ARIEL Scheduling

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Goal

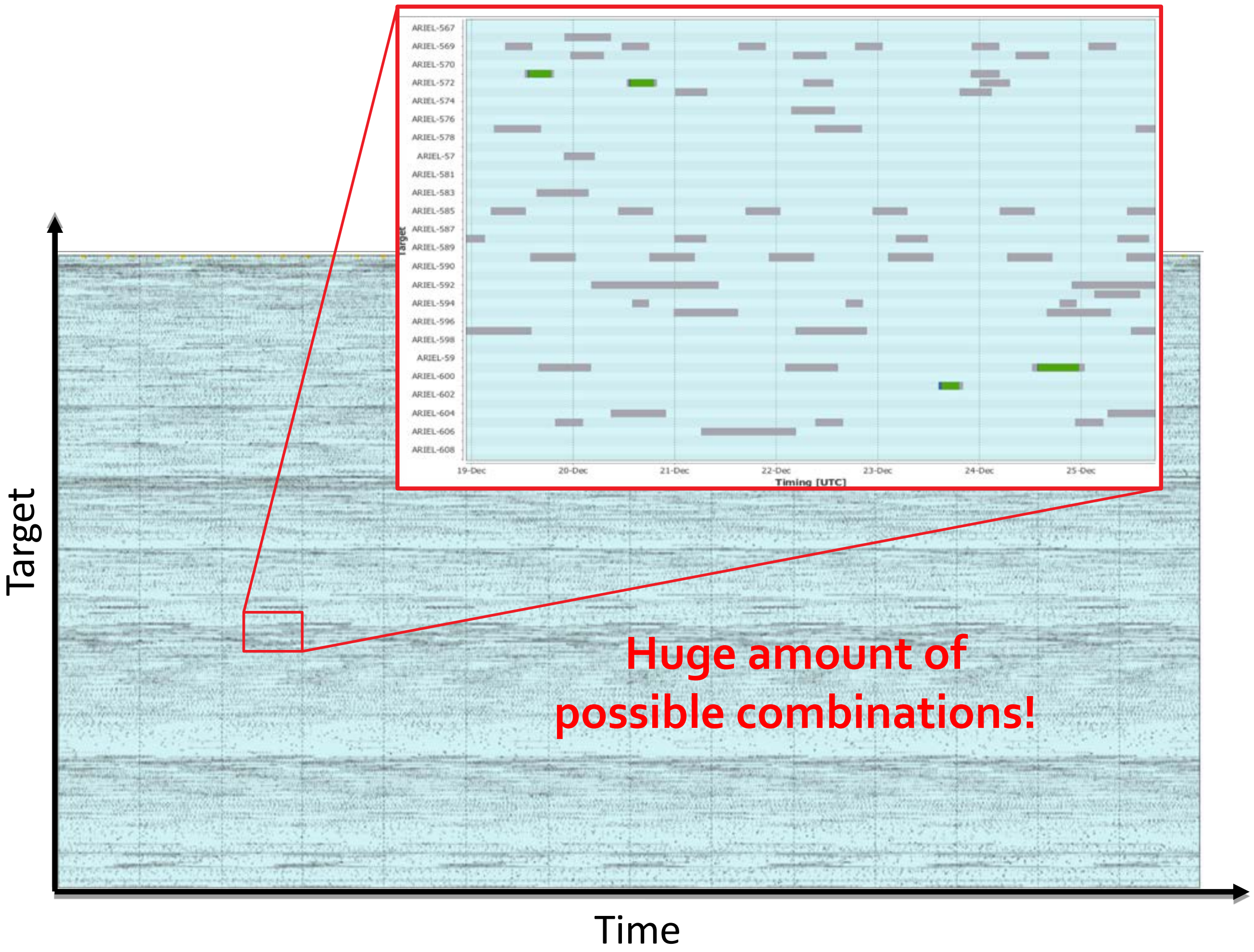
- Prepare a tool to <u>automatically</u> plan ARIEL observations and operations
- Study the feasibility of the ARIEL science goals within the mission lifetime
  → Survey 1000 exoplanets
- But also, analysis of the targets sample, mission parameters trade-off analysis.

Input

- List of targets and requirements
- Payload operations: calibrations, house keeping…
- Mission constraints: orbit, field of regard…

Output

- Timeline of the mission including: target observations, slew, calibrations, station keeping…
- Monthly update recalculation during operations: feedback, new targets…



ARIEL Scheduling

Input target list (Edwards, 2019, AJ 157, 242)
Includes coordinates, ephemerides, number of observations, priorities…

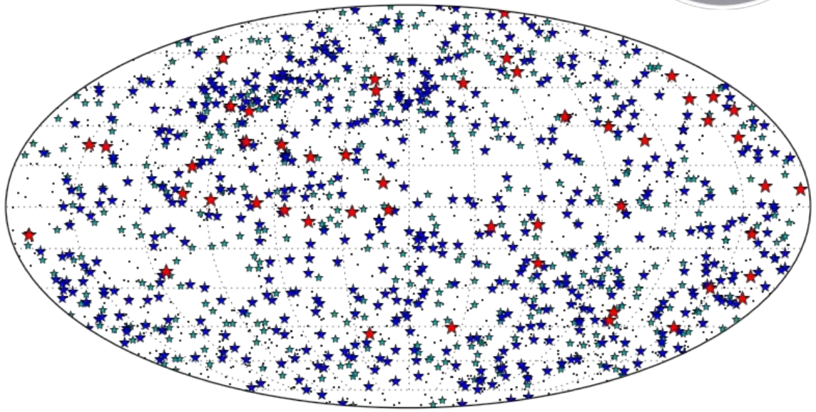
Three Tiers approach : 1000 planets

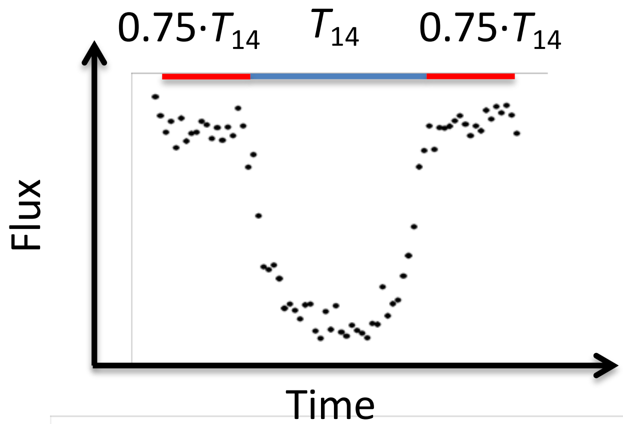
- Tier 1 - Survey planets: 400 (*397 without ph-curves*)
  1-5 obs/target (~ 1.2 obs/target)
  Event duration ~ 9 h

- Tier 2 - Deep planets: 550 (*526 without ph-curves*)
  1-19 obs/target (~ 4.1 obs/target)
  Event duration ~ 8.5 h

- Tier 3 - Benchmark planets: 50 (*40 without ph-curves*)
  1-2 obs/target (~ 1.8 obs/target) but re-visits desired
  Event duration ~ 6 h

- Back-up targets: 1093
  1-5 obs/target (~ 3.3 obs/targets)



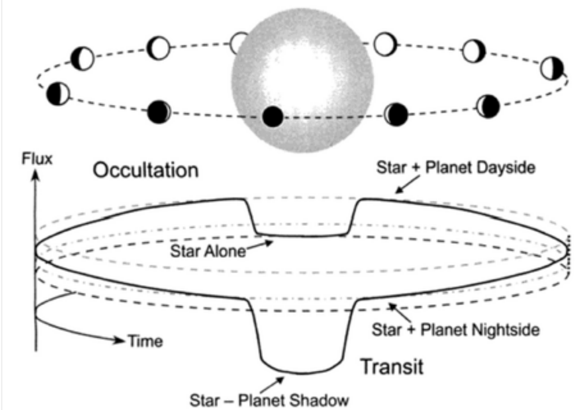


Observations
Time constrained:

- Transits
- Occultations (eclipses)

} Total duration: 2.5 x T_{14}

- Phase curves (~ 5 – 10% mission lifetime)
  → Also time constrained from occultation to occultation

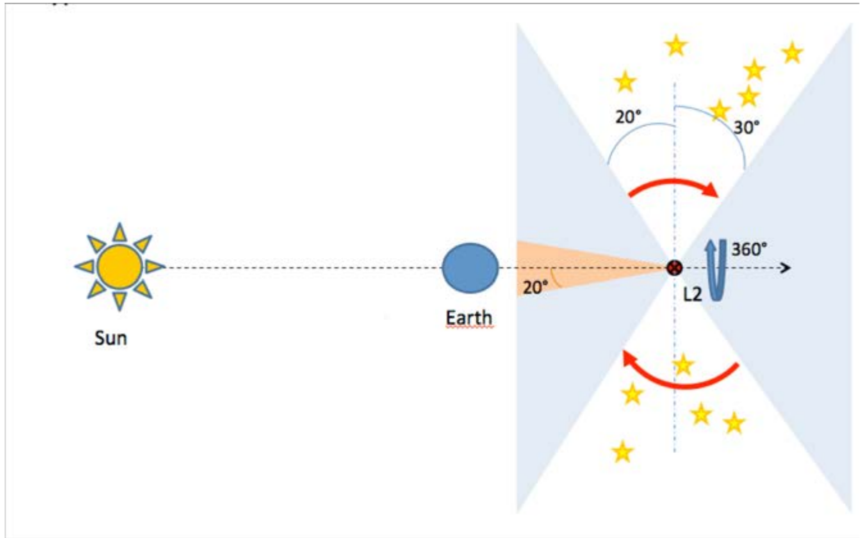


Mission constraints

Observational constraints:

- L2 orbit
- 3.5 years operations (mid-2028 to 2031)
- Field of regard: 20-30 deg
- Telescope slew time: 4.5 deg/min + 5 min
- Observable target events

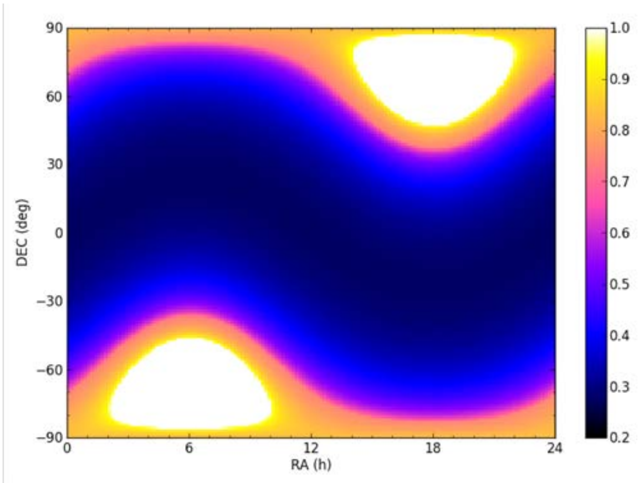
predictable



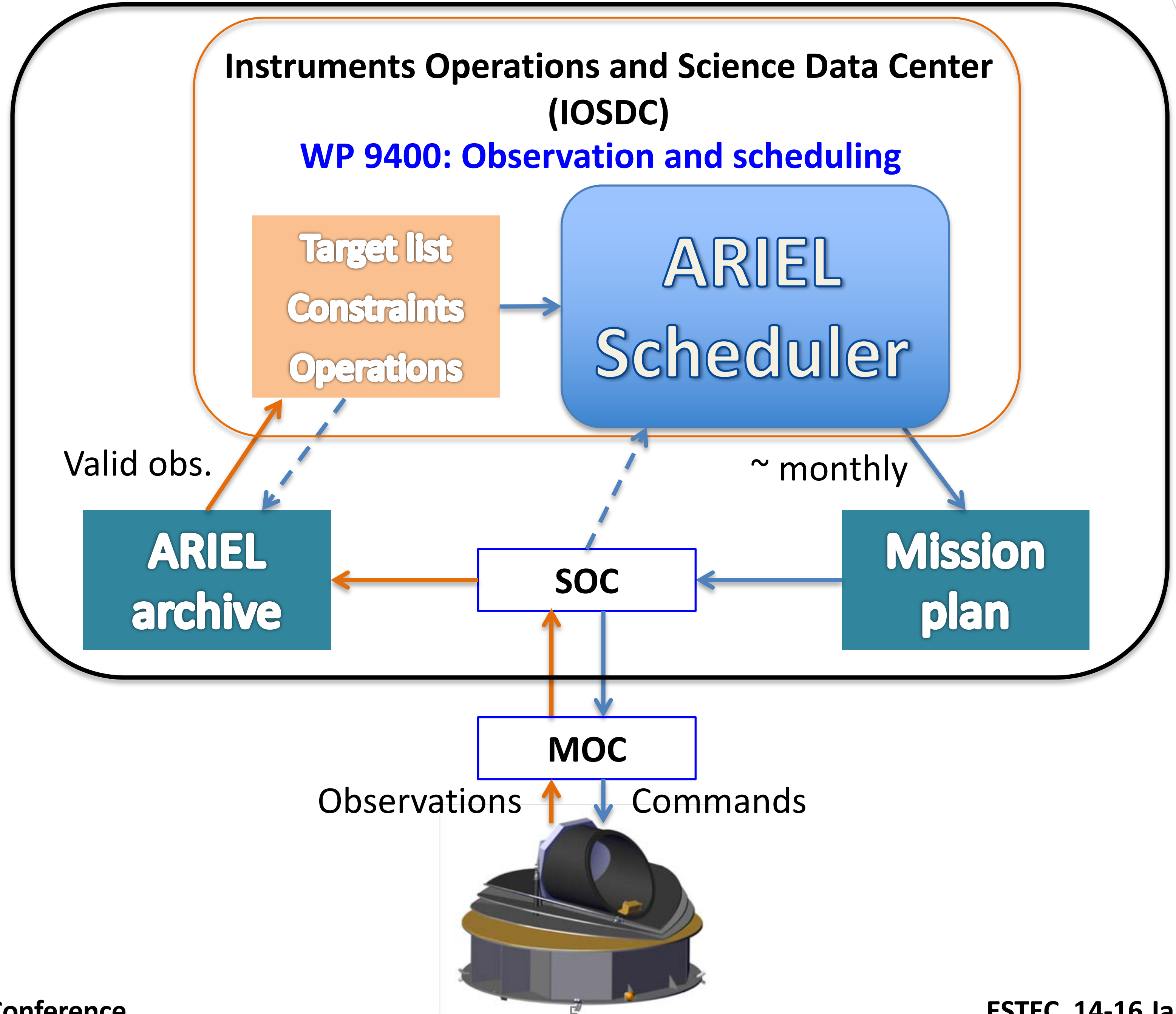
Operation tasks:

- Calibration observations: observe stable G stars
  - → Short calibrations: 1h every 36 ± 12 hours
  - → Long calibrations: 6h every 15 ± 5 days
- House keeping operations: 4 hours every 28 ± 3 days
- No overlap with observations
- Downlinks (not affecting scheduler)

~ flexible constraints



Mission planning during ARIEL operations



Scheduling algorithm: Evolutionary Multi-objective Optimization (IEEC, Barcelona)

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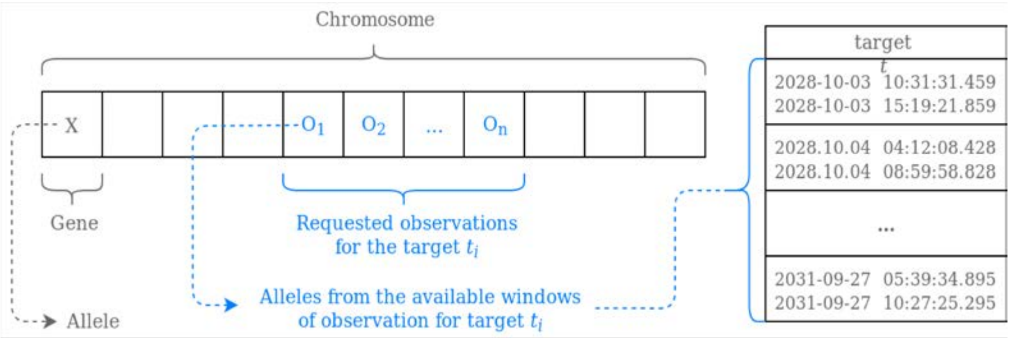
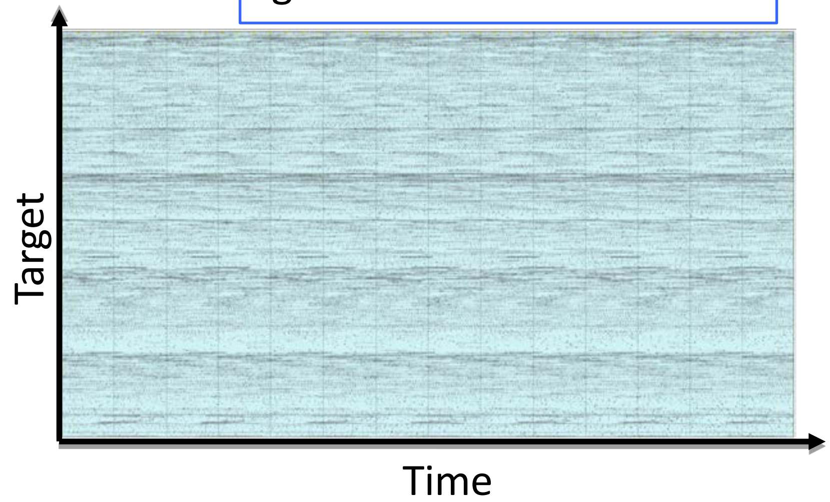
Ignasi Ribas

Genetic algorithms

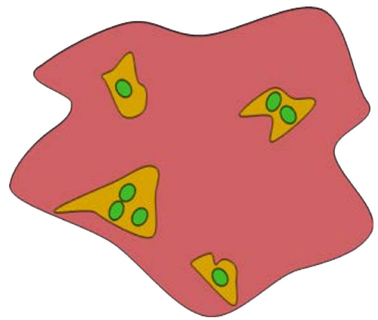
- Parameter space exploration and optimization
  → Start from random plans fulfilling constraints
  → Produce a population solutions by crossover and mutation
  → Select best plans according to optimization criteria





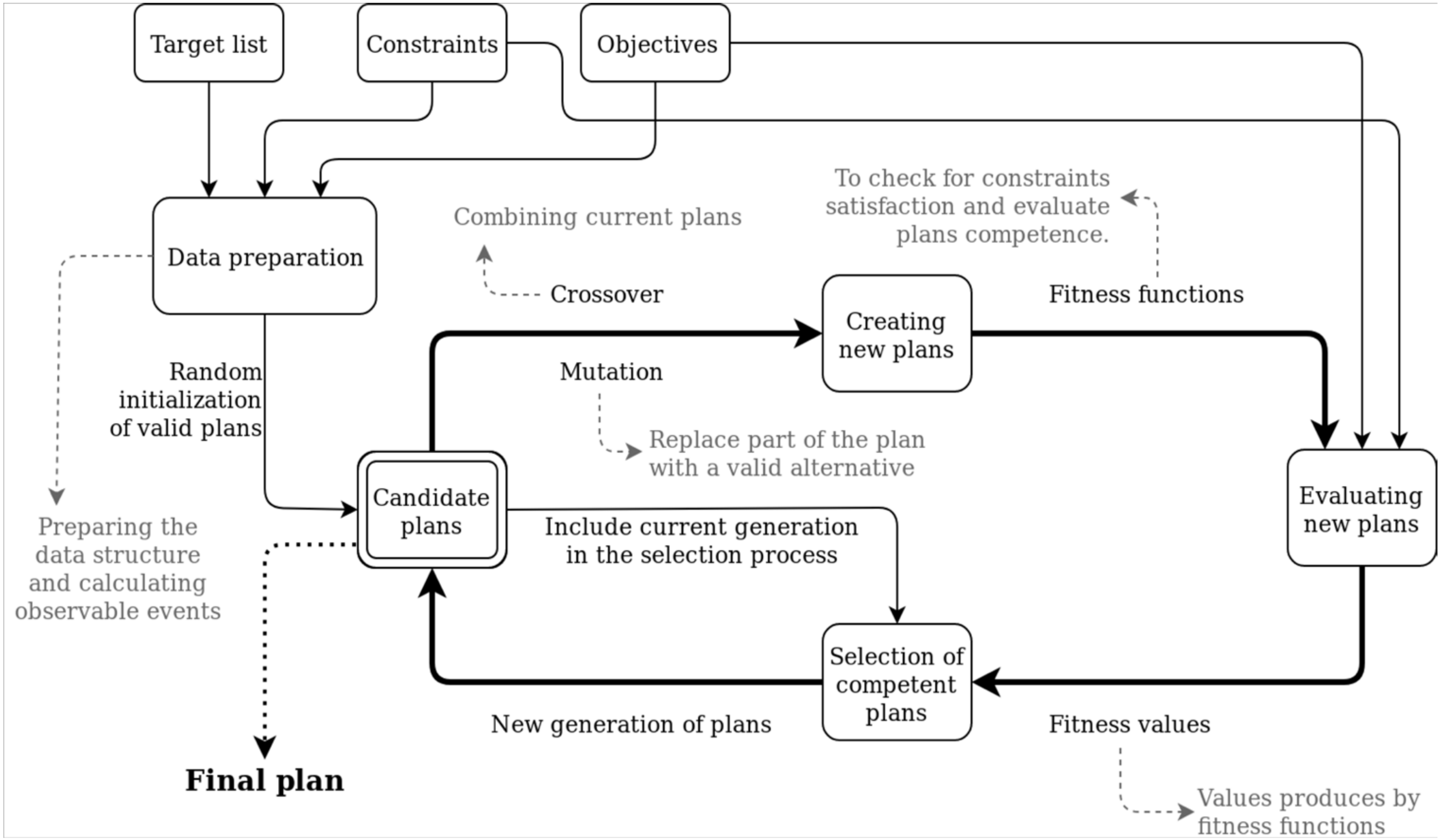
Pros:
- Constraints easily adapted: visibility, number of visits per target, calibration sequences, slew rate, overlapping tasks…
- Several simultaneous optimization criteria
  → Maximize the total time on targets (i.e. minimize slew)
  → Maximize the number of completed sequences
  …
- Exploration of the full parameter space to avoid local minima

Cons:
- Computationally expensive… but only ~20 minutes
  … and working to improve (adding new targets < 1 sec)



- Region with all the combinations
- Region with feasible solutions (search space)
- Efficient solution

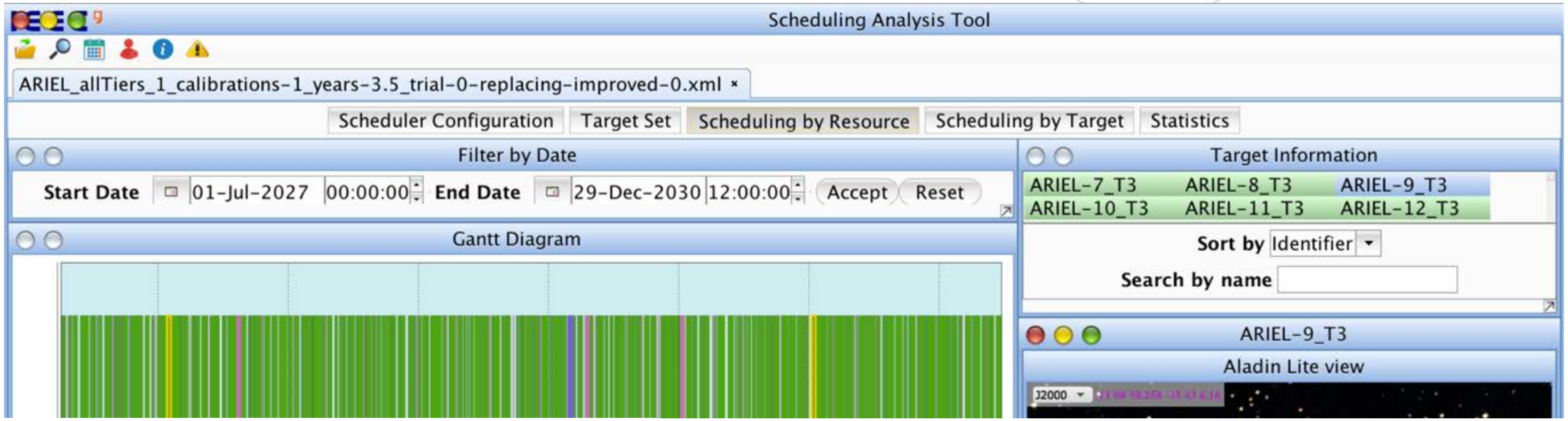
Scheduling algorithm: Evolutionary Multi-objective Optimization (IEEC, Barcelona)



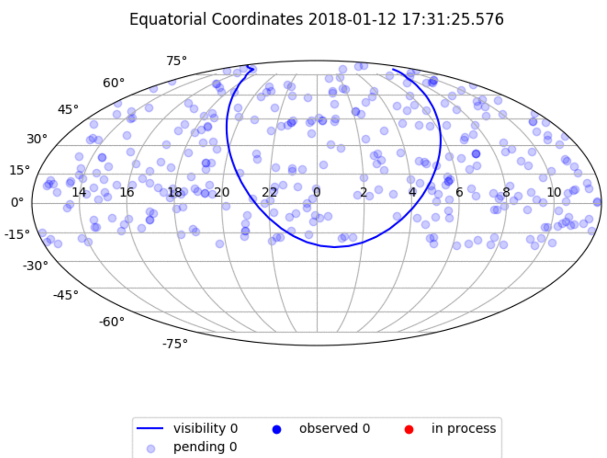
Scheduling algorithm: Evolutionary Multi-objective Optimization (IEEC, Barcelona)

Tool already in operation

Garcia-Piquer et al. (2017)



CARMENES



ARIEL

HJD start	HJD end	Task	Target
2461811.35980324	2461811.36535879	slewing to	ARIEL-1392_T1
2461811.36535879	2461811.49997685	tracking	ARIEL-1392_T1
2461811.50000000	2461811.83333333	station_keeping	
2461811.91269675	2461811.93020833	slewing to	ARIEL-339_T2
2461811.93020833	2461812.21916666	tracking	ARIEL-339_T2
2461812.26692129	2461812.28706018	slewing to	ARIEL-613_T1
2461812.28706018	2461812.34229166	tracking	ARIEL-613_T1
2461812.37726851	2461812.39648148	slewing to	ARIEL-46_T3
2461812.39648148	2461812.58192129	tracking	ARIEL-46_T3
2461812.58194444	2461812.58750000	slewing to	Calibration 23
2461812.58750000	2461812.62847222	calibration	Calibration 23
2461812.62848379	2461812.63403935	slewing to	ARIEL-895_T1
2461812.63403935	2461812.91254629	tracking	ARIEL-895_T1
2461812.93690972	2461812.95318287	slewing to	ARIEL-1216_T1
2461812.95318287	2461813.09372685	tracking	ARIEL-1216_T1
2461813.09375000	2461813.10030092	slewing to	ARIEL-284_T2
2461813.10030092	2461813.42968750	tracking	ARIEL-284_T2

Scheduling algorithm: Evolutionary Multi-objective Optimization (IEEC, Barcelona)

Scheduling process:

Mission Reference Sample, 1000 targets (+1093 back-up): T1 – 400 (+1093), T2 – 550, T3 – 50

Target	Preferred Observation	Tier 1 Obs	Tier 2 Obse	Tier 3 Obs	Type	Tier
ARIEL-2	Eclipse	1	1	1	K-H-J	3
ARIEL-3	Eclipse	1	1	1	G-VH-J	3
ARIEL-4	Transit	1	1	2	M-W-SN	3
ARIEL-5	Transit	1	1	1	K-H-J	3
ARIEL-6	Eclipse	1	1	1	G-VH-MJ	3
ARIEL-7	Eclipse	1	1	2	K-VH-J	3
ARIEL-7	Transit	1	1	1	F-VH-J	3
ARIEL-8	Eclipse	1	1	1	G-UH-MJ	3
ARIEL-9	Eclipse	1	1	1	F-VH-MJ	3
ARIEL-10	Eclipse	1	1	1	G-VH-J	3

Observations for each TIER block

Requested TIER

<u>Schedule sequence:</u>

1. Schedule targets to complete highest TIER block
2. Remove uncompleted TIER blocks
3. Fill gaps with targets that can be completed
4. Evaluate gaps between transit observations
5. Fill gaps re-visiting targets or with back-up targets

Case 1 (steps 1–3)

Case 1-fill (steps 4–5)

Scheduling algorithm: Evolutionary Multi-objective Optimization (IEEC, Barcelona)

Scheduling results:

→ **Mission Reference Sample** (MRS), 1000 targets: T1 – 400, T2 – 550, T3 – 50

Test case	Completed targets	Working time			Waiting time
		On targets	Slewing	Cal. + S. Keep	
Case 1	989	68.7 %	3.7 %	4.1%	23.5 %

Case 1 (MRS) → **On targets** 3132 events (~ 21100 hours)

Slewing: ~ 1200 h
Calibrations: ~ 1200 h
Station Keeping: 180 h
Waiting time: ~ 7000 h

Scheduling algorithm: Evolutionary Multi-objective Optimization (IEEC, Barcelona)

Scheduling results:

→ **Mission Reference Sample** (MRS), 1000 targets: T1 – 400, T2 – 550, T3 – 50

→ **MRS + re-visits + back-up targets**: 1000 (+1093): T1 – 400 (+1093), T2 – 550, T3 – 50

Test case	Completed targets	Working time			Waiting time
		On targets	Slewing	Cal. + S. Keep	
Case 1	989	68.7 %	3.7 %	4.1%	23.5 %
Case 1-fill	1194	77.5 %	4.7 %	4.1%	13.7 %

On targets

Case 1 (MRS) → 3132 events (~ 21100 hours)

Re-visits + back-up targets ↓

Case 1-fill (MRS + revisits + back-up) → +900 events (+2700 hours)

↓

~4000 events
~23800 hours

Slewing: ~ 1400 h
Calibrations: ~ 1200 h
Station Keeping: 180 h
Waiting time: ~ 4100 h

Scheduling algorithm: Evolutionary Multi-objective Optimization (IEEC, Barcelona)

Scheduling results:

→ **Mission Reference Sample** (MRS), 1000 targets: T1 – 400, T2 – 550, T3 – 50

→ **MRS + re-visits + back-up targets**: 1000 (+1093): T1 – 400 (+1093), T2 – 550, T3 – 50

→ **Phase curves**

Test case	Completed targets	Working time			Waiting time
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Case 1	989	68.7 %	3.7 %	4.1%	23.5 %
Case 1-fill	1194	77.5 %	4.7 %	4.1%	13.7 %
Case 1-fill + phase curves	1181	77.6 %	4.7 %	4.1%	13.7 %

On targets

Case 1 (MRS) → 3132 events (~ 21100 hours)

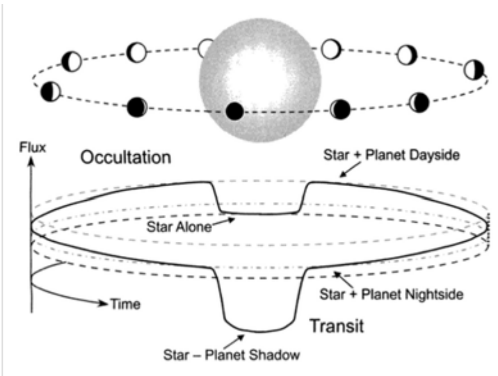
Re-visits + back-up targets ↓

Case 1-fill (MRS + revisits + back-up) → +900 events (+2700 hours)

↓

~ 15 phase curves ~4000 events ~23800 hours

Slewing: ~ 1400 h
Calibrations: ~ 1200 h
Station Keeping: 180 h
Waiting time: ~ 4100 h



Scheduling algorithm: Evolutionary Multi-objective Optimization (IEEC, Barcelona)

Scheduling results:

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→ **Phase curves**

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Phase curves

- Do not significantly change time efficiency
- Small effect on completed targets

Distribution of targets

- Follows Mission Reference Sample
  - → Can be changed using priorities for each target

Waiting time

- Inherent to the scheduling of time constrained events (details in coming slides)

CNES Mission planning & Scheduling Approach

Aymeric ***Walker-Deemin*** *(CNES)*
Jean ***Jaubert*** *(CNES)*

Andrea ***Moneti*** *(IAP)*
Jean-Philippe ***Beaulieu*** *(IAP)*

CNES Mission planning & Scheduling Approach : Method

- **Core Process** : "Hierarchical Greedy" scheduling
  - well-*known problem-solving heuristic, making locally optimal choice at each stage (sequential process), with the intent of finding approximations of global optimum*.
  - Requires an initial "ranking" of all candidate observations according to **mission** and **scheduling optimization** criteria
  - Uses a practical heuristic to decide where to insert a new element in the schedule

- **Additional logics** : tuneable complementary "rules", to meet specific **user needs**, which are likely to evolve throughout mission lifetime.

CNES Mission planning & Scheduling Approach : Functional Algorithm (*simplified*)

Preliminary stage : Computation of all **Transit / Eclipse opportunities** for each target over 3.5 years (combination of periodic Tr/Ecl obs. slots with accessibility time windows of target from ARIEL position)

Main algorithm : (*Greedy hierarchical principle*)

Scheduling of **Phase Curve sequences**

For all targets with objective (tier) = **Bench**, then **Deep**, then **Survey**

Ranking of targets according to: **User Priority**, then **Flexibility** (Easy2Hard or Hard2Easy)

For every target of the ranked list, **scheduling (attempt)** of the sequence's 1st **visit** :

Insertion of **all required observations** to complete the **sequence objective**, while considering :

- **Slew** from/to other targets already scheduled
- **G-star calibration** before/after each observation if required
- For tier **Deep** only, **postponing** of observations above sublevel Survey after 12-18 months

If insertion of all observations of the sequence is **possible** : sequence → « SUCCESSFUL »

Otherwise (if at least 1 of the observations could not be inserted) : sequence → « NOT SUCCESSFUL »

- If primary tier = Survey: **Removing** all observations inserted in the schedule
- If primary tier = Deep or Bench **and a sub-tier is reached**, the target **tier is downgraded** to the closest sublevel (Survey or Deep): sequence → DOWNGRADED

Scheduling of routine calibrations & house-keeping activities

Scheduling of **additional visits** (*similar process as for sequence's 1st visit*)

CNES Mission planning & Scheduling Approach : Key Characteristics

Many **settings, options and parameters** are made available for users to **adapt the mission schedule to user preferences** and **to various catalogs** of requests with different features :

- Tiers' intrinsic priorities are manageable (e.g. to favour the scheduling of all benchmark sequences of the catalogue)
- User priorities are taken into account at top level
- Possibility to favour the scheduling of "easy" or "hard" sequences (*related to: flexibility factor, number & duration of observations...*)

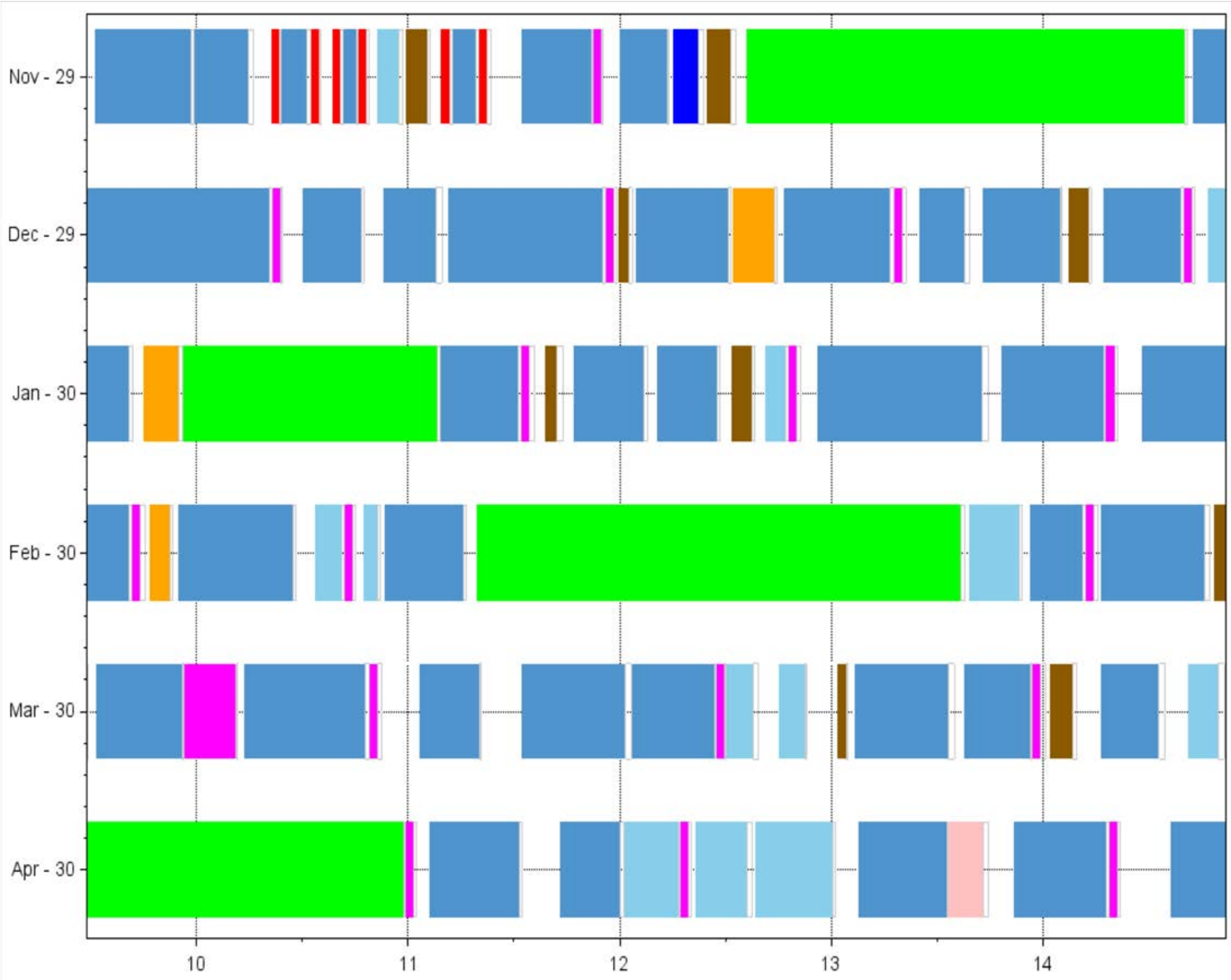
$$F = 1 - \frac{Nb\ of\ obs.required}{Nb\ of\ opportunities}$$

- Maximum percentage of Phase-curves desired is tuneable.
- Influencing the number of survey done within the first year is possible (cf. related mission "goal").
- The algorithm is designed to schedule **all observations** of a given sequence **as closely as possible from each other**, for both "user" and also "risk mitigation" interest.

$$\rho = \begin{cases} \frac{t_{obs}^{last} - t_{obs}^{first}}{T.(N-1)}, & If\ N \geq 2 \\ 0, & Else \end{cases}$$

with : N = sequence's number of observations, T = Planet's Transit/Eclipse period

CNES Mission planning & Scheduling Approach : Schedule – Zoom



Phase-curve obs.

Transit/occult observation :

- Benchmark
- Deep
- Survey

Slew after an obs.

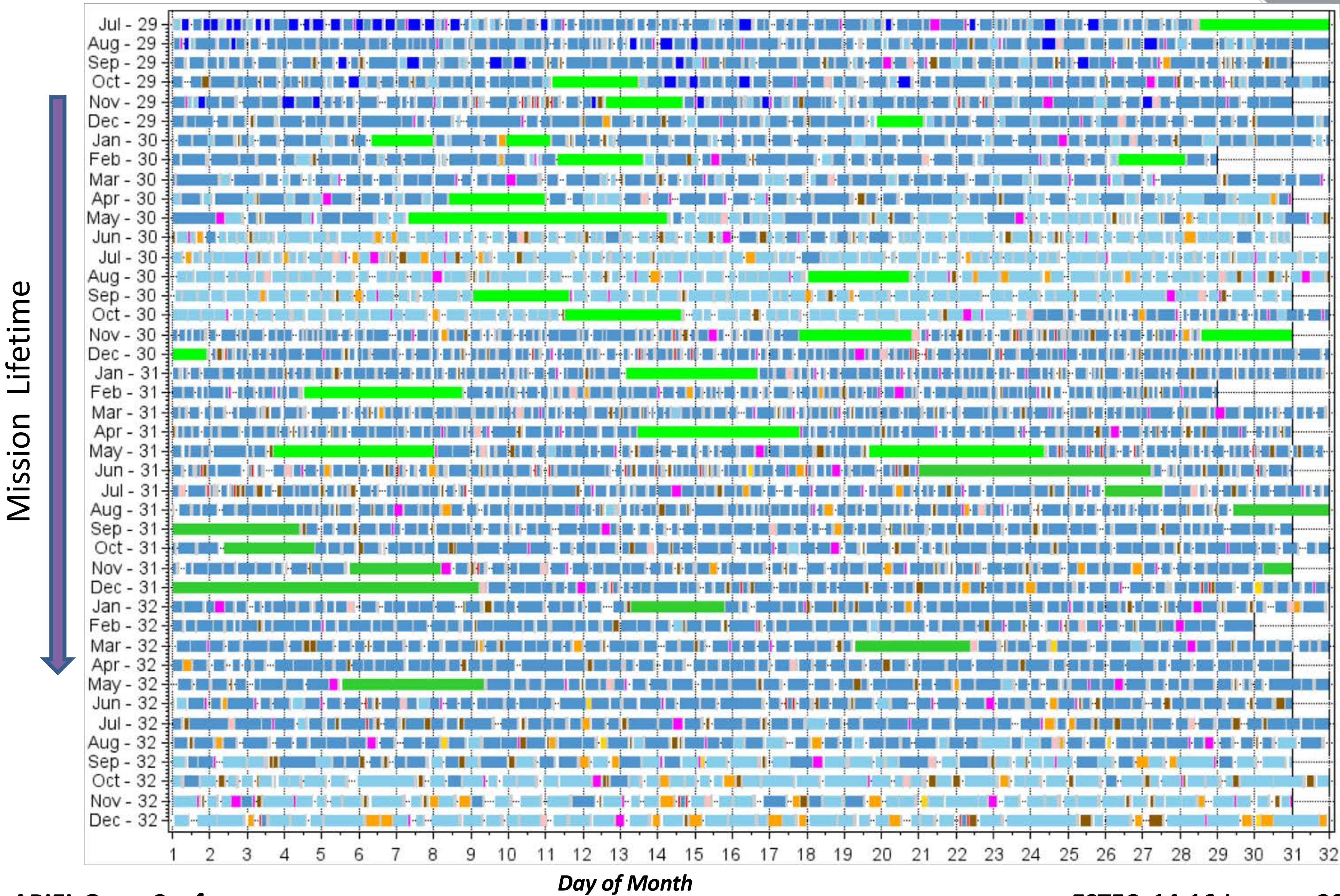
Calibration (red) before/after an obs.

Short routine calibration

Long routine calibration

House-keeping

CNES Mission planning & Scheduling Approach : Schedule - Overview



CNES Mission planning & Scheduling Approach : Results

Scheduled targets :

- **Phase-curves** : 29 targets scheduled, so as to occupy ~8% of mission-time (mission allocation)
- Tiers 3 (**Benchmark**) and 2 (**Deep**) : **100%** of catalogue's **sequences are scheduled** (40 and 526 targets respectively)
- Tier 1 (**Survey**) : **90% of catalogue's sequences are scheduled** (358 targets)

Mission Goals :

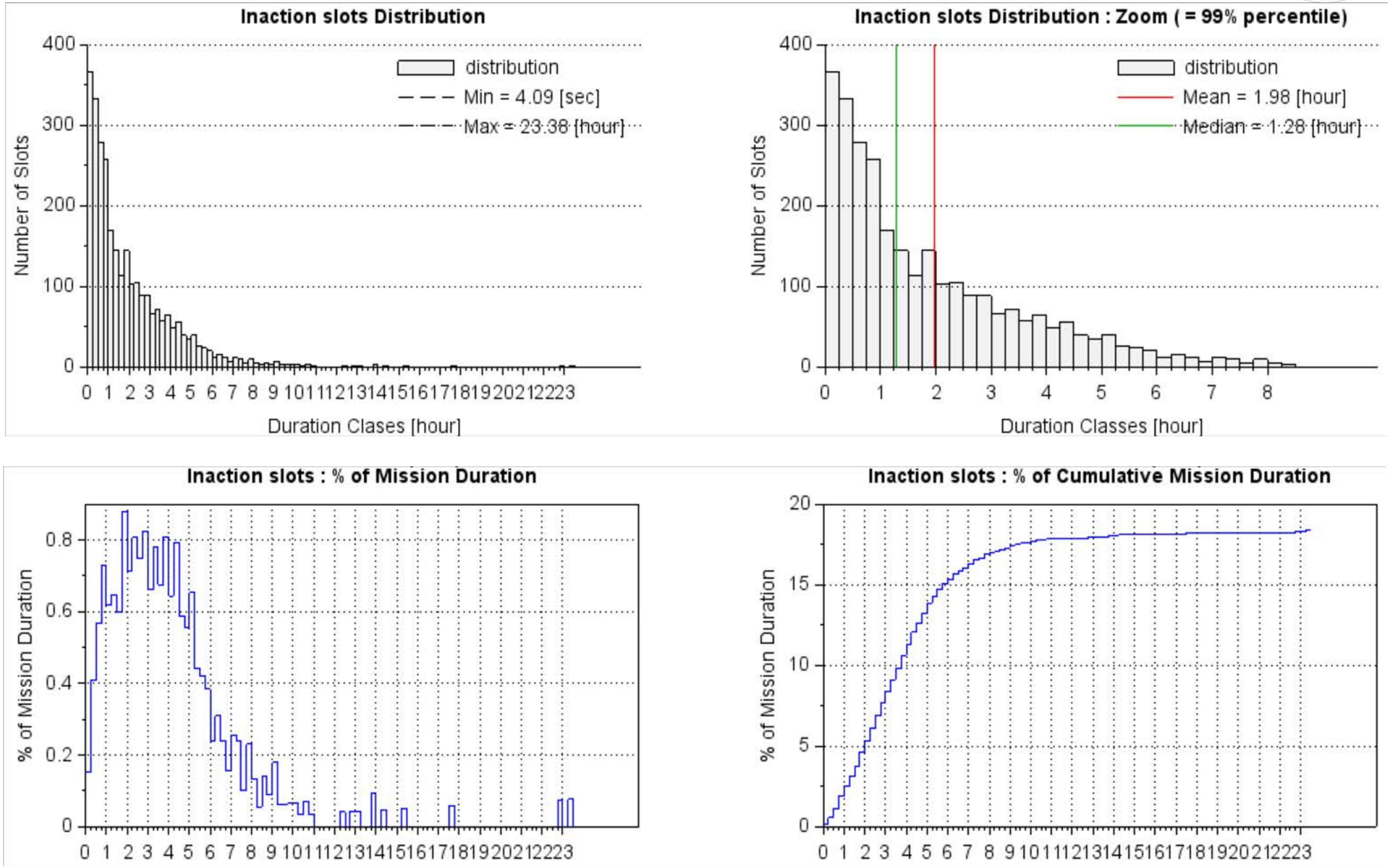
- Number of targets with primary or sub-tier Survey scheduled within the 1st year : 637 (goal = 500)
- All benchmark targets are scheduled within the 1st semester (goal = "within the 1-st year")

Time occupation optimization:

Due to the nature of ARIEL scheduling problem (*constrained transit/eclipse dates*), the presence of **inaction slots** in the mission-timeline is unavoidable → But **a significant number could be used cleverly** :

- **Inaction slots < 1 hr** : can be used to extend observations, allowing for more settling time and improved signal baseline determination
- **1 hr < Inaction slots < 2 hr** : can be used for ancillary science.
- **Inaction slots > 2 hr:** can **accommodate revisits** of already fully scheduled targets, which can be of interest for "variability" analysis

CNES Mission planning & Scheduling Approach : Inaction Slots Analysis



CNES Mission planning & Scheduling Approach : Results (*cont'd*)

Best tuning for :
- Time-occupation
- Bench & Deep completion

	Baseline *		With Extra Revisits **	
Number of targets observed	953	96.0 %	953	96.0 %
Number of observations scheduled	2941		3290	
Total shutter time on target [hr]	22 826	74.3 %	23 570	76.7 %
Total shutter time on calibration stars [hr]	1 212	3.9 %	1 212	3.9 %
Total slew/settling time [hr]	1 314	4.3 %	1 462	4.8 %
Scheduled HK activities	184	0.6 %	184	0.6 %
Inaction slots < 2 hr	1 509	4.9 %	1 958	6.4 %
Inaction slots > 2 hr	3 675	12 %	2 334	7.6 %
Total	30 720	100 %	30 720	100 %

Time occupation for Science :
- 80.6 %
- 87 %

* **Baseline** : only observations requested by MRS list are scheduled
** **With Extra Revisits** : Baseline + extra visits **of same MRS targets**

Similar results to those of the **IEEC-ICE-CSIC** team

Planet Types : All types of planets are scheduled
→ Representative of the MRS catalogue's distribution

	Ultra Hot	Very Hot	Hot	Warm	Temperate
Massive Jupiter	**7** / 8	**105** / 115	**9** / 10	x	x
Jupiter	**35** / 43	**275** / 300	**223** / 234	**77** / 79	**4** / 7
Neptune	**4** / 4	**13** / 14	**18** / 21	**24** / 26	**4** / 4
Sub-Neptune	**1** / 1	**4** / 8	**12** / 14	**37** / 39	**27** / 27
Earth & Super-Earth	x	**2** / 2	**6** / 6	**17** / 18	**20** / 20

* **A / B** = Scheduled / Catalogue

General conclusion of ARIEL mission-planning workgroup activities

- **Two different approaches** and tools presented with different methods and specific features :

  → 2 different representative mission schedules obtained over the 3.5 years lifetime from current Mission Reference Sample

  → Similar performance w.r.t. mission requirements and objectives

  → **Good confidence in results produced** thanks to this cross-validation

- **Most MRS targets can be visited**

  → Distribution of planet types well represented

- **Between 85%-90% of the mission-time can be devoted to science** (including extra revisits and/or backup targets, and ancillary science), knowing that inaction slots are inherent to ARIEL context.

  → ~ 24000 h on targets (~ 3500 transit/eclipse events)

- **Fast runtime** of scheduling process allows for multiple updates of the mission schedule

- **Future work** :

  ✓ Take into account :

    - updated MRS
    - **very likely new mission and system** (spacecraft, ground) constraints and needs

  ✓ Refine the scheduling process

Thank you!