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NASA's astrophysics cross-observatory science support (ACROSS) initiative: enabling time-domain and multimessenger astrophysics

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The Astro2020 Decadal Survey recommended an investment in Time-Domain and Multimessenger Astrophysics (TDAMM) as the top-priority sustaining activity in space for the coming decade. One aspect of NASA's response to this recommendation is a pilot project, the Astrophysics Cross-Observatory Science Support (ACROSS) initiative, designed to provide support to both missions and observers as they pursue TDAMM science. Here, we present our observations of needs in the community and initial plans for ACROSS activities, including services to facilitate and improve cross-mission follow-up planning and execution; a multimessenger web portal with links to existing mission resources, community tools, and information targeted for TDAMM general observers; development of "Smart target-of-opportunity submission page" proof-of-concepts; and ongoing development of a potential TDAMM general observing competitive grant solicitation. As the ACROSS pilot phase begins, we invite discussion of our plans with both missions and observers to better understand their needs and concerns.

KEYWORDS

time domain, multimessenger, infrastructure, realtime, software

1 Introduction

Driven by the exciting firsts of 2017 – the first coincidence of a gravitational wave (GW) event, GW170817, with a short gamma-ray burst (GRB), kilonova, and off-axis jet (Abbott et al., 2017) and the first strong indication of an association between an astrophysical neutrino, IceCube-170922, and an active galactic nucleus (AGN), TXS 0506 + 056 (IceCube Collaboration et al., 2018) – the new capabilities encompassed by Time-Domain and Multimessenger Astrophysics (TDAMM) were called out highlighted by the Astro2020 Decadal Survey (National Academies of Sciences, Engineering, and Medicine, 2023) as the "highest priority sustaining activity" in space for the coming decade.

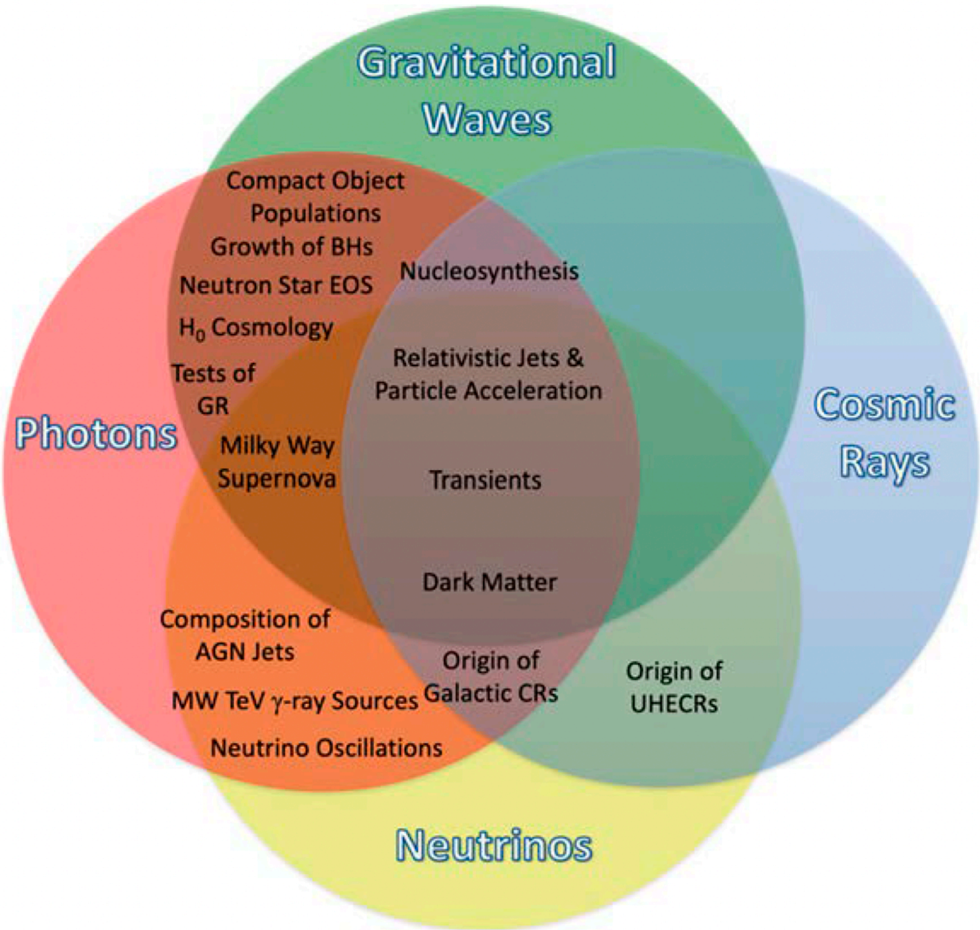

FIGURE 1
A schematic diagram indicating the science questions best answered by different combinations of messenger, emphasizing the range of critical science questions that are impacted by multimessenger observations (National Academies of Sciences, Engineering, and Medicine, 2023).

Much time-domain and multimessenger science can only be performed using space-based assets, thus creating a unique opportunity for NASA contributions. Astro2020 recognized that to "advance this science, it is essential to maintain and expand space-based time-domain and follow up facilities." The landscape of science accessible via multimessenger observations is extremely rich, as indicated in Figure 1. In the coming years, exploration of this broad range of science will be enabled by NASA's fleet in synergy with ground-based observatories spanning all messengers, as indicated in Figure 2. For NASA to meet the vision outlined in the Astro2020 Decadal Survey it must invest in the infrastructure needed to enable multimessenger and time-domain astronomy discoveries.

As was recognized by Astro 2020, a "suite of space-based electromagnetic capabilities [is] required to study transient and time-variable phenomena." Numerous currently operating facilities that contribute to time-domain science are working to improve how they serve the time-domain astronomy community and expand how they can work collaboratively with other space and ground-based observatories. However, up until this point these collaborations between facilities have been largely bilateral and coordination has generally been on an *ad hoc* basis. This has sometimes led to a failure to capture rare and exciting scientific opportunities arising from transients whose brightness fades on time scales of seconds to days, depending on the facilities required to observe them. For example, in the case of GRB 230307A, for the first time a late-time infrared spectrum resulting from r-process nucleosynthesis was measured. However, delays in localizing the event due to a lack of automated infrastructure meant that key observations were not made in the first few hours after the initial detection that would have helped to understand the evolution of the afterglow and the apparent kilonova emission (Burns et al., 2023). In 2019, NASA commissioned a Gravitational-Wave Electromagnetic (GW-EM) Task Force to assess the status of community resources. The study found that the extent to which observatories collaborate is inconsistent, is not especially well coordinated, and does not currently serve the science community as well as it could (Racusin et al., 2019).

General Observer Facilities (GOFs, e.g., the *Fermi* Science Support Center) exist to support the science community in using NASA's space-based observatories. GOFs implement processes for community engagement, science prioritization, and proposal selection. Additionally, GOFs provide organizational, financial and

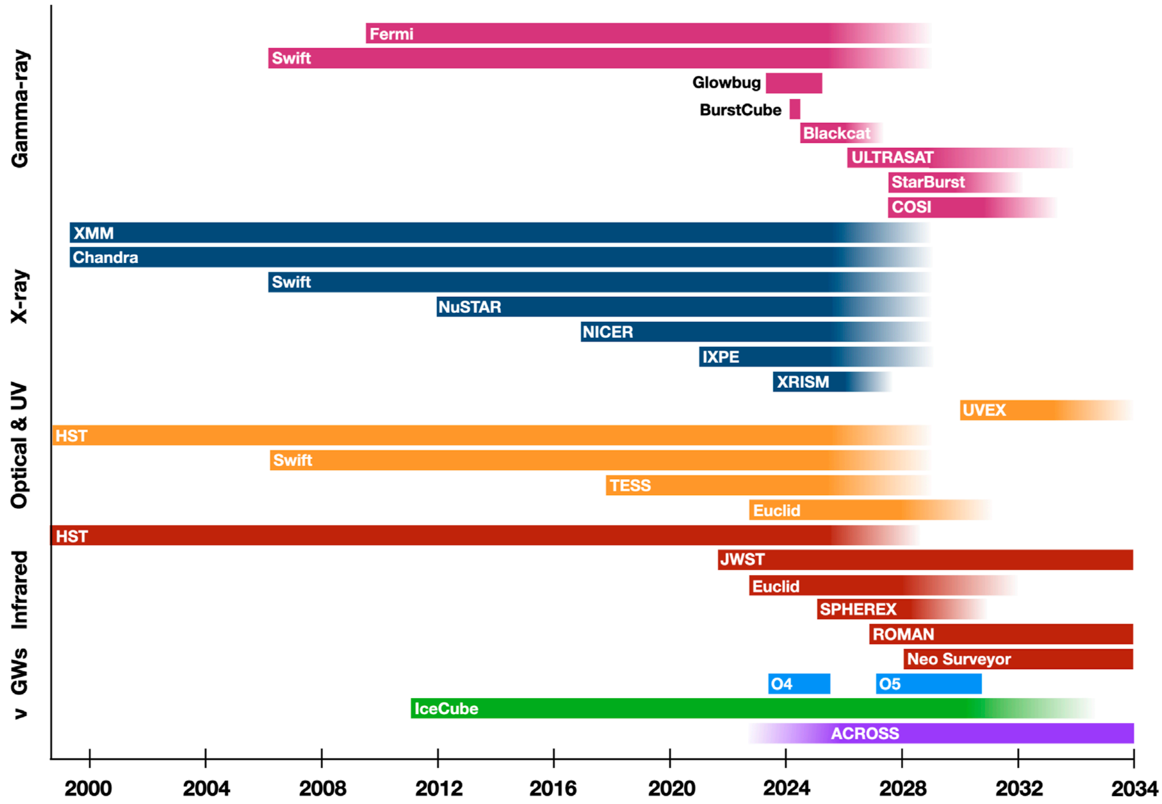

FIGURE 2
Multimessenger observatory timeline, showing that the ACROSS operations phase coincides with the next round of gravitational wave observations. NASA missions that are in their prime mission are shown as fading out after their prime mission completes; missions in their extended phase are shown to fade out beginning in 2025. Any of them may be extended, pending results of the 2025 Senior Review. GWs are based on current LVK plans (IGWN, 2024). The ACROSS pilot phase, discussed below in Section 3, is shown as a fade in, reaching an anticipated "initial operating capability" milestone in late 2025 that corresponds to the launch of the public web portal and tools, following which ACROSS would enter into a continuous improvement and sustainment phase.

technical resources (such as analysis tools, documentation, and tutorials) to improve the effectiveness and efficiency of scientific investigations involving NASA observatories. Although existing GOFs support many joint-observation programs, NASA's GOFs have been primarily organized to support investigations involving single observatories. Furthermore, rare and time-sensitive TDAMM science cases involving multiple observatories require a greater degree of collaboration and coordination than can be achieved by existing GOFs.

A recent workshop[1] on the scientific opportunities afforded by TDAMM was held in Annapolis, MD, August 22–24, 2022, with nearly 200 attendees in person and robust participation by another 150 attendees online. The workshop and its resulting white paper (Andrews et al., 2022) demonstrated the level of excitement in the community for opportunities to coordinate across instruments and wavelengths and across space and ground. A session on TDAMM infrastructure, covering space communications systems, alert systems, and data archives, showed that dedicated consideration of how to robustly ensure we have the capabilities to respond rapidly to rare but vital transient events is needed and new structures may need to be built to enable broad access to these capabilities for the entire astrophysical community. Subsequent workshops in this series have been hosted by NOIRLab in 2023[2] and Louisiana State University in 2024[3], emphasizing infrastructure and interdisciplinary science, respectively.

As one aspect of its response to the Astro2020 Decadal Survey's recommendations highlighting the importance of time-domain and multimessenger science and in light of the studies noted above, the NASA Astrophysics Division commissioned a 3-year study to investigate how to implement a GOF or similar facility that would address these issues. The study's charge for its first year was to focus on NASA's space-based observatories and to provide the following items.

1. A set of top-level requirements and architecture concept models for enabling a space-based follow-up observing capability.
2. Processes for TDAMM community engagement, proposal solicitations, and award management.

1 https://pcos.gsfc.nasa.gov/TDAMM/TDAMM.php

2 https://noirlab.edu/science/events/websites/MMA2023

3 https://sites.google.com/view/3rd-tdamm-workshop/home

3. A motivating set of TDAMM science cases and an analysis of the associated agreements, tools, process flows, and interfaces necessary to support those cases.
4. One or more implementation strategies for utilizing NASA assets to achieve an initial operating capability by FY26.
5. A best-value recommendation for a particular implementation strategy if more than one option is evaluated.

Subsequent years of the study are expected to expand the scope to consider opportunities to improve coordination with ground-based observatories, typically involving funding from multiple agencies, and with international facilities.

2 Literature review and stakeholder interviews

The study interviewed mission science operations teams, observers, and other stakeholders in the TDAMM enterprise, and reviewed the reports of previous studies into aspects of multimessenger follow-up and time-domain astronomy. Those interviews reinforced many of the findings of those previous studies, particularly those of the NASA GW-EM Task Force report and the 2019[4] and 2022[5] Senior Review reports. Those findings are summarized below. They motivate the main recommendation of this report: to launch a pilot initiative aimed at beginning to implement the required software infrastructure to improve mission coordination and observer workflows in a learn-by-doing model. This will allow rapid prototyping and changes in direction in response to ongoing stakeholder feedback.

2.1 Gravitational wave - electromagnetic counterpart task force

In an effort to enhance NASA's multimessenger astronomy capabilities and promote better collaboration between NASA missions and the wider scientific community, the NASA Astrophysics Division established the GW-EM Task Force in the spring of 2019. In addition to providing specific findings on the top-level capabilities of future missions in response to projected GW-EM scientific needs, the Task Force also identified several areas for improvement to maximize the scientific output of missions currently in operation or under development. These improvements include a) upgrading target-of-opportunity (ToO) capabilities, such as expanding the time allotted for ToOs and accelerating response times; b) fostering better communication and coordination within NASA missions, between NASA missions and observers, within the scientific community, and in liaison with the NSF; and c) making necessary modifications to Guest Observer (GO), Guest Investigator (GI), and Research and Analysis (R&A) programs.

Firstly, they recommended that NASA missions enhance their follow-up coordination to optimize the scientific yield from the entire NASA Astrophysics portfolio. For instance, they suggested that the *Swift* and Hubble Space Telescope missions adopt a rapid communication protocol for UV observations of GW counterparts. They also proposed a similar protocol for X-ray counterpart searches and follow-up involving *Swift*, NuSTAR, NICER, *Chandra*, XMM, IXPE, and XRISM. Furthermore, the task force encouraged gamma-ray burst monitors to collaborate for detections, sub-threshold searches, and localizations to facilitate the quick identification of neutron star (NS) mergers to initiate follow-up observations.

Improved communication with the broader astronomical community was also highlighted. The Task Force recommended the implementation of common reporting standards for planned and executed observations, and the detection of transient sources. These standards should ideally align with those adopted by NSF-funded (e.g., the Vera Rubin Observatory) and internationally funded (e.g., SKA) facilities. They also emphasized the importance of centralized, standardized data archiving, suggesting that all missions should store both data and data products in shared archives, utilizing modern application programming interfaces (APIs) and, where possible, common standards. They also encouraged improved advertisement of existing capabilities and development of new resources for cross-mission archival searches, both within NASA and between NASA missions and ground-based facilities.

In addition, they highlighted the potential of new scientific opportunities enabled by a funding mechanism supporting community efforts to improve existing tools such as the General Coordinates Network (GCN)[6] (Barthelmy et al., 1995) and develop new resources/tools (e.g., Treasure Map[7] (Wyatt et al., 2019), NASA Extragalactic Database (NED) Gravitational-Wave Follow-Up service[8]) to better coordinate the community and enable more effective follow-up observations and sub-threshold coincidence searches.

Finally, given the inherently multi-wavelength nature of time-domain and multimessenger science, joint observing proposals played an important role in GW170817, and will continue to do so for future discoveries. To improve opportunities for such joint programs in the future, the Task Force found that NASA should maintain an updated list of joint observing opportunities, make this list readily available to the community, and should pursue additional joint programs where scientifically relevant.

2.2 Key findings from other reports

In 2019, the Senior Review report highlighted the key importance of the existing NASA fleet for multimessenger astrophysics and encouraged NASA to investigate ways to better coordinate its operating missions to optimize their science return. Similar recommendations were voiced in the white paper produced by the first NASA TDAMM Workshop in August 2022 (Andrews et al., 2022). One scenario for the implementation of a

4 https://science.nasa.gov/astrophysics/resources/documents/2019-senior-review-operating-missions/

5 https://science.nasa.gov/astrophysics/resources/documents/2022-senior-review-operating-missions/

6 https://gcn.nasa.gov/

7 https://treasuremap.space/

8 https://ned.ipac.caltech.edu/NED::GWFoverview/

coordinating facility for multimessenger follow-up observations was presented by the Multimessenger Operational Science Support & Astrophysical Information Collaboration (MOSSAIC) collaboration (Sambruna et al., 2022), which is looking to serve as a community-oriented group aiming to highlight priorities for tool and coordination needs.

2.3 Response to GRB 221009A

There has yet to be a notable transformation in the way NASA conducts multi-mission follow-ups, particularly in dealing with exceptional and uncommon occurrences. This was evident during the investigation of the Brightest of All Time (BOAT), GRB 221009A, 5 years after the seminal events of 2017. Once again, the case of GRB 221009A showcased the community's capacity for self-organization and coordination (relying significantly on GCN) in executing an extensive follow-up endeavor. However, the systemic inefficiencies exacerbated the workload for both observers and science operations teams, while simultaneously missing out on potential scientific opportunities.

For instance, there remain challenges in predicting the necessary observational parameters weeks in advance for flagship missions. This has often resulted in under-prepared responses and less-than-optimal data collection. Furthermore, the lack of an automated GRB collation and association process to identify and consolidate observations means observers and science operations teams still need to manually determine the nature of events observed by *Swift* and *Fermi* (Burns et al., 2023). This process, unfortunately, results in delays in the initiation of the follow-up observations, causing a setback in scientific progress (for example, missing the early evolution of the GRB afterglow or, as mentioned above, the apparent kilonova in the case of GRB 230307A (Burns et al., 2023)).

However, amidst these shortcomings, there were promising signs as well. The use of Slack for rapid human-to-human communication and as an open forum greatly facilitated and accelerated information sharing and decision-making processes. Moreover, the timing of the 10th International Fermi symposium[9] coinciding with the event turned out to be a fortunate coincidence, as it enabled a large number of relevant experts to work together in person, thereby greatly enhancing collaborative efforts and results. These positive aspects should guide our future responses, ensuring that the entire astronomical community can quickly react and collaborate in response to rare and unusual astronomical events, ideally without relying on the serendipity of attendance at a relevant topical conference or membership in the right Slack workspaces.

2.4 TDAMM and general observer facilities

One key finding of the study is that a potential TDAMM GOF differs significantly from mission GOFs. Mission GOFs exist to incentivize and support observers using NASA observatories. GOFs are active during the operations and sustainment phase of the NASA mission lifecycle. They implement community engagement and proposal selection processes. GOFs provide scientific and technical expertise, financial resources, and technical resources for the community. Although NASA's mission GOFs have similar functions, their implementations vary across the fleet–the terms "science support center" (SSC) and "GOF" are used interchangeably (e.g., TESS SSC, *Fermi* SSC, *Swift* GOF, etc.). Although GOFs support some joint observing programs, GOFs are primarily scoped and organized to support their missions and generally do not have the resources or personnel to build coordination-focused tools.

In contrast, a TDAMM GOF does not have a "parent" mission organization or observatory to support. Rather, a TDAMM GOF should incentivize and foster cross-observatory science cases that exceed the capabilities of a single observatory or science team. While, as noted by the Astrophysics Advisory Committee (APAC)[10] (Holley-Bockelmann, 2023), there is not yet a generally accepted definition of TDAMM science cases, multimessenger/multi-wavelength science cases with time-sensitive space-based follow-up are the motivating cases for the study. Science planning and execution of such science cases without the perception of bias requires willing participation of mission science teams.

2.5 Recommendations

In response to the findings described above, as well as similar recommendations for better communication and coordination presented in the Physics of the Cosmos Program Analysis Group (PhysPAG) Science Analysis Group (SAG) on Multimessenger Astrophysics (MMA)[11] Final Report (Brandt et al., 2020), the 2020 Decadal Review of Astronomy and Astrophysics (National Academies of Sciences, Engineering, and Medicine, 2023), and the Chandra Time Domain Working Group report (Miller et al., 2022), the primary recommendation of this study is to initiate the Astrophysics Cross-Observatory Science Support (ACROSS) pilot. Building upon these conclusions, ACROSS aims to facilitate "all-of-astrophysics" science cases and streamline intricate, time-sensitive observing strategies that surpass the capabilities of any single observatory or mission team. In parallel with the pilot initiative, conversations with the community will continue and expand to include ground-based observatories (both triggering and follow-up) and international partners, to ensure that the pilot initiative's activities are fulfilling the community's needs.

In addition to the ACROSS pilot, both the Astro2020 Decadal Survey and the 2022 TDAMM workshop endorsed the idea of a persistent, community-led organization as a valuable forum for enumerating the driving science cases for NASA's TDAMM science support efforts and for providing feedback to NASA on the specific priorities and features needed by the community. The recently formed TDAMM Science Interest Group[12], chaired by members of the Physics of the Cosmos, Cosmic Origins, and Exoplanet Exploration Program Analysis Groups, is designed to fulfill that roll.

9 https://indico.cern.ch/event/1091305/

10 https://science.nasa.gov/researchers/nac/science-advisory-committees/apac

11 https://pcos.gsfc.nasa.gov/sags/mmasag.php

12 https://pcos.gsfc.nasa.gov/sigs/tdamm-sig.php

Given the rapid-development culture of TDAMM, we find that the best way to proceed in implementing the functions listed above is a pilot program that allows implementation and evaluation to proceed iteratively and rapidly, providing small but useful deliverables to the community to establish trust and build an understanding of the community's needs and adding deliverables and functionality as we go.

3 ACROSS pilot plans

The ACROSS pilot has been set up to determine how to better coordinate in realtime the coordinated observations of unexpected events like GW170817 and GRB221009A. ACROSS will serve as a center of excellence for TDAMM science, to aid observers and observatory science teams with planning and executing complex observing plans. To enable this, ACROSS will provide expertise, software tools, and critical realtime information through web pages and APIs. ACROSS will utilize an agile development process in order to respond to lessons learned and as plans evolve in response to ongoing interactions with and feedback from stakeholders.

Figure 3 illustrates the response to an interesting astrophysical event. The left panel focuses on the workflow to prepare follow-up observations by a single observatory: information about the initial detection is disseminated to the community via one of several alert systems, e.g., GCN. Interested observers respond by requesting follow-up observations by a specific observatory, either triggering a pre-approved ToO program or requesting director's discretionary time (DDT) observations. The observatory science team evaluates the request and, if approved, develops a new observation timeline that incorporates the requested observation. The constraints (and correspondingly the timelines) involved in developing a new plan vary widely between missions, from as short as minutes for a mission like *Swift* that has been designed for rapid follow-up, and whose ground systems have seen substantial effort to upgrade specifically for this purpose, to as long as weeks for flagship missions whose observing programs include numerous time-sensitive observations, or missions for which their technical constraints depend on the sequence of pointings. Once a new observing timeline is established, the updated sequence of commands must be uploaded to the observatory at the next available communications opportunity. Finally, the observatory executes the updated command sequence, carrying out the requested follow-up observations.

The center panel of Figure 3 illustrates how, in most cases, this sequence of steps is repeated independently by each mission in the NASA fleet. This is driven–at least in part–by NASA's competitive selection processes that deliver a fleet whose individual missions are optimized to carry out a specific set of science cases without dependence on other missions flying concurrently, which would add risk. Mission development and operations funding structures ensure efficient, focused, and lean science teams, but have unintended consequences. When a science event of mutual interest occurs, this siloed structure results in follow-up that is often *ad hoc*, inefficient, and less scientifically effective than it could be.

New infrastructure is required to fully realize the TDAMM science potential from past and future investments in NASA's Astrophysics fleet. The right panel of Figure 3 shows where the ACROSS pilot fits into this mission ecosystem, by providing tools that improve situational awareness both across the fleet and for observers, as well as planning tools for observers and cross-mission follow-up decision support tools. A fleet becomes an observing system when supported by organizational, human, and technical infrastructure. TDAMM science cases drive requirements for essential cross-observatory science support infrastructure. However, once in place this infrastructure supports a wide range of science cases, amplifying the return on investment. The primary users of the support infrastructure are general observers and observatory (mission) science teams.

The goals of the ACROSS pilot are to (1) enable rapid and complete-as-possible information sharing between missions and with observers; (2) simplify the process for observers to request follow-up observations; (3) provide decision-support tools to assist observers and mission teams in evaluating and planning observations; and (4) engage the community to enable equitable access to TDAMM resources and science for all. To keep the scope of the pilot activities tractable, we will focus initially on a limited number of operating missions. These missions include the pointed X-ray missions *Swift*-XRT, NICER, NuSTAR, and IXPE (together providing a good mix of complementary and overlapping capabilities), the wide-field gamma-ray telescopes aboard the *Fermi* Gamma-ray Space Telescope and the *Swift*-BAT, and the Keck Observatory as an opportunity to prototype interfaces with ground-based facilities. The scope of the pilot will expand to include other missions as availability of resources and their interest allow. The notional schedules for the ongoing TDAMM study and the ACROSS pilot are shown in Figure 4. The objective is to have an initial operating capability of web-based ACROSS tools in time for the O5 observing run of the gravitational wave observatories, as shown in Figure 2. The following sections briefly describe the initial activities targeted at achieving these goals.

3.1 TDAMM toolkit

ACROSS is developing an API to expose and retrieve observatory state and status information as well as observing plans and history and (to the extent feasible) constraints on target observability. By providing this information via an API, it allows users to immediately incorporate necessary information flows into the products needed for their use cases. Another development activity in this API is to support new missions (and existing missions, if they so choose) by providing a toolkit for building ToO request submission and evaluation interfaces. Altogether, this TDAMM toolkit will facilitate streamlined, standardized, and automated submission of ToO requests, for example, based on input from transient brokers, enabling faster response times. The TDAMM Toolkit design is based upon the successful deployment of the *Swift* ToO API and website, but will be customizable for specific mission needs, enabling a streamlined, standardized, and automated workflow for ToOs, and critically an easy-to-deploy API interface that allows integration of ToO submission into third-party products such as the Target and Observation Monitor (TOM) Toolkit (Street et al., 2018) and SkyPortal (Coughlin et al., 2023). TOM Toolkit and SkyPortal, examples of tools widely used in the ground-based community, both already have the ability to submit ToO requests to *Swift*. The initial release of the toolkit will support

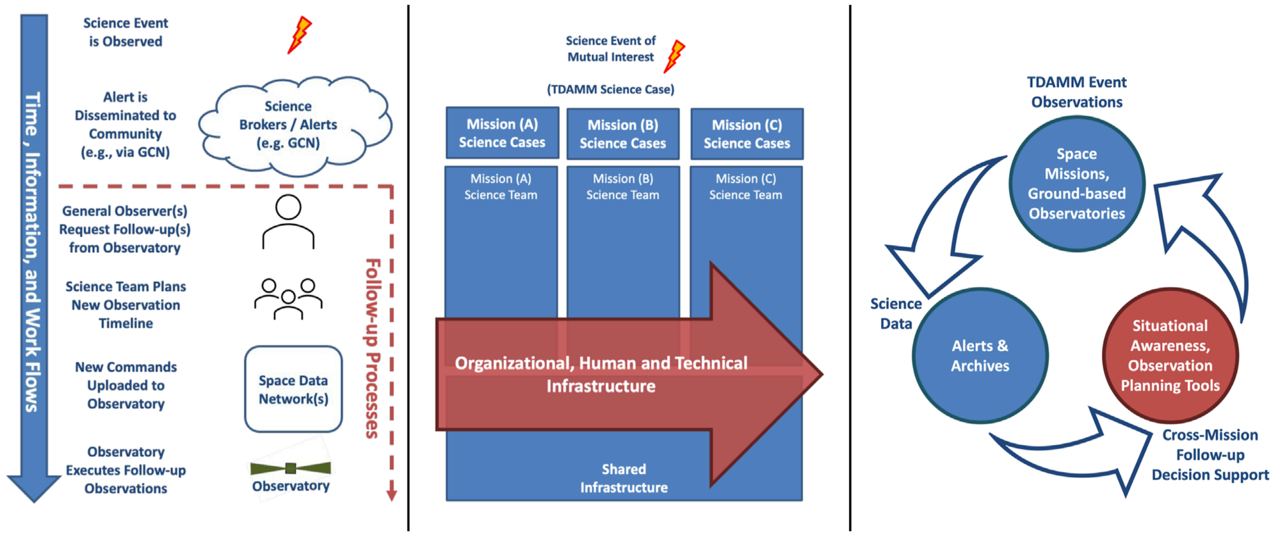

FIGURE 3
Typical follow-up response work flow for (left) one or (center) multiple observatories. The workflow indicated in the left panel is typically repeated for each mission in the center panel; ACROSS aims to improve the cross-cutting infrastructure that supports multi-mission planning and execution. (right) The role of ACROSS in the observing and follow-up ecosystem is to strengthen the cross-mission follow-up decision support infrastructure by providing situational awareness and observation planning tools.

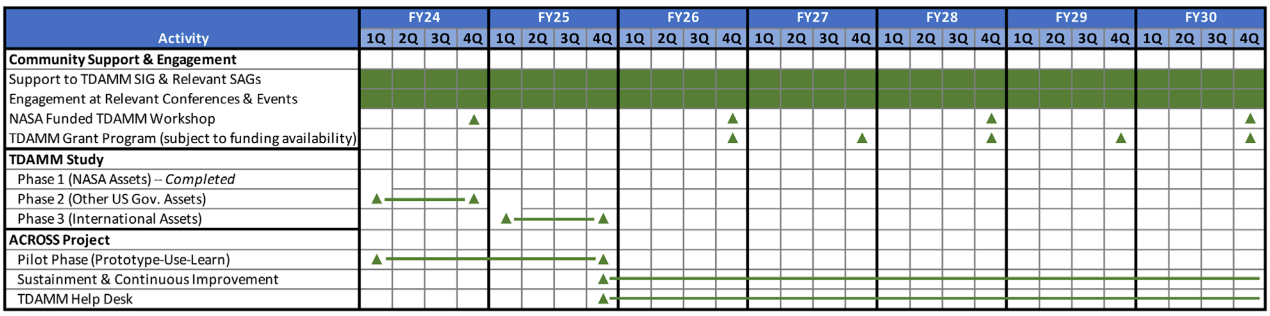

FIGURE 4
Timeline for the PhysCOS TDAMM study and ACROSS pilot project. Support and engagement activities run continuously as indicated by the solid green fill; key dates associated with other activities are indicated with green triangles.

simple API and web-based submission and evaluation interfaces for ToO requests. Later releases of the toolkit will incorporate cross-observatory science feasibility information streams and follow-up decision support tools. The TDAMM toolkit will be developed as an open-source project. As a proof of principle, the ACROSS pilot is providing the ToO API interface for BurstCube in 2024, and for StarBurst in 2025. Since these two wide-field GRB detectors are not pointed instruments, the interface enables a "download of opportunity" (DoO) to facilitate downlink of time-tagged event data from onboard buffers around times of interest for transients detected by other facilities.

Tasks to be executed during the ACROSS pilot period include:

1. Define the necessary state and status information and follow-up observation parameters.
2. Assess availability of state and status information parameters, by mission.
3. Define relevant observing and scheduling constraints.
4. Negotiate implementation resources and schedule, by mission.
5. Implement API state and status information streams.
6. Implement API for ToO construction/submission.
7. Deploy mission state and status information streams on publicly accessible cloud infrastructure.
8. Develop and deploy visualization and other situational awareness functions or applications.
9. Deploy mission ToO API on publicly accessible cloud infrastructure.

3.2 TDAMM web portal

To enable the TDAMM community to efficiently respond to new alerts and coordinate follow-up planning, the ACROSS pilot will develop, deploy, and maintain a web portal collecting in one place all of the tools and information needed by the community. The web portal will include capability summaries for TDAMM-relevant observatories, links to ACROSS and community-developed tools, links to ToO submission pages for all missions, and links to funding opportunities, conferences, and workshops. The web portal will also include "Events of Interest" pages, both static (curated by humans) and dynamic (built from near-term observing plans and recent observation history for popular TDAMM events). Tasks to be executed during the ACROSS pilot period include:

1. Develop a conceptual design and layout for portal content.
2. Seek and obtain approval for a NASA domain URL.
3. Evaluate technical software implementation and cloud hosting options.
4. Implement a U.S. Web Design System (USWDS)[13] compliant framework.
5. Populate framework with content.
6. Deploy web portal to publicly accessible cloud infrastructure.
7. Maintain web portal content.

3.3 TDAMM research announcement

A funding opportunity tailored to fill gaps in the tools and coordinated science observations needed to maximize the TDAMM science return from the NASA fleet is targeted for an initial call no later than 2026, subject to availability of funds. The scope and types of projects to be funded are to be examined during the pilot phase. There are three areas of scope to be considered.

1. A research announcement (RA) targeted specifically at development of tools or observing modes that will enable new science cases. Open questions to resolve include the criteria that would define the range of tools that would be considered eligible (for example, must the tool play a role in planning or conducting observations?) and the requirements on the deliverables. The pilot period will provide an opportunity to gain experience in defining tools and their development and delivery as the ACROSS team begins by prioritizing an initial list and identifying optimal acquisition strategies. That experience is expected to be useful in defining the criteria needed for a successful tools RA.
2. An opportunity for funding of DDT observations made by "rest of fleet" missions, like those provided by the flagships in response to DDTs. Open questions to resolve include avoiding creation of a perverse incentive that discourages applications to existing RAs, defining criteria for which DDTs are of sufficient interest to warrant financial support for the analysis and interpretation of the resulting data, determining which observers should be eligible for consideration for funding after a particular set of DDT observations are made, and determining an appropriate level of support to provide. If these questions can be satisfactorily resolved, this type of funding opportunity might be the most useful to implement first as it would both close a clear gap and provide valuable experience that would likely inform construction of a cross-mission observing RA.
3. An RA designed to fill the gaps between existing mission calls and remove the risk of double jeopardy by explicitly supporting observing programs that require coordination between two or more observatories. Open questions to resolve include how to establish a pool of observing time across the fleet, what criteria would define eligible proposals, how many awards are anticipated, how to coordinate accepted programs across the missions involved, how to avoid overlap with existing mission RAs and bilateral agreements, and more. The pilot period will provide an opportunity to observe how mission teams interact with each other, particularly as enhanced coordination tools are rolled out, and will afford ACROSS team members an opportunity to more clearly define the remaining gaps such a call would fill.

Tasks to be executed during the ACROSS pilot include:

1. Develop an initial research announcement based on options identified in Phase 1 Study.
2. Elicit feedback from the NASA Astrophysics Division, mission, and community stakeholders.
3. Negotiate and refine implementation of the research announcement.
4. Funding permitting, execute initial call in 2026 in advance of the fifth observing run of the International Gravitational-Wave Observatory Network.

3.4 Community support

ACROSS will also provide support to the community in the form of a virtual help desk staffed by domain experts who can assist observers in submitting ToO requests and coordinating with observatory teams. Additional support in the forms of documentation, tutorials, and workshops will be provided to advertise the tools described above and lower the barriers to entry to their usage. ACROSS is working with the Physics of the Cosmos Program Office and the TDAMM SIG to organize another TDAMM-focused workshop targeted for September 2024, and anticipate providing a preview or introductions to some of the tools above at the workshop and solicit feedback on them.

3.5 Inter-observatory communications

Inspired by the need for coordination during the LIGO-Virgo-KAGRA (LVK) fourth observing run (O4), which began in May 2023, ACROSS initiated a meeting between representatives of the X-ray observatories of the NASA fleet (including XMM-*Newton*) to discuss the pre-approved gravitational-wave follow-up observing programs for each observatory. Participants gained an awareness of each program's science objectives, triggering criteria and whether any dependencies or redundancies were likely among the programs. As an outcome of this meeting, ACROSS created a dedicated Slack channel for rapid, asynchronous communications among the participating science operations teams used to ensure

13 https://designsystem.digital.gov/

situational awareness and facilitate coordination should a high-priority gravitational-wave event occur. While the poorer-than-expected localizations achieved (and the lack of binary neutron star mergers) thus far by O4 have meant this channel has not yet proven its value, ACROSS has extended the model of using Slack communications channels to engage with missions and sets of missions for specific purposes. For example, ACROSS has established a channel with NuSTAR to discuss development of an interface to expose observation planning status information. ACROSS is open to supporting tools for communication between observatory operations teams to support observation planning going forward and are happy to discuss needs and opportunities to do so as they arise.

4 Conclusions and next steps

The first phase of NASA's TDAMM study was charged with focusing on the space-based observatories in the NASA fleet and to look at ways to improve coordination and community engagement in response to TDAMM science cases. The key findings were consistent with previous, similar studies. First, additional software infrastructure is needed to support both missions and the community by providing awareness of the fleet's observing plans and status. Second, this software infrastructure needs to extend to simplifying the process for requesting follow-up observations and providing decision-support tools to assist observers and mission teams. Third, a combination of software and human infrastructure is needed to enable equitable access to TDAMM science for the entire community. Finally, developing the above infrastructure in a new organization separate from but with close ties to the existing mission GOFs will enable it to focus on the needed cross-cutting infrastructure without interfering with their work. The primary recommendation of this study is to initiate the ACROSS pilot.

The ACROSS pilot provides the best path to proceed to rapidly implement and evaluate elements of the software infrastructure needed to support efficient follow-up coordination of time-domain and multimessenger triggers. The objective is to have an initial operating capability of web-based ACROSS tools in time for the O5 observing run of the gravitational wave observatories, as shown in Figure 2. In parallel, the TDAMM study continues through the pilot phase, enabling feedback from stakeholders–both mission teams and observers–to be solicited and incorporated continuously, and expanding the scope to explore and incorporate coordination with ground-based and international partners.

Data availability statement

The datasets presented in this article are not readily available because the raw data supporting the conclusions of this article consist of interviews with relevant stakeholders. Requests to access the datasets should be directed to T. B. Humensky, thomas.b.humensky@nasa.gov.

Author contributions

TH: Conceptualization, Investigation, Project administration, Writing–original draft, Writing–review and editing, Methodology. CR: Conceptualization, Investigation, Methodology, Supervision, Writing–review and editing, Formal Analysis, Funding acquisition, Resources, Validation, Visualization, Writing–original draft. TB: Conceptualization, Investigation, Writing–review and editing. RC: Conceptualization, Investigation, Methodology, Writing–review and editing, Validation. SC: Conceptualization, Investigation, Methodology, Supervision, Writing–review and editing, Validation. FC: Investigation, Writing–review and editing, Validation. JD: Conceptualization, Investigation, Writing–review and editing. CH: Investigation, Validation, Writing–review and editing, Conceptualization. MH: Investigation, Writing–review and editing. JK: Investigation, Writing–review and editing, Conceptualization, Formal Analysis, Methodology, Project administration, Software, Supervision, Writing–original draft. DK: Investigation, Visualization, Writing–original draft, Writing–review and editing. JR: Investigation, Methodology, Validation, Writing–review and editing. BR: Investigation, Writing–review and editing. RS: Investigation, Methodology, Supervision, Validation, Writing–review and editing. JS: Investigation, Methodology, Writing–review and editing.

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Conflict of interest

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