Integrated High Energy Alert Network

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Abstract

Multiwavelength, multimessenger, rapid transient events are increasingly important in astrophysics. The AAVSO International High Energy Network Observing Section is collaborating with several other organizations to develop an integrated early-warning system so that optical follow-up to high energy events can be rapidly organized. Among these organizations are the SuperNova Early Warning System (SNEWS) (1) and GRANDMA/Kilonova Catcher. Events to be captured include the neutrino precursors of Local Group supernovae, optically bright gravitational-wave events, gamma-ray bursts, and cataclysmic variables. These various events span widely different time frames, from a few per century (Local Group supernovae) to one per day for gamma-ray bursts. It would be advantageous if an integrated system could be implemented to detect the rare events as well as the more frequently occurring events. In this report are described the logical structure of the early-warning network, the facilities available for optical follow-up, and the hardware and software available to participating optical observers.

1. Introduction and Background

There are several types or categories of high energy targets that would greatly benefit from follow-up optical observations from both professional and amateur astronomers. In addition to the galactic supernova, detected with the initial neutrino bursts, other potential high energy targets include Gamma Ray Bursts (GRBs) and GRB afterglow, kilonova, cataclysmic variables including classical novae, dwarf novae, recurrent novae, polars, and symbiotic variables. Additionally, there are several types of Gravitational Wave (GW) events such as neutron star-neutron star (NS-NS) mergers which can result in the formation of kilonovas, neutron star-black hole (NS-BH) mergers, and black hole-black hole (BH-BH) mergers. Each of these high energy events is based upon its own specific physics and detection mechanisms, but all of them require rapid optical follow-up observations. A brief description of the physics and detection mechanism for each type of high energy event follows.

1.1 Galactic Supernova: These are extremely rare events, occurring 2-4 times per century. As such, it is important to have the technical capability to detect galactic supernovae and quickly perform as much follow-on optical backup as possible. When a massive star reaches the end of its life, its core collapses. More than 99% of the binding energy of the resulting neutron star is released in the form of neutrinos and antineutrinos of all flavors, with energies in the tens of MeV (million electron volt) range. The energy leaves via neutrinos/antineutrinos because neutrinos/antineutrinos interact so weakly that they readily leave the star. They bring information from deep inside the stellar core and great insight about core collapse physics. The time scale of neutrino/antineutrino emission is a few tens of seconds immediately after core collapse. The optical photon signal, in contrast, can take hours to days to emerge from the stellar envelope. Therefore, the detection of a burst of neutrinos will give an early warning of the supernova collapse so that optical followup will be possible.

1.2 Gamma Ray Bursts and Afterglow: In gamma-ray astronomy, gamma-ray bursts (GRBs) are extremely energetic explosions that have been observed in distant galaxies. They are the brightest electromagnetic events known to occur in the universe. Bursts can last from ten milliseconds to several hours. After an initial flash of gamma rays, a longer-lived "afterglow" is usually emitted at longer wavelengths (X-ray, ultraviolet, optical, infrared, microwave, and radio). The intense radiation of most observed GRBs is thought to be released during a supernova or superluminous supernova as a high-mass star implodes to form a neutron star or a black hole.

A subclass of GRBs (the "short" bursts) appears to originate from the merger of binary neutron stars. The cause of the precursor burst observed in some of these short events may be the development of a resonance between the crust and core of such stars as a result of the massive tidal forces experienced in the seconds leading up to their collision, causing the entire crust of the star to shatter.

The sources of most GRBs are billions of light years away from Earth, implying that the explosions are both extremely energetic (a typical burst releases as much energy in a few seconds as the Sun will in its entire 10-billion-year lifetime) and extremely rare (a few per galaxy per million years). All observed GRBs have originated from outside the Milky Way galaxy, although a related class of phenomena, soft gamma repeater flares, is associated with magnetars within the Milky Way.

GRBs were first detected in 1967 by the Vela satellites which had been designed to detect covert nuclear weapons tests; this was declassified and published in 1973. Following their discovery, hundreds of theoretical models were proposed to explain these bursts, such as collisions between comets and neutron stars. Little information was available to verify these models until the 1997 detection of the first X-ray and optical afterglows and direct measurement of their redshifts using optical spectroscopy, and thereby indicating their distances and energy outputs. These discoveries, and subsequent studies of the galaxies and supernovae associated with the bursts, clarified the distance and luminosity of GRBs, definitively placing them in distant galaxies.

There are two kinds of gamma-ray bursts, known as long-soft and short-hard, referring to their duration and the nature of their gamma-ray emission. Long-soft bursts last for a few dozens of seconds, and emit less energetic ("soft") gamma rays; short-hard bursts last for a second or less and emit very energetic ("hard") gamma rays.

The long-soft GRBs are the ones which have been detected most often at other wavelengths, and they are believed to be associated with the collapse of supermassive stars, in an event known as a hypernova. When a massive star runs out of the nuclear fuel that makes it shine, the core of the star collapses. If the core collapses into a black hole, the remainder of the star will begin to fall onto it. Black holes sometimes produce jets of material that fly away from the black hole at close to the speed of light, and in a hypernova, the infalling stellar material acts as a source for these jets. These events probably happen dozens of times a day across the entire universe, but we only detect them as a gamma-ray burst if, by chance, the jet from the black hole happens to be pointed in our direction. GRBs produce the most intense radiation along the direction of the jet, and so we only detect them when they're pointed right at us.

Although they haven't been studied as well, the short-hard GRBs are also believed to originate from the formation of a black hole. In this case it is thought that they come from the merger of two black holes or two neutron stars in orbit around one another. Both black holes and neutron stars are very massive and extremely small in size, and when they orbit one another closely, they move very rapidly. If they spiral together and merge with one another, their collision may result in a huge explosion that occurs very quickly, producing a rapid burst of gamma-rays at high energies.

Most of the energy emitted by a gamma-ray burst comes out as gamma-rays, but the jets that create them and the resulting hypernova emits light at other wavelengths too, and by studying the afterglow, more can be learned about the object that created the GRB than can be from just studying the gamma-ray emission. The light emitted in X-rays, optical light, and radio waves can often persist for hours or days after the gamma-ray burst, and because of the nature of radiation at these wavelengths, it is easier to pinpoint where the GRB is from the afterglow than it is from the gamma-ray burst itself. It can be determined what kind of star it was that exploded, how the explosion progressed, or what the environment was like around that star by studying the afterglow.

GRB afterglows are hard to find, but there is now a network of space-based and ground-based observatories dedicated to their detection and localization. Satellites like

Swift are designed to quickly detect and localize GRBs to much higher precision than was previously possible. Satellites can now provide gamma-ray localizations to less than 0.5 degrees (sometimes much less), making it easier for ground-based observers to concentrate their search on a particular spot in the sky. The satellite radios the coordinates back to Earth, and these coordinates are then relayed to observatories around the world via the Gamma Ray Burst Coordinates Network or GCN.

1.3 Cataclysmic Variables: There are several types of Cataclysmic Variables (CVs), including classical novae, dwarf novae, recurrent novae, symbiotic variables, and polars. Classical Novae occurs when runaway nuclear fusion (a thermonuclear explosion) occurs on the surface of a white dwarf. In these systems, the gravitational energy liberated by accreting material from the donor star heats the white dwarf. The white dwarf becomes so hot that its top layer (which will tend to be dominated by hydrogen atoms) will be able to undergo a thermonuclear explosion. The energy of this explosion will dominate over the gravitational energy. The CV will rapidly get extremely bright optically and part of the white dwarf's atmosphere will be expelled into space.

Dwarf Novae are a type of non-magnetic CV where the variability observed is due to variations in the accretion flow onto the white dwarf. For long periods of time, a dwarf nova system will only slowly accrete matter onto the white dwarf. But a change in the viscosity of the accretion disk dramatically increases the rate of mass transfer through the disk, heating the disk. This leads to strongly increased optical output that is typically not as bright as in a classical nova.

Some non-magnetic CVs have undergone only one classical nova over a century of observations, while other non-magnetic CVs can undergo recurrent novae. Most CVs undergoing novae show continuous accretion through the accretion disk, and are thus relatively steady sources outside the nova eruption itself.

Red giants, stars near the end of their lives, have much stronger stellar winds than most stars in the prime of their lives. This allows a white dwarf to accrete at high rates from the wind of the red giant. Such accreting white dwarfs can occur in binary systems where the donor star and the white dwarf are separated by a much farther distance (what is called a "wide binary"). These Symbiotic Stars can undergo some of the same behaviour seen in other accreting white dwarfs, like classical nova.

Polars occur when white dwarfs have the strongest magnetic fields (10-100 million gauss or 1-10 thousand teslas). The exceptionally large magnetic field of the white dwarf can funnel nearly the entire accretion stream of material from the donor directly onto the two magnetic poles, without intermediate steps. The extreme magnetic field dominated accretion onto the poles of the white dwarf shocks the accreting material and generates copious optical light.

1.4 Gravitational Wave Events: Gravitational Wave (GW) events consist of three fundamental types of phenomena. These include Neutron Star-Neutron Star (NS-NS) mergers (also known as Binary Neutron Star or BNS mergers), Neutron Star-Black Hole (NS-BH) mergers, and Black Hole-Black Hole (BH-BH) mergers (also known as Binary Black Hole or BBH mergers). Additionally, kilonovas are associated with NS-NS GW events. A kilonova is a transient phenomenon that is relatively fast (days to weeks timescale) and has a faint visible and infrared optical signature. The radiation is fairly isotropic ejecta emitted at fractions of the speed of light (approximately 30%). The kilonova emissions are powered by the radioactive decay of heavy nuclei within the ejecta from intense bombardment of nuclei lighter than iron by energetic neutrons. Called the r-process, the physics requires an energetic and extremely neutron-rich environment to be effective. The violent matter ejections resulting from the coalescence of two neutron stars can produce such an environment and has been proposed as being the main candidates of kilonovae and the production sites of the heaviest elements in the universe.

2. Instrumentation and Methods

Given the numerous types of high energy phenomena discussed above, as well as the widely varying time scales for these phenomena, an integrated high energy alert network must of necessity incorporate multiple types of detectors and detection systems to take advantage of gaps in coverage of any single individual high energy phenomenon. Each detector/detection system is likely designed for a very specific type of event, such as a galactic supernova. In order to develop an overall integrated high energy alert network, the various individually optimized detectors must be combined to effectively operate as a hierarchical system.

For the proposed integrated high energy alert network, the individual detector/detection systems are described below. Additionally, it is shown how these individual systems can be combined to form an integrated network. There are five main high energy event triggers:

1. SNEWS (SuperNova Early Warning System)
2. LIGO (Laser Interferometer Gravitational-wave Observatory)/Virgo
3. GRANDMA (Global Rapid Advanced Network Devoted to the Multi-messenger Addicts)/Kilonova Catcher
4. NASA Goddard Space Flight Center (GSFC)
5. Zwicky Transient Facility (ZTF)

These systems detect high energy events and trigger the follow up optical/electromagnetic observations by professional and/or amateur telescopes. Detailed descriptions of each of these triggering systems are presented below.

2.1 System/Subsystem Architecture

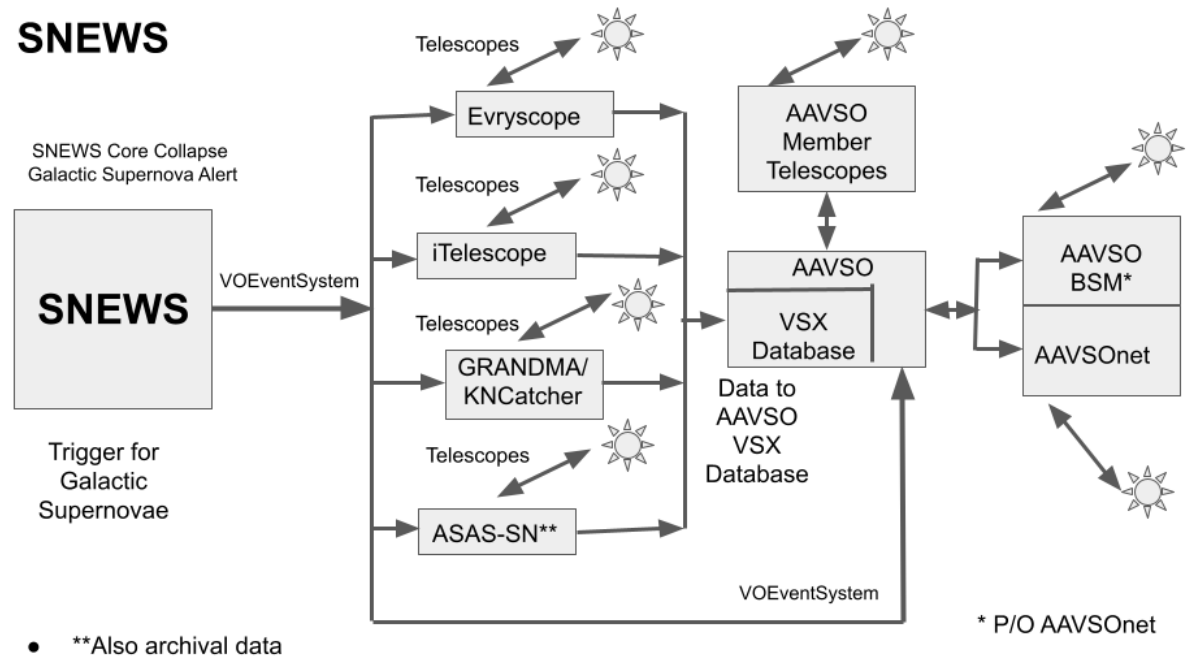

Figure 1: SNEWS (SuperNova Early Warning System); Galactic Supernova Trigger

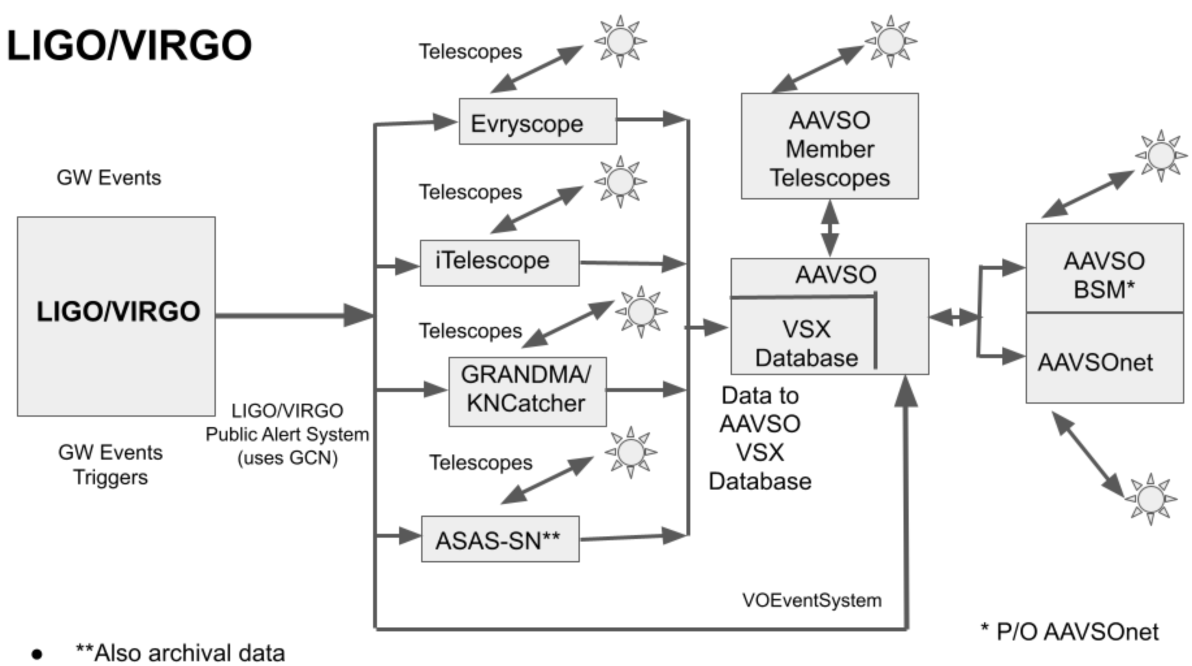

Figure 2: LIGO/Virgo; Gravitational Wave Events Trigger

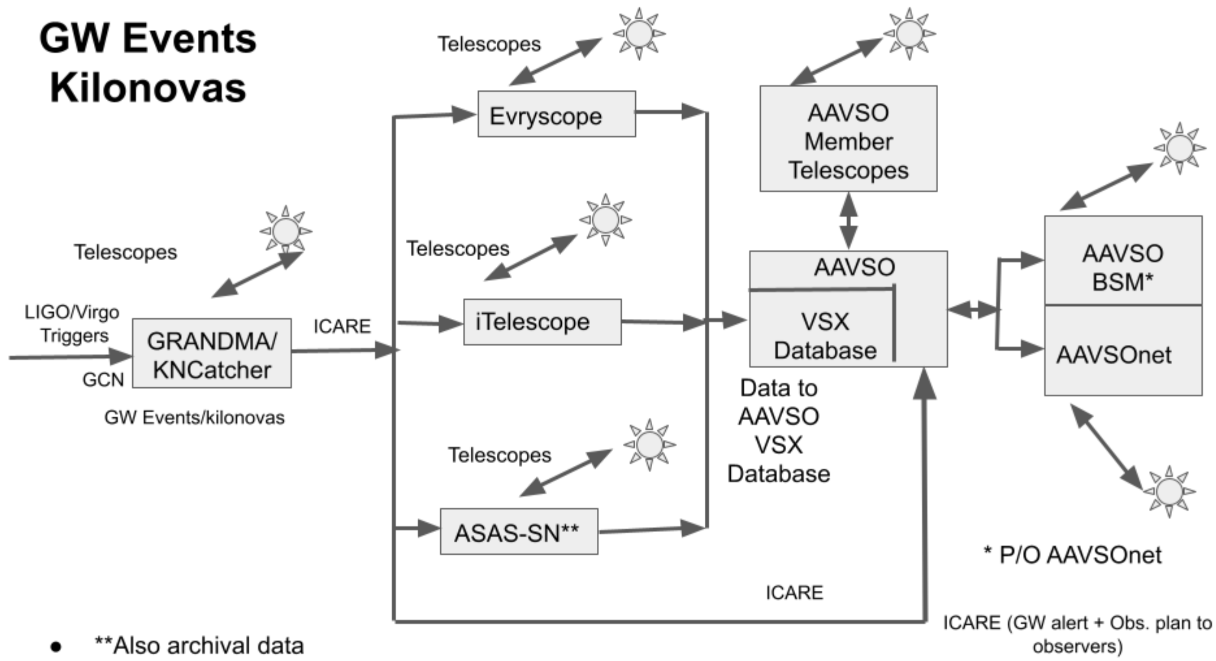

Figure 3: GRANDMA/Kilonova Catcher; follow up optical observations triggered by LIGO/Virgo trigger

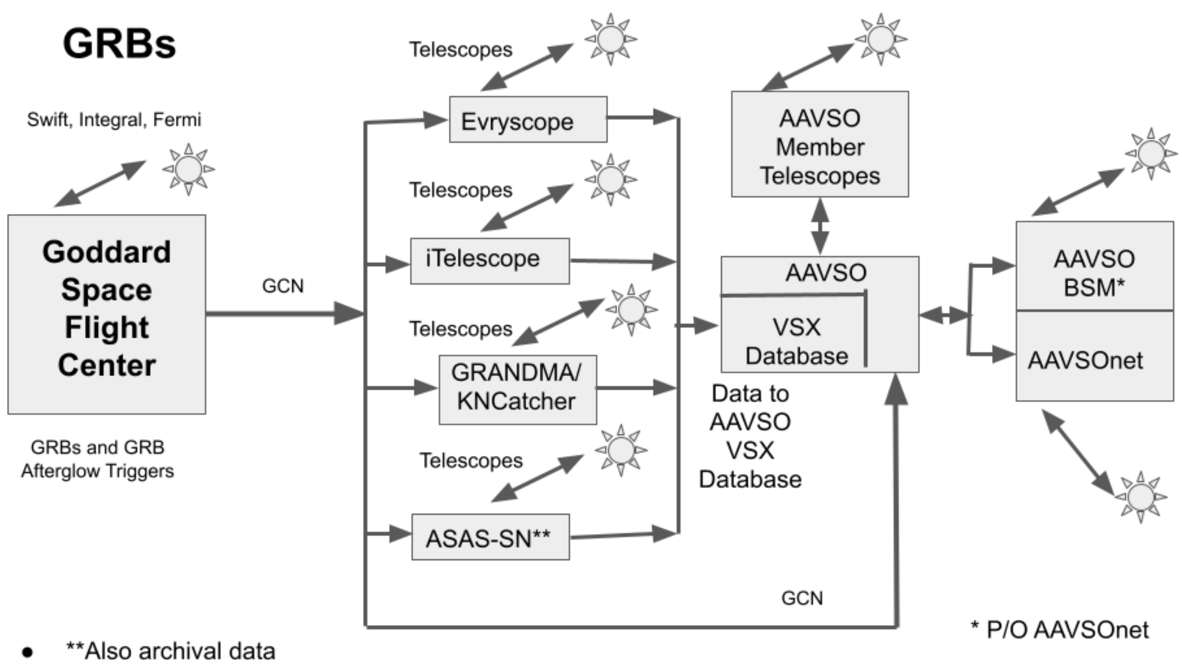

Figure 4: Goddard Space Flight Center (GSFC); GRB/GRB afterglow trigger

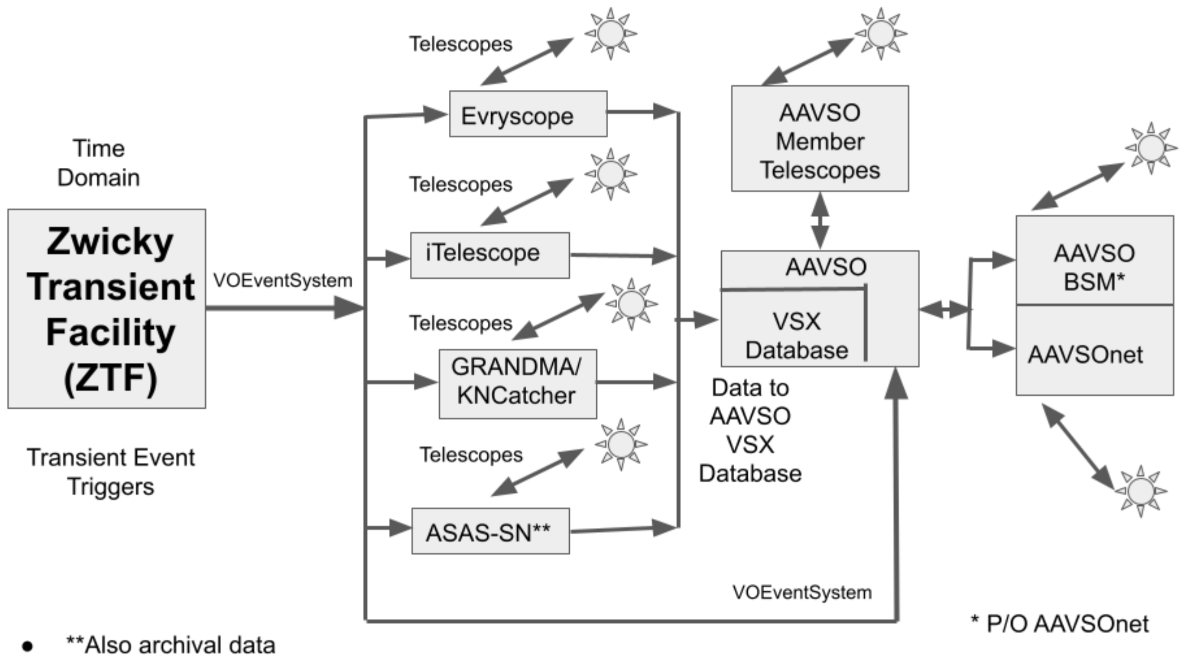

Figure 5: Zwicky Transient Facility (ZTF); trigger for astrophysical phenomena in the time domain

2.2 High Energy Event Triggers and Alerts

2.2.1 GCN: There are two parts to the GRB Coordinates Network (GCN; Transient Astronomy Network (TAN): (1) the distribution of GRB/transient locations detected by various spacecraft, and (2) receiving and automatically distributing to the GRB/transient community prose-style e-mail messages about follow-up observations on various GRBs/transients.

Part 1 (the GCN Notices):

This portion of GCN/TAN consists of distributing the GRB/transient locations determined by the Fermi, Swift, INTEGRAL, IPN (Interplanetary Network), MOA (micro-lensing events), and other spacecraft systems. The collection and distribution of these Notices is done without any humans-in-the-loop, and as such for missions with real-time downlinks, the time delays from when the GRB/transient happened to when the Notices are being sent out the customer/observer is in the 2-10 sec range. Many socket-based and email-based formats and protocols are available. This combining of all the sources of GRB/transient location information into a single network means that user sites need only maintain a single interface for all their GRB/transient needs.

Part 2 (the GCN Circulars):

This part allows the GRB community to submit messages to a central queue where they are automatically vetted and distributed (via email) to the entire GRB community. These are prose-style messages (as opposed to the "TOKEN: value" style of the GCN e-mail Notices) from follow-up observers reporting on their results (detections or upper limits) or for coordinating with others.

2.2.2 VOEvent: VOEvent is a standardized language used to report observations of astronomical events. Though most VOEvent messages currently issued are related to supernovae, gravitational microlensing, and gamma-ray bursts, they are intended to be general enough to describe all types of observations of astronomical events, including gravitational wave events. Messages are written in XML, providing a structured metadata description of both the observations and the inferences derived from those observations. The rapid dissemination of event data with a formalized language was the original impetus for the creation of VOEvents and the network (now called VOEventNet) used to transport the messages over the internet. In addition to distributing alerts regarding astronomical transients, other related information (current telescope pointings, planned observations, provisional classifications, etc.) can be processed. Open-source libraries and tools for working with VOEvents are available. With a little effort and a few lines of Python code, custom filters can be set up that trigger email alerts, SMS text alerts, desktop notifications, or even fully robotic telescope-observation triggers. Additionally, VOEvents describing what has been observed can be published. VOEvent brokers provide real-time alerts from NASA-GCN, Gaia, and ASAS-SN.

A typical VOEvent message contains the following tags:

<who> - describing who is responsible (the author and the publisher) for the information contained in the message
<how> - a description of the instrumental setup on which the data were obtained
<what> - the data (such as source flux) associated with the observations of the event
<why> - inferences about the nature of the event
<wherewhen> - description of the place and time where the event was recorded

A VOEvent Example is shown here.

2.2.3 ICARE: ICARE (Interface and Communication for Addicts of the Rapid followup in the multi-messenger Era), is unique to GRANDMA to support operations and make the collaboration competitive in multi-messenger time-domain astronomy. This infrastructure is composed of a set of tools and interfaces for coordinating telescope operations, easing data reduction and analysis, and allowing automated communications with the transient astronomy community. ICARE relies on the automatic reception of a GW alert and creation of an automatic observation plan that is then sent to the telescopes in the network, a central database, and cloud applications to monitor the full network. The central system is responsible for integrating transient alerts coming from various platforms, such as GCN notices from LIGO/Virgo. The system can also receive the current status of the various observatories in terms of availability and weather forecast. ICARE distributes a dedicated observational plan to all telescopes within the network via a broker delivering standard VO events.

2.2.4 Raspberry Pi: Raspberry Pi is an inexpensive, single board microcomputer that can be programmed for a wide variety of applications. One such application is an alert system that receives, processes, and displays GCN alerts from LIGO/VIRGO, Goddard Space Flight Center, and any detector/trigger that requires a rapid follow-up response (e.g., an optical observation of a Gamma Ray Burst or Gravitational Wave Event). Raspberry Pi can be utilized by amateur observers and/or robotic telescope systems to configure their equipment to perform observations.

2.2.5 Mobile/Cell Phone Apps (iPhone/Android): One potentially important high energy event alert is mobile apps for cell phones, both iPhone and Android. These apps receive a GCN or similar high energy event trigger and generate an SMS/text message to a user's mobile device. This would likely be one of the quickest ways to alert observers that an event has occurred, since cell phone use is ubiquitous. There are two unofficial apps for mobile devices that can be used to view GW alerts on smartphones or tablets. These can be found here Mobile Device GW Alerts.

2.3 High Energy Event Trigger and Alert Priority Levels

One way to prioritize observations is to determine the frequency of occurrence of various high energy events that require some sort of follow-up optical observations. A candidate approach is to assign the highest priority to the rarest events and lower priority to more common events. Therefore, the following priority levels are proposed.

Level 1: Galactic Supernova; 3-4 per century (from SNEWS); all other observations in the system are interrupted/suspended until completion of alert.

Level 2: Cataclysmic Variables; around six galactic novae are discovered each year, while models based on observations in other galaxies suggest that the rate of occurrence ought to be between 20 and 50. This discrepancy is due partly to obscuration by interstellar dust and partly to a lack of observations in the southern hemisphere as well as the difficulties of observing while the sun is up and at full moon (Wikipedia).

Level 3: Gravitational Wave Events; 50-55 per year based upon GRANDMA/KNC LIGO/Virgo Third Operational Campaign (03) alerts.

Level 4: GRBs/GRB afterglow; satellites detect about 1 per day, but it is estimated that roughly 500 are occurring within the same time period. So far, gamma-ray bursts have only been detected in distant galaxies.

Based upon these numbers, they can be normalized to the rarest event, i.e., Galactic Supernova. Assuming 4 per century, this would be 1 per every 25 years. At 6 cataclysmic variable events per year, this would be 150 per 25 years. Gravitational wave events would be in the range of 1250-1375 events per 25 years and GRBs would be 9125 per 25 years. Given these numbers, the four priority levels are as shown above for the corresponding high energy events.

3. Results and Discussion

3.1 SuperNova Early Warning System (SNEWS)

When a massive star collapses at the end of its life, most of the binding energy is emitted in the form of neutrinos and antineutrinos. These neutrinos/antineutrinos come in all flavors and emerge promptly from the stellar envelope over a time scale of tens of seconds. If the star later explodes, the burst of supernova photons does not become visible until hours later. The observation of a neutrino/antineutrino burst can provide a warning that the opportunity to get a rare glimpse at the collapse of a star (called core collapse) resulting in a supernova, may soon present itself. A number of neutrino experiments with sensitivity to a gravitational collapse event in our galaxy are currently online or will be in the near future.

The basic idea of the early supernova alert project is to have a central computer which accepts neutrino burst candidate messages from neutrino detectors around the world and sends an alarm message to astronomers if it finds a coincidence within a short period of time (10 seconds). The central computer is located at Brookhaven National Lab. The coincidence search is both “blind” (decision is made when messages are received without polling the other experiments) and automated (alerts go out without human intervention for maximum speed). The neutrino experiments currently involved are Super-K, LVD, IceCube, Borexino, KamLAND, Daya Bay, and HALO. This is depicted in Figure 6 along with the interface to telescope systems for followup electromagnetic/optical observations.

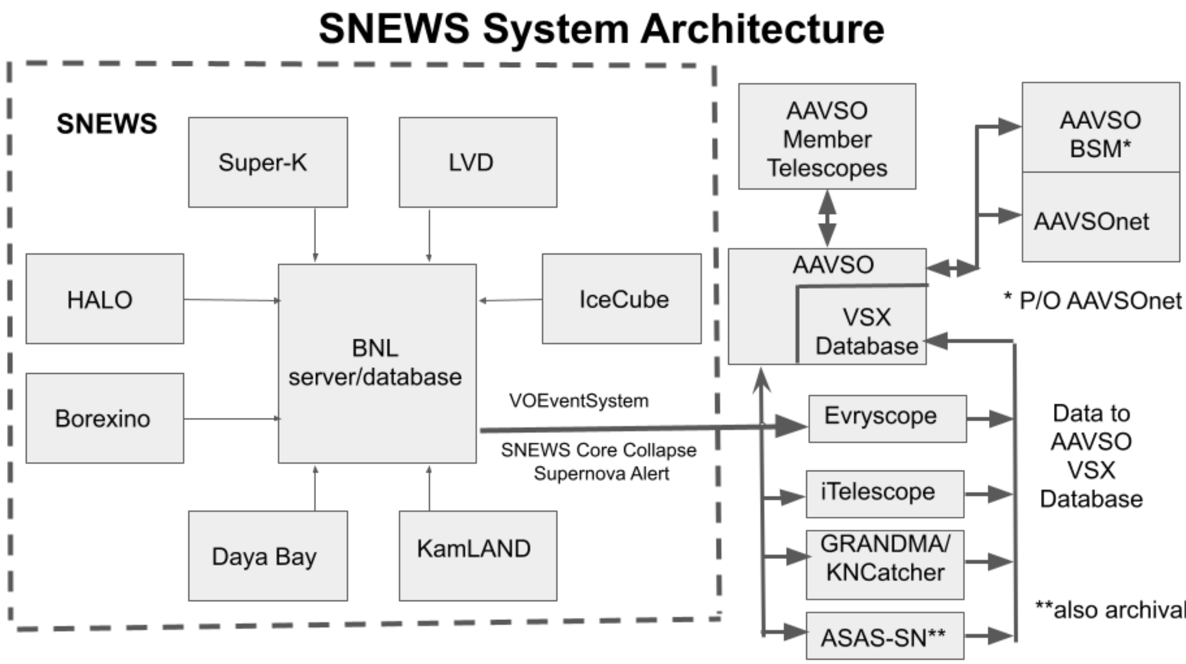

Figure 6: SNEWS Systems Architecture

3.2 Global Rapid Advanced Network Devoted to the Multi-messenger Addicts (GRANDMA)

GRANDMA is a network of 25 telescopes of different sizes, including both photometric and spectroscopic facilities. The network aims to coordinate follow-up observations of gravitational-wave candidate alerts, especially those with large localization uncertainties, to reduce the delay between the initial detection and the optical confirmation. To do so, observation efficiency is characterized in terms of delay between gravitational-wave candidate trigger time, observations, and the total coverage. Using an optimized and robust coordination system, GRANDMA has followed up about 90% of the gravitational-wave candidate alerts. This allows coverage of over 9000 square degrees. The delay between the gravitational-wave candidate trigger and the first observation is typically below 1.5 hour for 50% of the alerts. The coordination of joint observations across a telescope network, above and beyond just recording independent observations from various groups, is an important goal for deriving multi-messenger science with electromagnetic and Gravitational Wave data.

3.3 KilonovaCatcher

Kilonova Catcher is focused on the optical followup of any gravitational wave event that is detected by the currently operating gravitational wave observatories (LIGO/Virgo), specifically to catch the kilonova emissions emerging from the coalescence of two neutron stars bound in a compact binary system. Kilonova Catcher is closely associated with GRANDMA. A functional diagram of GRANDMA/Kilonova Catcher is shown in Figure 7.

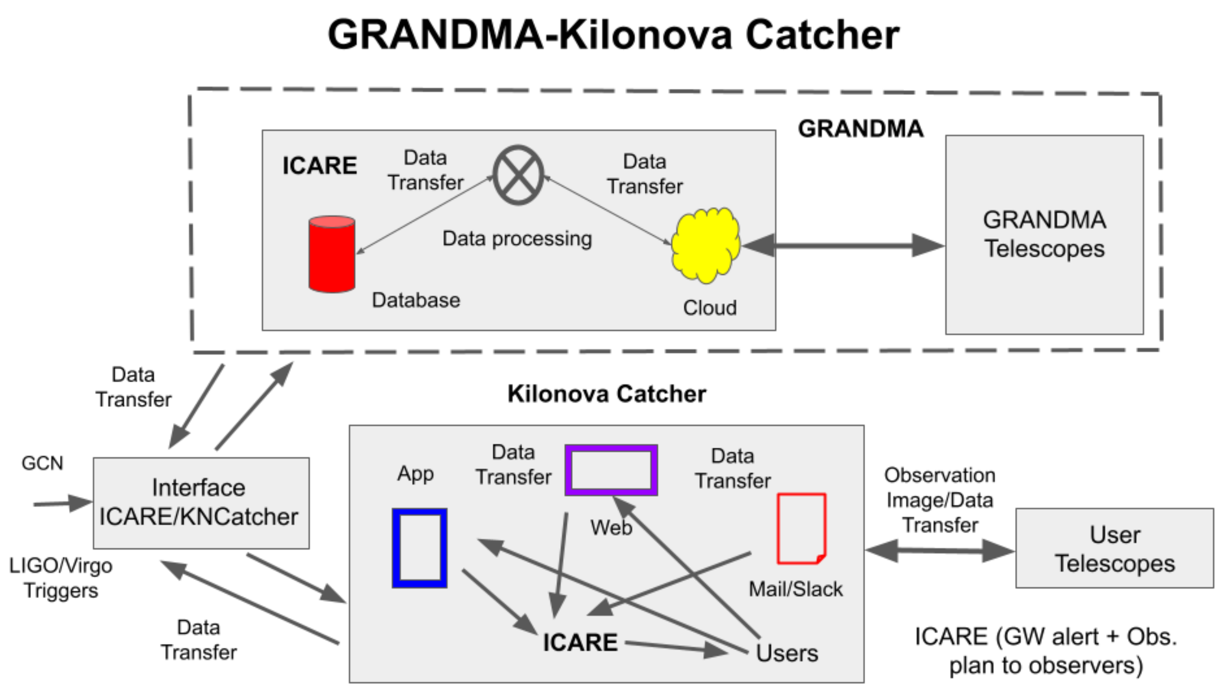

Figure 7: GRANDMA/Kilonova Catcher

3.4 Evryscope

The Evryscope is a telescope array designed to open a new parameter space in optical astronomy, detecting short timescale events across extremely large sky areas simultaneously. The system consists of a 780 Megapixel 22-camera array with an 8150 square degree field of view, 13" per pixel sampling, and the ability to detect objects down to 16 magnitude in each 2 minute dark-sky exposure. The Evryscope, covering 18,400 square degrees with hours of high-cadence exposure time each night, is designed to find the rare events that require all-sky monitoring, including transiting exoplanets around exotic stars like white dwarfs and hot subdwarfs, stellar activity of all types within our galaxy, nearby supernovae, and other transient events such as gamma ray bursts and gravitational-wave electromagnetic counterparts. The system averages 5000 images per night with approximately 300,000 sources per image, and to date has taken over 3.0 million images, totaling 250 TeraBytes of raw data. The resulting light curve database has light curves for 9.3 million targets, averaging 32,600 epochs per target through 2018. The Argus Array, an advanced follow-on system, has received funding from the National Science Foundation.

3.5 iTelescope

iTelescope is a worldwide network of robotically controlled telescopes. It is comprised of four observatories in both the Northern and Southern Hemispheres; Siding Springs Observatory, Australia; Astrocamp, Nerpio, Spain; New Mexico Skies, New Mexico; and Sierra Remote Observatory, California. These observatories host 20 robotic telescopes with varying capabilities controlled across the internet. iTelescope is an important asset for amateur participation in the Integrated High Energy Alert Network.

3.6 All Sky Automated Survey for Super Novae (ASAS-SN)

The All Sky Automated Survey for Super Novae (ASAS-SN) is an automated program to search for new supernovae and other astronomical transients, headed by astronomers from Ohio State University. It has 24 robotic telescopes in both the northern and southern hemispheres. It can survey the entire sky approximately once every day. All the telescopes (Nikon telephoto f400/2.8 lenses) have a diameter of 14 cm and ProLine PL230 CCD cameras. The pixels in the cameras span 7.8 arc seconds, so follow up observations on other telescopes are usually required to get a more accurate location. The main goal of the project is to look for bright supernovae, and its discoveries have included the most powerful supernova event ever discovered, ASASSN-15lh. However, other transient objects are frequently discovered, including nearby tidal disruption events (TDEs), e.g., ASASSN-19bt, Galactic novae (e.g., ASASSN-16kt, ASASSN-16ma, and ASASSN-18fv), cataclysmic variables, and stellar flares, including several of the largest flares ever seen. In July 2017 ASAS-SN discovered its first comet, ASASSN1, and in July 2019 it provided crucial data for the near-Earth asteroid 2019OK. It can detect new objects with magnitudes between 18 and 8. ASAS-SN can also provide an important archival capability for its observations.

3.7 Laser Interferometer Gravitational-wave Observatory (LIGO)

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a large-scale physics experiment and observatory to detect cosmic gravitational waves and to develop gravitational wave observations as an astronomical tool. Two large observatories were built in the United States (Hanford, Washington and Livingston, Louisiana) with the aim of detecting gravitational waves by laser interferometry. These observatories use mirrors spaced four kilometers apart which are capable of detecting a change of less than one ten-thousandth the charge diameter of a proton. LIGO detectors use laser interferometry to measure the distortions in space-time occurring between stationary, hanging masses (mirrors) caused by passing gravitational waves. The distortions in space-time were predicted by Einstein’s General Theory of Relativity. This is shown in Figure 8.

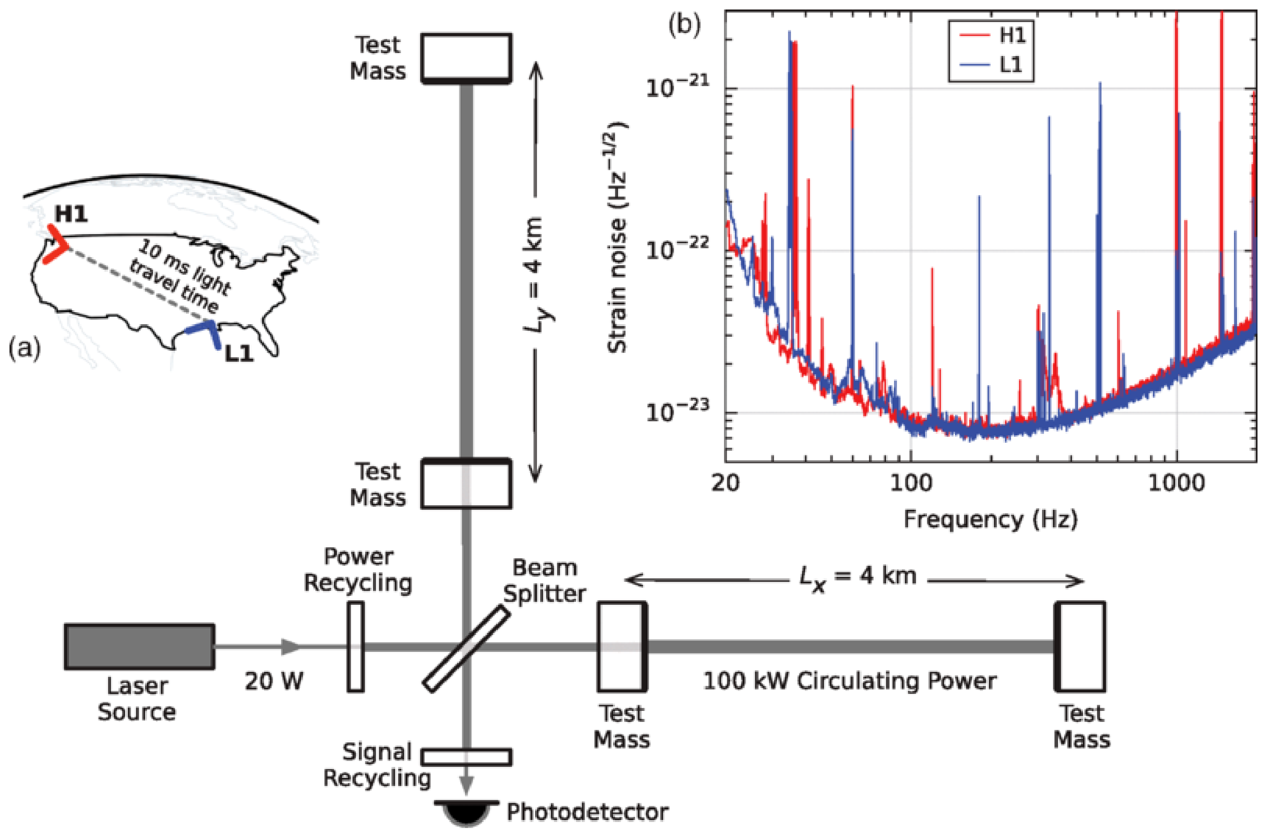

Figure 8: LIGO Gravitational Wave Detector (Abbot, B.P., et.al, LIGO Scientific Collaboration and Virgo Collaboration)

3.8 Virgo

Advanced Virgo is an interferometric detector of gravitational waves hosted by the European Gravitational Observatory (EGO) near Pisa, Italy. It can measure gravitational waves in a wide frequency range; from 10 Hz to 10000 Hz. Advanced Virgo is a laser interferometer with perpendicular, 3 km long arms and suspended mirrors. This is the configuration presently adopted in Advanced Virgo, during the third observation run (named O3, lasting 1 year from April 2019 to April 2020) performed jointly with the two Advanced LIGO detectors in the US. The Virgo system is similar to that of LIGO as shown in Figure 8.

3.9 Zwicky Transient Facility (ZTF)

The Zwicky Transient Facility (ZTF) Observing System (OS) is the data collector for the ZTF project to study astrophysical phenomena in the time domain. ZTF OS is based upon the 48-inch aperture Schmidt-type design Samuel Oschin Telescope at the Palomar Observatory in Southern California. It incorporates new telescope aspheric corrector optics, dome and telescope drives, a large-format exposure shutter, a flat-field illumination system, a robotic bandpass filter exchanger, and the key element: a new 47-square-degree, 600 megapixel cryogenic CCD mosaic science camera, along with supporting equipment. The OS collects and delivers digitized survey data to the ZTF Data System.

The ZTF OS scans large areas of the available sky several times per night to search for transient optical events using near-real-time reference image subtraction. In addition to acquiring 240-300 two-band images at each location in the Northern Hemisphere per year in execution of a fast-transient survey, the full ZTF data set will be combined to create a deep reference field of the Northern declination cap in support of source selection for the Dark Energy Spectroscopic Instrument (DESI) survey (Dey et al. 2018). ZTF prioritizes field of view over depth to bias transient event detection towards targets that are bright enough for follow-up spectroscopy, a fundamental difference and complementary function to the Large Synoptic Survey Telescope (LSST-now called the Vera C. Rubin Observatory). The ZTF OS is designed with 1.01 arcsecond pixel sampling, selected to match the (ZTF-g, ZTF-r, ZTF-i) band image quality of (2.2, 2.0, 2.0) arcseconds full-width at half-maximum (FWHM). For 30 second exposures during dark time, the 5-sigma limiting magnitude of ZTF in (ZTF-g, ZTF-r, ZTF-i) band is (21.1, 20.9, 20.2). By reducing overheads from 46 seconds to 8.66 seconds, through faster CCD readout and telescope and dome drive upgrades, it has been possible to reduce exposure time from 60 seconds to 30 seconds, improving nightly frame rate by a factor of 2.7, and increase open-shutter duty cycle from 57% to 78%, another factor of 1.3, all while remaining sky noise limited (darkest Palomar sky signal in ZTF-r band > 25 e- /s/pixel). At 386 mm × 395 mm corner to corner and 86.7% fill factor, the ZTF CCD mosaic has 8% greater field of view than the 14-inch photographic plates used on the same telescope during the two color Palomar Optical all Sky Survey (POSS) from 1950 to 1957 (Minkowski & Abell 1963). ZTF observes the same number (33,660) of square degrees as POSS to similar depth, in just 8 hours per color, revisiting the same coordinates several times per night. Images are relayed in near real time to Caltech's Infrared Processing and Analysis Center (IPAC), where they are processed and compared automatically to detect new transients within minutes of the latest observation. At a slower rate, IPAC processes fully calibrated data and also houses a legacy archive of all ZTF data.

3.10 NASA Goddard Space Flight Center (Astrophysics Science Division)

The Astrophysics Science Division supports the GSFC astrophysics projects by providing scientific leadership and undertakes a research program to achieve NASA's strategic science goals. The key questions addressed by the Division's research programs include:

- How do galaxies, stars, and planetary systems form and evolve?
- What is the diversity of worlds beyond our solar system?
- Which planets might harbor life?

- What powered the big bang?
- What is Dark Energy?
- What happens to space, time and matter at the edge of a black hole?
- What are the cycles of matter & energy in the evolving universe?

To do this the division conducts a broad program of research in the realm of Astronomy, Astrophysics and Fundamental Physics. This is the study, by way of photons, particles, and gravitational waves, of processes in cosmic sites and the physics principles operating therein. These involve complementary studies using sub-millimeter, infra-red, optical, uv, x-ray, and gamma-ray wavelengths, gravitational waves, and energetic charged particles. The division scientists develop theoretical models of the origin and structure of astrophysical objects and processes, design experimental approaches and hardware to test these theories, and interpret and evaluate data gathered from the experiments, archive and disseminate the data, provide expert user support to the community, publish conclusions drawn there-from, and undertake education and public outreach programs centered on the Divisions science missions.

Additionally, GSFC Astrophysics Science Division operates several spacecraft assets involved in high energy phenomena, specifically Gamma Ray Bursts, including Swift, Fermi, and INTEGRAL. These assets provide triggers, via GCN, to cue the various telescope systems for optical followup of Gamma Ray Burst and afterglow events.

3.11 AAVSO (American Association of Variable Star Observers)

The AAVSO is a non-profit worldwide scientific and educational organization of amateur and professional astronomers who are interested in stars that change in brightness—variable stars. This is accomplished by carrying out the following activities:

- observation and analysis of variable stars
- collecting and archiving observations for worldwide access
- forging strong collaborations between amateur and professional astronomers
- promoting scientific research, education, and public outreach using variable star data

As a component of an Integrated High Energy Alert Network, the AAVSO contributes several important functions. First and foremost, the AAVSO members are experienced and sophisticated observers that can quickly respond to high energy alerts with a combination of personal and robotic telescopes. In addition, the AAVSO has its own robotic telescope network, the AAVSOnet. The AAVSOnet is a network of remote, robotically controlled, and automatically queued telescopes for the use of its members. The telescopes are automatically scheduled using ACP, with image acquisition and telescope control by MaxIm DL. Time on the telescopes is shared between AAVSO key projects (primarily surveys and field calibrations) and AAVSO member programs. AAVSOnet telescope time is awarded on a nominally competitive basis, although the systems may be used by members for any reasonable purpose if time is available.

An important subset of the AAVSOnet system is the Bright Star Monitor (BSM) component, consisting of six observatories. They offer members an opportunity to do CCD multi-filter observations of stars from 2.0 to 13.6 in Vmag with robotically controlled telescopes that are located from New Hampshire to Australia. Images are automatically calibrated and are provided to the user for analysis. They can also be directly forwarded to a VPhot account. VPhot is an online tool for photometric analysis. Users can upload their own FITS images to VPhot or have images taken via the AAVSOnet or BSM which are automatically sent to the user's VPhot account. VPhot will undoubtedly play an important role in the processing of images taken for optical followup of high energy events.

Finally, the AAVSO hosts the VSX (Variable Star Exchange) database. The mission of VSX is to bring all new information together in a single data repository, make it accessible to the public via a simple web interface, and provide the tools necessary for the controlled and secure revising of the data. Web-based tools for querying VSX in various ways are available to the public. The public data returned in a query transaction contains all the accumulated data for the most recent revision level for each star in the recordset, including details of all modifications made to the data, and references to support those changes. Previous revisions may also be viewed. The public interface does not include the means for modifying the data in any way (only registered users may do this). As indicated in Figures 1-6, the AAVSO VSX database could easily be utilized to collect the data obtained by observers for optical followup of high energy events.

4. Conclusion

Given the numerous types of high energy phenomena discussed above, as well as the widely varying time scales for these phenomena, an integrated high energy alert network must of necessity incorporate multiple types of detectors and detection systems to take advantage of gaps in coverage of any single individual high energy phenomenon. Each detector/detection system is likely designed for a very specific type of event, such as the neutrino detectors for galactic supernovae. In order to develop an overall integrated high energy alert network, the various individually optimized detectors must be combined to effectively operate as a hierarchical system. It would be highly advantageous if a system could be implemented to not only detect the rare Galactic Supernovae, but also more frequently occurring high energy events such as Gamma Ray Bursts (GRBs), Gravitational Wave (GW) events, and Cataclysmic Variables (CVs) such as classical and dwarf novae. This paper presented such an integrated high energy alert network. However, such a complex system requires a top-down systems engineering approach in order to ensure seamless end-to-end operation across all high energy events. Appendix A briefly summarizes the salient points and features of the System Engineering approach.

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Appendices

Appendix A - Systems Engineering Approach

Systems Engineering is a developmental methodology and the application of techniques designed to break down very complex systems into subsystems and subfunctions, hardware and software components, and operational considerations to ensure that all parts of the overall system are able to work together such that the system meets all of its desired performance goals. Systems Engineering includes such things as concept development/concept of operations, system requirements definition, system architecture configuration, internal/external interface definition, performance and test requirements, detailed design of hardware/software/firmware subsystems, systems integration, system test and evaluation against test specifications, and even training procedures. Incorporation of Systems Engineering methodology and techniques will be critical for the successful development and operation of an Integrated High Energy Alert Network.