AIKO

INFINITE WAYS TO AUTONOMY

SmallSat Conference 2022

# LOW-THRUST **RECONFIGURATION STRATEGY** FOR FLEXIBLE SATELLITE CONSTELLATIONS

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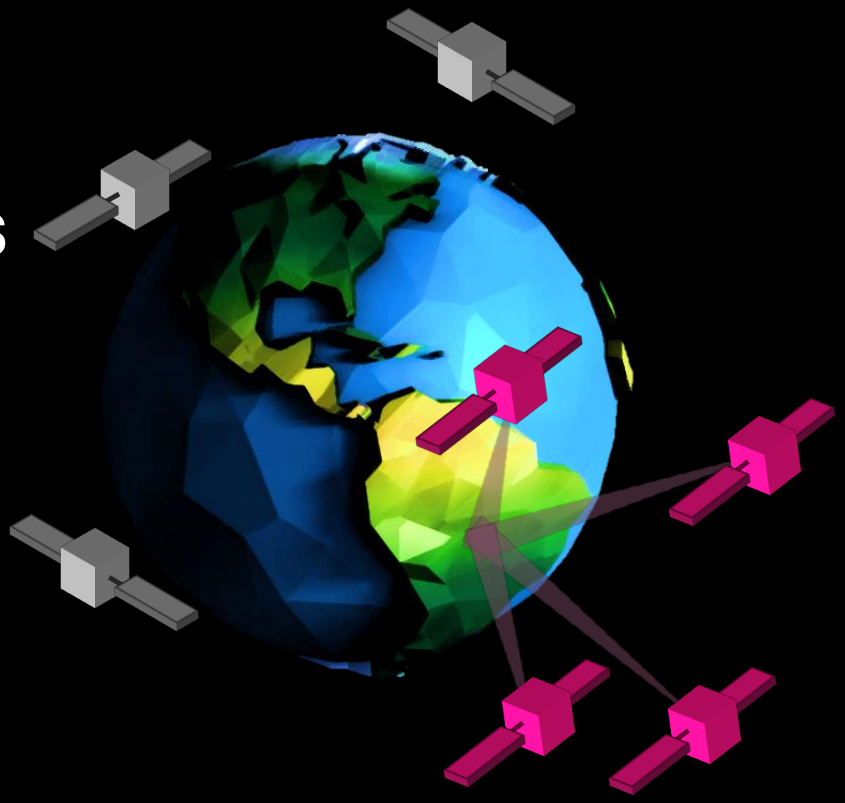
# Changes in the **space ecosystem** and increasing **commercialization**

# NEW **OPPORTUNITIES**

Changes in the **space ecosystem** and increasing **commercialization**

**Reconfigurable** constellations enabled by advancements in **electric propulsion** technologies and able to offer **enhanced flexibility**



# **Reconfigurable constellations** to overcome the limitations of **standard approaches**

**Low-thrust** reconfiguration strategy to provide **feasible** constellation geometries that guarantee **enhanced coverage** over a desired target. The cost of the **maneuvers** needed to reach the target pattern is **minimized**.

**GA-BASED OPTIMIZATION**

ENABLE
**COMPLEX COVERAGE**

TRADE-OFF
**PERFORMANCE METRICS**

FOCUS
**AVAILABLE RESOURCES**

**COVERAGE**
MODEL

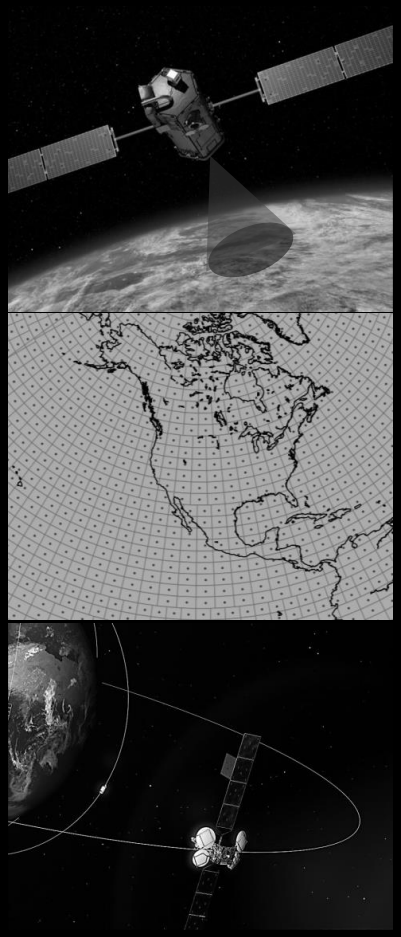
Circular Field of View

**TARGET**
POINTS

Near-equal area tiles

**SATELLITE**
POSITION

Propagation with RKF45



PROBLEM **DEFINITION**

# Mathematical **modeling**

**Classical orbital parameters** taken as optimization variables. **Multi-processing architecture** to distribute the computational load amongst several processes.

# **Maneuvers** strategy

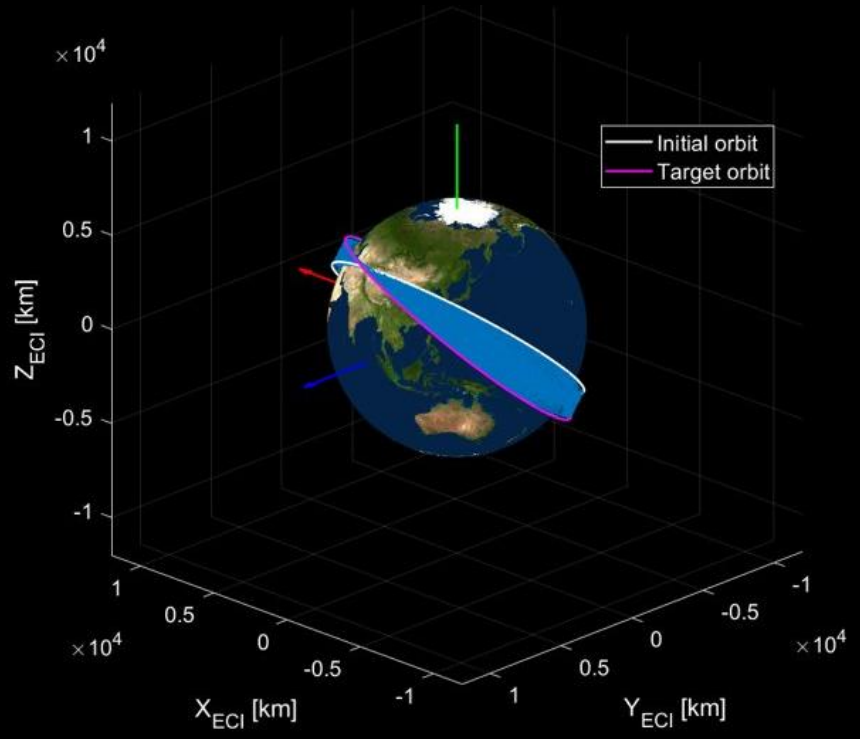
The **cost** to reach a target orbit is assessed in terms of **required** $\Delta V$.

## **SEPARATE** MANEUVERS

+ Changes performed **separately** on different orbital parameters
+ Analytical expressions available in *Ruggiero et al. (2011)*

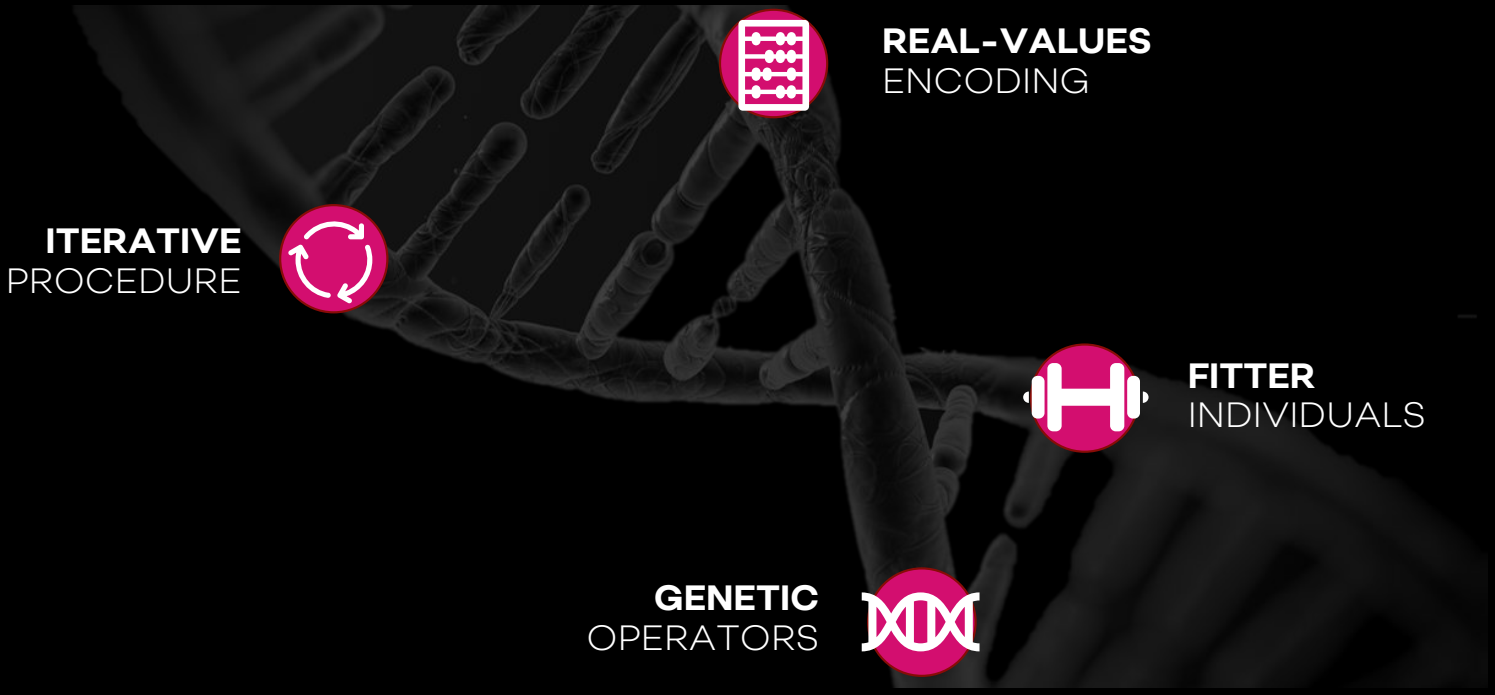
## **COMBINED** MANEUVERS

+ Orbital parameters vary **together** during the maneuver
+ Analytical expressions available in *Di Carlo, Vasile (2021)*



# **GENETIC** ALGORITHM

Fast **exploration** of the wide solution space.



**REAL-VALUES**
ENCODING

**ITERATIVE**
PROCEDURE

**FITTER**
INDIVIDUALS

**GENETIC**
OPERATORS

FITNESS **METRICS**

# **Multi-objective** evaluation of candidate solutions

**FIVE CONTRIBUTIONS** ARE COMBINED IN THE OVERALL FITNESS FUNCTION.

**PERCENT**
COVERAGE

**TIME**
COVERAGE

**MAXIMUM**
REVISIT TIME

**AVERAGE**
REVISIT TIME

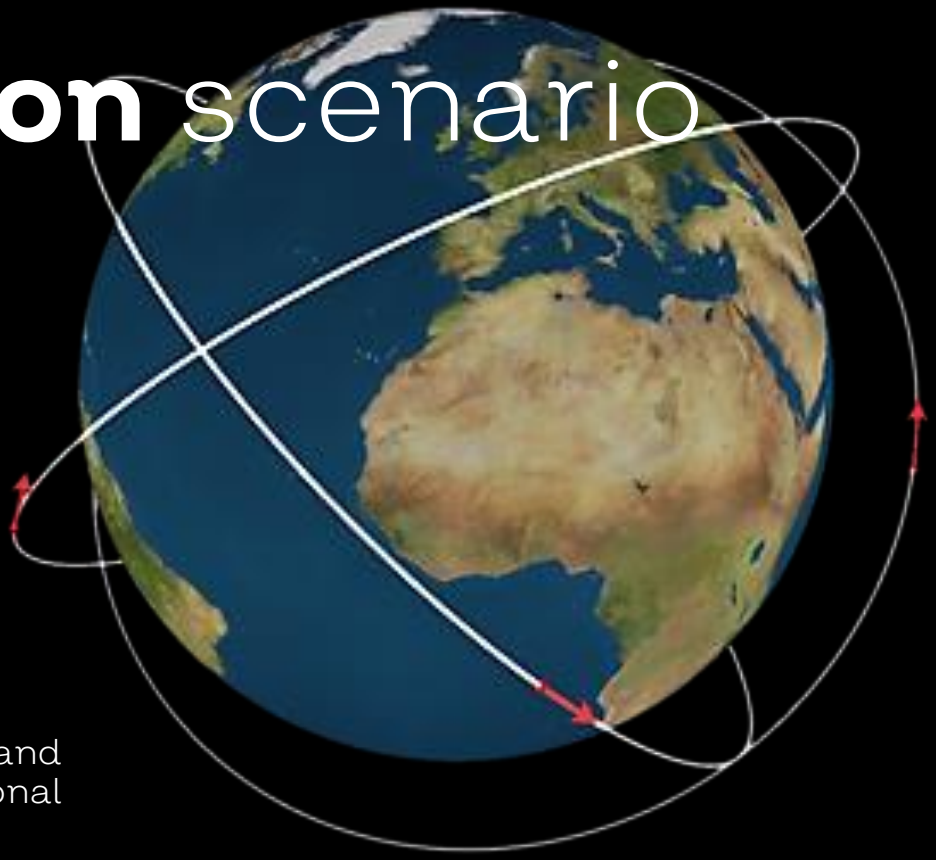
**MANEUVER**
COST

# **Simulation** scenario

**+** 6 satellites
**+** 3 orbital planes

**+ 10°** Field of View
**+ ROI** in central Europe
**+ 48 hours** propagation horizon
**+ Reconfiguration** from Walker-δ (64) 6/3/2

# **Simulation** scenario



## **NARROW** ROI

Study the GA **behavior** with an increasing number of optimization variables.

## **WIDE** ROI

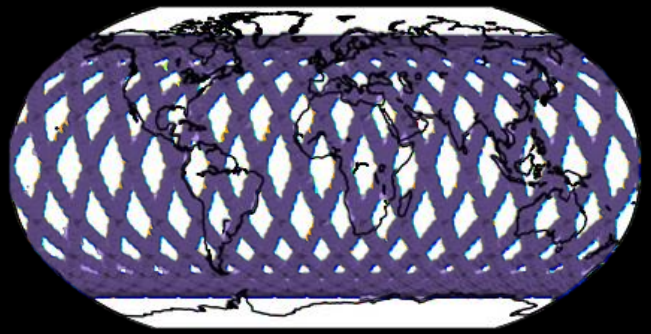
Assess the GA **performance** and show its advantages for regional observations.

# **NARROW ROI** SCENARIO

Analyze the GA **behavior** and its **sensitivity** to the set of optimization variables.

## **REPEATING GROUND TRACK** ORBITS

+ Commonly used for **regional coverage**
+ Obtained through simple **SMA changes**
+ RGT constraints **included in the GA**

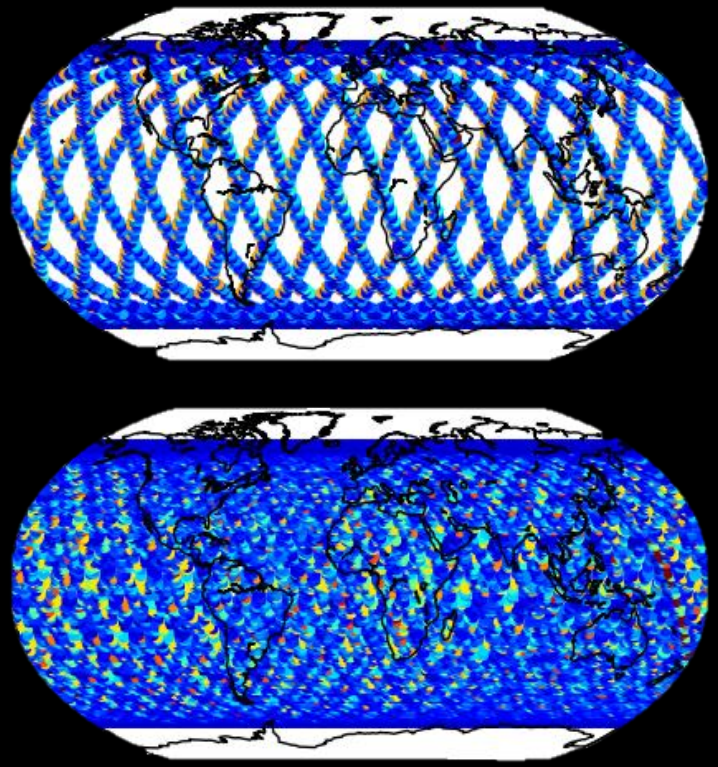


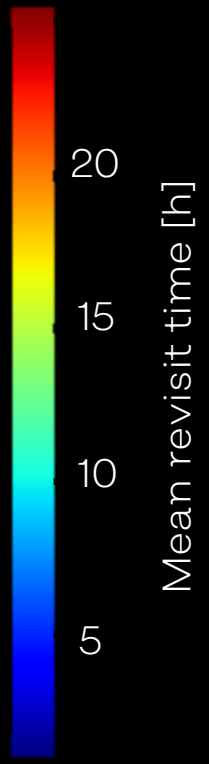
Obtain **comparable observation performance** with a **smaller** $\Delta V$

# **NARROW ROI** SCENARIO

**RGT**
configuration

**GA-based**
configuration



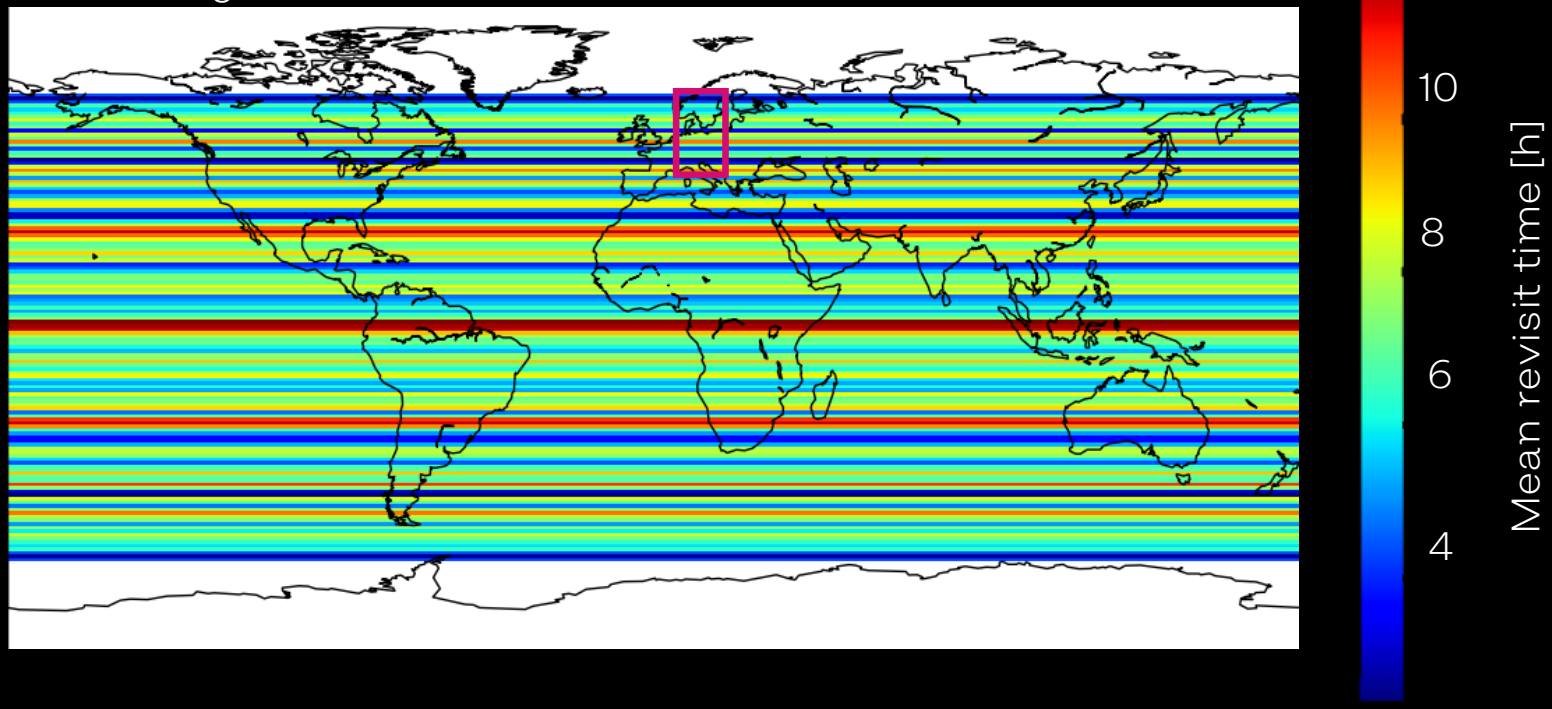


# **WIDE ROI** SCENARIO

Assess the GA **performance** in achieving regional coverage.

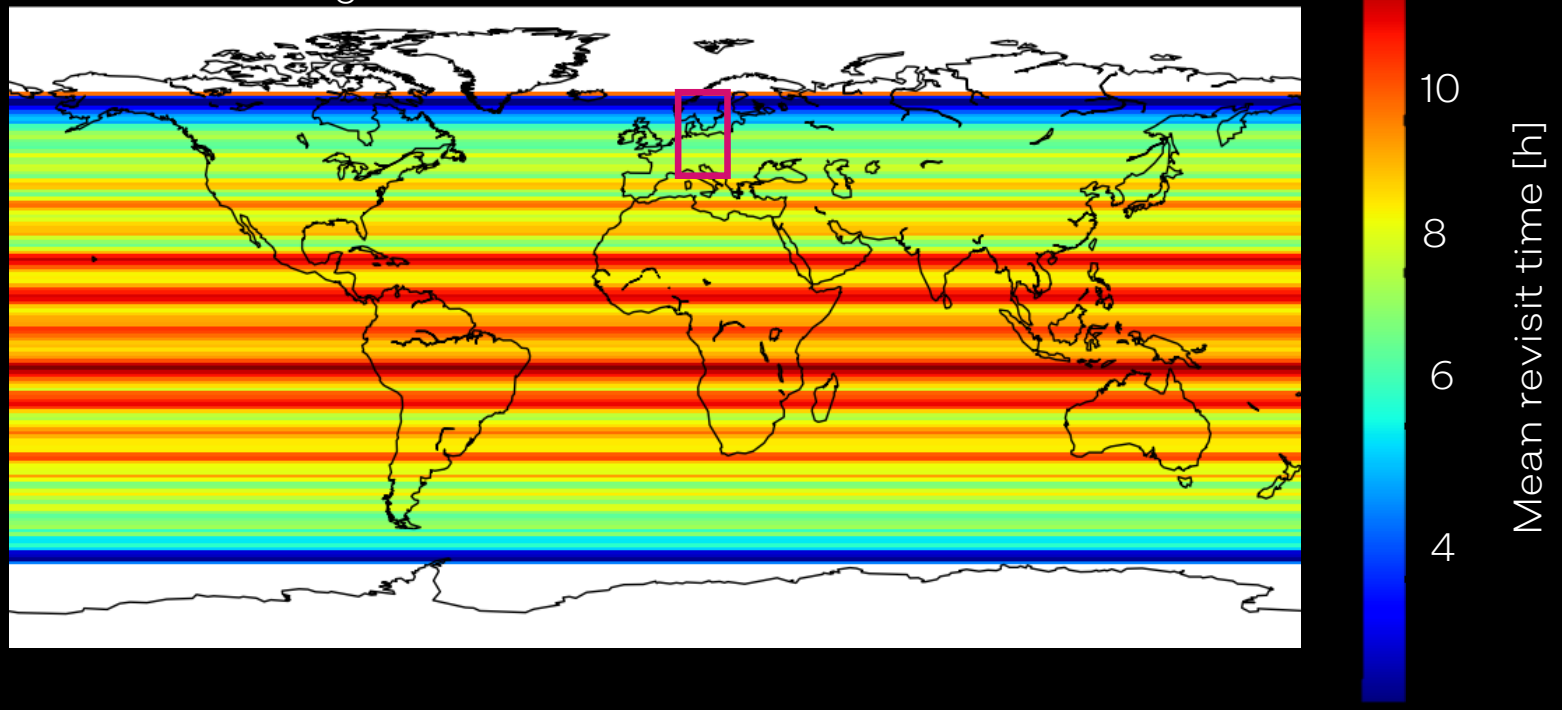
# **WIDE ROI** SCENARIO

## **RGT** configuration



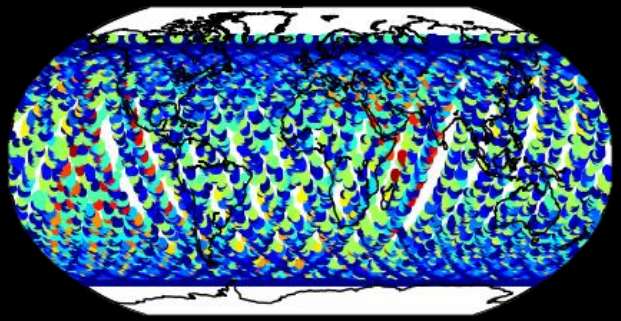
# **WIDE ROI** SCENARIO

**GA-based** configuration

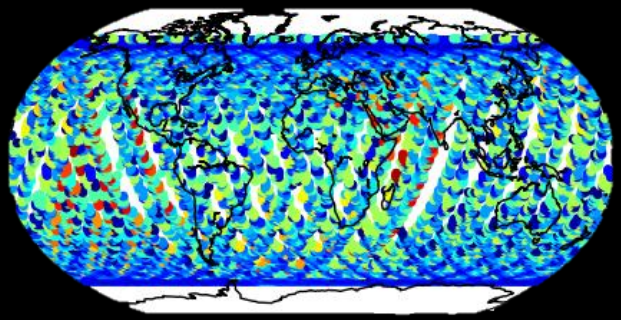


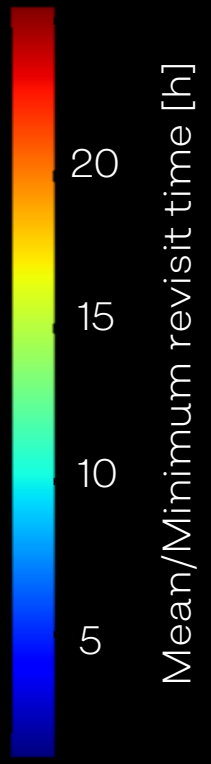
# **WIDE ROI** SCENARIO

**MEAN** REVISIT TIME



**MINIMUM** REVISIT TIME

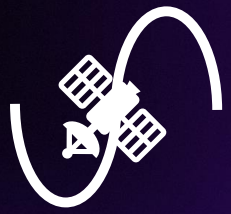




**GA-BASED** ALGORITHM

**MULTI-OBJECTIVE** OPTIMIZATION

**REPEATING** GROUND TRACK



**LEO SCENARIO** VALIDATION

# Take-away points

Future work will make the problem closer to a **real scenario**. Additional constellation configurations will be included in the analysis to provide a **practical tool** to identify reconfiguration opportunities.

**Thanks** for your attention!

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LOW-THRUST
**RECONFIGURATION**
**STRATEGY** FOR FLEXIBLE
SATELLITE CONSTELLATIONS

**Images credits**:
[5.a] Jet Propulsion Laboratory
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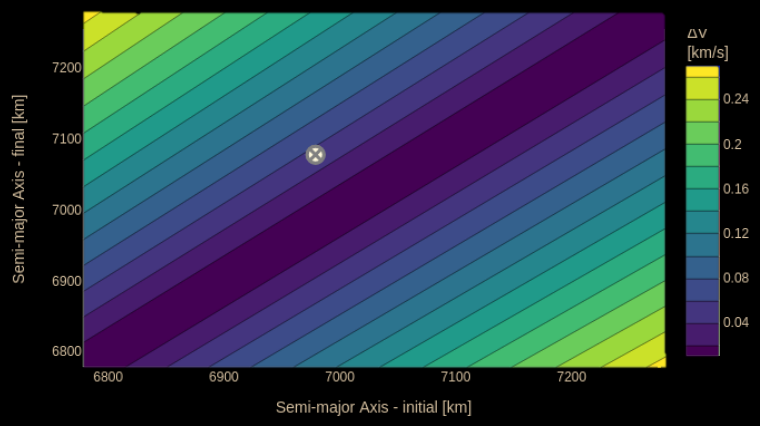
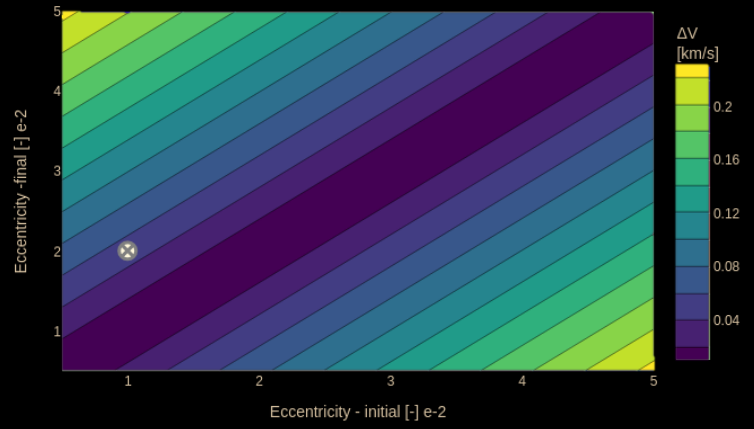
# **BACKUP** SLIDES.

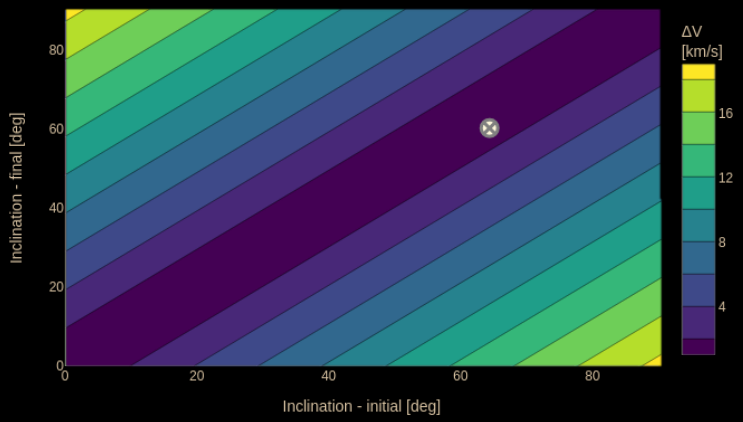
# **MANEUVERS** COSTS

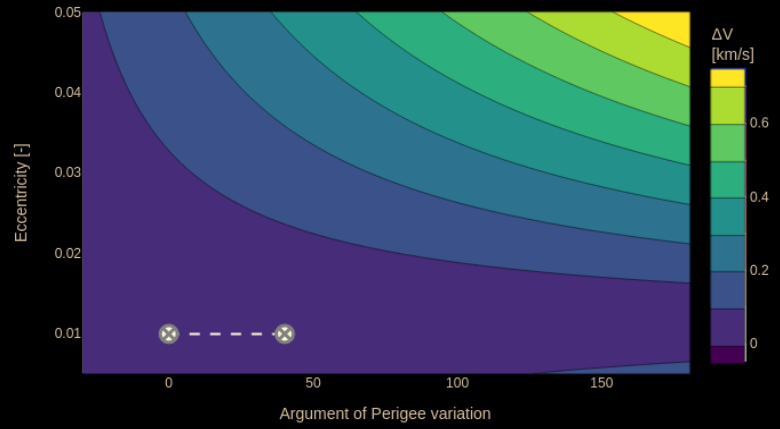
**Reconfiguration** from Walker-δ (64)6/3/2

| Parameter | Unit | Initial value | Target value |
|---|---|---|---|
| $a$ | km | 6978 | 7078 |
| $e$ | [-] | 0.01 | 0.02 |
| $i$ | deg | 64 | 60 |
| $\omega$ | deg | 10 | 50 |


Semi-major Axis - final [km]
7200
7100
7000
6900
6800
6800
6900
7000
7100
7200
Semi-major Axis - initial [km]
ΔV [km/s]
0.24
0.2
0.16
0.12
0.08
0.04


Eccentricity -final [-] e-2
5
4
3
2
1
1
2
3
4
5
Eccentricity - initial [-] e-2
ΔV [km/s]
0.2
0.16
0.12
0.08
0.04


Inclination - final [deg]
80
60
40
20
0
0
20
40
60
80
Inclination - initial [deg]
ΔV [km/s]
16
12
8
4


Eccentricity [-]
0.05
0.04
0.03
0.02
0.01
0
50
100
150
Argument of Perigee variation
ΔV [km/s]
0.6
0.4
0.2
0

# **NARROW ROI** SCENARIO

Analyze the GA **behavior** and its **sensitivity** to the set of optimization variables.

| Test case | RGT | Maneuvering | Optimization variable | | | | | | GA parameters | | | Runtime |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | a | e | i | Ω | ω | ν | Pop size | Max gen | Elitism | |
| 0 | Yes | Separate | 1 | | | | | 6 | 100 | 100 | 5 | 747 min |
| 1 | | Separate | 1 | | | | | 6 | 100 | 100 | 5 | 752 min |
| 2 | | Separate | 3 | | | | | 6 | 120 | 100 | 6 | 798 min |
| 3 | Yes | Separate | 1 | 3 | | | 3 | 6 | 150 | 100 | 8 | 927 min |
| 4 | | Separate | 3 | 3 | | | 3 | 6 | 150 | 100 | 8 | 983 min |
| 5 | | Separate | 3 | 3 | 3 | | 3 | 6 | 150 | 150 | 8 | 1132 min |
| 6 | | Combined | 3 | 3 | | | 3 | 6 | 150 | 100 | 8 | 986 min |
| 7 | | Combined | 3 | 3 | 3 | | 3 | 6 | 150 | 150 | 8 | 1160 min |
| 8 | | Combined | 3 | 3 | 3 | 3 | 3 | 6 | 150 | 150 | 8 | 1232 min |

# **NARROW ROI** SCENARIO

Analyze the GA **behavior** and its **sensitivity** to the set of optimization variables.

| Test case | f2 [min] | f3 [h] | f4 [h] | f5 [m/s] |
|---|---|---|---|---|
| Walker-$\delta$ | 1 | 31.93 | 23.99 | - |
| 0 | 14 | 7.866 | 3.18 | 48.117 |
| 1 | 7.2 | 7.95 | 5.87 | 2.708 |
| 2 | 9.3 | 8.1 | 4.68 | 6.667 |
| 3 | 14 | 7.88 | 3.18 | 195 |
| 4 | 11 | 7.73 | 3.98 | 169 |
| 5 | 10 | 7.9 | 4.07 | 253 |
| 6 | 10.98 | 7.93 | 3.98 | 49 |
| 7 | 12.6 | 7.85 | 3.54 | 312 |
| 8 | 16 | 6.76 | 2.8 | 700 |

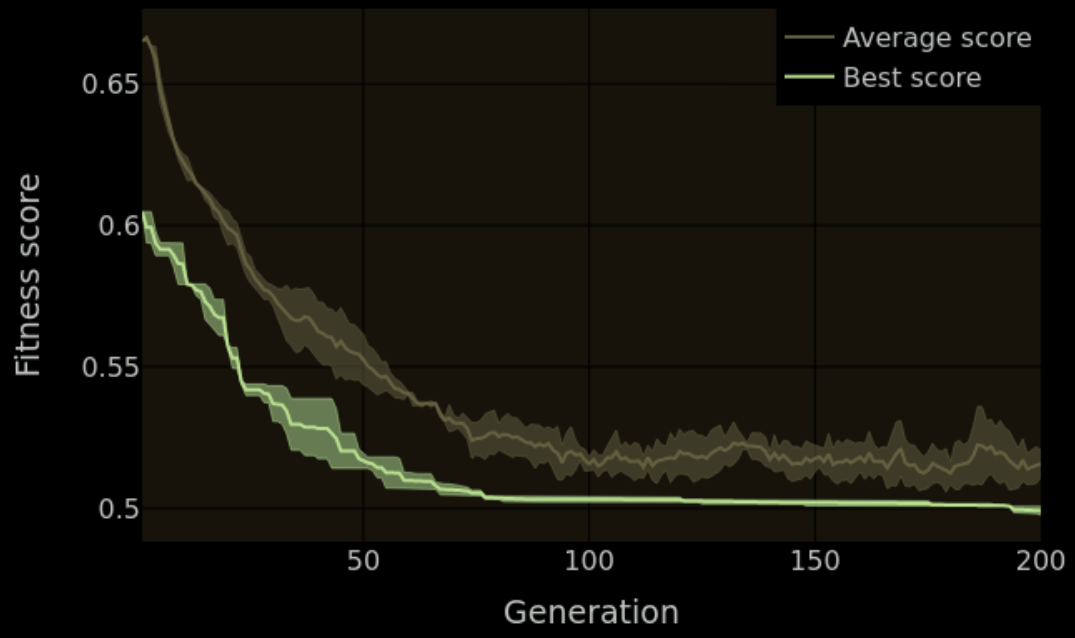
# **WIDE ROI** SCENARIO

| Variable | Unit | Plane #1 | Plane #2 | Plane #3 |
|---|---|---|---|---|
| a | $km$ | 6890 | 6890 | 6890 |
| | | 7046 | 7168 | 7157 |
| e | – | 0.01 | 0.01 | 0.01 |
| | | 0.0005 | 0.0188 | 0.0295 |
| i | deg | 64 | 64 | 64 |
| | | 63 | 64 | 64 |
| $\Omega$ | deg | 0 | 120 | 240 |
| | | 107 | 73 | 234 |
| $\omega$ | deg | 0 | 0 | 0 |
| | | 193 | 249 | 232 |
| $\nu_1$ | deg | 4 | 176 | 103 |
| | | 201 | 91 | 52 |
| $\theta$ | deg | 21 | 145 | 122 |
| | | 32 | 143 | 116 |

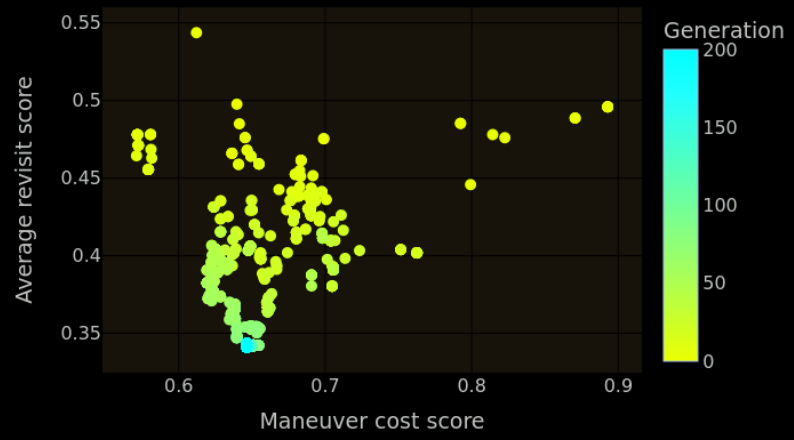
**RECONFIGURATION** COST

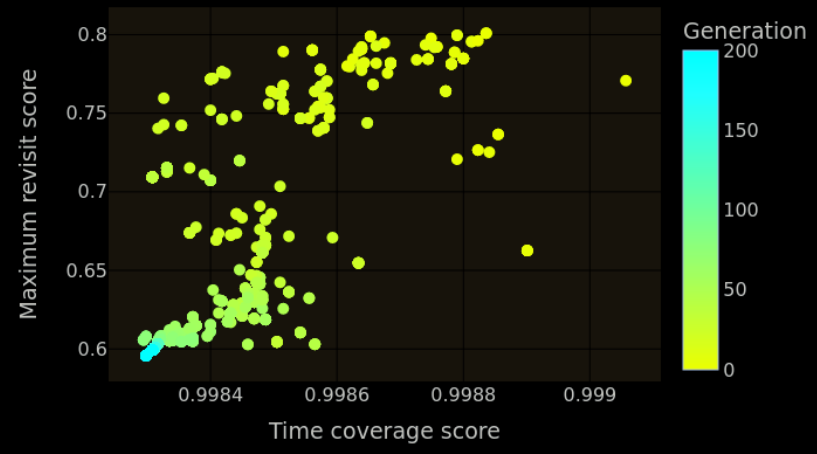
+ RGT configuration
  + 20 m/s
+ GA-based configuration
  + 110 m/s

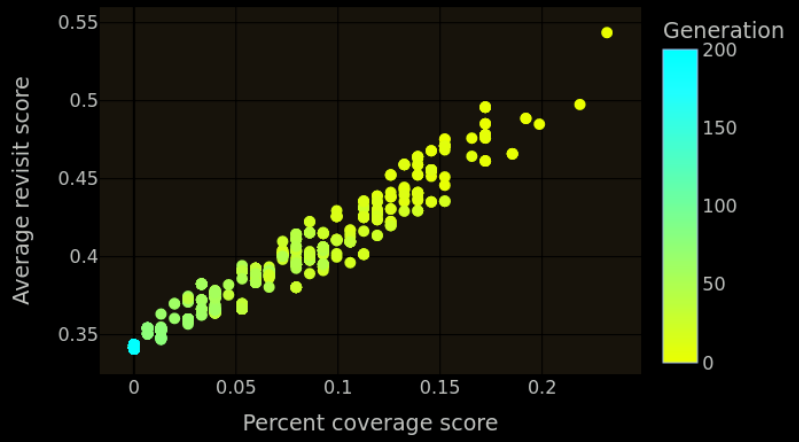
# **WIDE ROI** SCENARIO




+ 200 max generations
+ 250 population size
+ 8 elitism
+ 500m/s max $\Delta V$


Average revisit score
0.55
0.5
0.45
0.4
0.35
0.6
0.7
0.8
0.9
Maneuver cost score
Generation
200
150
100
50
0


Maximum revisit score
0.8
0.75
0.7
0.65
0.6
0.9984
0.9986
0.9988
0.999
Time coverage score
Generation
200
150
100
50
0


Average revisit score
0.55
0.5
0.45
0.4
0.35
0
0.05
0.1
0.15
0.2
Percent coverage score
Generation
200
150
100
50
0