Vera C. Rubin Observatory
Rubin Observatory Operations

Target-of-Opportunity Operations During the Science Verification Surveys

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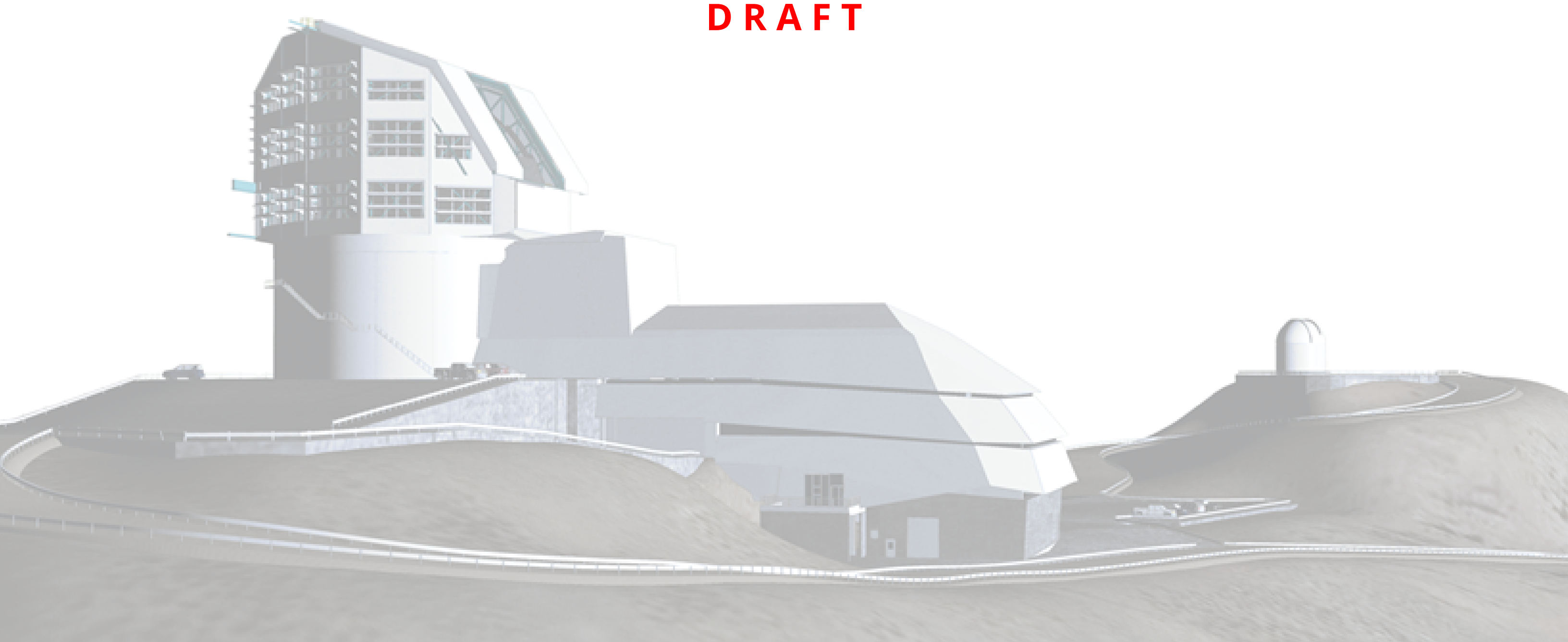

Abstract

We describe the procedures and workflows for Target-of-Opportunity observations during commissioning and the science verification surveys. We describe the global state of the Rubin ToO system, the workflow during the early commissioning period, the responses to real and mock alerts, and lessons learned from this period.

Change Record

Version	Date	Description	Owner name
1	2025-05-29	First revision, covering intro and systems overview.	Sean MacBride

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1 Introduction

The LSST covers a wide swath of unique science cases and observation types. Rubin Observatory will enable many scientific discoveries, especially target-of-opportunity (ToO) observations during the early commissioning period.

Rubin Observatory is uniquely positioned to lead ToO observations through the 2020's and beyond due to it's unique technical capabilities. The $\sim 10\,\mathrm{deg}^2$ field-of-view of the Rubin optical system allow ToO observations to survey a wide area, while the single-visit depth of the LSST-Camera allows single observations to observe the southern sky for faint transient phenomena. The combination of the large FOV and deep observations make Rubin Observatory an ideal tool for discovery of ToO phenomena.

The Rubin ToO program encompasses 3% of the LSST, and includes GW, high-energy neutrino, potentially hazardous asteroids, and other time-sensitive astrophysical phenomena as different targets. Each target has a different observing strategy based on observing conditions, the conditions of the astrophysical event, and other parameters. The observing strategies are the product of community input, and were revised in 2024 (Andreoni et al. (2024)). These recommendations were accepted by the survey cadence optimization committee in January 2025 (The Rubin Observatory Survey Cadence Optimization Committee (PSTN-056)).

While other components of the LSST are not limited by the specific time of observation, ToO is uniquely in that the confirmation of a ToO counterpart requires rapid observations, ranging from mere minutes of alert receipt to hours. The unique nature of observations requires different workflows, communication channels, and operations to ensure that ToO observations are valuable to the LSST.

In the forthcoming sections, we describe the state and workflow of the Rubin ToO system during the SV period (section 2), the responses to mock and real alerts (section 3), and lessons learned from the early commissioning and science verification period (section 4).

2 Systems Overview

The Rubin ToO system is composed of five distinct components, each responsible for a different aspect of ToO operations and observations.

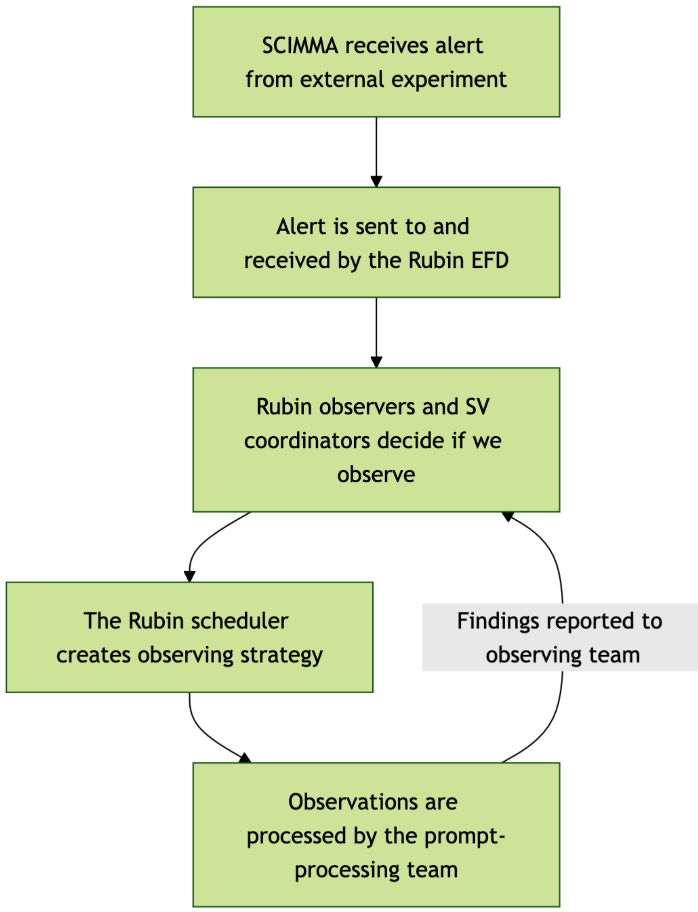

FIGURE 1: The general workflow during the SV period, with the five separate teams and their main responsibilities listed.

2.1 Incoming alert stream

The Rubin ToO system starts at the incoming alert stream. The incoming alert stream is responsible for parsing alerts from external experiments and sending them to Rubin infrastructure.

Rubin Observatory considers ToO alerts from a variety of astrophysical phenomena and experiments, including

- **Gravitational waves:** LIGO-Virgo-KAGRA (LVK) Collaboration
- **High energy neutrinos:** IceCube Neutrino Observatory
- **Potentially hazardous objects:** The NASA Jet Propulsion Laboratory (JPL) Scout and JPL Sentry experiments
- **Galactic supernovae:** The Supernova Early Warning System (SNEWS) and the Super-Kamiokande (Super-K) experiment
- **Lensed GRBs:** LVK and the Neil Gehrels Swift Observatory

All incoming alerts are handled by Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics (SCiMMA) HopSkotch. Alerts are received from different experiments before being assessed for alert quality. Alerts of a certain quality are then passed to Rubin infrastructure. In this way, all alerts that arrive at Rubin infrastructure are high quality alerts worthy of follow-up. This enables future revisions of Rubin observing strategy related to ToO to be developed internal to the Rubin Scheduler.

Alert quality for Rubin observations is set by the Rubin science community, who developed a set of criteria for ToO observations in their 2024 recommendation (Andreoni et al. (2024)). This recommendation has been adopted by SCiMMA to ensure the EFD and Rubin scheduler do not need to perform additional checks of alert quality.

2.2 Engineering facility database

The Rubin engineering facility database (EFD) hosts telemetry and information about every Rubin Observatory component that interacts with middleware. For ToO purposes, this includes SCiMMA alerts. These alerts are received at the summit, including skymap information for the alerts.

The Scheduler Commandable SAL Component (CSC) collects telemetry from the EFD and hands them over to the Driver, which formats it in a way the scheduling algorithm understands. By using a general purpose interface for collecting and passing telemetry from the EFD to the scheduling algorithm, it allows us to easily add new data sources as long as the data is in the EFD. This flexible design supports the SCiMMA alert stream, but also manual alert information added by observing specialists or other ToO scientists to the EFD (Ribeiro (TSTN-035)).

Rubin Scheduler ToO configuration	Strategy from Andreoni et al. (2024)
GW_case_B	GW, neutron star component, gold ($\Omega < 100\,\mathrm{deg}^2$)
GW_case_C	GW, Unidentified source, gold ($\Omega < 100\,\mathrm{deg}^2$)
GW_case_D	GW, neutron star component, silver ($\Omega < 500\,\mathrm{deg}^2$)
GW_case_E	GW, Unidentified source, silver ($\Omega < 500\,\mathrm{deg}^2$)
BBH_case_A	GW, Binary black-hole, dark time, nearby event
BBH_case_B	GW, Binary black-hole, dark time, distant event
BBH_case_C	GW, Binary black-hole, bright time
GW_case_large	GW, large skymaps ($\Omega > 500\,\mathrm{deg}^2$)
lensed_BNS_case_A	Lensed BNS, $\sim 900\,\mathrm{deg}^2$ skymap
lensed_BNS_case_B	Lensed BNS, $\sim 15\,\mathrm{deg}^2$ skymap
neutrino and neutrino_u	High energy neutrino event
SSO_night and SSO_twilight	Potentially hazardous asteroid
SN_Galactic	Galactic supernova
Lensed_GRB	Lensed GRB

TABLE 1: The strategy naming used in the Rubin Scheduler (left) to execute the community observing strategy recommendations (right) from Andreoni et al. (2024).

2.3 The Rubin Scheduler

The Rubin scheduler is responsible for scheduling and executing observations for the LSST. The Rubin scheduler executes different surveys for the LSST, each of which has different goals and targeted observations. ToO observations, all of which require first-night observations of phenomena, will schedule observations according to the community designed strategies.

SCiMMA alerts passed to the EFD will have metadata associated with them that denotes the alert type. This piece of metadata is passed to the Rubin scheduler to execute the appropriate strategy, as listed in table 1.

GW observing strategies are differentiated by the 90% confidence interval area (Ω) from LVK alerts. Unidentified GW sources and NS component sources of similar skymap size (i.e. gold or silver) follow identical strategy. Binary black-hole event strategy is differentiated by the distance of the event and the observing conditions (dark or bright time). All strategies except for large GW skymaps and lensed GRBs have been tested and verified in the Rubin Scheduler. Large GW skymaps require specific coordination with the SCOC to cover the area, and lensed GRBs do not have an explicit strategy recommendation in Andreoni et al. (2024).

2.4 The Prompt Processing Pipeline

Alerts generated by the LSST prompt processing pipeline are LSST's real-time data product. For prompt-processing to function at full capacity, template coverage of the sky must exist in the ToO region of interest. In the commissioning and early operations era, templates will not be available in many areas, and hence standard alert processing cannot be used to disseminate candidates.

Where LSST templates exist, standard LSST processing can proceed as normal, and is currently operating in a commissioning state. In regions of insufficient or uncovered template coverage, custom processing will be required. A team of Rubin staff with experience in difference-imaging analysis has been assembled to support on-call processing of ToO areas that are insufficiently covered by existing Rubin templates.

In the case of insufficient Rubin template coverage, two options exist for custom image processing:

- **Difference imaging with external template sources:** template coverage exists from other southern-sky galaxy surveys. The best instrument for alternative template sources is DECam, and the feasibility of template generation with DECam is currently being evaluated.
- **Self-templating:** By taking images over multiple epochs, it is possible to pursue a ToO with a fast evolving lightcurve. The epoch of observation would need to be modified for the ToO in question in order to maximize the probability of detecting a variable lightcurve.

Both methods are available to the on-call processing team, and the method of choice will be pursued based on the existing template coverage for the ToO.

2.5 The Observing and Science Validation teams

In a non-commissioning environment, ToO observations are automated with minimal intervention by observers or ToO scientists. In the era of early Rubin operations, this is not the case. Owing to the commissioning of other Rubin Observatory systems and minimal Rubin template coverage in early operations, ToO observations will require significant intervention and support from the Rubin science community and the prompt-processing groups.

In line with the recommendations from the SCOC (The Rubin Observatory Survey Cadence Optimization Committee (PSTN-056)), a ToO advisory committee has been formed. The aim of this committee is to assess the viability of pursuing a ToO during the early operations period. The decision to pursue a particular ToO event, in no particular order, is based upon the following criteria:

1. The preparedness of the Observatory to respond to a ToO
2. The scientific impact of a Rubin-led discovery
3. The level of disruption to the SV surveys

The ToO advisory committee is composed of Rubin Observatory members with a wide range of expertise. The current committee members are:

- Sean MacBride - Chair, Rubin ToO coordinator
- Zeljko Ivezic - Project leadership
- Bob Blum - Project leadership
- Keith Bechtol - System Verification and Validation Scientist
- Robert Lupton - Commissioning scientist
- Yousuke Utsumi - ToO Scientist and Camera expert
- Eric Bellm - Prompt processing lead
- Federica Bianco - Deputy project scientist, Survey cadence optimization committee
- Tiago Ribeiro - Scheduler scientist and software architect
- Shreya Anand - Rubin-LVK Liaison
- Deep Chatterjee - LVK Liaison

3 Tests and ToO Responses

3.1 Responses to mock alerts

3.2 Responses to real alerts

4 Lessons learned from SV testing

A References

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B Acronyms

Acronym	Description
BBH	Binary black-hole
BNS	Binary Neutron Star
CSC	Commandable SAL Component
DECam	Dark Energy Camera
EFD	Engineering and Facility Database
FOV	field of view
GRB	Gamma-Ray Burst
GW	Gravitational Wave
JPL	Jet Propulsion Laboratory (DE ephemerides)
KAGRA	Kamioka Gravitational Wave Detector
LIGO	Laser Interferometer Gravitational-Wave Observatory
LSST	Legacy Survey of Space and Time (formerly Large Synoptic Survey Telescope)
LVK	LIGO-Virgo-KAGRA
NASA	National Aeronautics and Space Administration
NS	Neutron star
OPS	Operations
PP	Post processing
PSTN	Project Science Technical Note
RTN	Rubin Technical Note
SAL	Service Abstraction Layer
SCOC	Survey Cadence Optimization Committee
SN	SuperNovae
SNEWS	SuperNova Early Warning System
SSO	Solar System Object
SV	Science Validation
TSTN	Telescope and Site Tech Note
ToO	Target of Opportunity