Ariel Short-Sighted Mission Scheduler

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December 5, 2023

Abstract

Our current short-sighted scheduler for the upcoming Ariel mission is not planned to replace current algorithms, but instead to set a standard that current & future schedulers must meet or surpass. The primary objective of this scheduler is to provide the most pessimistic estimate of the total number of targets that Ariel could reasonably observe throughout its 3.5 to 4 year mission. Currently, the scheduler observes 79.0% of tier 1 targets, 40.7% of tier 2 targets, and 30.6% of tier 3 targets. From simulations using this scheduler, 76.9% and 12.2% of the mission is dedicated to scientific observations and idle time, respectively, with the rest of the time being dedicated to calibrations and telescope slewing. The scheduler only simulates missions for a single tier at a time (if updated, the scheduler should be able to simulate all tiers during a single mission), and it does not include phase curve observations. Additionally, the target list that has been used thus far is limited, comprised of 604 targets, which is insufficient given that Ariel is supposed to observe upwards of 1000 exoplanets.

1 Introduction

Ariel is a space telescope set to launch in 2029, with a mission to observe anywhere from several hundred to over a thousand exoplanets. Narrowing down this expansive target list to only include those of interest for Ariel is known as the selection process. A scheduler, however, seeks to optimize the order in which targets are observed throughout the mission. Clever schedulers have already been devised, employing sophisticated techniques such as evolutionary algorithms to optimize telescope time [1]. The primary objective of my work has been to design a short-sighted scheduler for Ariel, which can serve as a benchmark for current and future schedulers, as well as investigate the viability of such a simple scheduler for this survey mission.

2 Ariel Scheduler

The simple scheduler only considers transits and secondary eclipses (occultations) thus far, and ignores phase curve observations. Transits and eclipses occur when the planet blocks the light from its host star and when the host star blocks reflected light from the planet's surface, respectively. By studying the spectra taken during these events, one can study the planet's atmosphere. To acquire data with little noise, observations of these events can take quite some time, and one can predict which targets will need less observing time than others by using certain metrics. The metrics of interest for this projects are the Ariel Transmission Spectroscopy Metric (ATSM) and the Ariel Emission Spectroscopy Metric (AESM) (Wang & Cowan [2]).

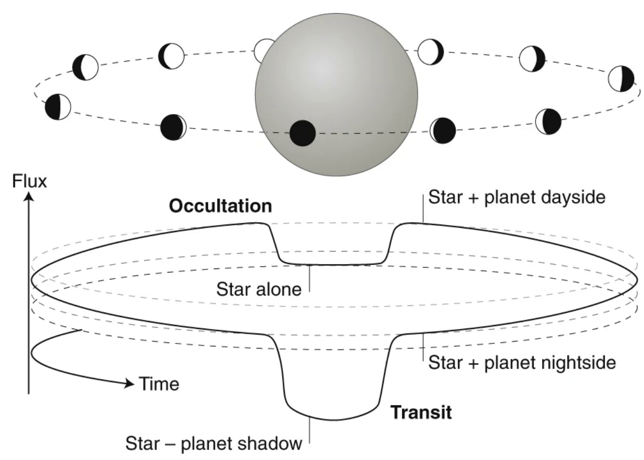


Figure 1: Diagram showing the difference between transit and secondary eclipse (labelled as occultation) [3].

2.1 Mission Constraints

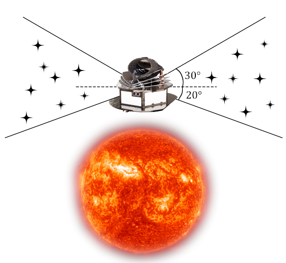
There are some important constraints to consider when designing a scheduler for Ariel. The constraints currently considered by the scheduler are as follows:

- **Mission duration**: Ariel is expected to have a total mission duration of approximately 4 years, including initial commissioning, the payload verification, and science demonstration phases which are expected to last 6 months in total. Nominal operations are thus expected to last about 3.5 years in duration [4].

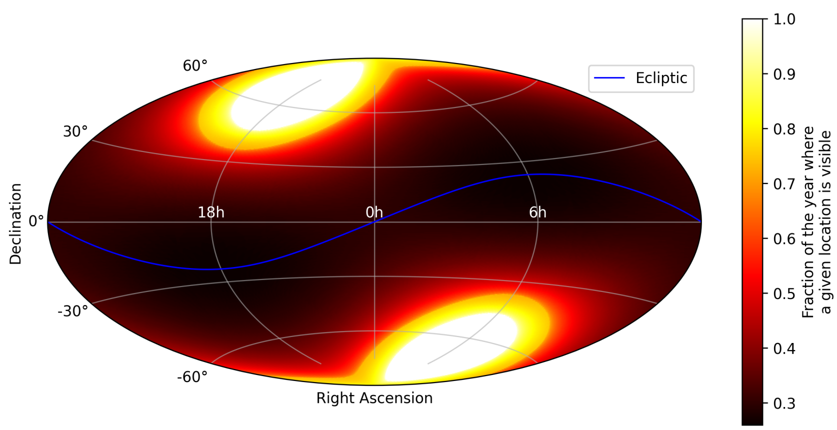
- **Event Timing**: Events of interest (transits and secondary eclipses) each occur once per orbit (see Fig.1). Phase curves (observations throughout a planet's orbit) are also events of interest for this mission, though they have not been included in the simple scheduler thus far.

- **Event Duration**: The duration of events is target-specific, though baseline duration is constant. For the sake of simplicity, a fixed total baseline duration of $t_{\text{baseline}} = 120$ minutes has been chosen.

- **Orbital Constraint**: Ariel's view of the sky is limited by the Sun's position at a given



(a) Sky constraints.



(b) Sky view.

Figure 2: Simple diagram showing the sky constraints of Ariel relative to the Sun's position (a) and Ariel's view of the sky throughout the year, plotted with the ecliptic (b). Brighter sections of the sky are visible for more throughout the year, and any point is visible for a minimum of ∼30% of a year. Ariel telescope image courtesy of Airbus.

time. According the Ariel definition study report [4], the telescope is limited to 70° towards the Sun and 60° away [1] (see Fig.2a). Fig.2b shows the fraction of the year for which each location in the sky is visible.

- **Telescope Slew & Settle Time**: Ariel is expected to have a slew-rate of approximately 4.5°/min [1]. We assume an additional $t_{\text{settle}} = 10$ minutes for the telescope to settle and refine its pointing position after each slew.
- **Telescope Calibration**: Ariel requires both short calibrations (1 hour every 36 ± 12 hours) and long calibrations (6 hours every 30 ± 10 days) [1] throughout the mission.
- **Ariel Tiers**: Ariel has 4 tiers, though tier 4 is solely for phase curves (which have been excluded from this short-sighted scheduler thus far). Tier 1 targets are observed at lowest resolution, while tier 2 and tier 3 targets are observed at increasingly higher resolutions [4].
- **Target Completeness**: The Ariel team has decided on a minimum Signal-to-Noise Ratio (*SNR*) of 7 to be ideal for scientific observations [4]. As such, an SNR of 7 was chosen to be the threshold beyond which a target is deemed 'complete', i.e., the target has sufficient data for scientific value.

2.2 Fitness Function

At a given time, Ariel will have many visible targets to observe. In order to choose which one to observe next, a weight (or rather, fitness) can be ascribed to each target. This can be calculated by a fitness function, where better candidates will have a greater value.

The fitness function has been designed to prioritize targets with greater metric quality (ATSM for transits, AESM for secondary eclipses), with longer orbital periods since longer periods mean less frequent events, shorter wait times to reduce idle time, and SNRs between 0 and 7 (see *Target Completeness* in 2.1) to maximize the number of completed targets. Therefore, the fitness has be defined as follows:

$$\text{Fitness} = \begin{cases} \frac{T \cdot Q_{\text{metric}}}{t_{\text{wait}}+1}(\text{SNR}+1)e^{-(\text{SNR}-7)/2} & \text{if } t_{\text{wait}} \geq 0 \\ 0 & \text{if } t_{\text{wait}} < 0 \end{cases}, \tag{1}$$

where the additional integer in the denominator prevents a discontinuity at $t_{wait} = 0$. Note also that T is the orbital period of the planet and t_{wait} is the wait time, defined as:

$$t_{\text{wait}} = t_{\text{event}} - (t_{\text{slew}} + t_{\text{settle}} + t_{\text{baseline}}/2)\,, \tag{2}$$

where $t_{\text{slew}} = \frac{\text{distance}}{\text{slewrate}}$ is the slew time, t_{baseline} is the baseline time (see *Event Duration* in 2.1), and t_{event} is the time at which the target's next event commences, given by:

$$t_{\text{event}} = T - (t_{\text{current}} - t_0) \pmod{T}, \tag{3}$$

where t_{current} is the current time (or a time of interest) and t_0 is some reference time, i.e., a known time at which the target transited before. Note that distance in this case is the

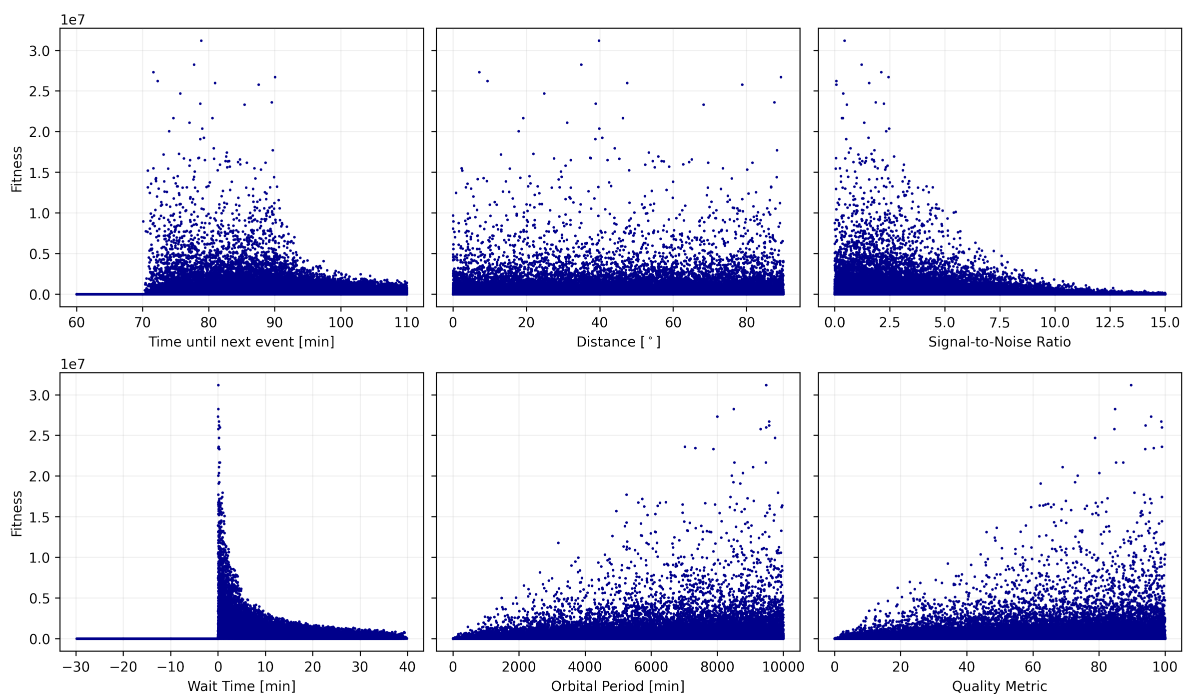


Figure 3: Fitness function and its various parameters, using simulated data.

great-circle distance, which is the shortest distance (in radians) along a sphere [5] defined as:

$$\text{Distance} = \arccos\left(\sin\delta_1 \sin\delta_2 + \cos\delta_1 \cos\delta_2 \cos\left(\alpha_1 - \alpha_2\right),\right. \tag{4}$$

where δ_1 & δ_2 are the initial and final declinations, respectively, while α_1 & α_2 are the initial and final right ascensions, respectively[1].

Fig.3 shows how each parameter affects the fitness function. Notice how the function behaves as expected.

2.3 Current Scheduler Performance

The simple scheduler has only been tested on a limited target list, containing 604 targets in total. Running the scheduler and simulating a 4 year mission (including 6 months for commissioning) starting on 1 January 2029 for each tier yields 477 completed tier 1 targets, 246 tier 2 targets, and 185 tier 3 targets.

	Tier 1	**Tier 2**	**Tier 3**
Total Observations	4205	4306	4450
Targets Observed	584 96.7%	448 74.2%	420 69.5%
Targets Completed	477 79.0%	246 40.7%	185 30.6%

Table 1: Results from simple scheduler simulations starting on 1 January 2029 and lasting 4 years (including initial commissioning phase). 604 total targets available in target list. Percentages represent the fraction of the total number of targets. Separate simulations were run for each tier.

Bear in mind that this number is significantly less than the desired number of completed targets for the Ariel mission (again, the hope is to observe upwards of 1000 targets), and as such one should expect the results from the simple scheduler to be on the very pessimistic

[1]Using some trigonometric identities, this can be modified to make it less computationally intensive, which can be important when running this function many times. See Appendix A. for the optimized formula.

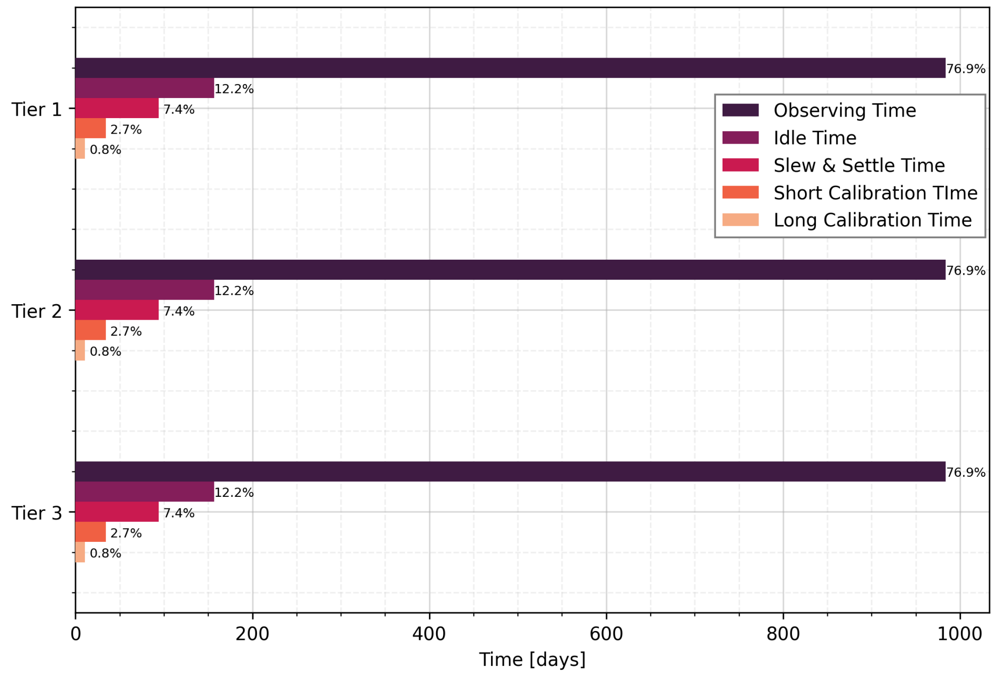


Figure 4: Time allocated to different phases of the mission for different tiers.

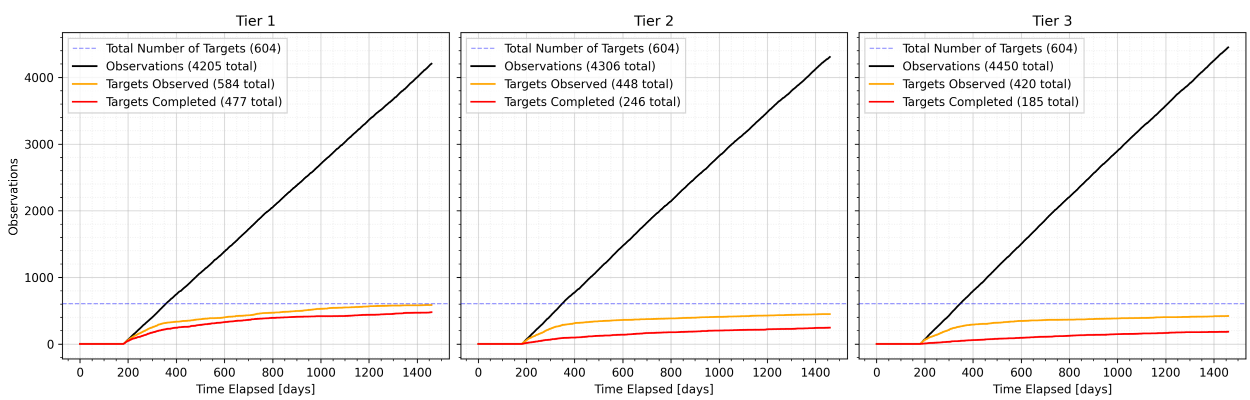


Figure 5: Observations over the course of the 4 year mission. The flat line at the beginning indicates the commissioning phase. *Targets Observed* represents when a target has been observed for the first time during the mission, whereas *Completed Targets* represents the number of targets with SNR ≥ 7.

side[2]. Interestingly, the time spent for each phase of the mission is the same for every tier, with 76.9% of the mission being dedicated to scientific observations (see Fig.4).

Note further that tier 2 and tier 3 targets need more observations on average to achieve an SNR of 7, so it is unsurprising that far more tier 1 targets are complete by the end of the

[2]With a more extensive list, we would expect the scheduler to perform better since it would have a larger selection of good targets at any given moment.

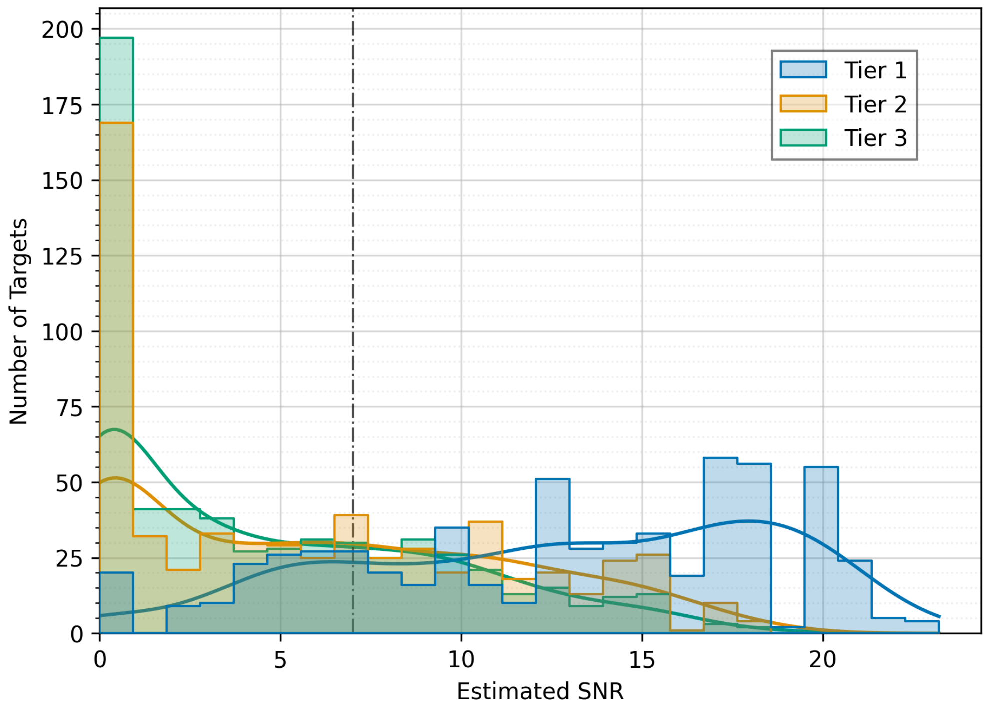


Figure 6: SNR density distribution for different tiers. The vertical line represents the threshold for completeness, i.e., SNR=7. As such, targets to the right of the line are deemed completed.

mission.

A quick note on the fitness function: in Fig.6, notice that there few tier 1 targets with SNR between 0 and 7, which is a good indicator that the SNR-portion of the fitness function is working as expected (see Appendix B. for an in-depth look on the SNR-dependency of the fitness function).

Overall, the main takeaway is that the simple scheduler get the majority of tier 1 target to SNR$\geq$ 7, while the number of completed tier 2 & tier 3 targets are also relatively high (given that those tiers imply higher resolution observations, and hence more observations on average to get a target to greater SNR). Additionally, the scheduler shows Ariel will be idle for 12.2% of the mission, meaning that the billion dollar mission will indeed be spending the majority of the expected 3.5 years of operation collecting scientifically useful data.

	Tier 1	Tier 2	Tier 3
Mean SNR	12.7	5.9	4.7
Standard Deviation	5.8	5.3	4.7
Minimum SNR	0.0	0.0	0.0
Maximum SNR	23.2	18.5	18.5

Table 2: SNR statistics from the simple scheduler simulation for each tier.

3 Conclusion

The short-sighted scheduler for the Ariel mission has made some significant progress since the beginning of the project, though it still lacks some key functionality. Most notably, it doesn't simulate a mission where it can observe all tiers (it only considers one tier at a time). Additionally, it excludes tier 4 observations (phase curves).

In spite of that, it performs well, completing 79.0% of tier 1 targets, 40.7% of tier 2 targets and 30.6% of tier 3 targets during a 3.5 year window, where the majority (76.9%) of the mission time is dedicated to actual observations. Granted, these percentages are with respect to the length of the used target list, which is limited to 604 total targets, roughly 400 targets shy of Ariel's desired target quantity. It would be interesting to see the simple scheduler's performance with a more extensive target selection. Despite its current limitations, this simple scheduler provides a benchmark against which all other scheduling algorithms should match or surpass, particularly regarding time spent conducting scientific observations.

4 Acknowledgements

Special thanks to my supervisor Nicolas B. Cowan for making this project possible and for providing helpful feedback throughout the project.

References

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[3] H.A. Knutson D. Deming. Highlights of exoplanetary science from spitzer. *Nature Astronomy 4*, pages 453–466, 2020. 2

[4] ESA. Ariel definition study report [red book], 2020. 3, 4

[5] Eric W. Weisstein. Great circle. 6

Appendix A. Optimized Distance Equation

The shortest distance (in radians) along a sphere given in Eq.4 can be optimized slightly for quicker computation, which is ideal given that this calculation needs to be done for every target every time the scheduler is searching for the next target to observe. Using trigonometric identities yields the optimized equation:

$$\text{Distance} = \arccos\left[\frac{1}{2}\Big(\cos(\delta_2-\delta_1)(f(\alpha_1,\alpha_2)+1)+\cos(\delta_2+\delta_1)(f(\alpha_1,\alpha_2)-1)\Big)\right], \quad \text{(A. 1)}$$

where $f(\alpha_1, \alpha_2) = \cos(\alpha_2 - \alpha_1)$, effectively reducing the number of trigonometric computations from 6 down to 4, since $f(\alpha_1, \alpha_2)$ only needs to be computed once (but used twice) to determine the distance.

Appendix B. SNR-Independent Fitness Function

The following are some plots showing the scheduler results when using the SNR-independent fitness function (i.e., a fitness function that does not prioritize SNR between 0 and 7).
The SNR-independent fitness function is as follows:

$$\text{Fitness} = \begin{cases} \frac{T \cdot Q_{\text{metric}}}{t_{\text{wait}}+1} & \text{if } t_{\text{wait}} \geq 0 \\ 0 & \text{if } t_{\text{wait}} < 0 \end{cases}. \quad \text{(B. 1)}$$

Notice how few targets are completed by the end of the mission, despite the fact that the total number of observations are up to 4600 for all tiers. Looking at table B.1 and Fig.B. 2, we get a better idea as to why that is: certain targets get observed far more than others. This likely results from the fact that certain targets have very high quality metrics and only need to be observe a couple of times before reaching SNR=7, meaning that their fitness values are nearly always superior to others. It was this that lead to the updated fitness function from Eq.1 that prioritizes targets with SNR between 0 and 7, which indeed increases the number of completed targets by the end of the mission.

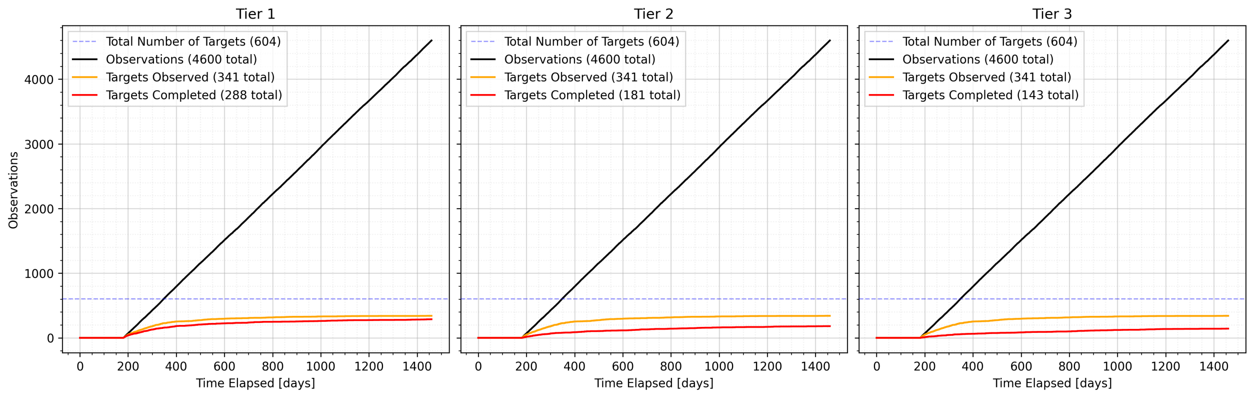

Figure B. 1: Observations over time for each tier, using the SNR-independent fitness function. Separate simulations run for each tier.

	Tier 1	Tier 2	Tier 3
Mean SNR	11.3	7.5	6.0
Standard Deviation	14.4	12.6	11.6
Minimum SNR	0.0	0.0	0.0
Maximum SNR	110.9	110.9	110.9

Table B.1: SNR statistics from the simple scheduler simulation for each tier, but using the SNR-independent fitness function.

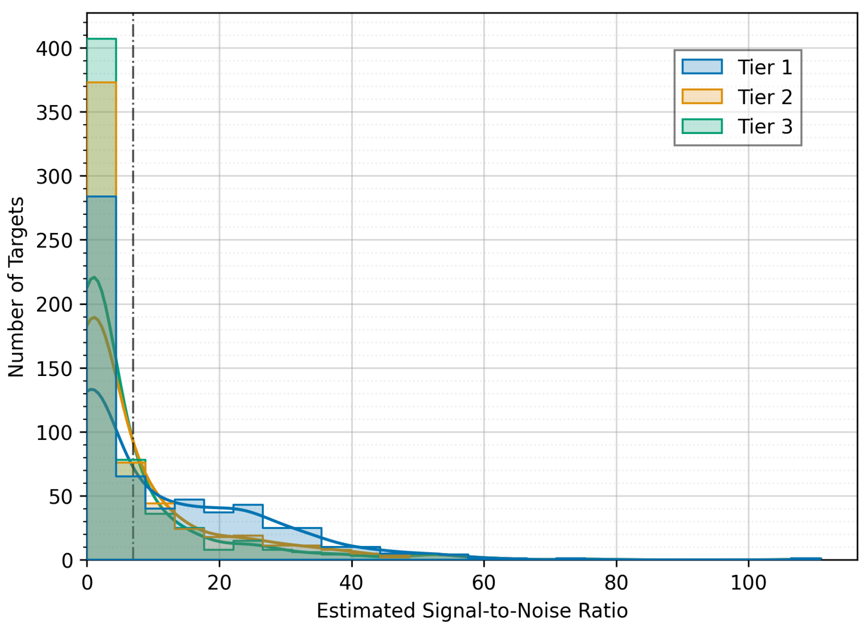

Figure B. 2: Density Distribution for different tiers. Vertical line represents the threshold for completeness, i.e., SNR=7. Notice that very few targets have SNR$\geq$ 7.