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Astronomical observation tasks short-term scheduling using PDDS algorithm

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ABSTRACT

A concept of the ground-based optical astronomical observation efficiency is considered in this paper. We believe that a telescope efficiency can be increased by properly allocating observation tasks with respect to the current environment state and probability to obtain the data with required properties under the current conditions. An online observations scheduling is assumed to be an essential part for raising the efficiency. The short-term online scheduling is treated as the discrete optimisation problems which are stated using several abstraction levels. The optimisation problems are solved using the parallel depth-bounded discrepancy search (PDDS) algorithm by Moisan et al. (2014). Some aspects of the algorithm performance are discussed. The presented algorithm is a core of open-source `chelyabinsk` C++ library which is planned to be used at 2.5 m telescope of Sternberg Astronomical Institute of Lomonosov Moscow State University.

1. Introduction

Since an efficiency is a philosophic concept, it is impossible to give it a unique and precise definition both in general and in the particular case of astronomical observations. Even when ground-based optical astronomy is considered, different concepts are used as an efficiency. In case of dedicated small robotic observatories, open-shutter time is considered as a measure of an efficiency. A fast cadence is desired when surveys are performed. More classical definition by Bowen (1964) assumes that efficiency is related to the limiting magnitude of a telescope. In other words, it is assumed that unexplored and challenging targets belong mostly to the faint object area. In some sense, this assumption is still valid today.

Further, we accept Bowen point and try to develop this idea. We consider a set of an atmosphere, an optical system and an equipment as a single physical system used for carrying experiments (astronomical observations in our case). Modern ground-based astronomical observations are affected by different external factors, for instance, an atmospheric optical turbulence is commonly mentioned as a phenomenon limiting optical angular resolution. Effect of the optical turbulence does not remain the same but constantly changes over the time. We may consider the physical system evolution as a track in a phase space, where each axis corresponds to a physical quantity affecting astronomical observations. The physical quantities are divided into different groups. Those which do not vary significantly over the time: a telescope aperture size, a CCD readout noise, etc. The quantities which are under our control, for instance, equipment settings or a telescope mount position. The last part is the quantities which are not under control: an atmospheric optical turbulence power, an atmospheric extinction, a night sky brightness, etc. In other words, the system evolves stochastically over corresponding axes.

It is assumed that the system is in the particular area of the phase space during classical ground-based astronomical observations of a specific target. For instance, to carry out separate photometry of a binary star with the separation of 1.4″, we have the reasons to demand that the optical resolution should be well better than 0.7″. For each particular observation task a feasible area has different size and form. Even more, time resources of almost any modern general-purpose optical telescope are limited. Different scientific tasks and programs have to compete with each other for available resources.

The astronomical observation scheduling concept is usually divided into a long-term scheduling and a short-term one. The long-term scheduling considers time ranges of days, weeks, or months. It may use some statistical information about environment, but the long-term scheduling is not required to be performed online. The short-term scheduling considers ongoing night and is usually thought as of online procedure using live data about environment (Gómez de Castro and Yáñez, 2003). Only short-term online scheduling is considered further in the paper.

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The short-term online scheduling is supposed to raise an efficiency at least by avoiding idles due to unfeasible conditions. We essentially follow the idea behind Bowen formula that supposes a telescope can be considered to be more efficient than another one if more observation tasks can be carried out within the same time interval (and time resources are left for more observations).

We assume that for the upcoming night there is a task set generated by a long-term scheduling process (either automatic or manual). For any particular time moment of an ongoing night we want to select an ordered subset of tasks to observe right now and in the near future. It is assumed that the subset is selected in globally effective way. We do not consider further what happens with the tasks that have not been selected and have not been observed. However, the most obvious way would be to return the tasks to the long-term scheduler.

2. Optimisation problems

As soon as we talk about automatic scheduling (i.e. a kind of algorithm in generic sense) a concept of efficiency has to be operationalised in a specific way. A variety of astronomical observational tasks (and scientific knowledge) is to be reduced to a single number. Definitely, it cannot be done uniquely and precisely. Nevertheless, the following quantities are introduced.

Let T be a set of all available observational tasks. For any observational task $i \in T$ let $p_i(t|\theta)$ be conditional success probability viewed as a function of task observation start time moment t. Here the current system state (which is the system state history in essence) is denoted by θ and will be skipped in the further equations for brevity. An observation task is said to be successfully carried out when the system is in appropriate area of the state space during observation of the task. We assume that the system trajectory in the state space can be somehow forecasted given that the current state θ is known. The state is supposed to be known by means of dedicated monitoring systems (Colomé et al., 2010) or by means of online observation processing pipelines (Delgado and Schumacher, 2014). A relative weight of observational task is called an *yield* and is denoted by $y_i(t)$. The set T is considered to be finite, then without loss of generality, it can be assumed that $0 \le y_i(t) \le 1$. A set of all non-empty finite sequences consisted of members of T is denoted by T^+. Let $S \in T^+$ be a non-empty finite task sequence, further we assume that $\forall i \ne j, S_i \ne S_j$. The number of elements in S is denoted by $|S|$.

Finally, a total yield is defined as the following:

$$\mathcal{Y} = \sum_{i=1}^{|S|} y_{S_i}(t_{S_i}) \xi_{S_i}(t_{S_i}), \tag{1}$$

where $\xi_{S_i}(t_{S_i})$ are random binary variables being 1 with probability of $p_{S_i}(t_{S_i})$. All ξ_i are assumed to be independent for the sake of simplicity. t_{S_i} are introduced in the following recurrent manner:

$$t_{S_{i+1}} = t_{S_i} + d_{S_i}(t_{S_i}) + s_{S_i,S_{i+1}}\left(t_{S_i} + d_{S_i}(t_{S_i})\right), \tag{2}$$

where t_{S_1} is the initial time moment. Without loss of generality, one may assume that $t_{S_1} = 0$. $d_{S_i}(t)$ is a duration of task observation process when started at t, $s_{S_i,S_{i+1}}(t)$ denotes a setup time required to start task S_{i+1} after task S_i has been completed. The mean of (1) is called a mean total yield:

$$Y \equiv \mathrm{E}[\mathcal{Y}] = \sum_{i=1}^{|S|} y_{S_i}(t_{S_i}) p_{S_i}(t_{S_i}). \tag{3}$$

Note that the total yield is the weighted number of successfully completed observational tasks in essence.

By the previous assumptions, the probability of finite task sequence S success is the following:

$$\Pi = \prod_{i=1}^{|S|} p_{S_i}(t_{S_i}). \tag{4}$$

Let us state two following discrete optimisation problems which are considered further as observational scheduling problems. Then, mean total yield maximisation problem is

$$Y^* = \max_{S\in T^+}\left(\sum_{i=1}^{|S|} y_{S_i}(t_{S_i}) p_{S_i}(t_{S_i})\right). \tag{5}$$

Success probability maximisation problem is

$$\Pi^* = \max_{S\in T^+}\left(\prod_{i=1}^{|S|} p_{S_i}(t_{S_i})\right). \tag{6}$$

Constraints for sequence length are provided for both of the problems. In the first case:

$$t_{S_{|S|}} + d(t_{S_{|S|}}) \le D, \tag{7}$$

in the second case:

$$t_{S_{|S|}} \ge D, \tag{8}$$

where D has a sense of scheduling horizon or sunrise moment. The function $S^*(\theta) = \arg\max_{S\in T^+}\left(\sum_{i=1}^{|S|} y_{S_i}(t_{S_i}) p_{S_i}(t_{S_i}|\theta)\right)$ (and its analogue for case (6)) is also usually called as decision process a-priory policy.

Therefore, we connect a concept of ground-based astronomical observations efficiency with the yield in (5), or with success probability in (6). The problems are complementary in some sense. The number of successes is maximised in (5) and the number of failures is minimised in (6). These quantities are based on some natural concepts (i.e. number of performed tasks) and replicate existing models (Gómez de Castro and Yáñez, 2003) in some sense.

Let us again emphasise that there is a crucial logical gap between philosophical concept and any its specific numerical measure. Thus, instead of giving ultimate formal proof of equivalence between a concept and its measure, we can consider the measure only as a representation for the concept. It is for end users to decide whether the particular measure is relevant to the concept. The decision is based on current understanding what the telescope efficiency concept really is under particular circumstances. Moreover, the understanding will inevitably be changed as gaining practical experience. Therefore, our approach should be flexible enough to be modified in future with new demands.

Consequently, it is also impossible to determine which approach (mean total yield maximisation problem (5) or success probability maximisation problem (6)) is the most right one, because the comparison is possible only on philosophical or methodological levels, which is behind the scope of this paper. Indeed, let S_1^* and S_2^* be solutions for (5) and (6) respectively. Also, let f be a metric such that the higher the value $f(S_{1,2}^*)$ the more correctly and more adequately the problem has been formulated. Then (5) and (6) are to be considered as approximations to the maximisation problem of $f(S)$ which is actually being solved and f is implicitly considered as another efficiency measure.

2.1. Forms of $p(t)$, $d(t)$, $s(t)$

Let us consider possible forms of the functions $p(t)$, $d(t)$, and $s(t)$ from (5) and (6). Also it will become more clear what we assume as an abstraction called an observational task. All tasks of T may have different origin, but the functions $p(t)$, $d(t)$, and $s(t)$ form an abstraction level between physical model and the optimisation problem. Further we consider different kinds (or classes) of observational tasks: a group, a repeat, CCD-based photometry task.