Optimization and control theory applications in space missions

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Aerospace Engineering at University of Seville

- Aerospace Engineering started in 2002, in the Univ. Of Seville School of Engineering (strong tradition in Mechanical, Electrical and Chemical Engineering since the 60s)
- Teaches Undergraduate Degree, Master's Degree and also PhD
- Mainly focused in aeronautics (a traditional industry in Seville) but there are courses in Orbital Mechanics, Spacecraft Dynamics and Spacecraft Propulsion
- The Department of Aerospace Engineering was created in 2006
- Some lines of research related to space have emerged, in collaboration with other departments

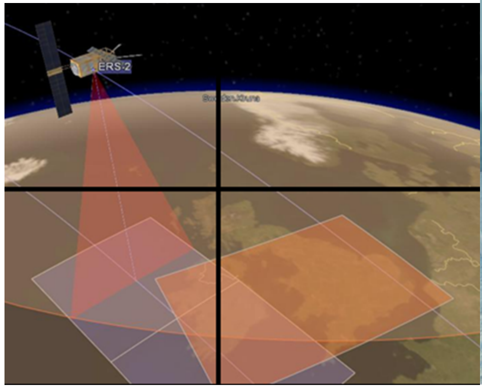
Past and Ongoing Projects

- Three main areas:
  - Planning and scheduling for space missions (R. Vazquez, J. Galan, JM Melendez and others). Problems related to optimization. Collaboration between engineers, mathematicians and industry (Taitus software).
  - Rendezvous and formation flying of space vehicles (R. Vazquez, E.F. Camacho, F. Gavilan, J. Sanchez, JM Montilla and others). Analysis and control of relative position and velocity for close spacecraft. Applications of control theory. Collaboration between aerospace engineers and control engineers.
  - Inertia-free and adaptive attitude control laws (S. Esteban, M. Camblor in collaboration with U. Michigan). Analysis and synthesis of automatic attitude control laws that do not require knowledge of spacecraft mass distribution.
- All these lines have already produced journal and conference papers.

Past and Ongoing projects

- Besides these, other seminal lines yet to produce publications:
  - Application of statistical tools to study uncertainty in orbital mechanics problems, such as orbit decay (R. Vazquez, FJ Camacho)
  - Analysis of groundtrak self-intersections for geocentric satellites(R. Vazquez, E. Teson, J. Galan)
  - Applications of the three-body problem dynamics to mission design (J. Galan, R.Vazquez)

Optimization in Space



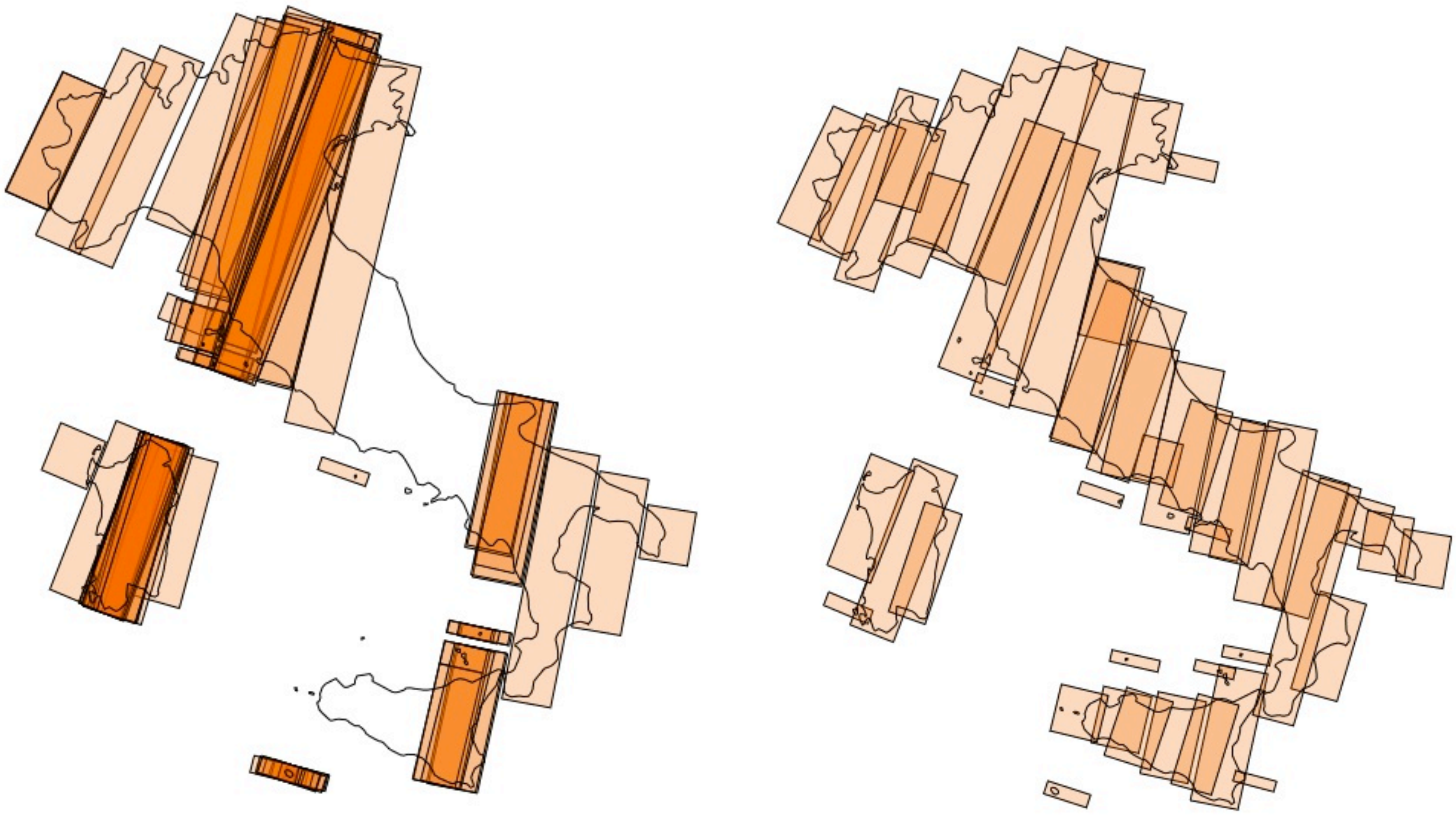
- Project 1: Design and integration of a real time optimal planner for swath acquisitions for multiple EOS satellites.

  Swath acquisition planning in multiple-mission EOSs: exact and heuristic approaches. IEEE Trans. Aerospace Elec. Systems (51) 1717-1725. 2015.

- Project 2: Minimize the number of cancellations of satellite-antenna requests due to conflicts in real time.

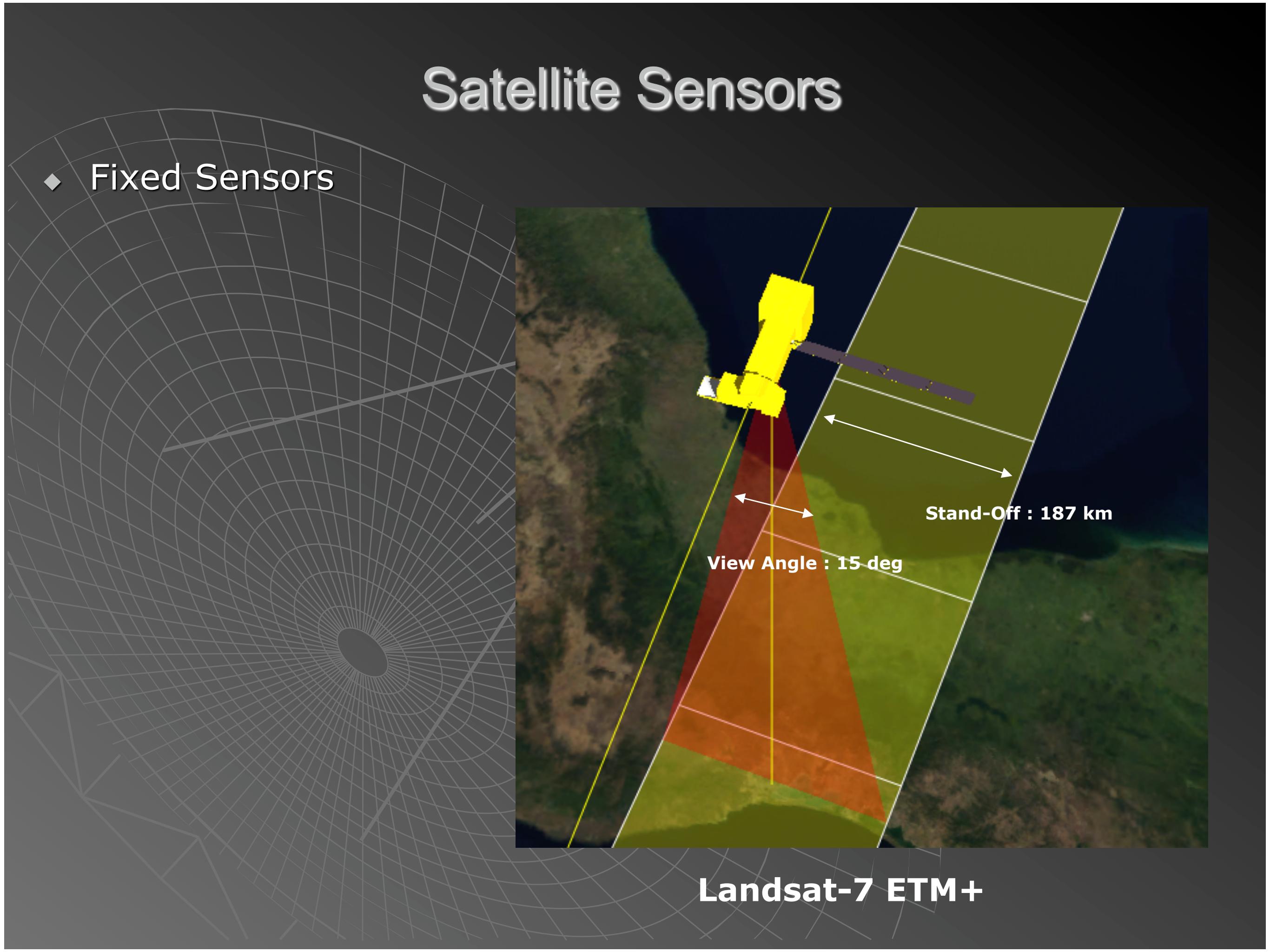
  Resolution of an Antenna-Satellite assignment problem by means of Integer Linear Programming. Aerospace Science and Technology (39) 567-574, 2014

Project 1: swath acquisitions to cover an area



How do we select the images?
How close is a feasible solution to the optimal one?

Mathematical Modeling I:



Mathematical Modeling I:

Let $\mathcal{R}$ be a region, n acquisitions a_i of cost c_i.
Solve the Integer Linear Programming (ILP) problem where x_i is 1 if the acquisition a_i is used and 0 if not used.

$$min \quad \sum_{i=1}^{n} c_i x_i \quad cost \quad function$$

$$\text{s.t.} \quad \bigcup_{i:x_i=1} a_i \supset \mathcal{R} \quad geometrical \quad condition$$

$$x_i \in \{0,1\}, \quad \forall\, i = 1, 2, \ldots, n.$$

Note that the problem may be infeasible.

Translating geometry into equations

Find all the intersection between the acquisitions in $\mathcal{R}$. Let us define an $m \times n$ swath-subregion matrix Q whose entry q_{ij} takes the value 1 if subregion SR_j is covered by acquisition a_i, and 0 otherwise.
The ILP is now:

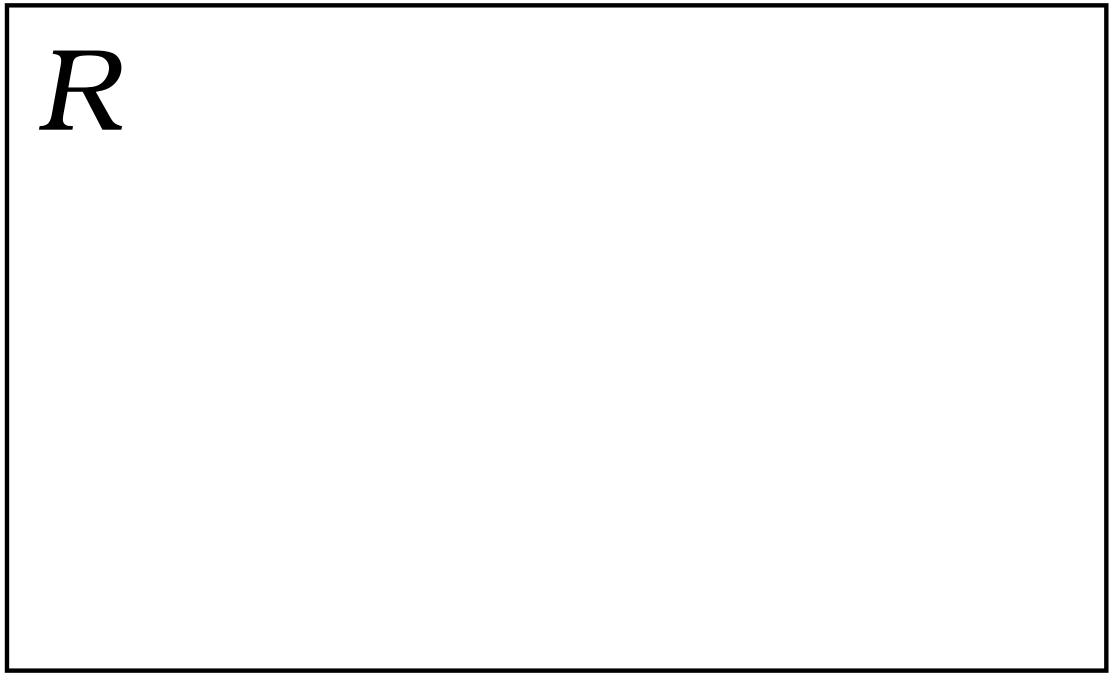
$$min \quad \sum_{i=1}^{n} c_i x_i$$

$$\text{s.t.} \quad \sum_{i=1}^{n} x_i q_{ij} \geq 1, \quad \forall\, j = 1, ..., m$$

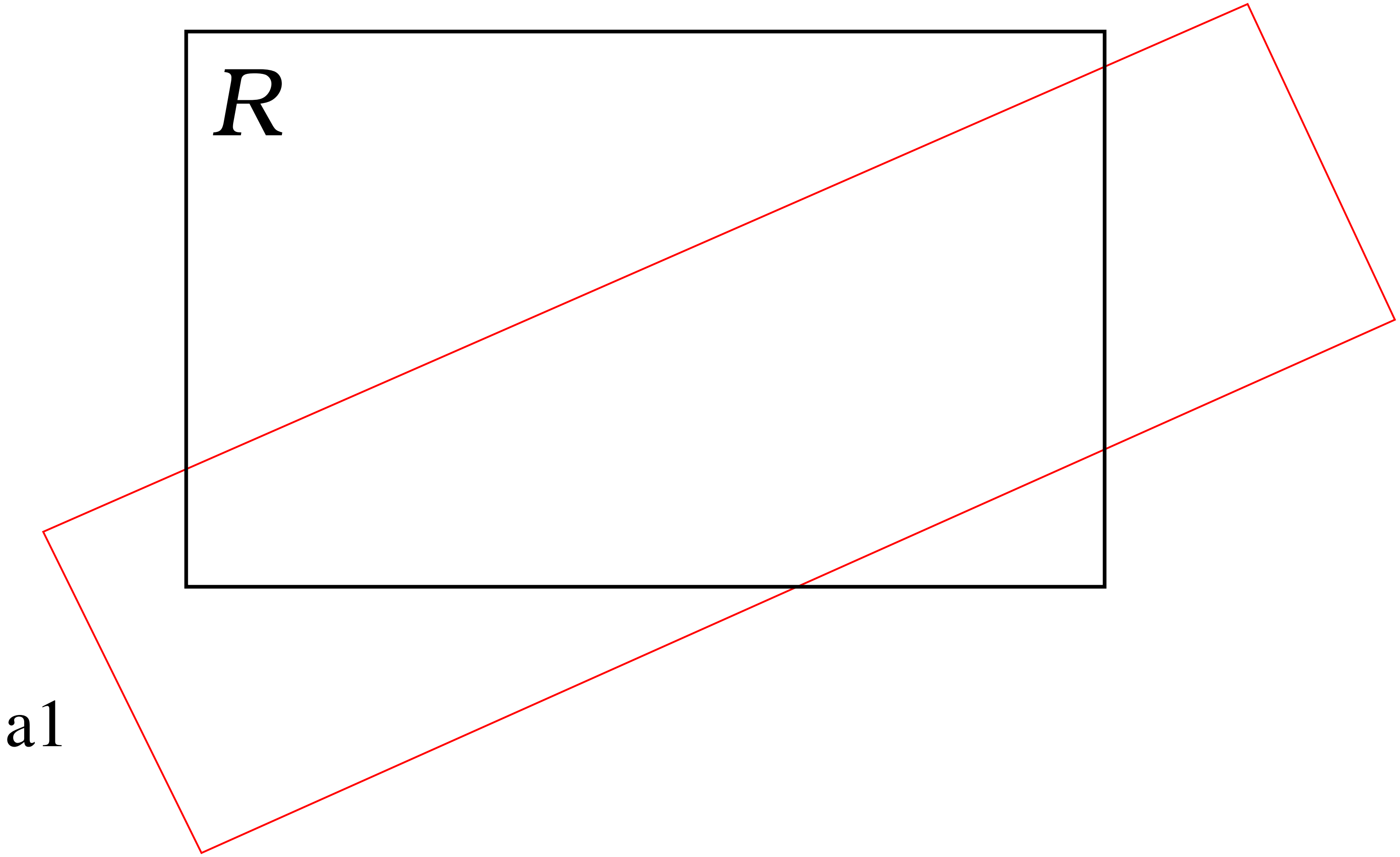
$$x_i \in \{0, 1\}, \quad \forall\, i = 1, 2, \ldots, n,$$

The solution is the optimal covering of region $\mathcal{R}$.

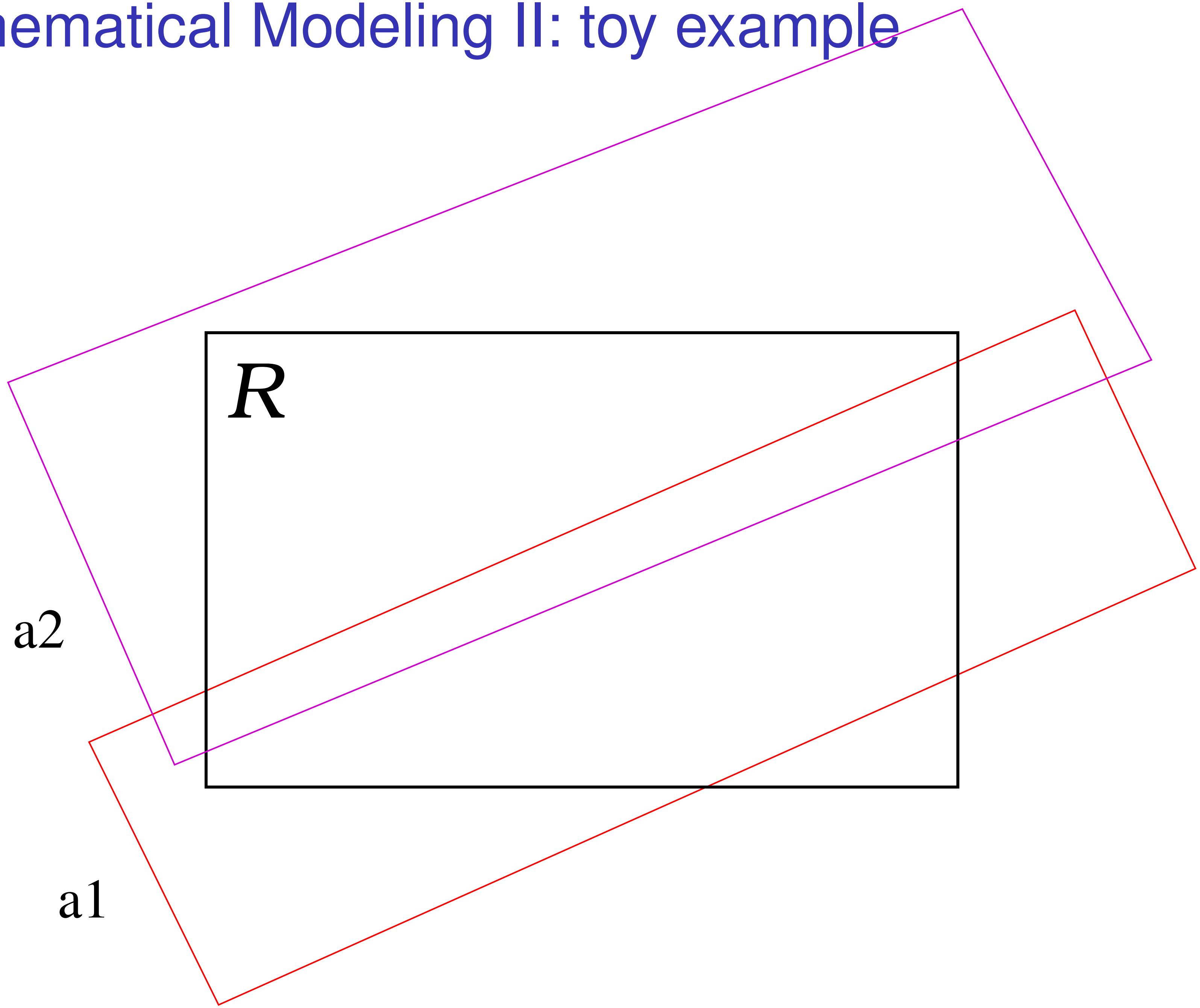
Mathematical Modeling II: toy example



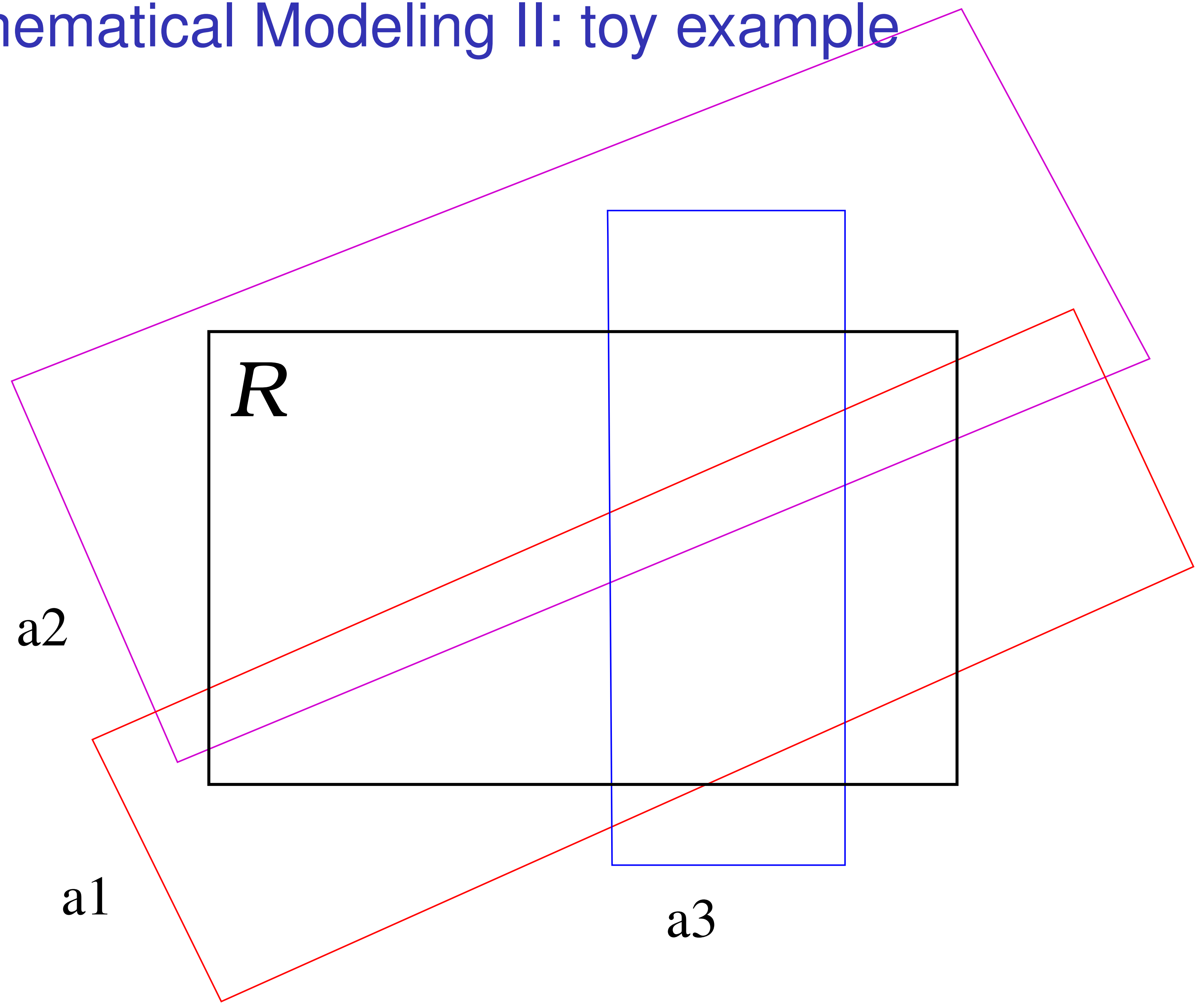
Mathematical Modeling II: toy example



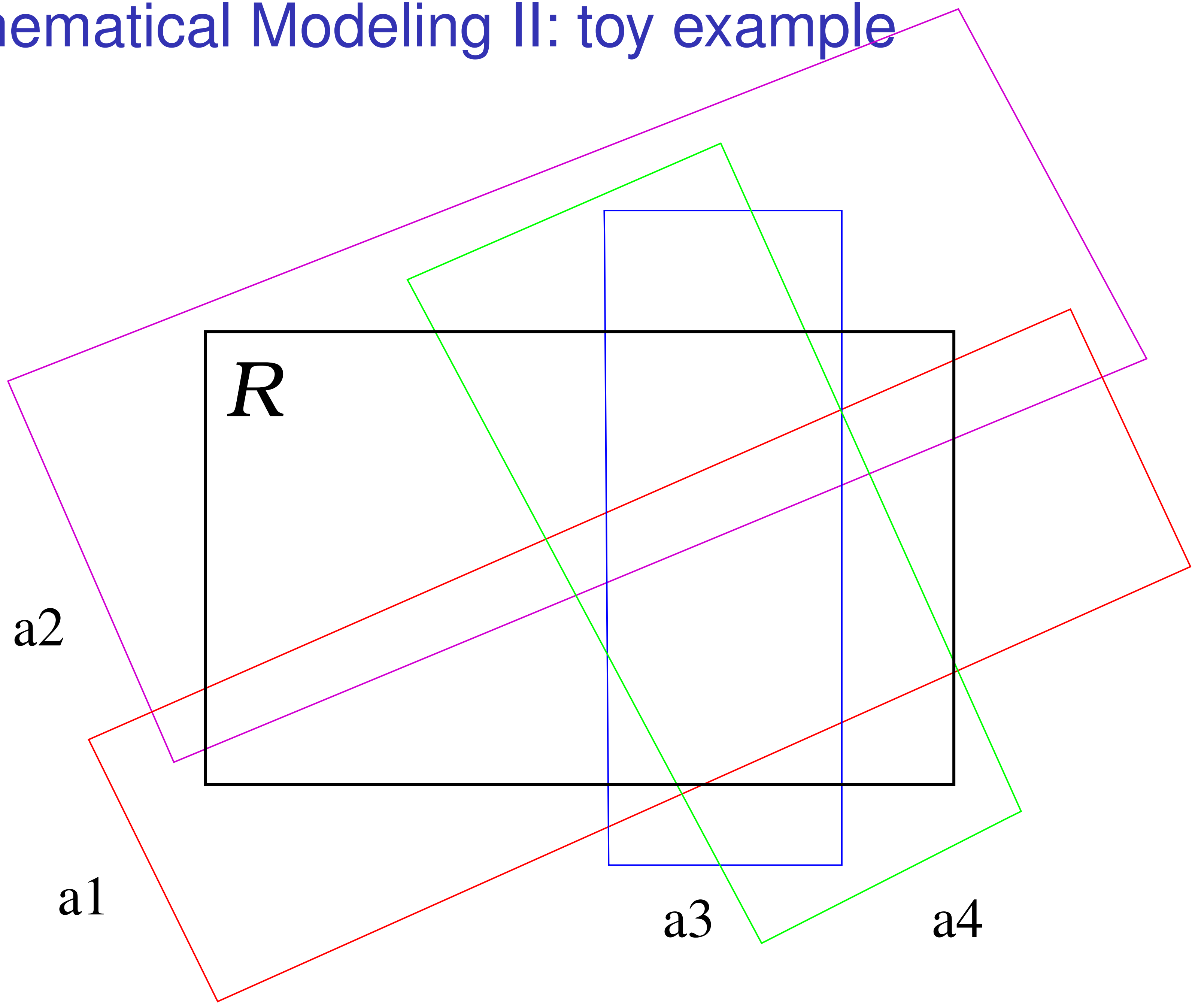
Mathematical Modeling II: toy example



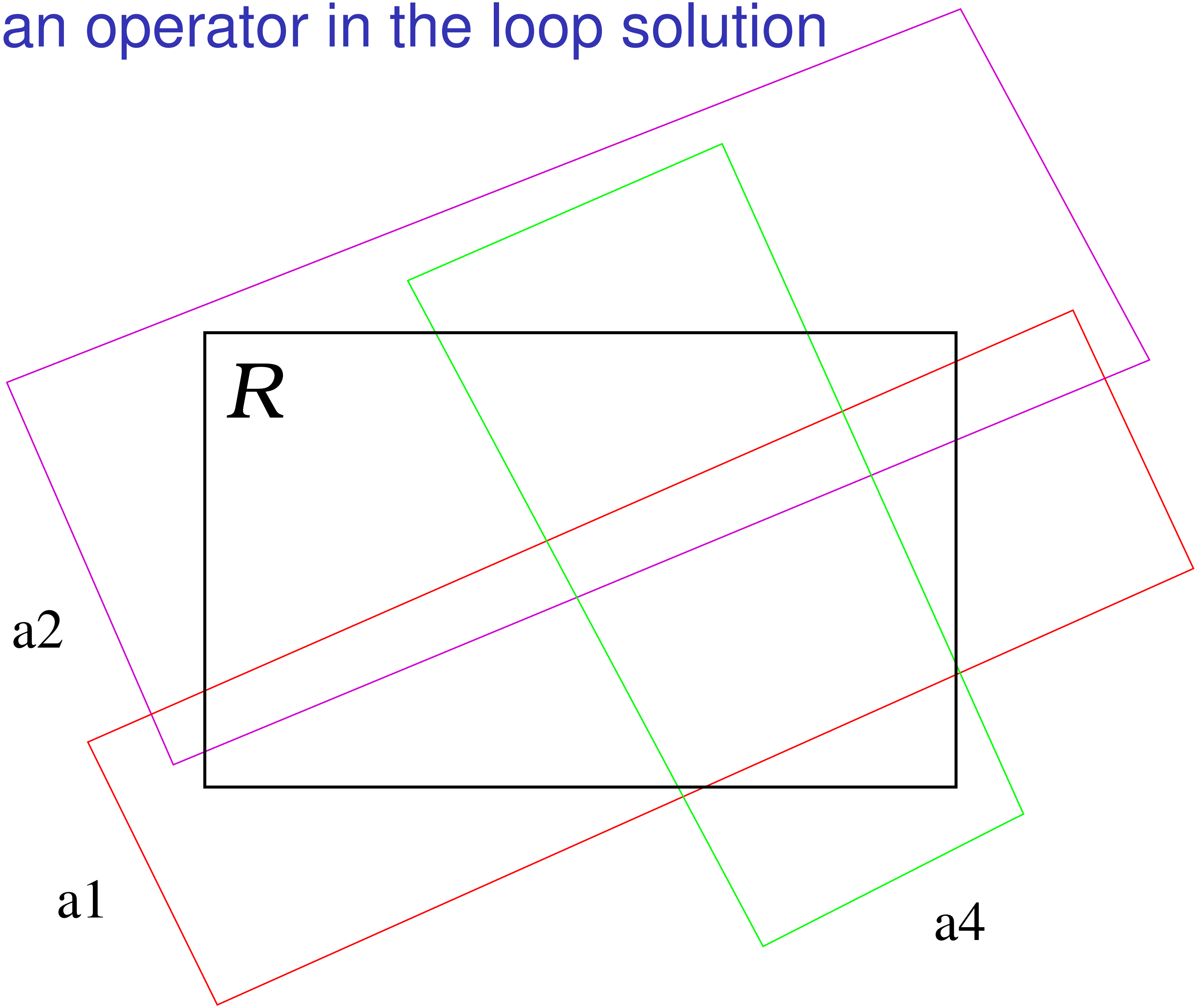
Mathematical Modeling II: toy example



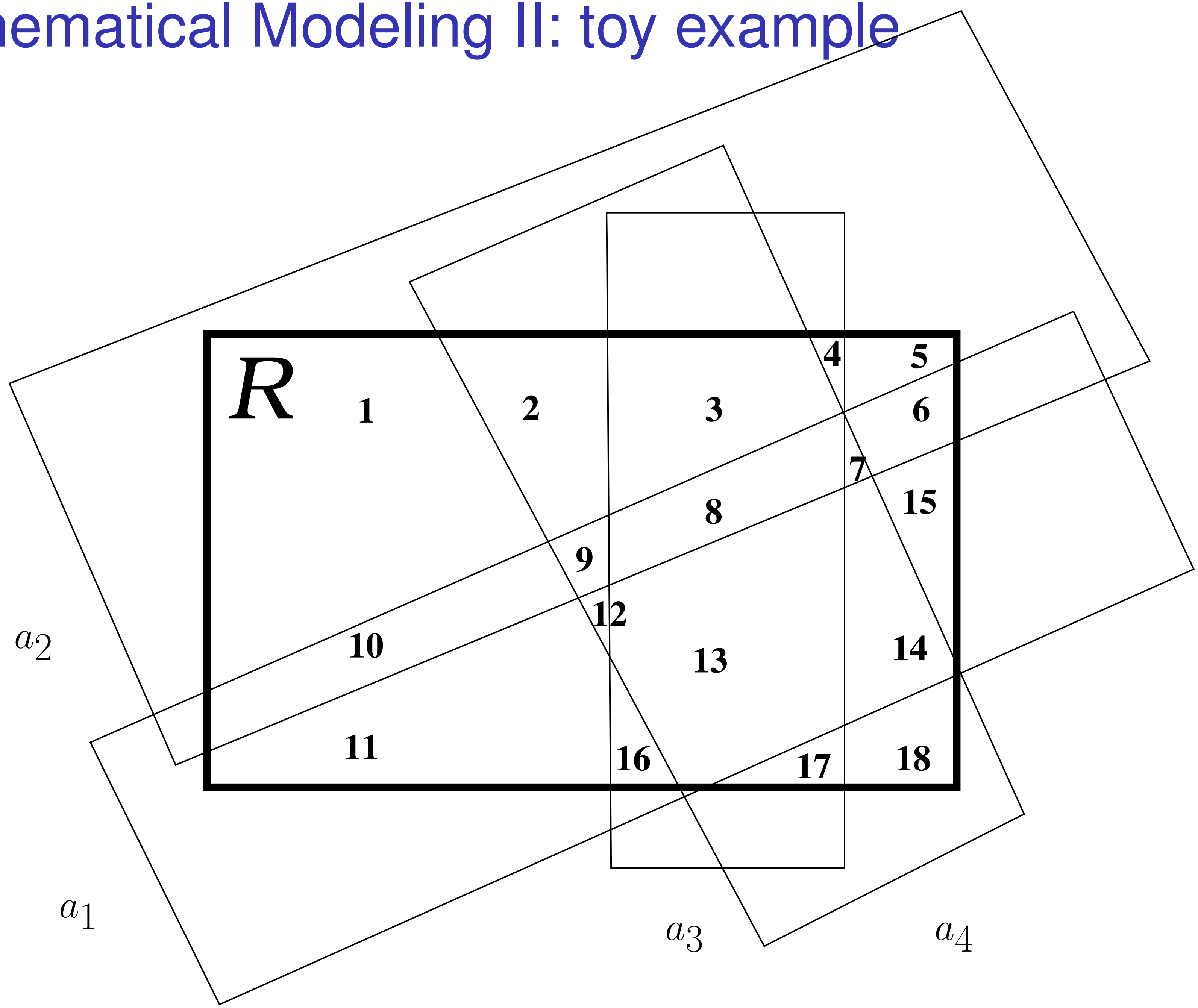
Mathematical Modeling II: toy example



Human operator in the loop solution



Mathematical Modeling II: toy example



$$Q = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

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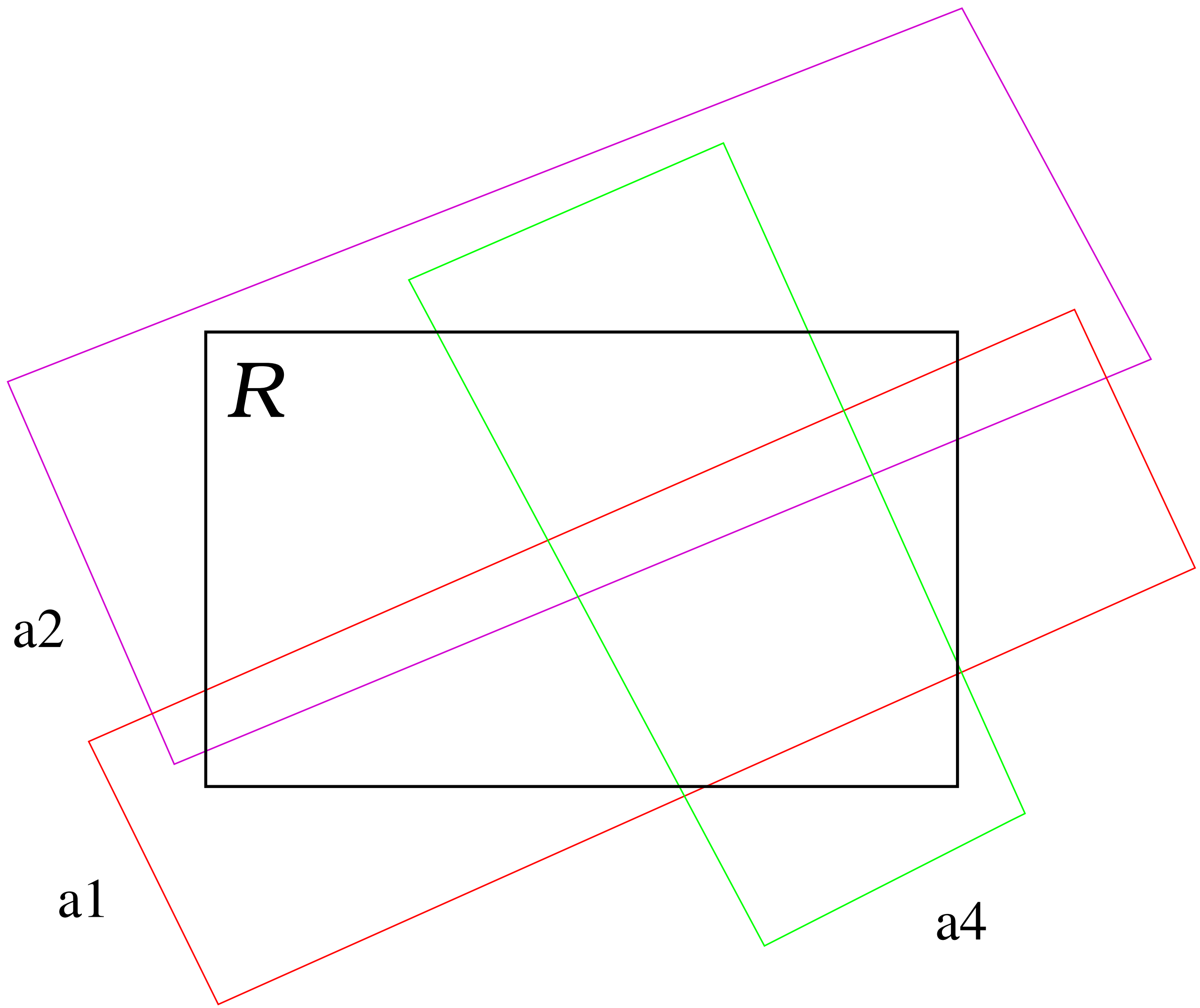
Optimal solution

Given the region $\mathcal{R}$ and the set of acquisitions $\{a_1, a_2, a_3, a_4\}$

the optimal solutions is $\{1, 1, 0, 1\} = \{a_1, a_2, a_4\}$

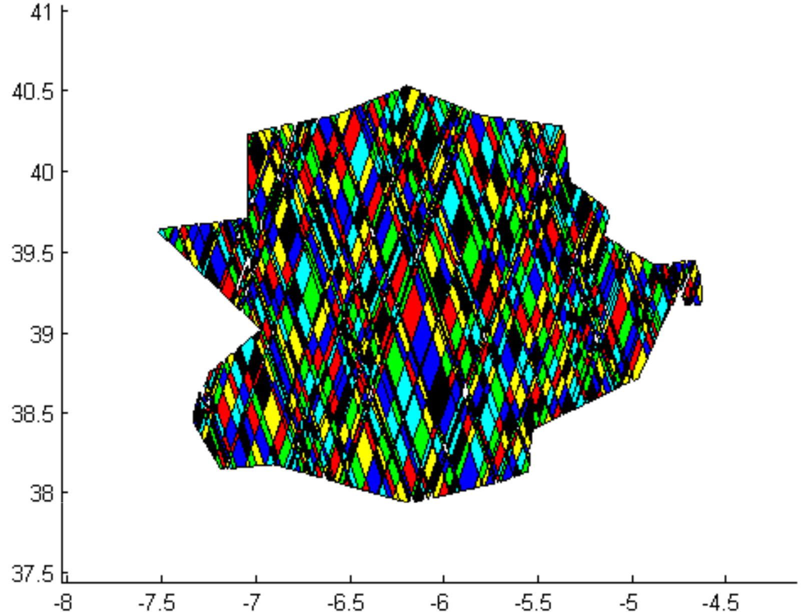


Generalizations and Limitations

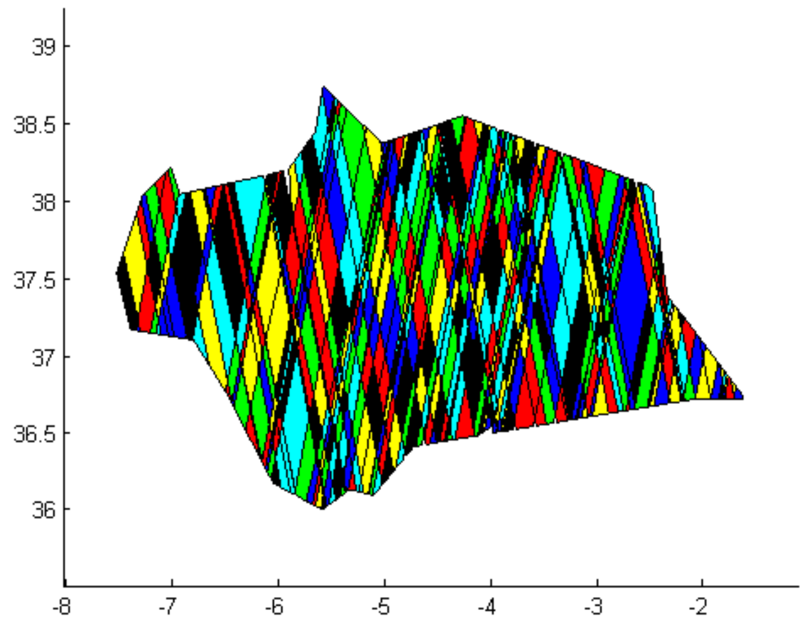
- It is straightforward to include multiple modes for each satellite (additional restrictions).
- Optimization in time.
- Optimization in number and cost of images.

For planning purposes we need real time solutions.

- The bottleneck of the present calculatons is the computation of the Q matrix.
- We have implemented greedy, GRASP (Greedy randomized Adaptatve Search Procedure) and two steps optimizations algorithms.

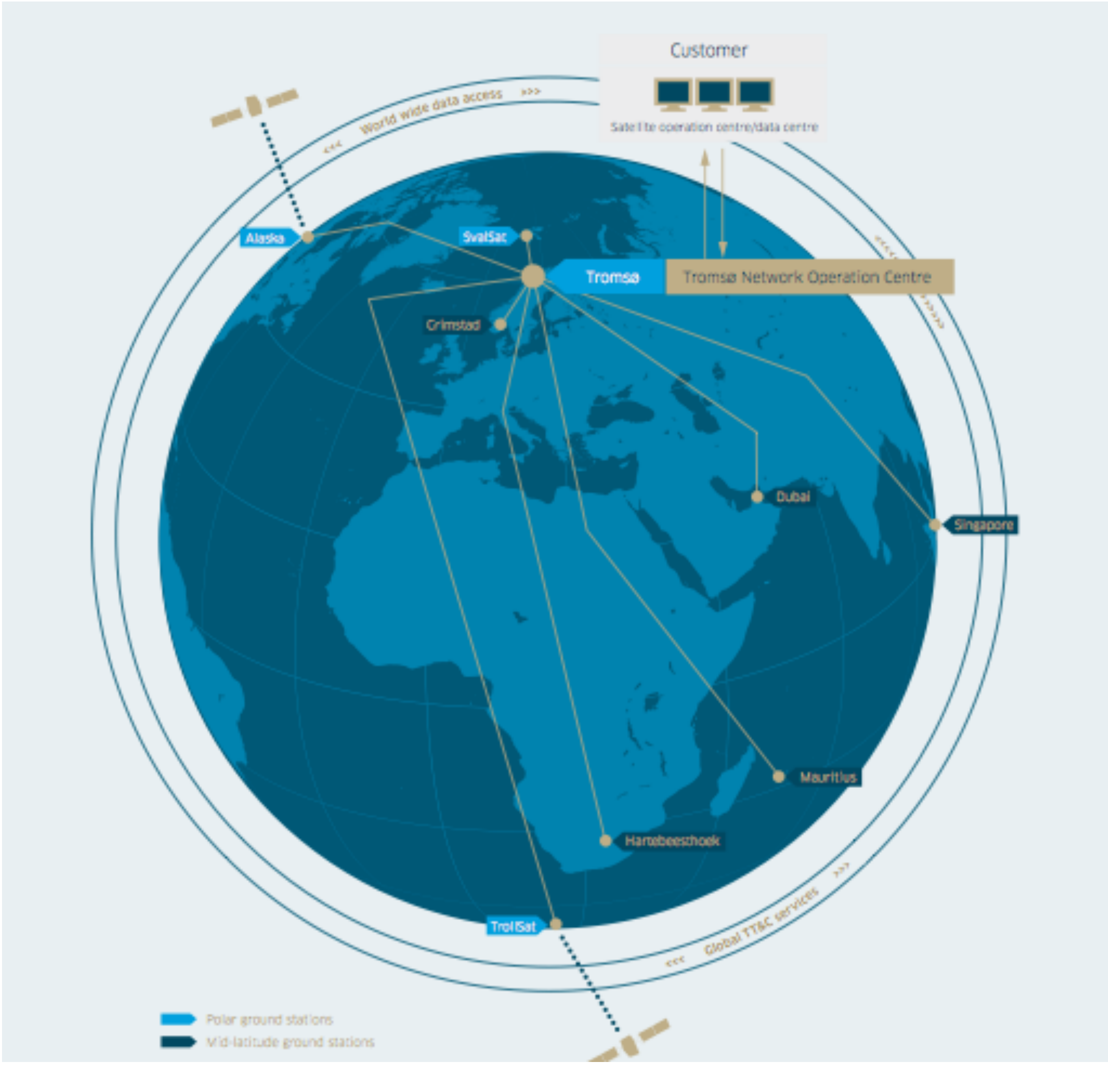


More complicated regions and acquisitions: Extremadura, Andalucia

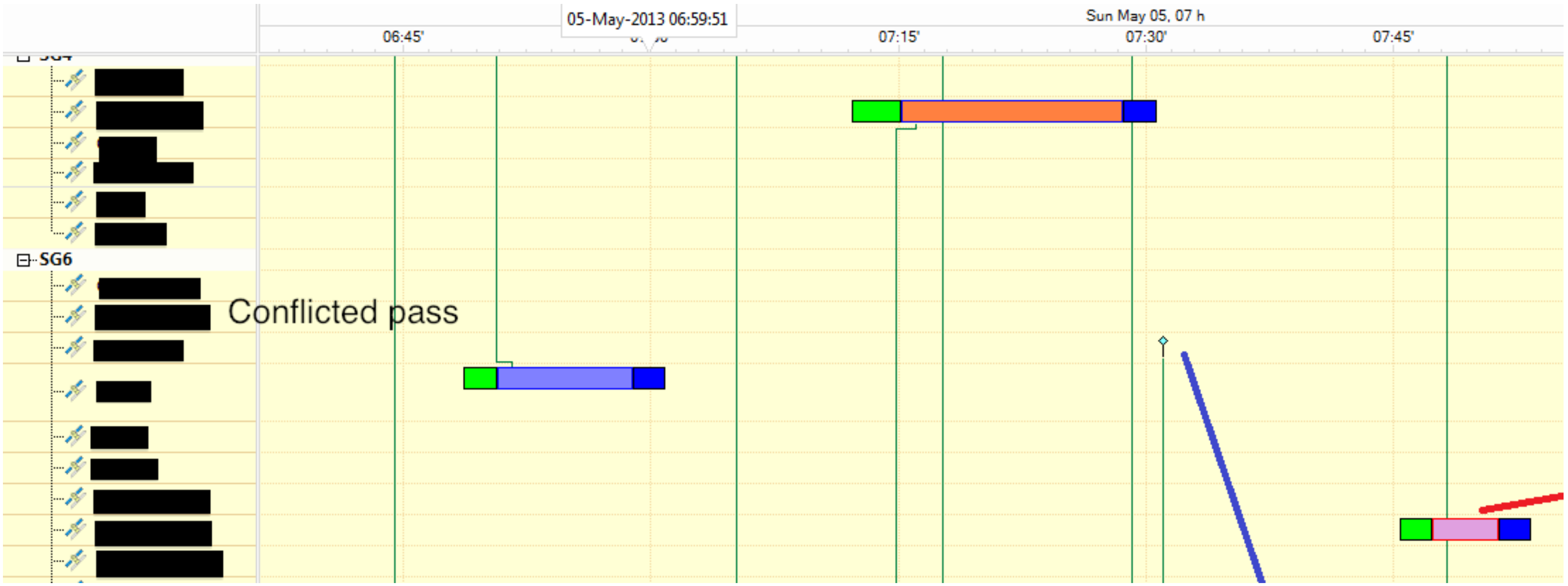


Project 2: Satellite Range Problem

Ksat Global Network



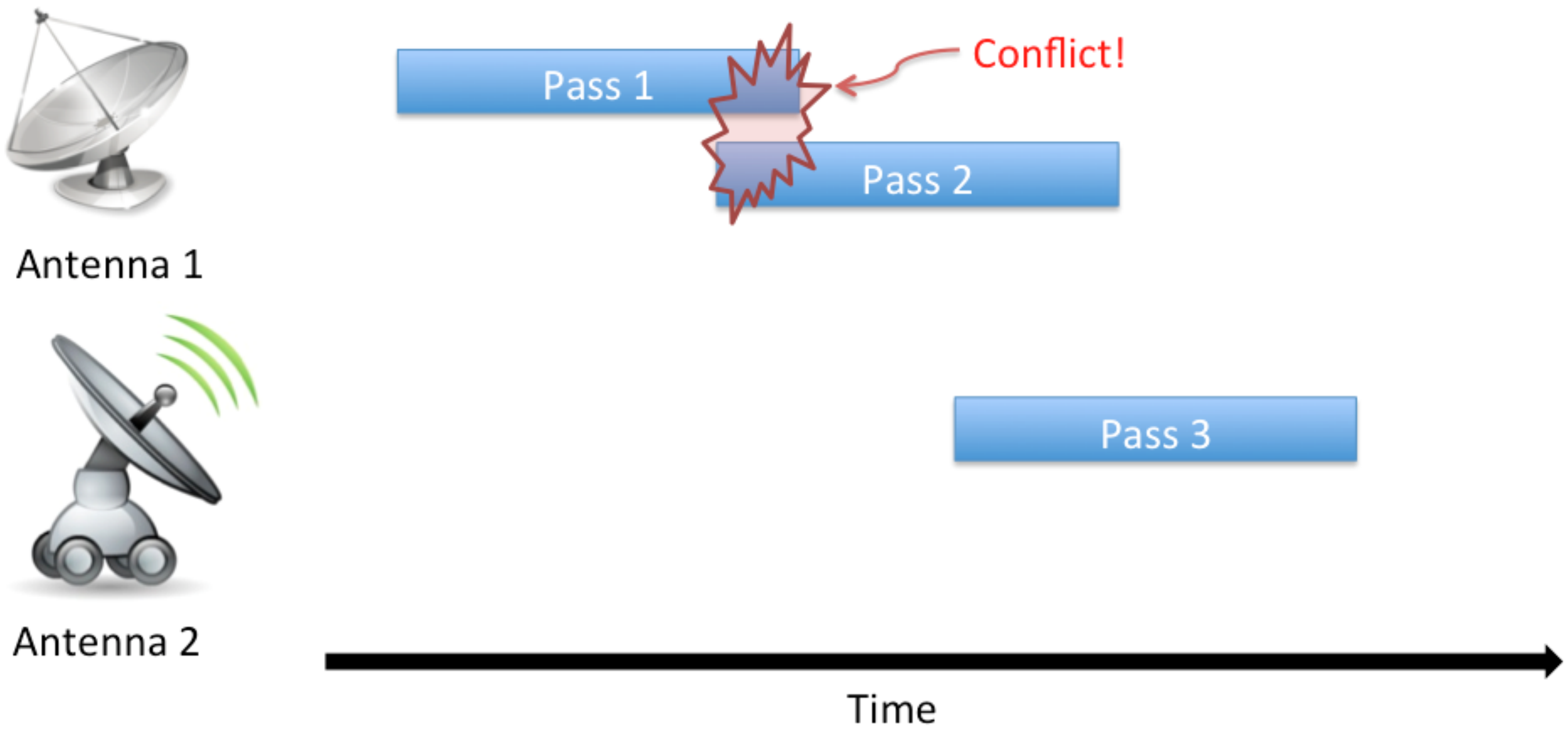
Some orders of magnitude



- # antennas $\sim$ 50 (9 ground stations, pole to pole)
- # satellites $\sim$ 80.
- # revisits $\rightarrow$ up to 14 a day (polar orbiting satellites).
- Optimization horizon $\rightarrow$ one week $\rightarrow$ 3000 p/w ($\sim$ 45%).
- Typical pass duration $\rightarrow$ 10-20 minutes.
- operating restrictions (bands, up/down links, priorities)
- KSAT already had a deconflicting procedure (KNOS+WM).

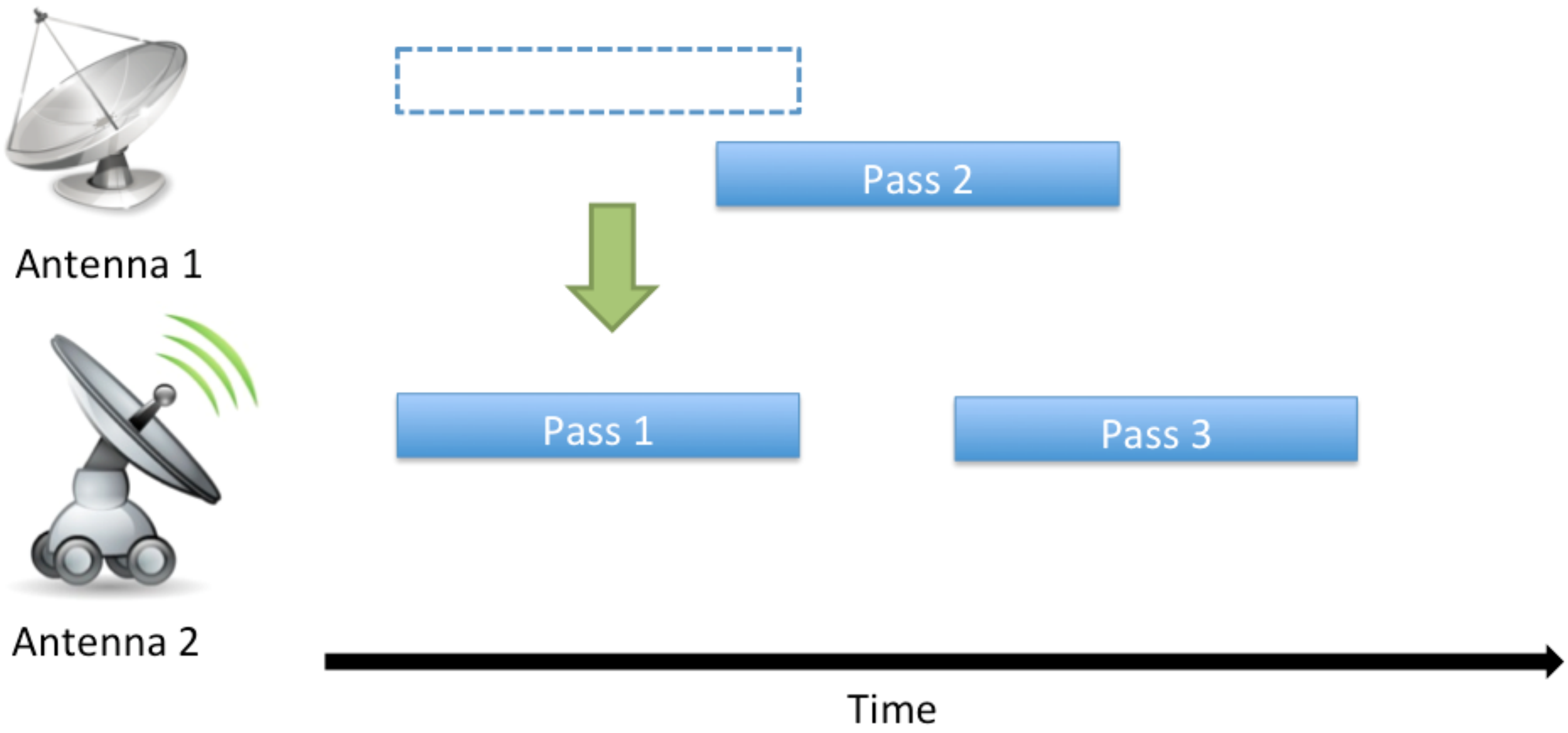
KSAT Facility at Tromso, Norway

Some definitions



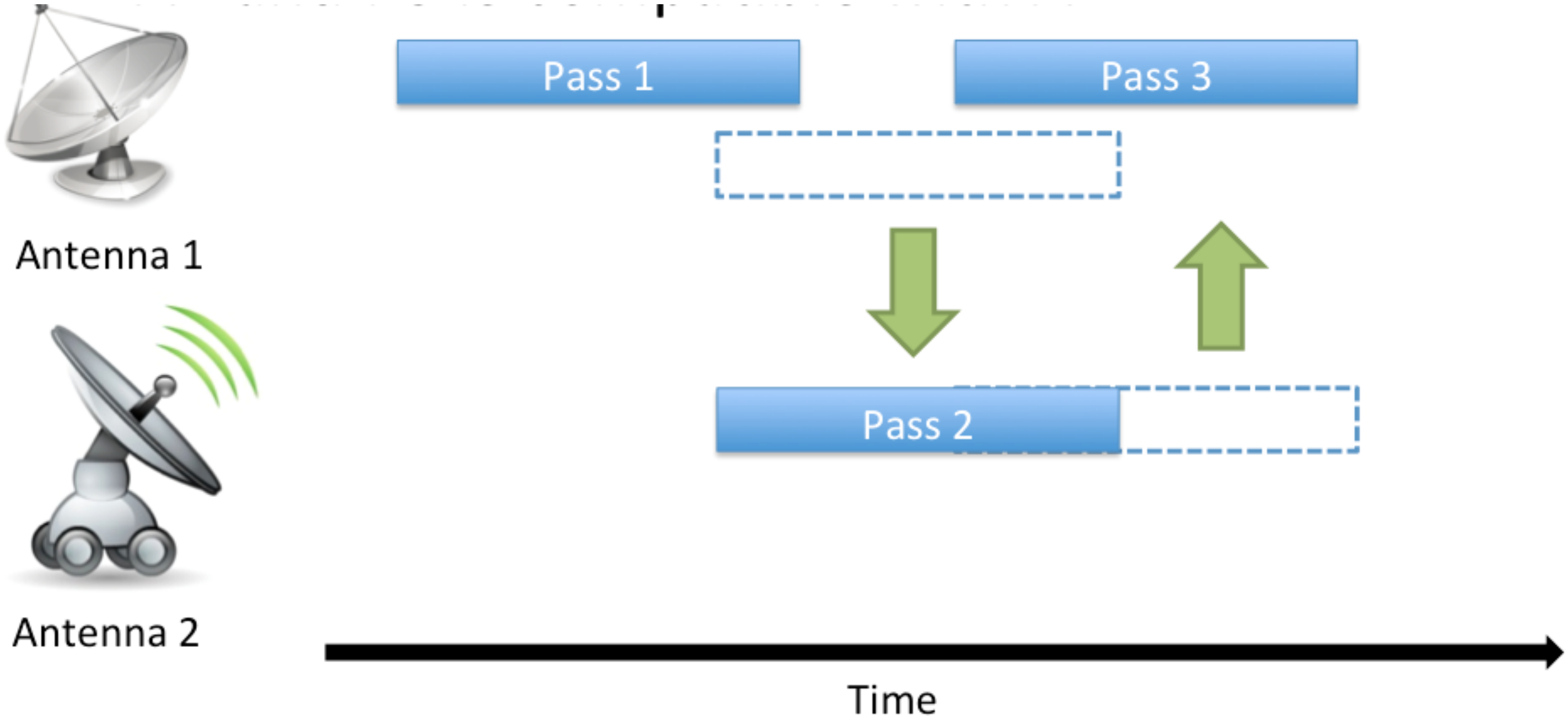
Keywords: timeline, passes, conflicts, ASAP=SRS, deconflicting tool, real time.

Deconflicting I: moving passes



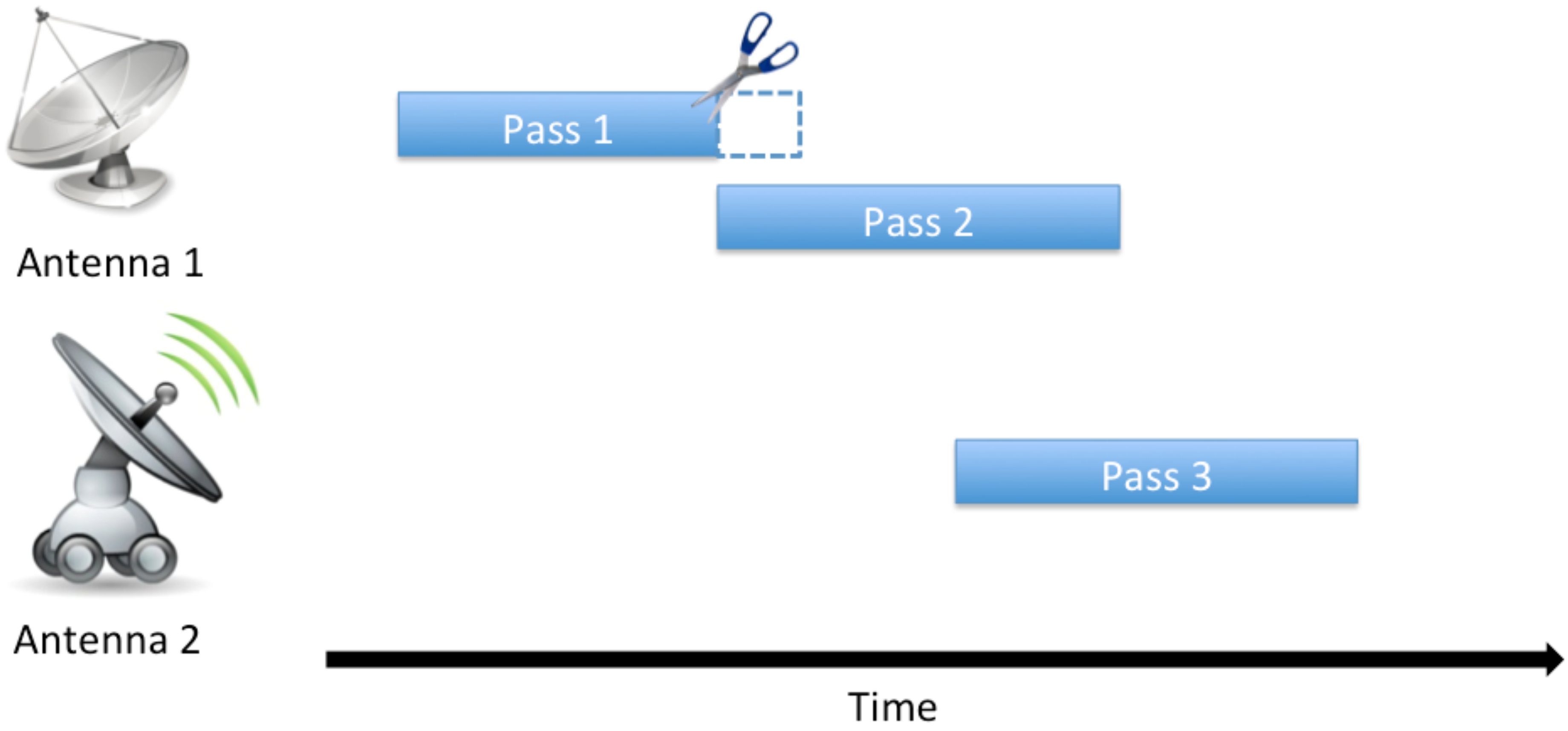
If pass 1 is also compatible with antenna 2 $\rightarrow$ move the pass!

Deconflicting II: multiple moving passes



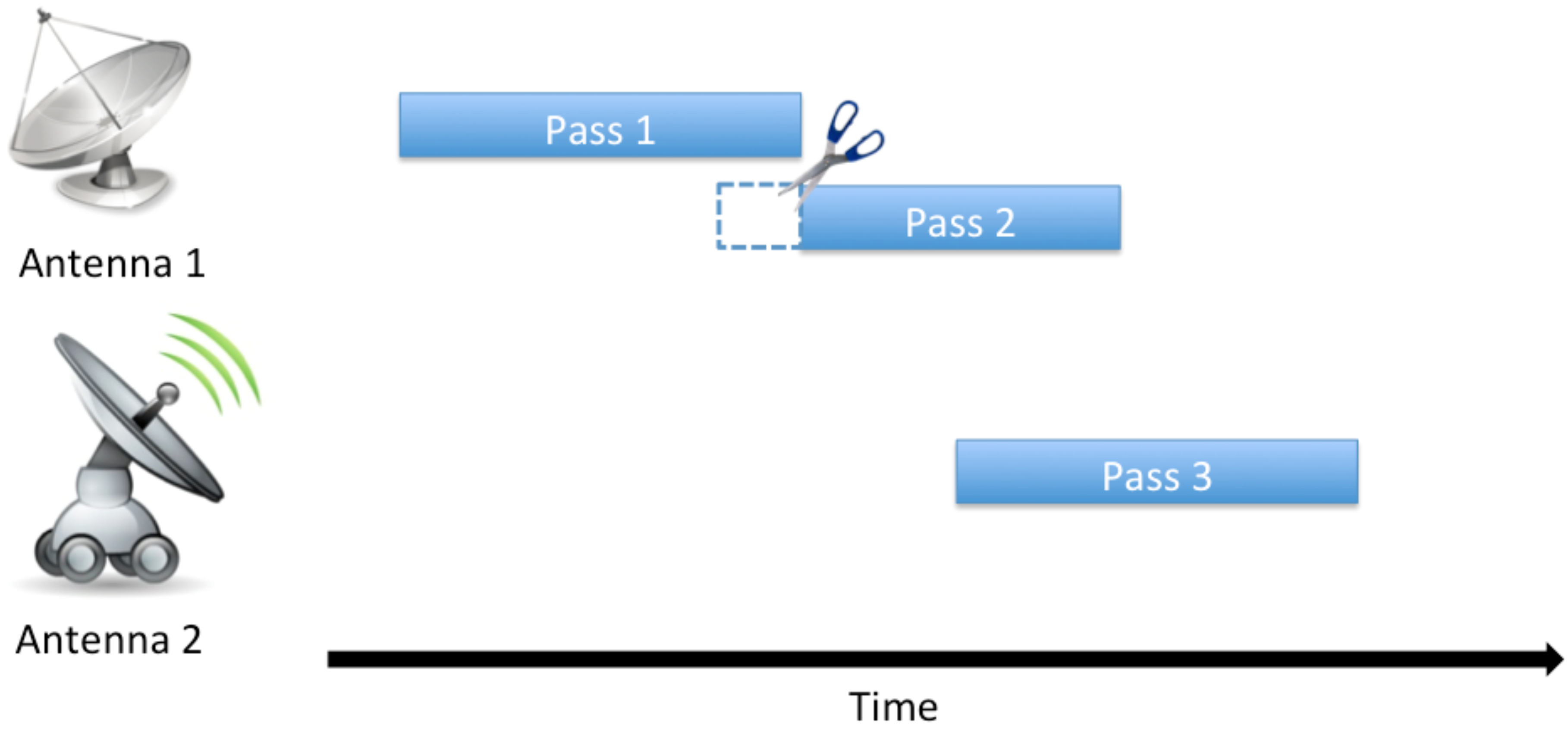
moving may involve more than one pass $\to$ domino effect.

Deconflicting III: shortening of passes



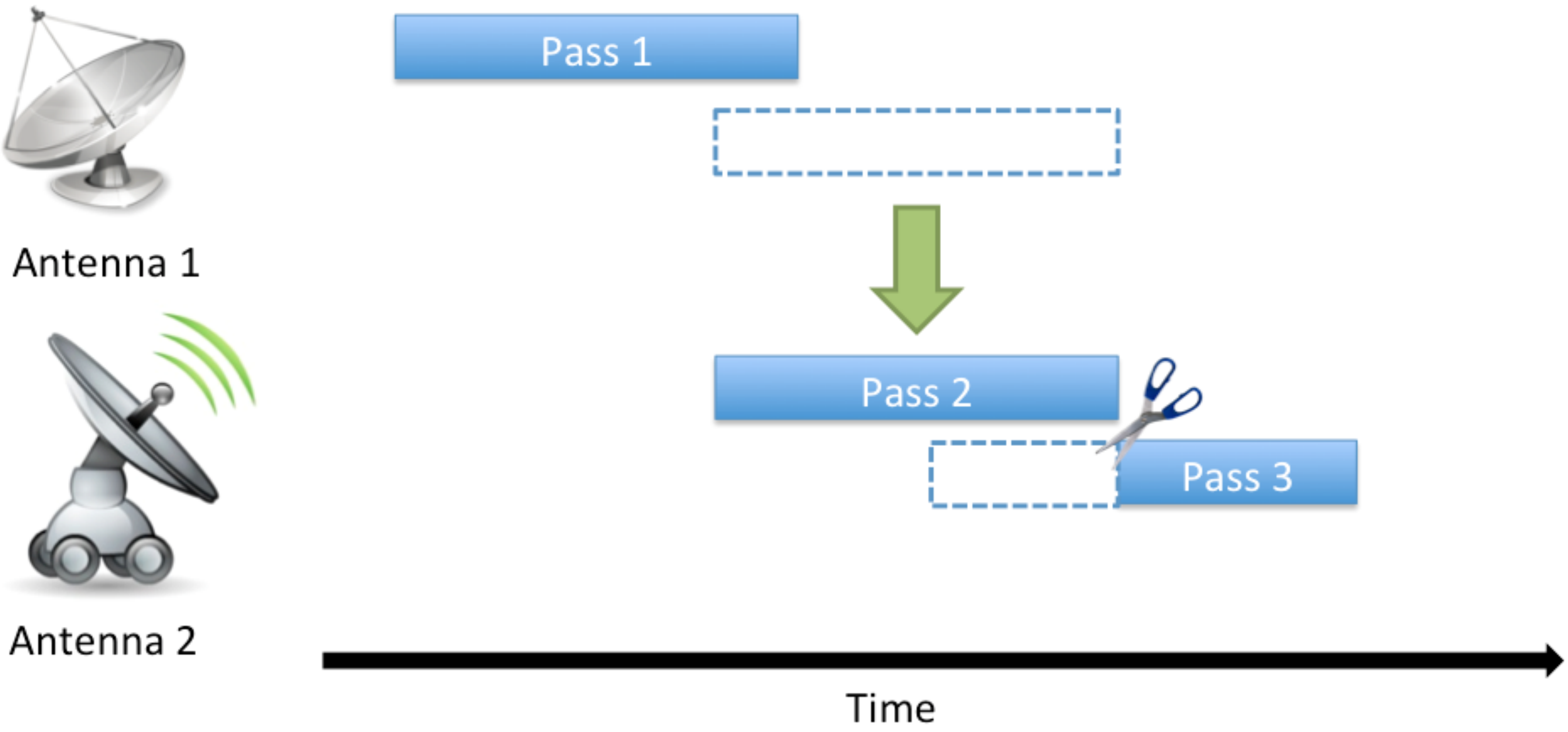
If pass 1 is shortable → allocated time slot > minimum duration

Deconflicting III: shortening of passes



If pass 2 is shortable $\rightarrow$ allocated time slot > minimum duration

Deconflicting IV: moving and shortening of passes

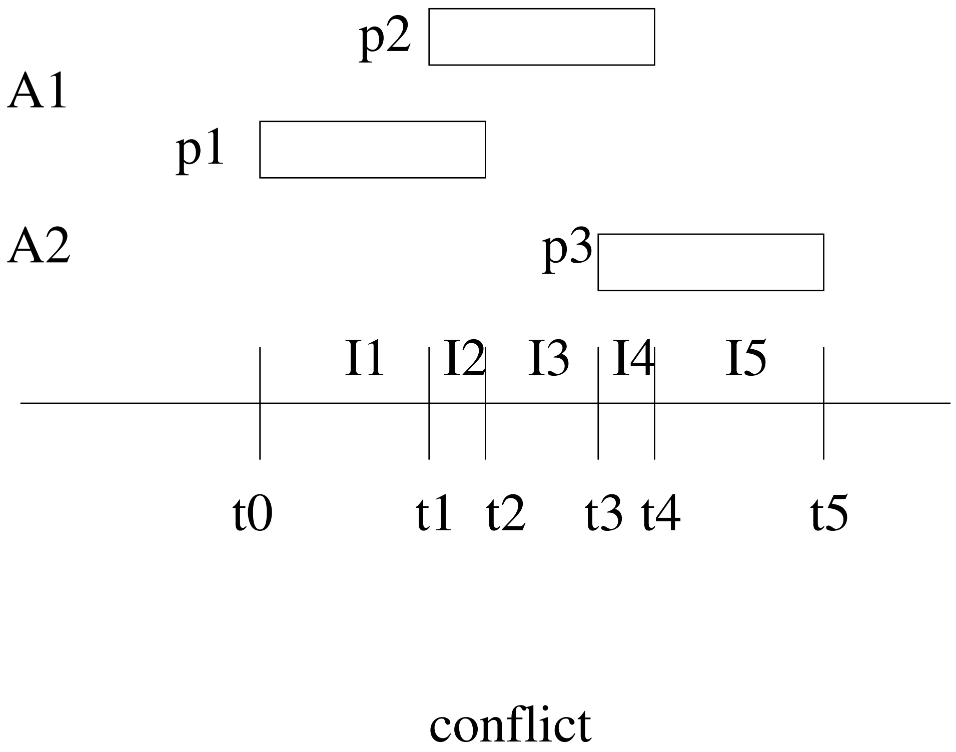


If pass 2 is movable and pass 3 shortable

Can we build an automatic **Deconflicting tool**?

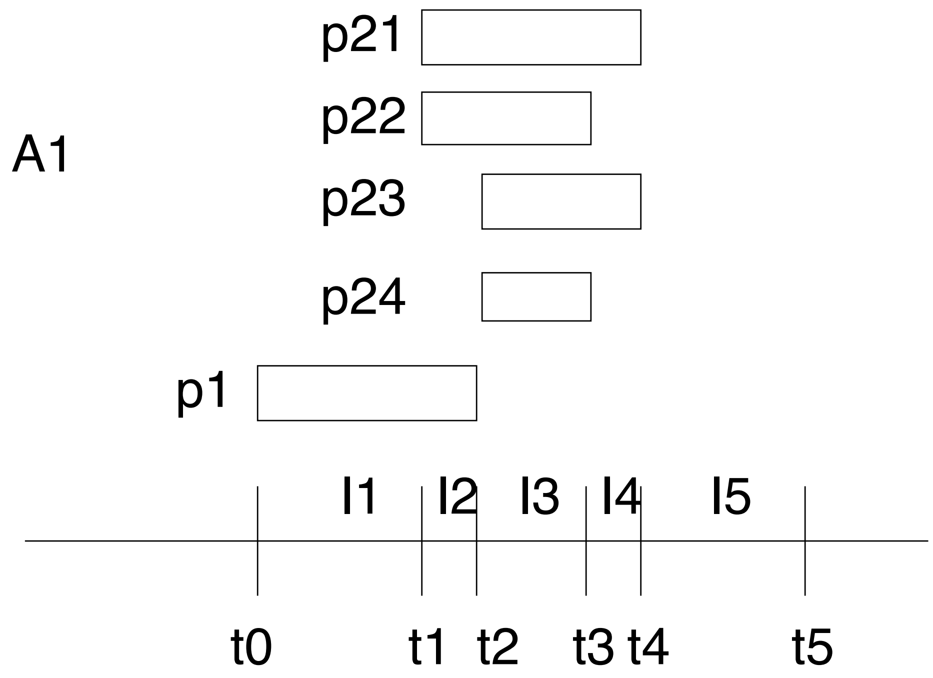
- Clearly define the hierarchy of allowed deconflicting mechanisms.
- define a decision variable (if possible binary).
- define a cost function.
- implement an optimization procedure.
- test against **experimental** data.
- use the tool to deconflict passes and (hopefully) make design decisions.

Mathematical modeling of deconflicting I



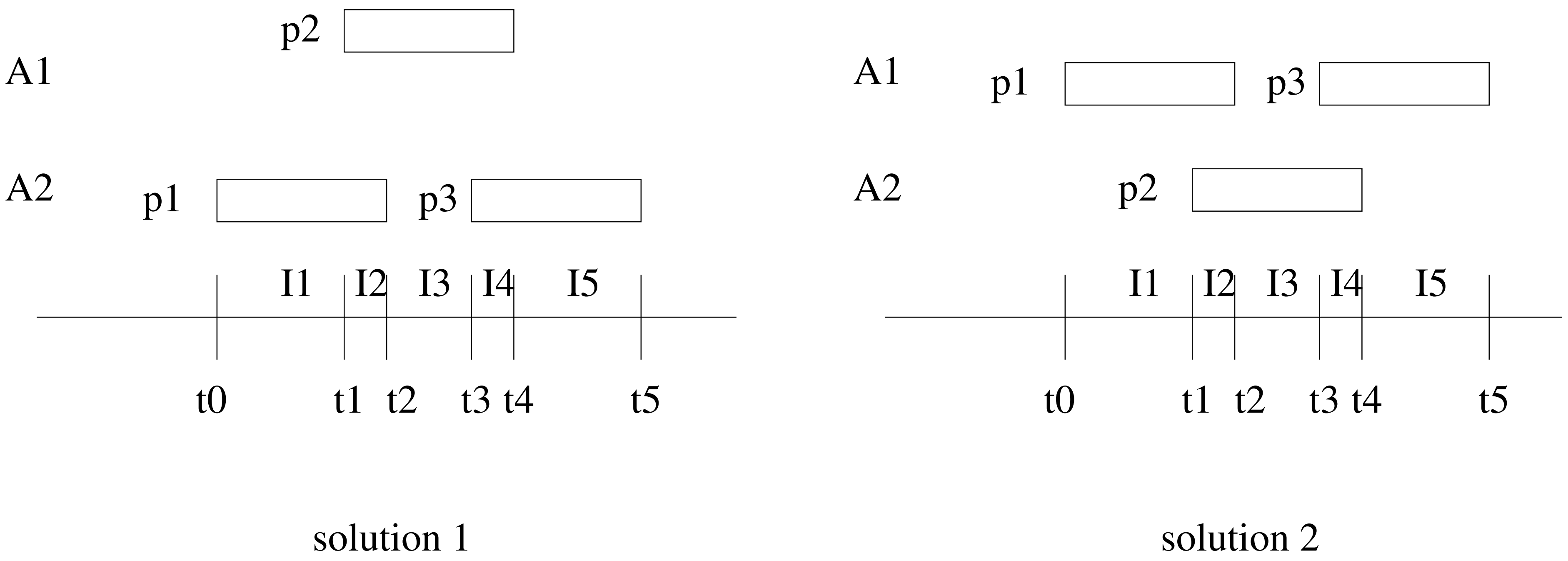
- compute the time intervals along the time line

Mathematical modeling of deconflicting II



- for each pass and its alternatives generate all possible compatible subpasses in al the alternative antennas. KEY INGREDIENT

Mathematical modeling of deconflicting: solutions



- assign a **binary** value for each pass
- add **feasibility** conditions
- define an appropriate linear cost function
- optimize (ILP).

Mathematical modeling:equations

Define the binary variable y_{ik} that is 1 if pass P_i is assigned to antenna A_k and 0 otherwise.
Constraints:

1. Every pass has to be assigned at most to one antenna.

$$\sum_{k \in C_i} y_{ik} \leq 1, \forall i \in F.$$

2. For a given antenna A_k and a time interval $I_{j\,k}$ available for passes, there should be no conflict among the passes.

$$\sum_{i \in F:\, j \in S_{ik}, k \in C_i} y_{ik} \leq 1, \ \forall\ k, j : \cup_{i \in F} S_{ik} \neq \emptyset.$$

Maximize the linear cost function:

$$J = \sum_{i \in F} \sum_{k \in C_i} (p^* - p_{ik} + 1)\xi_{ik} y_{ik},$$

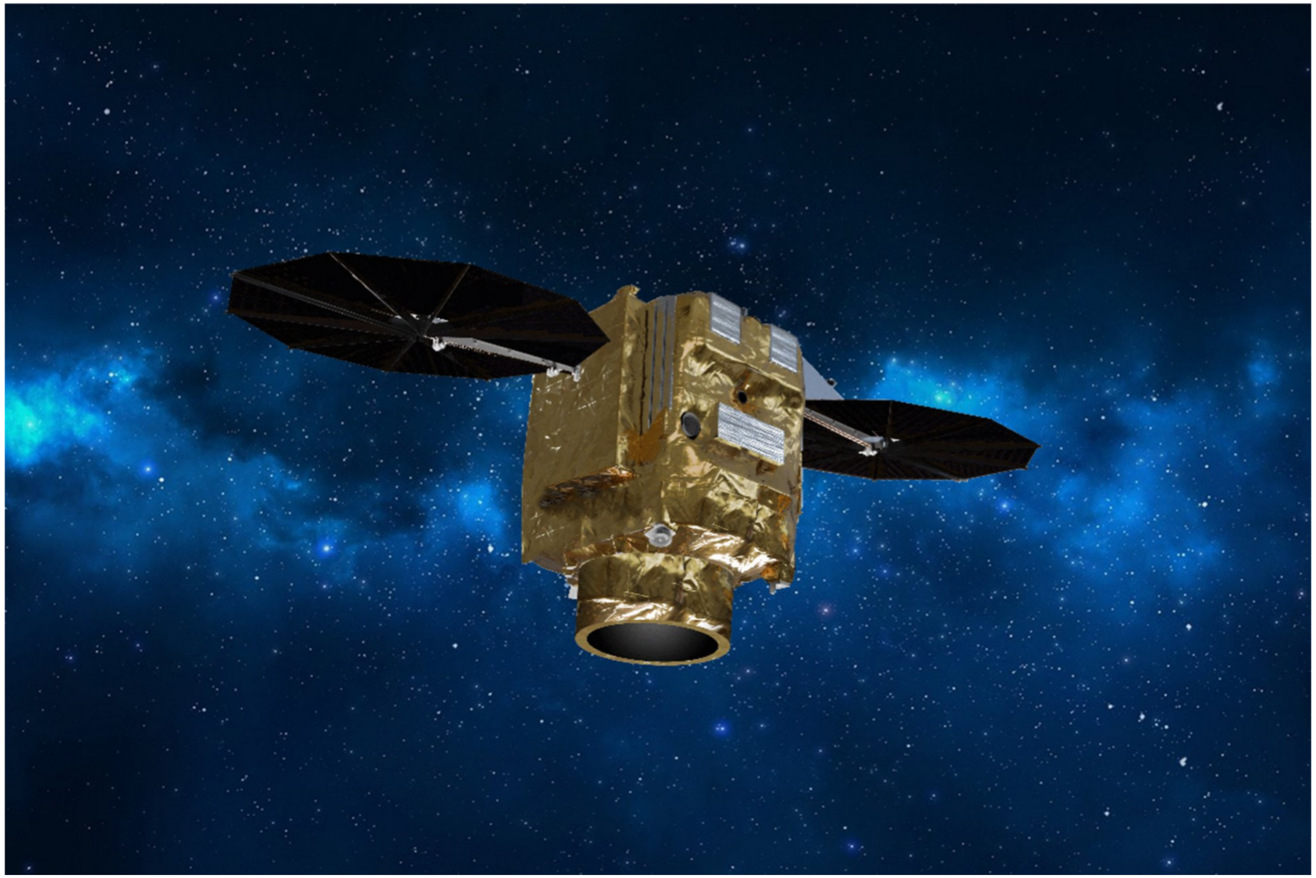
where $p^* = \max_i p_i$ and ξ_{ik} is a weighting function

Does it work?

Passes	Ant.	Sat.	Shortable passes (%)	Conflicts	Cancell.	Short.	Move. total (other site)	Vars.	Constr.	Time (s)
3356	22	49	22	537	116	1	839 (13)	8090	9322	64
3006	22	47	22	196	75	3	703 (5)	11219	12157	61
3356	22	49	22	231	94	0	517 (6)	12465	12245	73
3566	22	50	22	306	114	1	561 (11)	12360	12714	73
3470	22	52	22	253	100	0	557 (17)	12016	12788	80
3408	22	52	22	196	91	0	478 (5)	12289	12025	71
1573	14	47	24	68	0	0	487 (7)	7143	4467	64
384	20	46	22	33	21	0	101 (0)	1247	1075	22
1586	16	45	24	6	2	0	479 (2)	7892	4964	63
2287	18	55	26	1053	250	4	312 (35)	6820	8380	77

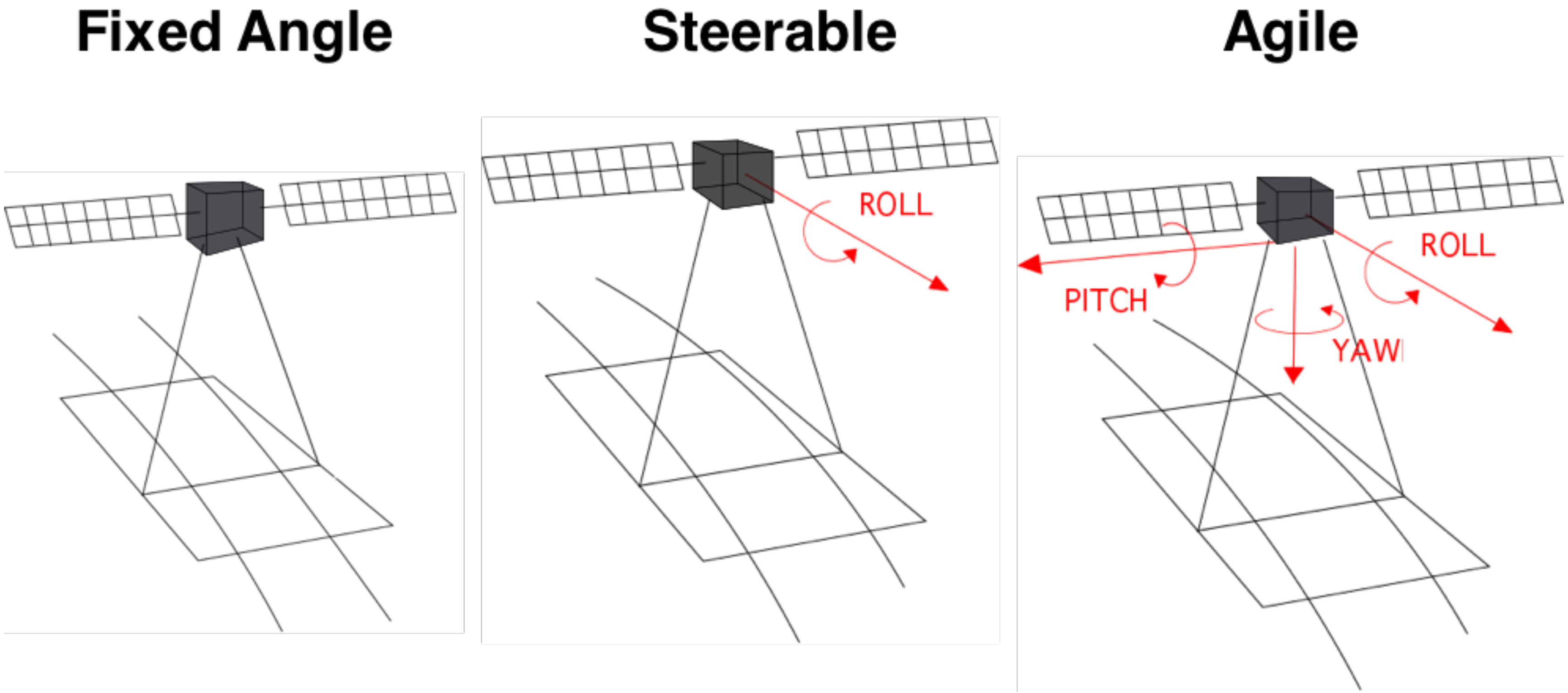
- Implemented in C++ within a Savoir tool
- The **bottleneck** is not the dimension or the ILP solver (LPSOLVE) but the preprocessing and the **complexity** of the conflicts (Gurobi).
- We perform in real time at least as good (slightly better) as the trained deconflicting department.

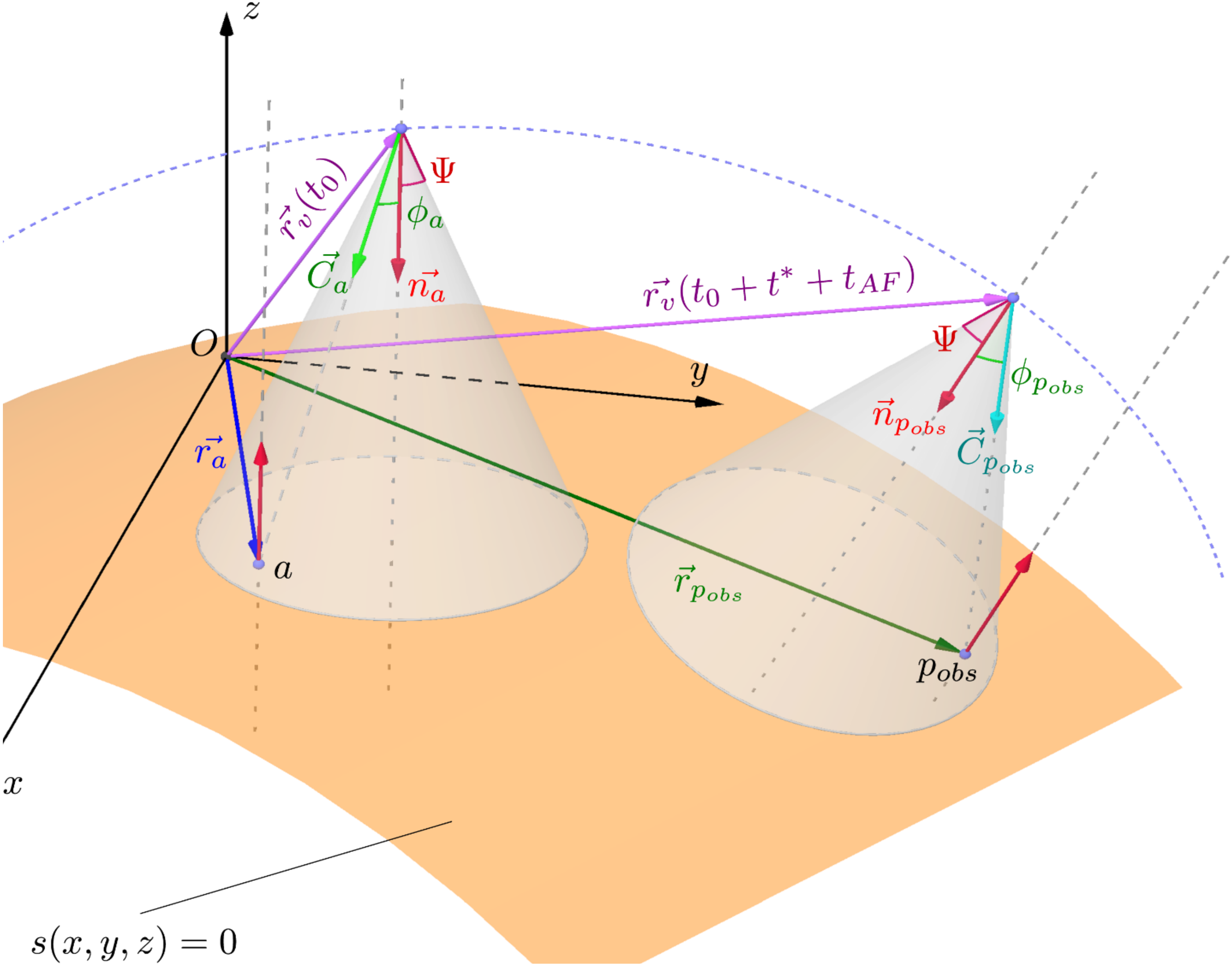
Other projects… (a bit more academic)



Planning of acquisitions for agile satellites in snapshot mode.

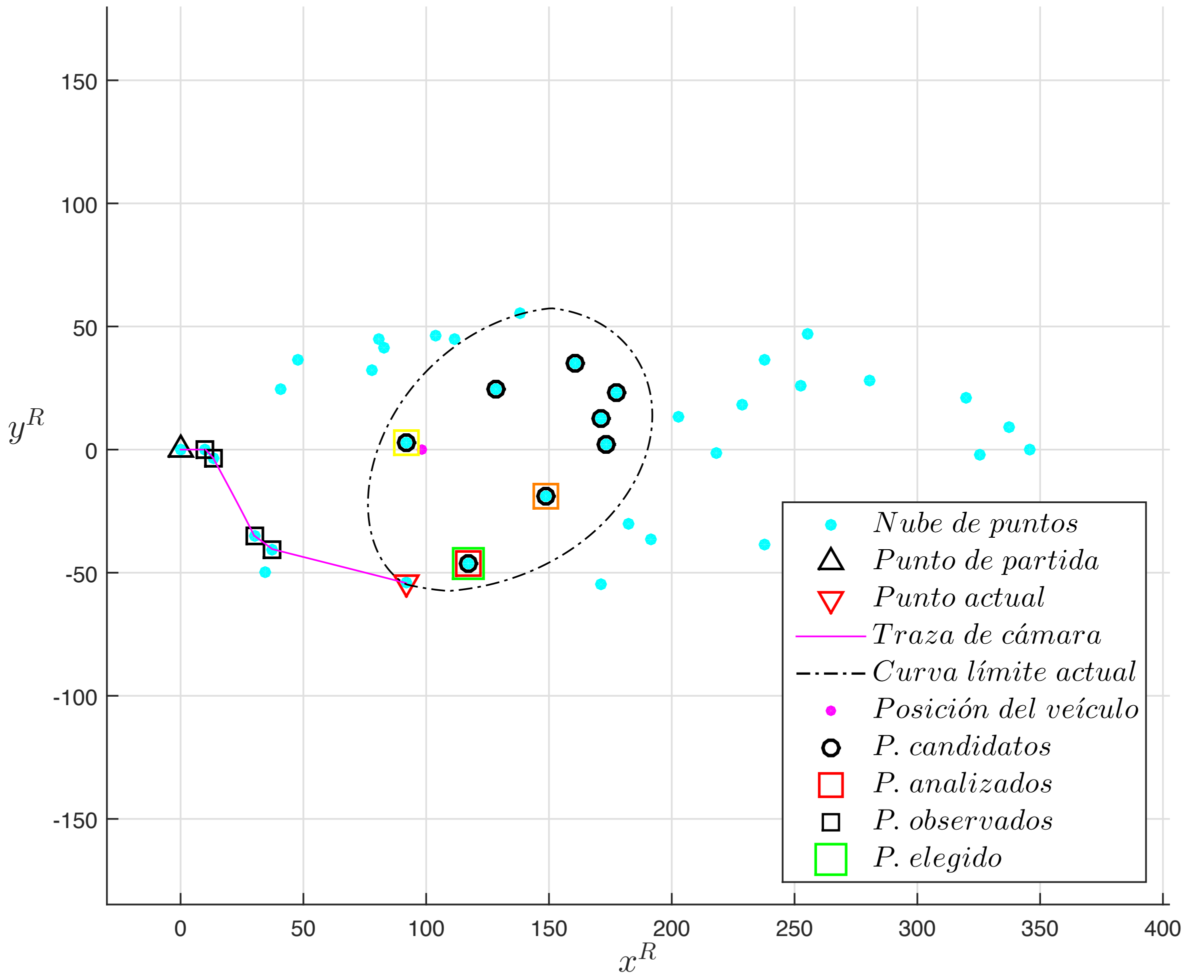
- Agile satellites: allow rotation in all directions to acquire images
- Snapshot mode: individual images for selected coordinates





z
$\vec{r_v}(t_0)$
Ψ
ϕ_a
$\vec{C_a}$
$\vec{n_a}$
$\vec{r_v}(t_0 + t^* + t_{AF})$
O
y
Ψ
$\phi_{p_{obs}}$
$\vec{n}_{p_{obs}}$
$\vec{C}_{p_{obs}}$
$\vec{r_a}$
a
$\vec{r}_{p_{obs}}$
p_{obs}
x
$s(x, y, z) = 0$

Planning of acquisitions for agile satellites in snapshot mode.



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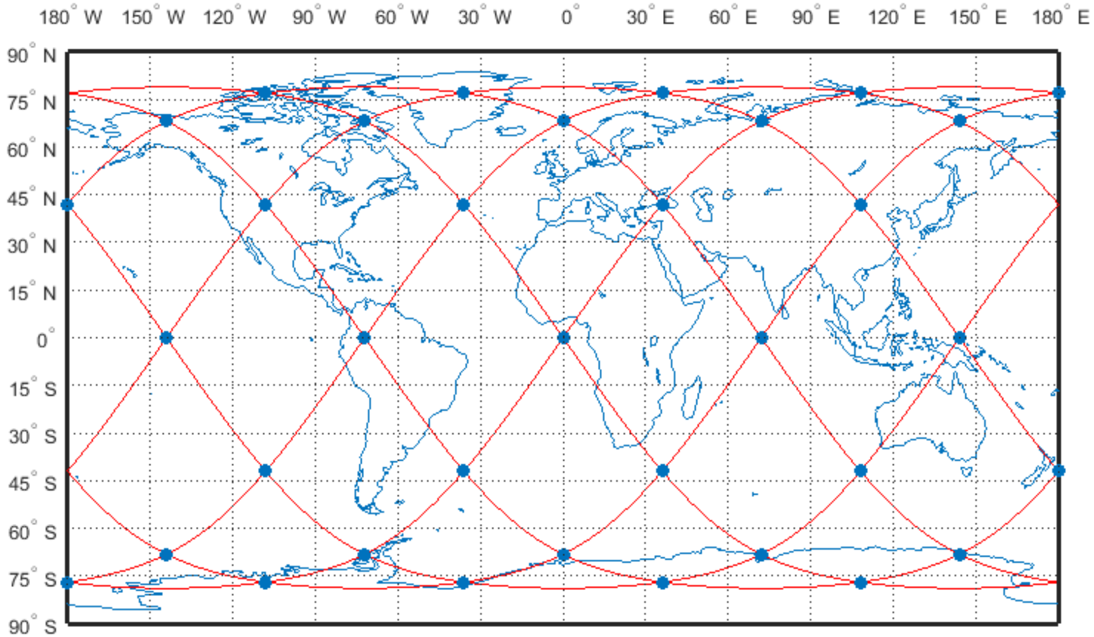
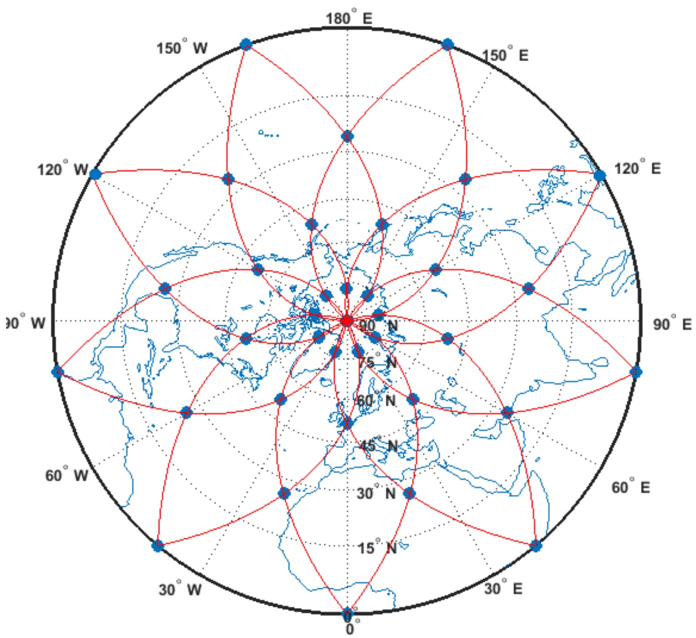
Analysis of groundtrack self-intersections for geocentric satellites

- Satellites with repeating groundtrack may or may not have points of self-intersection depending on orbital elements.
- Self-intersection are of interest because they represent points of opportunity for repeated communication and/or observation





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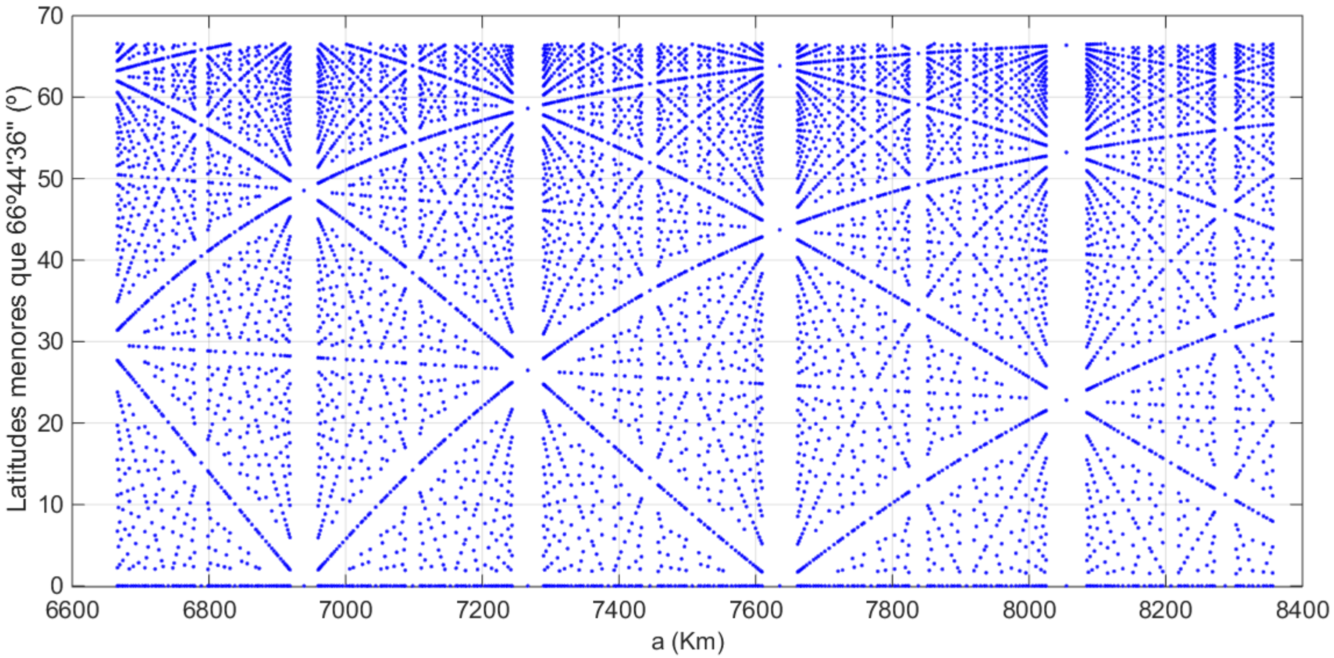
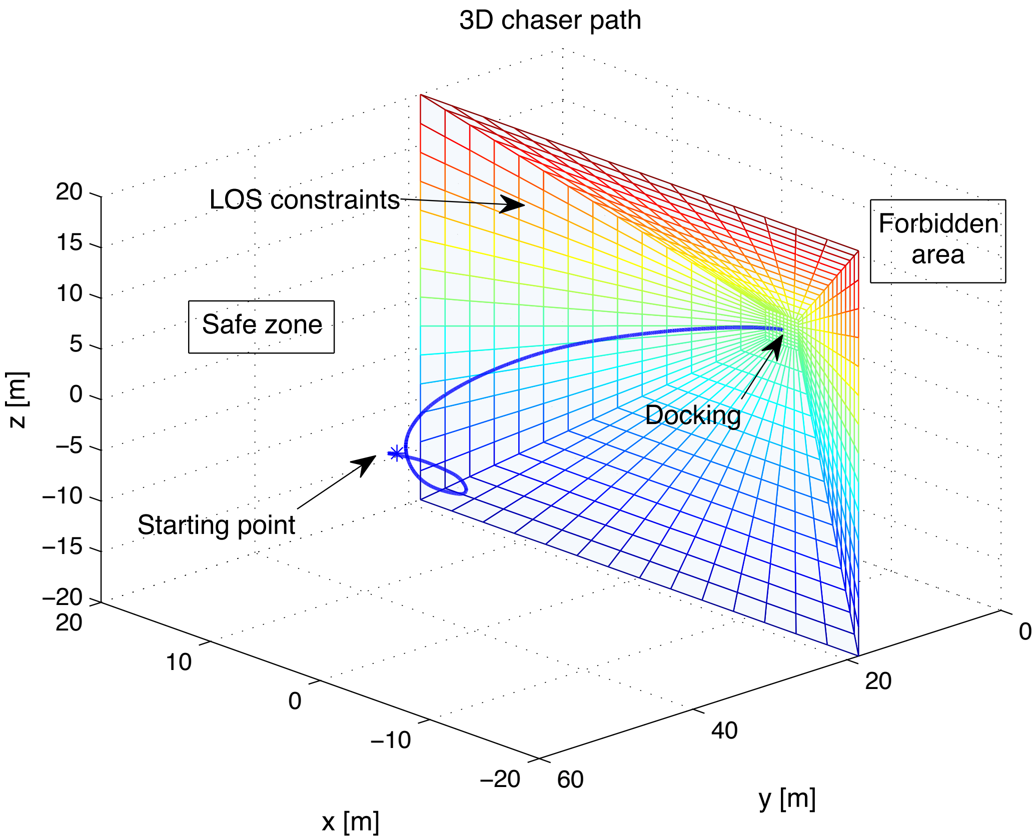
Analysis of groundtrack self-intersections for geocentric satellites

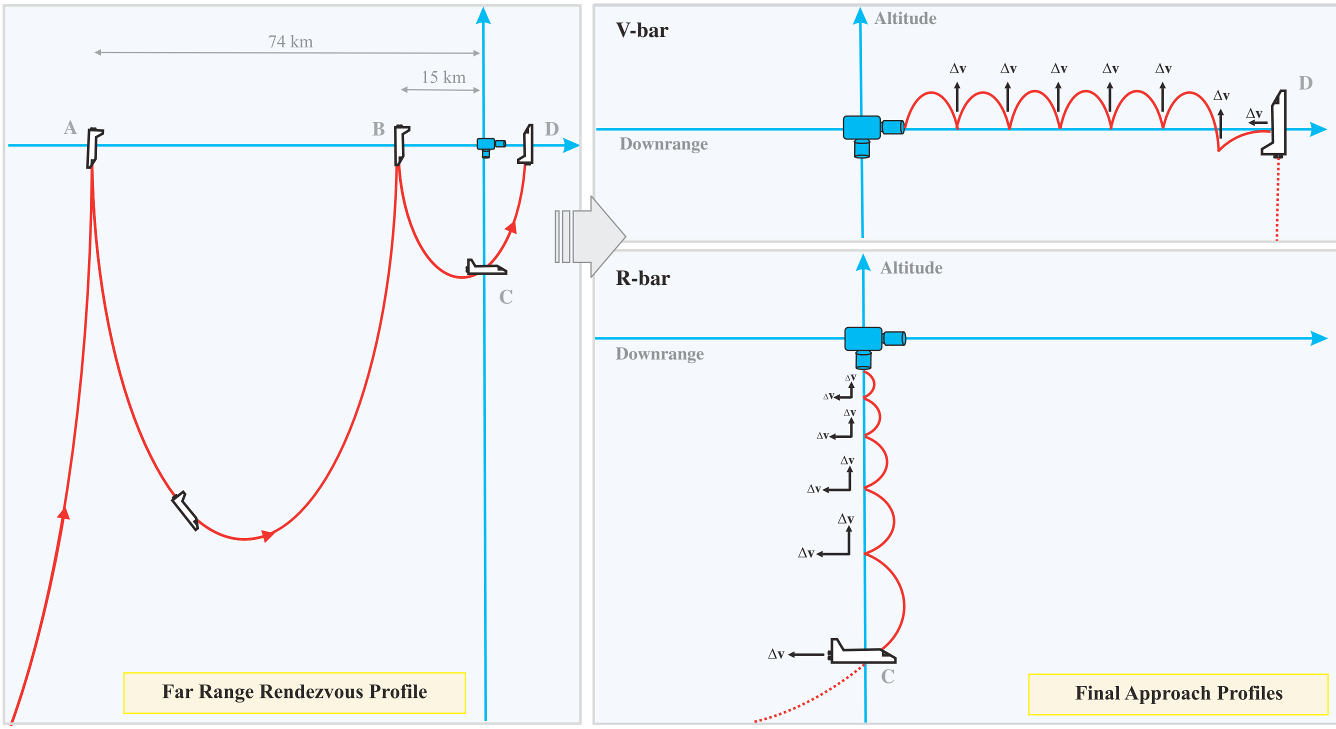
- In the circular case the altitude (which determine repeating properties) and inclination are the key values.
- In the circular case, we have developed algorithms that give the exact number of self-intersection and their locations. These algorithms may help in orbit design.



Now some control theory: Rendezvous and formation flying of space vehicles



Examples: Space Shuttle



- Different phases according to proximity.
- Close approach is manual.

Examples: Soyuz

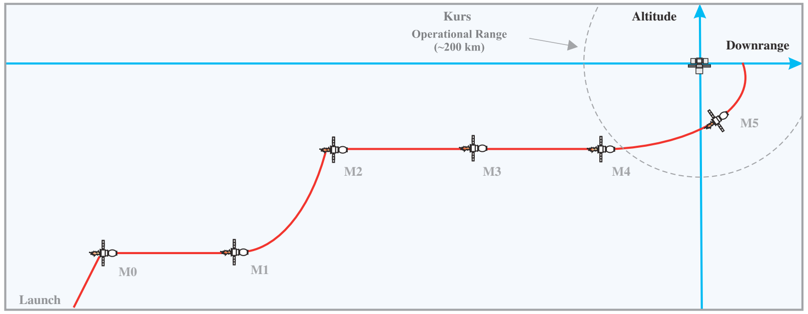
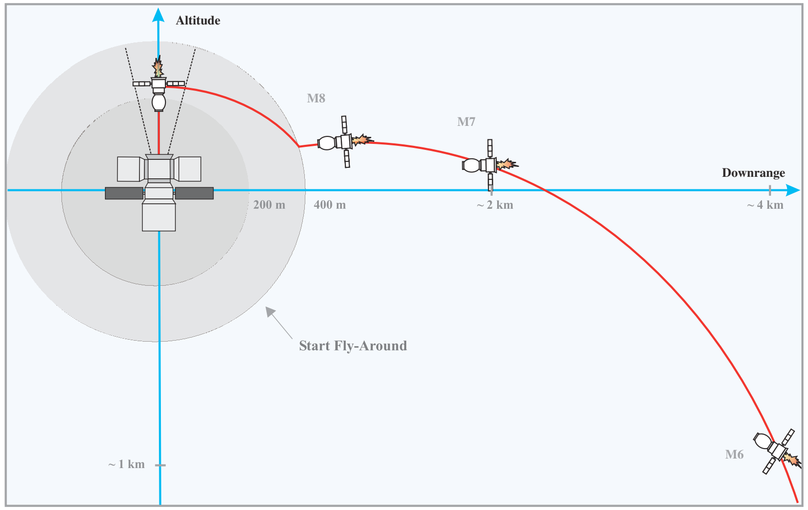
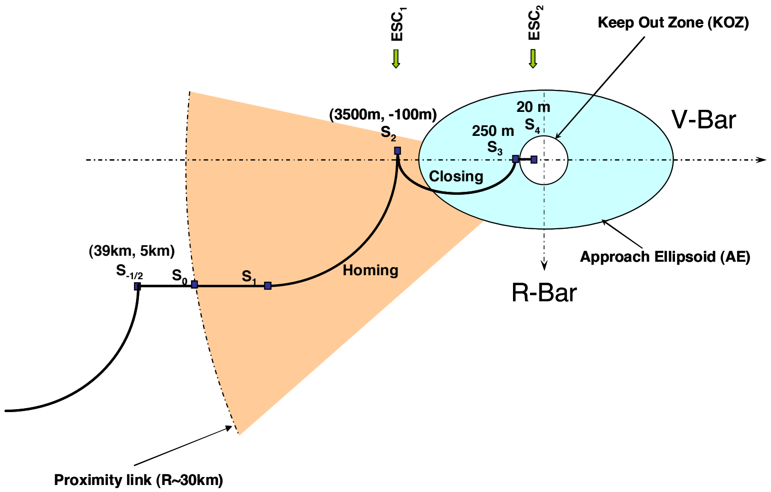


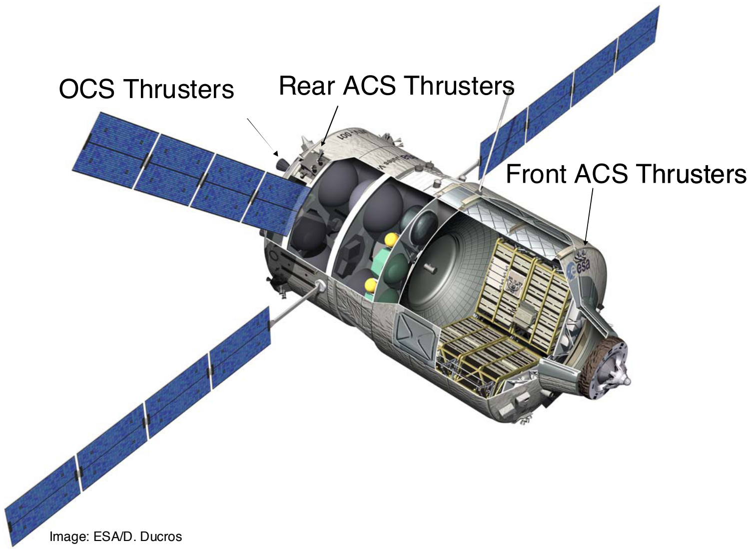
Fig. 6 Phasing and rendezvous sequence for Soyuz/Progress vehicles.



- Russian approach: Kurs system.
- Used for MIR.
- Automatic system, does not require target actions (but requires system installed on-board target).
- Weight of 85 kg., 270 Watts of consumption (both on target and chaser).

Examples: ATV





- ATV (Automated Transfer Vehicle) from ESA carries supplies to ISS and at the end of its lifetime is ejected elevating the orbit (and carrying waste away).
- Uses relative GPS and follows a pre-programmed maneuver.
- Additional pre-programmed maneuvers for all possible scenarios.
- 5 ATV vehicles had been launched (Jules Verne, Johannes Kepler, Edoardo Amaldi, Albert Einstein, Georges Lemaître).

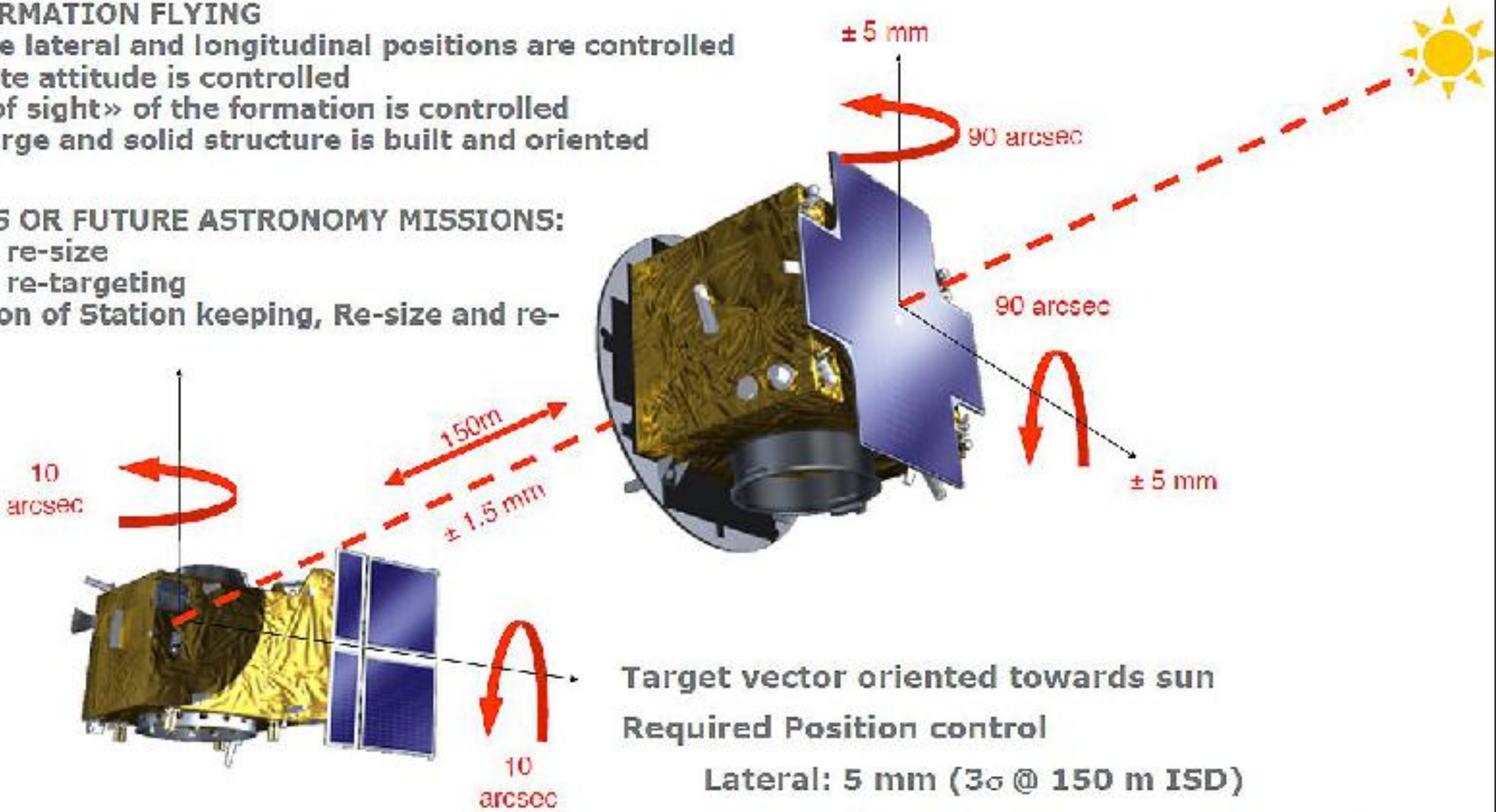
PROBA-3 MISSION (ESA)

PRECISE FORMATION FLYING

- The relative lateral and longitudinal positions are controlled
- The absolute attitude is controlled
- The «line of sight» of the formation is controlled
- A virtual large and solid structure is built and oriented

MANEUVERS OR FUTURE ASTRONOMY MISSIONS:

- Formation re-size
- Formation re-targeting
- Combination of Station keeping, Re-size and re-targeting



Target vector oriented towards sun

Required Position control

Lateral: 5 mm (3σ @ 150 m ISD)

Longitudinal: 1.5 mm (3σ @ 150 m ISD)

Automatic Rendezvous

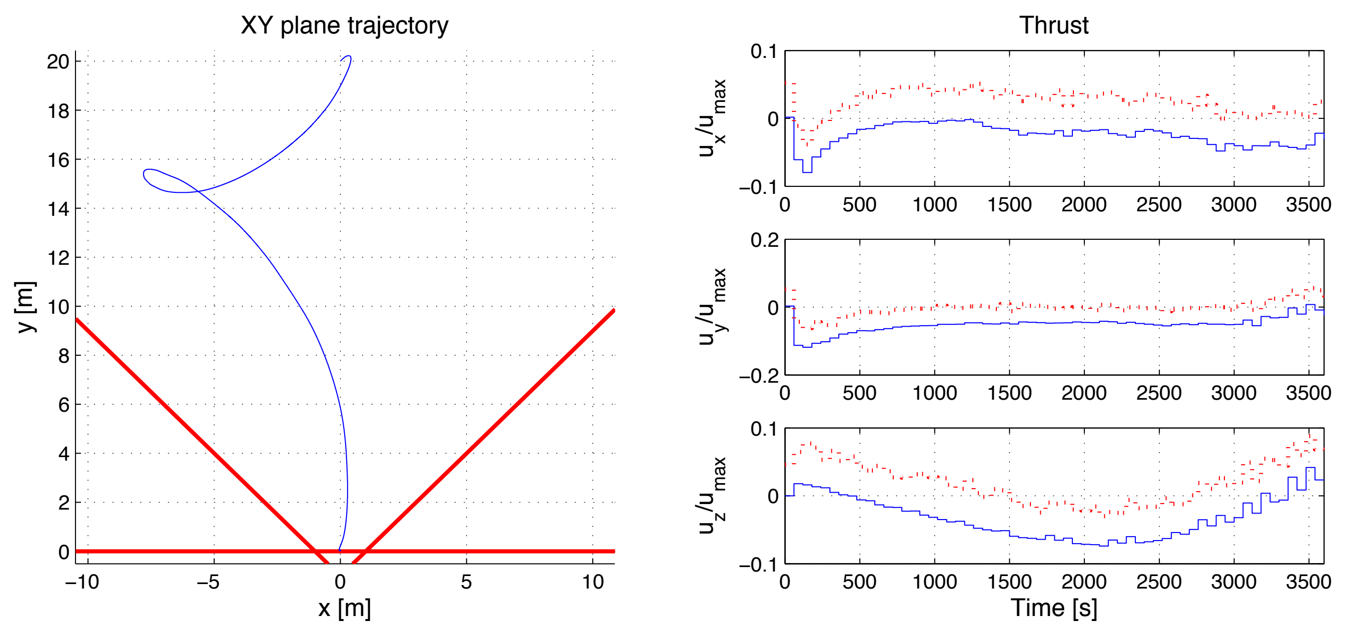
- The problem of designing an automatic rendezvous system of low weight and consumption is still open and an active field of research.
- This would be specially attractive for small satellites that could rendezvous with larger spacecraft, such as space stations.

Rendezvous and formation flying of space vehicles

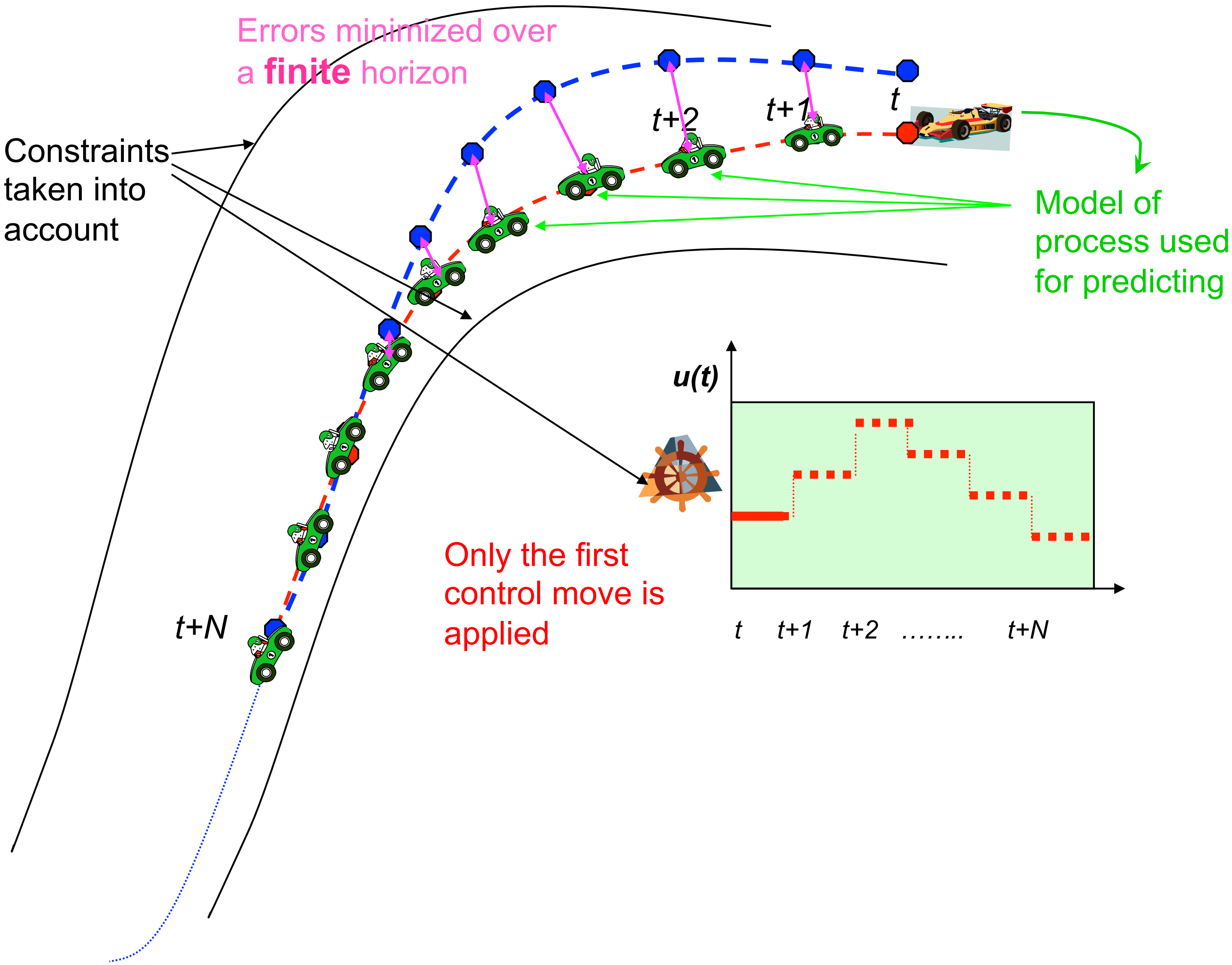
- This was one of the lines of research in F. Gavilan PhD Thesis (2012).
- We have considered two main problems:
  - Safe & optimal rendezvous subject to model uncertainties
  - Fast algorithms for rendezvous with on-off thrusters
- The problem can be modeled by linear equations when vehicles in close proximity but is time-varying (Tschauner-Hempel model)
- On-off thrusters make the problem nonlinear

Safe & optimal rendezvous subject to model uncertainties

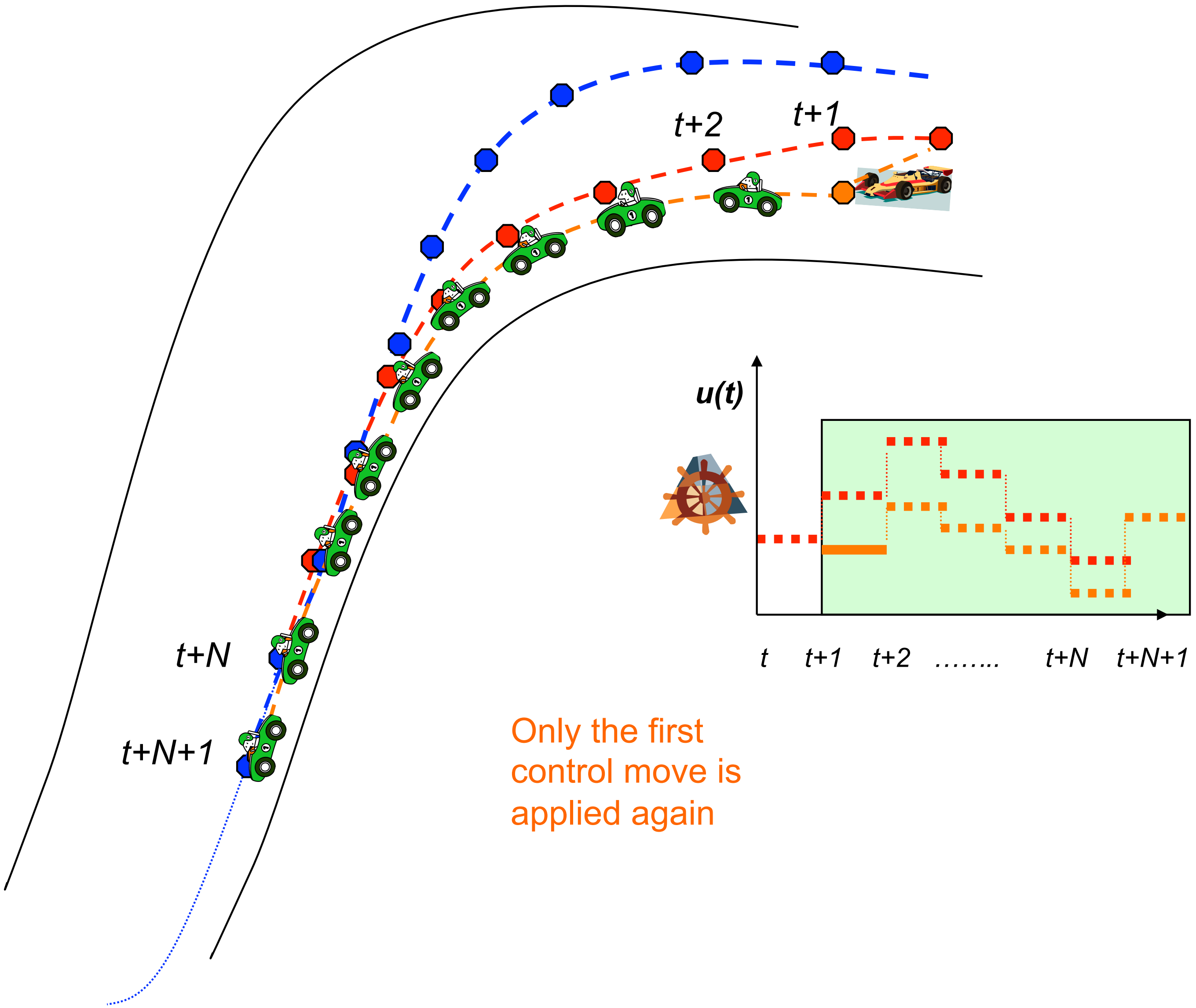
- Problem classicaly solved assuming everything is known.
- If there are uncertainties, to get a robust controller, one has to solve a min-max problem: minimize fuel consumption and verify system constraints even for worst possible uncertainties
- Uncertainties have to be estimated on-line
- Use of Model Predictive Control



Model Predictive Control



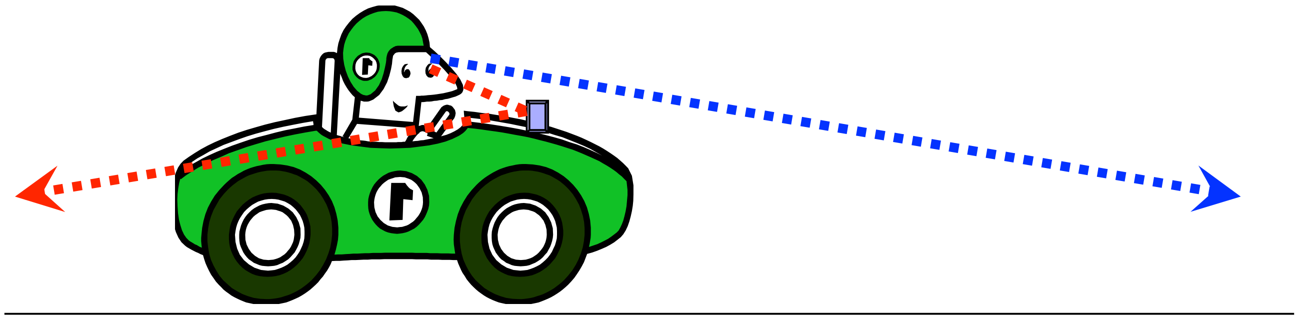
Model Predictive Control



Only the first control move is applied again

MPC vs PID

MPC vs. PID

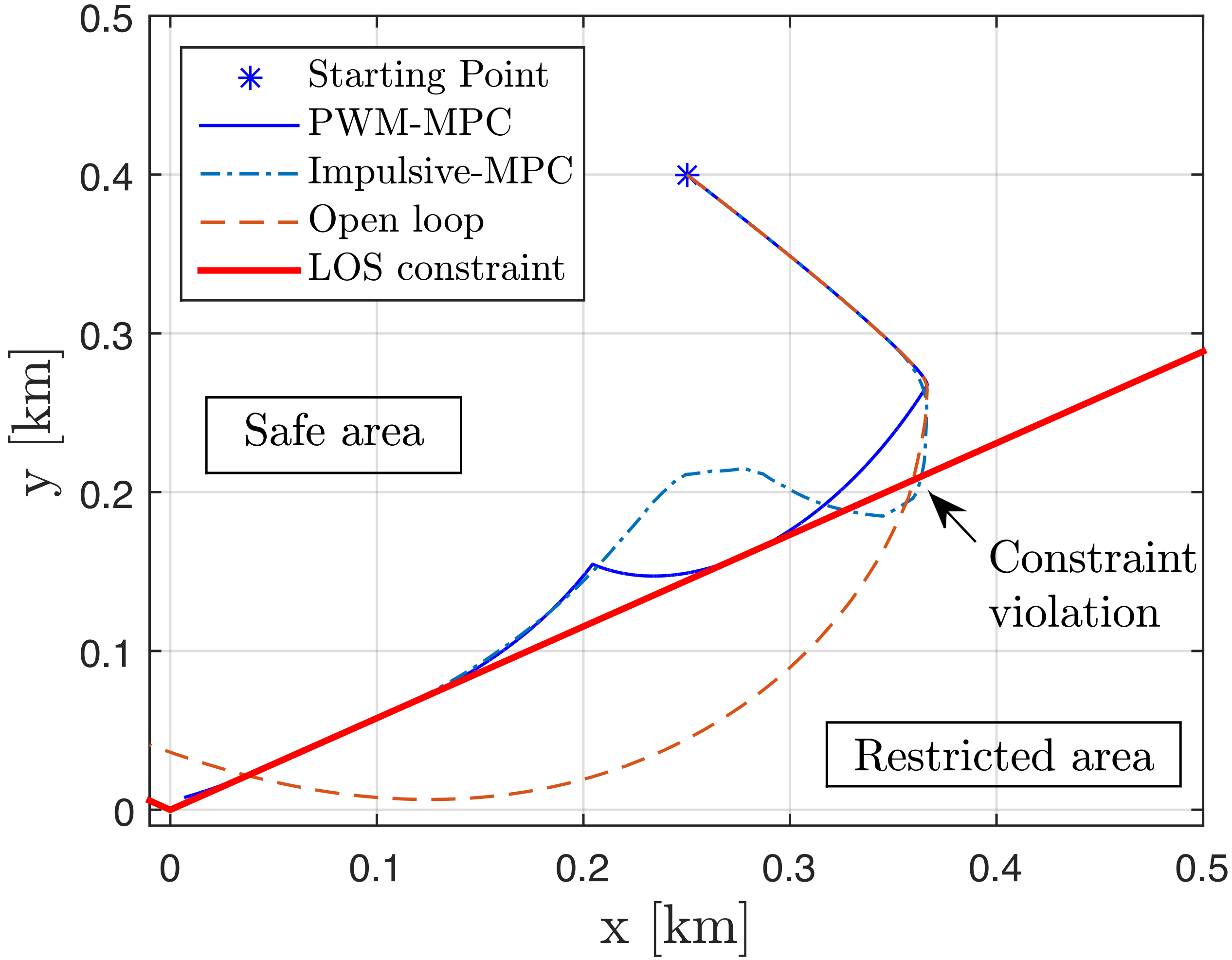


PID: $u(t)=u(t-1)+g_0\, e(t) + g_1\, e(t-1) + g_2\, e(t-2)$

Rendezvous with on-off thrusters

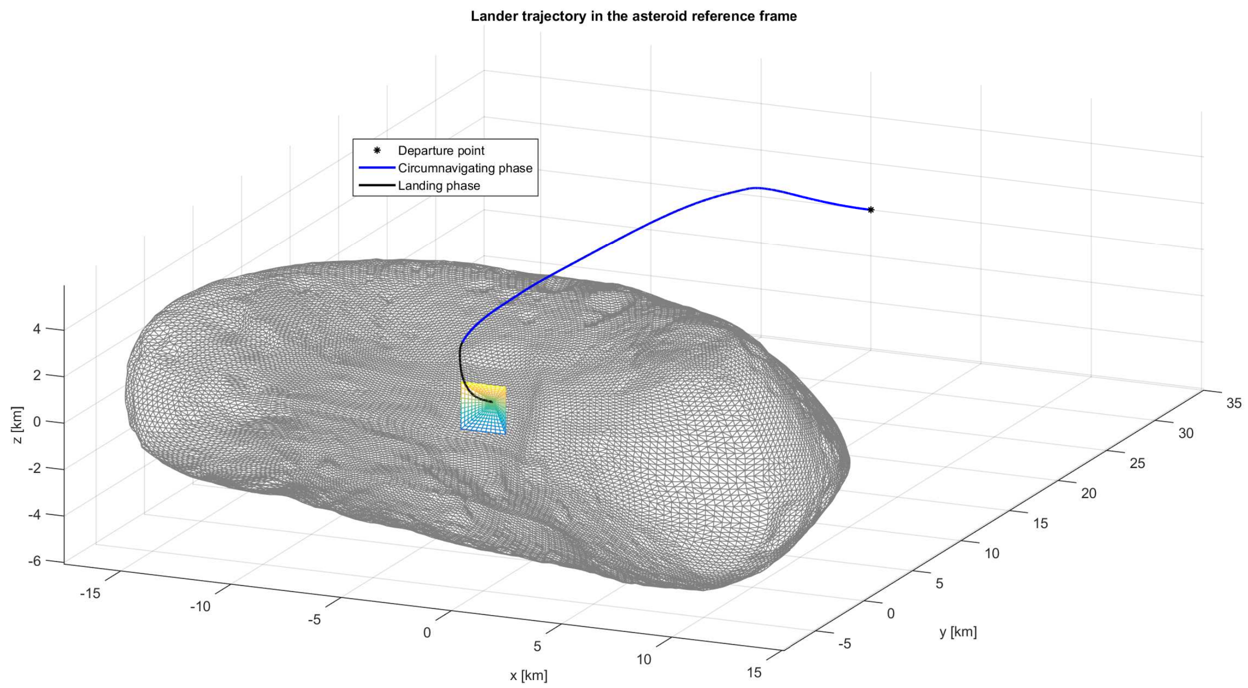
- Development of an algorithm (PWM-MPC) which consider realistic thrusters or any other type of time-varying actuation (e.g. Rotating spacecraft)
- Two main ingredients:
  - Hotstart for optimization computed from impulsive actuation
  - Improvement through successive linearizations until convergence or computation time is up.

Rendezvous with on-off thrusters

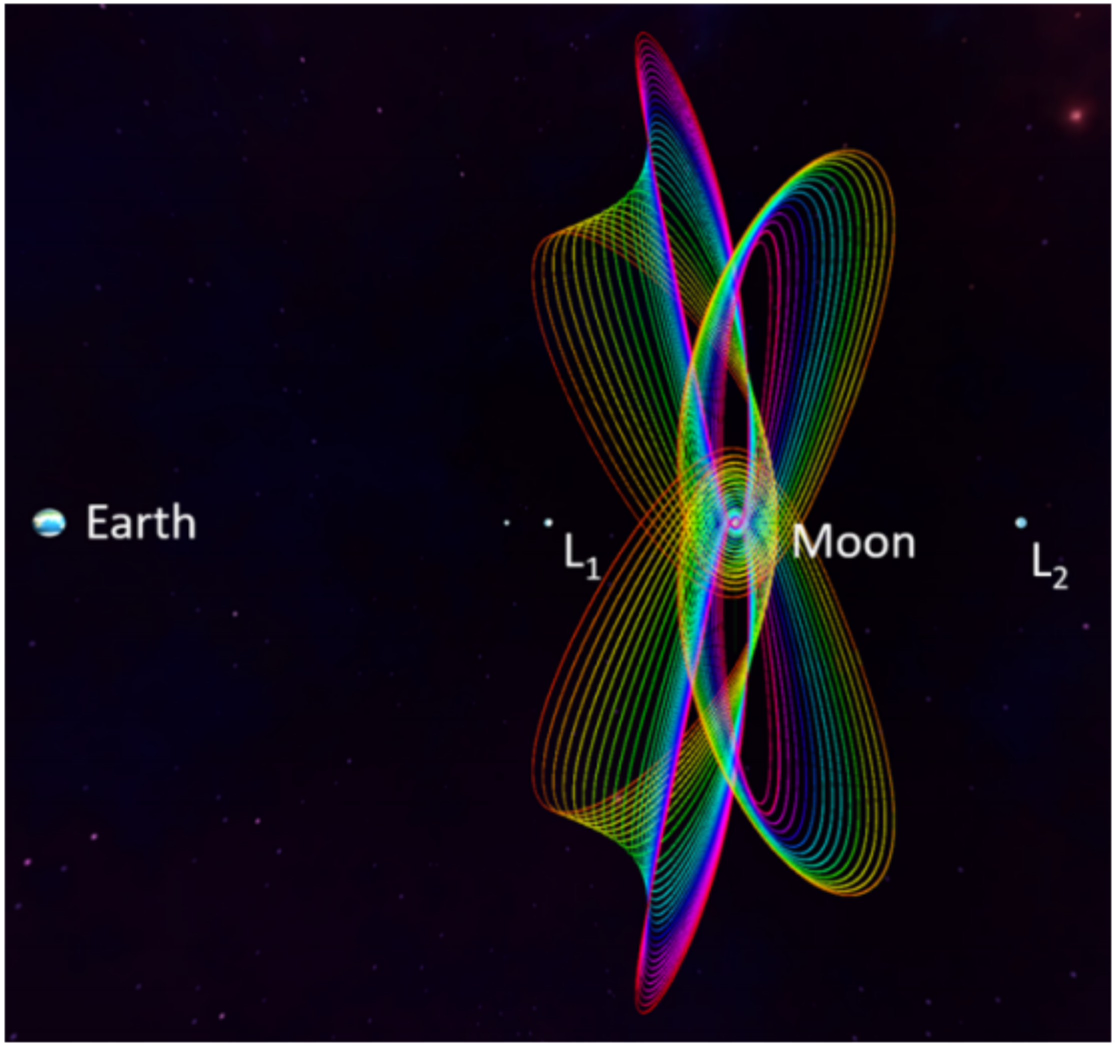


Rendezvous of spacecraft

- Other prospective lines:
  - Rendezvous for a small chaser spacecraft with only 1 or 2 thrusters, and attitude control (J Sanchez Master's Thesis). Challenging if the attitude actuator saturates. Mixes relative dynamics and attitude dynamics.
  - Rendezvous with an asteroid. Considers a triaxial asteroid, major axis spinner. To avoid impact, a tangent plane (rotating with the asteroid) can be used to establish a constraint. (JM Montilla & J Sanchez)

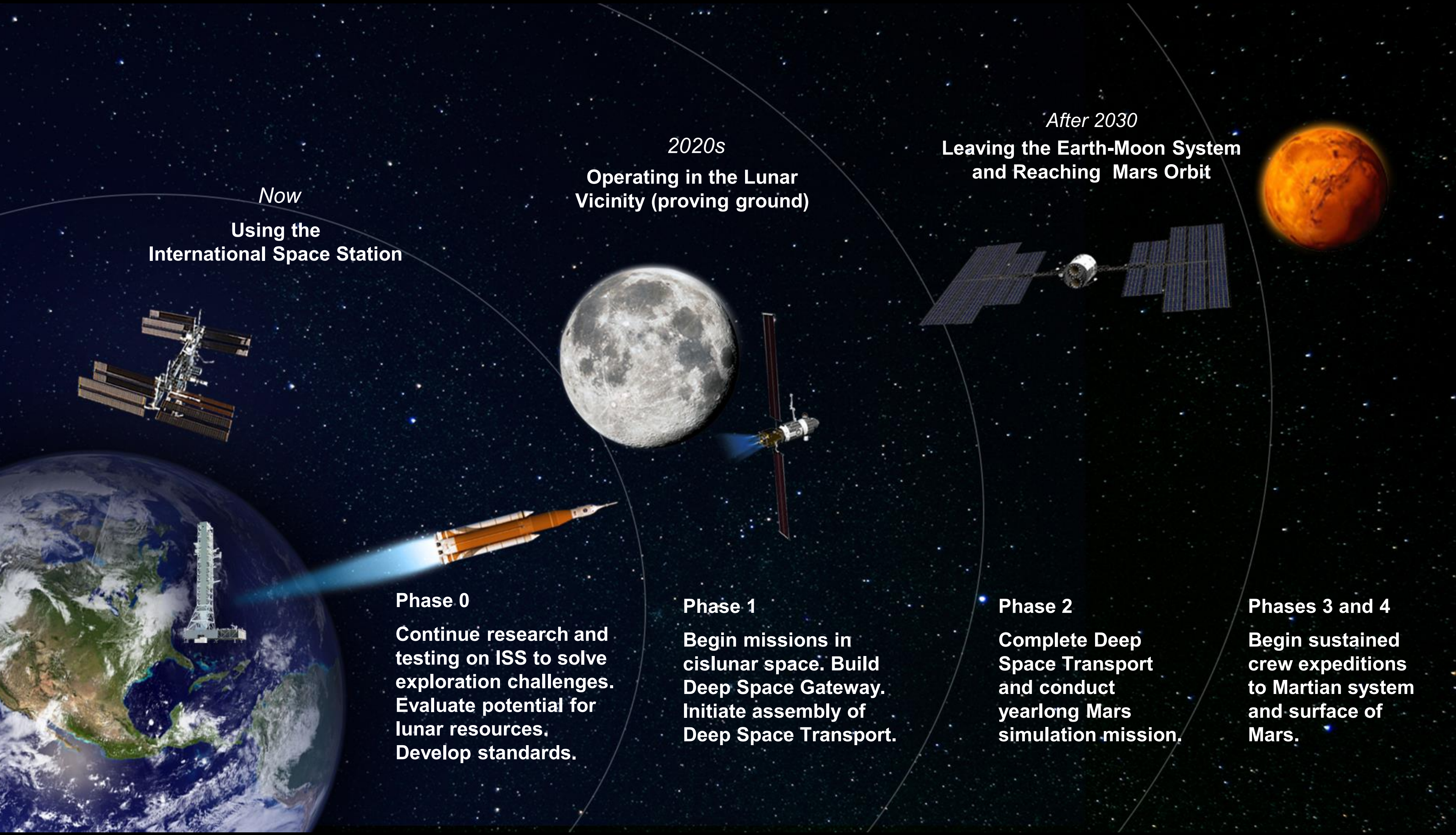


Rendezvous with spacecraft in NRHO (Deep Space Gateway)



EXPANDING HUMAN PRESENCE IN PARTNERSHIP

CREATING ECONOMIC OPPORTUNITIES, ADVANCING TECHNOLOGIES, AND ENABLING DISCOVERY



Conclusions from these projects

- The problems are complex and challenging and there exists a nonzero overlap between the academic and the industry interests.
- Academia needs industry to know what problems are of practical interest and get out of the “ivory tower”...
- Industry can tap into the knowledge of academia and learn about other perspectives and ideas with minimal costs

Thanks!

Questions?