1 Title: A VISTA/VIRCAM survey for kilonova counterparts to gravitational wave sources

VINROUGE / VIsta Near-infraRed Observations Unveiling Gravitational wave Events

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1.1 Abstract

This public survey will conduct near-infrared follow-up imaging of the error regions for gravitational wave (GW) detections. Specifically we will target events for which the GW analysis suggests they are likely due to a merger of a compact binary including at least one neutron star. Such systems are also expected to give rise to r-process kilonovae/macronovae, with spectral energy distributions peaking in the near-IR in the days following the merger. Detection of an electromagnetic (EM) counterpart would trigger considerable further follow-up, providing the route to the redshift and host environment, and heralding a new era of GW+EM astrophysics.

Our strategy will evolve with our improving understanding of kilonova behaviour, and will also be tailored to the parameters of each event. In particular, if the 90% error region is more than $\sim$50 sq-deg in extent, only a subset of the total error region will be imaged, prioritised based on convolving the density field of nearby galaxies with the GW likelihood map. As the GW network improves, the average positional error regions will reduce in size (reasonable numbers expected with $<$20 sq-deg) and the horizon distance increase. Although the rate of neutron star merger systems is not yet well constrained, if there are sufficient events we will prioritise favourable cases, for instance where the distance is thought to be $<$ 100 Mpc. Our baseline plan is to image in three filters in the first visit (YJKs) and one filter (J) in a repeat epoch to help search for variability. Typically we expect to reach mag J(AB)$\sim$ 21.

Our total time request is 420 hr, nominally for up to ten triggers, likely resulting in $\sim$ 300 sq-deg coverage. At the PSP request, we will provide ESO with a review of the progress and update on the observing strategy after five triggers. Observations will be tied to the primary science runs of the GW network: provisionally the second science run is expected to be ongoing at the start of the survey, ending in mid-2017; the third science run is expected to begin late 2017 and last about 9 months, and the fourth to start in early 2019. Subsequent runs are not yet planned in detail, but it is likely that the duty cycle will increase with time, and certainly will provide good prospects for completing this programme by the beginning of 4MOST installation. Given the nature of the survey, we do not apply any restrictions on observing conditions, although it may be that particularly bad

conditions over multiple nights may render it unfeasible to perform the planned follow-up of a given event.

Currently the GW-EM follow-up community is still bound by its confidentiality agreement with the LIGO-Virgo Collaboration (LVC). In this regard, even the fact that a follow-up trigger has occurred potentially represents an unwanted leak of information. However, the baseline expectation is that this will be lifted after the first four GW detections have been announced (at the time of writing there are two from the first science run), and so it is likely that that these restrictions will have been partially or fully lifted by the start of our survey. A remaining complication is that it is still undecided whether there may be additional restrictions associated specifically with neutron star events, particularly how much information about the triggers will be publicly released. At this stage we therefore do not ask for any special treatment for our public survey in this regard, although if this becomes an issue in the future, we will discuss with ESO the possibility of, for example, a short proprietary period if that would give sufficient time for the LVC to make their public announcement.

2 Survey Observing Strategy

As a target-of-opportunity programme, our campaign necessarily must operate in a rather distinct way. The procedure, which has been trialled in pilot programmes in normal time, is that a range of OB templates will be pre-defined in Phase 2, allowing for flexibility in observing strategy on an event by event basis. At the time of triggering, we will use the SADT to perform the tiling for the error region of the given gravitational wave detection. Where possible we will use the same field centres as used for the VHS (or other VISTA survey data, if available) in the relevant region of the sky. This defined survey area (the XML file output from SADT) will then be forwarded to the service observers at the telescope and combined with requested OB templates to create the actual survey OBs.

For the second epoch observations, typically expected to be one to two weeks after the first, it will generally be possible for us to create and submit the final OBs ourselves.

The imaging obtained under this programme will be useful for other variability searches, particularly of the high latitude sky, and will provide somewhat deeper imaging for regions of the sky currently covered only by the VISTA Hemisphere Survey (VHS). The survey does not require any protected targets, but on occasions our survey area may overlap with protected targets from other surveys, which we presume would not be a problem, given that our data will also be public, and in any case relatively shallow.

2.1 Scheduling requirements

Observations will be tied to the primary science runs of the GW network: provisionally the second science run should be ongoing at the start of period 99, running until mid-2017; the third science run is expected to begin late 2017 and last about 9 months; and the fourth to start in early 2019. Subsequent runs are not yet planned in detail, but it is likely that the duty cycle will increase with time. There may also be periods of engineering runs when triggers on bright events may still occur. Given this, and the stochastic nature of our targets, we request flexibility in distributing observing time amongst the periods. The figures in Table 1 therefore represent a plausible split of time only.

When triggers occur we have found a response time of 24-48 hr is possible for the first observations to be made, and this generally fits in well with the few day brightening time expected for kilonovae/macronovae.

2.2 Observing requirements

As indicated in Table 1, the instrumental requirements for our survey are likely to be fairly standard YJKs imaging, although exact requirements will vary from event to event, and the strategy is likely to evolve over the course of the campaign reflecting the changing capabilities of the GW network, and our developing understanding of the kilonova/macronova sources we are searching for.

Table 1: Representative scheduling plan and observing requirements, subject to the stochastic occurrence of triggers, and the possible changes in the timetable of GW science runs.

Period	Target name	RA	DEC	Filter setup	Tot. exp. time [hrs]	Tot. exec. time [hrs]	Seeing/FLI/ transparency
P99	GW events	Any	$< +40$	YJKs	18	30	Any
P100	GW events	Any	$< +40$	YJKs	45	75	Any
P101	GW events	Any	$< +40$	YJKs	60	100	Any
P102	GW events	Any	$< +40$	YJKs	30	50	Any
P103	GW events	Any	$< +40$	YJKs	60	100	Any
P104	GW events	Any	$< +40$	YJKs	40	65	Any

3 Survey data calibration needs

No special calibrations are required. The J and Ks band observations will be tied photometrically to 2MASS, whereas the Y band calibration will be assumed based on extrapolation of 2MASS to the Y band found by Hodgkin et al. (2009), subject to possible improvement if a better calibration is available for particular sky regions.

From the point of view of the primary science, requirements for absolute photometric calibration are not stringent, since we are initially looking for variability between images.

4 Data reduction process

The initial pipelining will be done at CASU following well established procedures built into the VISTA Data Flow System (VDFS) for producing calibrated imaging and source catalogues, as illustrated in Figure 1. The requirement for rapid analysis means that we must have a "fast" reduction pipeline, as well as a "slow" pipeline for highest quality data reduction. In the case of the "fast" reduction, calibration frames (flat fields etc.) will be the best available, but may be non-optimal; in O1 we were able to produce these fast data products within ~ 72 hr of the data being obtained at the telescope, and hope to improve on this. The "slow" pipeline will use the standard updated calibrations, and its output will be what is delivered to the archive and form the basis of the Phase 3 data-products.

Once calibrated images are available, we will perform a transient search for new point sources by comparison with available prior imaging (Figure 1). In parallel we will run (a) an automated pipeline based on image subtraction, with (b) an eyeball search, focussing particularly on known galaxies in the likely distance regime. The eyeball search may have some advantages, particularly for sources that are superimposed on complex regions of their host galaxies, and will also provide an additional cross-check on the automated search. Our experience to date suggests that the automated search also requires significant human oversight and validation to remove spurious sources. Once our second epoch is obtained, we will similarly search for variability between the two epochs, and compute provisional light curves for any sources that have already been identified.

Final photometry for candidates will usually be done "by hand" given the likelihood that they will often be point sources overlying a host galaxy, with potentially complex substructure. Depending on the particular source we may use a variety of software to model the background, and obtain either aperture or psf-fitting photometry as appropriate for the transient point sources.

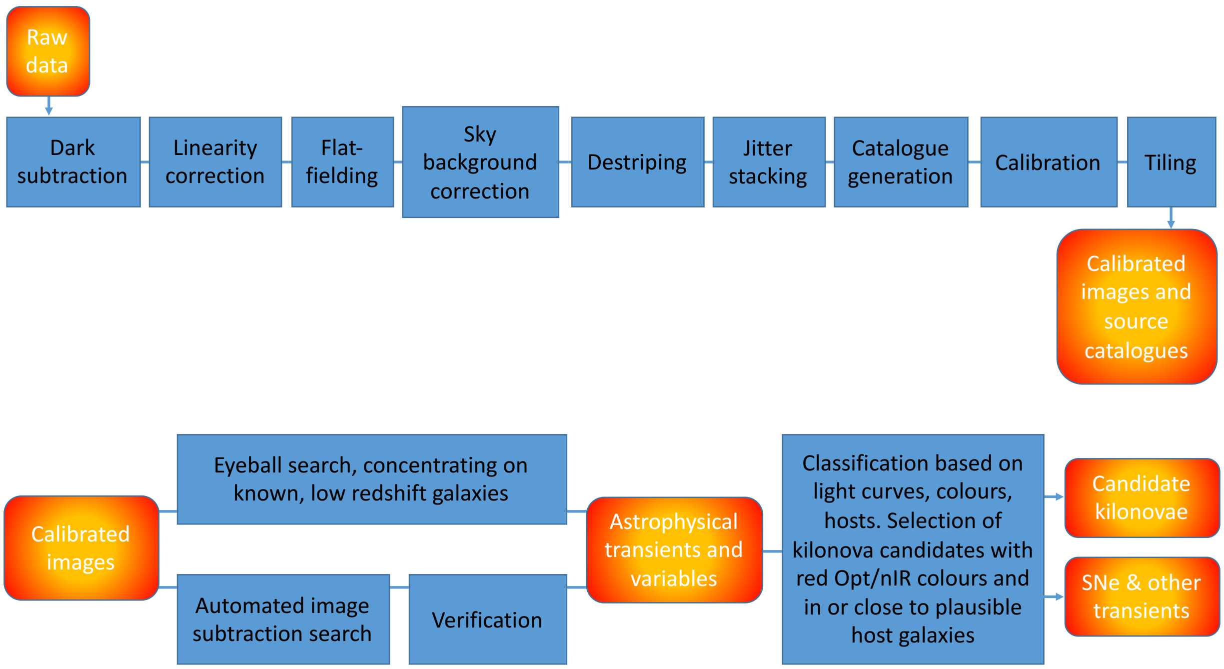

Figure 1: A block diagram illustrating [top:] basic reduction steps to be performed at CASU using the standard VDFS pipeline (run initially with provisional calibrations for rapid transient searching, and subsequently with standard calibrations for production of final data products); and [bottom:] our parallel strategy of automated and manual searches for identifying astrophysical transients, and hence candidate kilonovae.

5 Manpower and hardware capabilities devoted to data reduction and quality assessment

Our team is necessarily a large one, as shown in Table 2, due to the requirement to coordinate with numerous other surveys and follow-up campaigns. The effort in terms of the VISTA Public Survey will largely be borne by the people indicated at the top of Table 2. In-house routines to assist with the survey definition and transient pipeline are already in place from our experience with the pilot project, although we will work to make these more sophisticated and robust.

6 Data quality assessment process

Since our survey is target-of-opportunity driven, there will generally not be a chance to repeat observations at a later time unless problems are identified on the night, and so necessarily we will have to work with the images as they are first acquired. For this reason we have no specific quality control requirements, beyond accurately reporting basic observational parameters (seeing, depth etc. as derived from the standard VDFS analysis), and flagging regions/frames of poor quality. In the situation where a second, comparison epoch is obtained which turns out to be significantly inferior to the initial epoch, then in those circumstances observations may be repeated.

Table 2: Allocation of resources within the team, including (lower part) coordination with other surveys and of follow-up programmes (FTE allocation only recorded against roles specifically associated with this programme, rather than further follow-up, coordination with other surveys etc.)

Name	Function	Affiliation	Country	FTE on project
N. R. Tanvir	PI; Phase 2; OPC report; Science exploitation	University of Leicester	UK	0.5
A. J. Levan	Transient ID	University of Warwick	UK	0.2
S. Rosetti	Transient ID, exploitation	University of Leicester	UK	1.0
B. Milvang-Jensen	Observation planning	University Copenhagen	Dk	0.1
E. Rol	Tiling strategy	University of Monash	Aus	0.1
K. Ulaczyk	Transient pipeline	University of Warwick	UK	0.2
K. Wiersema	GCNs; Phase 3	University of Leicester	UK	0.3
M. J. Irwin	Data pipeline	University of Cambridge	UK	0.1
C. Gonzales Fernandez	Data pipeline	University of Cambridge	UK	0.2
A. Yoldas	Data pipeline	University of Cambridge	UK	0.1
E. Gonzalez Solares	Data pipeline	University of Cambridge	UK	0.1
J. Lyman	SN ID and reporting	University of Warwick	UK	
D. White	Galaxy catalogues	University of Edinburgh	UK	
D. Perley	Host analysis	University Copenhagen	Dk	
P. Sutton	LIGO/VIRGO coord	University of Cardiff	UK	
S. Fairhurst	LIGO/VIRGO coord	University of Cardiff	UK	
I. Mandel	LIGO/VIRGO coord	University of Birmingham	UK	
R. G. McMahon	VHS coord	University of Cambridge	UK	
J. Hjorth	NOT coord	University Copenhagen	Dk	
J. P. U. Fynbo	NOT coord	University Copenhagen	Dk	
D. Malesani	NOT coord	University Copenhagen	Dk	
D. Watson	Wider strategy	University Copenhagen	Dk	
J. C. Greiner	GROND coord	MPE	DE	
T. Kruehler	GROND coord	MPE	DE	
E. Pian	VLT coord	Scuola Normale Superiore Pisa	It	
E. Palazzi	VST coord	INAF - IASF di Bologna	It	
D. Steeghs	GOTO coord	University of Warwick	UK	
S. Schulze	Gemini coord	Pontificia Univ. Catolica Chile	Chile	
Z. Cano	Gemini coord	Inst. Astrofisica de Andalucia	Sp	
A. Ugarte-Postigo	GTC coord	Inst. Astrofisica de Andalucia	Sp	
C. T. Thöne	GTC coord	Inst. Astrofisica de Andalucia	Sp	
C. Copperwheat	LT coord	Liverpool JMU	UK	
P. A. Evans	Swift coord	University of Leicester	UK	
J. P. Osborne	Swift coord	University of Leicester	UK	
P. T. O'Brien	Swift coord	University of Leicester	UK	
A. Rowlinson	Radio survey coord	Univ. Amsterdam & ASTRON	NL	
S. Rosswog	Theory	Stockholm University	Swe	

7 External Data products and Phase 3 compliance

A key aspect of our survey is the necessity for us to report candidate electromagnetic counterparts quickly enough that further followup (spectroscopy, deeper imaging etc.) can be obtained. These reports will be sent primarily via the LIGO-Virgo Electromagnetic Followup Consortium (LV-EM) GCN system. At the time of writing, this system remains restricted to groups holding MoU agreements with the LIGO-Virgo Consortium (LVC), being made publicly available after the relevant GW result itself is announced. The expectation is that the system will be made public in the future. Indeed, the original memoranda specified that the public phase would begin after publication of the first four confirmed GW events, making it likely to occur near the beginning of our survey. Some transients, particularly candidate supernovae, will also be announced via ATels.

We will submit as Phase 3 products, the imaging tiles and pawprints, associated confidence maps and catalogues produced by the "slow" VDFS pipeline reduction, described above. Light curves for sources identified as the same source through positional cross-matching will be included. We will also submit a Phase 3 compliant summary catalogue of the ($> 10\sigma$) transient/variable sources identified for each trigger. The latter will include the photometry we have obtained from the VISTA observations, namely point-source magnitudes and errors (or limits where undetected) at each visit in each filter, including from any prior reference epoch of pre-existing imaging. For cases where a host galaxy is identified, we shall supply coordinates and estimates of the total host magnitudes from the VISTA imaging, and aperture matched colours. Since in most cases there will be at most two new visits to the same area of sky, deep stacking will not be relevant.

Linked information from other non-VISTA observations, where appropriate and available, including more fully-sampled light curves, photometry in other wavebands, spectra, and source identification where that has been ascertained, will be made available through the project web site. For events that remain good candidate counterparts after follow-up, we will submit these ancillary data as Phase 3 products.

8 Delivery timeline of data products to the ESO archive

Our intention is that final delivery of standard VDFS imaging and source catalogue products, together with the separate catalogue of transient/variable point sources, will be done within six months of the end of each period. Given that imaging will be taken in a variety of conditions, parameters such as seeing and depth reached will depend on circumstances. In order to allow us to synthesise VISTA data with data from other sources, we propose an annual release of our final catalogue of transient sources identified in our campaign of targeting candidate GW counterparts (this in addition to real-time communications of provisional results through GCNs).

At the request of the PSP, we will provide ESO with a review of the progress and update on the observing strategy after five triggers.