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# A model, a heuristic and a decision support system to solve the scheduling problem of an earth observing satellite constellation

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ABSTRACT

China plans to launch four small optical satellites and four small SAR satellites to form a natural disaster monitoring constellation. Data can be obtained by the constellation in all weather conditions for disaster alert and environmental damage analysis. The scheduling problem for the constellation consists of selecting and timetabling the observation activities to acquire the requested images of the earth surface and scheduling the download activities to transmit the image files to a set of ground stations. The scheduling problem is required to be solved every day in a typical 1-day horizon and it must respect complex satellite operational constraints as well as request preferences, such as visibility time windows, transition time between consecutive observations or downloads, memory capacity, energy capacity, polygon target requests and priorities. The objective is to maximize the rewards of the images taken and transmitted. We present a nonlinear model of the scheduling problem, develop a priority-based heuristic with conflict-avoided, limited backtracking and download-as-needed features, which produces satisfactory feasible plans in a very short time. A decision support system based on the model and the heuristic is also provided. The system performance shows a significant improvement with respect to faster and better scheduling of an earth observing satellite constellation.

## 1. The natural disaster monitoring constellation of china

The first environmental and disaster monitoring and prediction satellite constellation of China consists of four small optical satellites and four small SAR (Synthetic Aperture Radar) satellites, which are typical earth observing satellites. The constellation's aim is to obtain earth images in all weather conditions and over a large area, providing the abilities for natural disaster alert and environmental damage analysis. The first phase of the project sees the launch of two optical satellites, i.e., HJ-1A and HJ-1B (HJ is short for Huan Jing, which means Environment), which were already shot in September 2008, and the first SAR satellite, HJ-1C, is planned for 2010.

The two optical satellites of the constellation are located in the same orbital plane of 97.95° at 650 km altitude and are phased at 180° from each other, covering all Chinese territory in 48 h. HJ-1C will follow a heliosynchronous low orbit (about 500 km above the earth surface) around the earth at the inclination of 97.37°, and it will run 15.2258 orbits a day.

The three satellites of the constellation's first phase have complementary advantages: they will allow periodically repeated observations of a same site, and the infra-red camera of HJ-1B and the SAR technology on-board HJ-1C will provide high resolution images regardless of illumination or weather conditions. The constellation is intended for both national and international use. Besides being applied to natural disaster monitoring purpose within Chinese territory, the constellation will also make contribution to the International Charter 'Space and Major Disasters', a joint initiative that aims to provide emergency response satellite data free of charge to those affected by disasters anywhere in the world.

The constellation is supposed to satisfy different customers, such as China National Disaster Deduction Commission, normal civilians who require for images of area interested, and China Center for Resource Satellite Data and Applications (CRESDA), who is responsible for the ground segment that consists of a Mission Command and Control Center, and several telemetry, tracking and communication ground stations both for uploading the operational commands to the satellites and for receiving images from them.

We have been participating in the constellation program since January 2008 with CRESDA, who is in charge of the development of the scheduling algorithm.

## 2. The scheduling problem

The scheduling problem of an earth observing satellite constellation is to specify the start times and the durations of the

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observation activities to acquire the requested images of the earth surface, as well as to specify the start times and the durations of the download activities to transmit the images back to a set of ground stations.

The problem is difficult because of lots of characteristics associated with satellite observation and download capabilities, such as observation and download time windows, on-board storage capacities, transition times between consecutive activities, and chronological sequence requirements between observations and downloads. The problem difficulty also comes from the large scale of the real problem instances. Take the typical one-day schedule horizon for example, due to the satellite agility, satellites can look at the left and right sides of their ground tracks, and they can also image the targets before or after flying above the targets. Therefore, each target can have up to 10 observation opportunities, and each opportunity corresponds to a time window larger than the observation span required. If every day we have hundreds of requested targets, the number of observation time windows could be thousands, so could the download time windows between satellites and ground stations. The high freedom for the time window selection and the start time selection makes the problem complexity higher.

### 2.1. Literature review

Since lots of satellite applications in practice require an optimal, if possible, or a satisfactory observing schedule for a special satellite, most researchers concentrate on single satellite scheduling problems. Hall and Magazine (1994) considered an observation scheduling problem for a spacecraft respecting time window constraints. Bensana, Verfaillie, Agnese, Bataille, and Blumstein (1996, 1999) and Vasquez and Hao (2001) studied the daily observation scheduling problem for Spot satellite of France. Single-satellite-single-orbit scheduling problems were also researched by Gabrel, Moulet, Murat, and Paschos (1997) and Cordeau and Laporte (2005), and the latter solved instances with up to 50 requests through tabu search techniques. A SAR satellite scheduling problem was solved by Harrison, Price, and Philpott (1999) through a partial enumeration method.

Although the technical development of satellites and payloads makes the satellite agility possible in the recent years, most earth observing satellites are still non-agile satellites. For non-agile satellites, since the observation start time is fixed in the time window, the problem is actually a selection problem, whereas, for agile satellites, since the observation start time is variable, the problem is a selection and scheduling problem. The agility gives rise to much more scheduling opportunities, therefore brings a potentially better efficiency of the satellites. On the other hand, the agile satellite scheduling problem is much more difficult due to the fact that the compatibilities between images can be no longer easily precomputed. All of the above literature considered problems for non-agile satellites, although Hall and Magazine (1994) took the start time as a variable, they did not take into account the compatibilities between images, and so did Cordeau and Laporte (2005). Gabrel et al. (1997) actually researched on an agile satellite, because they discussed in details about the rolling and pitching angle adjustment, despite not mentioning the agility explicitly. It is believed that Lemaître, Verfaillie, Jouhaud, Lachiver, and Bataille (2002) are the first to introduce the selecting and scheduling problem for an agile earth observation satellite. They discussed polygon target observations, polygon target decomposition methods and the increased observation freedom brought by the agility, as well as the complicated transition times. However, they only modeled a simplified version of the problem, i.e., the single track (half orbit) selection and scheduling problem with limited agility. And they made comparison of several algorithms: greedy search, local search, constraint programming and dynamic programming.

For the past few years, with the advancement of small satellite techniques, there emerges a trend to fulfill large or complex earth observation missions through a group of satellites, i.e., a satellite fleet or constellation. Even though multi-satellite brings more observation opportunities for each target, the increase of the observation requirements far exceeds the increase of the observation capabilities. Most of the time, the scheduling problem of an earth observing satellite constellation is still an oversubscribed problem. Even for a non-oversubscribed problem instance with a less constrained solution space, it is rather difficult to find an optimal or sub-optimal solution. Those who researched on multi-non-agile-satellite scheduling problems are typically as follows: Abramson et al. (2001) presented initial results from the algorithms developed for a small number of satellites and a single target on earth, with the objective to maximize the total observing time of the target. They provided detailed astrodynamics analysis on the maneuver operation required by the target observation, and constructed a state-transition graph. They formulated the problem as an integer program and used the classical algorithms for the simplified shortest path problem. No computational results were reported in the paper. Bianchessi, Cordeau, Desrosiers, Laporte, and Raymond (2007) considered the observation scheduling problem for a constellation of agile satellites. Tabu search algorithm was devised to produce solutions, whose qualities were evaluated by a column generation algorithm on a linear programming relaxation of the problem. Chien et al. (2004, 2005) provided a sensorweb detection and response architecture, in order to coordinate a constellation of earth observing satellites to track unexpected ground phenomena. No models and experiments were reported. Dungan, Frank, Jónsson, Morris, and Smith (2002) described the planning and scheduling problem of the observation activities of a satellite fleet. A declarative model and a stochastic sampling method were provided. The solution method was based on resource contention heuristics. Globus, Crawford, Lohn, and Morris (2003a, 2003b) devised genetic algorithms for the same problem, and they compared various approaches: hill-climbing, simulated annealing and genetic algorithms.

In spite of the fact that a complete fulfillment of an observation request is to first take the image of the target, and then to download the image to a ground station, observation scheduling problem and download scheduling problem (or from the ground station's point of view, so-called satellite range problem according to some literature) are separately researched.

For the satellite download scheduling problem, Burrowbridge (1999) proposed a greedy algorithm to schedule the download activities of multiple satellites to ground stations. Barbulescu, Howe, and Whitley (2006) compared three algorithms, i.e., local search, mixed-integer programming combined with insertion heuristics, and a genetic algorithm, for scheduling ground station support times to a group of satellites. Inspired by the graph coloring problem and related solution methods, Zufferey, Amstutz, and Giaccari (2008) designed a tabu search and an adaptive memory algorithm for the multi-station (or antennas of the station) version of the download scheduling problem.

As far as we know, the satellite constellation scheduling problem taking into account both observations and downloads received only limited attention. Abramson, Carter, Kolitz, Ricard, and Scheidler (2002) took the download as program input and added decision variables for observation angles in the model compared with their previous work Abramson et al., 2001. Damiani, Verfaillie, and Charmeau (2005) presented the problem of managing a constellation of earth watching satellites, each of which is equipped with a special instrument to detect forest fires or volcanic eruptions. The satellites are actually non-agile satellites. And the selecting and scheduling problem was solved via time interval reasoning in an incremental manner. Frank, Jonsson, Morris, and Smith