Planning the Galileo Mission

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Abstract. This paper introduces issues raised by the planning of ESA's Galileo mission, concentrating on emergency replanning, and describes an approach based on the generation of robust schedules.

1 Introduction

Galileo is Europe's own global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control.

The Galileo system will eventually consist of 30 satellites positioned in three circular Medium Earth Orbit (MEO) planes, and at an inclination of the orbital planes of 56 degrees with reference to the equatorial plane.

The control of the satellites and the mission management will be performed at two Galileo Control Centres (GCC) located in Europe. The control centres will rely on data collected through a network of twenty Sensor Stations (GSS) to compute the integrity information and synchronize the time signal of all satellites and of the ground station clocks. S-band stations and C-band heads distributed on 9 sites will ensure the communication between the GCC and the satellites.

The Galileo mission planning challenge lies in the high number of resources to consider (Spacecraft, S-band TT&C Stations, C-band Uplink Stations, Communication Networks, etc.), and the characteristics of the specific services to be maintained (safety critical, integrity, etc.).

This paper introduces the basics of the Galileo mission planning problem, concentrating on the issues raised by replanning in case of satellite or station failure.

2 Galileo Mission Planning

The Galileo mission planning coordinates the activities of various components of the space and ground segment, in order to maintain the level of service of the Galileo constellation.

The Galileo services essentially require the dissemination of navigation related messages, and integrity messages, which provide information about the validity of each spacecraft signal for navigation.

The Galileo constellation is logically divided into two subconstellations:

- The navigation subconstellation, responsible for the emission of the navigation signal
- The integrity subconstellation, responsible for the transmission to the users of the integrity messages specifying the validity of the navigation signal provided by each satellite of the other subconstellation

The subconstellations are dynamic, and the satellites assigned to each subconstellation change in order to maintain continuously the Galileo services with the evolution of the constellation state.

The Galileo services are supported by a dedicated network of 9 C-band Uplink Stations (ULS), each of which has a specific maximum number of independent available heads.

The dissemination of the messages through the overall system is not under control of mission planning, whose main responsibility is to plan the contacts between the spacecraft and the C-band ULS's required to support the services, taking into account the resources in terms of satellites and ULS heads available at any point in time.

In addition to the essential functionality supporting the core of the mission, mission planning is in charge of scheduling housekeeping activities for the space and ground segment:

- Regular maintenance windows for spacecraft as well as for stations
- Spacecraft manoeuvres (provided by Flight Dynamics)
- On-board Software upgrades

Those activities are essentially related to the monitoring of the spacecraft health and spacecraft maintenance, and are performed via a separate network of 5 S-band TT&C stations.

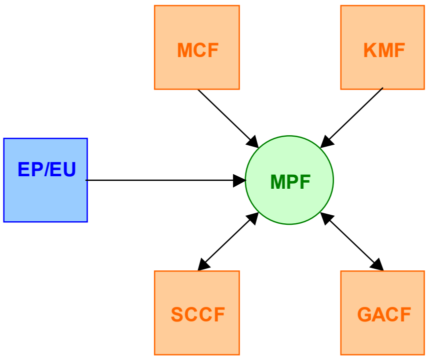

Figure 1 MPS Logical Interfaces

The Galileo mission planning functionality is physically distributed within several control facilities of the ground segment:

- The *Mission Planning Facility* (MPF), responsible for the planning of spacecraft and ground operations for the entire Galileo mission.
- The *Satellite Constellation Control Facility* (SCCF), responsible for monitoring and control of satellites operations
- The *Ground Assets Control Facility* (GACF), responsible for monitoring and control of the ground assets
- The *Mission Control Facility* (MCF), responsible for monitoring and control of the mission status, i.e. monitoring of the status of the navigation and Integrity services, and controlling of the mission configuration in order to maintain the services
- The *Key Management Facility* (KMF), responsible for the generation, management and implementation of Communications Security protection mechanisms

The core planning functionality is concentrated in the MPF, which interacts with all the other facilities, and interfaces in addition with External Users or Providers (EU/EP), which issue requests for planning of specific operations, or provide external additional data, such as LEOP Plans.

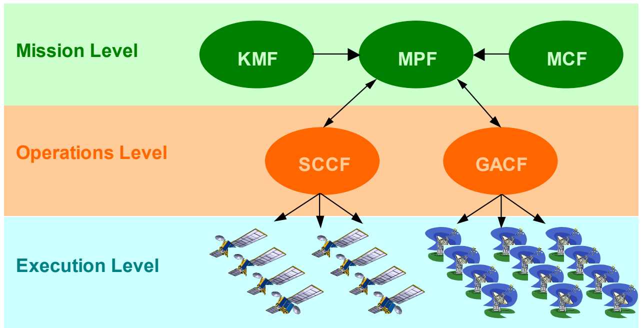

Figure 2 Mission Levels

The mission is hierarchically organised in three levels:

- Mission Level, responsible for ensuring that the Galileo mission services are maintained. This includes most of the Mission Planning functionality, but also all the processing of mission messages.
- Operations Level, which concentrates on the operation of the space and ground equipment, and is responsible for monitoring and control of the satellite constellation and of the ground station network.
- Execution level, limited to the actual units executing the scheduled operations, such as ground station computer, on-board computer, etc.

3 Galileo Contact Planning

The planning of the satellite to ground station contact is central to the Galileo mission planning. It requires

- Planning the contacts between the S-band TT&C stations and the satellites, which support the satellite routine operations and maintenance activities
- Planning the contacts between the C-band ULS's and the satellites, which support the navigation and integrity services

The planning problem has different characteristics in each case.

The calculation of the contacts with each network is performed independently, and takes into account the configuration of the subconstellation as well as satellite or station unavailabilities.

3.1 S-band TT&C Contact Planning

The planning of the satellite contacts to S-Band station requires that each satellite been allocated a number of contacts of configurable duration (depending on the satellite status) per orbit. Specific maintenance tasks and manoeuvres can then be scheduled during these contacts.

The inputs to the TT&C contact planning are the following.

- The visibility from the ground station for each spacecraft
- The pre-pass and post-pass margins for each station
- The duration of contact slots per satellite

The only constraint to maintain between the contacts is the mutually exclusive use of the stations.

3.2 C-band ULS Contact Planning

The planning of the satellite contacts to C-Band stations differs depending on the subconstellation to which the satellite belongs.

- Satellites from the integrity subconstellation require permanent contact with the stations with overlapping between successive contacts, in order to always ensure the immediate transmission of the integrity messages.
- Remaining satellites from the constellation supporting navigation require a contact of a configurable duration periodically at configurable intervals (typically 1 minute every 100 minutes).

The C-band ULS planning contact problem is more demanding than the S-band TT&C contact problem, due to the characteristics of the planning and to the number of resources to be allocated.

4 Emergency Replanning

The Galileo nominal planning process is illustrated in Table 1, where each column represents an actor of the planning process and its activities. The steps are executed from the top of the table to the bottom. Activities that are performed concurrently are listed in the same row of the table and different columns. The actors synchronise at the limit of each row.

The nominal planning scenario is based on a continuous iterative refinement of a plan that incorporates updates to requests and orbital information until the deadline for producing and disseminating executable schedules for the satellite and ground control systems is reached. In such a planning concept, replanning is therefore permanently ongoing.

Emergency replanning must be considered if schedules are modified that have already been committed for operation and passed to the controlling facilities, and is related to the status of the plan with respect to the external world (originator, executors, etc.), and not to the nature of the plan itself. Emergency replanning is required in case of late changes that affect the mission state and require immediate action. For instance, a satellite failure will require new or extended contact slots for satellite recovery, but also modification of the usage of the constellation to take into account the impact of the failure at service level.

The capability of reaction of the Galileo ground and space segment to anomalies is driven by several factors:

- On detection of an anomaly (e.g. a satellite failure), the Galileo requirements enforce very short delay for reaction and recovery.
- The availability of personnel resources (operators, engineers) required to operate the recovery and reconfiguration depends on the mission level at which the anomaly is raised.

time	I/O Manager	Operator	Automated Planner	Schedule Generator
T-6 months	Receive Long Term Orbit Event File			
Repeat Block (Monthly)	Receive Manoeuvre, Maintenance, Test Plans			
		Visualise Requests		
			Perform Constraint Checking	
	Deliver Planning Reports			
T-1 month	Receive Medium term Orbit Event File			
Repeat Block (Weekly)	Receive any available Updated Requests			
		Perform Nominal Planning Session		
			Plan All Activities	
	Deliver Planning Reports			
T-1 week	Receive Short term Orbit Event File			
Repeat Block (Daily)		Perform Scheduling Session		
				Generate Executable Schedules
	Deliver Executable Schedules			

Figure 3 Galileo Nominal Planning Cycle

In order to meet Galileo's strong requirements on anomaly recovery, the operational concept must ensure that an anomaly is addressed at the lowest possible level in the mission hierarchy, so that the reaction time is kept to a minimum.

- At the Execution Level, priority is given to safety considerations, and the equipment will react automatically, e.g. by switching to backup equipments, by switching off equipments, or by removing logically a satellite from the constellation
- At the Operations Level, the systems as well as the operators have the possibility to recover from the

anomalies by taking advantage of the robustness of the schedules generated by mission planning.

- At Mission Level, there is usually no time and personnel available to update the plans, and disseminate the updated schedules in the required tight mission time constraints. Therefore only two types of action can be taken: (1) sufficient flexibility must be introduced in the plan generated by the MPF, so that the recovery actions can be performed directly at Operations Level without on-line contribution of the planning system; (2) the impact of the decision taken and reactions triggered at the lower levels are analysed a posteriori in the nominal planning cycle, and taken into account when generating future plans. The deterioration of the situation to a point that cannot be handled any more at Operations Level is considered a major anomaly requiring full replanning, for the recovery of which the system can be taken to degraded mode of operations.

This approach requires therefore from the mission planning the generation of robust schedules, which include enough freedom in their execution to allow for real-time replanning by simple actions at the Operations Level.

The capability to interact at very short notice with any component of the Galileo ground and space segment must also be ensured, in order to propagate throughout the overall mission the decisions taken at the Operations Level.

5 Reaction to Anomalies

The Galileo services rely essentially on the transmission of valid navigation and integrity information to the user of the Galileo services. Any failure that would prevent this transmission threatens the maintenance of the services.

The robustness of the mission against these failures is ensured at several levels:

- Any single failure of equipment is handled at execution level by equipment redundancy
- The inability of a satellite to support the Galileo services is detected and handled at execution level, i.e. by on-board and on-ground automated systems that ensure that the satellite is logically removed from the constellation.
- Transmission of erroneous navigation information is detected via the network of sensor stations, and leads to a modification of the satellite integrity propagated by the satellites of the integrity subconstellation
- Several parallel paths to the user are used to propagate the satellite integrity, in order to cover for the failure of a satellite or station involved in the transmission

Only the last of these points is relevant to mission planning, as it adds constraints on the planning of the ULS to satellite contacts that ensure multiple transmission paths to the user.

The maintenance activities performed via the TT&C station network are not assumed to be essential to the maintenance of the service either. If the monitoring and management activities fail, and this failure impacts the service, it will be taken into account automatically if the satellite is actively supporting the mission service at the time of the failure.

Any single failure is therefore taken into account in the mission design, in such a way that no immediate action is required to ensure the maintenance of the Galileo services in case of failure, apart from the propagation of the information regarding the unavailability of the failing resource throughout the space and ground segment.

The concept of emergency replanning is therefore required to cover secondary issues only:

- To ensure that recovery actions can take place as soon as possible from the SCCF after detection of an on-board anomaly, therefore limiting the risk to lose or damage the spacecraft
- To allow switching to a backup configuration of the satellite sub-constellations in case of failure of a satellite of the integrity subconstellation, and restore the robustness of the mission to one single failure of this type without delay
- To cover for the significant issue of the loss of a station head

These anomalies can be handled by robust schedules generated by the MPF during the nominal planning cycle, and which include alternatives satellite to station contacts.

6 Generation of Robust Schedules

The requirements on the replanning in case of failure of a satellite affect both the S-band TT&C and the C-band ULS contact planning.

- Additional or extended S-band TT&C contact windows must be made available to the engineers to investigate the failure and recover the satellite.
- The satellite must be automatically removed from the constellation, i.e. be ignored for both integrity and navigation dissemination. If the satellite is part of the integrity subconstellation, the subconstellation must be reconfigured, and the schedules modified accordingly.

In order to minimise the reaction time and minimize the required personnel, the schedules generated must include enough flexibility to allow for real-time replanning at the Control Facilities.

6.1 S-band TT&C Contact Contingency Plans

Activities scheduled for execution in the S-band TT&C contact windows are classified in primary and secondary activities. Secondary activities include tasks that are not essential for the achievement of the mission goal (i.e. maintaining the mission services), or can be postponed to a later time. The secondary activities are grouped together in the contact window, so that they can be dropped if needed to reallocate a TT&C station to a satellite in difficulty. The contact planning generates a backup plan for each satellite, where additional contacts are scheduled based on the assumption that all secondary activities executed by all the other satellites are dropped. The contact plans are robust to the failure of one satellite of the constellation at a time only.

The flight control team at the control facilities can make direct use of the contingency plans to obtain the additional contact time required to investigate and recover satellite failures. The scenario for anomaly handling is depicted in Figure 4.

time

SCCF (Automated Task Executor)	SCCF (Spacecraft Operations Engineer)	GACF (Ground Operations Engineer)	MPF
Raise alarm			
Call-out Engineer			
Perform immediate recovery action			
Disable interlocked procedures			
	Assess need for maintenance/analysis		
	Select and clear slots required for recovery/analysis		
		Clear slots required for recovery/analysis	
		Manually configure the TT&C station for satellite tracking	
	Issue unplanned unavailabilities	Issue unplanned unavailabilities	
			Handle Unplanned Unavailabilities
Load Updated Schedules			

Figure 4 Example of anomaly handling

The derivation of the contingency plans is based on simple queries of the plans to extract for each satellite the time windows assigned to secondary activities for all satellites that can be reused directly. The approach can be extended to cover for more than one satellite failure by reassigning those slots using an algorithm similar to the basic TT&C contact allocation algorithm.

6.2 Multiple Paths to the User

The ULS contact planning for the integrity subconstellation must ensure the safe dissemination of the integrity messages with very short delays. In case of failure of a path, due for instance to station unavailability, no time is available for replanning a new contact.

The ULS contact planning must therefore ensure that the contacts support multiple paths from the control centre to a user anywhere on earth.

Multiple access paths to the user are ensured by enforcing triplets of satellite that are close to each other in the constellation to use different upload sites at any one time.

This configuration covers failures of both the satellite and station (whole site).

No action is required at operations level to take advantage of the schedule robustness. The failure of a satellite or station link, and therefore the failure of the dissemination through them will simply not affect the mission goal.

6.3 Subconstellation Reconfiguration

The multiple paths to the user ensure the robustness of the mission to the failure of one satellite of the integrity subconstellation. The failure of a second satellite in the same neighbourhood would lead to the degradation of the mission service level.

In order to restore the level of robustness to a single satellite failure, the integrity subconstellation must be reconfigured to include again the required number of satellites. The impact of the reconfiguration on the subconstellation should be minimal.

Figure 5 illustrates the distribution of the satellites of the integrity subconstellation across the three orbital planes. The satellites surrounded in black in the picture represent the prime subconstellation configuration, and each set surrounded in colour is one backup configuration in the plane. Each satellite in a plane belongs to two possible subconstellation configurations. The failure of a satellite can be compensated by switching over to the configuration to which it does not belong. Three satellites only are different between the prime and backup subconstellations.

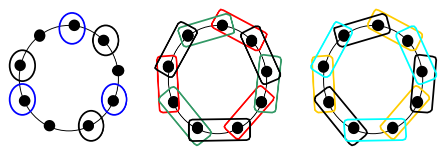

Figure 5 Integrity subconstellation and backups

The calculation of the C-band ULS contacts for the prime and each backup subconstellation can be calculated in advance, so that the switch over can be performed at the control facilities without intervention of the MPF.

The C-band ULS contacts for integrity dissemination are calculated for each backup integrity subconstellation resulting from the failure of one satellite only. The backup contacts are consistent with the contact windows of the original solution for the satellite that are common to the prime and backup subconstellation, in order to minimise the delta between the prime and backup schedules.

A reconfiguration plan must also be generated, which provides the sequence for moving from the prime to the backup configuration at a given time with the support of a minimum number of additional heads.

7 Prototyping the Contact Planning

7.1 Purpose of the Prototyping

The purpose of the prototyping of the contact planning is to assess the feasibility of the S-band TT&C and C-band ULS contact planning within the nominal resources of the mission in terms of number of satellites and station heads.

Although the result of this assessment affects the dimensioning of the ground segment, the prototyping does not aim at optimising the use of the resources, but only at finding a solution within the resource envelope, which can be used to evaluate the operational validity of the planning and replanning concepts.

7.2 General Approach

The prototyping of the contact planning is based on the combination of rule-based and constraints based techniques, where rules are used to create and control the resolution of a Constraint Satisfaction Problem for each contact problem.

The prototype relies on the re-use of the Mission Planning Kernel developed by Anite in the context of the development of ESA's Envisat Mission Planning System, which has since then been reused successfully to develop at low price the ESA's Mars-Express MPS, and is now being applied to the development of the ESA's Venus-Express MPS.

The Mission Planning Kernel provides a set of C++ libraries of re-usable components that cover the main areas of the Mission Planning domain.

Note that the contact planning problems for both TT&C and ULS resources are modelled using the same basic components of the kernel, the difference being in the constraints applying to each problem and in the control of the search. So both problems can be solved within the same framework, avoiding duplication and redundancy of code.

7.3 S-band TT&C Contact Planning

Problem. The parameters of the TT&C contact planning problem that was prototyped are the following.

- Contacts were calculated for all 27 prime satellites (i.e. the 3 backup satellites were not included) for the full duration of the constellation cycle (3 days).
- A least one contact of a configurable duration was provided per orbit (~14 hours), preceded by a configurable period for pre-pass activities and followed by a configurable period of lag time.
- Each contact is divided in two sections, one for primary activities, and one for secondary activities which can be dropped to support the TT&C contact replanning.
- The TT&C network is composed of 5 stations located at Kiruna, Kourou, Noumea, Papeete, and La Réunion, with a single head per station
- The time delay between consecutive contacts for the same satellite was set to a minimum of 10 hours and a maximum of 18 hours.
- The ground station visibility segments for the 27 prime satellites of the constellation are provided as input

Modelling and Algorithm. The modelling of the problem selected for the prototyping relies on a simple modelling of activities provided by the planning tool for the representation of visibility and contact periods.

The algorithm below was used to allocate the contacts.

```
Set orbital window to 14 hours for all satellites

Until end of planning horizon

  {

    For each satellite, set domain of
    contacts to the visibility segments
    from all stations filtered on the
    orbital window

    Until all satellites assigned

    {

      Select satellite

      Select contact for satellite,
      backtrack if not possible

      Remove satellite from the problem

      Propagate constraints on other
      satellite contact domains

    }

    For each satellite, set orbital window
    to the last contact + [10, 18] hours

  }
```

Results. Assignments have been derived from the test data provided and for a period of 3 days for contacts of 90 minutes, with 15 minutes lead-time. The 90 minutes are divided into 60 minutes of primary activities and 30 minutes of secondary activities, which can be recovered and assigned to another satellite at real-time replanning. Failure of assignment are detected rapidly, for instance in case of station unavailability, in which case the contact duration per satellite must be reduced.

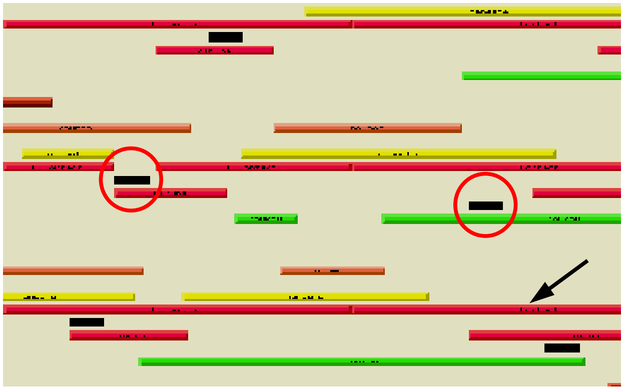

Figure 6 S-band TT&C Contact Plan

The Gantt Chart of Figure 6 illustrates an S-band TT&C Contact Plan, where the visibility windows from stations are displayed in colour, one colour per station, and the actual selected contacts are displayed in black. Two consecutive contacts for the same spacecraft are shown on the picture, surrounded by red circles.

7.4 S-band TT&C Contact Replanning

Problem. Additional contacts must be provided for each satellite if needed to support on-board anomaly investigation.

Modelling and Algorithm. No specific modelling was required, as the identification of the contact windows are performed by querying the nominal plan generated for all contact scheduled for secondary activities that can be cleared to support the satellite that encounters an anomaly.

No care was taken of trying to limit the fragmentation of the slots, or to distribute the slots between several satellites.

Results. The prototyping shows that quasi-permanent contact can be derived for any satellite from the reassignment of secondary activity slots.

In Figure 6, the satellite contingency timeline for the satellite covered by the two contacts in red is displayed, pointed by a black arrow.

7.5 C-band ULS Contact Planning

Problem. The parameters of the C-band ULS contact planning problem that was prototyped are the following.

- Contacts were calculated for the Galileo integrity subconstellation only.
- Permanent contact was ensured for each of the 15 satellites of the integrity subconstellation, with configurable overlapping between consecutive contacts.
- The ULS network is composed of 9 stations located at Kiruna, Kourou, Noumea, Papeete, La Réunion, Trivandrum, Vancouver, Santiago de Chile, and New Norcia. Each C-band ULS station has a maximum of 4 heads (actual antennas).
- Configurable times for pre-pass operations and station handover were included
- The integrity subconstellation, and visibility segments for the satellites of the all constellation for 1 month were provided as input

Modelling and Algorithm. The problem modelling is based on a segmentation of the planning horizon in sections over which the visibility patterns of the satellites of the constellation are fixed.

Figure 7 illustrates and example of a planning horizon [Ts, Te[divided in 5 sections.

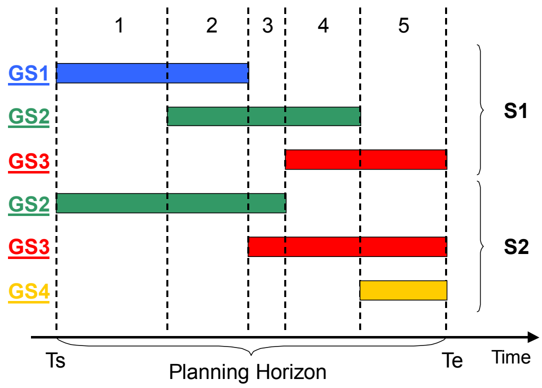

Figure 7 Segmentation of planning horizon

The rationale for the segmentation is that the allocation of station heads to satellites should not be modified in sections when the visibility constraint is constant.

The allocation problem can then expressed as one CSP per segment, where the satellites are the variables, the station heads the values, and the domain of each satellite variable is the set of stations that are visible from the satellite in the segment. The same satellite is denoted by a different variable for each segment, but the same station head is always represented by the same value.

Constraints on the minimum duration of the contacts, on the hand-over, and on the pre-pass are expressed as additional constraints between the variables of the individual segments which are checked whenever possible after the resolution of each CSP, and lead to backtracking if they are not met by the partial solution.

The algorithm implemented in the prototype is given hereafter.

```
Segment planning horizon
Create individual CSP's
Until all CSP's solved
  {
    Solve first pending problem
    If no solution then Backtrack
    If Station Handover Constraint not met then Backtrack
    If Pre-pass constraint not met then backtrack
    If Minimum Contact Duration constraint not met then Backtrack
  }
```

The distribution of the functionality between the rule-based engine and the constraint reasoning engine of the planning infrastructure is illustrated in Figure 8.

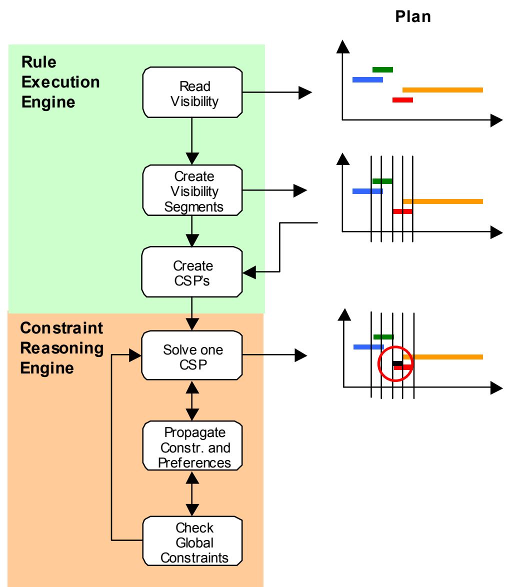

Figure 8 Rule and Constraint-based Architecture

Results. Assignments were derived for the test data provided and for a period of 3 days within an envelope of 18 C-band ULS heads, distributed equally between the station sites.

The Gantt chart of Figure 9 illustrate a section of a C-band ULS contact plan, where the visibility windows from stations are displayed in colour, one colour per station, and the actual selected contacts are displayed in black.

Figure 9 C-band ULS Contact Plan

7.6 Multiple Path to the User

Problem. Three independent paths must be enforced for broadcasting integrity to the user anywhere at anytime.

Modelling and Algorithm. The additional constraint is added that for each triplet of satellites of the constellation that are close to each others, the contact site must be different.

The angular distance between satellites has been used to define the triplets. The heads located at a same site are represented by integer values offset by 10, and the additional constraints that $S_i \neq S_j + 10\ n$ for each satellite number pair i,j of the triplet are added to each CSP.

The algorithm used to solve the basic contact problem is reused as such with the new constraints added.

Results. Assignments were derived for the test data provided and for a period of 3 days.

It must be noted that the selection of the angular distance to define the satellite triplets does not seem to be adequate and must be revisited.

7.7 Subconstellation Reconfiguration

Problem. C-band ULS contact plans must be pre-calculated for the prime integrity subconstellation, as well as for all backup integrity subconstellations that cover the failure of a single satellite of the prime subconstellation.

Modelling and Algorithm. The C-band ULS contact plan is calculated for the whole satellite constellation, with the constraints of the basic problem applying to the satellites of the prime and each of the 5 backup subconstellations.

The additional constraint that the allocation must be identical for the satellites of the prime subconstellation that are shared between the prime and the backups is enforced by identifying the variables representing these satellites in all problems.

The issue of generation of the reconfiguration sequence within limited additional resources was not addressed.

Results. Assignments were derived for the test data provided and for a period of 3 days with an envelope of 27 heads distributed equally between the ULS sites.

8 Conclusion

In this paper we have presented the basics of the Galileo Mission Planning concept and organization, and introduced an approach to real-time replanning by production of robust contact schedules covering single satellite or station failures.

This approach has been validated in a prototype planning system, which relies on rule-based and constraint-based techniques to generate contact plans between the satellites and the S-band TT&C and the C-band ULS.

The prototyping has demonstrated the feasibility of the contact planning and replanning within both the expected Galileo ground resource envelope and the planning time constraints.

Future work will cover the issues related to the schedule dissemination and implementation of switching from prime to back up schedules at the control facilities.

References

[1] Marc Niézette, Galileo Mission Planning Analysis, Technical Note ESA-APPNG-TN/00673, Issue 2.0, 8th December 2003.

[2] Galileo Mission Operations Concept Document (MOCD), GAL01011-TNO-100, Issue 5.0, June 2003.

[3] Joseph Pemberton and Flavius Galiber, A Constraint-Based Approach to Satellite Scheduling, DIMACS Workshop on Discrete Optimization, September 1998.