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Mission Analysis and Flight Dynamics Operations for Kinéis mission

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Abstract

Kinéis is a French satellite operator established in 2018 aiming to provide global IoT connectivity through a constellation of 25 nanosatellites distributed on 5 orbital planes and located in Low Earth Orbit at an altitude of about 650 km. The 25 satellites were launched from New Zealand in a series of five missions using Rocket Lab's Electron rocket, starting in June 2024 and concluding in March 2025. This paper extensively discusses the work and results of the close and effective collaboration between CNES and Kinéis teams during the last few years to define and implement the Flight Dynamics aspects of this mission.

Keywords: constellation, mission analysis, flight dynamics, operations, electric propulsion

Acronyms/Abbreviations

AIS	Automatic Identification System
AoL	Argument of Latitude
API	Application Programming Interface
ATOX	ATomic Oxygen
CNES	Centre National d'Etudes Spatiales – French National Space Agency
EOR	Electric Orbit Raising
EUSST	EU Space Surveillance and Tracking
FDS	Flight Dynamics System
GCS	Ground Control Segment
GRS	Ground Remote Stations
IoT	Internet of Things
IOV	In-Orbit Validation
LEOP	Launch and Early Orbit Phase
MCS	Mission Control System
MLTAN	Mean Local Time of Ascending Node
SC	Service Centre
TC	Telecommand
TM	Telemetry
TRL	Technology Readiness Level
UHF	Ultra High Frequency

1. Introduction

From June 2024 until March 2025, the 25 nanosatellites of the Kinéis constellation have been successfully launched to Low Earth Orbit. By the end of March 2025, the service is partially opened to customers based on the first set of satellites launched on June 2024 and the constellation is planned to be fully operational by Summer 2025.

This paper will extensively discuss the work and results of the close and effective collaboration between CNES and Kinéis teams during the last few years to define and implement the Flight Dynamics aspects of this mission, including:

- Constellation design in order to perform a double mission, optimize the concept of operations (CONOPS) and ensure robustness in case of contingencies. Kinéis system is designed to fulfill two missions: the main IoT mission, carried out by 4 satellites in each orbital plane, enabling precise location tracking and monitoring of objects all over the globe and a secondary AIS (Automatic Identification System) mission, carried out by 1 satellite in each plane, enhancing maritime safety and traffic monitoring.

- Mission analysis with focus on Kinéis mission specificities such as Electric Orbit Raising (EOR), station-keeping strategy and collision avoidance.
- Flight Dynamics System development and validation process based on CNES SIRIUS product line and emphasizing on critical aspects for operating a constellation of 25 satellites with reduced teams such as automation.
- First feedback and lessons learned on constellation deployment and first months of Flight Dynamics routine operations.

2. Kinéis mission overview

2.1 Mission overview

The Kinéis constellation design serves two missions: The IoT mission builds on the Argos system heritage to provide clients with a low power, low-rate, bi-directional global communication network. The AIS mission, by collecting messages emitted by vessels, allows ship-owners and government bodies to track their assets around the globe, in a timely manner.

The Kinéis constellation was finely tuned to address those two missions at once, as well as a couple of other constraints. At the time of constellation design, available launch opportunities were:

	Advantages	Disadvantages
Dedicated launcher	- Total schedule control	- Costly
Co-passenger	- Cheaper	- Launch schedule heavily dependent on the primary payload - In case of an earth-observation primary payload, may require high standards of cleanliness - May require extremely long EOR depending on launch profile
Ride-share with motorized dispenser	- Cheapest - Orbit raising is handled by the motorized dispenser	- No control over launch date / Access to the satellites on launch site / Battery charge - Satellites have to be qualified to handle orbit raising stacked to the dispenser (constraint on battery, vibrations, ATOX exposition, etc.) - Not a very high TRL at the time.

Table 1. Constellation launch strategies

2.2 Satellite overview

All satellites of the Kinéis constellation are built by HEMERIA, a leading French satellite manufacturer specializing in high-performance nanosatellite platforms and subsystems, and are cast in the same mold: a 16U cubesat form factor host the platform and the payloads computers, deployable solar arrays and antennas, and a protruding star-tracker. The ensemble weights a bit less than 30 kg.

10 of the satellites host both IoT and AIS payloads, and 15 only host IoT. TM is served through S-band, TC via UHF-band using the IoT antenna and payload. All satellites are equipped with an electric thruster from ENPULSION allowing them to perform orbit raising, station-keeping and collision-avoidance maneuvers.

Fig. 1 Kinéis satellite

2.3 Constellation overview

The constellation is a Walker-Star (20, 5, 1) [1] in which prime AIS satellites (in red in Fig. 2) are added to minimize collisions risks, and backup-AIS satellites are their nearest neighbours.

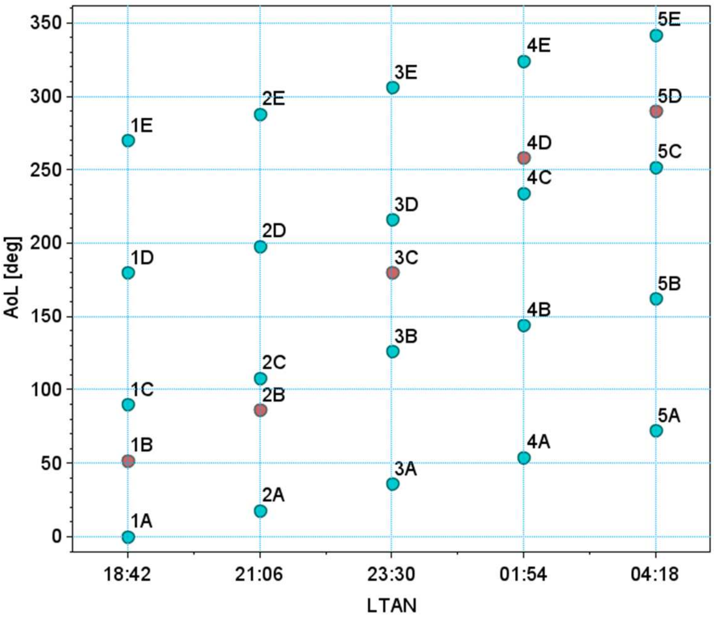

Fig. 2 Constellation diagram

This allows to perform both missions on all orbital planes, without interfering with each other.

The orbit is sun-synchronous around 650 km. The altitude and MLTAN choices were made to complement the existing Argos fleet[*], and maximize opportunities of co-passengers or ride shares. However, the project decided to use dedicated launchers for the benefit of total control over the launch schedule, which has proven to be a wise choice afterwards.

2.4 Ground system overview

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[*] The Argos system, created in 1978, is the predecessor of the Kineis IoT system. The space segment was composed of payloads on partners' satellites (NOAA, EUMETSAT, ISRO, etc.).

The Kinéis ground segment is composed of several entities:

- Ground Remote Stations (GRS): a dedicated network of 20 ground stations to ensure satellite communication and data reception across the globe.
- Mission Control System (MCS): is the central hub of the ground segment and is mainly responsible for processing, storing, and distributing data as well as monitoring the ground segment and payloads.
- Ground Control Segment (GCS) is in charge of control and monitoring the platform and integrates the Flight Dynamic System (FDS) responsible for flight dynamics computations.
- Service Center (SC): is in interface with final users and is in charge of managing beacon messages and localize user beacons.

A more detailed description of Kinéis system is available in [2].

3. Operational phases

3.1 Launch and Early Orbit Phase

Launches for the Kinéis constellation were provided by RocketLab, with Electron rockets launched from New-Zealand between June 2024 and Mars 2025.

The target injection orbits were approximately 15 km below the mission orbit (635 km altitude) for the first three launches and they were slightly increased to reach 638 km for the fourth launch and finally an altitude of 641 km for the fifth and final launch.

Satellite acquisition of signal was handled by the Kinéis GRS network, with CNES Multi-Mission Network as a fall-back. GRS network provided one-way Doppler measurements while CNES Multi-Mission Network also provided angular measurements necessary to realize orbit determination computations.

3.2 Propulsion Commissioning

After completing LEOP, when orbit determination and spacecraft status is stable, the In-Orbit Validation (IOV) phase begins. Among other tests on the spacecraft, propulsion commissioning is performed at this time in order to verify the proper functioning of each satellite's propulsion systems. This phase is culminated with the first calibration maneuvers commanded by the Flight Dynamics team. The principle of these calibration maneuvers is to perform for each satellite a sequence of purely positive tangential thrusts ($\Delta a>0$) in order to deduce through orbit determination the actual change in orbital parameters and thus determine the operating point in terms of propulsion characteristics (thrust force, duration, efficiency). These propulsion characteristics are crucial for orbit raising and station-keeping and will be thoroughly monitored during all lifespan.

After successfully performing these calibration maneuvers, each satellite is declared as maneuverable with respect to international space surveillance entities: 18th Space Defense Squadron (SDS) and EUSST.

3.3 Electric Orbit Raising

Once propulsion commissioning has ended and propulsion characteristics are well established for each thruster, it is time to define the orbit raising strategy.

The basic principle of our orbit raising strategy consists in computing for each satellite a target ascending trajectory with a constant semi major-axis increase rate that allows it to achieve both its desired altitude and orbital position. If possible, our baseline is to determine the optimal moment for each satellite to begin its ascent and then execute a direct continuous strategy without interruptions and without overshoot. However, as we also had to cope with different constraints, in particular due to the tight launch schedule and the team limited availability for monitoring critical activities such as begin of EOR while simultaneously conducting LEOP operations for another batch of satellites. In some exceptional cases it has been necessary to adapt the orbit raising strategy bringing forward the starting point and including a drift period in order to prioritize other batch LEOP operations. This occurred, for instance, during EOR of satellite KINEIS-2D, represented in blue in both plots in Fig. 3. In the first plot, we observe that the semi-major remains constant for about 10 days around March 18th 2025, date of the launch of the fifth set of satellites.

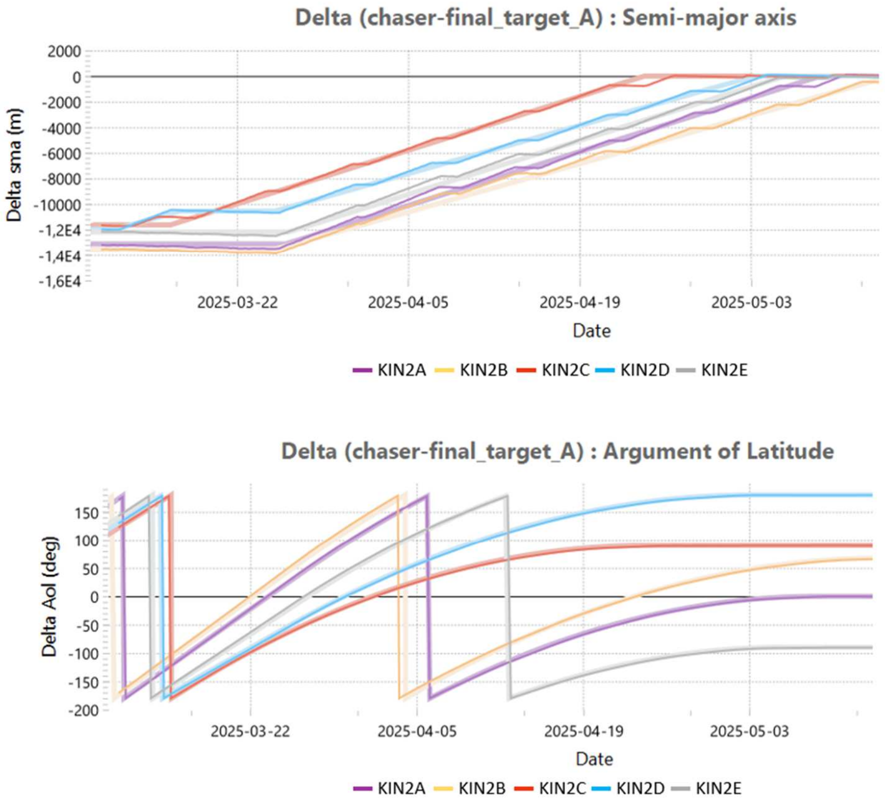


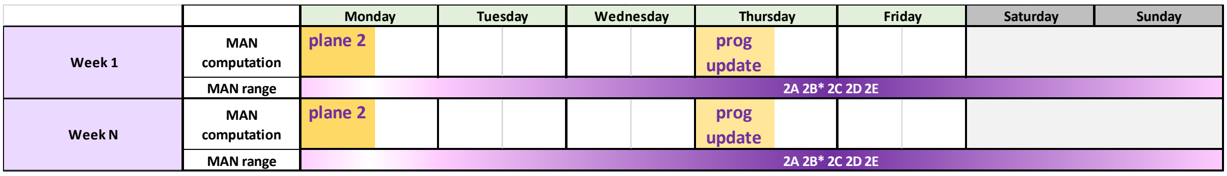
Fig. 3 Electric Orbit Raising profile for satellites KINEIS-2x

In addition to both initial and final orbit position, the driving parameter needed to compute the target ascending trajectory that reaches the operational orbit is the semi major-axis increase rate. This key value is obtained for each satellite from:

- its maximum thrust capacity (about 1/3 of each orbit)
- the estimated decrease in semi-major axis due to atmospheric drag
- a 20% margin applied to address potential uncertainties: compensating for maneuver execution errors, temporary unavailability for maneuvering (satellite in safe mode) or significant variations in solar activity level

Once the target ascending orbit is established, the EOR strategy implementation consists in performing orbital maneuvers in order to maintain the difference of AoL between actual and target trajectory within a given interval all along the orbit raising period, following the same principle employed during station-keeping, as explained in section 3.4. This approach has a major advantage from an operational point of view: it allows to reuse components initially designed for station-keeping purposes for computing the orbit raising strategy as well, simplifying operators' formation and transforming a typically critical phase such as EOR into almost fully automated routine operations, except during transition periods from IOV to EOR and from EOR to station-keeping.

Based on the station-keeping CONOPS (see section 3.4) we derived its counterpart for EOR phase: orbit raising maneuvers are divided into weekly cycles. They are automatically computed and programmed every Monday morning for on-board execution from Tuesday at midnight. This ensures that most thrusts occur during working days, allowing for timely intervention if needed. Once EOR phase begins, maneuvers are fully computed and programmed automatically with minimal human intervention, except for verifying proper execution and, if needed, updating predicted maneuvers efficiency based on previous maneuvers realization.



		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Week 1	MAN computation	plane 2			prog update			
	MAN range	2A 2B* 2C 2D 2E						
Week N	MAN computation	plane 2			prog update			
	MAN range	2A 2B* 2C 2D 2E						

Fig. 4 Electric Orbit Raising CONOPS. Example for plane 2.

The total duration of a direct EOR phase for the satellites of a given plane is about 2 months: 2 weeks in the worst case between the start of orbit raising for the first and the last satellite of the batch plus 1.5 months for the semi-major axis increase of each satellite until reaching its operational orbital position. When a satellite reaches its designated position, an evaluation is conducted to determine whether a final fine-tuning maneuver is required and it finally takes its place in the 28 days maneuver cycle as defined by station-keeping CONOPS (section 3.4).

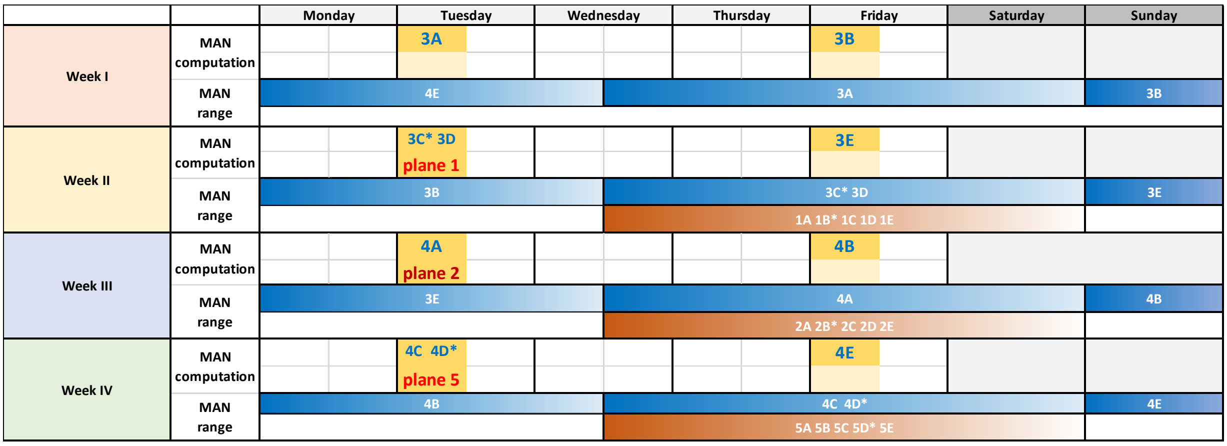
By the end of March 2025, the EOR for the fourth batch (plane 2, MLTAN 21:06) is ongoing and, due to the natural evolution of inclination and MLTAN for this orbital plane, it is the first time that it has been necessary to implement OER strategy including orbital inclination corrections along with semi-major axis increase.

3.4 Station-keeping

Due to a strict energy budget available on planes 3 (MLTAN 23:30) and 4 (01:54), also called "*cold planes*", the payload on these planes can't be operated at full capacity while maneuvering. We determined that the maximum incursion of the satellites around their ideal constellation slot, due to the modified Walker-Star, was around 8 degrees of argument of latitude.

We then computed that each satellite could move ± 4 degrees of argument of latitude around its ideal position, if maneuvering once a month, under the harshest conditions of solar activity (Marshall 95 [3]). In this conditions, each maneuver could last as long as 3.5 days.

We then created a CONOPS around these constraints, that allowed to minimize the effect of maneuvers of planes 3 and 4 on the whole IoT system capacity, as IoT satellites of these *cold planes* should not maneuver at the same time. On the other hand, AIS satellites on those planes and satellites of the other planes are allowed to maneuver at the same time, without impact on IoT system availability.



		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Week I	MAN computation		3A			3B		
	MAN range	4E		3A				3B
Week II	MAN computation		3C* 3D plane 1			3E		
	MAN range	3B		3C* 3D				3E
				1A 1B* 1C 1D 1E				
Week III	MAN computation		4A plane 2			4B		
	MAN range	3E		4A				4B
				2A 2B* 2C 2D 2E				
Week IV	MAN computation		4C 4D* plane 5			4E		
	MAN range	4B		4C 4D*				4E
				5A 5B 5C 5D* 5E				

Fig. 5 Station-Keeping CONOPS. AIS prime satellites are marked with *

Fig. 5 shows the 28 days sequence of the station-keeping CONOPS. If we take week II for example, the FDS commands the maneuvers for KINEIS-3C (AIS) and KINEIS-3D (IoT) satellites on Tuesday, with their maneuvers starting on Wednesday at noon, and ending no later than Sunday at midnight. On Friday, a maneuver is commanded for KINEIS-3E (IoT), that starts on Sunday at midnight and ends no later than Wednesday at noon. Hence each satellite maneuvers every 28 days, with a minimal overlap of IoT payload unavailability.

As Marshall models don’t emulate the solar activity tendency to change drastically in small timeframes (days or weeks), we knew that, in some instances, this CONOPS would not yield, and some satellites of *cold planes* would have to maneuver at the same time. The objective of the CONOPS was simply to minimize these occurrences.

3.5 Collision avoidance

Risk analysis and filtering is delegated to EUSST. The radius of the primary object (our satellite) is a prominent factor of probability of collision computation, and our satellites are quite small. Hence we only had to handle a few avoidance maneuver since the first launch. Today we handle a risk manually, with a coordination by mail and phone with EUSST.

In the future, we plan on automating the process, only keeping a final check by the on-call operator before sending the maneuver telecommands.

4. FDS development and architecture

4.1 FDS development

In the context of Kinéis mission, CNES is responsible for the development of the Ground Control Segment (GCS), including the Flight Dynamics System (FDS), and its operations during the deployment of the 25 nanosatellites of the constellation and the first months of routine operations. After that period, the handover from CNES to Kinéis will take place and operations will be fully assured by Kinéis team. For the last years, Flight Dynamics engineers from both CNES and Kinéis have worked together in an integrated team to contribute to the definition of the mission and to design and implement the flight dynamics operational means and concepts to successfully address it.

Within the GCS, the FDS is in charge mainly of:

- Orbit determination,
- Trajectory and orbital events prediction,
- Maneuvers computation for both EOR and station-keeping,
- Collision risk management, with the support of EUSST,
- Attitude guidance and on-board trajectory update command,
- Monitor flight dynamics related parameters for each satellite and for the complete constellation.

From the very first discussions about the operational flight dynamics software required for Kinéis mission, attention quickly turned to a solution based on the SIRIUS product line, the current generation of Flight Dynamics Systems for present and upcoming CNES missions [4]. The SIRIUS product line offered several major advantages:

- It already covered the vast majority of needs of Kinéis missions, namely:
  - Orbit determination based on one-way Doppler measurements, even from completely new ground station network,
  - Robust maneuver strategy computation algorithms for station-keeping (and EOR as seen in section 3.3) around both reference argument of latitude and mean local time,
  - Most high and low level services to command the satellite attitude (yaw-steering and yaw-fixed laws) and update on-board trajectory.
- It could be easily adapted to respond to Kinéis specific needs.
- It provided an off-the-shelf product, the Standard FDS [5,6], directly available after data instantiation for early qualification test phases.
- It was suited to meet the demands of a new space project such as Kinéis: very tight development schedule with very limited development cost.
- Its core functionalities had already been "flight-proven" on highly demanding French institutional missions and were ready to be used in other scientific missions such as SWOT, a mission jointly developed by NASA and CNES for hydrology and oceanography, and Microcarb, a French mission to measure atmospheric concentrations of carbon dioxide.
- Kinéis mission could benefit (and has significantly benefited indeed) from the feedback from other missions using the same product line.

The main features that were not already covered and that required specific development for the Kinéis were related to the use of electric propulsion and its associated constraints, since all previous missions that used an FDS based on SIRIUS product line were equipped with chemical propulsion. This new features include:

- A generalization of the algorithm used to split the total delta-V computed for a given maneuver strategy (station-keeping, collision avoidance…) in order to accurately model the constant-force, long and frequent low-intensity thrusts that characterize electric propulsion systems. In accordance with SIRIUS product

line philosophy and aiming to offer more flexibility in case adaptations are needed during the mission lifespan, this algorithm has been designed to allow the definition of *split patterns* based on different criteria: max delta-V per thrust, duration between consecutive thrusts, argument of latitude of thrust median date or distribution strategy about initial delta-V.
- Considering the impact of the uncertainty in maneuvers realization in the nominal predicted trajectory, and not only in covariance prediction, according to Gates' model [7].
- As for every new satellite platform, implementing some low-level services in order to fulfil its specificities in terms of attitude and orbital maneuvers command.
- As for every new mission, implementing some constraints verification, in particular related to the electric propulsion technology used: minimal thrust duration, minimal number of thrusts per thruster actuation, optimal thrust slots in order to respect energy requirements…).

One of the major challenges of the Kinéis mission was the management and monitoring of 25 satellites in parallel. Although other missions using SIRIUS-based FDS had a fairly high level of automation of operations and some already dealt with several satellites (up to 3 satellites in formation), it was necessary to push automation even further. What is acceptable to do “manually” when operating a couple of satellites may become cumbersome and source of operational errors when having 25 satellites to manage. Automation was not an option!

The FDS provides a full operable scripting API in Groovy language (an extension of the Java language) that allows to automatically perform any action an operator can do : create, retrieve or modify data, execute a flight dynamics service, plot results, generate reports… This scripting API plays a key role in the implementation of the DevOps approach within Kinéis flight dynamic operations as operators have at their disposal the means to directly respond to new operational needs or workaround potential problems they may face and, once the concept has been validated, they can easily automate it. This flexibility and short-time cycle was very useful and much appreciated during the deployment of the constellation and first months of operations and will certainly continue to be so during the next years.

4.2 FDS deployment architecture

One of the topics that we had to deal when implementing the Kinéis FDS was how to manage a constellation of 25 satellites in parallel, with sets of satellites in different operational phases that overlaps. The detailed schedule is discussed in [2].

Even though the SIRIUS product line was originally designed to manage up to 6 satellites, for mini-constellations or several satellites in formation flying, there were no real limitations preventing its use for a constellation of 25 satellites. However, it was necessary to find the architecture that best suited the mission requirements taken into account the available resources.

The optimal trade-off came directly from the disposition of the satellites in the constellation and the launch and deployment strategy. Since the constellation is composed of 5 plans of 5 satellites and this arrangement in planes is one of the key elements of the entire CONOPS, it was a natural choice that the FDS architecture should try to reproduce this organization. Therefore, the chosen solution was to have 5 instances of FDS, each one dedicated to manage the satellites of a plane. As the station-keeping orbital slot for each satellite is defined in an absolute way, independently of other satellites' slots, each satellite executes its processes individually, with very limited interaction with other satellites processes. The only use case identified at this day requiring multi-satellite computations is the analysis of intra-constellation potential conjunctions at the orbital crossings over the poles. This need could have been addressed by a sixth FDS instance dedicated to constellation level computations. However, due to the limited number of existing multi-satellite use cases it has been decided that this computation is to be performed in turns by the FDS instances already available for each plane computations.

5. Orbit determination: Some in-orbit feedback

5.1 Atmospheric drag modelling

Having a fleet of 25 satellites distributed across 5 orbital planes presents an exceptional opportunity for fine-tuning the parameters involved in orbit determination. Satellites within the same plane are all on the same orbit and experience the same space environment and forces. This is an advantage because it allows us to isolate ourselves from solar weather (solar flux and geomagnetic activity), which is difficult to predict, and atmospheric models, which are also inevitably imperfect. Any differences observed in orbit determination between two satellites in the same plane are necessarily due to other causes: different satellite modelling, different attitude, outgassing, etc. Within our FDS, we initially modelled all satellites in the same way: a cube representing the satellite body and two rectangular plates representing the solar panels. After a few months of operations with the first 5 satellites in flight, we realized that 2 of the satellites consistently had a higher drag coefficient than the other 3. These were the AIS satellites, which have a small additional antenna that we had considered negligible in the satellite modelling (the width of the antenna elements being barely 2 cm). Fig. 1 represents a Kinéis satellite equipped with an AIS antenna, composed by 6 independent stainless steel metal strands disposed around the helical-shape UHF antenna.

A little later, we conducted experiments changing the attitude mode from yaw steering to constant yaw in order to minimize drag and thus the number of station-keeping maneuvers. During this change, we noticed that the drag coefficient of the satellite switched to constant yaw was very off from the other satellites that remained in yaw steering. The reason was that the drag model did not account for the shadowing of the satellite body by the solar panels. Fortunately, another model already existed in the FDS that did take shadowing into account, which allowed us, after several adjustments (see figure below), to obtain a realistic model that predicts drag very well regardless of the satellite's attitude. These adjustments would not have been possible with only one satellite in flight because we would not have had a "calibration" satellite.

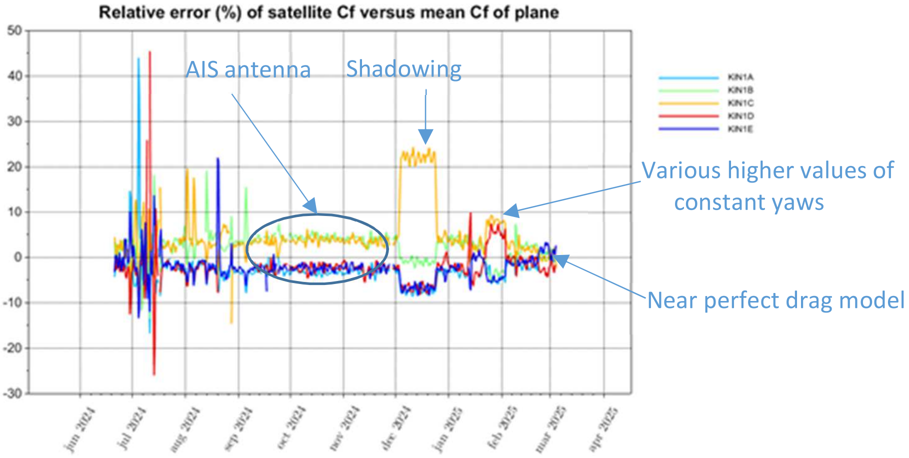
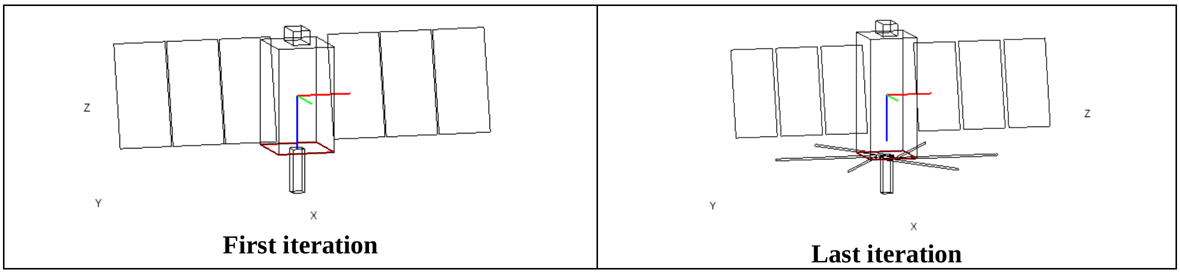


Fig. 6. Relative error of drag coefficient for plane 1

Fig. 6 shows the relative error of the drag coefficient of each satellite with respect to the mean drag coefficient of the plane. We can see the various relative errors due to modelling errors and how we fixed them through iterations until reaching a very accurate drag model in February 2025.



First iteration

Last iteration

Fig. 7. Drag model iterations

Fig. 7 shows the differences between first and last iterations of the drag model: we added the AIS antenna for the relevant satellites, shadowing and adjusted the size of the body and the solar arrays thanks to in-flight data.

A detailed understanding of the drag model is invaluable because it allows us to perform relative station-keeping between satellites within the same plane. For example, we can finely adjust the yaw angle of the satellites without the AIS antenna to achieve the same drag as those that do have the AIS antenna.

An additional concept we are currently using in operations is to minimize drag on the "cold planes" (planes 3 and 4) during solar eclipses. These planes have long eclipses during which there is no benefit in maintaining yaw steering since the solar panels are not exposed to the solar flux. We switch the satellites to a constant yaw such that the drag surface is as small as possible. The gains are on the order of 15% on average over the entirety of an orbit, which allows us to reduce the number of thruster activations.

5.2 Maneuvers estimation

Another relevant subject we faced was the orbit determination of quasi-permanent electric propulsion maneuvers over very long arcs. Electric propulsion maneuvers involve 17 minutes-long thrusts every half-orbit, and in the context of orbit raising, this occurs for entire weeks, and for station-keeping, for several days. Kinéis has a significant network of ground stations, which means the number of Doppler measurements is still quite high, but not enough to have passes every half-orbit! Therefore, it becomes complicated to estimate each maneuver separately from the others when there are no measurements between them: indeed, its estimation is completely unconstrained since one maneuver can be compensated by the next one. A recent development in the SIRIUS product line allows for the global estimation of maneuvers instead of estimating them independently, but as this feature is not available for Kinéis, so we opted to determine a reduced number of thrusts (one out of five) to ensure we always had measurements between the estimated maneuvers.

One more complication when estimating maneuvers over very long arcs – typically when maneuvering over the entire orbit determination arc (2 days) – is that the orbit determination algorithm can no longer distinguish drag from the maneuvers. There is a coupling effect between the two. Fortunately, not all 25 satellites in the constellation maneuver at the same time and, after fine-tuning of our atmospheric drag modelling (as explained in section 5.1), we have implemented a system to retrieve the drag coefficient of the maneuvering satellites from the non-maneuvering satellites. This mechanism has proven its reliability in flight and allows us to have precise orbits even during periods of prolonged maneuvering.

6. Conclusions

Defining the Kinéis mission, implementing it and deploying its 25 nanosatellites with a very constraint schedule and resources, was a major challenge for the joint Kinéis and CNES teams. This collaboration has been very enriching and fruitful for both organizations, and lead to many optimized concepts and automations that allow the Kinéis system to be operated by a reduced team. Kinéis has benefited from CNES's technical expertise in various domains, in particular, its experience in designing, developing and operating control centers and flight dynamics systems, acquired over decades of involvement in diverse space missions. For CNES it was a great opportunity to actively participate in an ambitious project, reinforcing its position in New Space, supporting the growth of the new actors of the French space industry, and showing its ability to drive innovation in satellite technology.

In particular, the joint CNES-Kinéis team in charge of mission analysis and flight dynamic operations has closely worked together during the last years and has been able to meet the challenges of this demanding mission thanks to its remarkable technical and human competences. These abilities allowed it to successfully adapt to a changing environment and unexpected events and propose innovative solutions to respond to the needs of the mission.

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