

GRAVITATIONAL WAVE BURST SEARCH

THE BURST GROUP

1. CHARACTER OF PROPOSED ACTIVITY

We will prepare for, carry out, and report on a search for burst-like events of gravitational wave origin in data to be collected in an Engineering Run that will have coincident data from operating interferometers at both Hanford and Livingston (hereinafter referred to as the Science Analysis Challenge or SAC).

By “burst-like events” (hereinafter “bursts”) we refer in the most general sense to transients, of gravitational wave origin, in the output of the interferometers. To limit the search to a practicable scope, we will identify bursts through the use of *filters* designed to span a rather general class of transients in the output (such as might be expected of impulsive events, like black hole ringdown or supernovae), rather than a set designed to match detailed models of gravitational waveforms. Thus, we describe our method as a search for “unmodeled” sources, rather than one based on, e.g., matched templates or other specialized methods.

Two lines of analysis are proposed. The first is driven by observations at the LIGO detectors. The second is driven by other, non-gravitational wave observations: e.g., triggers coming from SNEWS or operating γ -ray burst detectors.

This activity is simultaneously a “proof of principle” demonstration of a search for unmodeled bursts, a prototype development of one set of techniques for identifying and characterizing generic candidate gravitational wave bursts, a LAL and LSC software development effort and system test, and a data processing/interpretation activity. The over-arching goal of this activity, which will resolve all conflicts between these activities, is the analysis of detector data using the tools and techniques that will be used to analyze science run data.

2. SCIENTIFIC AND TECHNICAL RATIONALE

Strong gravitational wave sources involve the coherent acceleration of large mass concentrations to relativistic velocities over small distances. Strong electromagnetic sources, on the other hand, involve the incoherent motion of large numbers of charged particles. Consequently, the electromagnetic sky is not necessarily a good predictor of the gravitational wave sky. As our real expectations of astronomical gravitational wave sources are conditioned by our understanding of the sky through electromagnetic channels, there is good reason to search seriously for gravitational wave sources that are entirely unanticipated.

Even among sources that are anticipated, not all can be or have been well modeled: for example, the detailed waveform of gravitational waves from stellar core collapse remains

unknown. A search for unanticipated sources is necessarily a search for unmodeled ones; correspondingly, a search for unanticipated sources is also a search for anticipated sources that are not well-modeled.

When a signal is well-modeled — e.g., there is a well-defined waveform — then “detection” focuses on recognizing that unique signature in the detector output. When the signal is not well-modeled, however, detection involves distinguishing the signal from system noise. Such a distinction is possible only to the extent that the system noise can be characterized and that candidate bursts can be distinguished from instrumental or environmental artifacts. Thus, the search for unanticipated gravitational wave signals carries with it a greater than usual burden for excluding the possibility that the observed signal is of instrumental or other terrestrial origin. In making this distinction we are aided by

- LIGO’s large set of interferometer diagnostic channels and PEM channels, which will enable us to check for many plausible instrumental and environmental causes for a false gravitational wave signal; and
- the availability of signals from three interferometer at two sites, which will allow us to require that an actual burst must appear in the two detectors with similar signature, an appropriate amplitude ratio at the two sites, and within a time window consistent with a signal that travels at the speed of light.

The need for close collaboration with other gravity wave (GW) detectors and with other experiments capable of detecting other signatures of large scale cosmic events (e.g. neutrinos, GRB and optical) is particularly important for unmodeled burst searches. Correlations like these have the potential to dramatically increase our understanding of astronomical phenomena; additionally, coincident detection of a burst by LIGO and other cosmic burst sensitive searches may significantly increase the credibility and sensitivity of LIGO observations.

The proposed activity contributes directly to our principal goal of gravitational wave detection and the scientific investigations it enables. Additionally, owing to its strong emphasis on detector and data characterization, the proposed activities will contribute directly to our understanding of the cross-couplings between the “h”-channel and interferometer diagnostic or PEM channels at each detector, to our knowledge of the rate and character of terrestrial noise bursts at each detector and correlated between the two LIGO sites, and to the store of tools and techniques for detector and data characterization.

3. TECHNICAL APPROACH

Two lines of investigation are proposed. The first is driven exclusively by gravitational wave observations at the LIGO detectors. The second is driven by triggers arising from SNEWS or γ -ray burst detectors.

3.1. LIGO-driven analysis. We describe our search in four parts: *i*) preparation of the data for the identification of burst candidates; *ii*) identification of candidate bursts; *iii*) reduction of the candidate list by eliminating events of instrumental or environmental origin, or inconsistent with gravitational wave origin; and *iv*) interpretation. The first two steps take place separately at each detector. The third step starts separately at each interferometer

with the examination of environmental sensors and diagnostic signals, then continues with comparison of event lists from different detectors (including non-LIGO gravitational wave detectors). Interpretation of any gravitational wave burst candidates that survive beyond the third step, or the absence of any surviving bursts, takes place in the fourth and final stage of the analysis.

We assume the availability, at each detector, of $h(t)$ and a binary veto channel. We require approximate calibration information at the time of first analysis for the identification of burst candidates; however, we will require more precise information to set upper limits or interpret any bursts that are identified. Finally, simultaneous with $h(t)$ we assume the availability of data from select TBD PEM and interferometer diagnostic channels.

Data preparation. The “raw” detector data stream includes instrumental and environmental artifacts: e.g., suspension violin modes and spectral lines from the power mains. Data preparation involves removing these instrumental artifacts from the data stream¹ and possibly further whitening of the data stream.

The veto signal provided by the instrument team will necessarily be general. Data preparation may include also the generation of search-specific vetoes (to be determined) in the DMT.

Identification of candidates. The key component of the search is the identification of candidate bursts. The generation of candidate event lists will take place separately at each detector. The gravitational wave channel will be passed through a set of filters and the distribution of filter outputs constructed. Outliers in this distribution become candidate events.

This framework is specifically designed to be flexible enough to support different means of resolving the gravitational wave channel into sub-bands, identifying statistics on the sub-bands, and identifying epochs when the detector output is uncharacteristic of its behavior in the mean. Several different methods of resolving data segments into sub-bands will be investigated, including but not limited to a classical time-frequency analysis [1, e.g.,] and a wavelet-based analysis. If preliminary investigations suggest that these different methods have different efficiencies in identifying bursts of different character than all may be carried in the final analysis. *Our guiding principle will be to span as wide a space of possible transients as can be handled*, bearing in mind the the loss of significance associated with too exhaustive a filter space.

Event identification involves comparing the filter outputs to their overall distribution, which is identified from the data itself over epochs long compared to the support of the filter. These distribution will be determined “on-the-fly” using past history and then monitored and periodically updated to accommodate slow non-stationarities in the detector noise. Thresholds and efficiencies will be determined by Monte Carlo simulations. Efficiencies, in particular, will be evaluated over several classes of “bursts”, including but not restricted

¹This activity cuts across all of the upper limit groups.

to *i*) δ -functions (i.e., broadband bursts), *ii*) “ δ ”-functions with ms timescale (i.e., broadband to KHz frequencies), *iii*) sinusoidally modulated exponentially damped impulses (i.e., “black-hole ringdown”), *iv*) sinusoidally modulated gaussian pulses.

Reduction of candidate lists. The goal of this analysis step is to sort the candidate events into two classes: those that might have gravitational wave origin and those that cannot be genuine. The first part of this sort procedure will take place at each detector; the second part will involve the comparison of the remaining candidates at each detector for consistency with gravitational wave origin.

Simultaneously with the generation of candidate events a list of detector diagnostic and PEM “vetoes” will be generated and candidate events found to be in coincidence with veto events discarded. The specific diagnostic and PEM channels to be monitored is to be determined. For channels with small transfer functions to the “h” channel the veto list will be generated using the transient detection software being developed in the DMT. For channels with insufficient isolation from the gravitational wave channel we will use the same set of filters and statistics as is used to generate the candidate event list itself, in order to guarantee sufficient sensitivity.

The remaining list of candidate events at each detector will be checked for coincidence consistent with a plane wave incident on the two interferometers. This comparison involves event arrival time, amplitude, and character (as determined by individual statistics that characterize each sub-band); it may also involve cross-correlation of data from the individual detectors in short intervals surrounding the coincident events. Events on either list that do not correspond in this way to an event at the other detector will be discarded.

A crucial result of this activity will be knowledge gained about the performance of the interferometers: in this case, their tendency to generate spurious bursts. This requires a program of experimental characterization and optimization of the burst sensitivity of the interferometers, *prior* to the collection of science data. The focus of this experimental characterization activity is the identification and investigation of interferometer artifacts that overlap strongly with potential burst signals, with the goal of determining how this corresponding contamination can be mitigated by vetoes based on other data or by modifications to the “tuning” of the control or data acquisition parameters. Some investigations will be carried out in real time during scheduled engineering runs, while others will be carried out off-line using data recorded during such runs.

Interpretation. The final candidate event list will be interpreted in several different ways. As part of the qualification of the analysis pipeline, its detection efficiency and false alarm rate will be determined through Monte Carlo studies, which include the injection in hardware and software of a variety of test signals (see above). The final candidate event list will be interpreted in terms of an excluded region of a rate *vs.* strength diagram for an appropriate sub-set of these test signals. Individual events that may remain on the list will receive special treatment and interpretation. Finally, should the list contain more than a single event, events will be compared and cross-analyzed to assess whether they may be of common origin.

Other gravitational wave detectors. It is anticipated that ALLEGRO and GEO 600 will be collecting data simultaneously with LIGO during the SAC run. Fully characterized and qualified event lists generated by each of these detectors will be included in the coincidence analysis described above, as an additional layer above the LIGO detector coincidence analysis. Time and resources permitting these event lists may be generated using the same LDAS tools as are used to generate the LIGO candidate event lists. Discussions are underway with the IGEC, which may lead to the inclusion of additional event lists from that detector network as yet an additional layer, atop the LIGO, and LIGO/ALLEGRO/GEO, coincidence analysis.

3.2. External trigger analysis. This second line of analysis is driven by external triggers provided by, e.g., the SNEWS network or other operating γ -ray burst detectors, referred to hereafter as external events. The general method of analysis follows [7] and is summarized briefly here.

External events are distinguished phenomenologically: e.g., they may be γ -ray bursts, or supernovae, or Each external trigger suggests, through its associated astrophysical model, a possible gravitational wave burst arriving from a given direction at a related time. The total energy in the cross-correlation of the several operating detectors, over the expected arrival time, will be accumulated for all bursts associated with a common trigger. A larger set of cross-correlations, chosen at random times and for random sky directions, will also be calculated. Using Student's t -statistics these two distributions (associated with a source class and unassociated with any source class) will be compared for equality and an upper-limit on the rms in-band wave strength associated with that source class determined. For more details see [7].

This proposal is linked to the proposed LIGO supernova search (LIGO-G000313-00-D). That team has already explored established links with with neutrino, Gamma Ray (GRB) and astronomical searches and receives real time alerts from the SuperNova Early Warning System (SNEWS, a world-wide network of neutrino burst sensitive detectors) and GCN (formerly Bacodine, a global network of Gamma Ray Burst detectors).

4. DELIVERABLES

4.1. Software. All software will conform to the applicable standards.

- A (TBD) refined set of DMT monitor processes to trigger on burst-type events generated by the machine and the environment.
- An LDAS Filter system that
 - Analyzes conditioned data against an arbitrary basis of sub-filters,
 - Accumulates arbitrary statistics against the output of the sub-filters,
 - Reports the statistics to the metadatabase.
- Suspension violin mode line removal action for the LDAS datacondAPI (following [8]);
- Power-main spectral line removal action for the LDAS datacondAPI (following [6]);
- Auto- and cross-correlation and spectral analysis tools, implemented in either the datacondAPI or as an LDAS Filter;

- Post-processing analysis tools (which interface to the metadatabase):
 - An event “cluster analysis” tool, to handle cases (expected to be common) when a single event causes large excursions in the outputs of multiple triggers. This tool will recognize clusters, and choose the filter(s) that give the best characterization of the event.
 - An event correlation tool, to study the match between different signal channels for each event.
 - A histogram tool, for graphical display of data.

The following software analysis tools exist outside LDAS and any other LIGO/LSC defined tool-kit (e.g., NASA’s `autoclass` [3, 5, 2, 4, 9, 10, 11]):

- A system that evaluates a mixture Gaussian model of the distribution of events (retrieved from the database)
- A system that evaluates outlier events in the context of a mixture Gaussian distribution.
- Software for a Monte Carlo simulation of the analysis pipeline, determining false rates and detection efficiencies.

Finally, time permitting

- An LDAS Filter system that uses pattern recognition techniques to evaluate time-frequency or time-scale data for recognition of bursts that extend beyond the duration limit of our filter bank.

4.2. Databases.

- Statistical characterization of select PEM and IFO diagnostic channels;
- Transfer functions from select PEM and IFO diagnostic channels to the gravitational wave channel;
- Lists of characterized instrumental and environmental burst artifacts at each detector.
- Lists of characterized environmental burst artifacts cross-correlated between each detector, and between the PEM monitors in one detector and the “h”-channel in the other.
- A list (possibly empty) of candidate gravitational wave burst events.

4.3. Reports.

- A report describing the methods of the search and the results of tests of its effectiveness.
- A report describing the characterization of select PEM and interferometer diagnostic channels, including channel statistics and the transfer functions from the IFO/PEM channel to the gravitational wave channel.
- A report giving a detailed account of the results of the search.
 - Events found to be correlated between IFO diagnostic or PEM channels and the “h”-channel in each detector;
 - Events that pass the final cut in each detector (before checking for coincidence with the other detector);
 - Events that pass the coincidence check between detectors.

- Events found to be correlated between PEM channels at the different sites, or between PEM and “h”-channels at different sites.

4.4. Papers.

- For submission to PRL, a summary of the analysis and its results, tentatively titled “Results of the first LIGO search for gravitational wave bursts.”
- For submission to PRD, a detailed presentation of the analysis methodology and the results, tentatively titled “LIGO search for gravitational wave bursts.”

5. REQUIRED RESOURCES

5.1. Data.

- The SAC data set, including calibrated “h”, a quality bit channel, and other TBD select PEM and detector diagnostic channels;
- Extended data samples from prior engineering runs (for detector characterization and testing purposes).

5.2. Hardware.

- DMT specialized trigger generation;
- LDAS for data conditioning, analysis and event generation, and external event driven detector cross-correlations;
- LIGO metadatabase for trigger and event storage and retrieval.

5.3. Software.

- LDAS
 - managerAPI,
 - frameAPI,
 - datacondAPI,
 - metadataAPI,
 - eventmonAPI,
 - mpiAPI,
 - wrapperAPI
- DMT

6. MANAGEMENT

The search will be led by co-chairs Finn and Saulson, reporting to the LSC Spokesperson and to the LIGO Lab management. Responsibility for particular tasks identified on the attached Gantt chart have been assigned Task Leaders, who will coordinate the burst groups work in these areas

- DMT Triggers : J. Zweizig
- Data conditioning: S. Finn
- Filter development : E. Katsavanoudis
- Monte Carlo pipeline studies : A. Weinstein

- Post-processing tool development : D. Sigg
- External detectors and triggers : S. Marka
- Interferometer diagnostic studies : D. Shoemaker
- Burst analysis system integration: S. Finn

Task Leaders will meet with the co-chairs once a week to review progress and coordinate activities.

6.1. **Human resources.** The following estimates are *estimates*. One of the first responsibilities of the Task Leaders is to articulate in greater detail the scope of each task and refine the schedule and scope in light of the available resources. Estimates are integrated person-months:

- DMT Triggers: 3.0
- datacondAPI development: 3.0
- LDAS Filter development: 3.0
- Analysis pipeline integration: 1.0
- Monte Carlo tool development 3.0
- Post-processing tool development: 6.0
- External detectors and triggers: 2.0
- Interferometer Diagnostic Studies: 2.0
- Database generation: 5.0
- Interpretation: 2.0
- Results reports: 3.0
- Publications: 2.0

Total estimated person-months: 35.0

7. SCHEDULE

A *preliminary* schedule with milestones is provided on the attached Gantt Chart. One of the first responsibilities of the Task Leaders is to articulate in greater detail the scope of each task and refine the schedule in light of the available resources.

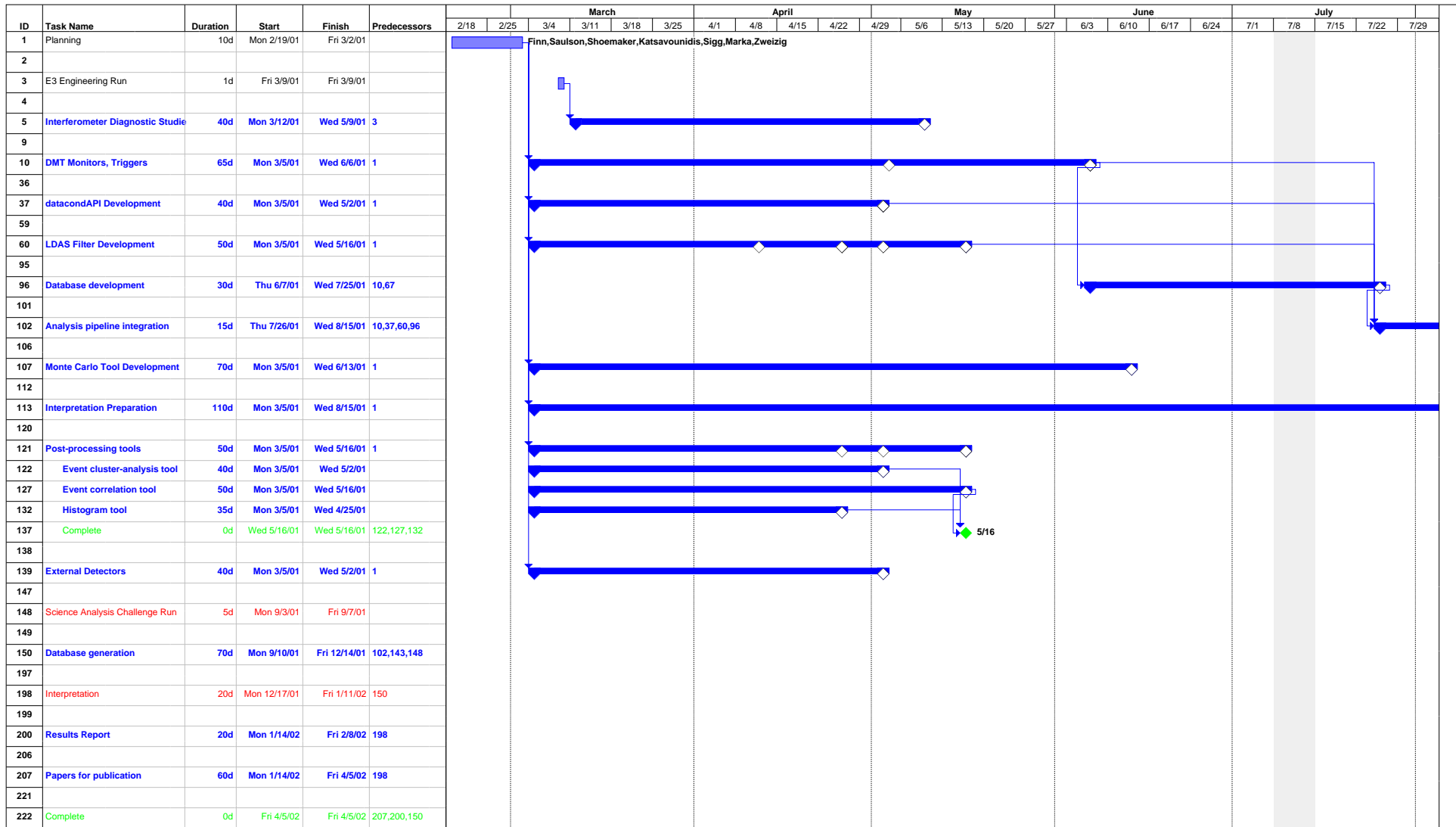
8. INCHPEBBLES

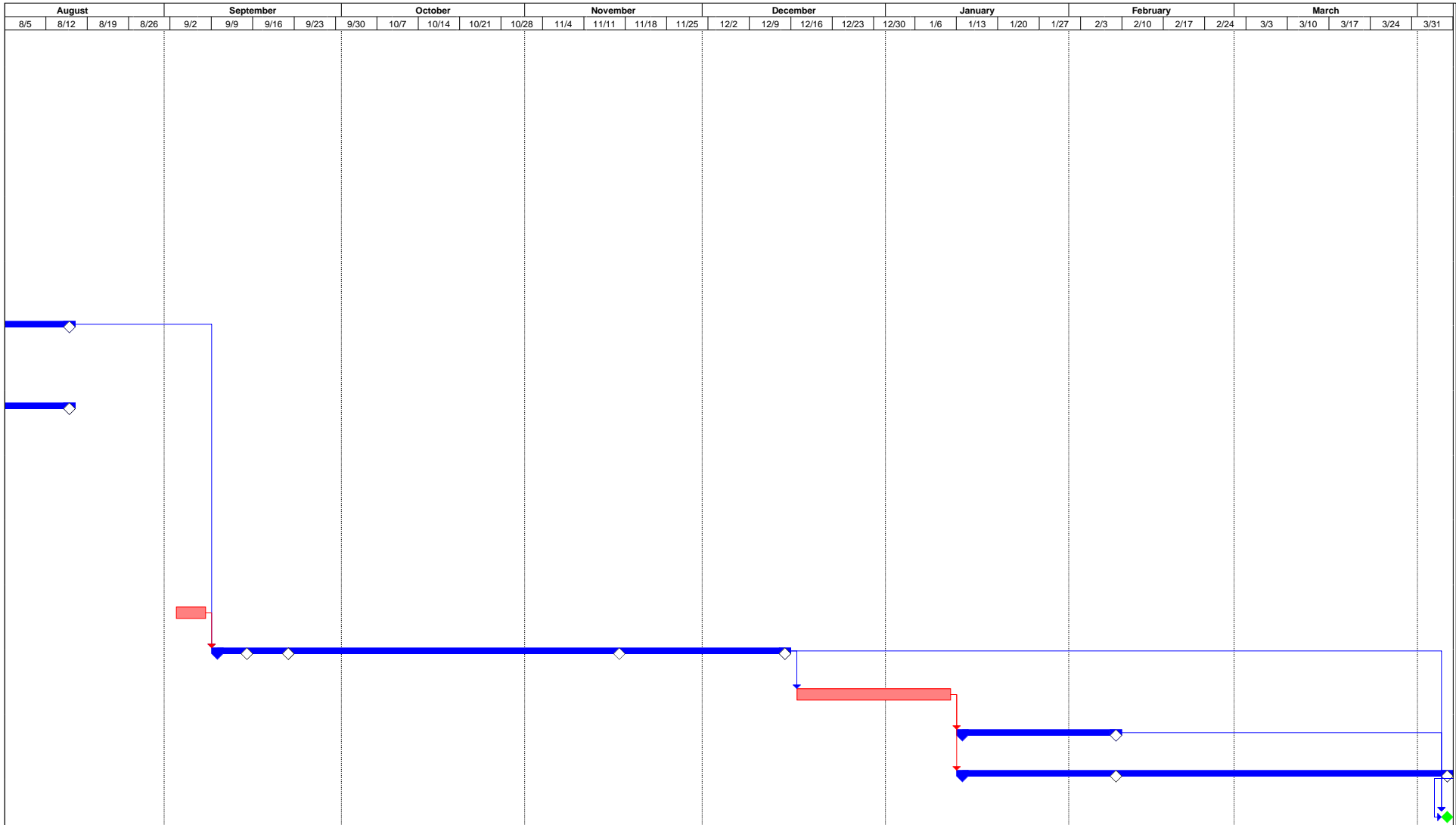
We identify the analysis system integration, which tests the analysis system pipeline beginning with the DMT and including the datacondAPI, the LAL analysis engines, and database registration, as an inch pebble.

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Project: Gravitational Wave Burst Upper Limit Analysis
 Date: Sun 2/18/01

Task		Progress		Summary		Rolled Up Critical Task		Rolled Up Progress	
Critical Task		Milestone		Rolled Up Task		Rolled Up Milestone			