Field of view	100 sq. degrees
Filter	Y, J, H, K
Detector type	4x H4RG or equivalent
Pixels per array	4096x4096
Pixel Size	12 µm
Plate scale	1.38 arcsec
Survey depth	23.4 MAB
Survey speed	2 hours

6. SUMMARY

We present a series of current and future infrared transient surveyors and all-sky surveys, each instrument will be able to survey the observable sky every 3 days or less down to a minimum of 16.4 M_{AB}. These instruments will allow us to conduct time-dependent observations as well as providing the capability for extremely rapid follow up to multi-messenger events. Palomar Gattini-IR is scheduled to be on-sky by the end of 2018 and initial construction of DREAMS will also begin by the end of 2018.

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