TELESPAZIO VEGA
DEUTSCHLAND
A Finmeccanica / Thales Company

Global Optimization with Hill Climbing in Earth Observation Mission Planning

Christian Wozar

Robin Steel

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OVERVIEW

- Introduction
- Planning Scope
- Planning Strategy
- Benchmark Results
- Conclusion

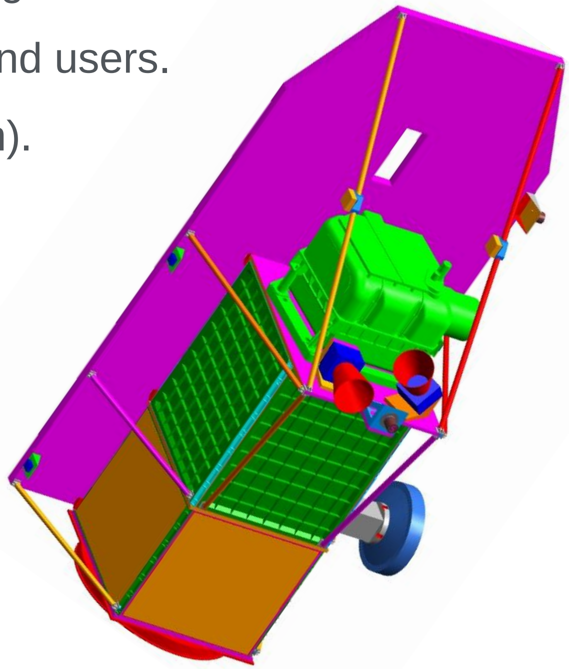
THE PLANNING PROBLEM

- Planning for the PRISMA mission.
- VEGA is developing a mission planning system for Telespazio SpA.
- Global optimisation with constraints:
  - Temporally local and non-local constraints.
  - Memory resource.
- Request and priority driven planning *(oversubscribed).*
- Maximization of priority dependent target function.

THE PRISMA MISSION

"Precursore IperSpettrale della Missione Operativa"

- Italian (ASI) Earth observation mission:
  - In-orbit qualification and verification.
  - State of the art hyperspectral technologies.
- Image data for scientific and institutional end users.
- Single satellite LEO (mean altitude 614 km).
- Frozen sun-synchronous orbit.
- Swath at nadir: 30 km
- Resolution:
  - Hyperspectral: 20 m
  - Panchromatic: 2.5 m



OBJECTS IN THE PLANNING PROCESS

The User Request (UR)

- Users can request images of the following target areas:
  - **Spot image:** 30x30 km
  - **Stripmap:** 30xL km, L = 30, 60, 90, ..., 1800.
- Such a request can be valid for up to 4 weeks.
- If *one* image is taken, the request is fulfilled!

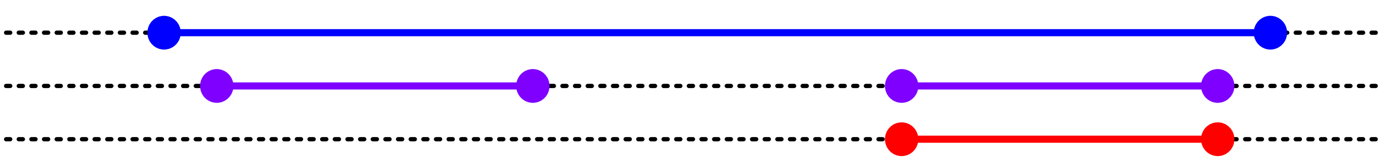
Here, we only consider the *spot images!*

OBJECTS IN THE PLANNING PROCESS

The Data Take Opportunity (DTO)

- For every UR there are a number of opportunities to take the image.
- Constraints on data takes:
  - Constant roll during acquisition (-18° to +18°).
  - *No* pitch flexibility.
- DTO duration is constructed from predicted orbit.

If one DTO is planned to a Data Take *Activity* (DTA), the UR is fulfilled.



OBJECTS IN THE PLANNING PROCESS

The Downlink Opportunity (DLO)

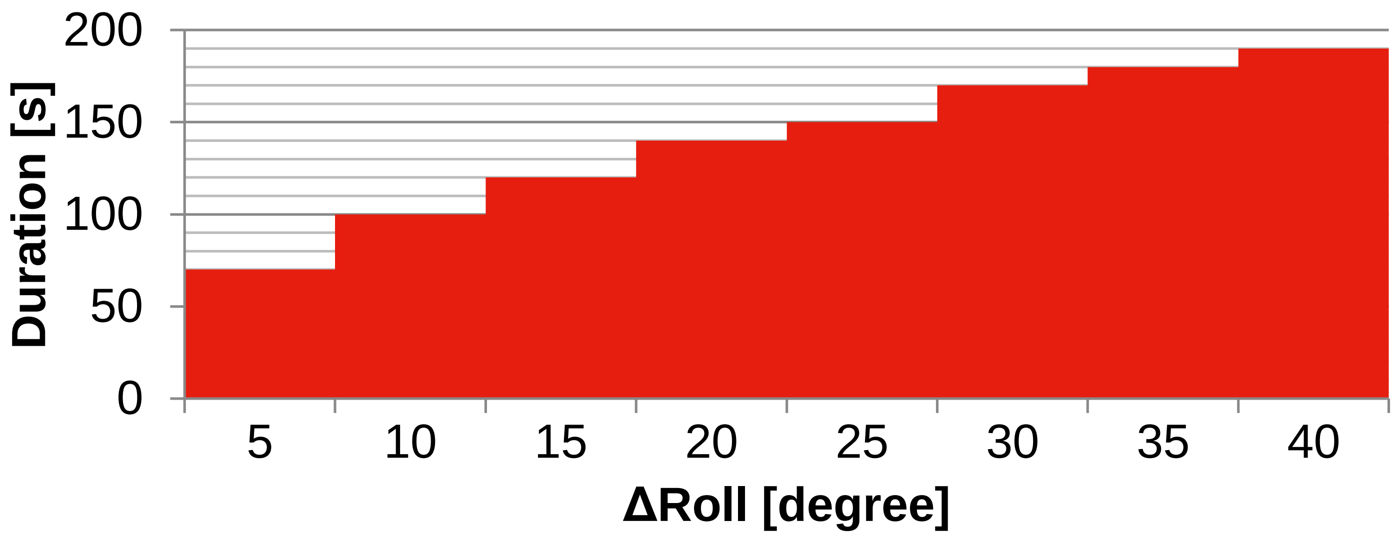
- Opportunities for downlink are derived from:
  - Ground station locations.
  - Roll angle profile (for image takes).
  - Predicted orbit.

- A Downlink Activity (DLA) must fulfill:
  - Full data of one UR is downlinked without interruption.
  - DLA to happen within DLO.
  - Downlink during data take is possible.

CONSTRAINT SETUP

C-1: Maneuver Duration

- Between any two planned DTAs:
  - A maneuver is required to change the roll angle.
  - Duration depends on the roll angle variation (between 0° and 36°).



CONSTRAINT SETUP

C-2: Earth Pointing Duration per Orbit

- For any orbit of ca. 97 min:
  - Only 15 min are allowed between start of first DTA/DLA and end of last DTA/DLA.

- This covers about 55° of latitude.
- Maximum of 13 images per orbit.

- Enough to cover “Primary Area of Interest” (30°N to 70°N, 10°W to 50°E).
- *Not enough* to cover the full area of interest (*60°S to 70°N*, any longitude)!

CONSTRAINT SETUP

C-3: Payload Duty Cycle

- Thermal constraint:
  - Only up to *four orbits in a row* for DTAs.
  - After any sequence of DTAs, at least *four orbits without DTAs.*

CONSTRAINT SETUP

C-4: Memory Fill Level

- On-board memory capacity of 256 Gbit.
- Enough to hold about 100 spot images.
- Memory can be re-used directly after downlink.

C-5: Downlink Budget

- DLO duration depends on the attitude taken during acquisitions:
  - Shorter duration if rolling away from ground station.
- If possible, satellite placed to nadir to allow for maximum DLO.

TARGET FUNCTION

- Every UR i has a priority level P_i.
- P_i will be between 2 and 100.
- Weight of the request is $1/P_i$.
- P=1 is reserved for *urgent requests*, which must be planned.

Target function: **$F_1 = Q$ (# planned urgent) + $\Sigma_i\ (1/P_i)$**

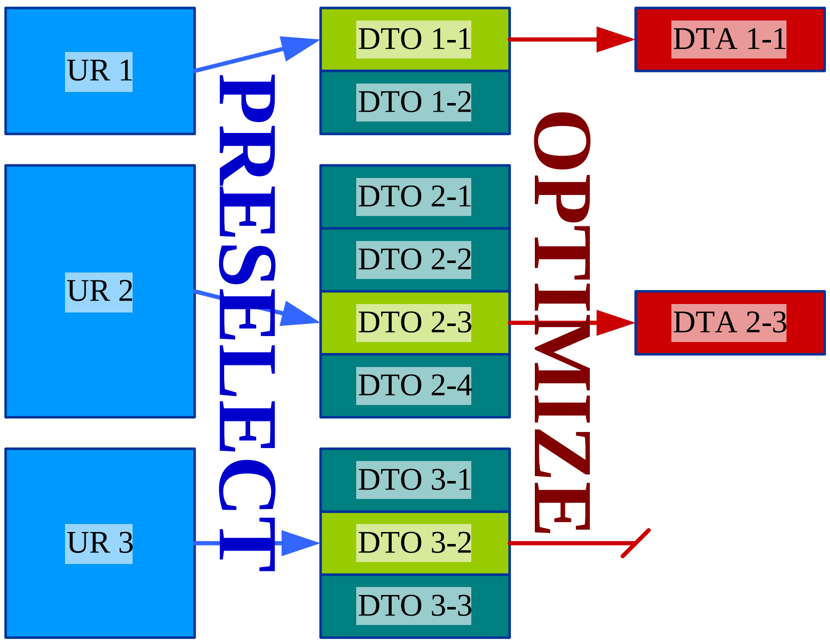
- Q is an arbitrary high number (e.g. 10,000).
- Sum runs over all successfully planned requests.

For benchmarking:

- F_1' = # planned urgent requests
- $F_1'' = \Sigma_i\ (1/P_i)$
- R = # planned requests in total

GLOBAL PLANNING LOOP – HILL CLIMBING

- **Configuration space:** Assignment of URs to one DTO per UR.
- Hill climbing does *preselection of DTOs.* (No knowledge about constraints.)
- Constraint solving and optimization derive DTAs (and DLAs) from exactly one DTO per UR. **=> Value of F_1**



GLOBAL PLANNING LOOP – HILL CLIMBING

Locality definition:

The assignment of URs to DTOs differs only on one UR.

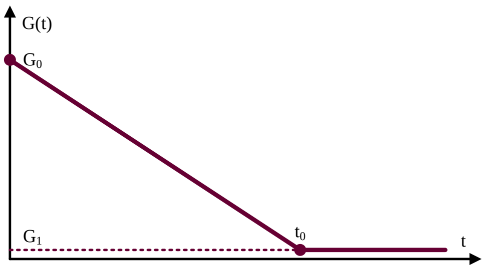
Hill climbing iteration:

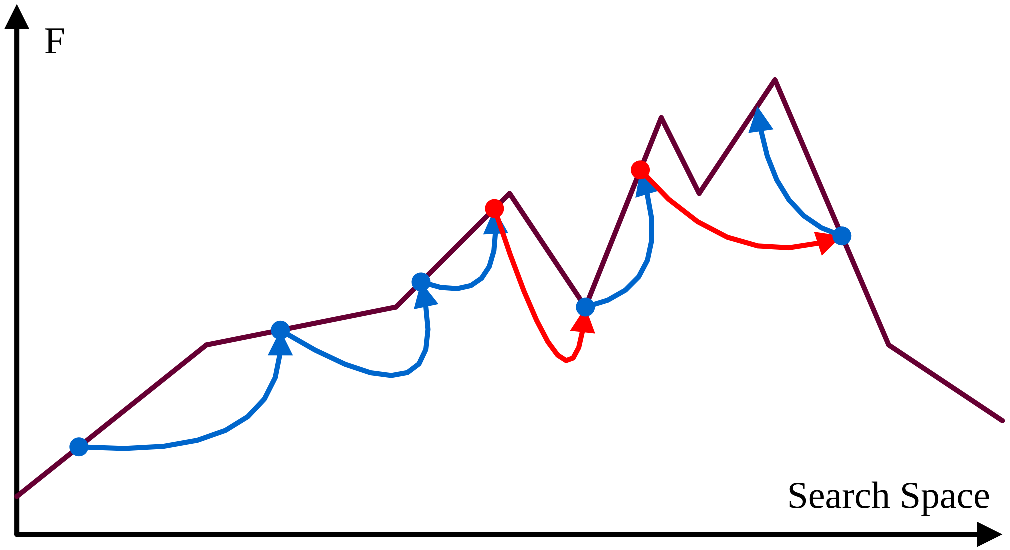
- Compute F_1 for all configurations in the local neighborhood.
- Select the optimal configuration (“steepest ascent”).

- Our version uses “coordinate ascent”:
  - Only configurations that vary the DTO selection **for exactly one UR** are compared.
  - Additional loop over all URs.

PERTURBED HILL CLIMBING

- Accept a new configuration, even if F_1 is lower than the last value, using a *perturbation function*.
- Perturbation function iteration number dependent.
- Store the configuration with the best F_1 over all iterations.

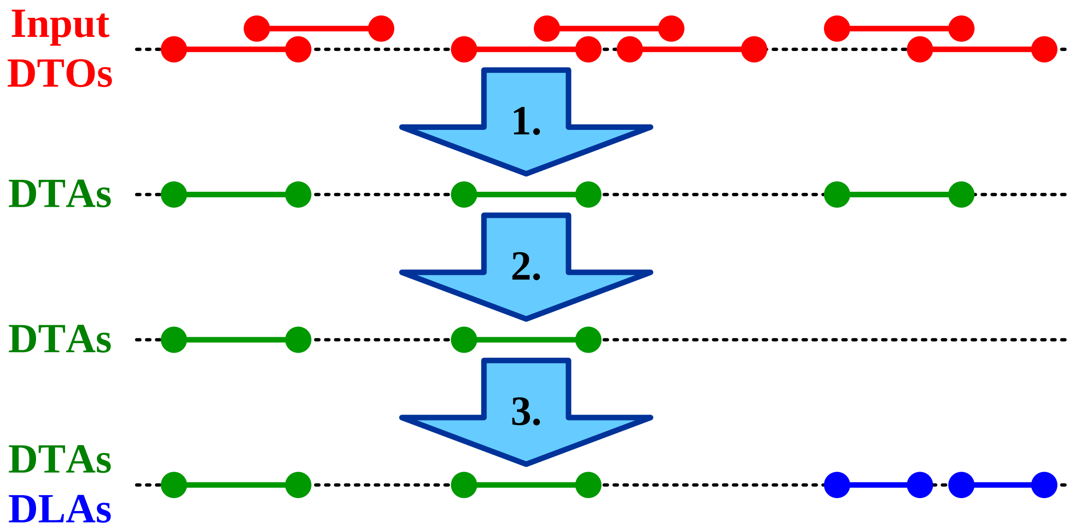




OPTIMIZATION AND CONSTRAINT SOLVING

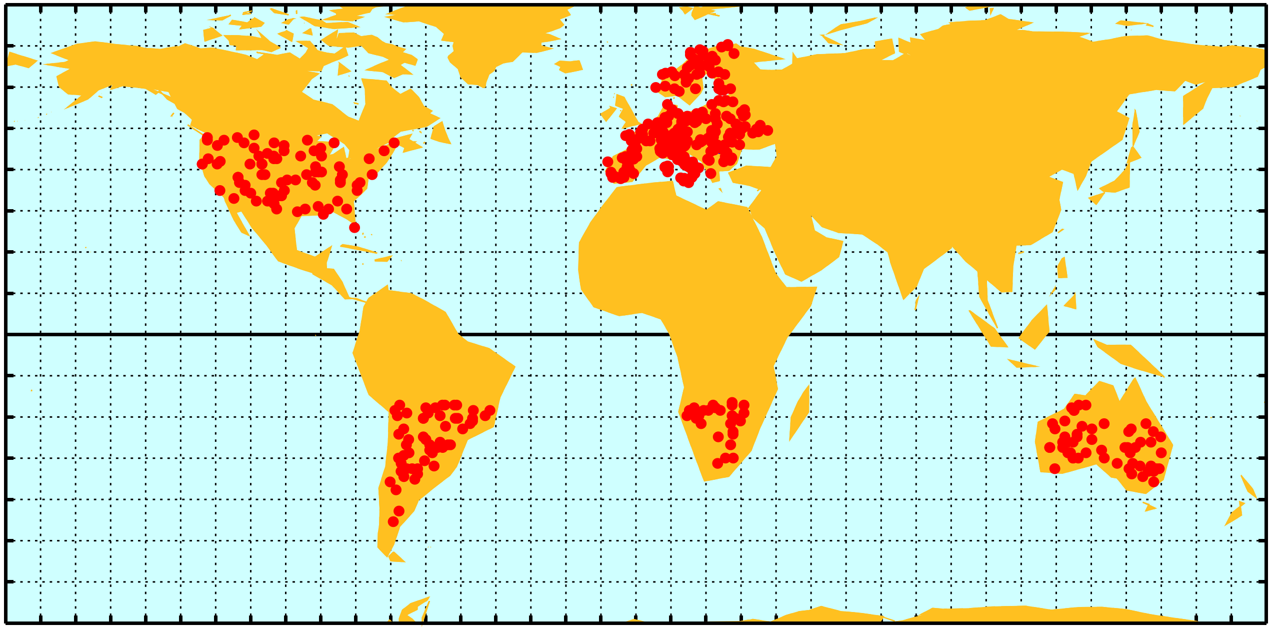
For any preselection of DTOs, an optimal result is computed by *hierarchization of constraints:*

1. Temporal constraints C-1 and C-2 are solved: **Dynamic programming.**
2. Orbits are optimized under C-3: **Dynamic programming.**
3. Downlinks are planned using C-4 and C-5: **Link budget / memory model and priority based assignment of DLAs.**



BENCHMARK INPUT DATA

- 500 URs for spot images (30x30 km).
- 28 day time range.
- 2103 DTOs in total.
- One downlink station in Matera (2 or 3 contacts every day and every night).

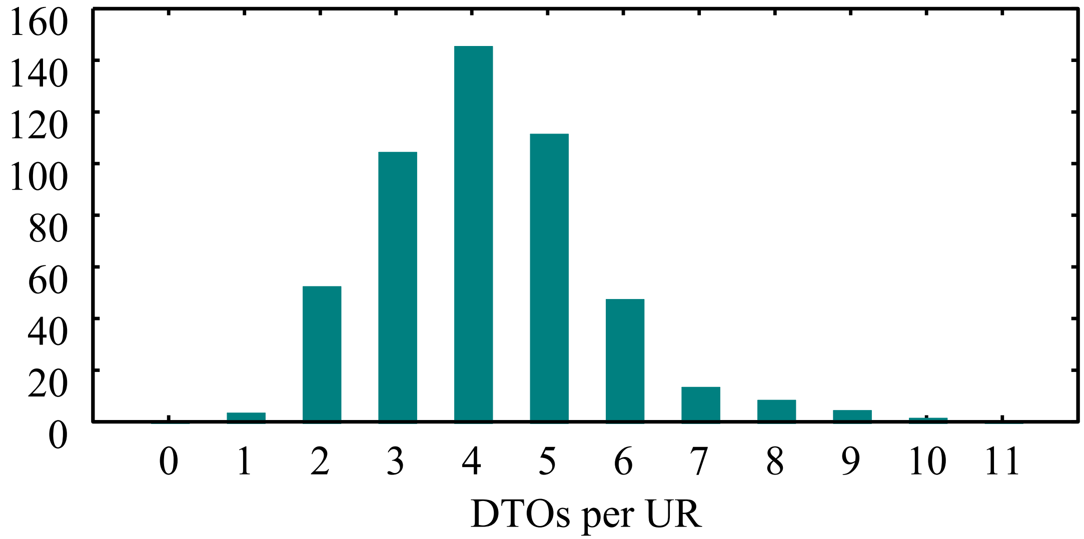


BENCHMARK INPUT DATA

Priority level distribution:

Priority	1	10	11	12	13	14	15	16
Count	4	141	126	51	41	46	53	38

DTOs per UR histogram:



ALGORITHM SHOOTOUT

Four different algorithms are compared:

- Perturbed Hill Climbing **(PHC)**
- Standard Hill Climbing **(SHC)**
- Simulated Annealing **(SA)**
- Simple Greedy search **(SG)**

Parameters are tuned for every algorithm (if possible).

Measurements are taken on Intel Xeon X5560 (2.8 GHz), single core.

ALGORITHM SHOOTOUT

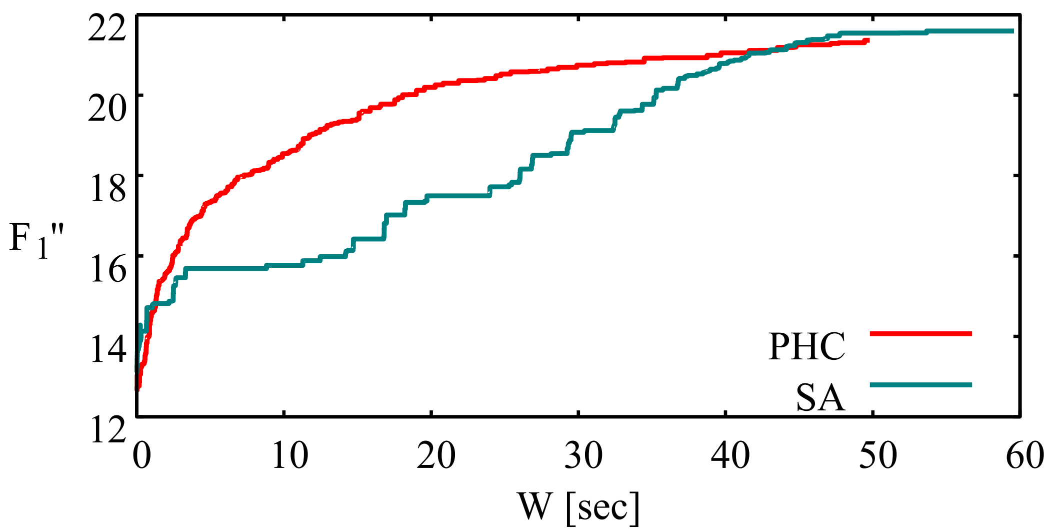
Planning Quality and Speed

Method	PHC	SHC	SA	SG
F_1'	4	4	4	4
F_1''	21.364	20.702	21.596	16.066
R	244	236	248	181
Wall time [sec]	49.8	51.6	59.6	1.1

- PHC better than SHC.
- SA slightly better than PCH.
- *SA found to be largely parameter dependent.*
- SG falls back behind any other algorithm.

ALGORITHM SHOOTOUT

PHC vs. SA Convergence



- PHC shows faster convergence!
  - PHC to be used in time-constraint planning situations.
    - Scenario: Urgent replanning minutes before contact.

PLANNING HORIZON DEPENDENCY

Using PHC

- The full scenario (4 weeks) is planned in blocks of B days.
- Unplanned URs are reused on the next block.

B	28	14	7	4	2
F_1'	4	4	4	4	4
F_1''	21.364	20.395	19.789	19.311	19.178
R	244	237	229	223	221

- Larger blocks give better results: **Global optimisation is effective!**
- For comparison: Nominal PRISMA planning horizon of **1 day!**

POSSIBLE ALGORITHMIC EXTENSIONS

- Boundary conditions can easily be taken into account:
  - Every constraint type considers its own conditions.

- Flexibility in replanning strategies:
  - Replanning from scratch.
  - Starting the hill climbing from the last solution and adding new URs:
    - Keeping only the old planned DTAs as input DTOs.
    - Allowing for all DTOs of already planned URs.

- Constraint solving for every DTO trial in one hill climbing step in parallel:
  - Using OpenMP a speedup of 1.5 on 2 cores is gained.

RESULT

Perturbed hill climbing found to be powerful for PRISMA planning!

- Main components of the planning:
  - Some constraints can be solved exactly.
  - Configuration space: Assignment of URs to DTOs *(and not DTAs).*
  - Valid solution is produced at every step.

- PHC should be considered when:
  - Some constraints can be solved exactly.
  - Multiple DTOs per UR within the planning horizon.
  - Time constrained planning operations.