Planning and Scheduling for Space Applications Part II

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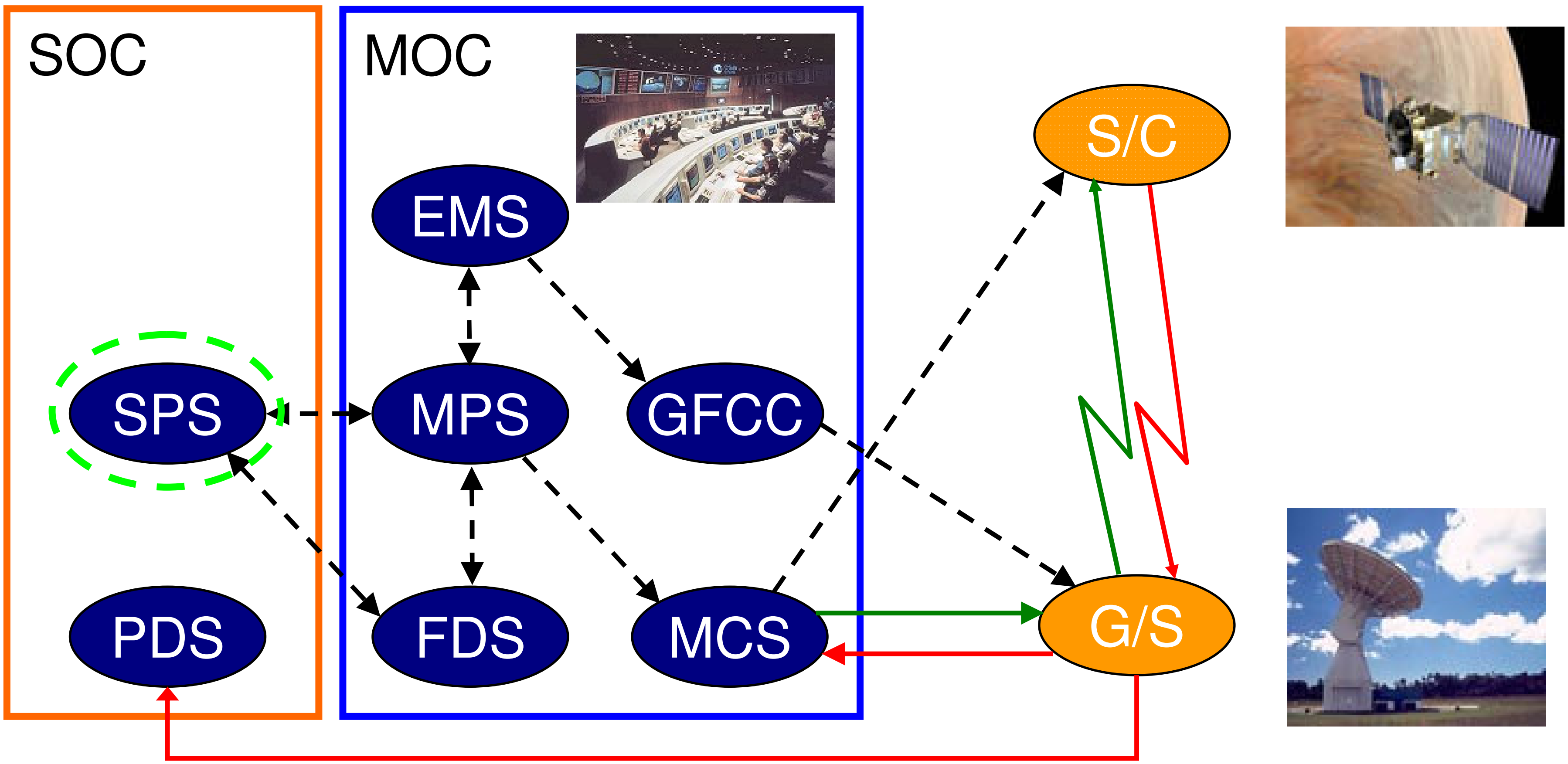
Presentation Outline (Part II)

- Science Operations Planning System
  - System requirements
  - Modelling
  - Planning problem generation
  - Planning problem solving
  - Results
- Ground Stations Allocation System
  - System requirements
  - Modelling
  - Planning problem generation
  - Planning problem solving
  - Results
- Discussion
  - Comparison of the two systems
  - Space operators and AI planning systems

Science operations planning



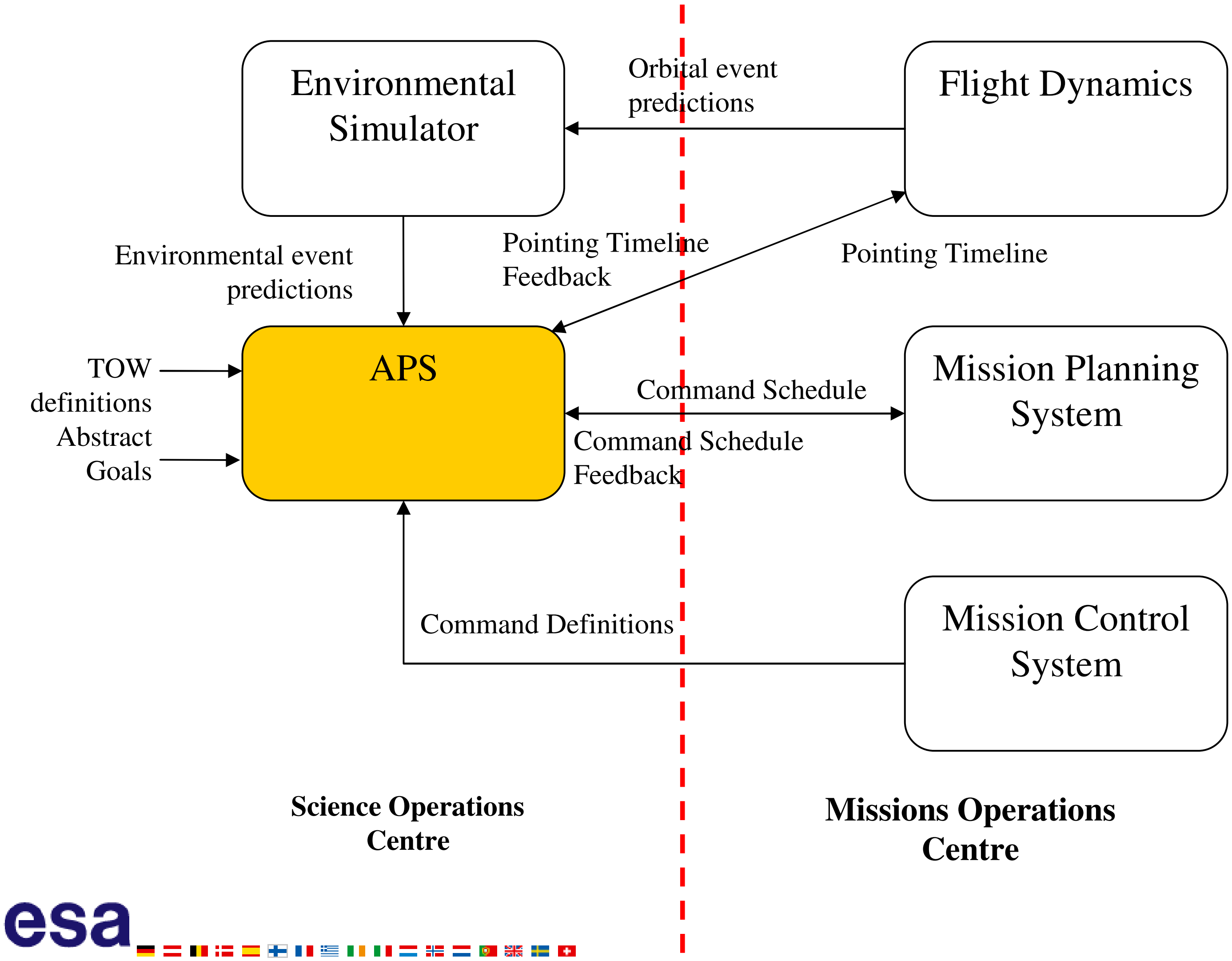
Planning of Deep Space Planetary Missions

- Common to all scientific spacecraft
  - Satisfaction of scientific and technical constraints
  - Maximal scientific return
- Specific to deep space missions
  - Communication time delays preventing real time communication
  - Distance variation changes the availability of resources (heliospheric distance changes power, Earth distance change link budget)
  - Long cruise journey duration with sporadic activities
  - Possible inclusion of Lander(s), implying co-ordination of Lander-Orbiter communication required

Science Planning Overview

- What is science planning?
  - Looking at environmental events
  - Defining observations that can be achieved given the conditions
  - Determining the compatibility between observations
  - Checking the maximum resource usage at any point
- Current status : a number of tools are used to generate the science plan nominally manually

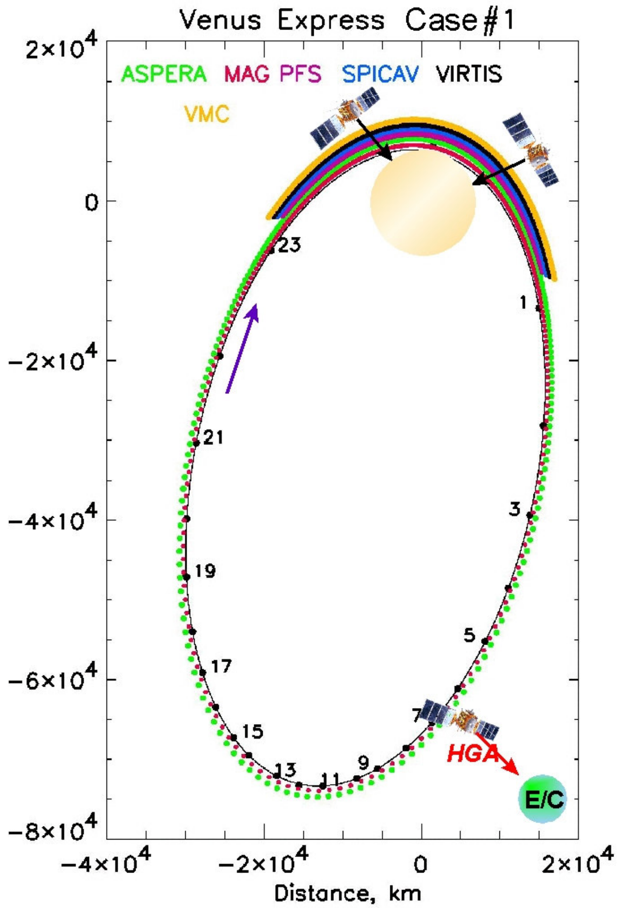
System Context



Aim of the system

- To automate the generation of the Science plan using a goal based approach with an adaptable optimisation mechanism
- To show that this can be achieved using a framework which is flexible, adaptable and pluggable, and can be used across different planetary-type missions
- To formalise in the system the requests from the Principle Investigators (PIs)
- To prototype the system and demonstrate using the Venus Express case

Mars/Venus-Express SOC Planning



- Identification of the Target of Opportunity Windows for the various observations requested by the Principal Investigators (PI's)
- Selection of the observations that maximize the mission return within the resource profiles
- Transfer of pointing timeline to FDS for checking
- Transfer of final science plan to MOC MPS for consolidation and final schedule generation

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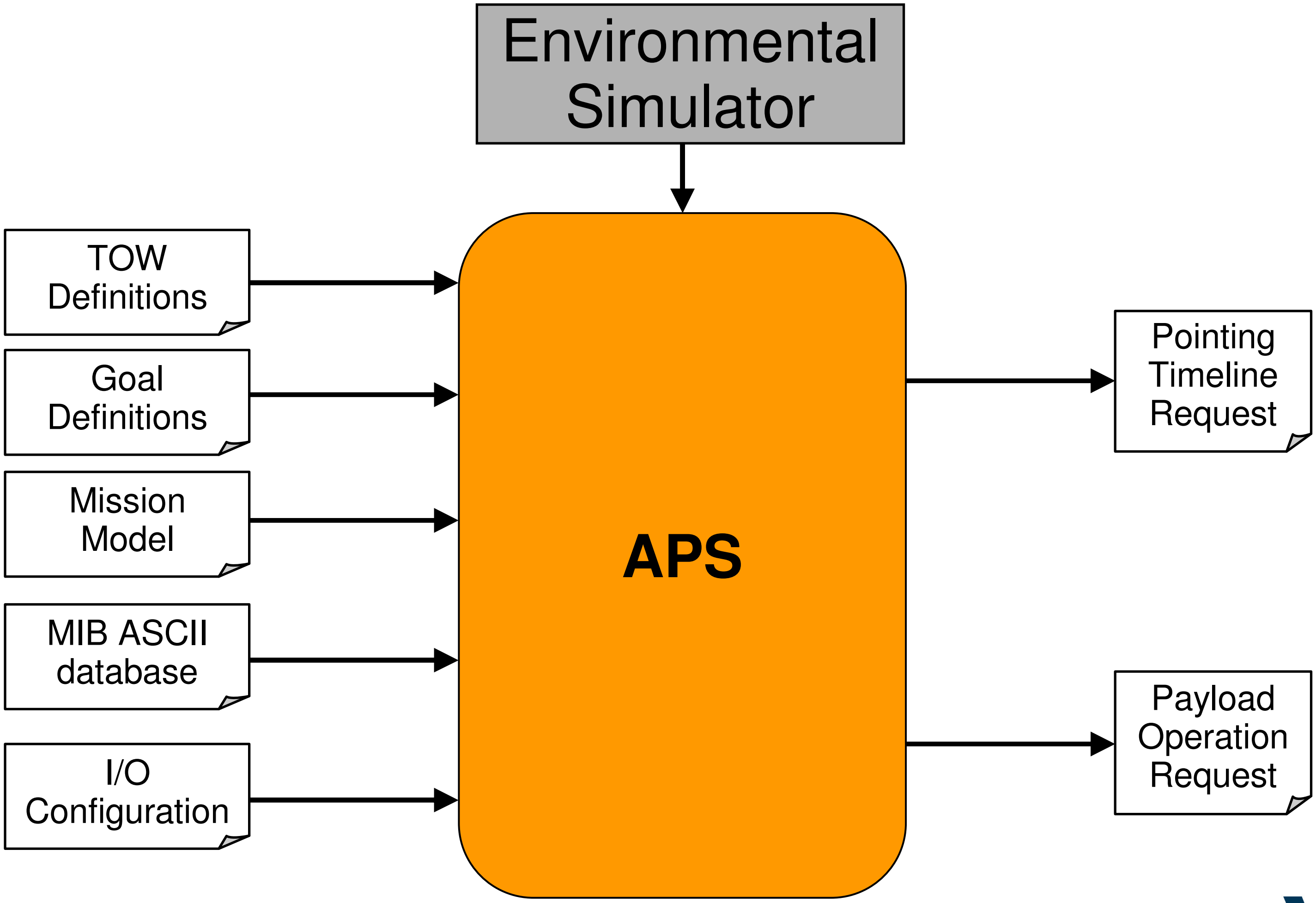
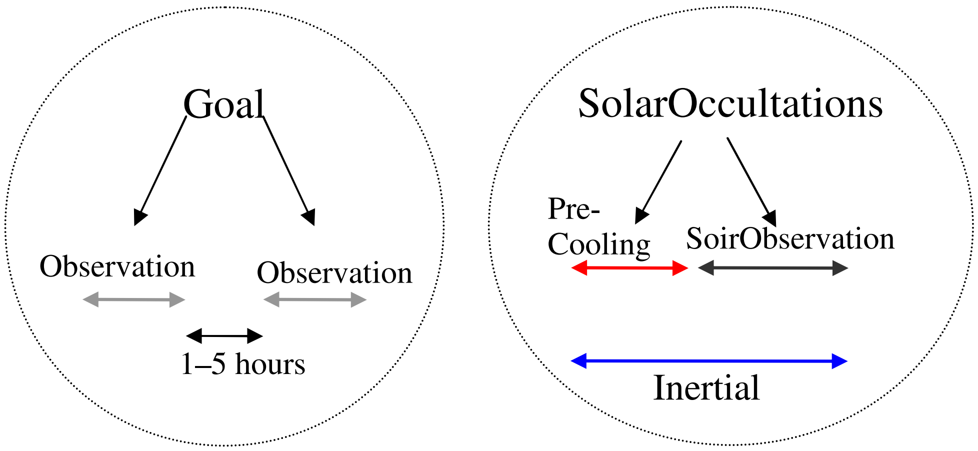
Data Input/Output



What is a Goal?

A definition of what observations/operations need to be carried out with associated constraints specifying timings, periodicity, durations, etc.

Example : Two observations need to be carried out one after the other with a minimum of 1 hour between the observations and a maximum of 5 hours between them.



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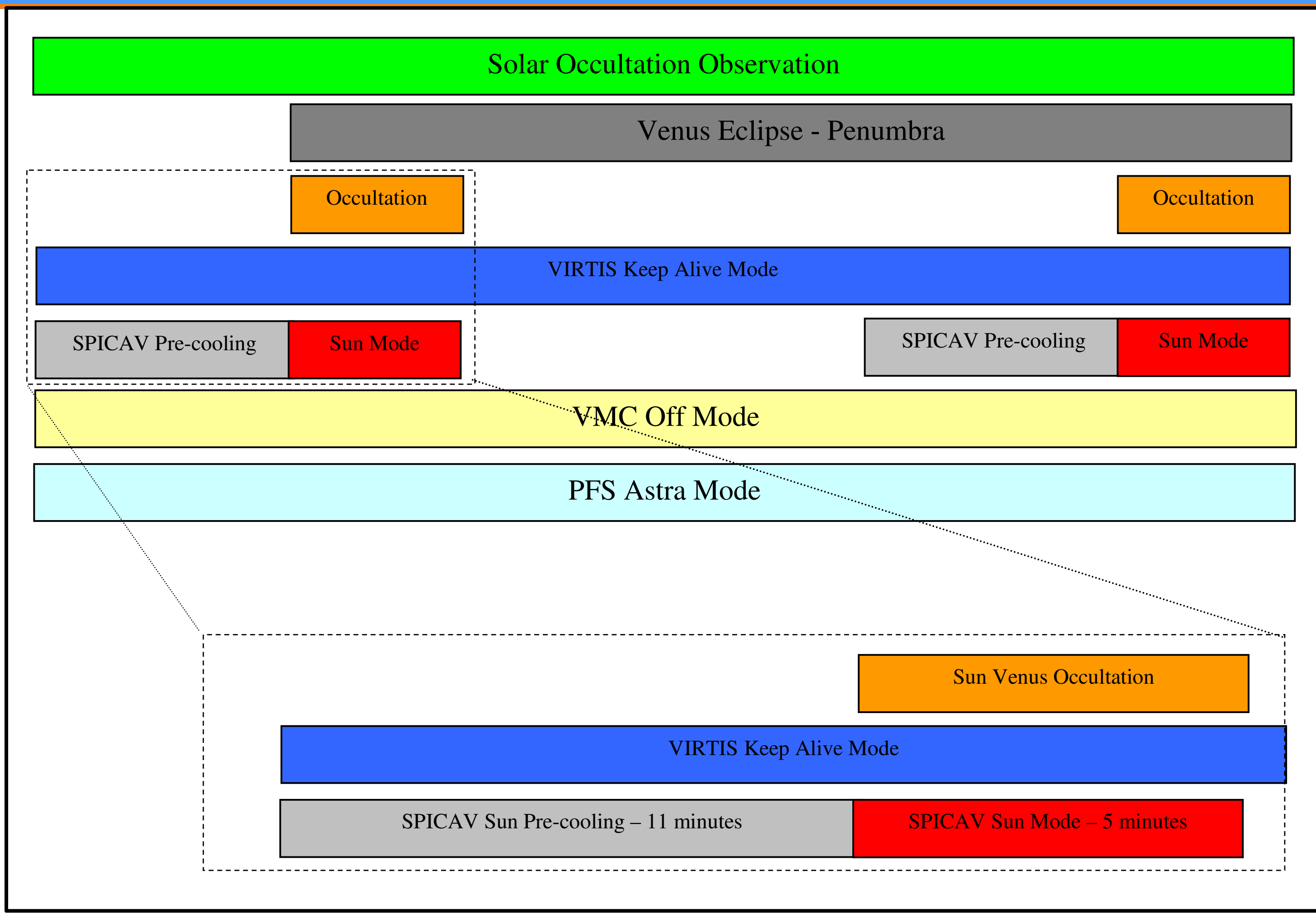
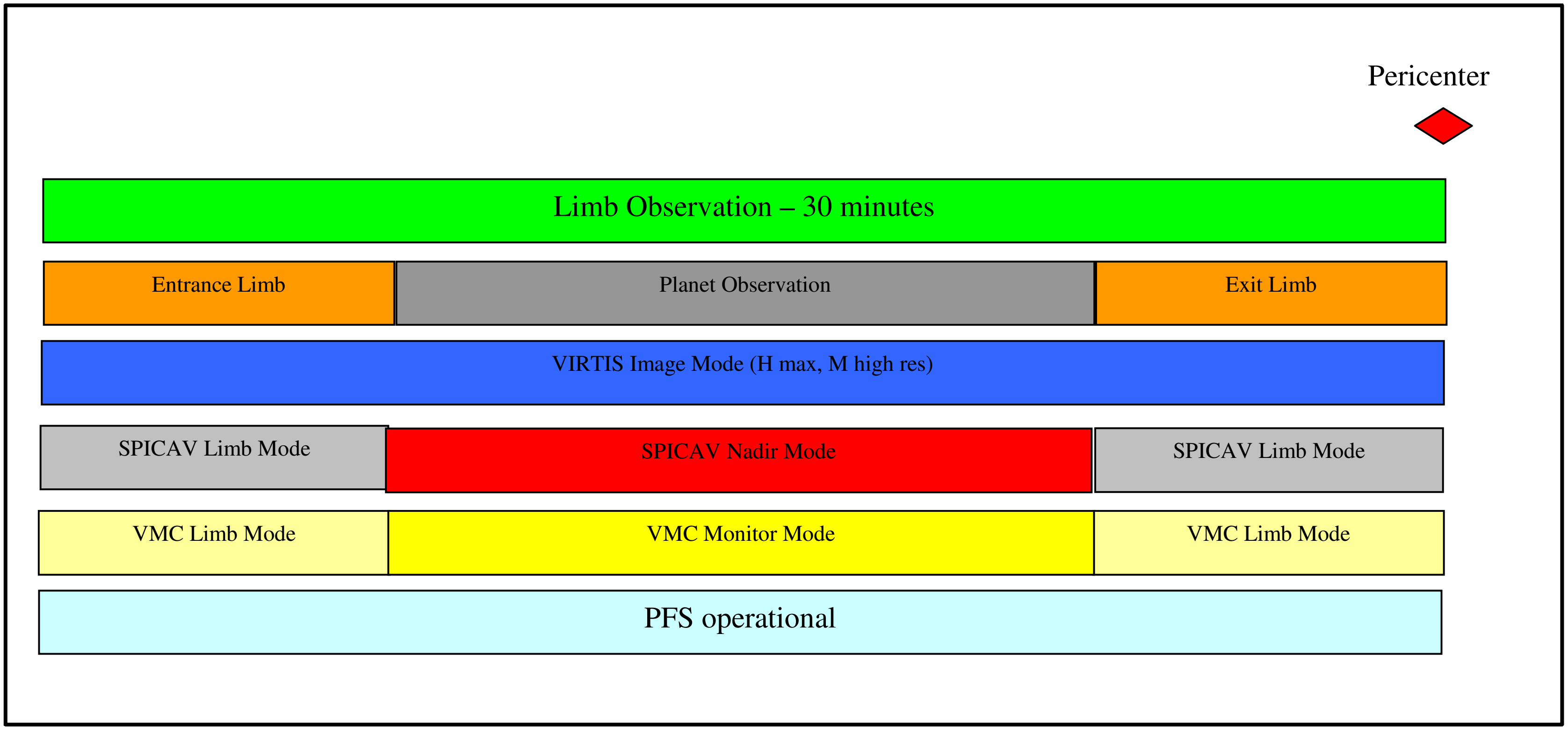
Candidate goal example
Solar Occultation



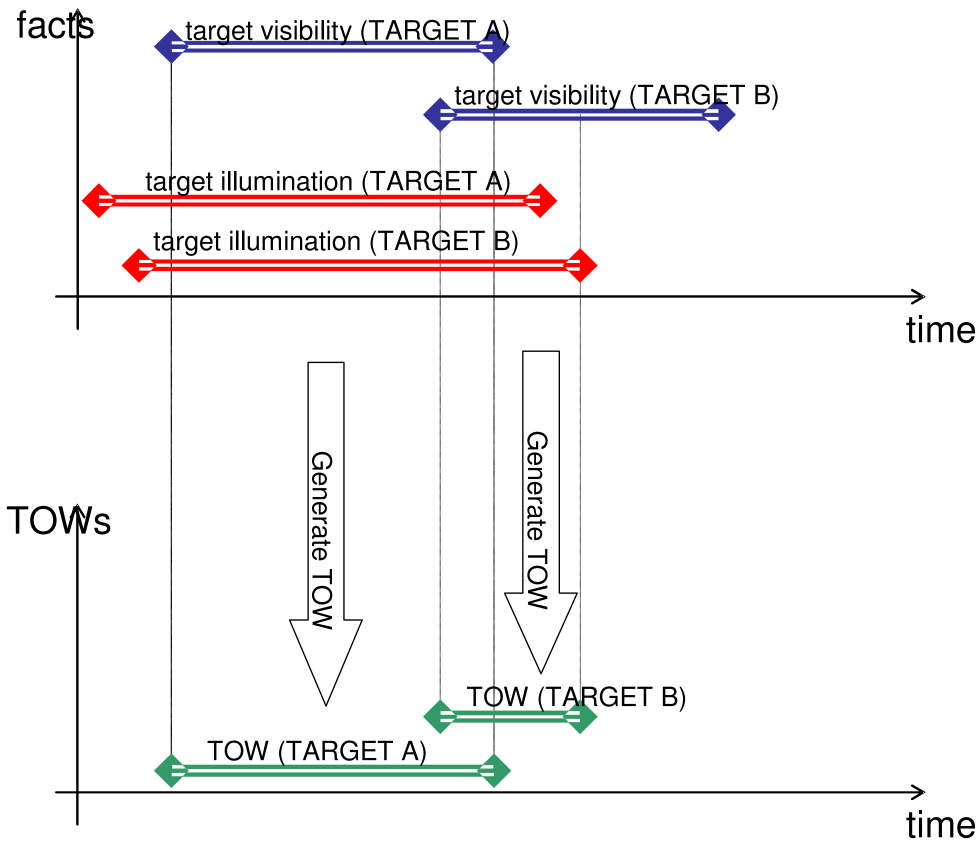
Candidate goal example
Limb Observation



Evaluation Function

- Function of the elements of the plan which returns its scientific value: goals and operations
- Defined by the user
- Aspects to be considered
  - Absolute total return of the plan
  - Balance of the distribution of scientific return to the users
  - Plan history
- Multi-criteria optimisation => merging function
  - Additive criteria: a parameterised template for the evaluation function
  - Egalitarian functions, e.g. max-min

Target Opportunity Window (TOW) Overview



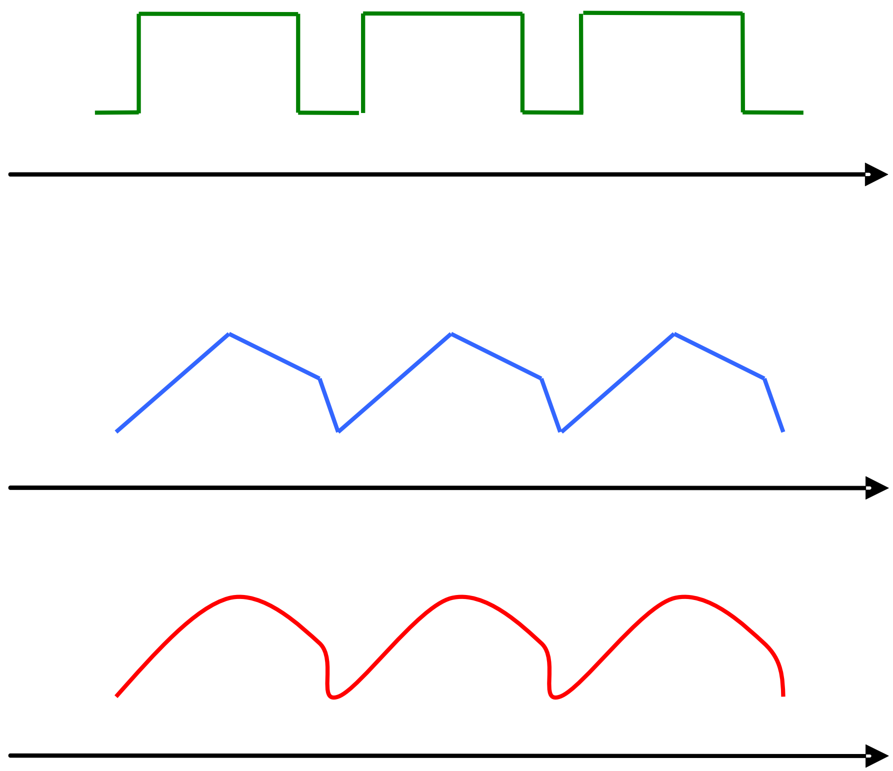
Resources modelling

- Rough models for planning
- Approximated models for internal checking
- Accurate models for external checking
- Reality

Approximation for high level planning

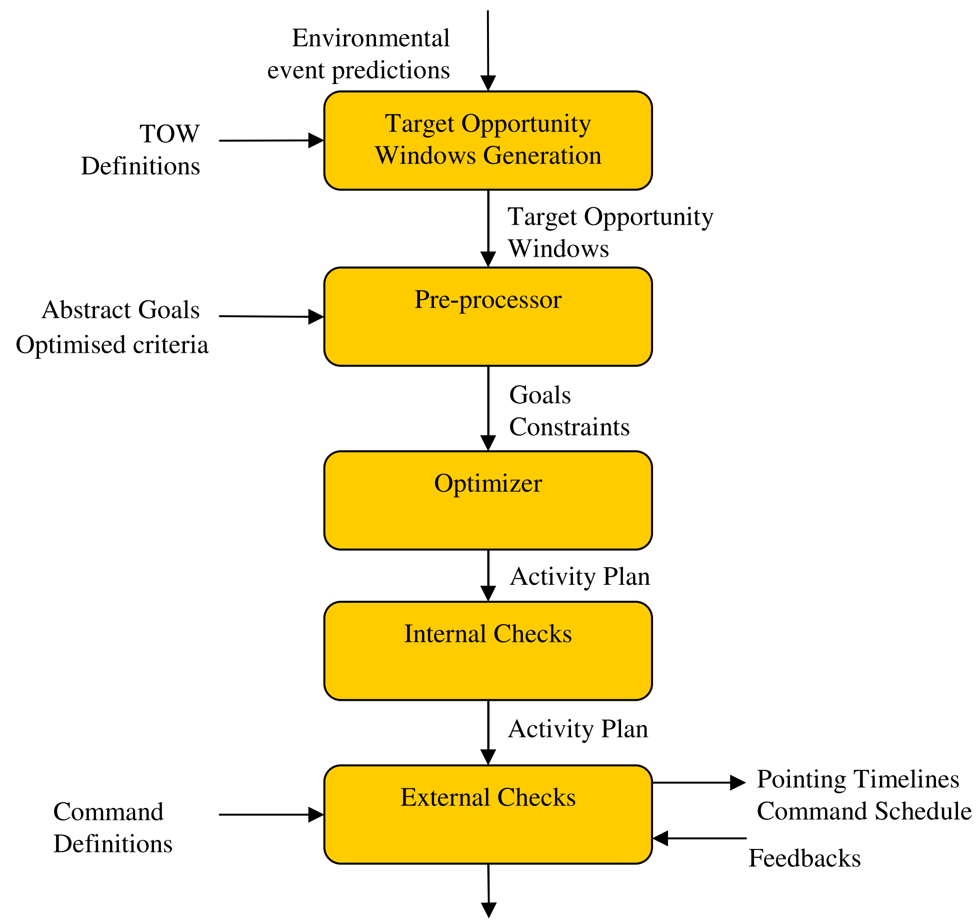
Approximation for constraint checking

Reality



System elements

- Data input/output
- TOW Generation
- Pre-processor
- Optimizer
- Internal checking
- External checking



Generation of operations availabilities - TOWs

fact(?id1, target_visibility, TARGET A, ?tvS, ?tvE)

^ fact(?id2, target_illumination, TARGET A, ?tiS, ?tiE,)

^ overlap(?tiS, ?tiE, ?tvS, ?tvE, ?toS, ?toE)

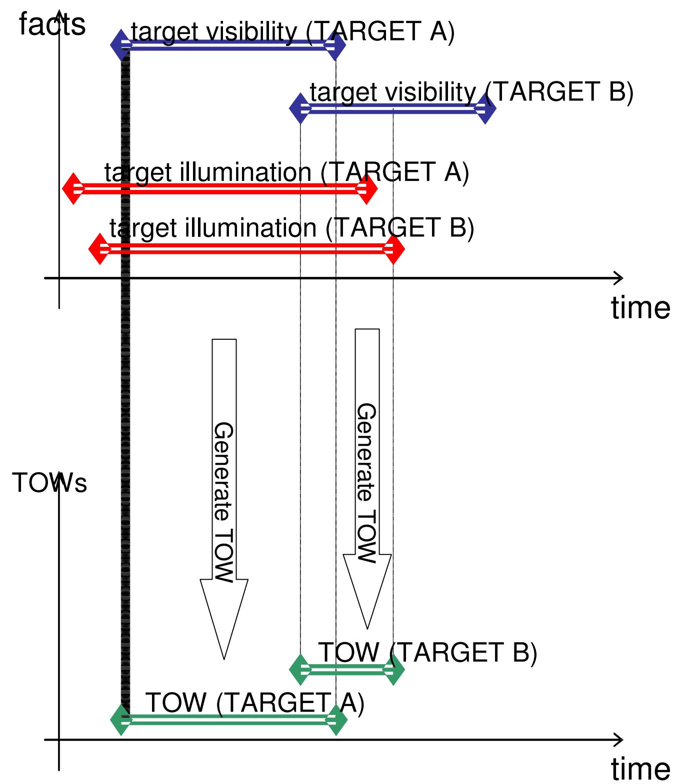
-> activity(?newId, operation_A, TOW, ?toS, ?toE)

fact(?id1, target_visibility, TARGET B, ?tvS, ?tvE)

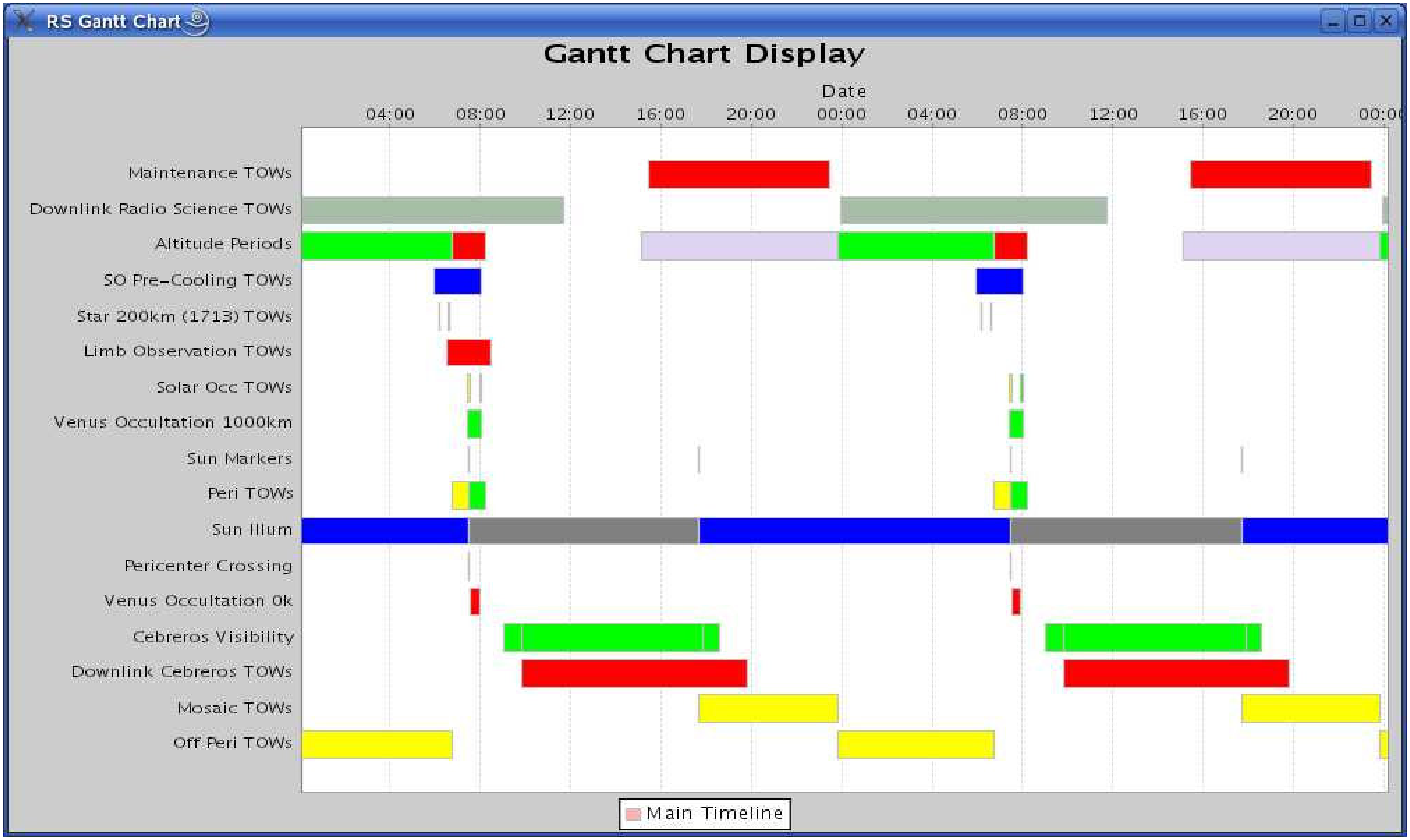
^ fact(?id2, target_illumination, TARGET B, ?tiS, ?tiE,)

^ overlap(?tiS, ?tiE, ?tvS, ?tvE, ?toS, ?toE)

-> activity(?newId, operation_B, TOW, ?toS, ?toE)



APS
Results: from events to TOWs



System elements

- Data input/output
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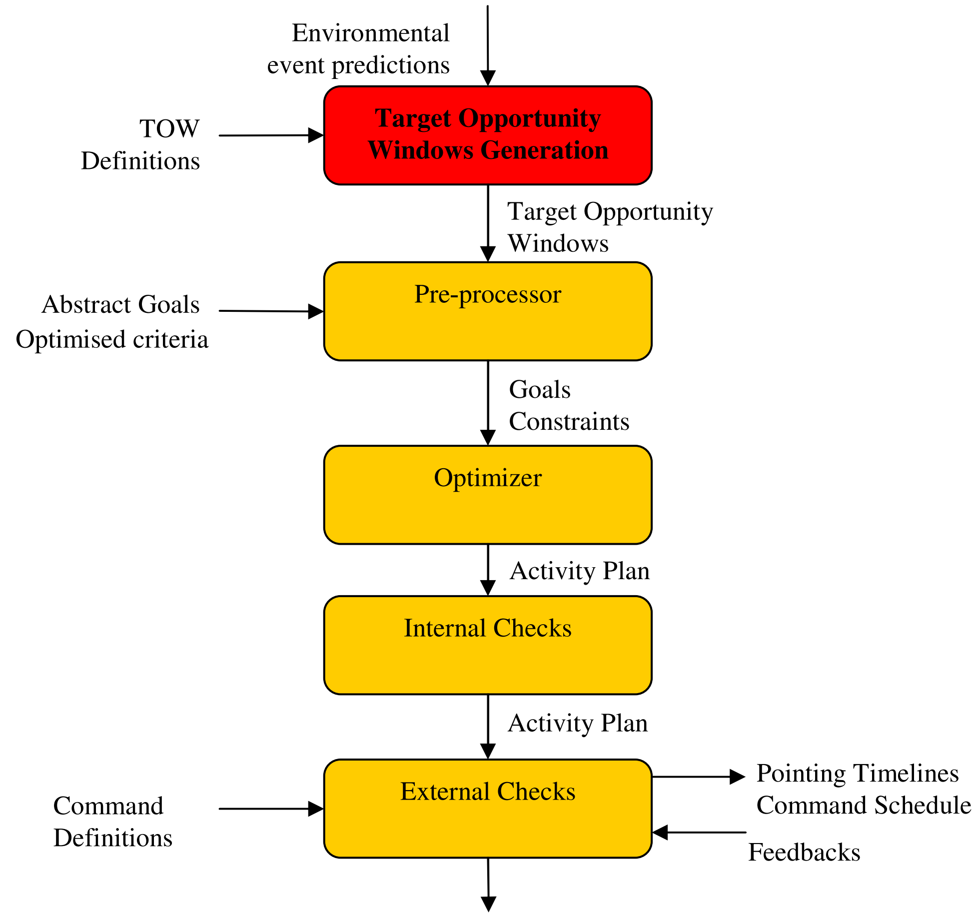
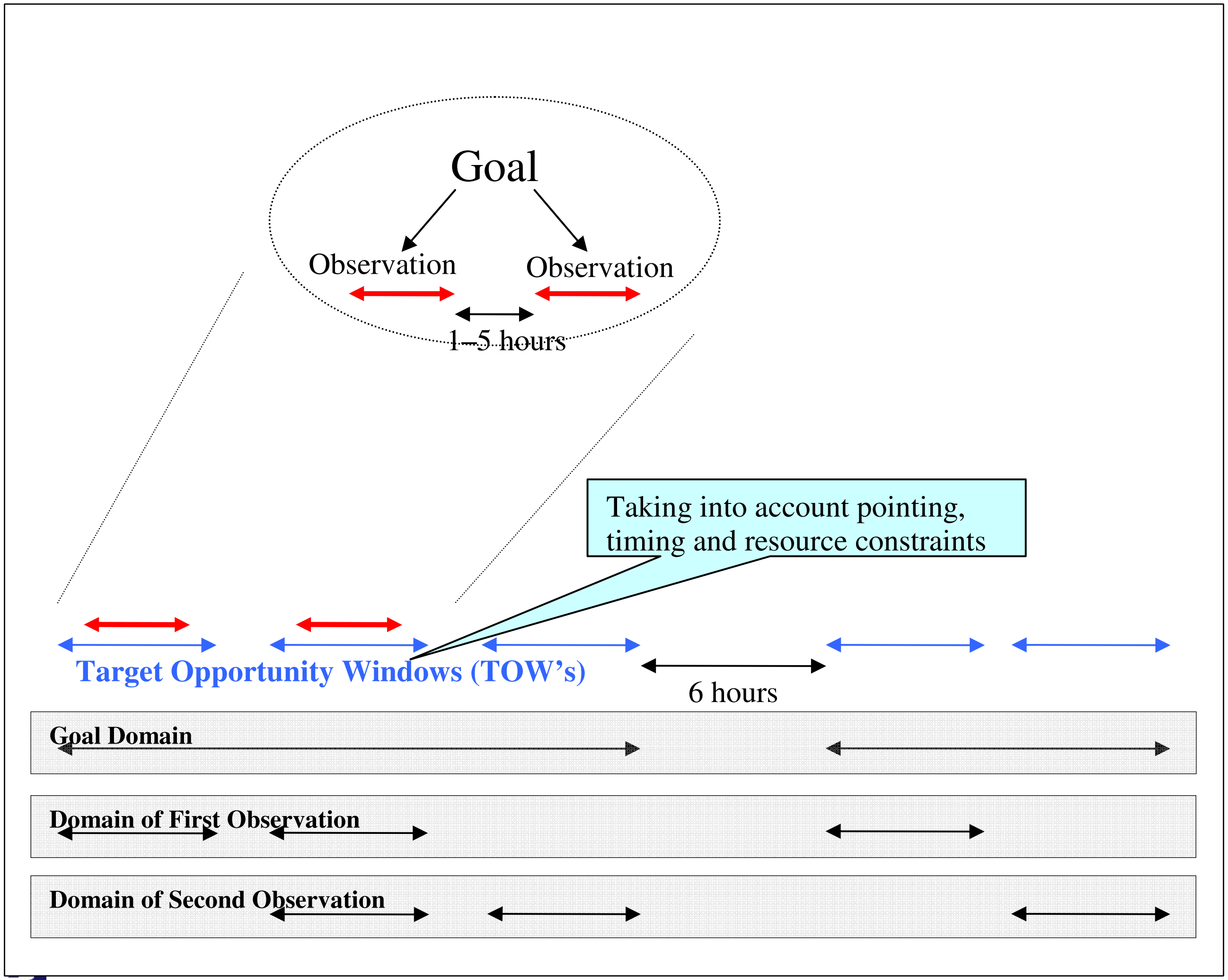


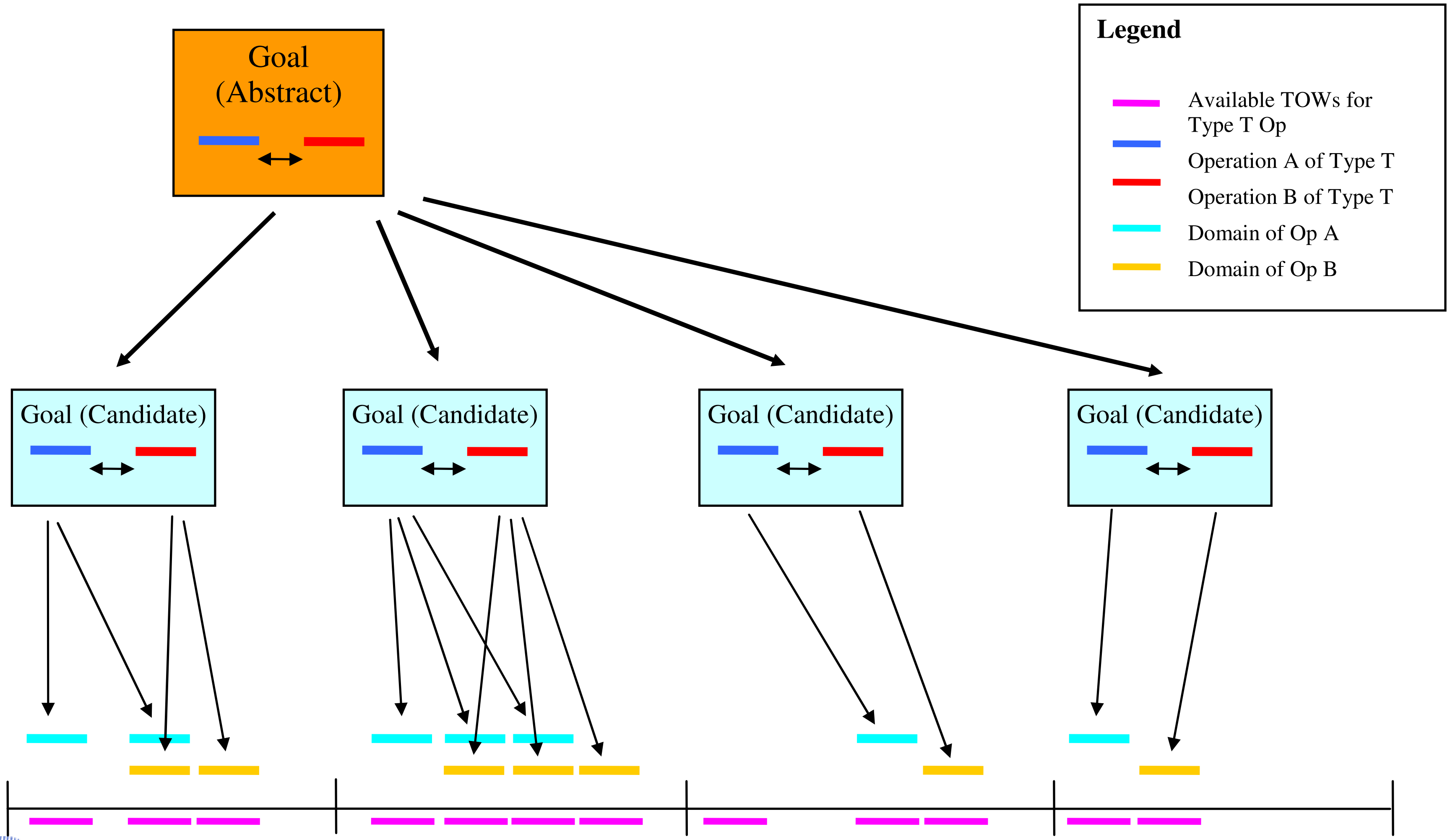
Pre-processing

- Goal extension
- Candidate goals location
- Input
  - Goal description: operations, periodicity, temporal constraints, priorities
  - Availabilities: TOWs
  - Planning period
  - Plan history and future
- Output
  - Oversubscribed plan of payload operations for the planning period

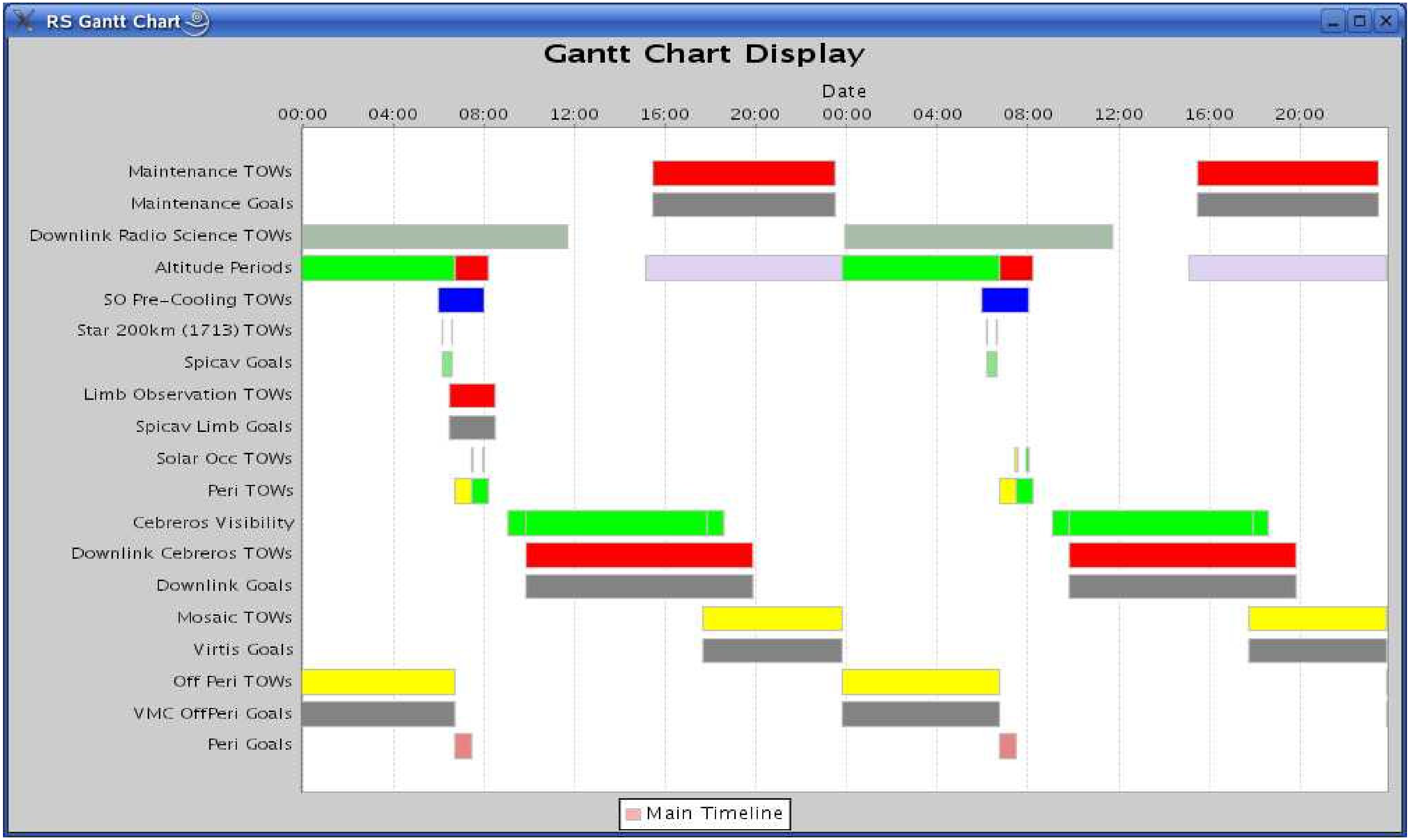
Example Goal Overview



Pre-Processor in action

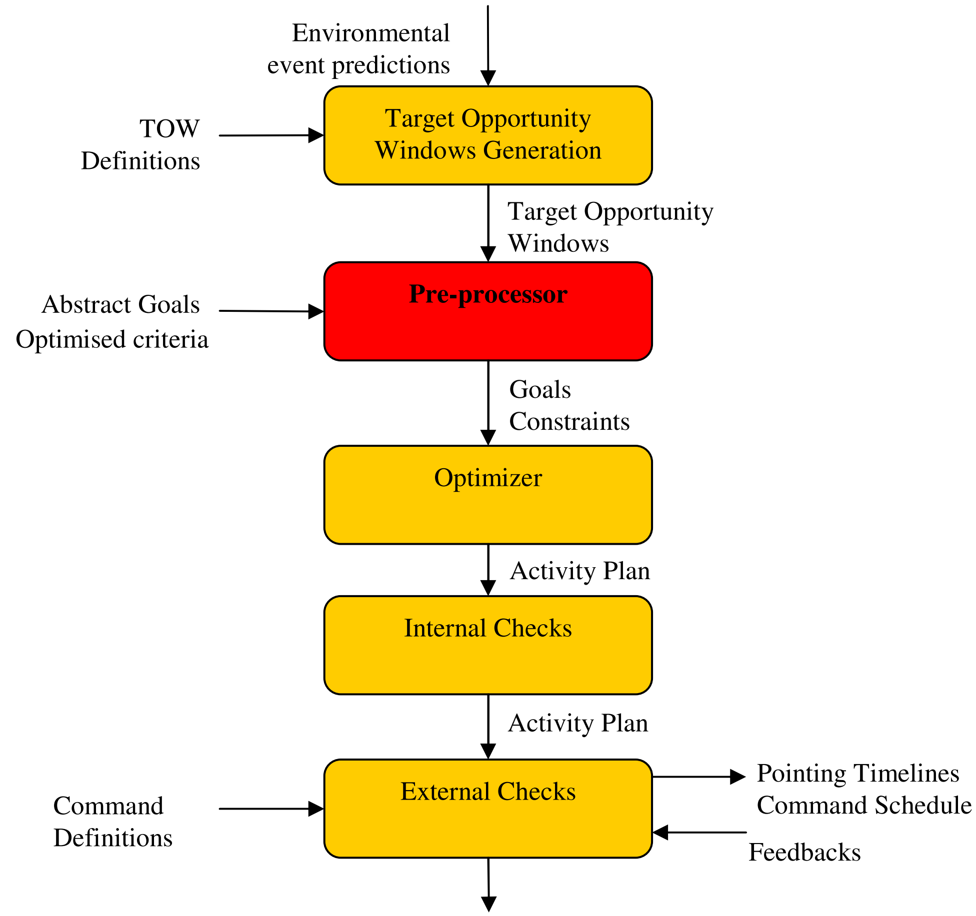


APS
Results: from TOWs to candidate goals



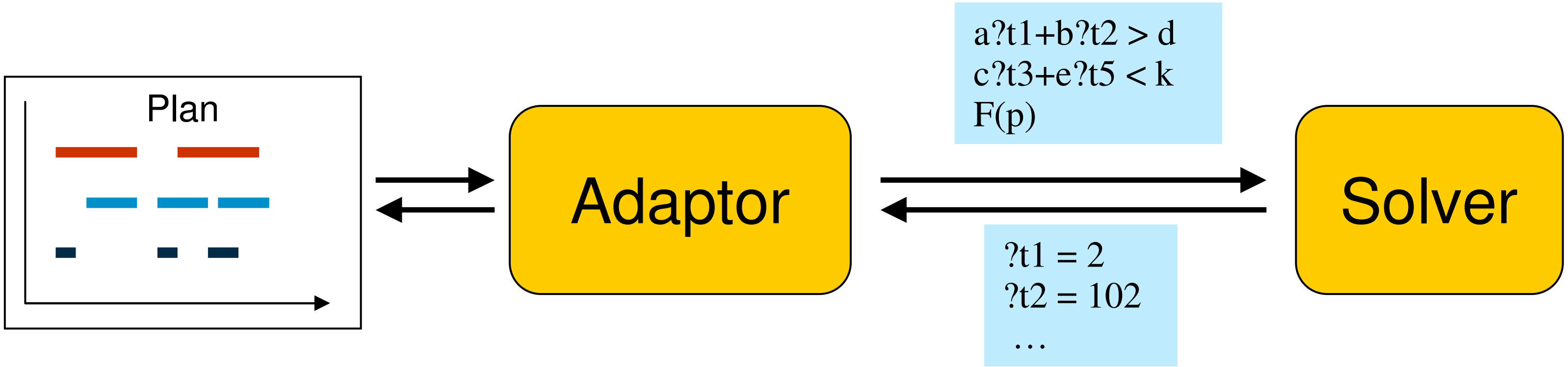
System elements

- Data input/output
- TOW Generation
- Pre-processor
- Optimizer
- Internal checking
- External checking



Optimizer

- Solving of optimisation problem created by the pre-processor
- Characterised by variables, constraints between the variables, domains of the variables and the evaluation function
- The modelling of the problem is using mixed integer programming (MIP)
- Gnu LP solver is used in the prototype



Adaptor
Problem Translation

- Example for Mixed Integer Programming modelling
- Input
  - Set of operations with modes, temporal windows, weight, pointing requirements
- Output
  - Linear programming problem with variables, constraints, function to optimise
- Types of variables and constraints
  - Start and end time of each operation => continuous
  - Chosen TOW per operation => integer
  - Mutual exclusion between operations => integer
  - Pointing: pointing modes, idem mutual exclusion
- Optimisation function
  - Reward for the implemented operations (weighted for fair repartition between PIs)
  - (Cost related to the use of physical resources)

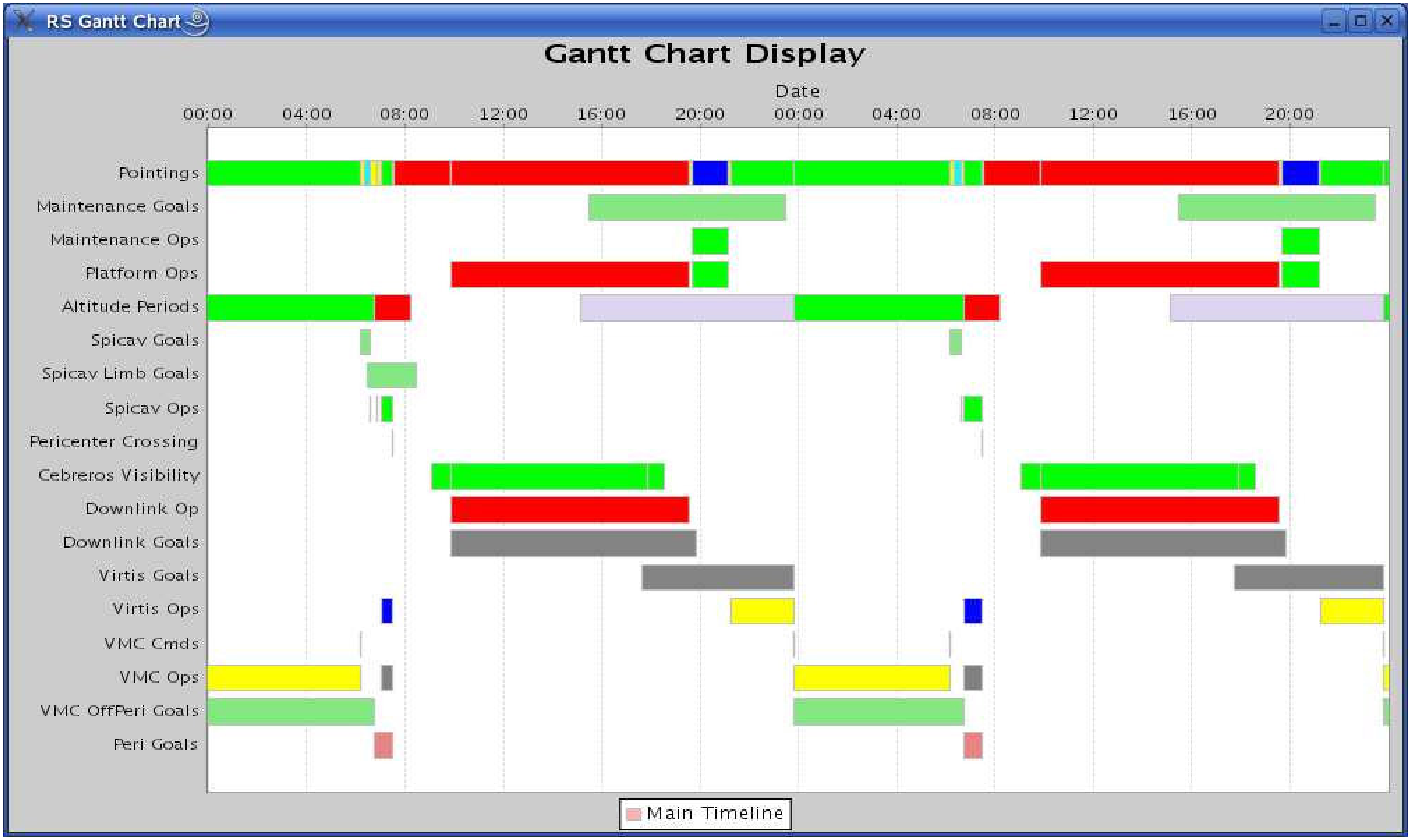
APS
Optimisation process

- Using GNU LP solver
- 10 days – about 600 constraints -> 1h30
- Before: 3 weeks of manual planning for one month
- Complexity grows exponentially with the number of integer variables
- Other optimisation approaches
  - Stochastic local search
  - Genetic algorithms

Output return

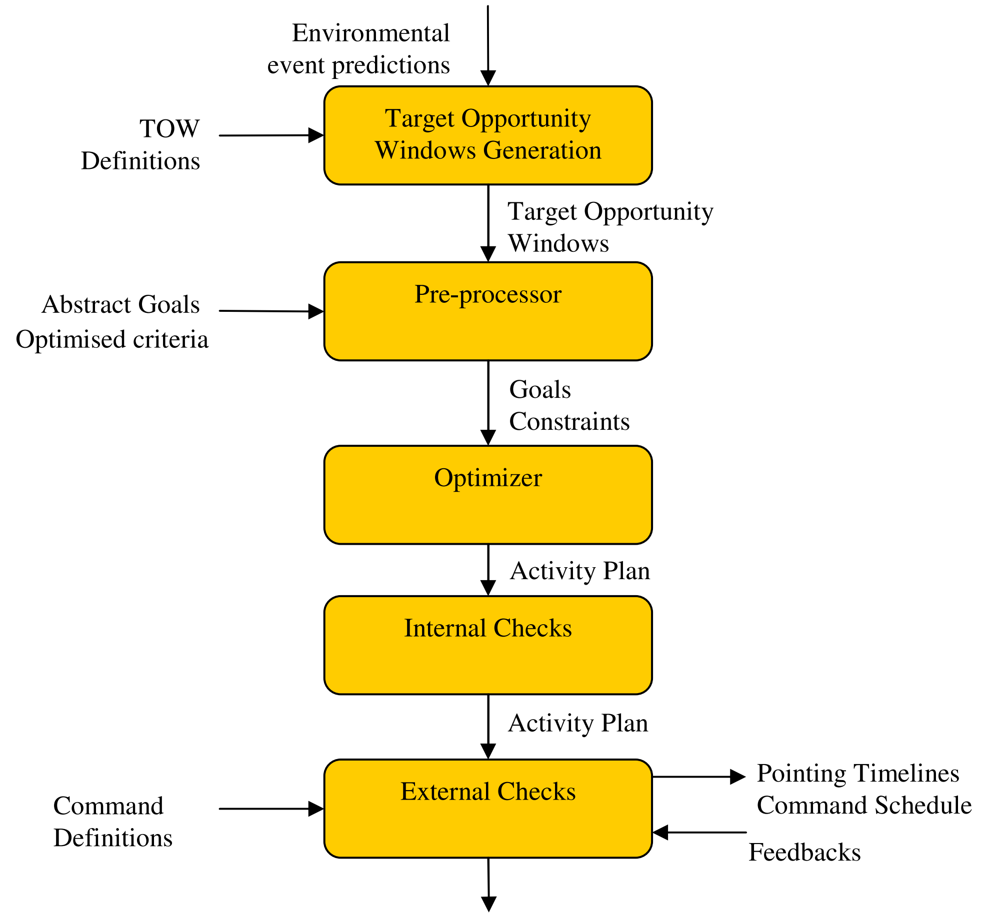
- Solver -> Adaptor
  - Sets the value of each variable
  - Provides the final value of the optimised function
- Adaptor -> Plan
  - Remaining operations with set start and end times
  - Update of pointing timeline

APS
Results: from candidate goals to operations

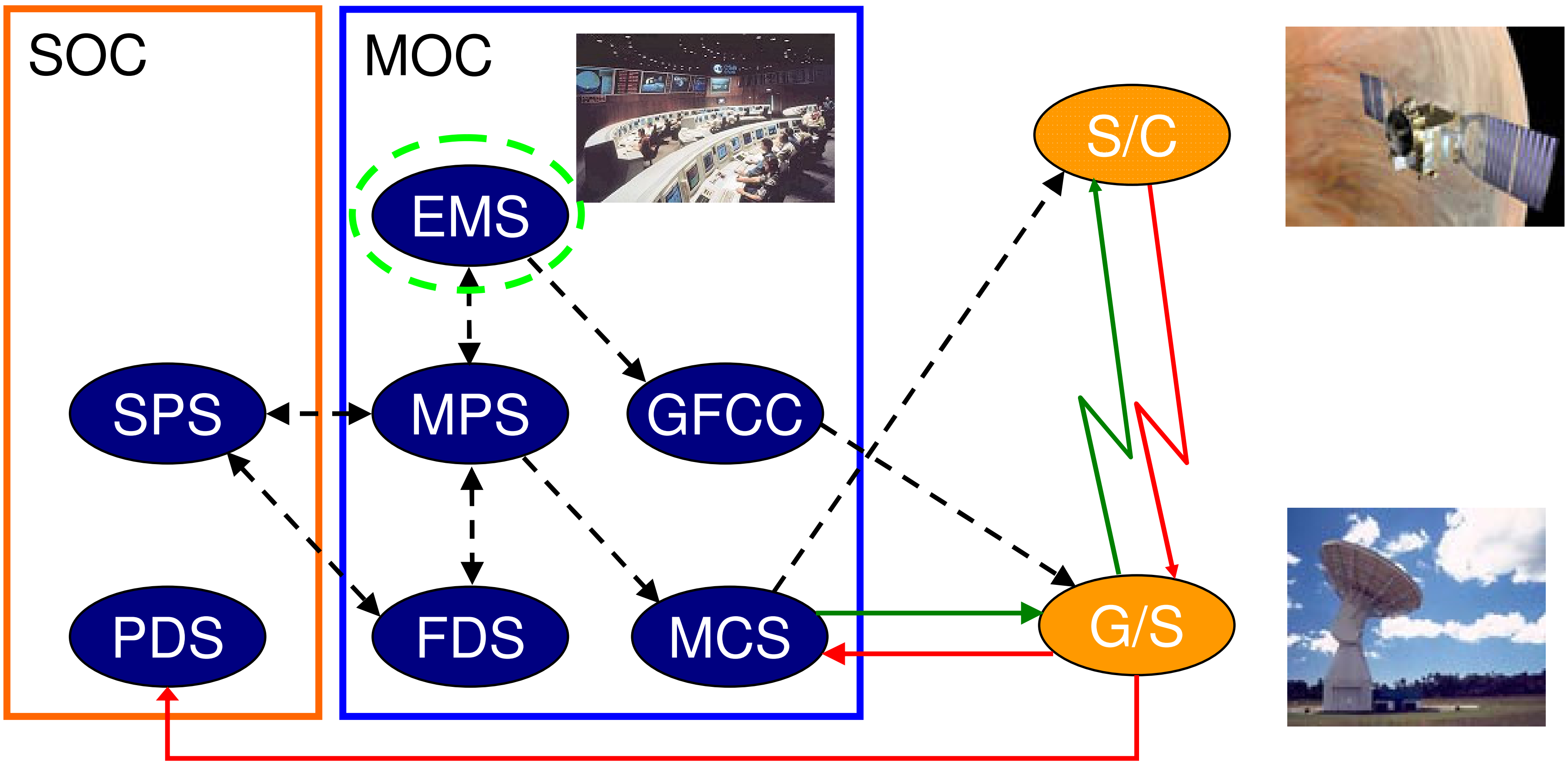


APS
Production of the final plan

- Several repair / refinement cycles
- Flexibility/robustness?



Ground station service allocation planning



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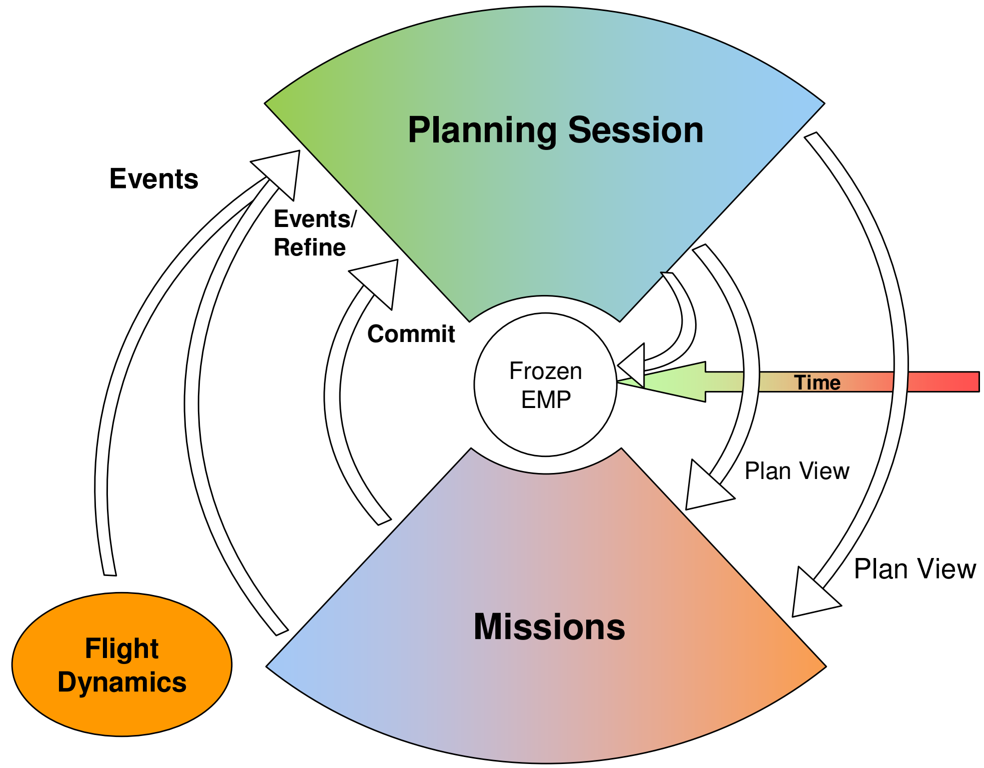
Dynamic use of the system

- Three levels
  - EMS system
  - Planning session
  - Planning run
- Plans are frozen one week before execution



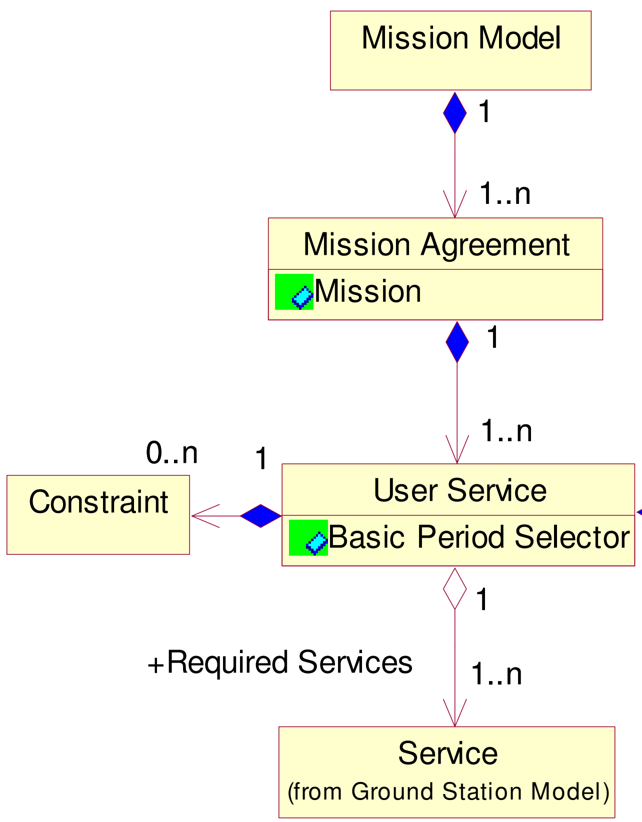
ESTRACK Service Allocation Requirements

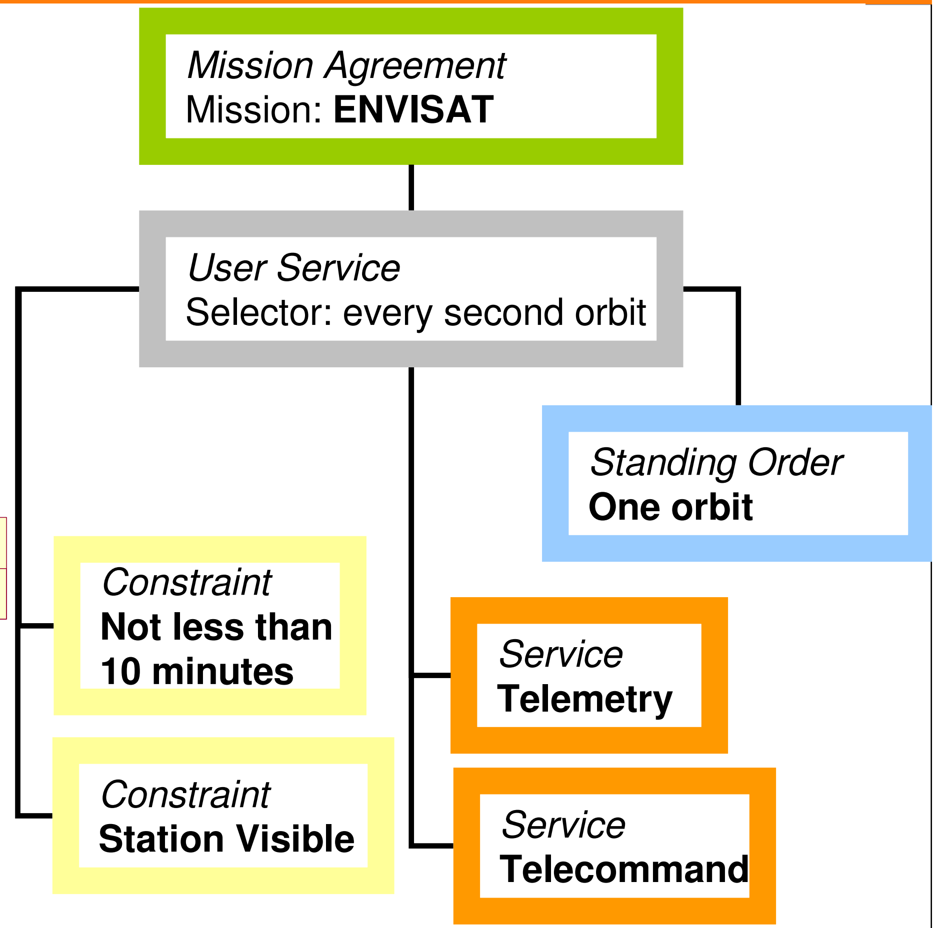
- One pass from AOS to LOS of a minimum duration per orbit
  (e.g. ENVISAT)
- Maximum continuous contact per orbit, with mandatory contact in a time period between two events specified for each orbit, and minimum hand-over duration
  (e.g. XMM, INTEGRAL)
- Maximum/Minimum total contact duration and number of passes within a period, with minimum pass duration
  (e.g. SMART-1)
- Maximum coverage for a constellation; in case of conflict between several S/C for the visibility of the same GS, the duration of the contact with the first S/C visible from the GS is maximized
  (e.g. CLUSTER)

HP Network Service Allocation Requirements

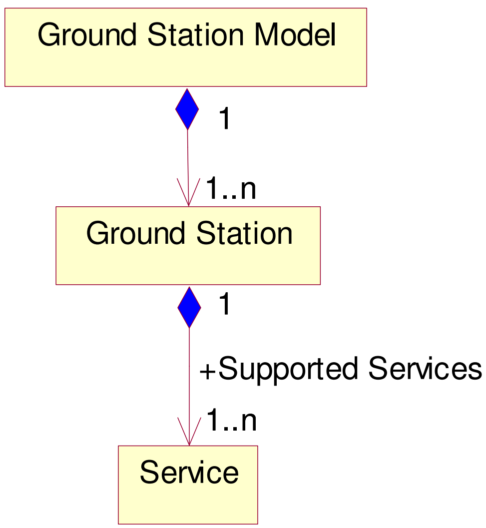
1. Lunar occultation periods have to be avoided.
2. The minimum pass duration is 3-hour for Herschel, selected from within the physical station visibility.
3. The minimum pass duration is 3-hour for Planck, selected from within the physical station visibility.
4. The separation of passes should be 24 hours +/- 30 minutes.
5. The minimum pass elevation should be 10°.
6. Herschel and Planck passes should be scheduled within a period of 8 hours. It is expected a ground station reconfigure time between spacecrafts of less than 30 minutes, including the pre-pass test.
7. The order Herschel-Planck or Planck-Herschel should be retained until a change is requested.
8. During some periods, due to the load on the NNO station it may be required to support one of the HP spacecrafts from Cebreros. The selection of the SC supported by Cebreros should be maintained for the full duration of the contention period.

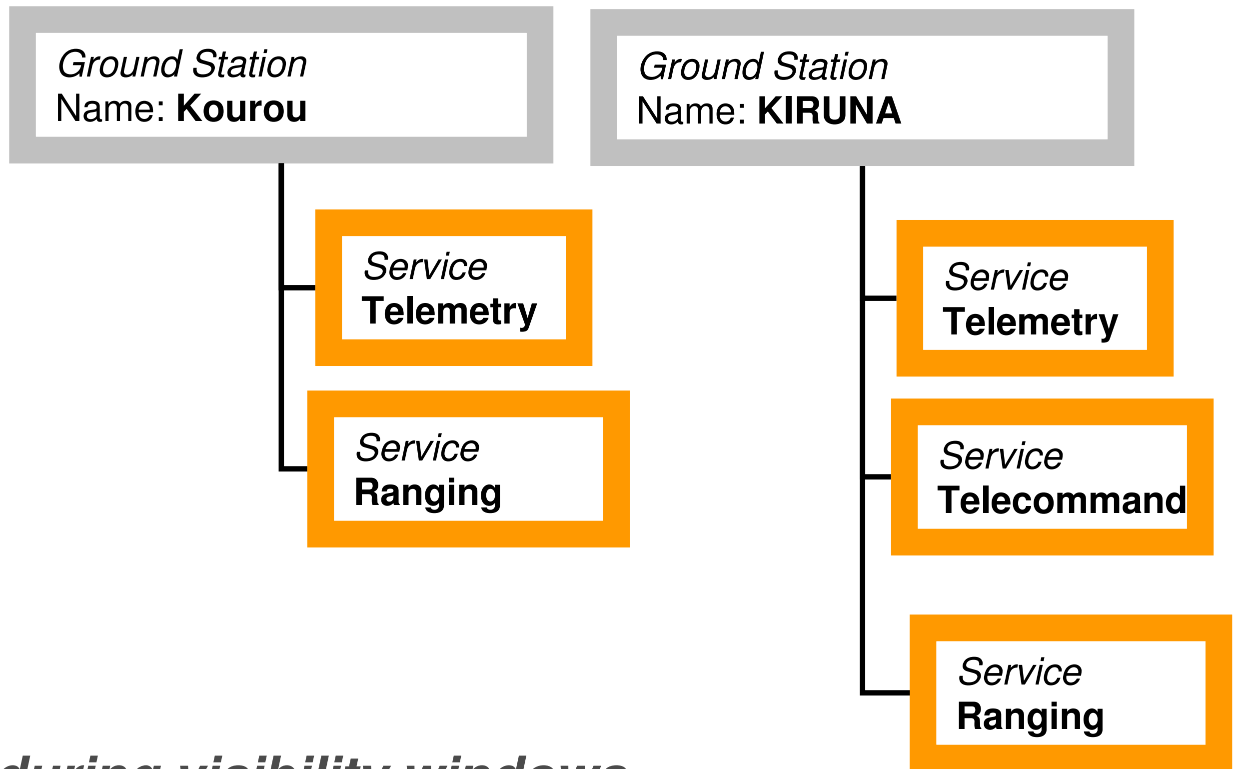
Modelling requirements





Modelling resources





- ***Services available during visibility windows***

Modelling preferences

- ESTRACK allocates priorities to the Mission Agreements for using Ground Stations
- Mission Agreements have internal preferences regarding the choice of the Ground Stations

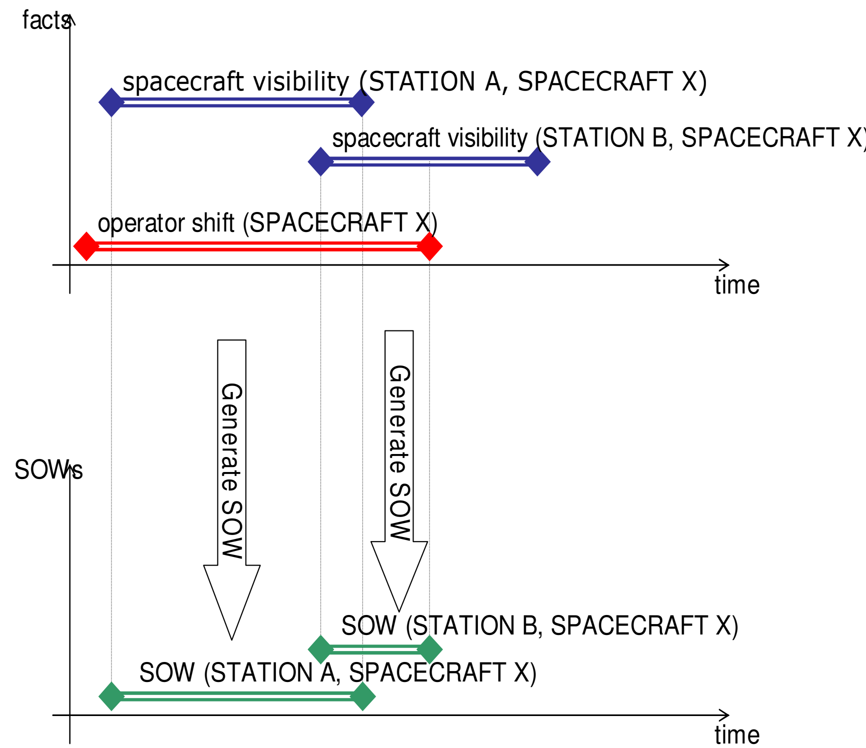
Mission\ Station	Santiago	Maspalomas	Kiruna
ERS 2	7	6	5
XMM	3	4	N/A
Cluster	2	1	8

Planning Objectives

- Every User Service must be completely implemented
- No global optimisation is required
- No alternative solutions are proposed to the user
- If no solution can be found the operator can enable degraded User Services

Planning problem generation
Resources

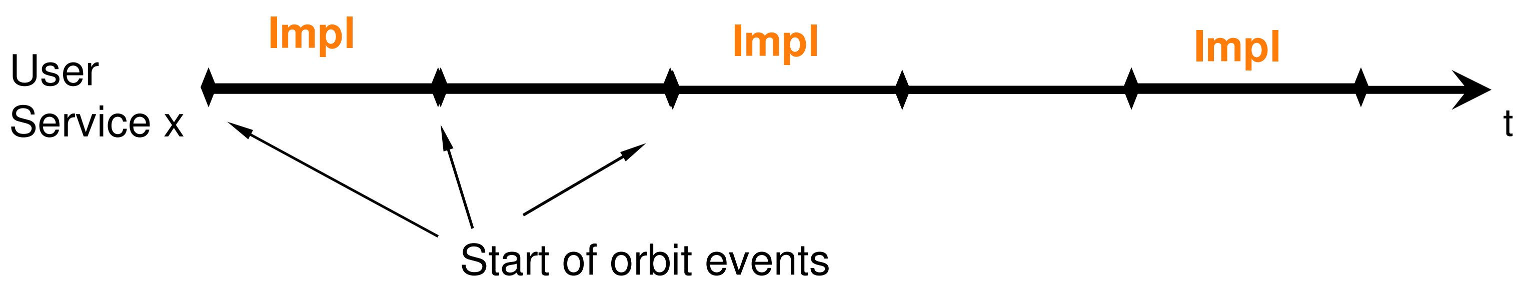
- Ground Station: *exclusive single capacity reusable* resource
- Rules to create all opportunities for all User Services taking into account all Ground Stations
- Other constraints can be specified (temporal filtering)
- Language for Mission Planning
- Service Opportunity Windows (SOWs)




```
(    fact(spacecraft_visibility, ?tvS, ?tvE, ?station, SPACECRAFT X)
  ^ fact(operator_shift, ?toS, ?toE, SPACECRAFT X)
  ^ ?toS < ?tvS - 10
  ^ ?t0E > ?tvE + 10
  -> sow(?station, ,operational_service_group_name, ?tvS, ?tvE)
)
```

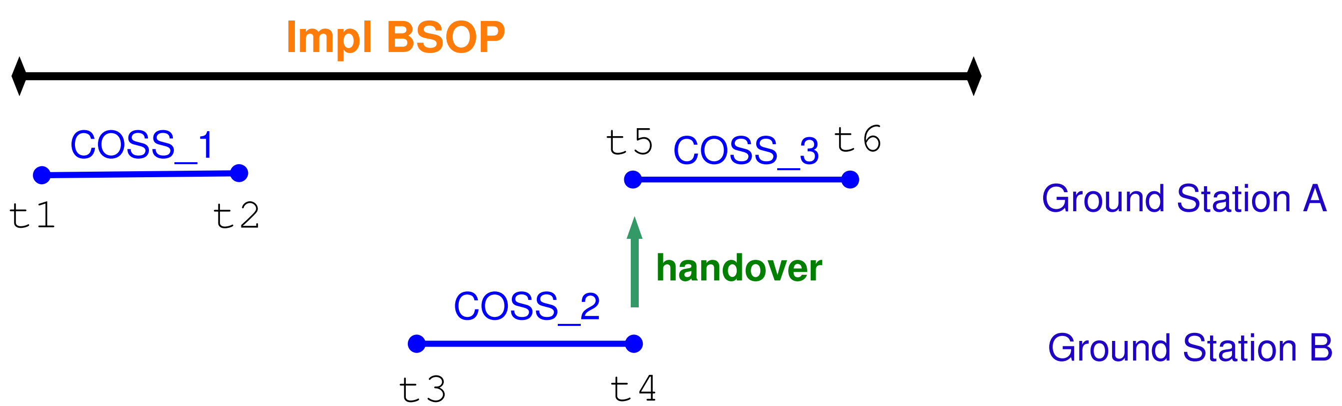
Planning problem generation
Goals

- Extending goals:
  - For each Mission Agreement
  - For each User Service
  - Generate all periods during which the User Service shall be implemented
- BSOP (Basic Standing Order Period)
- E.g. every second orbit
  - BSOP length: one orbit
  - BSOP Selector: 2



Planning problem generation
Activities

- Inside each BSOP to be planned, a pattern of activities must be implemented
- Each activity represents the use one of one Ground Station by one Spacecraft during one time interval
- Start and end times
  - are variables during the planning run
  - are fixed in the ESTRACK Management Plan
- Candidate Operational Service Sessions (COSSes)



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Planning problem generation
Domain

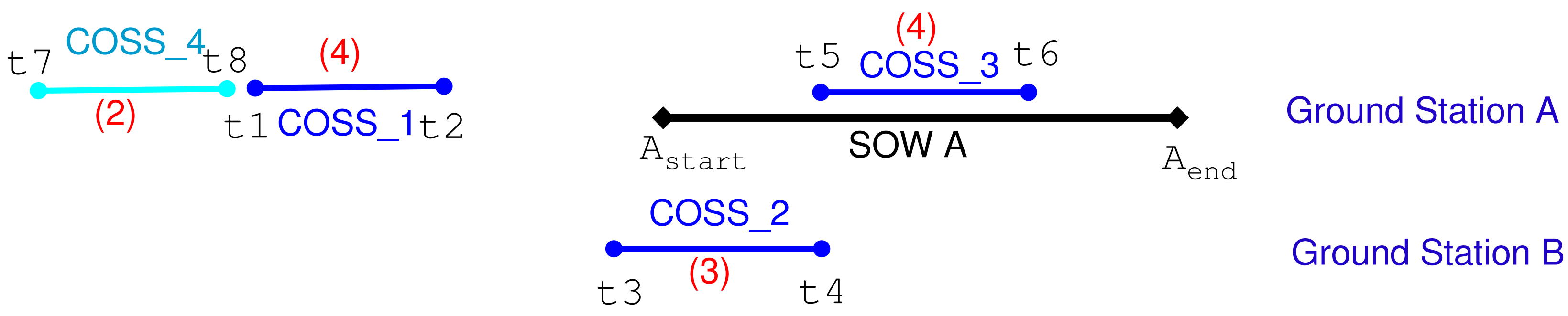
- Constraints attached to User Services: Rules defining the characteristics of the planning problem
  - E.g. minimum and maximum contact distance
    minimum and maximum contact duration

$$dist_{\min} \le t_3 - t_2 \le dist_{\max}$$
$$dur_{\min} \le (t_2 - t_1) + (t_4 - t_3) + (t_5 - t_6) \le dur_{\max}$$

- Implicit constraints of the domain
  - Availability constraints (each COSS inside one unique SOW)
  - Resource constraints (each GS used by one SC at a time)

$$A_{start} \le t_5 \le A_{end}$$
$$t_1 \ge t_8 \lor t_7 \ge t_2$$

- Priorities



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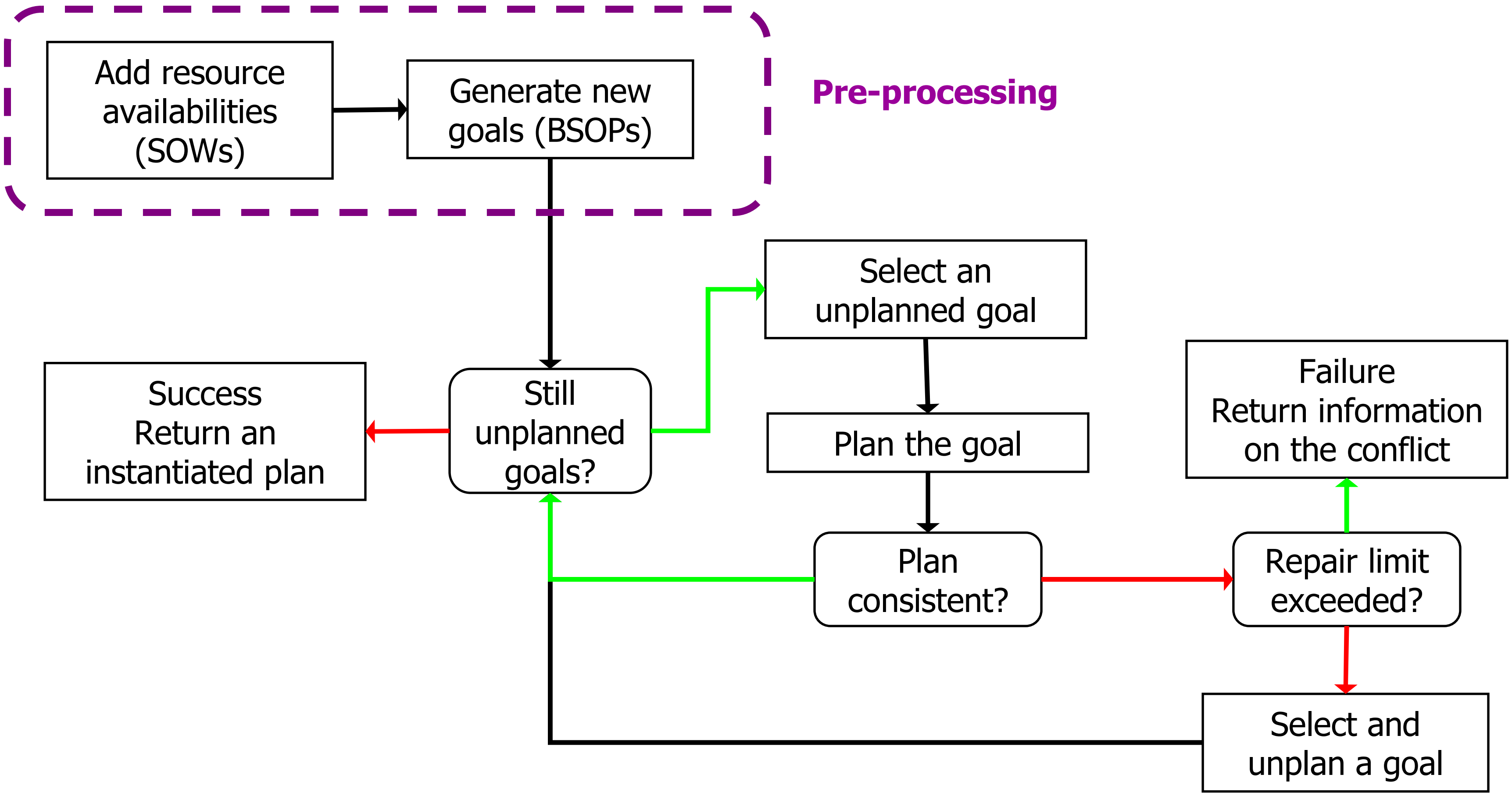
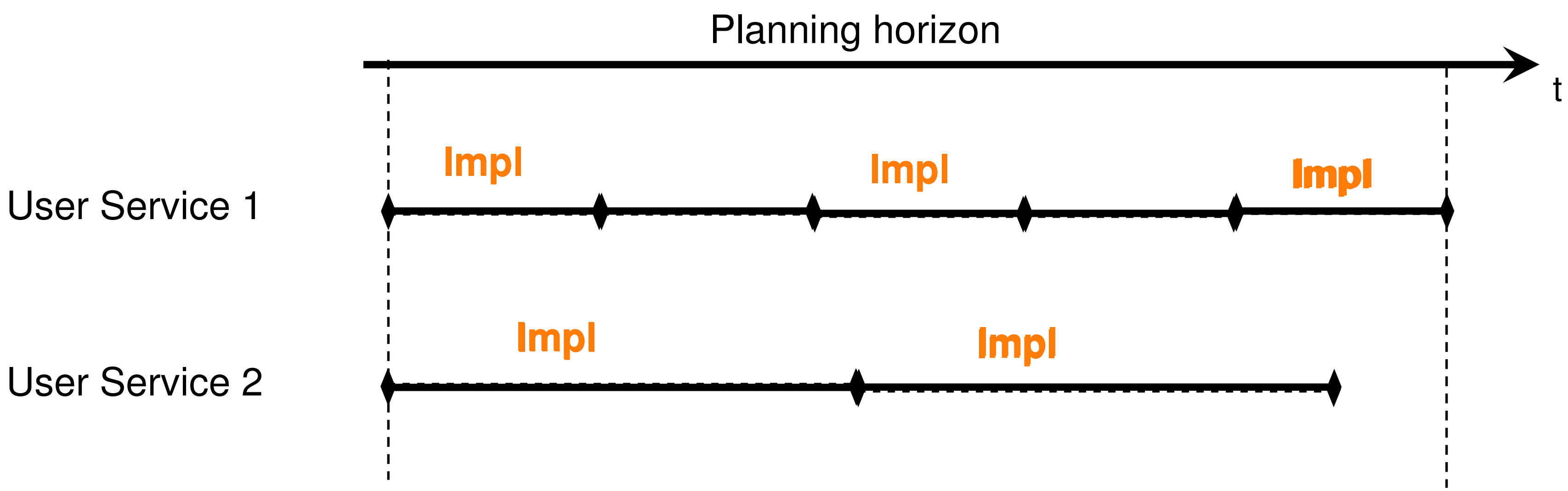
Planning Algorithms
Overview



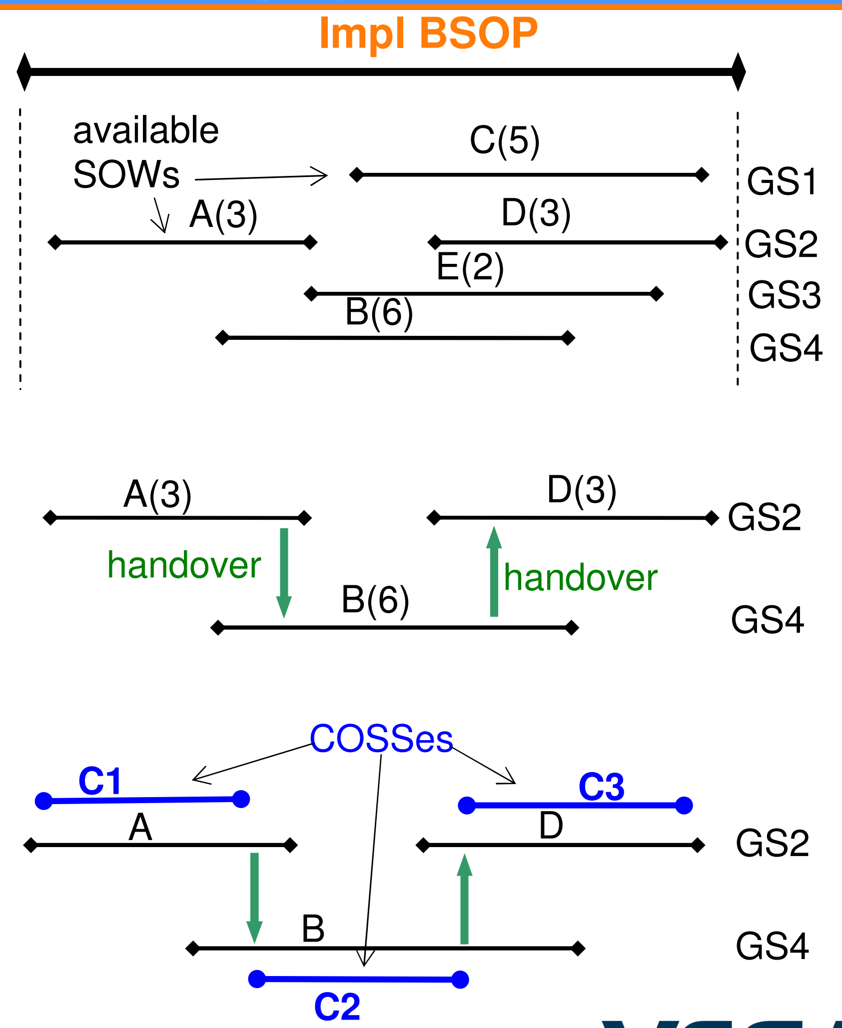
Planning Algorithms
Unplanned goal selection

- Try to minimise repairs
- Earliest deadline first ordering
- Plan is incrementally filled from the start to the end of the planning session



Planning Algorithms
Planning a goal – Contact activity generation

- Given one BSOP to implement and the set of available SOWs
- Select the SOWs to use and determine the handovers
  - Optimisation algorithm: maximise the overall contact time weighted by the preferences of the GS
  - Parameterised to obtain desired patterns
- Generate the COSSs and the temporal constraints



Planning Algorithms
Consistency check

- Check the consistency of the temporal constraint network
- Constraints
  - Simple binary constraints
  - Linear constraints
  - Disjunctions of binary constraints (partial orderings to avoid unary resource contentions)
- Generally speaking: Disjunctive Linear Problem [Li and Williams 2005]
  Mixed Integer Programming
- But relatively few linear constraints, not in disjunctions
- ➡ Solve of a Disjunctive Temporal Problem (DTP) [Stergiou and Boubarakis 1998]
- ➡ Check the linear constraints at each solution of the DTP

Planning Algorithms
DTP solving algorithm description

- Based on Epilitis [Tsamardinos and Pollack 2003]
  - Meta Variable: disjunction of binary constraints
  - Meta Domain: set of disjuncts
  - Meta Constraint: implicit (partial assignment valid iff underlying STP is consistent)
  - Conflict directed backtracking tree search with forward checking
  - Recursive algorithm which records conflict information (no-good: pair invalid partial assignment / involved variables)
- Dynamic meta-CSP
  - Adding activities: tightening Removing activities: relaxation
  - No-goods reuse
  - Oracles

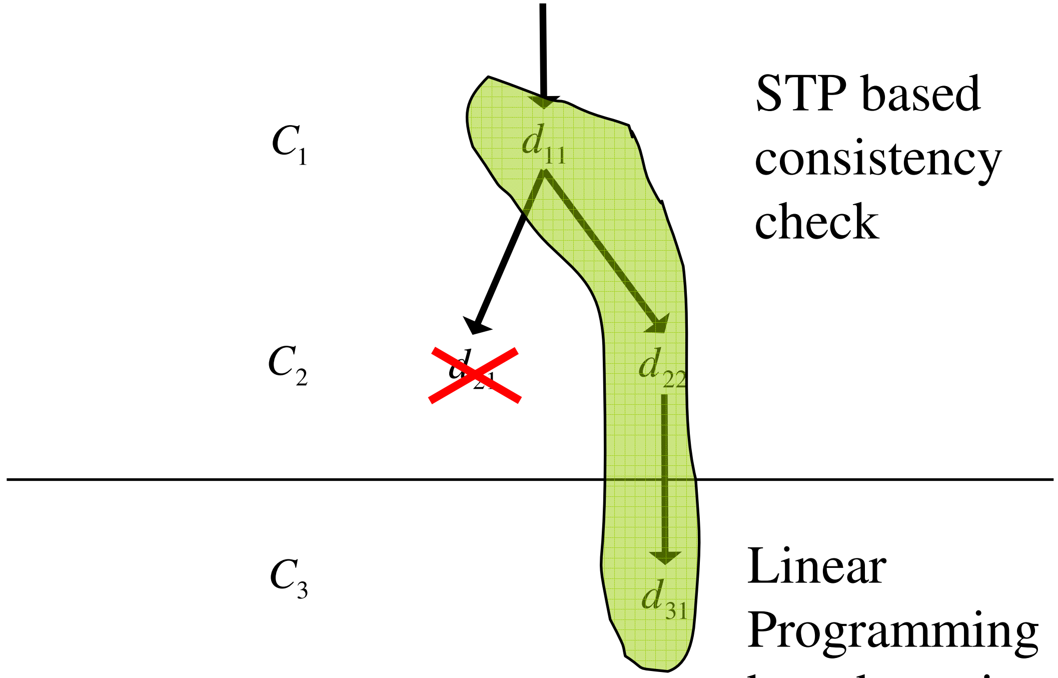
Planning Algorithms
Example: search tree

Meta-CSP generation

$$C_1 := t_1 - t_2 \le T_1$$
$$C_2 := t_8 - t_1 \le T_2 \vee t_2 - t_7 \le T_2$$
$$C_3 := \sum_i \alpha_i t_i \le T_3$$

$$C_1 := d_{11}$$
$$C_2 := d_{21} \vee d_{22}$$
$$C_3 := d_{31}$$

Search tree



STP based consistency check

Linear Programming based consistency check

No-good example

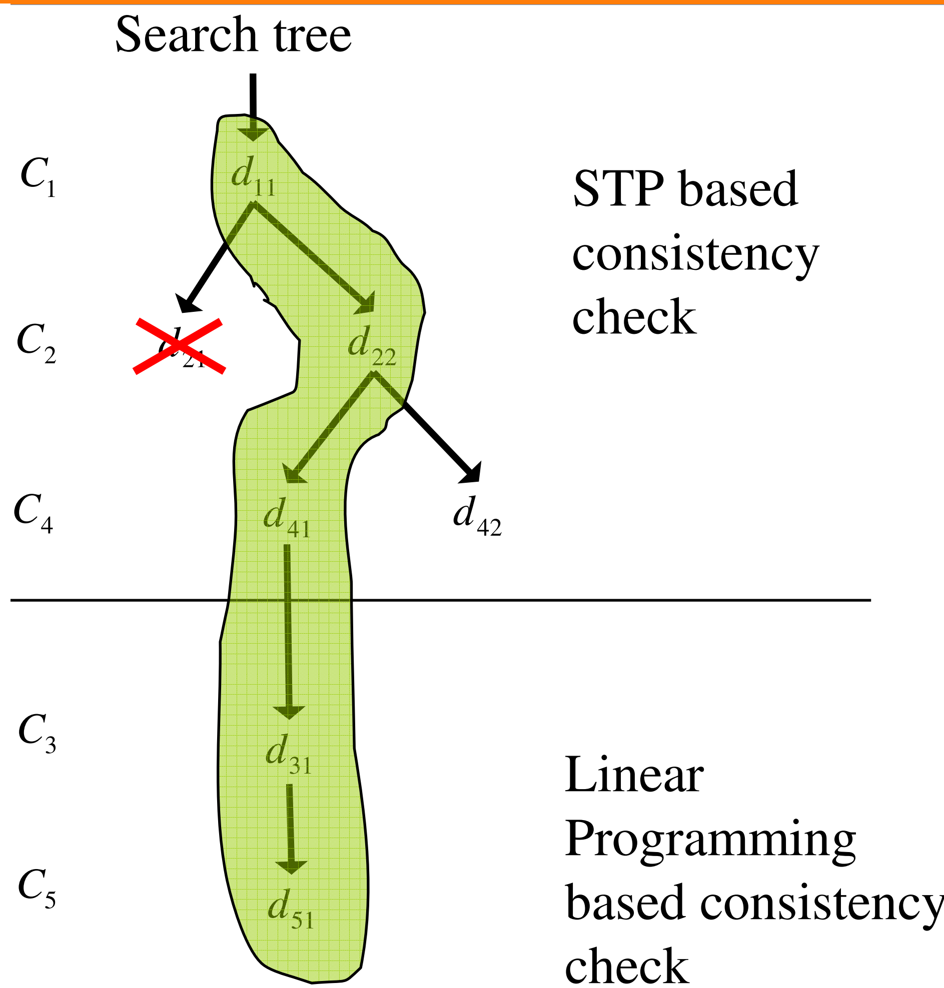
$$< \{C_1 \leftarrow d_{11}, C_2 \leftarrow d_{21}\}; \{C_1, C_2\} >$$

Planning Algorithms
Example: addition of constraints

- Planning of the next goal => generation of 2 new constraints
- Keep the path to the previous solution
- Keep the no-goods computed before

No-good example

$$<\{C_1 \leftarrow d_{11}, C_2 \leftarrow d_{21}\};\{C_1, C_2\}>$$



Planning Algorithms
Repair

- Conflict detection and selection: use the no-goods returned by Epilitis (associated to the empty assignment of the DTP)
- Activity selection: heuristics, e.g. delete the one with the lowest priority
- Modification of the associated BSOP (generate new pattern of activities)
- New consistency check
- If no solution found after a given number of repairs, report to the operator with incriminated BSOPs

$$< \phi; \{C_1, C_3\} >$$

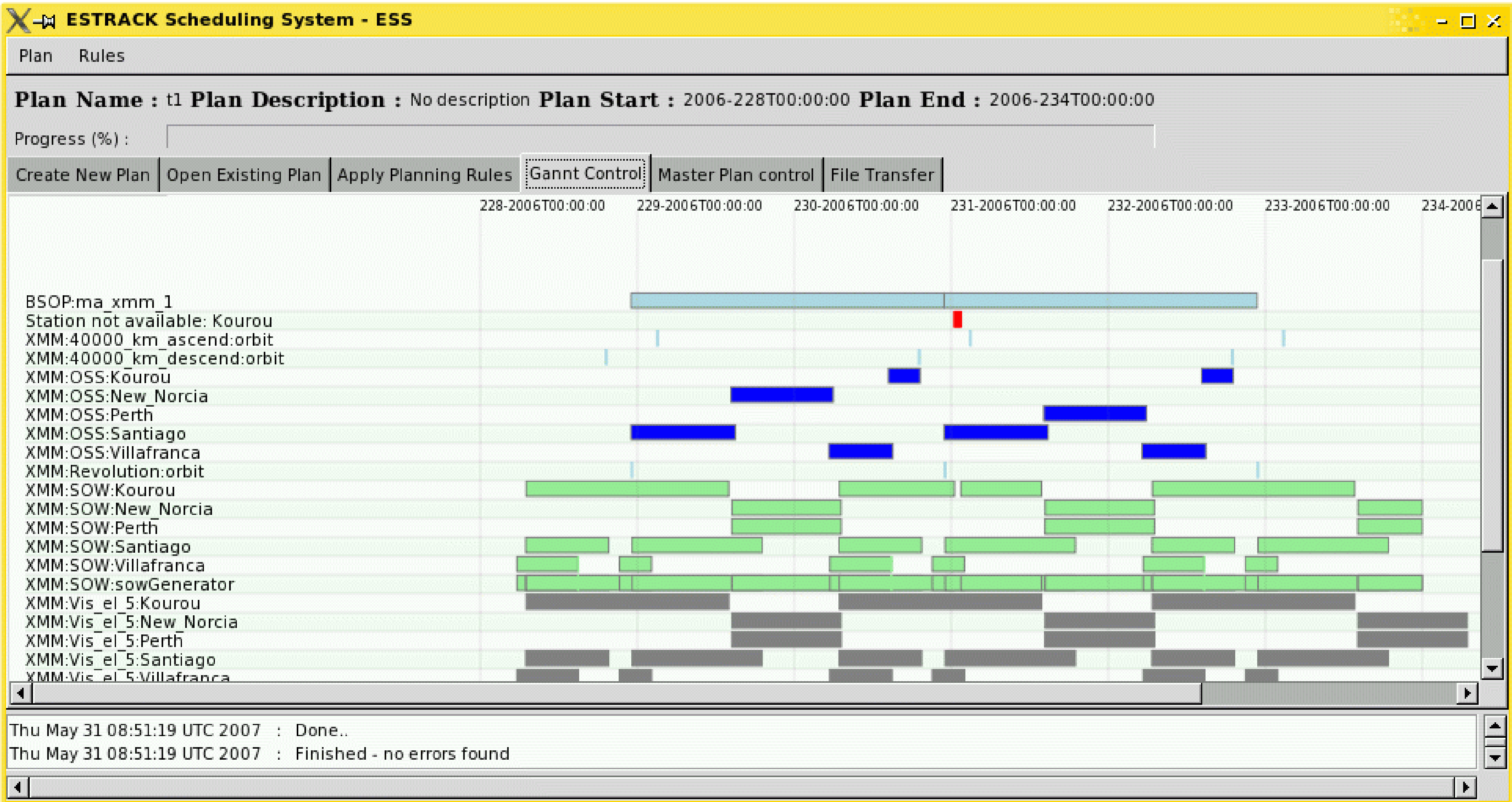
$$\{C_1, C_3\}$$

~~COSS_1 (3)~~

COSS_3 (2)

BSOP_2

Implementation results



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Implementation results
Computation time

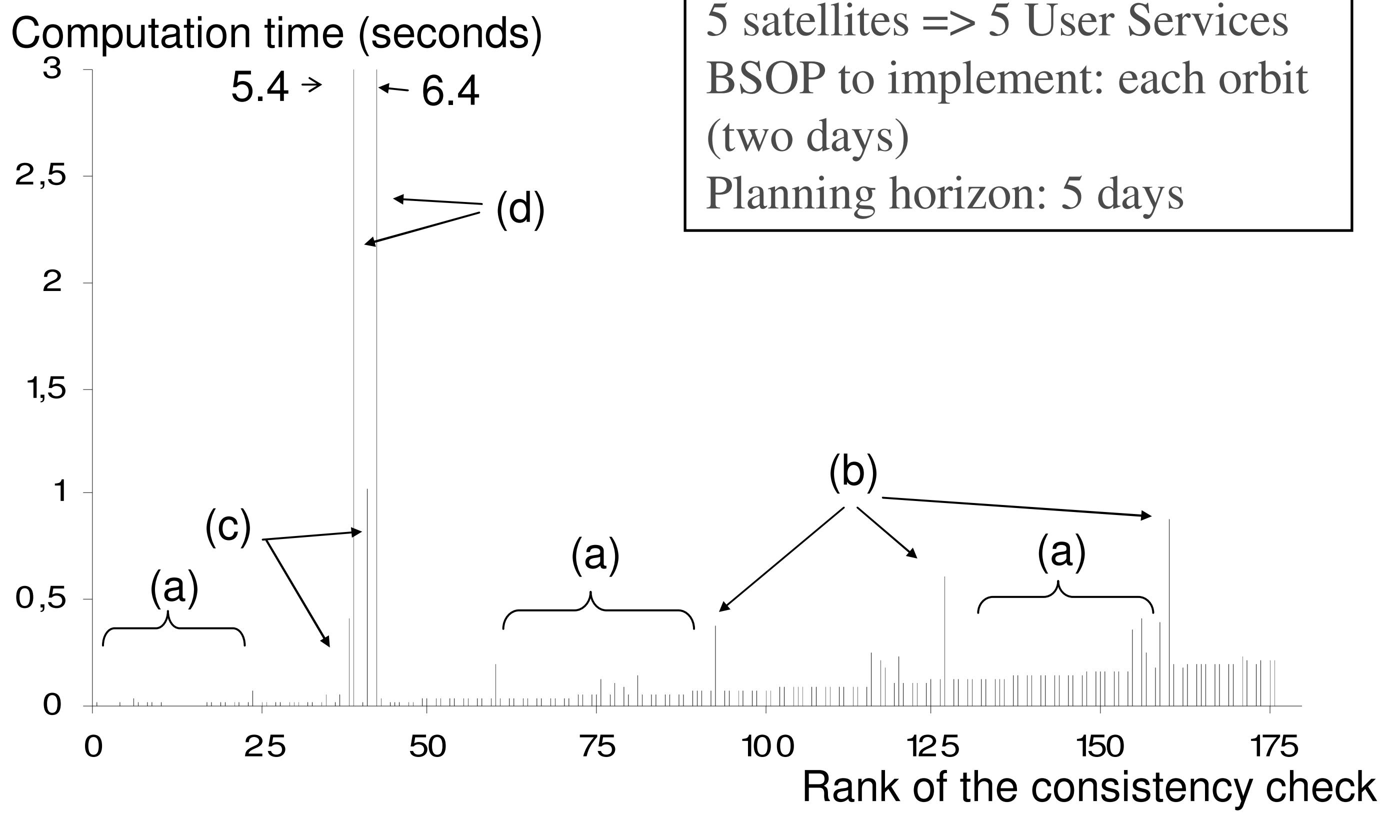
Total duration
94 seconds

219 activities

1533 binary constraints

25 disjunctive constraints

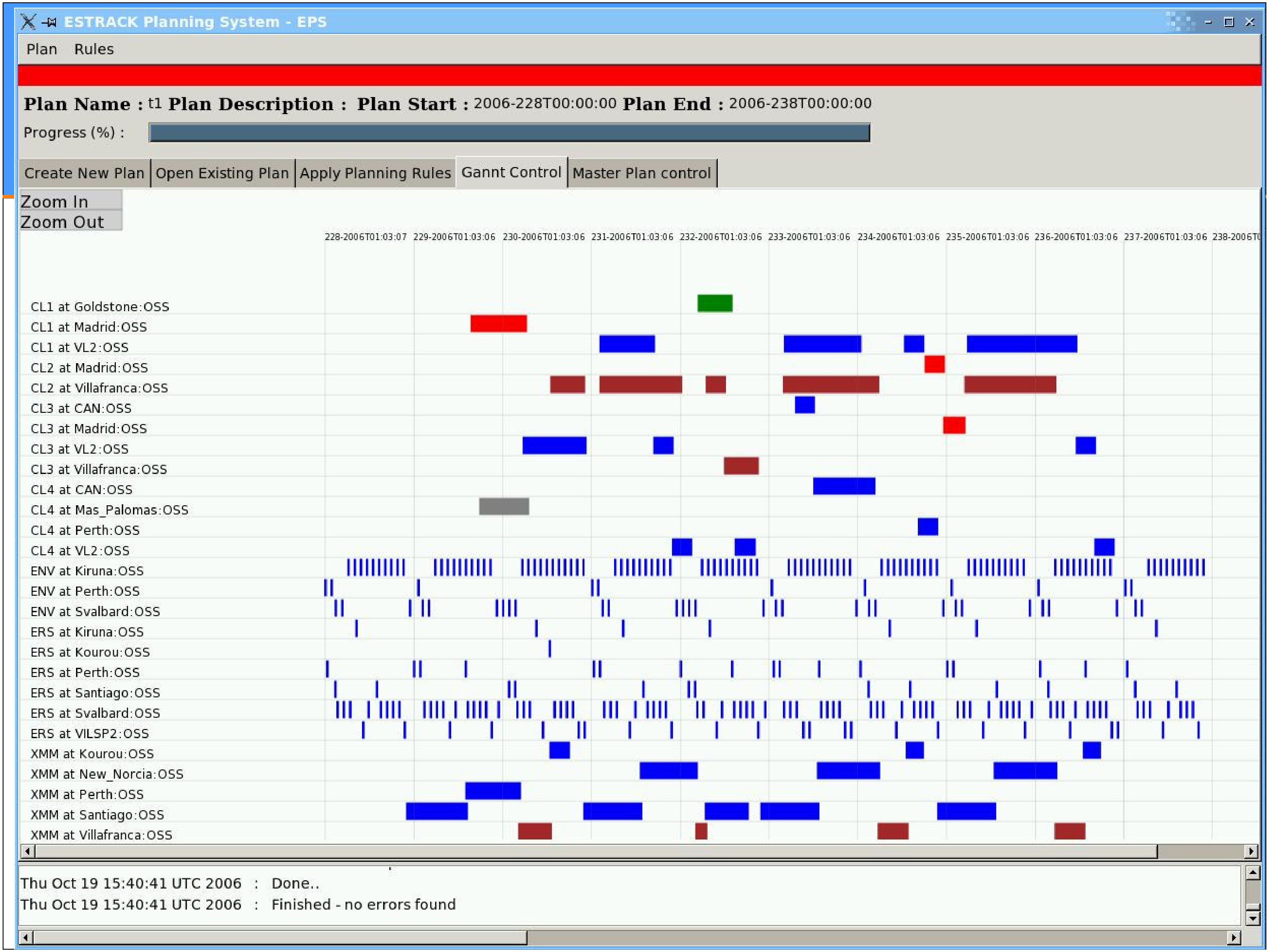
2 repairs



Input
5 satellites => 5 User Services
BSOP to implement: each orbit (two days)
Planning horizon: 5 days

Implementation results
Visualisation

- Input
  - 7 satellites (2 LEOs / 5 HEOs) => 7 User Services
  - BSOP to implement: each orbit (100 minutes / 2 days)
  - Planning horizon: 10 days
- Complexity
  - 325 activities
  - 18 disjunctive constraints
  - 2830 Simple Temporal Constraints
- Results
  - Planning duration: 804 seconds
  - Number of repairs: 23


ESTRACK Planning System - EPS
Plan
Rules
Plan Name : t1 Plan Description : Plan Start : 2006-228T00:00:00 Plan End : 2006-238T00:00:00
Progress (%) :
Create New Plan
Open Existing Plan
Apply Planning Rules
Gannt Control
Master Plan control
Zoom In
Zoom Out
228-2006T01:03:07
229-2006T01:03:06
230-2006T01:03:06
231-2006T01:03:06
232-2006T01:03:06
233-2006T01:03:06
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CL1 at Goldstone:OSS
CL1 at Madrid:OSS
CL1 at VL2:OSS
CL2 at Madrid:OSS
CL2 at Villafranca:OSS
CL3 at CAN:OSS
CL3 at Madrid:OSS
CL3 at VL2:OSS
CL3 at Villafranca:OSS
CL4 at CAN:OSS
CL4 at Mas_Palomas:OSS
CL4 at Perth:OSS
CL4 at VL2:OSS
ENV at Kiruna:OSS
ENV at Perth:OSS
ENV at Svalbard:OSS
ERS at Kiruna:OSS
ERS at Kourou:OSS
ERS at Perth:OSS
ERS at Santiago:OSS
ERS at Svalbard:OSS
ERS at VILSP2:OSS
XMM at Kourou:OSS
XMM at New_Norcia:OSS
XMM at Perth:OSS
XMM at Santiago:OSS
XMM at Villafranca:OSS
Thu Oct 19 15:40:41 UTC 2006 : Done..
Thu Oct 19 15:40:41 UTC 2006 : Finished - no errors found

Extensions

- Technical improvements
  - Guide the generation of the patterns of activities for one BSOP
  - Heuristics for conflict detection and selection
  - Repair algorithm
  - Dynamic meta-CSP resolution techniques (relaxation)
  - Adaptation of the plan following changes in events (flexibility)
- Implement further requirements
  - Granularity of the resources: from the ground stations to the services => discrete resources
  - Improve interaction of the operator with the plan view

Comparison APS (Science) / EPS (Ground stations)
Similarities

- Same plan representation (EKLOPS based)
- Systems used in an iterative way by the operators
- Abstraction of the goals and the resources as much as possible in order to lower the complexity of the problem
  - Ex: in EPS, COSSs actually represent ground station schedules which use different device at different times
- Pre-computation of the availability ranges for the actions
  - TOWs in APS, SOWs in ESS
- MIP planning problems
- Encoding of the constraints in the plan, translation into problems tackled by external solvers

Comparison APS (Science) / EPS (Ground stations)
Differences

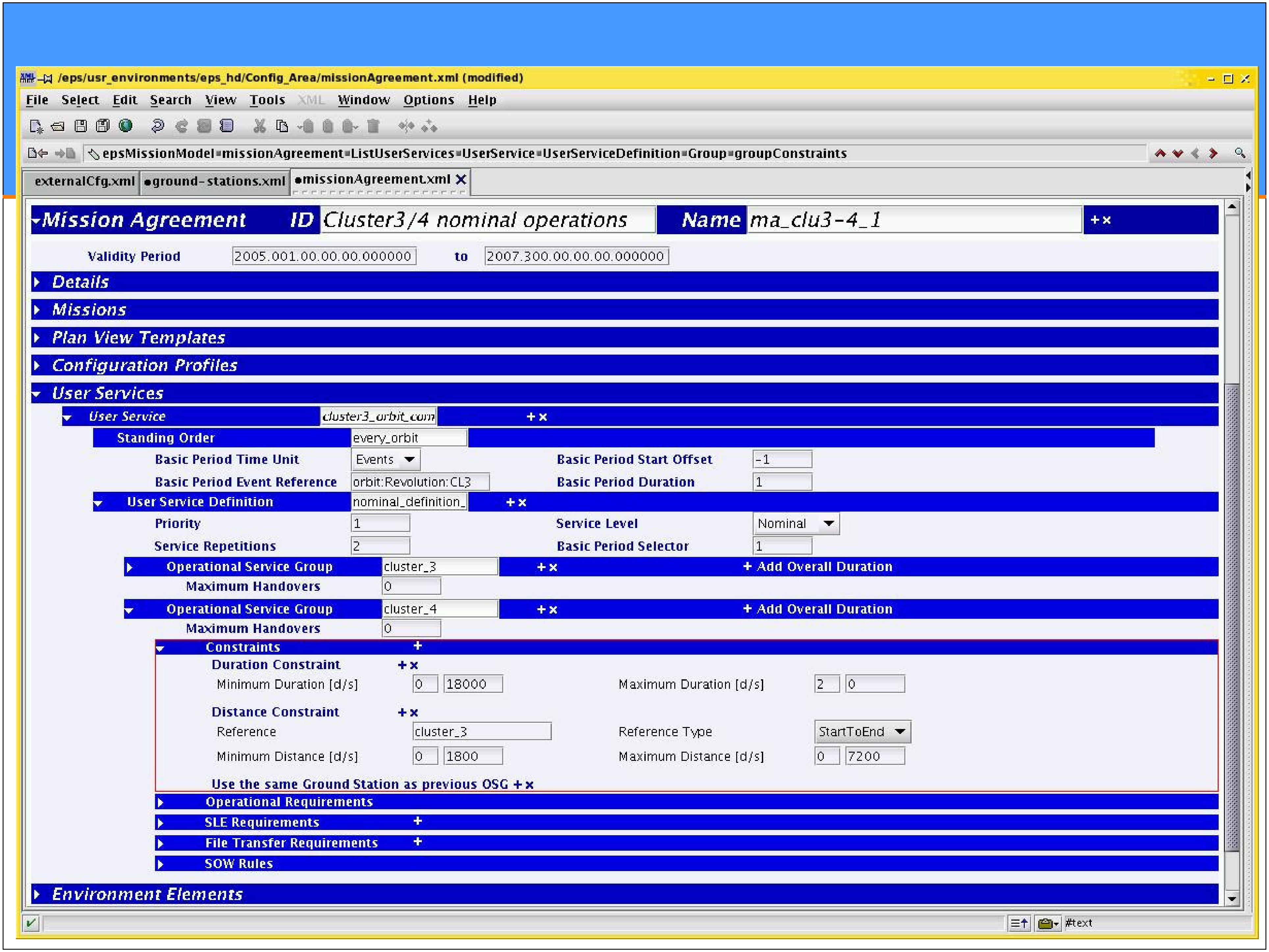
- Objective of the planning
  - APS: optimisation problem
  - EPS: satisfaction problem
- Boundary conditions management
  - APS: influence the return of the plan
  - EPS: constraints created with objects not in the plan range
- Solving approach
  - APS: all at once (global)
  - EPS: iterative solving
- Planning cycle length
  - no automated repair for APS

Space operators and planning systems Difficulties to define the requirements

- Too precise requirements: lack of abstraction (must be provided by the developers)
  - “During some periods, due to the load on the NNO station it may be required to support one of the HP spacecrafts from Cebreros. The selection of the SC supported by Cebreros should be maintained for the full duration of the contention period”
- Inconsistencies in the requirements:
  - “No global optimisation is required”
  - “The planning process shall maximise the coverage by each station and minimise the number of station handover activities in the plan”
- Cost evaluation

Space operators and planning systems Difficulties to use the system

- Abstraction of the languages
  - Ex: ELMP
- Complex configuration databases and configuration GUIs
- Users want to interfere, keep control on what the system does/decides
- Users want to hack the results!
  - Consistency issues
- Greedy for resource request -> need for coordination
  - EPS: degraded modes
  - NASA: multi-criteria optimisation



/eps/usr_environments/eps_hd/Config_Area/missionAgreement.xml (modified)
File Select Edit Search View Tools XML Window Options Help
epsMissionModel▪missionAgreement▪ListUserServices▪UserService▪UserServiceDefinition▪Group▪groupConstraints
externalCfg.xml
●ground-stations.xml
●missionAgreement.xml
Mission Agreement
ID
Cluster3/4 nominal operations
Name
ma_clu3-4_1
Validity Period
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to
2007.300.00.00.00.000000
Details
Missions
Plan View Templates
Configuration Profiles
User Services
User Service
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Standing Order
every_orbit
Basic Period Time Unit
Events
Basic Period Start Offset
-1
Basic Period Event Reference
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Basic Period Duration
1
User Service Definition
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Priority
1
Service Level
Nominal
Service Repetitions
2
Basic Period Selector
1
Operational Service Group
cluster_3
+ Add Overall Duration
Maximum Handovers
0
Operational Service Group
cluster_4
+ Add Overall Duration
Maximum Handovers
0
Constraints
Duration Constraint
Minimum Duration [d/s]
0
18000
Maximum Duration [d/s]
2
0
Distance Constraint
Reference
cluster_3
Reference Type
StartToEnd
Minimum Distance [d/s]
0
1800
Maximum Distance [d/s]
0
7200
Use the same Ground Station as previous OSG
Operational Requirements
SLE Requirements
File Transfer Requirements
SOW Rules
Environment Elements
#text