Memo 1

An ASKAP Survey for Variables and Slow Transients

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and the VAST Collaboration

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An ASKAP Survey for Variables and Slow Transients (VAST)

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Summary

ASKAP will give us an unprecedented opportunity to investigate the transient sky at radio wavelengths. Its wide-field survey capabilities will enable the discovery and investigation of variable and transient phenomena from the local to the cosmological, including flare stars, intermittent pulsars, X-ray binaries, magnetars, extreme scattering events, intra-day variables, radio supernovae and orphan afterglows of gamma ray bursts. In addition ASKAP probes unexplored regions of phase space where new classes of transient sources may be detected. We propose a comprehensive program based on a multi-tiered survey strategy to characterise the radio transient sky through detection and monitoring of transient and variable sources.

The science goals for our survey are:

- to determine the origin and nature of the structures responsible for extreme scattering events;
- to provide a direct detection of baryons in the intergalactic medium;
- to detect and monitor 'orphan' gamma-ray burst afterglows to understand their nature;
- to conduct an unbiased survey of radio supernovae in the local Universe;
- to discover flaring magnetars, intermittent or deeply nulling radio pulsars, and rotating radio transients through changes in their pulse-averaged emission;
- to detect and monitor flare stars, cataclysmic variables and X-ray binaries in our Galaxy; and
- to discover previously unknown classes of objects.

These science goals are organized around the broad themes of explosions, propagation effects, magnetic fields and accretion, as well as exploration of the unknown. The topics are united in this proposal through synergies in the science, multiwavelength follow-up and software development.

The power of ASKAP

The detection and characterisation of radio transients requires both the sampling of new regions of phase space, and the ability to monitor and follow-up known or newly detected sources. As such, a successful transient instrument requires a large field-of-view, rapid survey capabilities, high sensitivity and dynamic range, as well as sufficient angular resolution for unambiguous source identification and follow-up. ASKAP fulfills these criteria with its ability to achieve sub-milliJansky sensitivity across the entire visible sky in a single day of observing, which cannot be achieved by any other currently operating telescope. Transient sources are necessarily compact; the $10''$ resolution of ASKAP will permit source localisation to $\sim$arcsecond positional accuracy, enabling follow-up observations at other wavebands. In the VAST Design Study, we will develop sophisticated new algorithms for the detection of transients on timescales as short as 5 seconds and the combination of telescope hardware and software will make ASKAP the world's premier instrument for transient and variable science.

Investigators and Affiliations

Our collaboration members (listed below in alphabetical order) have expertise that encompasses radio interferometry, pipeline processing, database management, multi-wavelength follow-up and the science behind the transient and variable phenomena we will detect.

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Changes since EoI

This section is only accessible to VAST collaboration members.

1 Scientific Justification

1.1 Introduction

The radio sky is poorly characterised in the time domain, but many classes of objects are known to be variable radio sources, including the Sun, the planets, cool stars, stellar binary systems, neutron stars, supernovae, gamma-ray bursts and active galactic nuclei. ASKAP marks a revolution in our capability to observe radio transients — not only does it have good sensitivity (RMS of $\sim$1 mJy/beam in 10 s) but it covers 30 square degrees of sky in a single pointing, thus enabling all sky surveys with an unprecedented combination of speed and sensitivity. The science this enables takes us from the highly over-pressured regions of the local bubble to explosions in the far reaches of the Universe.

Astronomical transient phenomena are diverse in nature, but it is revealing that they can be broadly classified on the basis of their underlying physical mechanism into one of four categories: explosions, propagation effects, accretion, and magnetic fields. We discuss each of these areas in turn, as well as the potential to discover as yet unknown classes of objects, and then outline the survey strategy necessary to underpin this comprehensive science case.

1.2 Explosions

The most energetic explosions since the Big Bang pose several unresolved questions, including the existence of orphan afterglows, the beaming fraction of GRBs, and the current rate of massive star formation in the Universe, as traced by the cosmological radio supernova rate. These questions can be addressed by surveys that observe a large area of sky to good sensitivity, on a regular basis (see Section 1.6). Figure 1 shows that the capacity of VAST to answer these questions is orders of magnitude greater than previous surveys.

1.2.1 Gamma-Ray Bursts (GRBs)

The cosmological GRBs seen by VAST will, in general, be the rare and important nearby events. In the relativistic expansion phase (1 – 100 days), ASKAP monitoring in conjunction with optical and X-ray facilities will provide complementary and unique physical parameters such as the total kinetic energy of the explosion, the density of the circumburst medium and the geometry of the outflow. At later times, radio monitoring provides the most robust estimate of the kinetic energy (Frail et al. 2005) because the peak of the afterglow spectrum is at radio energies. This same late time behaviour may allow us to identify 'orphan afterglows', i.e. those majority of GRBs whose high energy emission was beamed away from us. They would be identified through the evolution and luminosity of their light curves, and their location towards GRB-like host galaxies and probable association with supernovae. The discovery of orphan afterglows would constrain the beaming fraction of GRBs — a key quantity for understanding the true GRB event rate, and potentially open up an order of magnitude more objects which can be scrutinised in detail. We expect to detect $\sim$10 orphan GRBs per year, and significantly more if we can stack the data from successive observations for extra sensitivity.

1.2.2 Supernovae (SNe)

While thermonuclear (Type Ia) SNe have proven to be extremely useful in measuring the acceleration of the Universe, no Type Ia SN has ever been detected at radio wavelengths (Panagia et al. 2006), indicating a very low density of circumstellar material. In contrast, many core-collapse SNe (those of Type Ib, Ic, and the various Type II sub-classes) have been detected and monitored at radio wavelengths (Weiler et al. 2002, Ryder et al. 2004). Radio observations replay the late phases of stellar evolution, and reveal clues about the late-time evolution of the progenitor system. Our survey will provide the first **unbiased census** of core-collapse SNe (essentially all of which emit at radio wavelengths), by allowing us to match radio detections against optically-discovered SNe. We will also detect new radio SNe that may have gone undetected in the optical or infrared due to significant amounts of dust (e.g. Kankare et al. 2008). Every new SN discovery is valuable for tying down the current rate of massive star formation in the Universe and for understanding how and when SNe explode in star-bursting galaxies. Core-collapse SNe 'turn on' within days, and reach their peak luminosity at 1.4 GHz as much as one year after explosion, typically 1 mJy at a distance of 50 Mpc (Gal-Yam et al. 2006), making them ideal targets to study with the sensitivity and cadence of VAST. With our planned survey, we would expect to detect $\sim$1 SN per month.

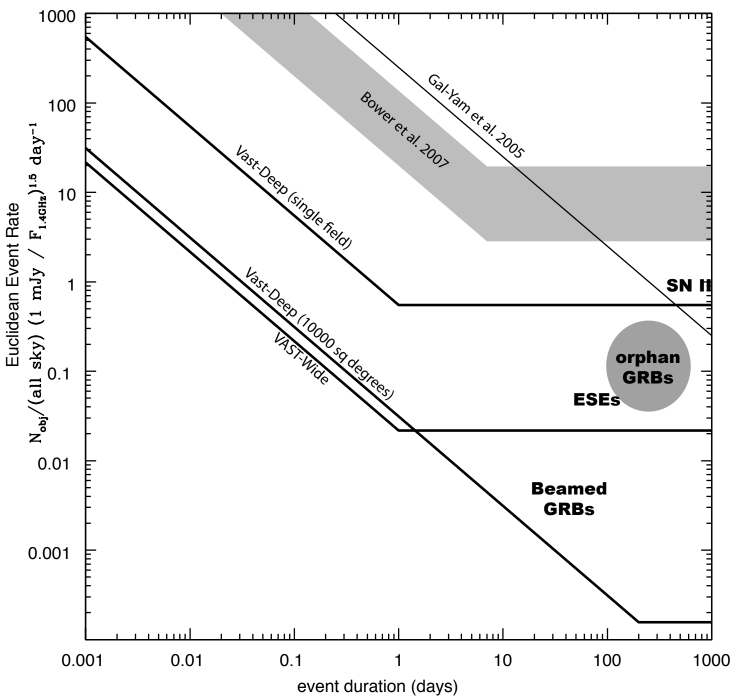

Figure 1: Transient object detection rate of VAST, compared to previous work. We assume events uniformly fill a Euclidean space, a valid assumption for extragalactic sources, nearby sources in the Milky Way Disk, and sources in the Milky Way Halo. The rate is normalised to 1 new transient event per day across the entire sky at 1 mJy, observed at 1.4 GHz. The known or expected event rate of selected types of objects is placed on the diagram. The Bower et al. (2007) results are extrapolated from 5 GHz with an indicative range of spectral slopes from $0 < \alpha^5_{1.4} < 1$. This diagram shows only the number of events a survey will discover, and does not include information on the quality and quantity of information on each object.

1.3 Propagation

Observations of extreme variability in background bright AGN and high frequency resolution observations of pulsars have shown that highly over-pressured structures exist in the local interstellar medium (ISM). These structures are highly anisotropic and are present in vast numbers, yet their origin, and their role, in ISM dynamics in general is poorly understood. Further, we do not yet understand the observed intermittency and apparent redshift dependence of AGN variability, nor how the brightness temperature of AGN emission appears to violate the inverse Compton limit.

These problems can all be addressed with a wide-area survey **repeated every day** in order to track rapid time variability. A sensitivity of 0.5 mJy/beam RMS is adequate because the survey can detect a 50% flux change in sources brighter than about 10 mJy/beam, and to this depth there should be 150,000 radio sources in the survey area (Wall 1994), of which we expect at least 30,000 sources to be compact enough (Jackson & Wall 1999) to exhibit fast flux variability.

1.3.1 Intra-Day Variables (IDVs)

A subset of compact quasars show variability on timescales of less than a day: the IDV sources (Kedziora-Chudczer et al. 1997). It is now established that these fast variations at cm-wavelengths are caused by interstellar scintillation (ISS), rather than intrinsic variability (Dennett-Thorpe & de Bruyn 2002, Bignall et al. 2003, 2006, Lovell et al. 2003, 2007).

IDVs are of astrophysical interest because the small angular sizes ($< 50\,\mu$as) that they must possess in order to exhibit ISS requires brightness temperatures near, or possibly in excess of, the 10^{12} K inverse Compton limit for incoherent synchrotron radiation. A wide-area survey with a daily cadence will answer the following fundamental questions:

- **What is the fraction and cause of IDV intermittency?** The four-epoch MASIV survey (Lovell et al. 2003) detected variability in 56% of the 482 sources observed but the variability itself was highly variable between epochs. By continuously observing a large sample over a long period, VAST will comprehensively determine the intermittency properties of IDVs. If the intermittency is ISM-related, the character of any polarization fluctuations associated with the IDV should evolve in the same way as the total intensity fluctuations. However, if the intermittency is source-related, the polarization variations are expected to evolve in a manner different to those in the unpolarized intensity. A complication arises because annual cycles in the variability timescale (caused by the Earth's velocity vector changing with respect to the scattering screens) need to be distinguished from true IDV intermittency. However, these two phenomena can be separated by making regular (daily) observations over the course of two years. The variations should be dissimilar between epochs if the source variability is intermittent.

- **Is AGN emission above the inverse Compton brightness limit?** The rise and fade times of fast variations in IDVs allow us to determine the longevity of μas components associated with intra-day variability: the rate at which the AGN supplies energy to power the bright emission that causes the variability, and the rate at which energy losses cause its eventual decay. These rates can then be compared with specific AGN processes to identify the mechanism associated with the super-Compton radio emission.

- **What is the baryonic content of the IGM as a function of redshift?** The MASIV survey showed that few sources above z$\sim$2 are variable (Lovell et al. 2007). This suppression of ISS as a function of redshift has a number of possible causes (1) intrinsic source evolution; (2) gravitational microlensing; and (3) scattering in the turbulent ionized IGM. If the latter is correct then the angular broadening is caused by the cumulative effect of all the baryons in the ionized IGM. The sheer number of sources ASKAP can monitor will enable us to probe in detail the evolution of structure in the ionized IGM as a function of redshift. We plan to complement these survey observations with optical follow-up to determine the redshifts of the radio sources surveyed.

1.3.2 Extreme Scattering Events (ESEs)

ESEs are a type of transient in which the flux variations are not intrinsic to the source but are caused by variations in refraction along the line-of-sight (Fiedler et al. 1987b, Romani et al. 1987; see Figure 2). The refracting lenses which cause ESEs must be Galactic in origin and probably lie within a few kpc, but in the 20 years since their discovery, no satisfactory physical model has emerged for the ESE phenomenon. The VAST wide-area survey, repeated daily, will give us the necessary data to address this problem in a comprehensive way.

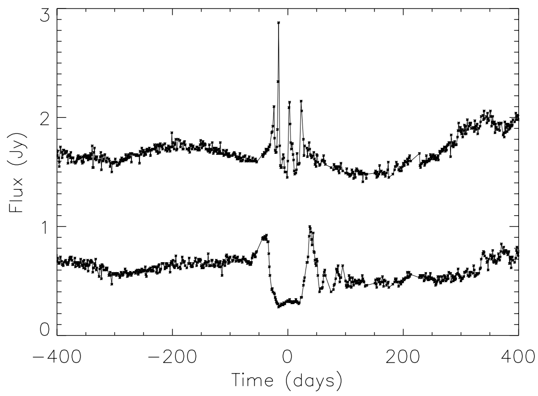

Figure 2: An Extreme Scattering Event in Q0954+658 at 8.1 GHz and 2.7 GHz adapted from Fiedler et al. (1987b). For clarity, an offset of 1 Jy has been added to the top trace. The necessity of regular sampling of the light curves over a long period is evident.

Population statistics: The existing data (Fiedler et al. 1994) has a total coverage of approximately 600 source-years; VAST will improve on this by a factor of roughly 300. Increased coverage will permit better definition of the light-curves of ESEs, information on the number and distribution of refracting lenses in the Galaxy, and measures of the clustering of these lenses.

Real-time characterisation of ESEs: Events like those seen by Fiedler et al. (1994) in Q0954+658 and Q1749+096 should be seen at the rate of roughly 60 per year, with 10 in progress at any given moment. VAST will therefore discover ESEs while they are in progress allowing the study of individual events with full polarisation information, good temporal sampling and good frequency coverage; and all this at high signal-to-noise ratio. We will do better still by obtaining high resolution (VLBI) images of the evolving source structure during the events, showing how the lenses distort the appearance of the source at various times. Multiple imaging is expected and the various images are expected to rotate on the sky, change in brightness, appear and disappear over the course of an event. If these effects can be measured then the data will place strong constraints on the electron column-density profile of the lenses, their distances and transverse velocities. Finally there are some key measurements which could be made at higher frequencies — i.e. the optical to X-ray band — which should directly reveal the dense neutral gas clouds responsible for ESEs via scattering, absorption and refraction (Draine 1998).

The nature of the refracting lenses: Analysis of existing data suggests that ESEs are caused by dense gas clouds which are unlike any other identified component of the ISM (Walker 2007). The data suggests that the individual lenses are spherical, and must therefore be associated with neutral, self-gravitating gas clouds, and that they are present in vast numbers in the Galaxy — probably dominating its total mass. One possible interpretation of this surprising result is that the Galaxy's Dark Matter is baryonic, directly challenging our prevailing understanding of cosmology.

1.4 Accretion and Magnetism

Along with explosions and propagation effects, accretion and magnetic fields are frequently implicated in transient events. Either individually or in conjunction, accretion and magnetic fields operate on scales from the local to the cosmological, powering phenomena as diverse as extragalactic blazars and active galactic nuclei, Galactic X-ray binaries, microquasars, pulsars, flare stars, and even radio emission from Jupiter and (possibly) Jupiter-like extrasolar planets. We propose to detect and characterize transients and variable sources that span the full range of such phenomena, with the ultimate goal of revealing the unifying physical principles that underlie such diverse behaviour.

1.4.1 Intrinsic Variability in Active Galactic Nuclei

Fiedler et al. (1987a) observed a set of 33 active galactic nuclei (AGN), with flux densities of a few Jy, every day for more than 6 years. All sources were variable over this time span with typically smooth variations in flux with quasi-periods of months to years. It is clear that ASKAP will see this sort of variability and produce light curves for more than 10^4 sources over the whole sky. The *Fermi* gamma-ray satellite observes the whole sky every day, and simultaneous measurements of the gamma-ray and radio variability in blazars provide us with a powerful tool for understanding the physics of the central engines in AGN.

1.4.2 Accreting Neutron Stars, Black Holes and Microquasars

Unravelling the 'accretion-disk/jet connection' in X-ray binaries (XRBs) requires correlated radio and X-ray observations (Fender 2006). VAST-GP will promptly reveal and subsequently measure the radio emission from a large number of XRBs and allow us to search for new radio outbursts. This, coupled with the recent availability of large field of view X-ray instruments like *Swift*-BAT and *Fermi*-GBM, will provide crucial insights. VAST will yield information on the population of XRBs showing quasi-steady state radio jets, which are mildly relativistic, and are associated with a limited range in X-ray states (Fender et al. 2004; McClintock & Remillard 2006) . As in the case of the transient radio emission, the detailed properties of these 'persistent' jets, their baryonic content, energy budget, emission mechanism, are not well constrained (Markoff et al. 2005; Narayan 1996; Yuan et al. 2005) and regular radio monitoring will have a significant impact on our understanding.

1.4.3 Cataclysmic Variables (CVs)

CVs are binary stars consisting of a white dwarf and a red dwarf with orbital periods of a few hours and are generally divided into two classes depending on magnetic field strength of the white dwarf. CVs are variable over all wavelengths and a wide variety of timescales but only the nearby magnetic CVs are persistent (weak) radio sources. Novae from CVs are occasionally seen in the radio band with flux densities in excess of 10 mJy (Dulk et al. 1983) and a radio jet has recently been detected from SS Cyg during an outburst with a peak flux above 1 mJy (Körding et al. 2008). With a total Galactic population in excess of 10^6, VAST is certain to detect many radio flares from these objects.

1.4.4 Flare Stars

A surprisingly large fraction of cool stars, with spectral types of M and later, are known to flare in the radio band and it has been argued that the radio observations are the best method for obtaining the stellar magnetic field strength (Berger 2006). However, it is not firmly established whether the flares are due to magnetic activity or accretion since they occur in both naked T Tauri stars and in systems with an infrared excess that indicates the presence of a disk (Osten & Wolk 2009). Flares show flux densities above $\sim$1 mJy, but there is also a quiescent emission at the sub-mJy level between the flares (e.g. Pestalozzi et al. 2000). The numbers of flaring events that are potentially detectable is unclear, but VAST will undertake a census of such stars in the local (10 pc) neighbourhood.

1.4.5 Neutron Stars

Of the known neutron stars (NS), the vast majority are pulsars that have been detected through their pulsed radio emission. VAST will not be sensitive to radio pulsations on typical pulsar timescales ($\lesssim$ 1 s), but will instead probe NS populations that are selected against in pulsar surveys. We will be sensitive to intermittent or deeply nulling radio pulsars as well as radio pulsars with large variations in their average pulsed flux. Magnetars will be detectable through their rare flaring events such as the giant flare and expanding radio nebula produced by SGR 1806−20 (Gaensler et al. 2005, Cameron et al. 2005). In addition, some magnetars are known to turn on as radio sources, and XTE J1810−197 was initially detected as a transient radio source (Halpern et al. 2005) before its radio pulsations were identified (Camilo et al. 2006). Finally, we may be able to detect bright intermittent pulses from the enigmatic rotating radio transients (RRATs; McLaughlin et al. 2006). VAST will thus reveal a broader census of the Galactic NS population than a standard pulsation search with subsequent implications for the overall supernova event rate in our Galaxy.

1.5 New Classes

The most interesting transient sources detected with VAST will undoubtedly be objects which we currently know nothing about. One of the advantages of a sensitive wide-area survey is that it is tailor-made for detecting the unknown. Although large-scale blind surveys for radio transients have been performed by a number of groups (Amy et al. 1989, Katz et al. 2003, Matsumura et al. 2007), these surveys have been severely limited in their sensitivity, sky coverage, and cadence. In spite of this, transient bursts of unknown origin have been detected at the ∼1 Jy level.

More recently, it has become clear that the radio sky contains many transient objects, the identity of which remain mysterious. For example, Hyman et al. (2005) discovered a bursting transient towards the Galactic Centre which lasted for only a few minutes but had a flux density in excess of 2 Jy. The bursts repeat at irregular intervals and the identification of this source remains unclear. Subsequently Bower et al. (2007) examined archival VLA data on a calibration field, spanning 22 years with observations approximately once per week. They detected 10 transient sources, at least six of which have no optical counterparts or quiescent radio emission. Bower et al. (2007) consider the classes of known transients and conclude that their sample is unlikely to be drawn from the known population. Finally, Lorimer et al. (2007) searched archival pulsar data taken with the Parkes telescope. They discovered a single millisecond pulse of extragalactic origin with the astonishing peak flux density of 30 Jy. These new discoveries illustrate that the phase space for radio variability has been explored remarkably sparsely so far (Figure 3).

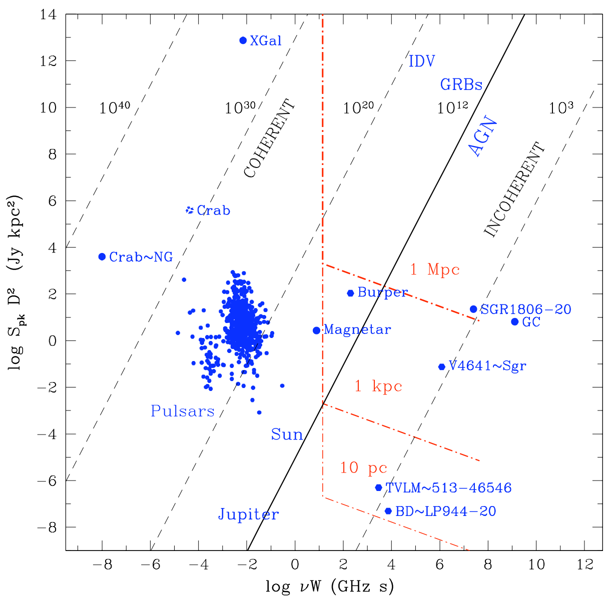

Figure 3: The phase space for radio transients, adapted from Cordes et al. (2004). Red lines indicate the sensitivity of ASKAP to sources at distances of 10 pc, 1 kpc and 1 Mpc. Diagonal lines indicate constant brightness temperature with $T = 10^{12}$ K marking the onset of coherent processes.

Bower et al. (2007) estimate that at ASKAP sensitivity, approximately 1 transient source per square degree, with a duration of order a week, will be present at any given time. A large scale survey such as VAST is therefore very likely to find large numbers of transient sources, and the bigger challenge may very well be the localisation, identification, and multi-wavelength follow-up of these sources.

1.6 Survey Strategy and Time Request

The key to the efficient detection and monitoring of transients and variable sources is repeated observation of each given field to sample the full range of cadences. Thus, while it is desirable to observe commensally with every ASKAP program, it is **not sufficient** to simply do so. Figure 1 demonstrates the discovery power of the VAST surveys in comparison to previous blind searches for radio transients. These order of magnitude leaps forward justify the need for a substantial program dedicated to transient and variable science.

Below we outline three complementary survey strategies that most efficiently cover the observational requirements of the VAST science goals. Our time request is 8560 hours over the first five years of ASKAP operations, in addition to continuous commensal observing.

VAST-Wide: 10,000 square degrees (400 pointings) observed for 6 hours per day (40 seconds per pointing plus overheads, RMS sensitivity 0.5 mJy/beam) every day for 2 years. Total time requested 4380 hours. The large area is needed to map the sky for stressed ISM structures, and to pick up the rare GRB and SN events. Daily cadences are required to fully sample the light curves of ESE events. Two years of data is required to discriminate between an annual cycle and intrinsic variability for IDV sources.

VAST-Deep: 10,000 square degrees (400 pointings) observed for 1 hour (RMS sensitivity 50 μJy/beam). Note that while both the Deep and the Wide surveys observe the same amount of sky, they are complementary in cadence and sensitivity.

One field, coinciding with the deep field requested by the EMU collaboration would be repeated daily for one year. The other fields would be repeated 8 times at irregularly spaced intervals. Total requested time is 3600 hours. This is the optimal survey to detect as yet unknown source classes (cf. Bower et al. 2007) and detect GRBs and SN to larger distances.

VAST-GP: 750 square degrees along the Galactic plane (30 pointings) plus 3 pointings to cover the Large and Small Magellanic Clouds observed for 9 hours per day (16 minutes per pointing, RMS sensitivity 0.1 mJy/beam) repeated weekly for 1 year with additional shorter intervals. Total time requested is 600 hours. This survey is optimised to find Galactic transients.

In addition to the planned surveys, we will operate our transient pipeline on **all** other observations in commensal mode. We recognise that many other large groups will operate in 'point and shoot' mode, covering the entire sky with significant integration time ($\sim$10 hrs) per pointing and no re-visits. This should allow detection and monitoring of short duration transients.

A crucial aspect of our design study (see section 2 below) will be to refine our survey strategy based on knowledge acquired over the next few years. We envisage that our strategy will evolve somewhat but the overall strategy as described above is our best estimate for optimising the science at the present time.

1.7 Follow-up Science

Merely detecting transient radio sources is not sufficient — much of the interesting physics will arise through multi-wavelength follow-up. For GRB and SN science, for example, identifying the host galaxy through optical observations will be crucial. For ESE science, follow-up at VLBI wavelengths will be key. Finally, it is important to catch the 'unknown' transients in real time and send out alerts world-wide for multi-wavelength follow-up. The VAST team has significant representation from the major observatories and all wavelengths, including access to radio facilities (ATCA, VLA, ATA, LOFAR, VLBI), large optical telescopes (Palomar, Keck, Gemini, Magellan, and Australian telescopes), X-ray (*Chandra*, XMM-*Newton*, *Swift*) and γ-ray (*Fermi*) facilities. The range and depth of expertise provided by our broad collaboration ensures that any event of interest will be promptly identified and followed up. Specific contributions of telescope access for multi-wavelength follow-up by VAST collaboration members are listed in Section 2.6.

1.8 Summary

We propose a comprehensive survey to search for and monitor variable and transient sources in the local and distant Universe. VAST will lead to breakthrough science and the discovery of new classes of astronomical phenomena. The combination of the survey speed and sensitivity of ASKAP with our team's expertise in transient and variable source science will make ASKAP the world's premier instrument for transient and variable science.

2 Design Study Implementation Plan

VAST is an ambitious project in terms of its scientific goals and technical challenges. During the time leading up to the commissioning of ASKAP, we will pursue a range of activities that will contribute to the eventual maximization of scientific returns from VAST:

- Running simulations to examine survey design and source detection trade-offs;
- Developing an analytical framework and metrics to characterize the behaviour of transients;
- Designing, developing, and benchmarking software pipelines;
- Using complementary efforts with other telescopes, including SKAMP, ATA, LOFAR, and MWA, to help characterize the transient sky and the MRO site as well as validating methods and algorithms;
- Running pathfinder observations with BETA as well as commissioning observations with ASKAP.

The timeline for this work is shown in Figure 4, and discussed in more detail in the rest of this section.

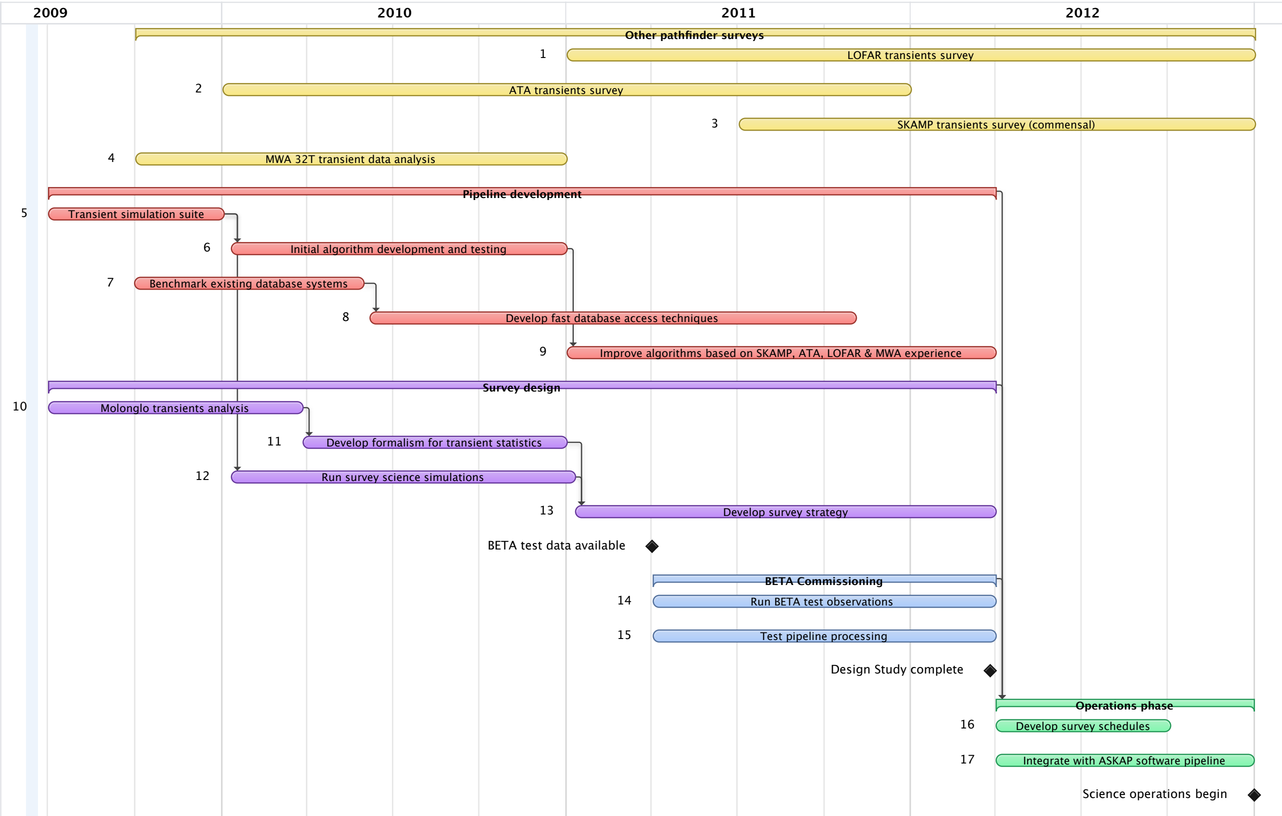

Figure 4: Timeline for the VAST Design Study, including approximate timeframes major tasks and for other pathfinder transient surveys that VAST team members will be running. The three milestones show the expected availability of BETA test data, the end of the Design Study phase, and the start of science operations, as estimated by the project scientists (Feain, private communication). Tasks are numbered and will be referred to in the text as [T1].

2.1 Science Simulations

We propose an extensive set of simulations to determine the optimal survey parameters and strategies, as well as to validate our detection algorithms and pipeline design.

- We will construct parameterized source models (flux density as a function of time and frequency) for a diverse range of transient and variable sources as input into survey simulations [T5].
- We will run simulations to determine optimal time and frequency sampling patterns for survey observations that will maximize the scientific yield given the constraints of time allocation and other demands on the telescope. For example, there is a trade-off between the detection of increasing numbers of transient sources, which benefits from logarithmic time sampling of the widest possible fields of view, and the characterization of detected sources, which requires even, dense time sampling of small patches of the sky [T12].

• We will run simulations to characterize our detection thresholds and source completeness limits. The eventual ASKAP configuration will determine source and sidelobe confusion levels, and we will attempt to account for other effects such as interstellar scintillation induced intermittency [T12].

• Given the characterization of variations in sensitivity across the field of view due to the use of focal plane arrays, we will incorporate these measurements into our simulations of source detection.

2.2 Software Pipeline Development

Advanced software, algorithms and data storage solutions will be critical for VAST. Our team has expertise in software development and database management (Curran, Fekete, Murphy, Whiting), experience in pipeline development for other major pathfinder projects (Fender, Kaplan, Murphy, Ord, Stappers, Stevens, Wayth) and for archival transient searches (Bower, Murphy). We also have experts in VOEventNet software development (Graham, Mahabal, Williams) and in developing transient and variable monitoring software for other wavebands (Schmidt).

Hence we are well placed to work with the ASKAP Computing Group to solve the many challenges of rapid transient detection with ASKAP. In particular, during the Design Study we will work on:

- Developing and benchmarking of on-the-fly pipelines and algorithms to detect transients [T6];
- Collaborating with other ASKAP projects such as EMU (Norris) to solve challenges in source finding;
- Investigating fast database access options to store candidate sources identified in real-time [T7,T8];
- Experimenting with methods of transient source identification and classification;
- Developing a transient source event handler that will trigger events for follow-up by other instruments and also receive events for possible follow-up with ASKAP;
- Developing robust quality control procedures to ensure high quality data products.

The specific design of the transient detection pipeline will be developed in conjunction with the ASKAP Computing Group. We anticipate the main components will be similar to the design in Figure 5.

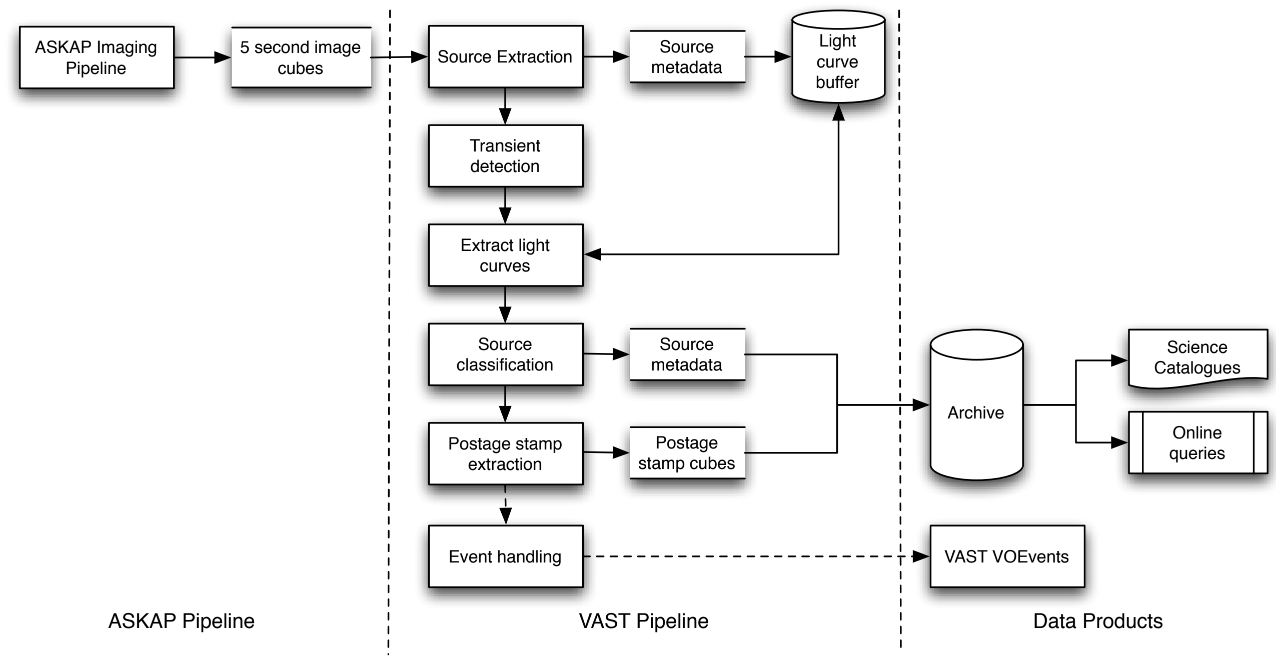

Figure 5: The VAST transient detection pipeline.

2.3 Statistics and Analysis

In addition to working on algorithms for detecting and characterising transient sources, we will formulate the new mathematical language needed to properly describe their behaviour. This builds on work already done by VAST team members (Bower, Chatterjee, Cordes, Gaensler, Lazio, McLaughlin).

A variety of descriptors have been previously developed to quantify the non-varying sky: examples include the differential source count distribution ($\log N - \log S$) and the two-point correlation function. However, there is currently no corresponding equations that can adequately describe populations of variable sources. For example, a $\log N - \log S$ function derived from a survey for transients (e.g., Bower et al. 2007) must incorporate three time scales (the length of each observation, the cadence between observations, and the time scale for source variability), and describe the distribution of fractional variation in source fluxes between epochs.

A key part of our effort during the Design Study will be to construct statistics that can meaningfully describe the variable sky. We will develop mathematical tools aimed at properly encapsulating the 'sensitivity to variability' of a survey, and the rate and degree by which sources vary. This will allow a meaningful comparison of transient surveys done with different instruments or with different observing strategies, and will provide the predictive power needed to estimate the likely yield of VAST.

2.4 Complementary Observational Studies

We have assembled a diverse international collaboration, and have synergies with many major instruments which will be essential for survey planning and for comprehensive multi-wavelength follow-up. Throughout the Design Phase we will carry out surveys for transients and variables on other radio pathfinder instruments. From these investigations we will be able to identify (and in many cases solve) technical challenges shared by VAST, and also further develop our survey design. Specific programs we will carry out as part of the VAST Design Study are:

MOST (Gaensler, Murphy, Chatterjee, with PhD student Bannister)
Work is underway to mine the Molonglo archive [T10], which spans over 20 years, for transient and variable phenomena. Typical time between observations on a single patch is $\sim$1 year, which does not allow the characterization of transient sources on intermediate and short timescales, but does allow us to calculate statistics that contribute to determining a $\log N - \log S$ distribution for transient sources. This work will also identify key challenges for the VAST transient detection algorithms.

SKAMP (Gaensler, Green, Hunstead, Murphy, Sadler)
The SKA Molonglo Prototype II is almost complete, extending the Molonglo Telescope to provide a tenfold improvement in sensitivity, and full spectroscopic capabilities. From mid-2010 to 2011 a major HI absorption line survey will be carried out at 843 MHz. We will operate in piggyback mode to conduct a survey for radio transients and variables [T3]. This will allow us to develop and test algorithms, as well as characterise the potential of SKAMP-II for follow-up of ASKAP-detected transients.

MWA (Chatterjee, Gaensler, Greenhill, Johnston, Kaplan, Murphy, Ord, Schmidt, Tingay, Wayth)
The MWA is a new low frequency ($80-300$ MHz) synthesis telescope under construction at the Murchison Radio Observatory (MRO). Like ASKAP, the MWA has a large FoV and is an excellent survey instrument. One of the four key projects for MWA is to study transient and variable radio sources. Preliminary plans for the surveys with the MWA call for regular wide surveys of the entire sky visible from the MRO, producing a dataset that will complement ASKAP [T4]. The MWA will face similar challenges to ASKAP in data processing. The opportunity for collaborative development of algorithms and data processing pipelines is excellent, and a number of VAST team members are core members of the MWA transients effort. Additionally, the MWA has developed a sophisticated set of simulation tools which may be useful for the Design Study phase of the project.

ATA (Bloom, Bower, Karastergiou, Lazio, Walker)
The Allen Telescope Array is an LNSD interferometer located in Northern California. The ATA has 42 6-meter diameter elements but an expansion to 200 elements is planned, giving it a survey speed comparable to ASKAP. The ATA will operate over a frequency range of 0.5 to 11 GHz. Prior to the launch of ASKAP surveys, the ATA is conducting imaging transient surveys [T2] that will systematically explore transient and variable source populations and statistics with the potential for significant discoveries. Both the statistical and serendipitous results of ATA surveys will be important in guiding the design of ASKAP surveys. Experience gained developing tools to detect and monitor transient sources will also be useful for the design and development of the ASKAP transient detection pipeline.

LOFAR (Fender, Stappers)
LOFAR is an ASTRON-led low-frequency ($30 - 240$ MHz) multi-beam 'software telescope' currently under construction across Europe. The first call for proposals will be issued this month (June 2009), with full array operations planned for 2011. A Key Science Project (KSP) for LOFAR is 'Transients and Pulsars' whose remit covers all radio variables and whose primary goals include characterising and recording the variability of the entire radio sky on a wide range of timescales [T1]. Very wide field studies of these LOFAR variables will help ASKAP to optimise the design of its own transient search and follow-up programs, and to jointly monitor rapidly evolving events (in the approx Dec range -10 to $+30$). The LOFAR Transients KSP is a partner in the ASKAP VAST proposal and is keen for both teams to exchange information, techniques, algorithms etc to better aid our exploration of the variable radio sky. We plan to ramp-up the knowledge exchange and collaboration over the period of the ASKAP design study (indeed this has already begun).

2.5 BETA and Commissioning Observations

We envisage that early versions of the transient detection pipeline will be adapted from the complementary surveys described above, and will operate off-line on all BETA observations [T14,T15]. We would collaborate extensively with ATNF staff in planning and analysing these observations, and as ATNF resources permit, we will be ready to migrate to real-time operation of the pipeline on BETA and the commissioning phase of ASKAP.

During early operations, rapid and shallow all-sky observations would be most useful for building up the ASKAP sky model, which will be essential for eventual real-time calibration and imaging, and for the characterization of real instrumental effects (such as $U-V$ coverage, sidelobe confusion, sensitivity variations across the field of view of focal plane arrays, etc) on source detection sensitivity. We will utilize these results to close the loop on our science simulations (discussed above). Such observations will also be suitable for searches for transient sources, and may be the most productive avenue for early scientific returns from ASKAP.

2.6 Contributions

This section is only accessible to VAST collaboration members.

3 Benefit to Community

The characterization of the radio transient sky through detection and monitoring (including VLBI) of transient and variable sources is one of the four key science goals for ASKAP[1]. VAST is an ambitious project that will carry out the most comprehensive study of radio transient and variable phenomena before the SKA. VAST will be exploring new realms of parameter space, and as such the scientific benefit to the community will be extensive. Achieving our scientific goals will require the development of new algorithms and software packages so that we can operate in this new paradigm of radio astronomy, in which not all data can be archived. These technical developments will be of enormous benefit to the community, both in other major ASKAP projects, the wider astronomical community, and in preparation for the SKA. Some specific benefits and products of our Design Study and survey are discussed below.

3.1 Data and Software Products

The VAST team is committed to releasing news of transient events as quickly as possible, through automatic event handling which is Virtual Observatory (VO) compatible (see Section 3.2). This will ensure that researchers around the world are able to follow-up on interesting objects. To do this, we will have to have a fast and highly accurate transient detection and classification process. In addition, we will provide the following datasets and software tools for the wider astronomical community.

3.1.1 Data products

- **Multi-epoch survey images:** We will carry out regular surveys that will result in images covering a large fraction of the sky. This will help characterise the radio sky for deeper surveys, and also characterise the variable radio sky for future projects. This dataset will be unique — it will be the largest study of transient and variable phenomena carried out in radio astronomy and hence will be a valuable resource for the entire community.
- **Searchable lightcurve database:** In addition to the science-quality images, we will provide a searchable online database of lightcurves for *all* objects observed by ASKAP while our software is running in piggy back mode. Every object that is observed multiple times by ASKAP will have its lightcurve extracted and stored. This database is a consequence of our transient search strategy, but will add value to all major ASKAP projects.
- **Catalogue of transients and variables:** All objects that are determined to be of interest for transient or variable science will be published in science-quality catalogues. This will be an important resource for science, that does not require detailed knowledge of ASKAP or the VAST survey strategy.
- **Raw transient event feed:** All transient events that pass certain quality and reliability criteria will be released immediately to the community through a VOEvent feed. This will ensure the science potential of VAST (and ASKAP) is maximised.
- **Classified event triggers:** In addition to this 'raw' feed, we will release classifications for a limited set of transient and variable sources. This will provide value-added information that will allow users to filter the feed on the basis of source type or various lightcurve properties, to restrict the large number of sources to those of interest to them.
- **Multi-wavelength followup:** Our team will conduct multi-wavelength follow-up observations of interesting new objects detected with ASKAP. Subject to the proprietary period conditions of other facilities, this data will be published and released to the community as a valuable additional resource to the original ASKAP data.

3.1.2 Software products

- **Transient detection algorithms:** To detect transients with VAST we will need to develop new algorithms for rapid, accurate source detection, extraction and classification. These algorithms will be useful across many applications in astronomy, particularly for other large survey projects, and of course for development towards the SKA.
- **Database access algorithms:** Transient detection with VAST will push current database technology in terms of rapid ingest and access for massive datasets. We will develop custom algorithms to run inside the database management systems to allow for this. These algorithms will be useful for all large astronomy surveys, and in the wider scientific community.

[1] ATNF Science in 2010 – 2015: Part 1 Overview

- **Event handling software:** Sending and receiving triggers will be an important part of the transient detection pipeline. We will develop an event handler that, in addition to sending triggers when new ASKAP transients are detected, will receive external triggers from other instruments. This information will be available to all astronomers in the ASKAP community, giving them the opportunity to follow-up on events if desired.
- **Source monitoring software:** Another byproduct of our transient detection package will be software to monitor any known sources that appear in the ASKAP field of view. This will be important to astronomers in the VAST team, but also of general interest to ASKAP astronomers who want to extract data for their objects of interest.

3.2 Data Release Policy

Rapid dissemination of results is critical to maximising the scientific gains from VAST. Once we are confident our software pipeline is working correctly, and the data has passed stringent quality criteria, we will release our data publicly through the following mechanisms:

- Triggers for individual transient events will be released through services such as VOEventNet as soon as they are detected. These events will have quality flags representing our confidence about the detection and will allow immediate follow-up of new discoveries by the wider community. (Timeframe: *seconds*)
- Triggers with value-added data such as classifications based on multi-wavelength archival crossmatching will be released as soon as our source classification pipeline has run. (Timeframe: *minutes*)
- Measurements of every source in every field will be entered into our lightcurve database in near real-time. This will be available immediately to the VAST collaboration. Once appropriate quality control has been completed, updates to the database will be made publicly available. (Timeframe: *days*).
- High quality scientific catalogues will be constructed from our lightcurve database. The results will be published and data made public as soon as possible after analysis is complete. (Timeframe: *months*).
- Images from VAST will be made available through the standard ASKAP archive. The timescale on which this happens will be determined in conjunction with the ASKAP Computing group and archive providers.

We will work with the archive providers to ensure that all datasets are as accessible as possible to the research community (e.g. through VO protocols) and the general public.

3.3 Education

A large fraction of the VAST team work in universities and so have the opportunity to educate and train a new generation of students throughout the Design Study phase and the survey itself. These will include postgraduate students based at The University of Sydney, University of Western Australia and Curtin University of Technology, who will work with key ASKAP staff at the ATNF to gain an understanding of the telescope as it develops. We will have many undergraduate and vacation projects focused on different aspects of the transient detection process. The computationally-intensive nature of the project means that it will also be suitable for computer science students and we plan to build on our existing links with computer scientists to get more students engaged with these problems. We will contribute to the training of students in the anaylsis techniques that will be required for working with massive datasets, through programs such as the Astroinformatics School (Murphy).

As discussed in Section 2, we will have a number of postdoctoral researchers working on the VAST Design Study. This will include having someone embedded in the ASKAP Computing team at ATNF. In addition to carrying out scientific research, students and postdoctoral researchers will develop skills in dealing with massive datasets that will be critical in future large-survey radio astronomy. There will be many opportunities for students and postdoctoral researchers to visit our international team members, and share their knowledge and experience gained from complementary projects such as MWA, LOFAR and the ATA.

3.4 Outreach

Running one of the major surveys on one of the best telescopes in the world will be an amazing opportunity to inspire the next generation of scientists. We plan to engage the public in mining the VAST archival data for transient detections and classification, using distributed computing in the style of SETI@home or Galaxy Zoo.

We will communicate our results to the public through lectures, school visits, magazine articles and existing outreach programs such as the International Science School.

4 Team Organisation

This section is only accessible to VAST collaboration members.

5 Technical Requirements

Our technical requirements for the telescope operation are summarized below.

	VAST-Wide	VAST-Deep		VAST-GP
Observing time (hrs)	4380	3200	400	600
Survey area (deg sq)	10 000	10 000	30	750
Time per field	40 s	1 hr	1 hr	16 min
Repeat	daily	7 times	daily	64 times
Observing freq (MHz)	1150–1450	1150–1450	1150–1450	1150–1450
Bandwidth (MHz)	300	300	300	300
Point source sensitivity	0.5 mJy/beam RMS	50 μJy/beam RMS		0.1 mJy/beam RMS
Field of view (sq deg)	30	30	30	30
Angular resolution	10″ (Maximum possible)			
Spectral resolution	$\sim$ 10 MHz			
Time resolution	5 seconds (Maximum possible)			
Polarisation products	IQUV	IQUV	IQUV	IQUV

5.1 General Requirements

- Essential: Maximum field of view (30 square degrees)
- Essential: Maximum sensitivity at the highest angular resolution
- Essential: VAST-Wide needs to cover 10,000 sq degrees in 6 hours observing, i.e. 40 s per field. Need to minimise slew times and other overheads.

5.2 Correlator Requirements

- Essential: 300 MHz bandwidth
- Essential: At least 8 frequency channels
- Desirable: 32 frequency channels
- Centre frequencies: Prefer to operate at the higher end of the band. We desire maximum sensitivity and field of view. At this stage we envisage something like $1200 - 1500$ MHz.
- Essential: The same centre frequency and correlator configuration to be used for observations over multiple epochs of observing.

5.3 Polarisation Requirements

- Essential: Stokes I and V (to understand the noise characteristics)
- Desirable: Full Stokes (I,Q,U,V)
- Desirable: Polarization purity of 30 dB to measure RMs

6 Detailed Functional Requirements

Details of the correlation configuration and polarization requirements are given in Section 5.

6.1 Dynamic Range Requirements

- Essential: 10^4 required for VAST-Wide (0.5 mJy/beam RMS required in the presence of 5 Jy sources) and is also the typical requirement on 5-second images.
- Essential: 10^5 required for VAST-Deep (0.05 mJy/beam RMS required in the presence of 5 Jy sources).
- Essential: For VAST-GP require confusion limited imaging in the Galactic plane. Need to reach 0.1 mJy/beam RMS in most regions (possibly excluding areas around very bright HII regions etc).

6.2 Imaging Requirements

- Essential: Deconvolved multichannel continuum images required at every cadence.
- Essential: Natural weighting to maximise sensitivity.
- Essential: Highest resolution imaging for accurate positions
- Essential: Absolute flux calibration to $\sim$1%.
- Essential: The stability of relative flux calibration over long (week to month) timescales.
- Essential: Accurate position IDs to better than 1/10th beam width
- Essential: Stability of pointing over long (week to month) timescales.
- Desirable: Keeping the full spectral cube, at least for a buffer period (see Section 2.2).
- Essential: Formation of postage stamp cubes around candidate sources

6.3 Data Products

- Essential: Retain continuum (minimum 8 channels, 300 channels desirable) visibilities every 5 seconds throughout the lifetime of ASKAP.
- Essential: Maintain light curves for all sources above $\sim 5\sigma$ in the FoV, on a range of time scales.
- Essential: Real-time extraction of transient sources (5 second timescale)
- Essential: Postage stamps of transients before during and after the transient event
- Essential: Ability to time average data and subsequently search for transients and variables

6.4 Catalogues

The VAST pipeline will build a database of lightcurves for all objects detected in each field, storing:

- A unique identifier for each detection (each object in each epoch)
- Sky coordinates and size, with associated error
- Flux density (peak and integrated) or limit with associated errors, in each spectral channel
- Polarisation (Q, U, V) with associated error
- Local RMS in field near object
- Quality flags from extraction process
- Multi-wavelength counterparts from archival databases

6.5 Data Volumes

The total imaging data generated by the VAST surveys (over 8540 hours) will be $\sim$ 50 PB $= 4096 \times 4096$ pix $\times 4$ pol $\times 32$ chan $\times 4$ bytes/voxel $\times \sim 6 \times 10^6$ timesteps. This is an upper limit on the overall storage required and will be scaled down depending on the likely storage available. For example, the space required for 5 minutes time resolution would be 0.8 PB for full cubes but only 50 TB for 8 channel Stokes I cubes.

The storage requirements for our lightcurve database will be $\sim$ 10 terabytes. Our software will run in piggy-back mode whenever possible, and we will record properties (see Section 6.4) of each source in each field, at various time resolutions depending on the commensal project. The data volume requirements for the database remain moderate compared to any image archiving.

6.6 Source finding and data processing

The transient detection pipeline(s) VAST will develop will also have substantial computing and storage requirements. We anticipate that some of these will be met by ICRAR (Staveley-Smith, Quinn, Dodson). Our pipelines will operate in several concurrent modes:

- **On-the-fly.** Particularly for the shortest timescales (5 s to ∼hours), we anticipate that the transient detection software will operate continuously at the back end of the imaging pipeline.
  Key input: Deconvolved images with flux calibration on the shortest timescales.
  Output product: Candidate transient events to be stored in a database and passed to an event handler, which communicates it to the 'observer', possibly with preliminary classification and detection quality information.
- **Post-processing.** On longer timescales, longer integrations on the same (or partially overlapping) fields of view will be compared, providing higher signal to noise ratio and enabling the detection of fainter sources. The inputs and outputs are identical to the item above, but do not necessarily require real-time operation.
- **Source detection.** A source detection module will extract source parameters (time, position, flux, spectrum, polarisation, detection quality) for *every* source in the field of view, and store it in a database, possibly with postage stamp image cubes.
  Key input: Deconvolved images with flux calibration on long timescales, down to shorter timescales as computing resources permit.
  Output product: Database with lightcurves for every source in the ASKAP sky, as sampled by all the different observation programs (piggyback or targeted).
- **Database analysis.** The database produced in the step above will be continuously examined by software transient detection 'agents'. We anticipate that these will begin as simple database queries, and slowly evolve to accommodate sophisticated algorithms, including e.g. the correlated variability of sources in different parts of the sky.
- **Archival analysis.** We plan to use a distributed computing approach to mining the long term archives for slow transients. This will allow sophisticated machine learning algorithms to be explored.

These proposed modes of operation pose several requirements, including the hosting of the database and computational resources to enable transient searches, as well as the appropriate 'hooks' for the operation of a real-time transient pipeline. We anticipate that the real time pipeline will be developed with BETA and in conjunction with ASKAP commissioning, while the rest of the infrastructure will initially be hosted remotely, possibly at the ASKAP data archive.

6.7 Survey Strategy

Our proposal consists of three parts: a large area shallow survey with a daily cadence (VAST-Wide), a large area deep survey at a range of cadences from daily to monthly (VAST-Deep), and a regular survey of the Galactic plane (VAST-GP).

VAST-Wide: VAST-Wide is a survey of ∼10 000 square degrees (400 pointings) to a sensitivity of ∼0.5 mJy/beam RMS. We will integrate for 40 seconds per pointing for a total of six hours per day, repeated daily for two years. The total time request is 4380 hours over the first two years of ASKAP operation.

VAST-Deep: We will observe ∼10 000 square degrees (400 pointings) to a sensitivity of $\sim 50\mu$Jy/beam RMS. We will integrate for 60 minutes per pointing. Each of the 400 pointings will be observed on days 1, 2, 3, 4, 7, 14 and 21 after a deep 12-hr pointing carried out as part of e.g. the EMU-Wide survey (or any other similar ASKAP survey).

In addition we will leverage EMU-Deep, which plans to survey a single pointing field (30 sq deg) for 2000 hours (split into $\sim 166\times$ 12 hour observations). We will reobserve the same field for one hour daily, for a year. VAST-Deep will be shallower than EMU-deep (reaching $\sim 50\mu$Jy RMS in each observation) but will provide valuable additional time baselines. The total time request for VAST-Deep is $3200 + 400 = 3600$ hours over one year.

VAST-GP: We will survey 30 pointings along the Galactic plane (out to $|b| \leq 2.5°$) with an additional 3 fields covering the Large and Small Magellanic clouds. In the Galactic plane we aim to reach a sensitivity of ~ 0.1 mJy/beam RMS. We will do this with 8 lots of 2 minute integrations on each field, spread over 12 hours. This will be repeated once per week for one year. In addition, we will have more densely sampled periods everything three months within the year, in a pattern of 4, 2, 1, 2, 4 days. The total time request for VAST-GP is 600 hours over one year.

7 Response to EoI Evaluation Committee

This section is only accessible to VAST collaboration members.