STARS: Telescope and space mission scheduling towards a multi-observatory framework
Applied to: ARIEL-ESA, CARMENES, CTA and CTA&SKA

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ADASS 2019, 9th October 2019, Groningen
Outline

• STARS framework
  ▪ Features
  ▪ Performance metrics
  ▪ Optimization strategies & algorithms
  ▪ ATP GUI

• Scheduling Applications
  ▪ Single telescope: ARIEL-ESA, CARMENES, TJO@OAdM
  ▪ Observatory with multiple sites and sub-arrays: CTA
  ▪ Multi-observatory
    o Coordinated planning (MM view): CTA&SKA, CTAN&S+GW
    o Follow-up infrastructure for ESA-PLATO
Why an automatic scheduling tool?

- Complexity of the problem
- Easy simulation for different scenarios before the mission
- Fast adaptability to changes during the mission

ESA-ARIEL survey in numbers

- Survey ~1000 exoplanets (from ~2000 available)
- 4 years mission lifetime (3.5 years survey)
- 1~20 events per target
- ~200 observable events for each target
- ~120 events at the same time
- ~13.5k total requested observations (for ~2000 targets)
- 2.5k~3.5k observations in the final plan
- About $e^{4800}$ possible combinations

Huge amount of possible combinations!
Searching all the options for the best plan would be infeasible
Scheduling application framework

**STARS framework:**
*Scheduling Technologies for Autonomous Robotic Systems*

- **Goals**
  - Tool to automatically plan observations and operations
  - Optimize the plan to fulfill science goals
  - Analyze mission scenarios:
    - Number of targets observed
    - Challenging targets and observation strategies
    - Impact of different operational constraints
    - …
  - Re-usable software for different projects and missions
Scheduling application framework

**STARS framework:**
*Scheduling Technologies for Autonomous Robotic Systems*
Features

• Libraries
  ▪ Definition of the survey: objects to be observed, features of the objects
  ▪ Definition of the observatory: location, number of telescopes, type of telescopes
  ▪ Astronomical calculations: object coordinates, object elevation, Sun and Moon position, Moon phase
  ▪ Long- and mid-term schedulers based on Evolutionary Algorithms, and for a short-term scheduler a dispatcher using astronomy-based heuristics

• I/O based on XML files (similar to RTML format)
Features

• Libraries
  ▪ Definition of the survey: objects to be observed, features of the objects
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Performance metrics

- Observing time optimization
  - The **time** in the schedule during which the **telescope** is **observing** objects should be maximized

- Optimization of scientific return
  - The **observation of completed targets** should be maximized in order to increase the scientific efficiency of the mission
  - **Observation of the priority targets** should be promoted
  - **Observation deviation** to ensure that all targets with the same priority will have a proper share of assigned observing time
  - **Observing cadence** according to the observation strategy
Optimization strategies

- **Off-line ➔ Long-term and Mid-term schedulers**
  - Time interval according to hard constraints that can be predicted

- **On-line ➔ Short-term scheduler**
  - It considers all constraints and adapts the mid-term plan to react to immediate circumstances

### Hard Constraints
- Priorities
- Night & Elevation
- Moon influence
- Visibility duration
- Pointing
- Overlapping
- Overhead time
- Environmental conditions

### Soft Constraints
- Observing time
- Observation deviation
- Observing cadence

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Optimization algorithms

• Scheduling optimization
  ▪ A global optimization problem
  ▪ Using local optimization algorithms significantly limits the search space for the best solution
  ▪ Multiple objectives to optimize (completed targets, observation time and the total slew time)
  ▪ Different tasks that have to be included in the final plan (target observations, calibrations, housekeeping, and slew times)

• Problem representation - Genetic structure
  ▪ Set of targets to observe $T = \{t_1, t_2, \ldots, t_T\}$
  ▪ Set of requested observations for each target
  ▪ Candidate solution:
Optimization algorithms

• Scheduling algorithm
  ▪ Evolutionary Multi-objective Optimization (EMO)
    o Combines (crossover, mutation) a set of candidate solutions to explore the parameter space of the problem
  ▪ Non dominated sorting genetic algorithm II (NSGA-II)
    o Few objectives
    o Not a complicated Pareto Front
      • Solutions that are not dominated by others
        o Loads of local minimums
        o Crowding distance consideration
Optimization algorithms

- Optimization process based on AI Algorithms

![Optimization Diagram]
Optimization algorithms

- **In-house implementation under revision to incorporate existing libraries**

- **Python**
  - Pros:
    - Less implementation time
    - Suitable for testing and investigating new algorithmic optimization
  - Cons:
    - Less optimized resource consumption
    - More execution time
  - Libraries: Platypus, DEAP, PyGMO

- **C++**
  - Pros:
    - Optimized resource allocation
    - Fast execution time
    - Suitable for the final program
  - Cons:
    - Extended development time
  - Libraries: PaGMO: Developed by European Space Agency (ESA) for parallel optimization
ATP GUI for STARS

Two sites: Paranal in the South and La Palma in the North
### ATP Configuration

#### Parameter Details

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Scheduling Date</td>
<td>01-Jan-2024</td>
<td></td>
</tr>
<tr>
<td>End Scheduling Date</td>
<td>31-Jan-2024</td>
<td></td>
</tr>
<tr>
<td>ICS mode</td>
<td>no</td>
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<tr>
<td>Read out duration [hh:mm:ss]</td>
<td>00:00:40</td>
<td></td>
</tr>
<tr>
<td>Minimum horizon for tellurics</td>
<td>-12</td>
<td></td>
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<tr>
<td>Minimum altitude</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Minimum altitude duration</td>
<td>00:00:00</td>
<td></td>
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<tr>
<td>Acceptable sky brightness</td>
<td>0.8</td>
<td></td>
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<tr>
<td>Long-term filtering</td>
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<tr>
<td>Consider priority in simulation</td>
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<tr>
<td>Long-term filtering scope</td>
<td>30</td>
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<tr>
<td>GA mid-term generations</td>
<td>1500</td>
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<tr>
<td>Control factor sky brightness</td>
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<tr>
<td>Long-term recalculation</td>
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<tr>
<td>Long-term filtering frequency</td>
<td>93</td>
<td></td>
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<tr>
<td>GA long-term generations</td>
<td>10000</td>
<td></td>
</tr>
<tr>
<td>GA crossover probability</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

#### End Scheduling Date

Over head duration [hh:mm:ss]: 00:02:00

Solar horizon: -12

Minimum observable duration [hh:mm:ss]: 00:00:00

Minimum moon distance [??]: 20
ATP Configuration

Telescope configuration

Manage subarrays

Manage telescopes
ATP GUI for STARS

Scheduling Analysis Tool

Scheduler Configuration | Target Set | Scheduling by Resource | Scheduling by Target | Statistics

Filter by Date
Start Date 01-Jul-2027 00:00:00 | End Date 29-Dec-2030 12:00:00

Target Information
ARIEL-4_T3 | ARIEL-5_T3 | ARIEL-6_T3
ARIEL-7_T3 | ARIEL-8_T3 | ARIEL-9_T3

Overview
Show by Targets | Y-axis | Declination | Right Ascension | X-axis

General Target Information
Name: ARIEL-9_T3
- Description
- Coordinates
- Required number of events to be observed
- Events required T1
- Events required T2
- Events required T3
- Magnitude
- Star Type
- Priority
ATP GUI for STARS

Scheduling Analysis Tool

Scheduler Configuration | Target Set | Scheduling by Resource | Scheduling by Target | Statistics

Filter by Date
Start Date: 01-Jul-2027 00:00:00 | End Date: 29-Dec-2030 12:00:00
Accept | Reset

Overview

Show by: Targets | Y-axis | Theoretical I... | Number of... | X-axis

General Target Information
Visible: 444 times
- Visibility periods
Observed: 2 times
Observation duration: 38119.688 seconds
- Observed periods
2028-06-07 11:20:52.593 UTC to 2028-06-07 16
2028-07-12 03:02:25.077 UTC to 2028-07-12 08
ATP GUI for STARS

Scheduling Analysis Tool

Scheduler Configuration | Target Set | Scheduling by Resource | Scheduling by Target | Statistics

Filter by Date

Start Date: 01-Jul-2027 00:00:00, End Date: 29-Dec-2030 12:00:00

ACE GUI for STARS

Gantt Diagram

Ariel-9_T3

Visible: 444 times
Visibility periods:
- 2028-06-07 11:20:52.593 UTC to 2028-06-07 16:28:21
- 2028-07-12 03:02:25.077 UTC to 2028-07-12 08:48:14

Aladin Lite view

General Target Information

Observed: 2 times
Observation duration: 38119.688 seconds

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ATP GUI for STARS

CARMENES

ARIEL


HJD start
2461811.3598324
2461811.36535879
2461811.5000000
2461811.91260675
2461811.93028033
2461812.26692129
2461812.28760118
2461812.37726051
2461812.39843104
2461812.58194444
2461812.58750000
2461812.63403935
2461812.93698972
2461812.9553207
2461813.09375000
2461813.10038092

HJD end
2461811.36535879
2461811.49997885
2461811.8333333
2461811.93028033
2461812.21916666
2461812.28760118
2461812.28760118
2461812.39648148
2461812.58194444
2461812.58750000
2461812.62847222
2461812.62847222
2461812.91254229
2461812.95318287
2461813.10038092
2461813.42968750

Task
slowing to tracking station keeping slowing to tracking slowing to tracking slowing to tracking slewing to slewing to slewing to slewing to slewing to slewing to
ARIEL-1392_T1 ARIEL-1392_T1 ARIEL-399_T1 ARIEL-399_T2 ARIEL-399_T2 ARIEL-46_T3 ARIEL-46_T3 ARIEL-46_T3 ARIEL-46_T3 ARIEL-46_T3

Target
ARIEL-1392_T1 ARIEL-399_T1 ARIEL-399_T2 ARIEL-399_T2 ARIEL-1216_T1 ARIEL-1216_T1 ARIEL-1216_T1 ARIEL-1216_T1 ARIEL-1216_T1 ARIEL-284_T2

Observation duration: 38119.688 seconds

- Observed periods
  2028-06-07 11:20:52.593 UTC to 2028-06-07 16:20:52.593 UTC
  2028-07-12 03:02:25.077 UTC to 2028-07-12 08:02:25.077 UTC
ATP GUI for STARS
ATP GUI for STARS

Scheduling Analysis Tool

ARIEL_allTiers_1_calibrations-1_years-3.3_trial-0-replacing-improved-0.xml

Scheduler Configuration | Target Set | Scheduling by Resource | Scheduling by Target | Statistics

Filter by Date

Start Date: 01-Jul-2027 00:00:00 | End Date: 29-Dec-2030 12:00:00

Global Statistics by Resource

Number of resources: 1
Number of days planned: 1277.5
Duration of observable periods: 30660 hours
Available observable periods: 100% (30660 hours)

Satellite resource
Duration of observable periods: 30660 hours
Available observable periods: 100% (30660 hours)
Observations done: 4080
Targets assigned: 2108
Targets planned: 1112 (52.75%)
Targets completed: 1037 (49.19%)
Working time (according to the available observable periods): 85.76% (26294.69 hours)
  - Time doing slewing: 5.56% (1461.49 hours)
  - Time doing tracking: 88.07% (23158.25 hours)
  - Time doing station keeping: 1.17% (360 hours)
  - Time doing calibration: 5% (1314.95 hours)
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ESA-ARIEL

- The Atmospheric Remote-Sensing Infrared Exoplanet Large-Survey (ARIEL), ESA M4 mission (launch 2028)
- Application focused on the mission operations planning ➔ Long-term
- Singular strategy: time-critical events
**ESA-ARIEL**

- Simulation results - Mission planning tool executions

<table>
<thead>
<tr>
<th>Mission lifetime period (Years from launch)</th>
<th>Planned targets</th>
<th>Working time</th>
<th>Waiting time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>On targets</td>
<td>Slewing</td>
</tr>
<tr>
<td>0.5 – 4.0 (No phase curves)</td>
<td>1112±8</td>
<td>67.85±0.31%</td>
<td>3.96±0.03%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(20804±96 h)</td>
<td>(1214±10 h)</td>
</tr>
<tr>
<td>0.5 – 4.0 (Phase curves)</td>
<td>1112±8%</td>
<td>68.46±0.31%</td>
<td>3.90±0.03%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(20991±94 h)</td>
<td>(1197±8 h)</td>
</tr>
<tr>
<td>0.5 – 4.0 (Phase curves + rep.)</td>
<td>1115±9%</td>
<td>75.75±0.18%</td>
<td>4.79±0.03%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(23224±56 h)</td>
<td>(1467±11 h)</td>
</tr>
</tbody>
</table>
CARMENES instrument

• Exoplanet research ➔ in operation since 2016
• Trade-off between conflicting soft-constraints
  ▪ Observing Time: maximize the time that the telescope is observing
  ▪ Observation Deviation: promote a proper distribution of the observations of the objects to mitigate the problem of scheduling the objects that require longer observations
A. Garcia-Piquer et al., “Efficient scheduling of astronomical observations Application to the CARMENES radial-velocity survey”, Astronomy & Astrophysics, 604(A87), 2017
Cherenkov Telescope Array

- CTA scheduling conditions
  - Operation tasks
    - Science, calibration, maintenance
  - Observation modes
    - Sub-arrays, compact
    - Convergent/ divergent modes
  - Observing time distribution (SB)
  - Two sites (CTAN@ORM / CTAS@Paranal)
    - 20-100 Telescopes/site
    - Independent & coordinated tasks
Cherenkov Telescope Array

- KSP simulations - 10 yr
- Two configurations (1/1/2021 to 1/1/2031):
  - Full Array – North & South (coordinated observations)
  - Sub Arrays – only in the South

Visibility plots-10 yrs
- Completed
- Uncompleted
- Unplanned
Multi-observatory coordinated planning

- Science cases: transient events (GRBs, GWs, etc.), surveys
- Problem conditions
  - Each observatory contains various subarrays
  - Each observatory has a role: leader, follower or independent
  - Additional Objective ➔ Maximize the simultaneity of observations (maximize coincident observations or minimize the distance between them)
Multi-observatory coordinated planning

• Strategies
  ▪ Subsidiary observations: leader - follower
  ▪ Interactive approach: leader - leader
  ▪ Multi-Messenger: random alerts (GW) observed by CTAN&CTAS

• Facilities
  ▪ CTA (CTAN - La Palma, Canary Islands; CTAS – Chile)
  ▪ SKA (Australia, South Africa) → GASKAP (Australia)
  ▪ William Herschell (La Palma, Canary Islands)
Multi-observatory coordinated planning

- Simulation configurations ➔ CTA and SKA coord.
  - Science test case:
    - CTA: North and South example surveys
    - SKA: GASKAP galactic survey (Dickey, 2013)
  - Scenario (max Zenith: 55°)
    - Leader: site SKA-AU, GASKAP survey
    - Follower: site CTA South, CTA South survey example (FOV: 8 deg Ø)
  - Leader and follower
    - Strategy 1: leader and follower subarrays are optimized simultaneously
    - Strategy 2: leader is optimized individually ➔ Followers do a follow-up
Multi-observatory coordinated planning

- Simulation results: No targets can be observed simultaneously in CTA South and SKA because of the maximum ZA (55°) → Optimization reduces time between observations

<table>
<thead>
<tr>
<th></th>
<th>MO Strategy 1</th>
<th>Individually</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SKA</td>
<td>CTA South</td>
</tr>
<tr>
<td>Required Time (h)</td>
<td>13300</td>
<td>2062.25</td>
</tr>
<tr>
<td>Targets in the survey</td>
<td>275</td>
<td>1356</td>
</tr>
<tr>
<td>Available Time (h)</td>
<td>6132</td>
<td>1149.78</td>
</tr>
<tr>
<td>Observing Time (h)</td>
<td>3968.67</td>
<td>713.33</td>
</tr>
<tr>
<td>Slew Time (h)</td>
<td>255.64</td>
<td>72.02</td>
</tr>
<tr>
<td>#Observations</td>
<td>11906</td>
<td>2140</td>
</tr>
<tr>
<td>Targets observed (#Planned (#Completed))</td>
<td>235 (19)</td>
<td>652 (212)</td>
</tr>
<tr>
<td>Survey completion (%)</td>
<td>29.84</td>
<td>34.59</td>
</tr>
</tbody>
</table>
Multi-observatory coordinated planning

- Simulation scenario ➔ **CTAN&S coordinated & GW transients follow-up**
  - Configuration: 854 targets, required time 7200 h (incl. 2000 h for transients), 2500 h/yr of available time
  - 10 yr simulation (figure: results after 1st yr)
Multi-observatory – ESA-PLATO FU Scheduler

- Overall architecture & requirements
- Interfaces and protocols
  - From Telescopes (visibility, availability, observing constraints)
  - Task submission to Telescopes
  - Task status from Telescopes to scheduler archive
  - Reactive or pro-active communication
  - Protocols: VO visibility & observing constraints, VOEvents, heterogeneous protocols
- Optimization metrics
- Identify existing tools, approaches or best practices that may be reused
  - E.g.: Las Cumbres Observatory (TOM), ESA VO protocols (ObjVisSAP, ObjLocTAP), TFOP, Gaia Alerts, LIGO/Virgo EM follow-up…

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Conclusions

• STARS is a framework for **observatory time scheduling**
  - Algorithms used are: GA, MOEA and astronomical heuristics. Other global search algorithms can be applied following the same steps
  - Hard and soft constraints can be adapted and generalized to different cases
  - Tool to estimate the efficiency of the survey, and to study the impact of different parameters or which targets are most restrictive
Conclusions

- STARS is applied to different projects:
  - In operation: CARMENES & TJO
  - Under construction (simulation mode): ARIEL-ESA, CTA & CTA-SKA
  - Research project (simulation mode): CTA & GASKAP, PLATO

Real-time service in an operational control architecture
Equatorial Coordinates 2018-01-15 17:34:08.576

Optimization of time-critical events
Equatorial Coordinates 2021-01-09 19:23:33.576

Multi-observatory coordinated observations & MM science
Equatorial Coordinates 2017-01-02 13:17:45.576
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