Design and implementation of scheduling system for disaster monitoring satellites of CHARTER mechanism

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Abstract: A system for scheduling of disaster monitoring satellites which follows the tenet and operation mechanism of CHARTER is developed. First, it introduces the significance and mechanism on which CHARTER is running and then details the design and implementation of the system. At the same time detailed function of each module is given out. Great attention is paid to the analysis module of tasks' time windows. In the process of the computation of the targets' time windows, a dynamic partition algorithm for area target is introduced. Then a dynamic scheduling algorithm is constructed to create schedule plan for disaster monitoring satellites. Also the paper develops three variables to evaluate the plan created, and gives out the meaning of each variable respectively.

Key words: mission planning, satellite scheduling, CHARTER, available time windows, area target

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1 INTRODUCTION

Sun Laiyan, the chief of Chinese Aerospace Bureau, signed "The international charter of space and the important disaster" on May 25, 2007, which indicated that China became a formal member of the CHARTER mechanism (Guo, 2002). CHARTER is a contractual organization and it aims to reduce the damage from natural disasters. The mechanism proposes that, only a country's remote sensing satellite resources are not enough to cope with the frequent natural and man-made major disasters (floods, forest fires, earthquakes, hurricanes, landslides, etc.). Thus, all the space agencies and satellite units need to strengthen international cooperation to share satellite resources and make full use of space technology for disaster monitoring. Its working mechanism (National Space Technology for Disaster Reduction Network) is shown in Fig. 1.

Remote sensing satellites play an increasingly prominent role in environmental monitoring and natural disasters rescue, which makes them the major information source for disaster mitigation and relief. Current researches on satellite mission planning are mostly for satellites' daily operation. In other words, to create satellite observation plan according to user requests (Robert *et al*., 2004; Nicola *et al*., 2008; Frank *et al*., 2002). There are also researchers who focus on re-scheduling method which considers cloud cover, unexpected events, and the failure of resources (Morris *et al*., 2004; Khatib *et al*., 2002).

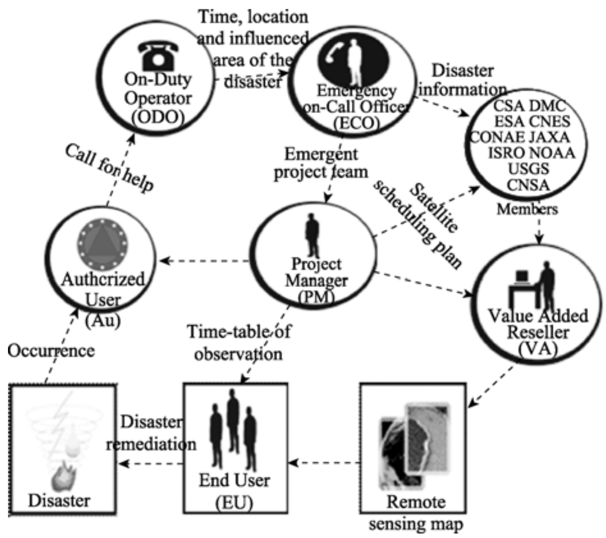

Fig. 1 Work flow of CHARTER

To create re-scheduling plan the satellite should have the ability to act independently, while most satellites do not own that ability. There are a number of well developed soft wares for Earth Observation Satellite Scheduling, including the American ASTER scheduling system (Cohen, 2002), the French SPOT5 satellite scheduling system (Vasquez *et al*., 2000) and the Cosmo-Pleiades scheduling system of European Space Agency (Bianchessi, 2005). These systems are mainly used to create daily schedule for satellites. And all these systems can not sup-

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port re-scheduling for emergent disasters. At the same time, these systems are dedicated scheduling system for satellites that are orbiting and of bad compatibility. Once a new satellite is launched, these systems will be inapplicable.

So far, CHARTER mechanism has incorporated more than ten space agencies all over the world, owning dozens of earth observation satellites. CHARTER was originally conceived to minimize human losses brought by sudden major disasters through global information sharing. In response to these sudden emergency events, how to choose satellite resources, how to generate an available satellite observation plan in the shortest time? The Charter system is designed and implemented, which follows the operating flow of CHARTER mechanism. The system can manage all the satellite resources effectively and support quick definition of target. Also the system can calculate satellite time windows for targets and generate observation plan for satellites, which can provide decision support for CHARTER manager.

2 DESCRIPTIONS OF THE PROBLEM AND SYSTEM DESIGN

This section details the problem of CHARTER satellite scheduling and also establishes a basic system model. Then it gives a short introduction about the function of system and each module.

2.1 Description of the problem

This problem is essentially an area target oriented emergency re-planning problem, which involving several key elements, including User requirements, resources and their constraints, time windows of new tasks and scheduled time windows.

2.1.1 User requirements

When encountered serious natural disasters and emergencies, the authorized user would apply CHARTER for satellite observations. Each application consists of at least four elements shown below.

• **Task types** $T^{y}_{(a)}$: including floods, earthquakes, and landslides. It is used to identify the needed satellite remote sensing devices to fulfill the task.

• **The task area** $R^{e}_{(a)}$: the geographical location information of the disaster, including longitude, latitude of the disaster core and the affected area.

• **Request Time** $T^{r}_{(a)}$: time when the authorized users submit their request to CHARTER. It is to define the nearest available time window of current satellite.

• **Deadline** $E^{t}_{(a)}$: to limit the latest observing time for satellites. Generally this property is always ignored.

2.1.2 Resources and its constraints

Resources can be classified as exclusive resources and accumulated resources. The exclusive resource mainly refers to the satellite time window, and its exclusivity can be manifested by Fig. 2. If the satellite time windows conflict then the satellite can only choose one of them. The so-called cumulative resources are mainly onboard power supply and satellite storage. Take power supply for example, all the satellite activities, such as imaging and position maneuver, will consume energy. However, as long as the left power capacity is not less than the accepted threshold the satellite can continue to work. When the satellite flew to sunlight its solar panel can be recharged. The resource constraints are shown as follows.

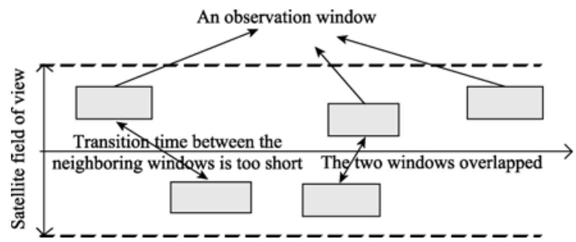

Fig. 2 Exclusiveness of the resource

• **The longest working time for single-boot** $D^{t}_{(s)}$: the imaging process consumes most satellite power, so the total time the satellite can work in a single boot process is rated.

• **The maximum slew time for each circle** $S^{c}_{(s)}$: position maneuver will also consumes great power, thus the time that a satellite can image with different look angles is limited.

• **Maximum storage capacity** $S^{m}_{(s)}$: due to the constraint of download link the satellite can not transmit its data back. Instead, these data will be stored in on-board memory and when the memory is full the satellite will not work until its memory is clear again.

2.1.3 Time windows for task T_i^{w}

The visible time period between the satellite sensors and ground targets that meet mission requirements (such as resolution, solar radiation, clouds and so on). Each time window can be defined as:

• **Start time** $S_{(a)}$: start time of the observation chance.

• **End time** $E_{(a)}$: end time of the observation chance.

• **Duration time** $T_{(a)}$: length of the observation time.

• **Look angle** $A_{(a)}$: departure angle of the sensor when satellite taking images of the target.

• **Image data** $D_{(a)}$: the image data produced for each observation.

• **Task priority** $P_{(a)}$: importance of the target, a bigger value means a more important target.

2.1.4 Scheduled time window

It is for the tasks that have been scheduled which are defined by start time, end time, duration time, look angle, image data and task priority.

To sum up, CHARTER disaster monitoring satellite scheduling problem is an area target oriented re-planning problem which should take the scheduled plans, user and resource constraints into consideration.

2.2 Design of the system

Based on the understanding of workflow of CHARTER mechanism, a Charter system which is used to support the scheduling of disaster monitoring satellites is built. The function of the system is summarized in the following five aspects.

(1) Design and define system tasks. The system must ensure the project manager of CHARTER model disaster area accurately for each user request.

(2) The system should help CHARTER with the daily management of satellites, including the updates of satellite orbit data, operation status and maintenance of satellite's own state. At the same time, it also supports the management of all satellite plans being performed.

(3) Calculate visible time windows between satellites and ground targets. As the targets to be observed are mainly area targets, the system must support the partition of them.

(4) Generate and simultaneously evaluate the final satellite scheduling plans. And also three assessment criteria's are defined in the system.

(5) Visualize the created plans and simulate the operation of satellites. Also, manage all the created scheduling plans.

To accomplish these tasks, the system is divided into five modules: task description module, resource management module, time window calculation module, plan generation and visual display module and the system control module. The overall structure of the system is shown in Fig. 3.

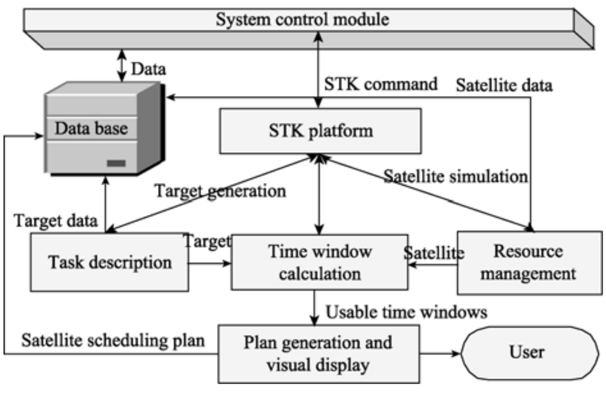

Fig. 3 Structure of the system

3 IMPLEMENTATION OF THE SYSTEM

3.1 Task description module

The main function of this module is to turn the authorized users' requests into tasks that the system can identify. Then, manage all the system tasks. System task management is primarily reflected by the management of the data base, which can help the CHARTER staff avoiding repetitious definitions of the same target. For each request from authorized user, it contains general information of the disaster such as type, location, time and influenced scope and so on. This information can not be directly used by the system. Task modeling is to construct a standardized target, which comprises all the properties of each request. This system provides two ways to define system targets: precise definition and two-dimensional view definition.

The so-called precise definition is to define a target using its coordinate information. The system provides an input interface for operator of the system (project manager), through which they can locate a detailed target. The system will generate a corresponding target according to its latitude and longitude. If only a pair of latitude and longitude information is given, the system will set it to be a fixed-point target (the center of disaster areas) automatically. If multiple pairs ($\geqslant 3$) are entered, the system will define them as an area target and connect these points orderly, which defines the border of area target.

In contrast, two-dimensional view definition is a more intuitive way. The target can be generated according to mouse clicks. The system will track and identify the mouse clicks and generate system targets accordingly. If the mouse is clicked only once the system will take it as a spot target and if more than three times it will be an area target. The system will connect all these points selected by the system operator together and the area target is created.

3.2 Resource management module

Resource management module is to realize management of imaging resource, where resources mainly refer to satellites. Its management includes adding satellites, satellite attribute information query, deleting satellites and update of the satellite status. Of these functions, the most significant is the update and maintenance of satellite information. Considering the special mechanism on which CHARTER is operating and the actual situations of satellites from different agencies, the system will access and update satellite parameters and missions everyday.

The satellite parameters here mainly refer to the internationally recognized two-line orbit parameters (Liu, 2000). It is measured with ground-based radar from the NORAD which is jointly built by Canada and the United States. These orbit parameters stand for instant position and velocity of the satellite in one day. According to these parameters, the system can extrapolate satellite's sub-line track and access of ground targets.

CHARTER is a contractual organization which means that it can not interfere with the daily operation of each satellite. And all the satellites contained in CHARTER will run regularly regardless of the sudden occurrence of disaster. Once the disaster strikes, the project manager will firstly arrange the satellite whose capacity is spare to collect information of disasters. If all the satellites are full-loaded, then he will choose the satellite whose tasks are of lower priority. In a word, the observation will be carried out and the interruption it brings to the already scheduled tasks should be as subtle as possible.

3.3 Time window calculation module

3.3.1 Calculation of available time window

Visible time windows between the satellite sensors and ground targets are visible time periods that meet mission requirements (such as resolution, sunlight, weather and so on). They are the basis of satellite mission planning and can be calculated through STK platform.

Though we have got visible time windows of the targets, they might not be available. As it would conflict with scheduled time windows. The available time windows are defined as these that not only are visible but also have no conflicts with scheduled ones. And Fig.4 illustrates the available time windows. Therefore, this module's ultimate goal is to calculate the available time windows of ground targets.

All the visible time windows on the target can be divided into spare time windows and conflicted ones. The spare time windows can be used directly, that is the available windows. For these conflicted windows, we need clearing up the conflicts first according to task priorities. However, the conflict is not absolute. If the target needs only one shot and the satellite pass over it several times, then we can choose a spare time window from multi observing opportunities.

3.3.2 Dynamic partition algorithm for area target

Generally speaking, the major disasters will affect a broad regions and it is therefore defined as area target. Because of its specificity, area target can not be covered by a single observation strip. To get the time windows of area targets, we need to partition it first. An improved dynamic partition algorithm for area target is proposed, which is based on the original deterministic algorithm (Ruan, 2006; Michel *et al*., 2002). The detailed partition process is described as below.

To start with the algorithm, a few denotations are defined. Satellite sets $S' = \{s_1, s_2, \cdots, s_{N_S}\}$, area target sets $T_p = \{t_1, t_2, \cdots, t_{N_T}\}$. For satellite s_j, it has a maximum slewing look angle $g_{\max}(j)$ and a minimum angle $g_{\min}(j)$. The remote sensor's field of the regard is Δg_j and the angle offset is $\Delta\lambda$ when partitioning. Suppose that in a scheduling period satellite s_j has N_{ij} observing opportunities for task t_j. If we partition task t_i in the k_{th} time window of satellite s_j, then we can get N_{ijk} meta tasks and the v_{th} meta task is noted as o_{ijkv}.

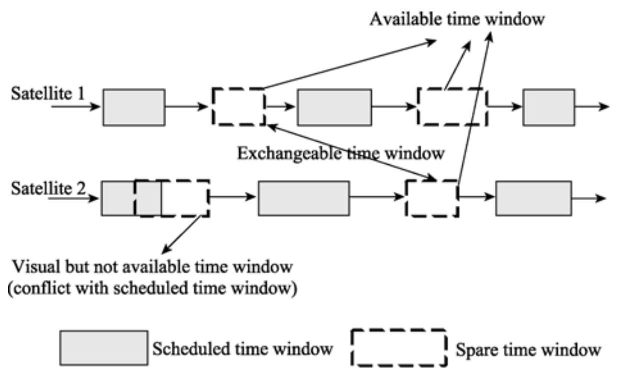

Fig. 4 Available time window

After partition, a meta task set O_i for task t_i can be got and it is notified as $O_i = \{O_{i1}, O_{i2}, \cdots, O_{iN_S}\}$. O_{ij} is the meta task set of task t_i which is partitioned according to satellite s_j and $O_{ij} = \{O_{ij1}, O_{ij2}, \cdots, O_{ijN_{ij}}\}$. For each time window it might be partitioned into several meta tasks and it constitute a meta task set O_{ijk}, where $O_{ijk} = \{o_{ijk1}, o_{ijk2}, \cdots, o_{ijkN_{ijk}}\}, k \in [1, N_{ij}]$.

Therefore, the meta task set partitioned from task t_j can be described by Eq. (1).

$$O_i = \bigcup_{j=1}^{N_S} \bigcup_{k=1}^{N_{ij}} \bigcup_{v=1}^{N_{ijk}} o_{ijkv}, i \in \{1, 2, \cdots, N_T\} \tag{1}$$

A dynamic partition algorithm for several satellites and multi-area targets will be discussed and the process is shown in Fig. 5.

Step 1: Traversing each area target t_i in T_p. Select a collection of available satellites according to the image type and resolution requirements of the targets. These satellites constitute a set S'.

Step 2 Traversing each satellite in S', decompose task t_i according to the selected satellite s_j.

Step 3 According to satellite orbit prediction, calculate the visible time windows $O_{\text{bs}}(i, j)$ between s_j and t_i and delete the ones that do not meet the time requirements.

Step 4 Traversing each time window o_{ijk} in $O_{\text{bs}}(i, j)$ and partition it orderly.

Step 4.1 For time window o_{ijk}, get the minimum and maximum look angles of the satellite towards the vertexes of area target t_i. And they can be noted as $g_{\min}(i, j)$ and $g_{\max}(i, j)$ respectively.

Step 4.2 Get the minimum effective look angle g_s and maximum effective look angle g_E towards task t_i.

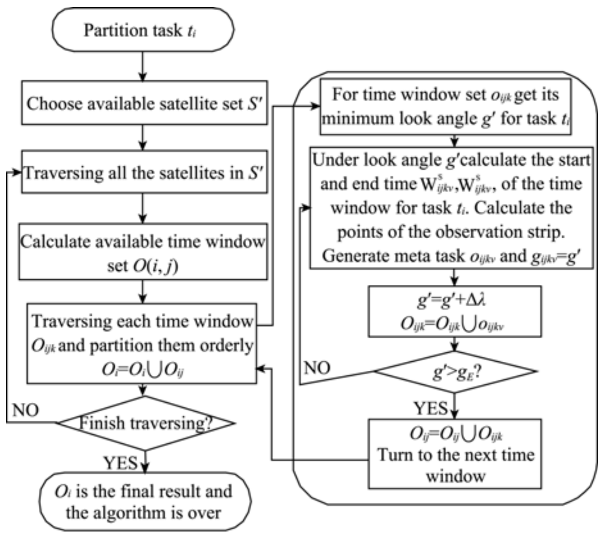

Fig. 5 Partition of the area target

$$g_S = \max\left\{g_{\min}(i,j) + \frac{1}{2}\Delta g_j, g_{\min}(j)\right\} \quad (2)$$

$$g_E = \min\left\{g_{\max}(i,j) - \frac{1}{2}\Delta g_j, g_{\max}(j)\right\} \quad (3)$$

Step 4.3 Partition the area target by different look angle g', starting with g_s and moving at a step length of $\Delta\lambda$ till arriving at g_E.

Step 4.4 In each observation point of view, a meta task o_{ijkv} is generated. For meta task o_{ijkv}, its observing angle is g_{ijkv} which equals g', start time is w_{ijkv}^{s}, and end time is w_{ijkv}^{e}. According to w_{ijkv}^{s} and w_{ijkv}^{e} we can get coordinates of its corresponding sub-line point. Then according to the formula of satellite ground coverage, we can get the vertex coordinates of the strip. By this way the whole strip is fixed on.

Step 4.5 Add all the meta tasks partitioned in the time window o_{ijk} into the set O_{ijk}.

Step 5 Traversing all the time windows of s_j towards t_i and add all the meta tasks partitioned in these time windows into set O_{ij}.

Step 6 Traversing the satellite set S', add all the meta tasks of task t_i partitioned by satellite s_j into the set O_i.

Step 7 Partition all the other tasks in the same way. When finished, return and output the final result.

Each meta task partitioned from area target is an optional activity for the satellite. To calculate the acreage of the area target covered by each meta task, we need to keep coordinate information of each strip. And the coordinate information of the strip is expressed by the longitude and latitude of the four vertexes clockwisely. For each meta task it can be described by a six-tuple $o_{ijkv} = \{A_{Id}, T_{Id}, S_{Id}, W_{in}, A_j, C_{ord}\}$. The elements in the six-tuple are respectively meta task id, task id, satellite id, time window id, look angle and coordinate information for the meta task.

3.4 Plan generation and visual display module

3.4.1 Generation of the satellite scheduling plan

The generation of CHARTER satellite scheduling plan is a complex process. Because it has to consider all-round factors such as satellite agencies, user requests, visible time windows, resource constraints and so on. To simplify the problem a rule-based dynamic heuristic algorithm is proposed, which includes establishment of heuristic rules and dynamic re-scheduling. Due to the limited space, only a brief description is given here.

Five heuristic rules are established for the problem of satellite scheduling under CHARTER mechanism. ① Available time windows will be arranged first, ② tasks of high-priority take precedence, ③ tasks of less remaining observation windows go first, ④ tasks that can be transmitted back earlier will be scheduled earlier, ⑤ rules of manual intervention. One point that must be pointed out is that the manual intervention rule is the final criterion. Once intervened, all the other rules would expire. The rule of manual intervention is out of CHARTER's contractual nature, which allows users to assign tasks manually.

Compare to the original scheduling plan, dynamic re-scheduling is reflected in three aspects: insert time windows of new tasks dynamically into satellites' observation plan, forward constraint checking and backward conflict elimination.

Insert of new task windows is a rules' matching process. First of all, determine whether there is human intervention and whether the new task conflicts with scheduled tasks. If no human intervention and conflicts are found, the new task can be inserted directly. Or schedule the tasks according to the rules defined in the previous section. Constraint checking is to check the rationality of the scheduling plan after inserting new time windows. And the constraints are mainly transition time between neighboring observation, power and storage capacity.

Backward conflict elimination, which is to solve the constraint conflicts and ensure the scheduling plan is feasible, is triggered by forward constraint checking. The backward traversing mechanism brings the smallest disturbance to original scheduling plan. The conflicts here contain both local and global ones. Global conflicts are introduced by global conflicts such as slew time and the longest working hours. Correspondingly, the local conflicts are mainly caused by the transition time between adjacent tasks.

3.4.2 Plan evaluation and visual display

The final scheduling plan is displayed by tables, Gantt chart, as well as pie chart. The evaluation of the plan is mainly from 5 perspectives: targets visited, access time, response time, time resolution and coverage of the area target. The latter three are quantitative evaluation parameters.

To display all the visited targets a table is constructed. The columns in table include remote sensor type, maximum slew angle of the sensor, resolution and duration of the visible time windows.

Access time is the time periods when the satellite fly over the target. It describes opportunities that the targets might be observed. For each task a Gantt chart is built, all the time windows of the task are annotated according to their start time.

Response time refers to the time difference between start time of the observation window and the time when user submits the application. It reflects time effectiveness of the satellite towards different missions. The shorter the response time, the sooner the satellite reacts. The earlier the task can be carried out the less loss will be suffered. And it can be calculated by Eq. (4).

$$R_{\text{time}} = \operatorname*{MAX}_{i=1}^{N_s}(E(a)_i - T_{(\mathrm{a})}^{\mathrm{r}}) \quad (4)$$

Time resolution is the maximum time span of all the observation time windows for the target, which reflects the satellite's continued observation capability. That is, greater time resolution means the satellite owns a stronger continued observation capability. Its calculation is shown in Eq. (5).

$$T_{\text{re}} = \operatorname*{MAX}_{i=1}^{N_T}(E(a)_i - S(a)_i) \quad (5)$$

Coverage of the area target is defined as the ratio of the total area covered to the designated observation area in a planning period. It reflects the processing capabilities of different scheduling plan. In practice, it is calculated by the ratio of the number of covered strip to the total number of partitioned strip. It can be got through Eq. (6).

$$R_{\text{cov}} = \frac{\sum_{i=1}^{|p|} S_i^p}{\sum_{i=1}^{|s|} S_i} \tag{6}$$

3.5 System control module

System Control module is the basis of system. It controls operation processes of entire system and data exchange within the system, provides a communication interface between different modules. It also provides a communication interface between the system and external environment, which concerns two aspects. The first is communication with STK. The system needs to send its requests of creating targets and satellites, calculating visible time windows between satellites and targets to STK. The second is communication with the database. On the one hand the system has to read the needed data from database, on the other hand it will write to database to update system data.

In order to realize the communication between system and STK, an interface class library for the communication of STK is packaged. It contains two classes: STKConnect and STKCommand. Through class of STKConnect the connection between STK and system can be established. Through class of STKCommand visible time windows between ground targets and satellites can be ordered and analyzed.

This module is the engine of system control. The operation process of system is as follows. The system first obtains the latest satellite information from resource management module, including information of satellite orbit and availability. Then transfer users' observing requests into system tasks through task description module. Accordingly a simulation scenario can be created. The following step is to get available time windows. The time window module will calculate all the visible time windows first and then delete the conflict ones. The available time windows will be sent to scheduling plan generation module. In this module, all the factors are considered and a final plan is generated. Finally, a platform is provided to display and evaluate the plan.

In addition, the system control module also provides a human-computer interaction interface and the corresponding communication mechanism. The system allows the manual intervention from project managers to a certain degree, which is to ensure the benefits of satellite agencies.

4 CONCLUSION

A scheduling system for disaster monitoring satellites is designed, which is based on the mechanism and work flow of the international charter of space and the important disaster. The system fully considers the emergency and uncertainty of natural disasters. Therefore, it provides users a flexible interface for task definition and description. Through the time window calculation module and a consultation mechanism, satellites' available time windows can be acquired. The system pays great attention to the area targets and a dynamic partition algorithm is proposed. Then a dynamic heuristic algorithm is constructed to generate a satellite scheduling plan. To effectively evaluate and display the generated plan, several evaluation parameters are defined. The system is of strong guiding significance for the scheduling of disaster monitoring satellites. At the same time it can support the CHARTER manager to make correct decision.

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CHARTER 机制下减灾卫星调度系统设计与实现

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摘　要： 针对空间与重大灾害国际宪章(CHARTER)的宗旨和运行机制设计开发了减灾卫星(主要为地球遥感卫星)调度系统。首先介绍了 CHARTER 机制的意义和工作流程，分析了当前减灾卫星调度所面临的问题，在此基础上给出了系统的总体设计和各子模块的功能，重点阐述了时间窗口计算模块，提出区域目标的动态分解算法。借助基于规则的动态启发式算法生成卫星任务规划方案，提出三项指标对方案进行评价。

关键词： 任务规划，减灾卫星调度，联合减灾宪章，可用时间窗口，区域目标

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Liu X L, Gao P, Chen Y G, Chen Y W. 2010. Design and implementation of scheduling system for disaster monitoring satellites of CHARTER mechanism. *Journal of Remote Sensing*. **14**(5): 1017—1028

1　引　言

2007-05-25 中国国家航天局局长孙来燕签署“空间和重大灾害国际宪章”，这标志着中国国家航天局成为“空间与重大自然灾害”国际契约性合作组织——国际减灾合作机制 CHARTER(郭陆军, 2002)的正式成员。该机制认为，在当今的环境条件下，仅靠一个国家的遥感卫星资源无法应付频繁发生的自然和人为重大灾害(洪灾、森林火灾、地震、飓风、泥石流等)，需要加强空间机构和卫星单位间的国际合作，以有效利用空间技术对重大灾害进行监测和管理。其工作机制(国家空间技术减灾网)如图 1。

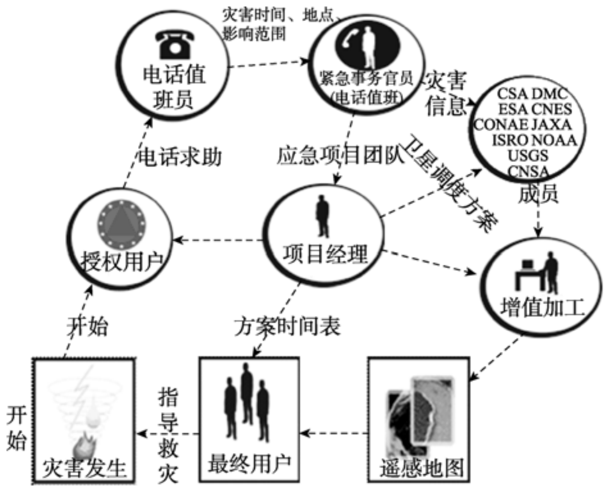

图 1　CHARTER 工作流程

地球遥感卫星在环境监测和重大自然灾害营救方面的作用越来越突出，已经成为减灾救灾的主要信息来源。当前关于卫星任务规划的研究大多是针对卫星日常运行的常规规划，即根据用户需求，对既定目标进行成像观测(Robert 等，2004; Nicola 等, 2008; Frank 等, 2002)。针对云层覆盖情况的变化、突发事件以及资源失效等情况，研究了具有星上自主处理能力的观测卫星调度执行和重调度方法(Robert 等, 2004; Lina 等, 2002)，但是当前很多卫星并不具备自主能力，因此使得这种重调度具有很大局限性。针对对地观测卫星调度开发了很多调度系统，包括美国的 ASTER 调度系统(Cohen, 2002)、法国的 SPOT5 卫星调度系统(Vasquez 等, 2000)以及欧洲空间局针对 Cosmo- Pleiades 计划开发的卫星星座的任务调度系统(Nicola, 2005)。这些系统多针对卫星的日常调度开发，没有针对突发重大灾害的应急调度，这些调度系统支持的卫星数量也比较少，一般只有几颗。同时，这些系统均是

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对已在轨运行的成像卫星开发的专用调度系统，当有新的卫星入轨时，这些系统将不适用，兼容性较差。

CHARTER 机制下包括了全球的几十颗对地观测卫星，其初衷是发挥全球卫星机构的信息共享优势，最大程度地减少突发重大灾害对人类带来的损失。针对上述的应急突发事件，应该如何选择观测卫星资源，如何在最短时间内生成可用的卫星观测方案?本文依据 CHARTER 的运行机制，设计实现了 CHARTER 系统，系统实现了 CHARTER 对所属卫星资源的有效管理，支持系统目标的快速生成，计算分析卫星对当前目标的可用时间窗口，根据各卫星的实际任务情况生成任务规划方案，进而为 CHARTER 值班人员提供决策支持。

2 问题描述及系统总体设计

对 CHARTER 所面临的问题进一步细化，建立了一个基本的系统模型，并在此基础上给出系统的总体构架，简要介绍了系统每个模块的功能。

2.1 问题描述

本问题实质上是一个针对区域目标的应急重规划问题，涉及的主要要素包括：用户任务需求、资源及其约束、任务时间窗口、已调度时间窗口。

2.1.1 用户任务需求

这里任务主要是指授权用户就一些紧急自然灾害向 CHARTER 提出的观测申请。具体包括：

- $T_{(a)}^{y}$ 任务类型 包括洪水、地震、泥石流等，用以确定所需要的遥感器类型。
- $R_{(a)}^{e}$ 任务区域 灾害的地理位置信息，包括灾害核心区域的经度 $L_{(a)}^{J}$、纬度 $L_{(a)}^{W}$ 及影响范围 $R_{(a)}^{area}$，用以限定卫星所要拍摄任务的区域。
- $T_{(a)}^{r}$ 请求时间 授权用户向 CHARTER 提出申请的时间，以界定卫星最近的可用时间窗口。
- $E_{(a)}^{t}$ 效用时间 用以限定进行观测的最晚时间，一般忽略该属性。

2.1.2 资源及约束

资源包括独占资源和可共享资源(或累积资源)，其中独占资源主要是指时间窗口，其独占性可以通过图 2 体现，卫星只能在冲突的窗口中选择一个进行观测。

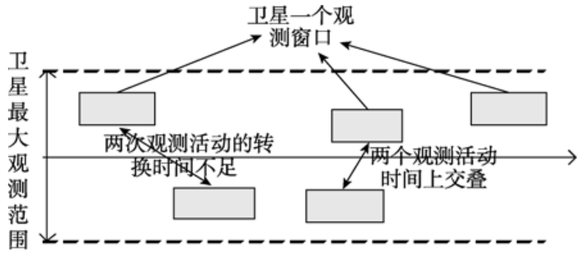

图 2 资源独占性示意图

所谓累积资源是类似星上电源或存储器之类的资源，以电源为例，卫星开关机、成像、侧摆等活动要消耗电量，但只要电量不低于卫星电量阈值就可以继续工作，当卫星飞至阳照区时就可以充电。主要包括：

- $D_{(s)}^{t}$ 单次开机最长工作时间 成像过程需要消耗电量，因此卫星一次开机所能成像的时间是一定的。
- $S_{(s)}^{c}$ 单圈最大侧摆次数 由于能量限制卫星在单圈内以不同角度成像的次数是有限的。
- $S_{(s)}^{m}$ 最大存储容量 由于回传能力限制，卫星必须将那些不能实传的任务存入星载存储器，若存储器已满卫星将不能成像，直到存储器被再次清空。

2.1.3 任务时间窗口 T_i^{w}

对应急目标而言，卫星传感器和地面目标之间满足任务要求(如分辨率、太阳光照、云层等)的可见时间区段。定义如下：

- $S_{(a)}$ 开始时间：观测机会的开始时间；
- $E_{(a)}$ 结束时间：观测机会的结束时间；
- $T_{(a)}$ 持续时间：观测机会的持续时间；
- $A_{(a)}$ 观测角度：卫星成像时相机的角度；
- $D_{(a)}$ 成像数据：观测期间生成的数据；
- $P_{(a)}$ 任务优先级：卫星观测任务的重要程度，应急任务的优先级最高。

2.1.4 已调度时间窗口

针对正执行的卫星观测方案而言，指那些已安排的任务所对应的时间窗口。包括：开始时间 $S_{(a)}$、结束时间 $E_{(a)}$、持续时间 $T_{(a)}$、观测角度 $A_{(a)}$、成像数据 $D_{(a)}$ 以及任务优先级 $P_{(a)}$，具体含义同上。

综上，CHARTER 减灾卫星调度问题是一个在已有卫星调度方案基础上考虑用户、资源约束的针对区域目标的重规划问题。

2.2 系统主要任务及总体设计

基于对 CHARTER 工作流程和问题的理解，设计开发了 CHARTER 机制下减灾卫星调度系统

CHARTER。其主要任务包括:

(1) 支持用户对系统任务的设计和定义, 即必须保证 CHARTER 项目经理对灾害区域进行详细建模。

(2) 支持 CHARTER 对系统内卫星的日常管理, 包括轨道根数更新、工作状态以及卫星自身状态的维护, 同时系统也支持对各卫星正执行的任务方案的管理。

(3) 支持卫星对地面目标可见时间窗口的计算, 系统所针对的目标主要是区域目标, 因此必须支持对区域目标的划分。

(4) 辅助项目经理生成最终的卫星调度方案, 通过定义评价指标对方案进行评估。

(5) 可视化的窗口界面和对历史方案的管理。

为完成上述任务, 系统设计了 5 个模块, 包括: 任务描述模块、资源管理模块、时间窗口计算模块、方案生成和可视化展示模块以及总控模块, 系统的总体结构如图 3。

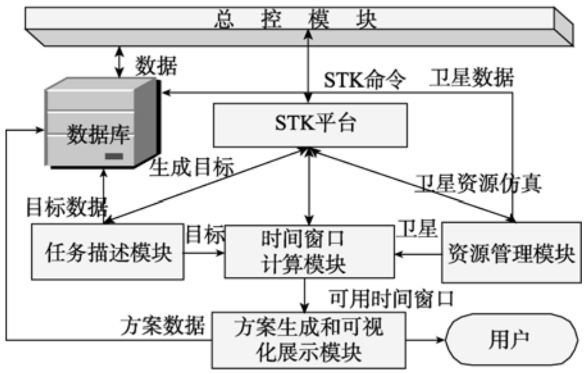

图 3 系统结构图

3 系统的实现

3.1 任务描述模块

任务描述模块的主要功能是把授权用户的请求转化为系统可识别的任务目标, 同时对所有观测任务进行管理。系统对任务的管理主要体现为对任务库的管理, 这可以帮助工作人员避免重复定义。授权用户的请求中包括灾害类型、发生地点、发生时间和影响范围等, 这些信息不能直接为系统所识别, 需要通过系统建模转化为规范的系统目标。本系统提供了两种目标定义方式: 精确定义与二维视图定义。

精确定义是用具体的坐标信息定位目标。系统提供了目标信息的录入接口, 系统操作人员(项目经理)根据用户请求在接口中输入目标的经纬度信息, 根据这些信息生成与之对应的目标, 包括点目标和区域目标。点目标对应为一对经纬度信息, 一般为灾害的中心; 区域目标对应多对(≥3)经纬度信息, 系统识别这些点列, 自动地连接相邻点作为目标边界。

相比而言, 二维视图定义是一种比较直观的方式, 操作人员在系统提供的二维视图中根据目标的性质和位置直接进行选点, 系统跟踪并识别鼠标所选择的点, 判断点击次数, 单次默认为点目标, 超过 3 次则认为是区域目标, 系统将根据点击的顺序将这些目标首尾相接生成相应的区域目标。

3.2 资源管理模块

资源管理模块主要实现对成像资源的管理, 这里的资源主要是指卫星资源, 包括: 添加卫星、查询卫星属性信息、删除卫星、更新卫星工作状态等。考虑到 CHARTER 的特殊运行机制和各国卫星的实际情况, 系统对卫星资源的管理体现为获取卫星轨道参数和任务情况, 实现对卫星信息的更新。

这里的卫星参数主要是指国际公认的两行根数(刘林, 2000),它是由加拿大和美国合建的北美联合防空司令部用地面雷达测量出来的, 此根数代表在某天瞬间时刻下, 所测量卫星的位置与速度。两行根数是进行轨道外推、正确计算卫星对地面目标时间窗口的基础。

卫星任务情况是指卫星当前的工作状态, CHARTER 是一个契约性的组织, 卫星并不会因为担心灾害的发生而空载, 因此当灾害发生时, 只有那些有空闲能力或当前所执行任务优先级比较低的卫星才能执行观测任务, 因此项目经理在选择卫星时应该本着尽量不冲突卫星国原本任务的原则进行。

3.3 时间窗口计算模块

3.3.1 可用时间窗口的计算

可见时间窗口是指卫星传感器和地面目标之间满足任务要求(如分辨率、光照、气象等要求)的可见时间区段, 它是进行卫星任务规划的基础。卫星对目标可见时间窗口的计算通过 STK 平台实现。

得到可见时间窗口并不意味着当前窗口可用, 因为卫星对当前目标的可见窗口可能与卫星的已调度窗口冲突。可用时间窗口指实际能为用户所用的卫星对目标的可见时间窗口, 如图 4。本模块的最终目的是计算卫星对地面目标的可用时间窗口。

卫星对目标的可见时间窗口分为空闲时间窗口和冲突的时间窗口, 空闲窗口可以直接使用, 即为可用窗口。对于冲突的窗口, 需要根据任务优先级

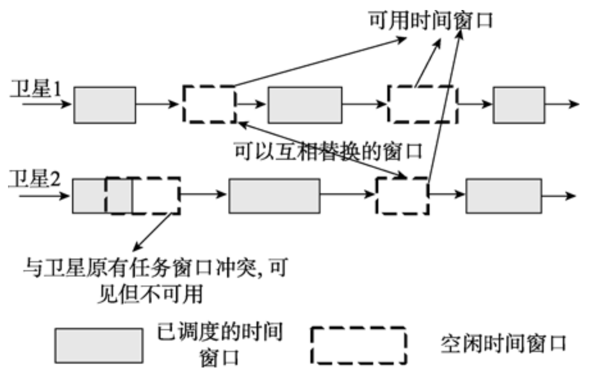

图 4 可用时间窗口

对其进行冲突消解。但是这种消解不是绝对的, 如果用户只要求对目标进行一次成像(不需要重复拍摄), 那么同一卫星对目标如果有多次观测机会就可以选取没有冲突的窗口进行观测。

3.3.2 区域目标动态分解算法

由于重大灾害的覆盖范围比较广, 一般将其定义为区域目标。区域目标由于其特殊性一般不能通过一次观测完成, 区域目标时间窗口的计算也相对特殊, 需要先进行分解, 然后再计算。本文在原有确定性划分算法(阮启明, 2006; Michel 等, 2002)基础上提出了改进的动态目标划分法, 具体实现如下所述。

为便于表述, 首先对符号进行定义。设卫星集合 $S=\{s_1,s_2,\cdots,s_{N_S}\}$, 区域目标集合 $T_P=\{t_1,t_2,\cdots,t_{N_T}\}$。卫星 s_j 的最大侧视角度 $g_{\max}(j)$, 最小侧视角度 $g_{\min}(j)$, 遥感器视场角Δg_j, 分解时的角度偏移量为$\Delta\lambda$。设调度时段内, 卫星 s_j 对区域目标任务 t_i 的时间窗口数量为 N_{ij}, 卫星 s_j 在第 k 个时间窗口内对任务 t_i 进行分解, 得到的子任务数量为 N_{ijk}, o_{ijkv} 表示卫星 s_j 在第 k 个时间窗口内对任务 t_i 进行分解, 得到的第 v 个子任务。

任务 t_i 经过分解后得到元任务集合 O_i, 记为: $O_i=\{O_{i1},O_{i2},\cdots,O_{iN_S}\}$。任务 t_i 依据卫星 s_j 进行分解可以得到元任务集合: $O_{ij}=\{O_{ij1},O_{ij2},\cdots,O_{ijN_{ij}}\}$。任务 t_i 依据卫星 s_j 的第 k 个时间窗口分解的元任务集合 $O_{ijk}=\{o_{ijk1},o_{ijk2},\cdots,o_{ijkN_{ijk}}\}$, 其中 $k\in[1,N_{ij}]$。

综上, 任务 t_i 分解后的子任务集合可以表示为:

$$O_i=\bigcup_{j=1}^{N_S}\bigcup_{k=1}^{N_{ij}}\bigcup_{v=1}^{N_{ijk}}o_{ijkv}, i\in\{1,2,\cdots,N_T\} \tag{1}$$

当多颗卫星对多个区域目标进行观测时, 区域目标的动态分解算法如下所述, 具体流程如图 5。

步骤 1 遍历 T 中的每个区域目标。针对区域

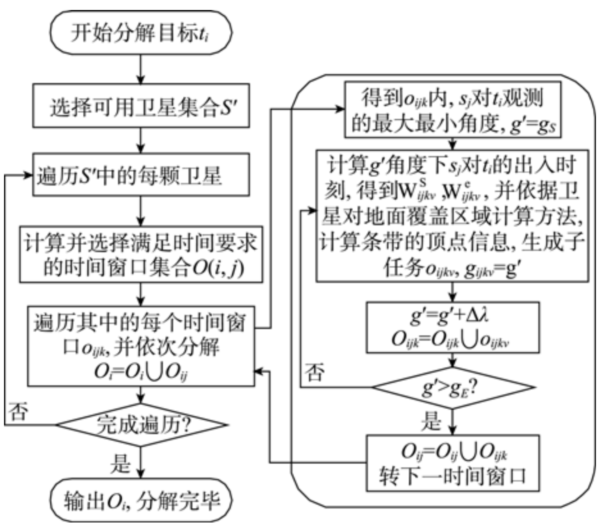

图 5 区域目标动态分解流程

目标 t_i 的遥感器类型要求及最低分辨率要求, 选择可用卫星集合 S'。

步骤 2 遍历 S'中的每个卫星, 根据每颗卫星 s_j 对 t_i 进行分解。

步骤 3 根据卫星轨道预报, 计算 s_j 与 t_i 的时间窗口集合 $O_{\mathrm{bs}}(i, j)$, 并删除其中不满足 t_i 时间要求的时间窗口。

步骤 4 遍历 $O_{\mathrm{bs}}(i, j)$中的每个时间窗口 o_{ijk}, 根据每个时间窗口进行分解。

步骤 4.1 得到时间窗口 $O_{\mathrm{bs}_{ijk}}$ 内, 卫星 s_j 指向区域目标 t_i 顶点的最小、最大角度分别为: $g_{\min}(i, j)$、$g_{\max}(i, j)$。

步骤 4.2 得到 O_{ijk} 内, 卫星对 t_i 有效观测的最小角度 g_S, 最大角度 g_E。

$$g_S=\max\left\{g_{\min}(i,j)+\frac{1}{2}\Delta g_j, g_{\min}(j)\right\} \tag{2}$$

$$g_E=\min\left\{g_{\max}(i,j)-\frac{1}{2}\Delta g_j, g_{\max}(j)\right\} \tag{3}$$

步骤 4.3 按照不同的观测角度 g'对区域进行分解。g'从最小角度 g_S 开始, 以$\Delta\lambda$为角度偏移量进行偏移, 直至最大角度 g_E 结束。

步骤 4.4 在每种观测角度 g'下, 均生成一个子任务 o_{ijkv}, o_{ijkv} 的观测角度 g_{ijkv} 为 g', 其开始时间 W^{s}_{ijkv}、结束时间 W^{e}_{ijkv} 分别为卫星采用 g'角度观测时, 出入区域目标的时刻。根据 W^{s}_{ijkv}, W^{e}_{ijkv} 及对应时刻的星下点坐标, 采用卫星对地面覆盖区域的计算公式, 得到卫星在此角度下覆盖的条带的顶点坐标, 从而得到条带的坐标信息。

步骤 4.5 将卫星 s_j 与 t_i 在时间窗口 o_{ijk} 内分解的子任务加入集合 O_{ijk}。

步骤 5 将卫星 s_j 与 t_i 在各个时间窗口内分解得

到的子任务加入集合 O_{ij}.

步骤 **6** 将所有卫星与 t_i 分解的子任务加入集合 O_i。

步骤 **7** 依次分解其他任务，若分解完毕，则返回并输出结果。

由于区域目标分解的每个子任务都是卫星的一个可选观测活动，为便于统计子任务对区域目标的覆盖关系，必须记录其坐标信息。子任务的坐标信息采用顺时针顺序的四个顶点的经纬度坐标表示。分解得到的子任务采用六元组表示:

$$O_{ijkv} = \{A_{Id}, T_{Id}, S_{Id}, W_{in}, A_j, C_{ord}\},$$

分别为子任务标识、任务标识、卫星标识、时间窗口、观测角度及子任务的坐标信息。

3.4 方案生成及可视化展示模块

3.4.1 卫星调度方案的生成

卫星调度方案生成是一个比较复杂的过程，需要考虑卫星方的利益、用户请求及卫星对目标的可见窗口和具体资源使用约束，系统采用了基于规则的动态启发式算法，算法包括规则建立和动态重调度两部分。

针对 CHARTER 减灾卫星调度，主要包括: ①可用时间窗口优先；②高优先级任务优先；③剩余观测窗口少的任务优先；④回传时间早的任务优先；⑤人工干预规则。需要重点指出的是人工干预规则，考虑到 CHARTER 的契约性，对于已调度的窗口，允许用户通过人工干预的方式安排任务，这种情况下其余规则将失效，以人工干预为准。

动态重调度是相对于原始调度方案，体现为 3 个方面: 新任务窗口动态插入，任务的前向约束检查和后向约束冲突回溯。

新任务窗口插入是一个规则判断的过程，首先判断是否有人工干预以及新任务是否与已调度窗口冲突，如果无人工干预且不冲突则任务直接插入，否则按照上一节中所定义的启发式规则进行。约束检查是对调整后的卫星调度方案的合理性进行检查，保证所生成的方案不违背卫星的使用约束，这里约束主要是任务间的成像转换时间、电量以及存储容量的限制。后向约束冲突回溯由约束检查触发，主要对约束检查中发现的冲突进行消解，采用自后向前的消解方式，可以保证对原调度方案的后续任务扰动最小，回溯冲突包括全局冲突和局部冲突: 全局约束冲突主要指卫星的单圈侧摆次数和最长工作时间，局部约束冲突是指相邻任务间的转换时间。

3.4.2 卫星调度方案的评估及展示

系统最终的调度方案通过列表、甘特图以及饼图的形式展现给用户，主要从 5 个侧面进行: 目标访问情况、访问时间、目标响应时间、目标时间分辨率和区域目标覆盖率，后三者是定量化的评估指标。

目标访问情况用以展现所有卫星对目标的具体访问情况，以列表的形式实现，表中包括遥感器类型、遥感器的侧摆角、分辨率以及可见窗口的开始、结束时间等。

访问时间是指每次卫星过境时对目标的可见时段，它描述了目标可能被观测的机会。系统以具体任务为对象，借助甘特图将卫星对任务的观测时间窗口按顺序排列，同时标注每个时间窗口图像分辨率情况。

响应时间是指卫星对目标可见时间窗口的开始时间与用户提交申请的时间差，目标响应时间反应了卫星对观测任务的时间效用，是卫星完成任务时效性的体现。响应时间越短说明卫星反应越快，越早执行任务，反之越晚，其计算如下所示:

$$R_{\text{time}} = \max_{i=1}^{N_s}(E(a)_i - T_{(a)}^{\text{r}}) \tag{4}$$

目标的时间分辨率是指观测目标的可见时间窗口开始时间和结束时间之间时间跨度的最大值，它反映了卫星对目标的持续观测能力。目标的时间分辨率越大，则卫星的持续观测的时间越长，持续观测能力越强，定义如下:

$$T_{\text{re}} = \max_{i=1}^{N_T}(E(a)_i - S(a)_i) \tag{5}$$

区域覆盖率是指在一个规划时段内，卫星及其有效载荷通过侧摆对指定观测区域内的总覆盖范围与指定观测区域范围之比。这一指标的高低反映了卫星对区域目标的处理能力。在实际的计算中采用区域目标分割成的各个条带观测完成数目与条带总数之比。

$$R_{\text{cov}} = \frac{\sum_{i=1}^{|p|} S_i^p}{\sum_{i=1}^{|s|} S_i} \tag{6}$$

3.5 总控模块

总控模块是整个系统运行的保证，该模块对系统的操作流程和系统内的数据交互进行控制，提供了各模块之间的通信接口，同时也提供了系统与外部环境的通信接口。系统与外界的通信主要表现为: (1)与 STK 的通信: 向 STK 发送场景创建请求，向 STK 定购卫星对目标的可见时间窗口；(2)与数据库的通信: 实现对资源、目标、调度方案等的管理，一

方面进行读操作从数据库中读取所需数据，另一方面进行写操作更新数据库数据。

为了实现与 STK 之间的通信，系统开发和封装了.Net 平台与 STK 之间的接口类库，包括 STKConnect 和 STKCommand 两个类，通过这两个类可以建立系统与 STK 之间的连接，并且向 STK 发送命令，订购和解析卫星对目标的时间窗口。

总控模块是系统的控制引擎，系统运行的流程为：系统首先从资源管理模块获取最新的资源状态，包括轨道根数和资源可用性信息，并依此创建仿真场景；调用任务生成模块将用户的观测请求转化为系统任务，并将生成的任务添加到仿真场景中；调用时间窗口计算模块，该模块首先依据各星的特点对区域目标进行划分，并计算卫星对目标的可见时间窗口，同时对时间窗口进行初步分析，去除不可用窗口，然后把这些信息发到调度方案生成模块；调度模块调用规划算法，并考虑人工干预生成减灾卫星调度方案，并对方案进行评估，最后将任务完成情况以及评估结果展现出来。

另外，总控模块还提供了人机交互的接口和相应的通信机制，系统要允许项目经理进行一定的人工干预，以保证卫星方既定任务的完成。

4 结 论

本文针对自然灾害的突发性和不确定性，基于空间与重大灾害国际宪章的工作机制和流程设计开发了一个减灾卫星调度系统。系统设计了灵活的任务定义接口，通过对可见时间窗口的计算和协商机制得到卫星对目标的可用时间窗口，并针对区域目标提出了区域目标动态分解算法，然后基于动态启发式算法生成卫星调度方案，定义了相关指标对方案进行评价和可视化展示。系统对于减灾卫星调度有很强的指导意义，并且可以为 CHARTER 值班人员提供决策支持。

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