Research on the Uplink Task Scheduling Strategy of Satellite Navigation System

LONG Yunjun[1], LI Jufang.[2], CHEN Yingwu[3], HE Renjie[4] and ZHANG Zhongshan[5]

National University of Defense Technology, Changsha, China, 410073

Abstract: In order to keep the service availability, continuity, and accuracy of satellite navigation system, the navigation data of the navigation constellation should be updated periodically. The navigation data are generated in the ground master control station, and are uploaded to the satellites by ground uplink facilities. Generally, in full operational phase, there will be about 30 satellites in space and several uplink facilities on ground. In order upload the navigation data timely to the satellites, ground facilities should be assigned to contact with the satellites. Due to the number of satellites and facilities, and the complex constraints in the uplink process, how to arrange the contact process is a complex problem. A mix-integer model is devised in this paper considering technological constraints in uplink process and different objective functions. Due to the complexity of the model, a two-phase algorithm based on rules is devised to solve the model. A set of scenarios for computational experience are devised consulting COMPASS of China, GPS and Galileo Satellite Navigation Systems. Our method is proved effective to the uplink task schedule process. Several factors that influence the completion of the uplink tasks are analyzed through the computational experience. The methods of this paper will be useful to the operations management of the Chinese COMPASS Satellite and forthcoming European GALILEO Navigation Systems.

I. Introduction

Satellite navigation system is comprised of three segments: navigation constellation in the space, ground control system and user receiving equipments. Satellite navigation system provides position, velocity and timing services to users by broadcasting navigation data to the gourd from the navigation constellation in space continuously. The navigation data are mainly consisted of satellite ephemeris, satellite clock parameters, ionosphere correction parameters, etc. Under the non-autonomous navigation mode, the ground control system generated new navigation data periodically. The navigation data should be uploaded to the satellites timely to ensure that the navigation data the navigation satellite broadcast are as fresh and precise as possible. The age of navigation data is a key factor that influences the service quality on position, velocity and timing of the satellite navigation system.

Generally, a global satellite navigation system consists of about 30 satellites in full operational phase. The control system on the ground has several uplink stations (e.g. GPS has four uplink stations, Galileo has nine uplink stations), and each station may have several uplink facilities. The navigation data can only be uploaded by the contact between the ground uplink facilities and navigation satellites. So, in order to complete the periodical navigation data uplink tasks, the uplink facilities must be arranged to contact with the navigation satellites. We call this process uplink tasks scheduling of satellite navigation system.

The uplink tasks scheduling focuses on solving the following problems: (1) whether the navigation data of each satellite in each period is uploaded; (2) if the navigation data is decided to be uploaded, which uplink facility is used to contact with the satellite that the navigation data belongs to; and (3) the time window that the contact is

[1] Ph.D, School of Information Systems and Management, No.47 Yanzheng Street, AIAA non-member.
[2] Associate professor, School of Information Systems and Management, No.47 Yanzheng Street, AIAA non-member.
[3] Professor, School of Information Systems and Management, No.47 Yanzheng Street, AIAA non-member.
[4] Associate professor, School of Information Systems and Management, No.47 Yanzheng Street, AIAA non-member.
[5] Master Student, School of Information Systems and Management, No.47 Yanzheng Street, AIAA non-member.

established. This paper is dedicated to solve the uplink scheduling problem concerning the unique technical constraints of satellite navigation system especially China's COMPASS.

II. Problem description

A. The Process of Navigation Data Uplink

The navigation data of the whole constellation should be updated periodically. As is showed in Figure 1, in each period a typical navigation data update process contains three phase: (1) data collection phase; (2) data generation phase; (3) data uplink phase.

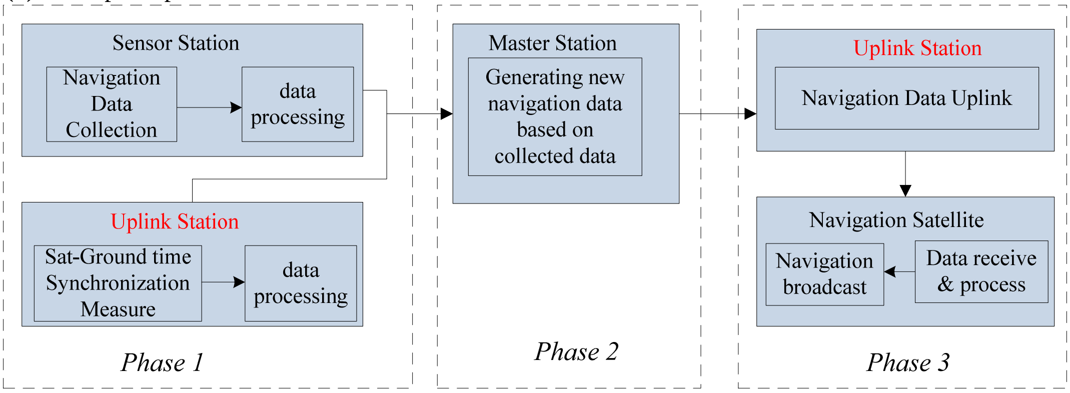

Figure 1. Navigation Data Uplink Process of Satellite Navigation System

Phase 1: Raw data collection. In this phase, raw data are collected and processed as input of generating new navigation data. The sensor station is used for one-way ranging measurements and monitoring of the signal in space of the navigation satellites. In this process, the sensor stations receive the signal in space passively, and no control or schedule to the sensor station is needed. Another way of collecting raw data is the two-way Satellite-Ground time synchronization ranging measure. Satellite should be contacted with the ground uplink station in this process. According to the system design, the satellite should keep contacted with a fixed uplink station for a minimum duration (e.g. 20 minutes) in order to fulfill the data collection requirements of generating new navigation data. Data collection process is a continuous process, and the collected data is sent to the master control station continuously.

Phase 2: Navigation data generation. At a fixed moment of each period (e.g. every 35th minute of each hour), the master control station generates new navigation data according to the collected data. The master control station generates navigation data for the entire constellation at a time. Of course, those satellites that provide more raw data to the master control station will get navigation data in better quality.

Phase 3: Navigation data uplink. The navigation data is uploaded to the satellite by the uplink station. In this process, satellite should be contacted with the ground uplink station. To assure the success of uplink, a satellite should be contacted with a fixed uplink facility for a minimum duration (e.g. 5 minutes) without interruption.

B. The Uplink Task Scheduling Problem

As is showed above, the uplink station plays a very important role in the process of navigation data uplink. For each satellite, updating the navigation data in good quality in each period needs to establish continuous contacts with the uplink station during the data collection phase and data uplink phase. The new navigation data can be generated in a short time after the raw data sent to the master control station. Due to the setup time of the uplink facilities to contact with different satellite, this time slot is hard to distribute to other satellite. For simple, if effective navigation data is uploaded to a navigation satellite, the satellite must contact with a fixed uplink facility continuously from the data collection phase to data uplink phase. As is shown in Figure 2, the master control station generates navigation data at time t_2 of each task period. If a satellite is updated with navigation data in good condition, contact with minimum duration of Δt_1 before t_2 and with minimum duration of Δt_2 after t_2 to a fixed ground uplink facility is prerequisite. In other words, during the time $[t_2 - \Delta t_1 , t_2 + \Delta t_2]$ the satellite must keep continuous contact with a fixed ground uplink facility. The time $[t_2 - \Delta t_1 , t_2 + \Delta t_2]$ is call minimum contact duration of a navigation uplink process. On the basis of satisfying the minimum contact duration, the longer a satellite contact with ground uplink facilities, the better navigation data it will be updated.

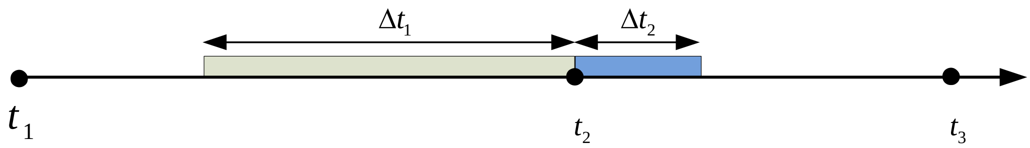

Figure 2. Uplink Task Minimum Duration Requirement

To ensure the service quality of the satellite navigation system, the navigation data on all satellites should be updated timely to reduce the age of data on navigation satellites. All the satellites should contact with the ground uplink facilities periodically.

Generally, a typical global satellite navigation system usually consists of about 30 satellites in full operational phase. The control system consists of several uplink stations, and each station may have several uplink facilities. There are mainly two kinds of ground uplink facilities: Multi-beam antenna and UHF antenna. Each kind of facility has different technical constraints, such as elevation angle range, maximum contact capacity, setup time and contact interface of multi-beam antenna. Besides, the uplink task of each satellite has different requirements on contact time window. In short, due to the number of satellites and facilities, and different kinds of constraints, arrange the navigation data uplink process for satellite navigation system is a complex work. The uplink facilities should be assigned rationally to fulfill the requirements of navigation data uplink.

C. Uplink Task Scheduling Problem Modeling

Based on the descriptions above, a mixed integer mathematical model will be devised. The model will be formulated from the following aspects: the resource description, task description, decision variable, donation of constraint, Objective function.

(1) Resource Description

$T=[T_s,T_e]$, the planning cycle, T_s 、 T_e represents the start time and end time of the planning cycle.

$S=(1,2,....,S)$, the navigation satellite constellation.

$M=(1,2,....,M)$, a set of ground facilities (antenna)，each facility has a unique serial number.

H_{sm}, the number of visible time windows for each pair of $(s,m)\in S\times M$ during the planning cycle.

$V(s,m)=\bigcup_{h=1,2,...,H_{sm}}\left[t_{sm}^{start(h)},t_{sm}^{end(h)}\right]$, the union of H_{sm} (disjoint) time windows, which can be calculated by STK(Satellite Tool Kit).

$C=(C_1,\cdots,C_M)$, the maximum number of satellite that each ground facility can contact with at a time. Multi-beam antenna can contact with 6 satellites at most, and UHF antenna can contact only with 1 satellite.

$ST=(ST_1,\cdots,ST_M)$, setup time to adjust the antenna to contact a different satellite.

(2) Uplink task description

$J=\{1,2,\dots,\ J\}$, the upload task set.

$s(j)\in S$, the (unique) satellite of task j.

$J(s)\subset J$, the set of tasks belong to satellite s.

Dur, the minimum duration of the (deterministic) processing time of each task, all the tasks have the same minimum duration.

$R(j)\in T$, the task release time, i.e., the time in which j becomes available for processing. In this paper, the release time of the tasks in each task cycle is same, that is the start time of the task cycle.

$r(j)\in T$, the latest start time of each task, the task is considered fail if it start after this time. The latest start time of the tasks in each task cycle is same, that is $r(j)=t_2-\Delta t_1$.

$D(j)\in T$, the task due-date, i.e., the time by which j must be completed. In this paper, the due-date of the tasks in each task cycle is same, that is the offer end time of the task cycle.

$d(j) \in T$, the earliest end time of the task, the task is considered fail if it end before this time. The earliest end time of the tasks in each task cycle is same, that is $r(j) = t_2 - \Delta t_2$.

$w(j) \in Z_+$, the revenue of each task j .

(3) Decision Variable

The ultimate purpose of unloading scheduling problem is to solve which tasks will be arranged. If any task is arranged, a facility and time window must be assigned to it. So the following decision variables are considered.

$x_{jm} = 1$, if task j is scheduled at facility m; otherwise, $x_{jm} = 0$.

$b_{jm} \in [R(j), r(j)]$, the contact start time of satellite j and ground facility m if task j is scheduled at facility m.

$e_{jm} \in [d(j), D(j)]$, the contact end time of satellite j and ground facility m if task j is scheduled at facility m.

(4) Objective Functions

Three objective functions will be considered in this paper: (A) maximum the total revenue of the scheduled tasks; (B) Maximum the total satellite – ground facility contact time of each satellite; (c) minimize the difference of total contact time of each satellite. All the three objective functions are as follows.

(A) $\max \sum_{j=1}^{J}\sum_{m=1}^{M} w(j)x_{jm}$

(B) $\max \sum_{j=1}^{J}\sum_{m=1}^{M} x_{jm}(e_{jm} - b_{jm})$

(C) $\min \sqrt{\sum_{s=1}^{S}(\sum_{j\in J(s)}\sum_{m=1}^{M} x_{jm}(e_{jm} - b_{jm}))^2}$

(5) Constraints

Constraints (1) state that each service can be processed at most once. Constraints (2) represent the ground facility capacity constraints: each ground station m can process, without preemption, at most C_m tasks. Constraints (3) represent time window constraints. If a task is assigned to the facility, the satellite that the task belongs to must be visible to the ground facility. Constraints (4) represent setup time constraints.

$$\sum_{m=1}^{M} x_{jm} \le 1, \quad j \in J \tag{1}$$

$$\sum_{j=1}^{J} x_{jm} \le C_m, \quad m \in M \tag{2}$$

$$\bigcup_{h=1,2,\dots,H_{sm}} \left(b_{jm} \in \left[t_{sm}^{start(h)}, t_{sm}^{end(h)}\right] \wedge e_{jm} \in \left[t_{sm}^{start(h)}, t_{sm}^{end(h)}\right]\right) \ne \varnothing, if \ x_{jm} = 1 \tag{3}$$

$$\begin{gathered}\min(e_{jm}, e_{hm}) + ST_m \le \max(b_{jm}, b_{hm}) \\ \forall m \in M, j \in J, h \in J, \text{while } x_{jm} = 1, \ x_{hm} = 1\end{gathered} \tag{4}$$

III. Model Solving Strategy

Uplink Task scheduling model is mixed integer planning model. The decision variable contains both integer variables and continuous variables. Four kinds of constraints are considered in the model, solving the model is a hard work with the increasing of ground facilities and satellites. Devising an effective algorithm to the model is a key work to solve the uploading problem.

Because of the complexity of the model, a two-phase solving strategy is devised to the model. In the first phase, the duration of all the tasks are cut to the minimum. Each task has fixed start time and end time. In this phase, each task will be determined to be assigned or not considering the objective function (A) and (C). In the second phase, the start time and end time of the assigned tasks will be extended considering the objective function (B) and (C).

A. Uplink Task Scheduling Considering Minimum Task Duration

According to problem description, each satellite has just one Uplink task in each task period. While the duration of all tasks is cut to the minimum, all tasks in the same task period have the same fixed start time and end time. The time slot between the end time of tasks in present period and the start time of tasks in the next period is long enough for the setup time of each ground faculty. So the setup time constraints are not considered in this phase. A set of schedule rules are devised as follow.

Rule 1: The task of the satellite which will lose sight with all ground facilities or have just come insight should be arranged first. The satellite may be not visible in long time to all any ground facility due to the geographical distribution of the ground facilities. The time the satellite losing sight with all the ground facilities is called leaving time, and the time the satellite coming into sight with all the ground facilities is called reaching time. The tasks near the leaving time or reaching time of each satellite should be arranged first.

Rule 2: If the task of a satellite in last period is not arranged, the task in present period has priority to be arranged compared to the tasks of other satellites.

Rule 3: The precedence of the ground facilities. The ground facilities that each satellite is visible to are sorted according some special rules. The first facility in the list is assigned to the satellite. The next facility in the list is considered only the previous facilities reach their maximum ability.

According to the rules, the uplink task schedule procedures to the problem considering minimum task duration are as follows.

(1) Calculating the time window of each satellite to all the facilities.

(2) According to the time window, the facilities that satisfy the minimum contact duration of each satellite's uplink task of in the present task period are calculated.

(3) If the satellite has more than one facility satisfying its task requirements in present task period, the satellite is ascertained whether its leaving time or reaching time is in the present task period. If yes, a label is attached to it.

(4) All the satellites in the present task period are sorted according if the satellite is labeled. Then the satellites are divided into two groups, labeled or not.

(5) The two satellites groups are sorted again according if the task of the satellite is assigned in last period. Then a new satellite sequence is get.

(6) One satellite is chose in turn. The ground facilities that satisfy the uplink task are sorted according to the precedence of the ground facilities.

(7) The first facility that doesn't reach its maximum capacity is assigned to the task of the satellite. If all the facilities reach their maximum ability, the task of the satellite in present task period is not arranged.

(8) Turn to process (2).

B. Extension of Start Time and End Time of Arranged Tasks

After the first schedule phase, some Uplink tasks are scheduled. But some visible time slots between the assigned tasks are unused. Those time slots are assigned to the satellites in this phase concerning the objective function (B) and (C).

The strategies and procedures of this phase are as follows.

(1) The total contact time of each satellite till present task period is calculated. The total time consist of two parts: sum of all the minimum duration of the uplink tasks assigned to the satellite according the schedule results in the first phase and the time slots assigned to the satellite till present period in this phase. The satellites are sort ascending by the total contact time.

(2) The start time and end time of the task in present task period is extended for each satellite in turn.

(A) A satellite s is chose in turn whose uplink task is assigned in the first phase schedule in present task period.

(B) The uplink task is assigned to facility m in the present task period in the first phase schedule. The visible time window $v(s,m)$ of satellite s and the facility m in present task period is calculated from $V(s,m)$. The start time of $v(s,m)$ is t_{sm}, and the end time of $v(s,m)$ is e_{sm}.

(C) The end time of the uplink task j is extended to e_{sm}.

(D) If the uplink task j of the satellite in present task period and the uplink task in past time period are assigned the same ground facility in the first phase schedule, the start time of the task in present task period is extend to its release time $R(j)$. In this case, $R(j)$ is equal to t_{sm}.

(E) Else, if the ground facility m is not reach its maximum capacity in the past task period, the start time of the task in present task period is extend to t_{sm}; else, the start time of the task in present task period is set as $e'_{sm} + ST_m$

considering the setup time of the facility. Here, e'_{sm} is the end time of the uplink task that facility m carried on in last task period.

(3) Turn to the next task period.

IV. Computational Experience and Result Analysis

The computational experience has two major purposes: (I) assessing the performance of the model and solving strategy to the uplink schedule problem; (II) shows the influence of changing some key parameters to the uplink scheduling objective function. As for (I), the solutions returned will be checked by constraints check program. To address point (II), we first consider different minimum task duration of the uplink tasks, so as to investigate the influence of the minimum duration to the schedule results. Then, we discuss the impact of the facilities' maximum capacity and the geographic distribution on accomplishing the uplink tasks.

A. Computational Scenario

According to the purpose of the computational experience, 7 different scenarios are devised. Here the scenario is devised mainly consulting Chinese COMPASS, GPS and Galileo Satellite Navigation Systems. The space segment is made of 24 identical satellites, all of which lying on three different orbital planes consisting a Walker Constellation. The configuration of the constellation is 24/3/2:55°, and the altitude is 21528km. All the 7 scenarios have the same plan cycle from the August 1 2011 00:00:00 to the August 9 2011 00:00:00（8 days）, which is the complete return cycle of the constellation.

The task period is set as one hour. All the navigation data of the satellites are generated by the major control station at the 35th minute of each period.

The minimum task duration and facilities parameters are different in each scenario.

Scenario1：Basic Computational Scenario

(1) Task Minimum Duration: 25 minutes, from the 15th minute to 40th minute of each task period.

(2) Facility Parameters:

Ground Facility Name	Facility Type	Maximum capacity	Setup Time	Geographical Position	Elevation Angle Range
Facility1	UHF antenna	1	10	（19.7，110.3）	（5，85）
Facility2	UHF antenna	1	10	（38.9，115.6）	（5，85）
Facility3	UHF antenna	1	10	（38.0，77.8）	（5，85）
Facility4	Multi-beam antenna	6	5	（19.7，110.3）	（15，90）
Facility5	Multi-beam antenna	6	5	（38.9，115.6）	（15，90）
Facility6	Multi-beam antenna	6	5	（38.0，77.8）	（15，90）
Facility7	UHF antenna	1	10	（38.9，115.6）	（5，85）

Table 1. Basic Parameters of the Ground Facilities

Scenario2：

(1) Task Minimum Duration: 45 minutes, from the 0th minute to 45th minute of each task period.

(2) Facility Parameters are the same as Scenario1.

Scenario3：

(1) Task Minimum Duration: 45 minutes, from the 15th minute to 60th minute of each task period.

(2) Facility Parameters are the same as Scenario1.

Scenario4：

(1) Task Minimum Duration is the same as Scenario1.

(2) Only the maximum capacity is changed as follows, that is equal to increasing some facilities. Other parameters remain unchanged compared with Scenario1.

Ground Facility Name	Facility1	Facility2	Facility3	Facility4	Facility5	Facility6	Facility7
Facility capacity	2	2	2	6	6	6	2

Table 2. Modified Ground Facilities' Capacity

***Scenario5*：**

(1) Task Minimum Duration is the same as Scenario1.

(2) Only the geographical positions are changed as follows, and other parameters are the same with Table 1.

Ground Facility Name	Facility1	Facility2	Facility3	Facility4	Facility5	Facility6	Facility7
Geographical Position	（0，159.9）	（0，29.9）	（0，100.5）	（0，134.9）	（0，1.9）	（0，120.4）	（0，137.4）

Table 3. Modified Ground Facilities' Geographical Position

***Scenario6*：**

(1) Task Minimum Duration is the same as Scenario1.

(2) Only the geographical positions and maximum capacity are changed as follows, and other parameters are the same with Table 1.

Ground Facility Name	Facility1	Facility2	Facility3	Facility4	Facility5	Facility6	Facility7
Geographical Position	（0，159.9）	（0，29.9）	（0，100.5）	（0，134.9）	（0，1.9）	（0，120.4）	（0，137.4）
Facility capacity	2	2	2	6	6	6	2

Table 4. Modified Geographical Position and Capacity of Ground Facilities

***Scenario7*：**

(1) Task Minimum Duration is the same as Scenario1.

(2) Only the Elevation Angle Range is changed, and other parameters are the same with Table 1.

Ground Facility Name	Facility1	Facility2	Facility3	Facility4	Facility5	Facility6	Facility7
Elevation Angle Range	（5，90）	（5，90）	（5，90）	（5，90）	（5，90）	（5，90）	（5，90）

Table 5. Modified Elevation Angle Range of Ground Facilities

B. Computational Results

The results are collected in Tables 1, reporting the following data: average task completion rate in plan cycle (Completion Rate), task fail rate caused by time window constraints (Fail By TW), task fail rate caused by resources conflict (Fail By Conflict), total contact rate with ground facility of the constellation (Contact Rate) and Maximum duration of un-contacted (Max Un-contacted).

Scenario	Completion Rate	Fail By TW	Fail By Conflict	Contact Rate	Max Un-contacted
Scenario1	40.34	58.05	1.61	37	66406
Scenario2	38.50	60.13	1.37	36.17	67199
Scenario3	38.61	60.00	1.39	37.16	66959
Scenario4	41.90	58.05	0.05	39.56	64638
Scenario5	87.91	8.72	3.36	85.43	7435
Scenario6	91.13	8.80	0.07	87.56	2437

Scenario7	41.95	58.05	0	38.62	65806

Table 6. Computational Results

C. Results Analysis

The solutions returned by our modeling and solving methods are proved valid by the constraint verification program. All the solutions are feasible, though they may be not optimized. Nevertheless, from these solutions of different scenarios one can observe the following results:

(1) Comparing the results of Scenario 1, 2 and 3, we can observe that the Completion Rate and the Task Fail Rate caused by resources conflict are slightly decreased. This shows that the minimum durations of the uplink tasks have little influence on the schedule of tasks.

(2) Comparing the results of Scenario 1and 4, we can observe that the Completion Rate is slightly increased and the Task Fail Rate caused by resources conflict is decreased near zero. This shows that the resources conflicts are mainly focused on the UHF Antennas which have lower Elevation Angle.

(3) Comparing the results of Scenario 1and 7, we can observe that the Completion Rate is slightly increased and no task is abandoned by resources conflicts. This result makes us to believe that the resources conflicts are focused on the UHF Antennas which have lower Elevation Angle.

(4) Comparing the results of Scenario 1and 5, we can observe that the Completion Rate is obviously increased and the Task Fail Rate caused by resources conflict is increased slightly. This shows that the aborted tasks are mainly caused by their un-visible to the ground facilities due to distribution of the Geographical Position.

(5) Comparing the results of Scenario 1, 5 and 6, we can observe that the Completion Rate in Scenario 6 is slightly increased compared with Scenario 5 and the Task Fail Rate caused by resources conflict is decreased near zero. This can draw the results that resource conflicts are focused on the low elevation angle of the UHF Antennas.

(6) The maximum duration that a satellite can not contact with any ground facility is about 18.5 hours in Scenario1, 2,3,4,7. But this number is decreased significantly while the distribution of the Geographical Position of the facilities is changed.

Then the follow conclusions can be draw from the conclusion:

(1) The main reason that the uplink tasks are abandoned is that they have no visible time window with the ground facilities because of the facilities' Geographical Position distribution.

(2) Extension on the minimum task duration has little influence on the completion of the tasks.

(3) The resources conflicts occur in the low elevation angle. This is because only the UHF antennas works in low elevation angle, but they UHF antenna can contact only one satellite at any time.

V. Conclusion

Uplink task scheduling is critical in the operation management of satellite navigation system, and it is a difficult problem due to the large number of satellites and ground facilities and the complex constraints. The paper contribution is threefold: on models, algorithms and practice. On models, we devised a mix-integer model to cope with real technological constraints and different objective functions. Generally, such model is hard to solve, it is time consuming to get the optimal results. But in really, it is not necessary to get the optimal solution, a feasible one is enough. So we devise a two-phase algorithm to solve the model based on a set of rules. Results show that our model and algorithm can get satisfying results. On the practical side, our method is quite useful to solve the uplink scheduling problem of China's COMPASS Satellite Navigation System, as well as GPS and Galileo. The algorithm used in this paper is somewhat simple. New algorithms will be devised in the future research.

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