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The Gravitational-wave Optical Transient Observer (GOTO)

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ABSTRACT

The Gravitational-wave Optical Transient Observer (GOTO) is a project dedicated to identifying optical counterparts to gravitational-wave detections using a network of dedicated, wide-field telescopes. After almost a decade of design, construction, and commissioning work, the GOTO network is now fully operational with two antipodal sites: La Palma in the Canary Islands and Siding Spring in Australia. Both sites host two independent robotic mounts, each with a field-of-view of 44 square degrees formed by an array of eight 40 cm telescopes, resulting in an instantaneous 88 square degree field-of-view per site. All four telescopes operate as a single integrated network, with the ultimate aim of surveying the entire sky every 2–3 days and allowing near-24-hour response to transient events within a minute of their detection. In the modern era of transient astronomy, automated telescopes like GOTO form a vital link between multi-messenger discovery facilities and in-depth follow-up by larger telescopes. GOTO is already producing a wide range of scientific results, assisted by an efficient discovery pipeline and a successful citizen science project: Kilonova Seekers.

Keywords: robotic telescopes – sky surveys – gravitational-wave counterparts – electromagnetic follow-up – multi-site observatories – wide-field telescopes – telescope arrays – observatories

1. THE GOTO NETWORK

The Gravitational-wave Optical Transient Observer (GOTO) collaboration* was founded in 2014, with the intent of constructing a global network of robotic telescopes to follow-up gravitational-wave detections and hunt for optical counterparts.[1,2] To achieve this, a robotic mount was designed to hold an array of "unit telescopes" (UTs): small, off-the-shelf telescopes which could be combined to form a large field of view in a scalable and cost-effective manner.

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Figure 1. The complete GOTO network as of April 2023. Top: GOTO-North on La Palma, with GOTO-1 on the left and GOTO-2 on the right. Bottom: GOTO-South at Siding Spring, with GOTO-3 on the left and GOTO-4 on the right.

A prototype telescope with four UTs was constructed at the Roque de los Muchachos Observatory on La Palma, Canary Islands, in 2017.[3] Following an extensive commissioning phase, a second-generation telescope with a full array of eight UTs was designed and installed in a neighbouring dome in 2021. Later that year, the prototype was also replaced with a second-generation telescope, forming the complete GOTO-North node. In 2023 two further telescopes were installed at Siding Spring Observatory in New South Wales, Australia, forming the GOTO-South node. These two antipodal sites allow the network to continuously monitor the sky with near 24-hour coverage. All four GOTO telescopes are shown in Figure 1.

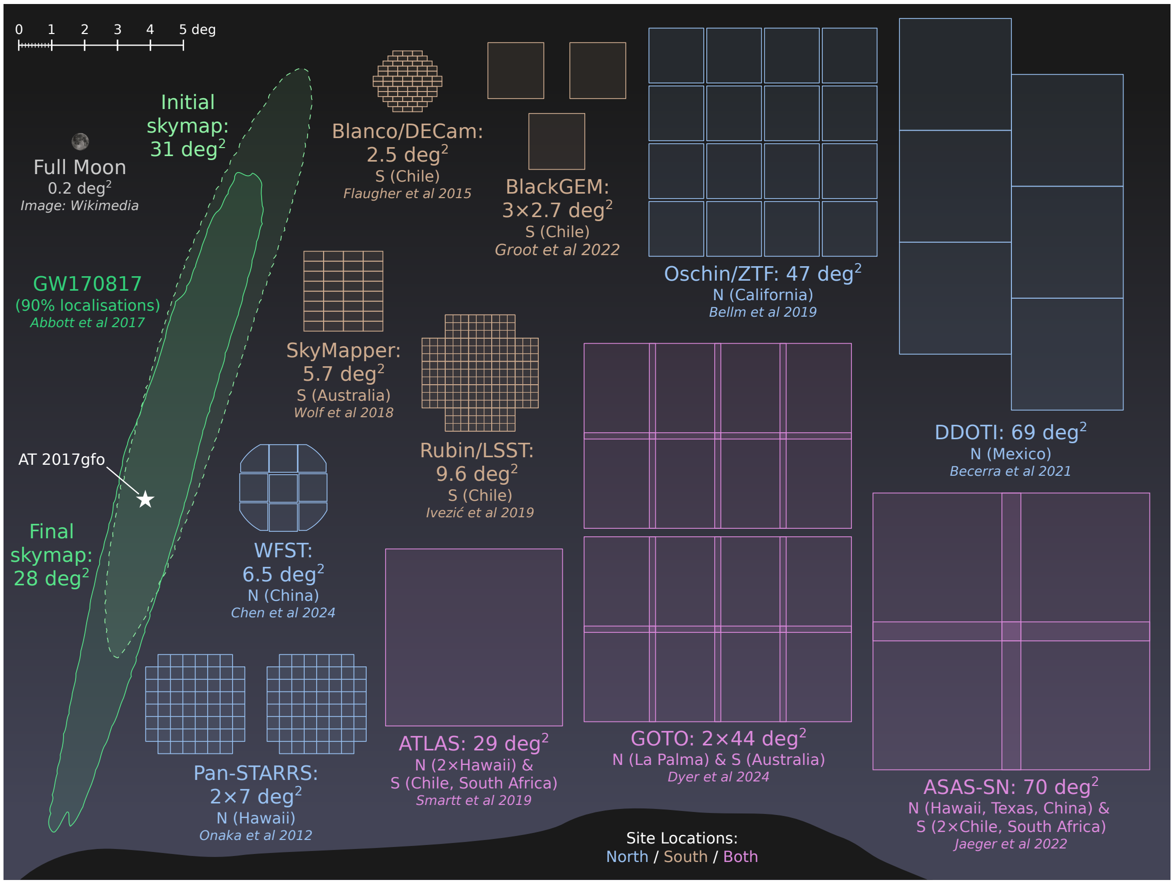

Figure 2. The field of view of selected wide-field telescopes. The depicted footprints represent the sky coverage available from each site; some projects (BlackGEM, GOTO, Pan-STARRS) have multiple mounts per site and some (ASAS-SN, ATLAS, GOTO) have multiple sites across the globe, with the colouring showing if the project has telescopes located in the northern (blue), southern (tan) or both (purple) hemispheres. Included projects: ASAS-SN,[4] ATLAS,[5] BlackGEM,[6] DDOTI,[7] DECam,[8] GOTO (this work), LSST,[9] Pan-STARRS,[10] SkyMapper,[11] WFST[12] and ZTF.[13] The initial and final skymaps for GW170817[14] (green) and the location of AT 2017gfy (white star) are also shown.

2. TELESCOPE HARDWARE AND OPERATIONS

The second-generation GOTO telescopes were built by ASA Astrosysteme, and are housed in AstroHaven clamshell domes. Each telescope consists of a direct-drive DDM500 German equatorial mount, with a boom-arm holding an array of eight unit telescopes, f2.4, 40 cm H400 Wynne–Riccardi astrographs, as shown in Figure 1. Each UT has a focuser, filter wheel (with Baader *LRGBC* filters), and an FLI ML50100 camera with a 50 megapixel KAF-50100 CCD detector, and has a field of view of $2.21^\circ \times 2.95^\circ$. The eight UTs on each mount are aligned to form a tiled array with a small amount of overlap between each field, combined these give a field of view of 44 square degrees as shown in Figure 2.

GOTO's standard survey observations consist of four 45 s exposures in the wide (400-700 nm) L filter[†], when stacked reaching a depth of 20 mag in dark time. With two independent mounts on each site, GOTO can observe an instantaneous area 88 square degrees. During normal operations, the GOTO telescopes carry out an all-sky survey in the L filter, and together the two antipodal sites cover the entire visible sky every 2–3 nights. This ensures recent comparison images are available to help distinguish potential counterparts during targeted event follow-up searches.

[†]The GOTO filter profiles are available on the SVO Filter Profile Service at http://svo2.cab.inta-csic.es/theory/fps/index.php?id=GOTO.

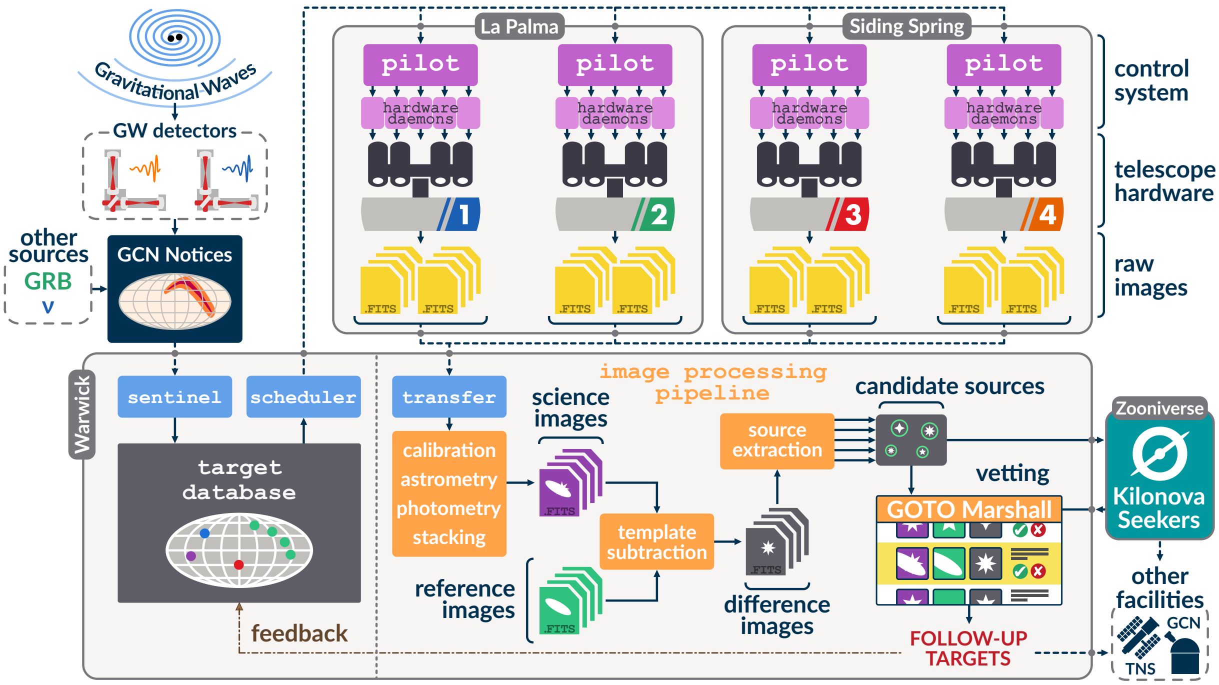

Figure 3. A flow chart visualising the GOTO network. Gravitational wave and other external transient alerts are received and inserted into the target database, which the central scheduler uses to direct observations to the individual telescopes. Raw images are then transferred back to Warwick for processing, with candidate sources being sent to the GOTO Marshall and Kilonova Seekers project for vetting.

3. AUTOMATION AND ANALYSIS SOFTWARE

Each GOTO telescope operates autonomously, while target scheduling is coordinated by a central system located at Warwick University in the UK.[15] A visual representation of the network is shown in Figure 3. The individual telescopes are operated using the GOTO Telescope Control System (G-TeCS),[16,17] with each using a "pilot" control program to issue commands and monitor feedback from individual hardware daemons. The pilots each receive pointings from the central scheduler, which ranks and distributes targets to each telescope. Outside the regular all-sky survey, targeted follow-up observations can be triggered by GCN Notices[18] received by the "sentinel" alert monitor. Alerts produced by the LIGO-Virgo-KAGRA gravitational-wave detector network[19] are ranked highest, but other sources include GRB alerts from *Fermi*-GBM,[20] *Swift*-BAT[21] and *GECAM*,[22] and neutrino detections from IceCube.[23] All observations are aligned to a grid of 1048 fixed sky positions, so processed images can be subtracted from archival reference images in order to detect any new sources.

After source extraction and machine filtering, any candidate sources are sent to the GOTO Marshall web interface for vetting by project members.[3] The Marshall, as shown in Figure 4, provides an easy method for members of the project to vet sources, and includes any historical detections at that point as well as contextual information such as nearby galaxies. Since July 2023 GOTO has also operated the Kilonova Seekers citizen science project[‡], with members of the public able to help classify and flag potential candidates. The volunteers are presented with a subset of the information available on the Marshall, including the discovery, reference, and difference images, and are asked to vote on if the source appears to be real. Kilonova Seekers has produced multiple discoveries of real sources that would otherwise have been missed, and the resulting data sets produced are being used to train new automated classifiers, which will further improve the efficiency and discovery speed of the network.[24]

[‡]http://kilonova-seekers.org/

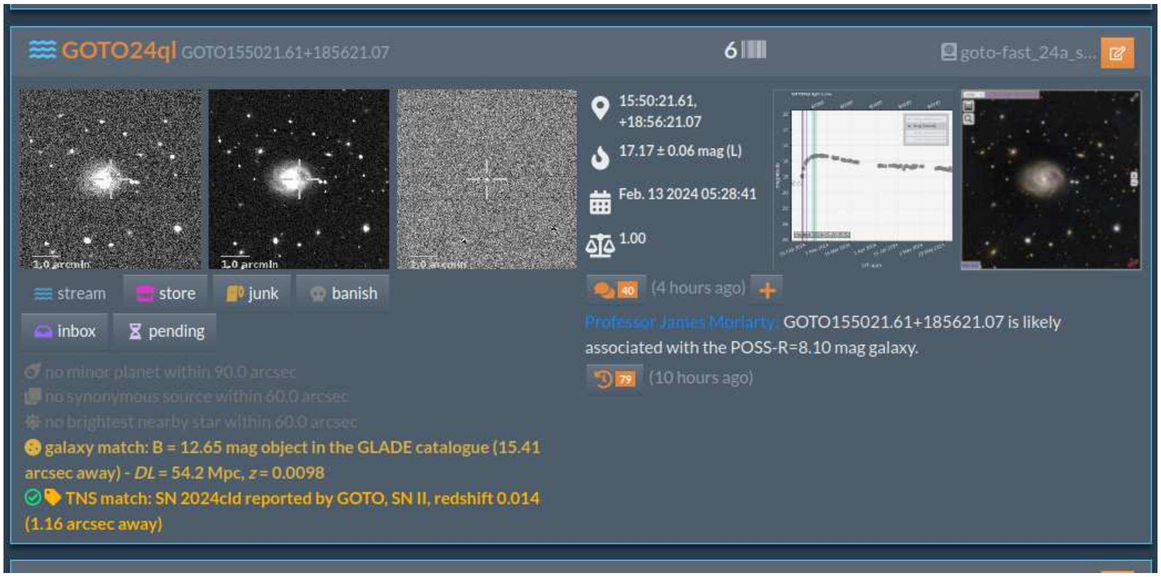

Figure 4. A screenshot of the GOTO Marshall web interface. The source shown is the type II supernova SN2024cld, which was discovered as part of the GOTO-FAST survey.[25,26]

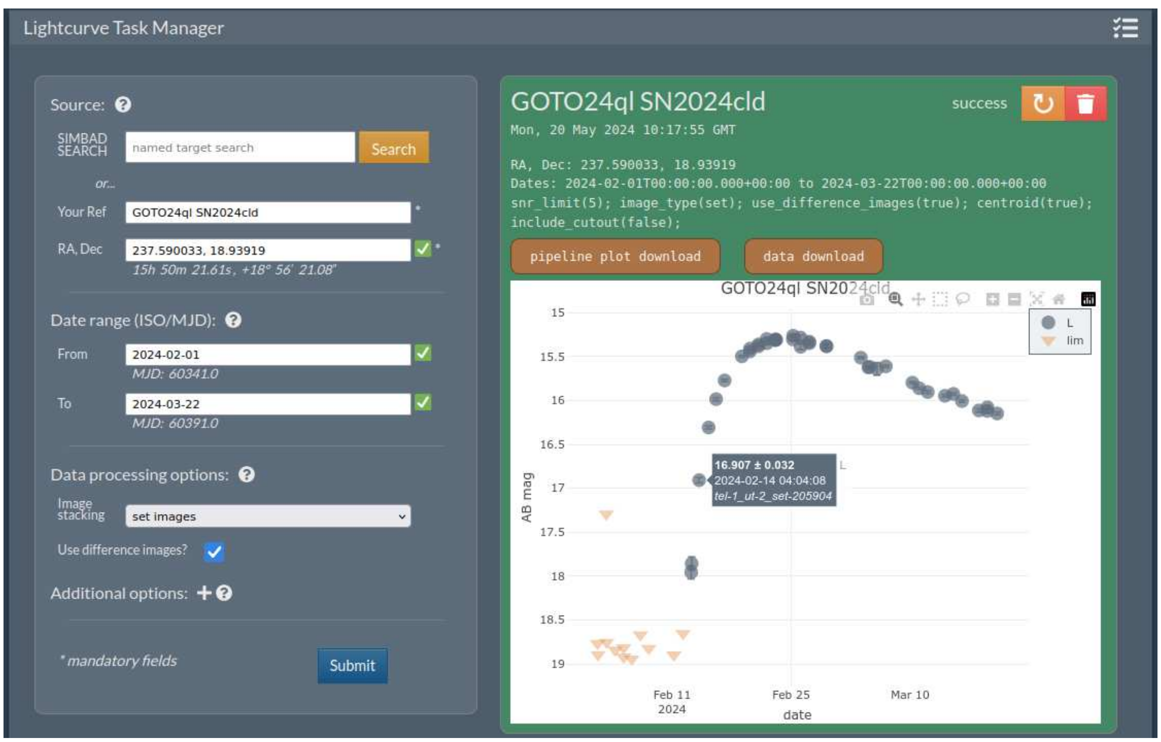

Figure 5. A screenshot of the in-development GOTO Lightcurve web interface for the forced-photometry service.

Another ongoing project being developed within the GOTO collaboration is a robust forced-photometry service, with the aim of making a publicly accessible API and web interface similar to those produced by ASAS-SN,[27] ATLAS[28] and ZTF.[29] A screenshot of the in-development Lightcurve web interface for forced photometry is shown in Figure 5.

4. RESULTS AND FUTURE DEVELOPMENTS

We have presented the GOTO project, a new network of wide-field robotic telescopes across the globe dedicated to detecting electromagnetic counterparts to gravitational-wave events and other multi-messenger alerts. The GOTO prototype responded to alerts from the Third LVK Observing Run (O3),[30] and since 2023 the full network has been following-up alerts from the ongoing O4 run. Other observing campaigns include regular follow-up of gamma-ray bursts.[31,32] The fully-automated nature of the network means that, when targets are visible, GOTO is able to start observations within 30 seconds of an alert being received. In April 2024 GOTO observed the candidate gravitational-wave event S240422ed, starting observations within 3 minutes of the trigger and covering 96.2% of the skymap within the first night.[33] GOTO-discovered transients are now regularly reported to the Transient Name Server,[34] exceeding 100 reports per month in May 2024, and GOTO has already entered the top 10 sources of transient since 2016[§].

Ongoing efforts to classify GOTO discoveries has also led to the GOTO-FAST program on the Isaac Newton Telescope, which produced immediate spectroscopic classifications of GOTO-discovered sources.[35] The GOTO Marshall includes quick follow-up triggers for the Liverpool Telescope[36] and pt5m[37] on La Palma, and other links are being developed with the ANU 2.3m telescope[38] at Siding Spring and the future New Robotic Telescope.[39]

Now that the GOTO Network is fully operational, the efforts of the collaboration are focused on continuing to follow-up transient alerts, as well as optimising the automated systems and preparing more public utilities including the forced-photometry service. With the fundamentals in place, GOTO should be well positioned to operate and make discoveries for many years to come.

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