

Agile Earth Observation Under Operational Constraints: CMG vs Reaction-Wheel ACS

Andrea Coco
Veoware
Leuven, Belgium
andrea.coco@veowarespace.com

Simon Debois
Veoware
Leuven, Belgium
simon.debois@veowarespace.com

Abstract— As small commercial Earth Observation constellations expand, operators strive to collect more data and increase value per spacecraft while maintaining low costs and deployment times. In this context, spacecraft agility is often overlooked in constellation design: how quickly a satellite can rotate and then meet pointing requirements largely sets how many targets it can image per orbit. Most small satellites use reaction wheel clusters for pointing and reorientation, but fast retargeting with wheels can be costly in both time and power, reducing the number of images that can be taken within a single pass.

Control Moment Gyroscopes (CMGs) offer a major improvement for high-agility missions. By producing control torque through momentum redirection, CMGs can provide much higher maneuver capability than reaction wheel clusters, enabling shorter maneuver times for the same pointing requirement.

This paper presents a comparative case study that measures the mission-level benefit of an agile spacecraft versus a reaction-wheel-actuated satellite for Earth Observation missions. Using a representative push-broom imaging payload and realistic operating constraints, including viewing geometry and cloud coverage, it was assessed how each cluster affects the number of executable collections and the ability to respond to urgent demands. Results show that CMG-enabled agility provides the largest benefit for time-critical imaging and for missions where it is crucial to collect as much information as possible within a limited timeframe. In addition, CMGs enable observation modes that are difficult to achieve with reaction wheels, such as imaging patterns that adapt to a user-defined area of interest. Overall, CMGs offer a practical way to increase per-satellite imaging output and improve responsiveness in time-critical operations.

Keywords—Attitude Control, Agile Satellite, Control Moment Gyroscopes, Earth Observation

I. INTRODUCTION

Earth Observation (EO) missions play a critical role across a wide range of applications, including agricultural monitoring, methane leak detection, and governmental and scientific activities. As the market rapidly expands, system architectures are increasingly driven by the need to maximize the value of the data acquired in orbit. In this evolving and highly competitive landscape, solutions that were once considered standard are no longer sufficient. Advanced capabilities such as on-board processing for cloud detection and real-time image filtering [1], in-orbit refueling to extend mission lifetime [2], and other enabling technologies are reshaping mission design and operational concepts.

When the objective is to increase the number of acquired targets, the most common solution remains the deployment of constellations, i.e., launching more satellites into orbit. This trend is clearly supported by lower launch costs, however, sooner or later, this approach will face limitations

related to congestion, operational complexity, and long-term sustainability.

Agile satellites are a compelling alternative. Starting from the ISS, which operates a cluster of dual-gimbal Control Moment Gyroscopes (CMGs) [1], to Airbus with the Pléiades satellites, where CMG-based agility has been developed and used [4], and now with multiple commercial CMG manufacturers for small satellites, the path is becoming concrete. In parallel, extensive studies already show the potential of agile platforms for faster retargeting and higher mission productivity.

Once high-torque actuators are available, the problem is no longer how fast the spacecraft can move, but which target to collect. The increased maneuverability shifts the focus to scheduling: selecting the right targets while respecting visibility windows, slew constraints, and mission priorities quickly becomes a non-trivial optimization problem. In this work, the advantages of a CMG-based attitude control system over a standard reaction wheel architecture are explored in representative Earth Observation scenarios, together with how a dedicated scheduling to maximize the number of collected targets.

II. MODELING

The agile satellite is modelled within the VEOMAT simulation tool [5], which integrates spacecraft dynamics, environmental effects, and target definition. The tool is tailored for Phase 0/A Earth Observation studies, where system-mission trade-offs are critical to identify the optimal configuration. Targets can be defined either as Areas of Interest (AoIs) or as point locations, for example imported from CSV files. A key feature of the tool is the ability to simulate different acquisition strategies, which is essential when simulating agile missions.

A. Attitude Control System

For typical Earth Observation satellites, momentum exchange devices (usually reaction wheels) are primarily used to maintain nadir-pointing attitude and to reject disturbance torques. These systems are typically sized based on momentum storage and steady-state pointing accuracy.

For agile satellites, an additional driver must be considered: the number of targets that can be collected within a given time interval. In this context, the limiting factors shift. Sensors, in particular star trackers, typically constrain the achievable angular velocity, while structural dynamics impose limits on the allowable angular acceleration.

For a satellite of class 100-600 kg, attitude control is typically achieved using clusters of reaction wheels. Beyond increasing the number of wheels or converting to a thruster-based control system, an alternative solution is represented

by Control Moment Gyroscopes (CMGs), in both Constant Speed and Variable Speed configurations.

B. Control Moment Gyroscope

A Control Moment Gyroscope enables a satellite to operate closer to its structural or sensor limits by providing high torque capability. The torque is generated by tilting a spinning flywheel, which stores angular momentum, thereby exploiting gyroscopic effects. By redirecting the momentum vector, large torques can be produced with relatively small gimbal motions, instead of relying on continuously spinning the wheel up and down as in typical reaction wheels.

The torque produced by a constant or variable speed CMG can be expressed as:

$$\tau = \dot{\delta} \times \Omega I_{FW} \hat{t} + \dot{\Omega} I_{FW} \hat{h}$$

Where δ it is represent the gimbal angle while Ω is the flywheel speed with I_{FW} being the flywheel inertia. In case of variable speed the torque generated will be the combination of the gyroscopic torque about the axis \hat{t} and the resulting from changes in the flywheel speed along \hat{h} .

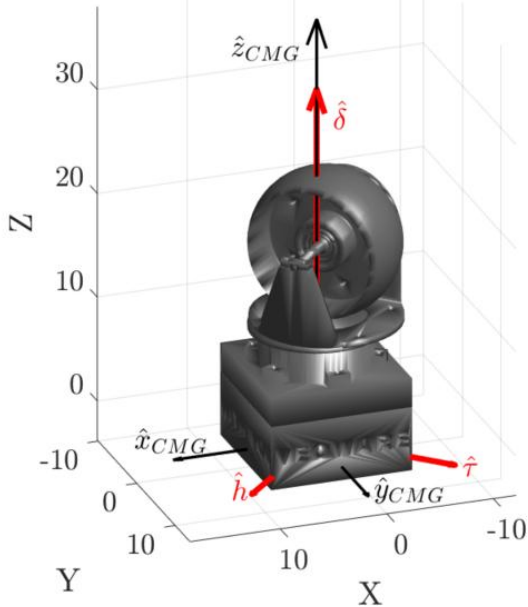


Figure 1 Veoware MicroCMG

In Figure 1 it is shown a CAD model of the MicroCMG where there are represented the torque axes introduced before.

The advantage of the variable-speed configuration is its ability to generate torque about two axes, while also mitigating singularities and providing reaction-wheel-like functionality when required.

Table 1 Veoware Control Moment Gyroscopes

	<i>MicroCMG</i>	<i>MiniCMG</i>	<i>MediumCMG</i>
Angular Momentum (Nms)	0.7	2.8	6
Max Torque (Nm)	1.1	4.4	9
Mass (kg)	2.4	3.2	4

	<i>MicroCMG</i>	<i>MiniCMG</i>	<i>MediumCMG</i>
Power (W)	15	20	30
Volume (mm)	97x97x189	125x125x218	220x220x320

C. Control Moment Gyroscopes Clusters

To ensure full controllability of the spacecraft attitude, multiple CMGs are grouped into cluster. The most common are the pyramid, rooftop, and box configurations, typically composed of four CMGs to provide redundancy. Among these, the pyramid configuration offers a more uniform performance across the pitch, roll, and yaw axes, while the rooftop configuration tends to concentrate momentum authority along a preferred direction. The box configuration also favors specific axes, but maintains a singularity-free region with a minimum radius of 1 h in the presence of a CMG failure.

Figure 2 shows an example of a box configuration cluster, where the pitch axis is selected to provide the highest torque and momentum capability.

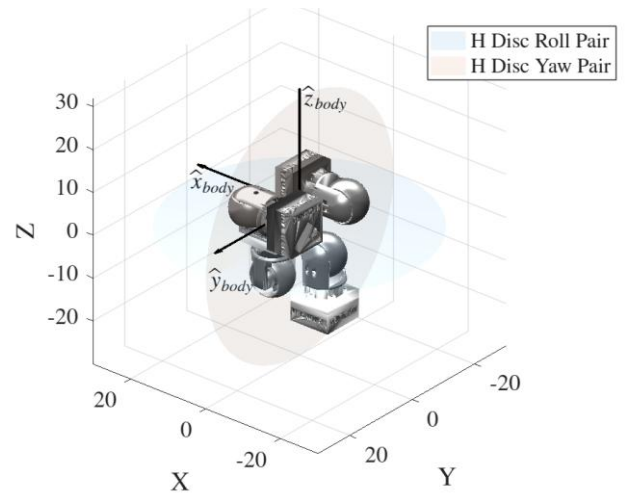


Figure 2 Box Configuration

To account for the gimbal-angle-dependent torque generation of CMGs and to effectively manage singularities, a steering algorithm is required to command a cluster of CMGs. The three-dimensional torque vector computed by the controller is mapped into actuator commands: gimbal rates and flywheel acceleration, through the steering algorithm. Singularities are geometric configurations in which the cluster loses the ability to generate torque in certain directions. From a mathematical standpoint, they correspond to a loss of rank in the allocation matrix (typically 3×4 for a four-CMG cluster), which becomes rank-deficient in these conditions. In addition, the steering algorithm provides null-motion capability, enabling internal momentum redistribution without affecting the net output torque, and supports momentum management to prevent actuator saturation.

Veoware has extensive experience in steering algorithms, covering constant and variable speed steering algorithms as well as more advanced techniques based on optimization algorithms such as Model Predictive Control (MPC).

$$[\dot{\delta}, \dot{\Omega}] = A(\delta, \Omega)^{-1} \tau_d = VS^{-1} U^T \tau_d$$

The Variable Speed Steering Law shown above provides the gimbal rate $\dot{\delta}$ and flywheel acceleration $\dot{\Omega}$ commands to generate the desired torque τ_d computed by the controller.

III. MISSION SCENARIOS

The mission analysis simulation has been carried out in the VEOMAT tool explained in [5]. A representative Earth Observation mission is considered, with the properties of the Sun-synchronous orbit and the agile and non-agile satellite configurations summarized in Table 2 and Table 3:

Table 2 Satellite Properties

Property	Agile	Non-agile
Inertia	[100,100,100] (kgm ²)	[100,100,100] (kgm ²)
Max speed	5 (deg/s)	5 (deg/s)
Max acceleration	5 (deg/s ²)	0.1 (deg/s ²)
Max jerk	10 (deg/s ³)	10 (deg/s ³)
Pitch angle	±20 (deg)	±20 (deg)
Roll angle	±20 (deg)	±20 (deg)
Instrument F.O.V.	0.01 (deg)	0.01 (deg)

Table 3 Orbit Properties

Property	Value
Orbit height	495 (km)
Inclination	97.6 (deg)
LTAN	10.30
Repeating ground track	~15 orbits
Period	96 (min)
Sensor's swath on ground	10 (km)

The two different attitude control system that differentiate the agile and non-agile satellite are listed in the Table 4:

Table 4 Cluster's performances

Cluster	Angular Momentum (Nms)	Torque (Nm)	Mass (kg)	Max Power (W)
Pyramid Mini CMG	[8.8, 8.8, 9.1]	[8.8, 8.8, 9.1]	~13	~80
Pyramid RW	[6.9, 6.9, 8]	[0.17, 0.17, 0.2]	~12	~800

It must be noted that the torque reported is not the maximum torque that can be applied by the CMGs, but it's the average that they provide over the entire momentum envelope.

The following Scenarios are simulated to show the benefits of the cluster of CMG:

A. Area of interest

The Suwałki border region was selected as the area of interest for the scenario comparison and is imported into the

simulator in .kml format. This area is considered one of the most strategic in Europe due to its location between Poland and Lithuania, and its proximity to Russia and Belarus. The guidance generator subdivides the region into rectangular strips compatible with pushbroom imaging, with their longitudinal axis aligned with the satellite ground track and their width defined by the instrument field of view.

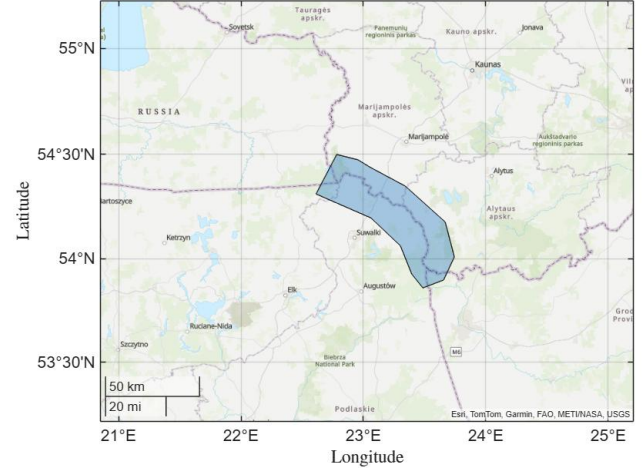


Figure 3 Suwałki Region

B. Strip of interest

Agile satellite can unlock acquisition techniques, often defined as “superagile modes”, that significantly change the benchmark for target acquisition performance. Being able to change the satellite’s slew rate with a strong control authority to cope with custom Line Of Sight trajectories, but also with low microvibrations generated by the gimbal maneuvering. In this scenario it was considered the NordStream 2 gas pipeline as a strip use case.



Figure 4 Nord Stream 2

C. Point-Stare

For targets smaller than the Instrument Field of View (IFOV), no area sweep is required. The satellite simply slews to the target, maintains pointing for an acquisition time defined by the payload, and then slews to the next target.

The ability of agile satellites to acquire multiple targets within a single pass introduces an optimization problem not present in classical state of the art Earth Observation mission: determining the optimal sequence of targets to observe.

When visibility constraints and the physical limits of slew maneuvers are taken into account, the problem becomes

analogous to the well-known Traveling Salesman Problem. In this context, a priority-based scheduling strategy may be required to ensure that the most important targets are acquired. In this work, simple and robust scheduling strategies are evaluated, avoiding complex global optimization or AI-based approaches. The following methods are considered:

1. First Visible
2. Shortest Slew
3. Shortest Two Slews
4. Priority Then Fill

First Visible selects targets based on the start of their visibility window, without priority. If a target is missed, the next one is considered.

Shortest Slew selects, among simultaneously visible targets, the one requiring the minimum retargeting maneuver. The “Shortest Two Slews” variant adds a 2 loop to look-ahead to reduce locally suboptimal choices.

Priority Then Fill enforces acquisition of high-priority targets while opportunistically selecting additional ones based on the “Shortest Slew” method, maximizing overall collection.

The different algorithms were compared using a Monte Carlo analysis. A set of 300 random targets was generated over Italy, and the number of targets collected was evaluated for a single satellite operating in a point-stare mode.

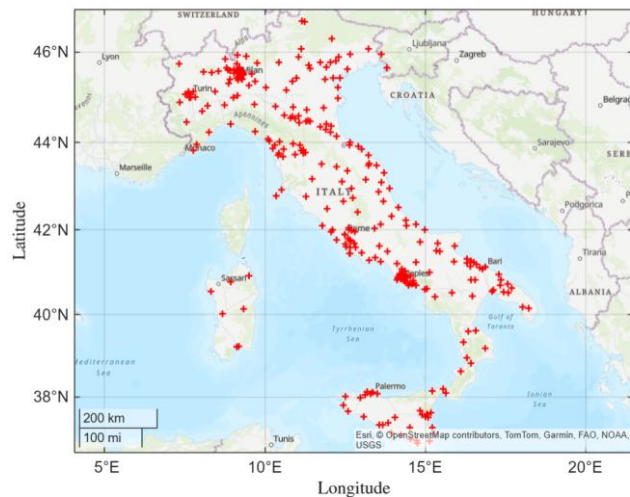


Figure 5 Point-Stare Locations

IV. RESULTS

The scenarios described above are evaluated for two configurations when possible: a CMG-based (agile) and a reaction wheel-based (non-agile) attitude control system.

A. Suwalki Region

The multi-strip acquisition is performed using a pushbroom imaging mode. Figure 6 illustrates the discretized acquisition rectangles, aligned with the satellite ground track (shown by the red line).

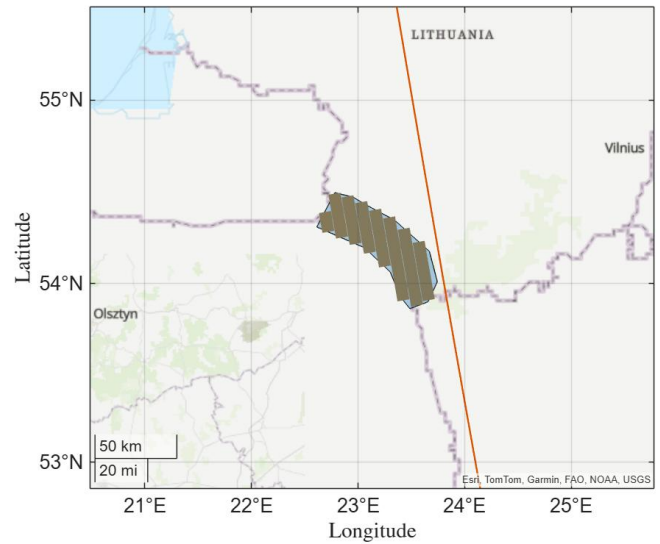


Figure 6 Discretization of the Suwalki Region

The number of sections that can be acquired depends primarily on spacecraft agility. This type of acquisition must be performed at orbital speed, and the total number of targets collected is largely driven by the time required for the spacecraft to slew between consecutive targets.

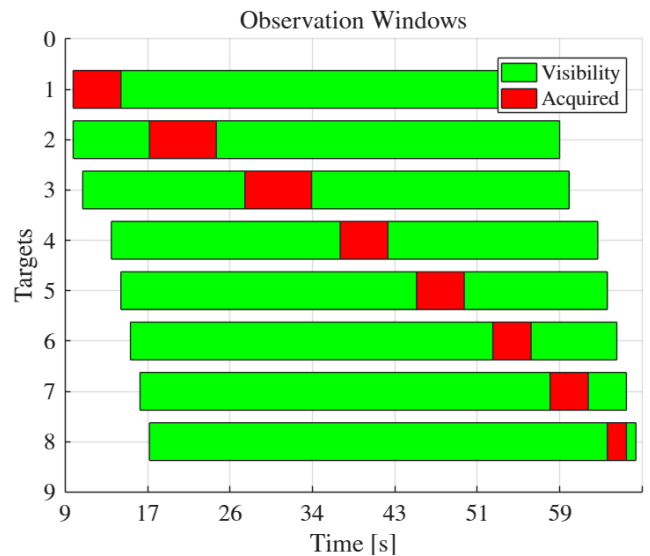


Figure 7 Agile Satellite Targets Collected

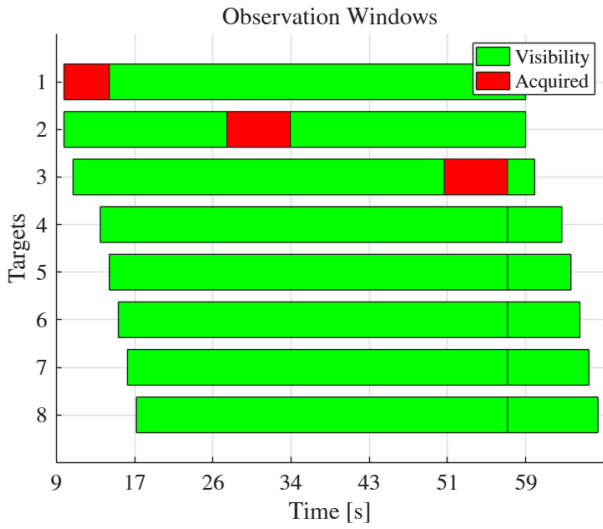


Figure 8 Non-agile Satellite Targets Collected

Figure 7 and Figure 8 shows the visibility windows and the target collected for the agile and non-agile satellite. The observation time are the same but the key difference is the shorter slew time between each targets collected. The slew maneuvers were indeed modelled according to a parametrization of a jerk limited profile that takes into account maximum jerk allowed, acceleration and velocity. An example can be seen in Figure 9.

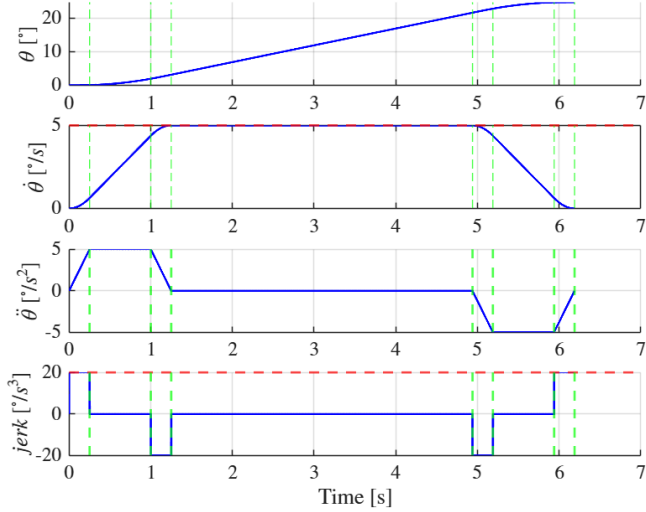


Figure 9 Agile Slew Maneuver Parametrization

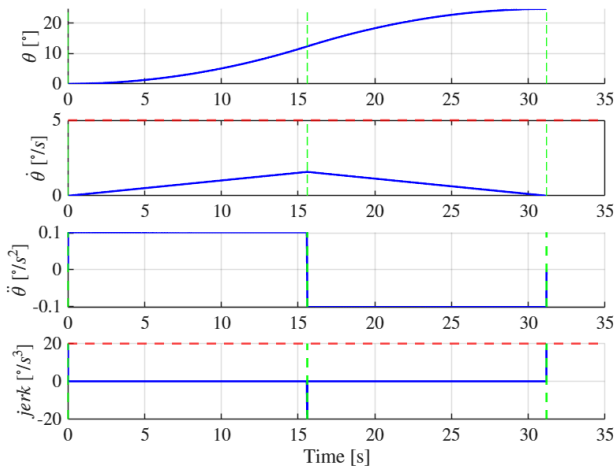


Figure 10 Non-Agile Slew Maneuver Parametrization

Figure 9 and Figure 10 show the difference between agile and non-agile maneuvers. High-torque actuators quickly reach saturation and enter a coasting phase, characterized by a constant slew rate. In contrast, the non-agile configuration does not reach the maximum velocity due to its limited acceleration capability.

B. Nord Stream 2 Monitoring

The Nord Stream 2 extends over approximately 1200 km, significantly exceeding the spacecraft cross-track Field of Regard. At an orbital altitude of 490 km and with a pitch capability of $\pm 10^\circ$, the resulting visibility window is limited to about 24 seconds. Even when exploiting roll agility up to $\pm 20^\circ$, the accessible cross-track swath remains on the order of 350 km.

To maximize coverage within a single pass, the spacecraft must sustain slew rates of up to 4 deg/s, while preserving sufficient control authority to reject disturbances and ensure accurate tracking. This operational scenario falls within the class of so-called super-agile acquisition modes, where the low jitter induced by CMG makes the difference in collecting good quality images.

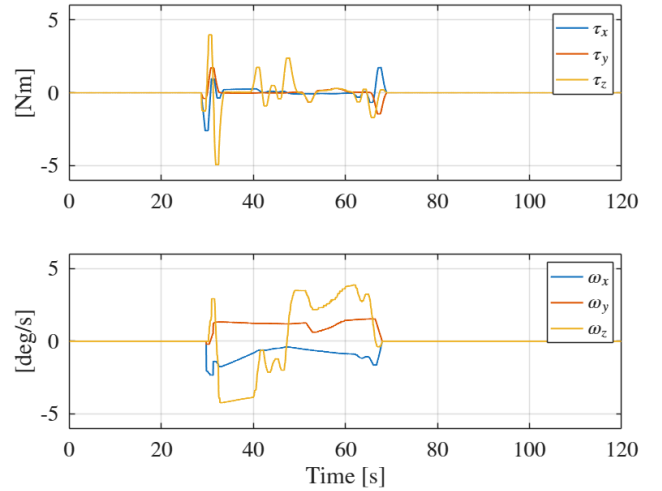


Figure 11 Torque and Angular Velocities

Figure 11 reports the torque that the cluster of CMGs have to provide to produce the angular velocity needed to track the visible portion of the pipeline. The spacecraft must vary its angular velocity along all three axes to maintain the camera perpendicular to the target direction. This results in a particularly high agility demand about the yaw axis, as can be observed in the figure above.

C. Point-Stare

The different algorithms were compared using a Monte Carlo analysis. A set of 300 random targets was generated over Italy, and the number of targets collected was evaluated for a single satellite operating in a point-stare mode. The so-called "Priority Then Fill" algorithm was also tested for a cluster of four reaction wheels, with each actuator capable of delivering up to 4 Nms of angular momentum and 0.1 Nm of torque.

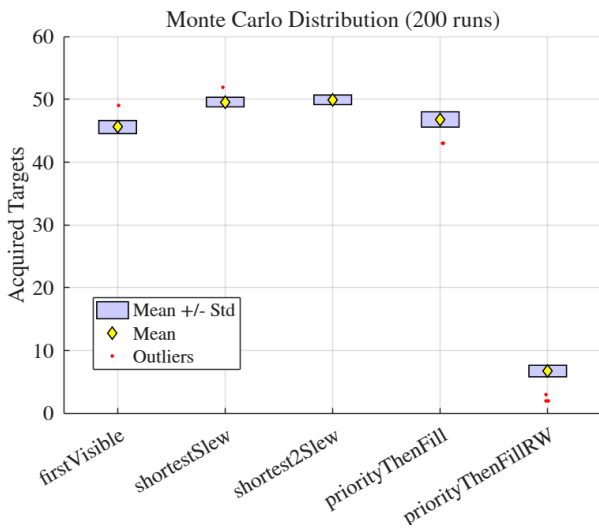


Figure 12 Algorithms comparison

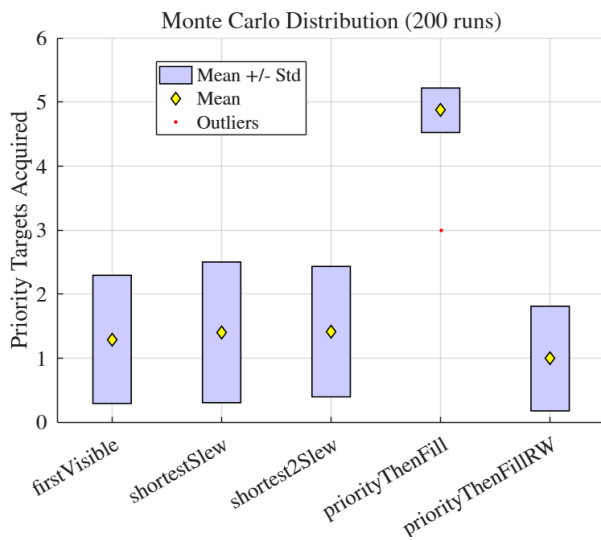


Figure 13 Priority Targets Collected

The results of the Monte Carlo analysis are shown in Figure 12 and Figure 13. The "Shortest Two Slews" method, when combined with a CMG-based cluster, provides the highest performance, closely followed by the "Shortest Slew" method. The similarity in results suggests that introducing a second look-ahead step does not yield a significant performance improvement in estimating the slewing time over successive maneuvers.

In contrast, the reaction-wheel-based configuration is strongly penalized by its limited angular acceleration capability, collecting fewer than 10 targets per pass

Regarding the acquisition of randomly assigned priority targets, only the agile CMG-based cluster combined with the "Priority-Then-Fill" strategy is able to collect nearly all of them. However, this method does not necessarily maximize the total number of targets acquired, as seen in Figure 12.

Although no global optimization algorithms were used here, it must be noted that these algorithms run in MATLAB, in an Intel 7, 16 core processor, in the order of milliseconds for a list of around 300 targets. Therefore they can be suited as simple on board autonomous guidance generation, in particular when the targets are covered by clouds and the autonomous algorithm decide which target to be acquired accordingly to the priority or penalization factor given.

V. CONCLUSION AND FUTURE WORK

The analysis presented in this work considered three distinct use cases, each characterized by different acquisition techniques. In all scenarios, a Control Moment Gyroscope (CMG)-based attitude control system demonstrated clear advantages over classical reaction wheel architectures. In addition, CMG-based devices exhibit lower power consumption, which can enable simultaneous payload operation during actuation, ultimately supporting the implementation of super-agile acquisition modes.

The modelling of environmental disturbances represents a key next step and is planned as part of future work. Accounting for disturbance rejection during maneuver planning may reduce the available momentum envelope; however, for short acquisition windows on the order of a few minutes, this effect is expected to remain limited.

- [1] <https://doi.org/10.5194/amt-2019-484>
- [2] "On-Orbit Satellite Servicing Study Project Report," NASA GSFC, October 2010, https://sspd.gsfc.nasa.gov/images/nasa_satellite%20servicing_project_report_0511.pdf
- [3] Bedrossian, Nazareth & Jang, Jiann-Woei (Jimmy) & Alaniz, Abran & Johnson, Michael & Sebelius, Karl. (2005). International Space Station US GN&C Attitude Hold Controller Design for Orbiter Repair Maneuver. 10.2514/6.2005-5853.
- [4] Thieuw, A. & Marcille, H.. (2007). Pleiades-HR CMGs-based attitude control system design, development status and performances. IFAC Proceedings Volumes (IFAC-PapersOnline). 17. 834-839.
- [5] Coco, A. and Debois, S., (2025), "Next-Generation Earth Observation: Agile Satellites With CMG Cluster for Enhanced Coverage"