DOI: 10.13009/EUCASS2017-597

Design of MICROSCOPE's Attitude-Guidance Strategy for Star-Tracker's Moon-Glare Management

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Abstract
During full-moon periods, MICROSCOPE's science mode must be interrupted due to star-tracker dazzling. However, the two-way transitions with the auxiliary magnetic-control AOCS mode require the use of the star-tracker near Moon-glare time-slots' limits. Since the attitude-laws of the two modes are completely different, a specific slew sequence is calculated along with precise orbital-position phasing to significantly minimize the interruption. Moreover, mission-planning requires anticipated knowledge of the unavailability slots over the entire mission. This constraint, and the need for a fully automated calculation, is addressed by a dedicated prediction model of moon-glare slots and of the associated slew calculation input parameters.

1. Introduction

MICROSCOPE (**MIC**) is a fundamental physics mission which was launched on April 25th 2016. Its prime objective is the test of the Equivalence Principle down to an accuracy of 10^{-15}. Both MICROSCOPE's ground-control center and satellite bus are based on CNES's microsatellite product family called MYRIADE.
One quite challenging aspect of the attitude-guidance design was the STR Moon-glare management strategy. Due to the characteristics of MIC's orbit, the attitude-guidance-law in science mode, and the STR mounting on the satellite, the Moon passes in the vicinity of the STR boresight once per month around the full moon period, leading to STR dazzling in most cases, which requires an interruption of the scientific mission.

The present paper focuses on this specific topic. First, essential elements and explanations are provided concerning the major attitude-guidance and AOCS characteristics needed for a better understanding of the problem at hands. Then, a discussion on the design process and solution is presented. Finally some flight results are presented.

2. Attitude-guidance and AOCS background elements

2.1 Mission attitude-guidance and star-tracker dazzling's overview

MIC's orbit is a 710 km dusk sun-synchronous (local time at ascending node 6pm), hence with an associated inclination of approximately 98°.
In science mode, a specific reference frame designed for the mission is used: the **INF** (**Inertial Nodal Frame,** whose actual name in french is "RNI"). It allows maitainaing the sensitive axis of the accelerometers in the "mean" orbital plane of the sun-synchronous orbit, a requirement resulting from MIC scientists team's analysis. The INF is recalculated for every scientific measurement session, based on a least-square estimation of the osculating orbit's normal vector (after parameterization) over the duration of the session.
The important element to retain for the purpose of the present paper it that:
- The **INF** is an "almost" inertial frame, except for its fixed-rate rotation corresponding to the mean sun-synchronous rate (i.e. close to 0.98°/day), hence its name.
- Its X axis is orthogonal to the "mean" associated orbital plane, and directed towards the SUN.
- Its Z axis is directed towards the ascending node of the "mean" associated orbital plane.

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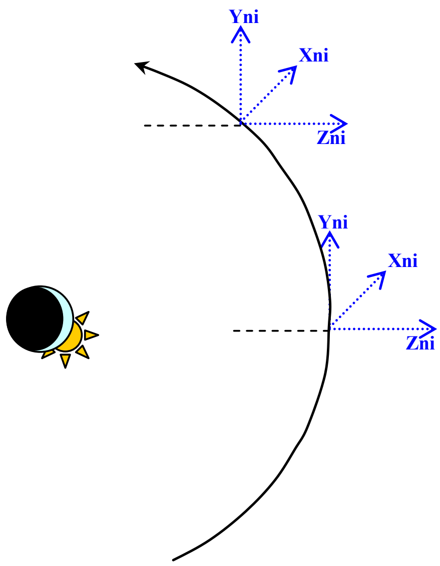

Figure 1: representation of the INF (Inertial Nodal reference Frame)

The science mission attitude-laws are designed to align the satellite's X-axis with the Inertial Nodal Frame's X-axis. Since the **STR** (**Star Tracker**) is mounted so that its boresight is aligned with –X sat, the Sun is always "in its back" (given the near-polar orbit constantly "facing" the sun) and can never cause any dazzling at all.
The only source of STR dazzling can be the Moon, and given the various elements just described, Moon-glare can happen around full-Moon periods only.

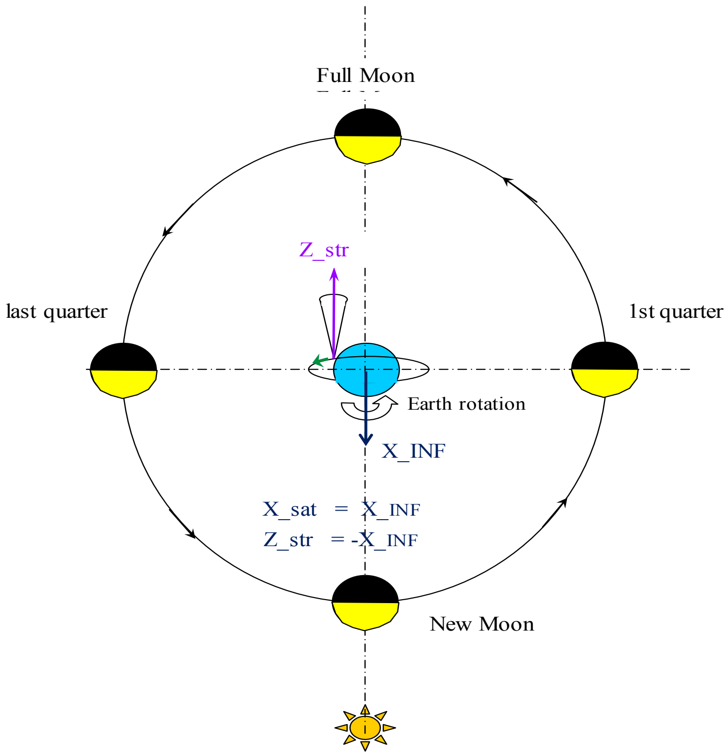

Figure 2: STR boresight with respect to MIC's orbit and the Moon

More details on the Mission concept and the INF calculation are presented in [1].

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2.2 Attitude and Orbit Control System's overview

Although the focus of this paper is on the attitude guidance strategy for STR Moon-glare management, it is essential to introduce a few elements of MICS'AOCS (Attitude and Orbit Control System). The reader is invited to consult [2] for the details of all the next AOCS-related explanations.
Note that for MIC, the AOCS is actually a DFACS (Drag-Free Attitude Control System), but we will keep the well-known AOCS terminology for clarity.
For the purpose of this paper and for the reader's convenience, we will also use a simplified terminology and description of the different modes, wich will be sufficient for the following discussion .

In essence, MIC's AOCS is composed of three modes :

- a "Science" Mode"
- an "Auxiliary/Servitude" Mode
- a "Transition" Mode

The **Science mode**, driving the scientific measurements, is quite complex and is actually divided into different sub-modes according to the different mission attitude-laws (expressed in the INF). The associated attitude-estimation obviously requires the use of the STR.

The **Auxiliary or Servitude mode** is used whenever the mission must be paused, whatever the reason, from a couple of days (typically during full-Moon periods) to a couple of months (during the yearly eclipse periods around the summer solstice).
It is a "magnetic" control mode, exclusively based on magnetometers measurement and magnetorquers actuators.
The prime interest of this mode is to save gas, the crucial resource of the scientific mission, anytime the science mission must be interrupted.
It is actually the only mode which does not use the STR.
This mode can only be activated when a special attitude law called "conical-spun" (cf. § 2.3) is established.

The **transition mode** is an intermediary mode capable of driving any MIC's attitude law, and therefore used for the attitude law transitions (slew) required before activating the Science mode or the Auxiliary mode when coming respectively from the other mode.
The transition mode also relies on the STR for its attitude estimation.

Last but not least concerning AOCS characteristics, very accurate actuation is required for MIC, and is ensured by the **Cold-Gas micro-Propulsion System** (**CGPS**). Except for the magnetorquers of the auxiliary mode, and in the absence of reactions-wheels (the only wheel of the satellite is a momentum wheel used for gyroscopic stiffness of X sat in the auxiliary magnetic mode), the micro-propulsion is the only actuation system.
The consquence is a very low torque capability (a few hundreds of µN.m per axis), which in terms of attitude-guidance translates into very slow kinematics, and thus long-duration slews.

2.3 Attitude-Guidance Laws' overview

In order to discuss the STR's Moon-glare Management topic, a very synthetic presentation of the different types of attitude-guidance laws is required.

Science attitude-laws:
There are strictly speaking three types of them, but the third one is used for a specific type of calibration and is somewhat out of the scope of this paper. The two other laws are the used for the characterisation of the equivalence principe, and are called "inertial" and "spun" laws.
The first one corresponds to a fixed attitude with respect to the INF (hence, the term "inertial", although it is a misnomer since the INF is not really inertiall, cf. § 2.1).
The second law corresponds to a constant spin with respect to the INF, around the sattellite X-axis.
We recall that the satellite X-axis is aligned in both cases with the INF X-axis, which is the mean normal of the orbital plane (cf. §2.1)

Servitude attitude-laws
The term "servitude" law is used to mention auxiliary attitude-laws that are not related to the primary scientific mission. There are two of them. One common feature is that they are both expressed with respect to the **LOF** (a

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classical **Local Orbital Frame**). This frame is based on the predicted osculating orbit. More preciely, one axis points towards the Earth's Centre, the second towards the orbit's normal, while the third axis completes the orthonormal frame and is almost aligned with the velocity vector as the orbit is almost circular.

(i) The main servitude attitude-law is called "**conical Spun**".
The satellite X-axis, which is otherwise always orthogonal to the orbital plane (either "osculating" or "mean"), is tilted by 10° towards the Earth (which means that –X sat, i.e. the direction of the STR boresight is pointed away from the orbit's normal and from Earth). As a result, when the satellite completes a full orbit the tilted X-axis generates a cone in space (hence "conical").
A the same time, the satellite is spun at 3 times the orbital pulsation (or 2 times with respect to the LOF) around the X-axis in order to acquire some gyroscopic stiffness.

It is important to understand and visualize the "conical" part of the spun-conical attitude law, in particular its influence on the direction of the STR boresight in space (cf. figure 3), while the "spin" part plays no role from a geometric point of view in the design of the STR Moon-glare management.
More specifically, the direction of the tilted –X axis in space (hence the direction of the STR boresight) is directly related to the position of the satellite on it's orbit.
MIC's orbit being quasi-circular, the orbital position of the satellite is actually pararmeterized (from an operational point of view) by the **Argument Of Latitude (AOL)** angle.
We recall that the **AOL** is an angular parameter that defines the position of a satellite moving along a Keplerian orbit. It is the angle between the ascending node and the satellite, which is (for a quasi circular-orbit) the sum of the true-anomaly and argument-of-periapsis parameters.
Therefore, while in conical-spun attitude, the direction of the STR boresight can be fully parameterized by the AOL.

(ii) The **geocentric** attitude-law is simply a fixed attitude law with respect to the LOF. This attitude-law was not forseen initialy. It was introduced later in the development phase, as a convenient way to serve two purposes at once.

- Its first usage is for collision avoidance manoeuvre, based on very long duration continuous-thrusting with the micropropulsion system.
- Its second usage is as an intermediary attitude law that helped solving elegantly the transition problem between the conical-spun (expressed in the LOF) and the science mission attitude-laws (expressed in the INF).

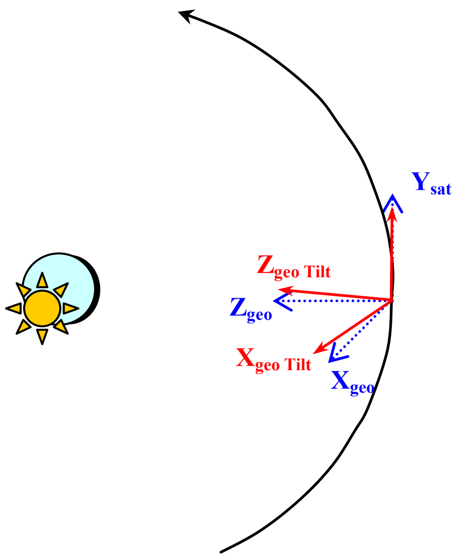

Figure 3: Geocentric attitude in blue, and conical-(spun) attitude in red

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2.4 Generic slew sequences between science and auxiliary modes’ overview

With the knowledge of the elements presented in the previous paragraphs, it can be further explained at this point that in order to avoid STR dazzling during periods of Moon-glare, the mission interruption consists in a transition from the science mode to the auxiliary mode, with a slew sequence driven by the transition mode, starting from the science attitude-law in progress, going through the intermediary geocentric attitude-law, and finally reaching the conical-spun attitude-law. Then, when the Moon-glare period is over, the reciprocal transition and slew sequence back to science mode is programmed.

For synthetic and clarity purposes, let us call :

- “**withdrawal**” transition the complete sequence from science mode to the auxiliary mode (both in terms of AOCS modes and of attitude-guidance),
- “**return**” transition the complete reciprocal sequence which allow to resume the science mission after an interruption.

The objective of this paragraph is to present the logic of the “withdrawal” and the “return” transitions from a general point of view, without any constraint related due to Moon-glare management.
Note that, this is not only a theoretical consideration since during the yearly eclipse period around the summer solstice, the mission is actually interrupted for a couple of months, and theses transitions are also used in this case (with the difference however, that the various steps are programmed by manual operations of the telecommand generator software).

For this purpose, we also need to introduce and explain some characteristics of the flight-dynamics software used for MYRIADE satellites, hence for MICROSCOPE, in order to generate telecommands related to satellite modes (closely related to AOCS modes) and attitude-guidance laws and slews. We will call it **Tele-Command Generator** (**TCG**) in the remainder of this paper.

MYRIADE’s attitude-guidance principle is based on angular velocity laws along with an initial quaternion, which are uploaded to the spacecraft via dedicated TCs. The attitude law is then computed on-board at 4Hz by first calculating the angular velocity vector (from the TC parameters) and then propagating the attitude quaternion based on the classical kinematics equation:

As far as slews are concerned, the mathematical form of the angular-velocity vector encoded in the associated telecommands is polynomial. It has been explained in [1] that for MIC, in spite of the dozen of functional slew required to switch from any kind of Mission-attitude law, to any kind of servitude law, an approach was found to reduce them to only two and a half forms:

- **(i)** A change of angular phase around a single axis: this type of slew is characterized by a null initial and final velocity and a null and final acceleration, with continuity in acceleration. This is done with a specific 4^{th} degree polynomial.
- **(ii)** A change of spin velocity: this type of slew is characterized by a null initial and final acceleration, and a different initial and final spin velocity, one of which can be null thus corresponding to the set-up or the cancellation of a spin attitude law, with continuity in acceleration. This is done with a specific 3^{rd} degree polynomial driving the angular velocity law.
- **(iii)** A spin cancellation (i.e. technically a subcase of above) but with a specified final angular phase, which requires an initial synchronization delay, so that the de-spin slew starts precisely when required in order to end at the specified final angular phase. Note that the worst-case value of the synchronization delay that can be computed by the TCG is thus equal to the spin-period (which can be up to one orbital period for MIC).

More details about the specific polynomials given in [1]

« Withdrawal » transition’s steps :
The “withdrawal” transition can be decomposed as follow in terms of mode transitions, attitude-law transitions, and slew:

Satellite Mode transition :
Science mode > Transition mode > Auxilliary mode

Attitude-law transitions :
inertial/spun law (INF) > 0 > inertial law (INF) > 1 > geocentric (LOF) > 2 > conical-spun (LOF)

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Associated slew types :
> 0 > : spin-cancellation type, around X-sat

> 1 > : spin-cancellation type, around X-sat, driven with respect to the LOF with the particularity that the TCG first converts the initial attitude from INF to LOF (this is based on two first-order approximations that simplified the problematic of this slew. The first approximation considers that the osculating and the mean orbital plane are close enough in this context, and the second approximation considers that the initial fixed attitude in the INF can be seen as a constant spin at the mean orbital pulsation in the LOF, and vice-versa for the “return” transition).

> 2 > : This functional slew is actually performed in two steps: first the tilting of the X-axis with the change-of-angular-phase method around the Y-axis, and then the set-up of the spin with the change-of-spin-velocity method around the X-axis (Note: to understand this two-step slew, the geocentric attitude can be somehow viewed as a conical-spun attitude, but with a zero tilt of the X-axis, and obviously a null spin, therefore each step is focused on one of these two aspects).

“Return” transition’s steps :
We will consider here that the “return” transition is the symmetrical transition of the “withdrawal” one, in terms of mode transitions, attitude-law transitions, and slew. Although this is not exactly true in every aspect, it is a reasonable simplification for the Moon-glare management topic.

3. STR Moon-glare management strategy

3.1 Objectives

The key objective expected from the “withdrawal” and “return” transition is to minimize the mission unavailability period. This is to equivalent to say :

- Remain as long as possible in Science Mode before the beginning of the Moon-glare slot.
- Leave the auxiliary mode as soon as possible after the end of the Moon-glare slot.

However, the essential difficulty to handle is that the conical-spun attitude-law of the auxiliary mode extends significantly the global period of STR dazzling, since the satellite X-axis, and therefore the STR boresight is tilted by ten degrees w.r.t the normal of the orbit. Therefore, even though the STR is not used in the auxiliary mode which drives the conical-spun law, the slews toward and from this mode, around a Moon-glare period are prone to cause STR dazzling (used by the transition mode, cf. § 2.2). The objective of the Moon-glare management strategy is thus to derive the best timing of the respective slew sequences presented in § 2.4.

3.2 Operational and Mission Constraints

Along with the main objective, the withdrawal and return strategies must be compatible with the following operational and mission-planning constraints :

- **(i)** The associated telecommands generation must be fully automatic and incorporated into the weekly mission-programming routine (see [1] for more details on the operational concept of the routine operations)
- **(ii)** It must be possible to trigger a “withdrawal” transition from any initial mission attitude-law.
- **(iii)** The information related to space-mechanics (dates et geometrical parameters of the problem) which allow to characterize the Moon-glare slot must be calculated at the start of the mission, typically during the **LEOP** (**Launch and Early Operations Phase**), and must cover the complete time-span of the mission (typically 1.5 years).

As a synthesis, the following consequences must be considered :

- Constraint (i) imposes a management of the programming of the Moon avoidance transitions by the automatic mode of the TCG (in other words, it cannot be handled by a manual procedure carried on by an expert operator based on up-to-date flight dynamics data (mainly, precise orbit knowledge from latest restitution), which would allow “human” optimization.

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- Constraint (ii) imposes a systematic first step for the slew sequence of the "withdrawal" transition (cf. § 2.4., slew "> 0 >") that lengthen artificially global Moon avoidance slots, and thus unavailability (but this lengthening is minor overall)
- Constraint (iii) requires a special modelling of the problem.

3.3 Characterization of a Moon passage and the virtual mission cone

Given the characteristics of MIC's orbit (cf. § 2.1), the attitude-guidance-law in science mode (cf. § 2.3), and of the SST mounting on the satellite, the Moon passes in the vicinity of the STR boresight once per month around the full moon period. The STR is then likely to be dazzled.

Exclusion cone :
In order to predict Moon-glare slots, it is necessary to define a practical criterion for STR dazzling. An **exclusion cone** is thus defined: the absence of optical-heads dazzling is guaranteed whenever the angle between the STR boresight and the direction of the Moon is greater than the angle of this cone (note that STR field of view is rectangular but it is classical to consider a conical exclusion shape for dazzling considerations in practice). The value of the exclusion cone considered for the design of the Moon-glare management strategy was 20° (including several degrees of margin), and during LEOP the actual value was found to be around 16°.

Virtual mission cone
We then define the very important concept of virtual exclusion-cone of the mission: it is the imaginary exclusion cone that precisely coincides with the actual when (or if) the satellite's active attitude-law is (or would be) the "inertial" science attitude-law. We will refer to it as the **virtual mission cone** in the remainder of this paper.

In practice, due to the relative configuration of both MIC and the Moon's orbit, STR dazzling does not occur at every full Moon, but rather 8-9 times a year. Furthermore, the worst-case in terms of dazzling duration is when the Moon's trajectory across the virtual mission cone is close to a "diameter" of the base-section: in such configurations, given the Moon's displacement rate, the STR unavailability period lasts more than 3 days.

Moon passage characteristics :
It is important to understand ant characterize the geometry of a Moon "passage" through the virtual mission cone in order to design a strategy that meets the expected objective and operational constraints presented in § 3.1 and 3.2.
The virtual mission cones's axis is the STR boresight, which is orthogonal to the mean quasi-polar sun- synchronous orbital plane, oriented in order to have the sun "in its back" (cf. §2.1). On a 2D-diagram, the virtual mission cone can be represented as a circle resulting from the projection of its base section on the unit sphere (but represented in 2D), and whose actual radius is correlated to the angle of the cone. To understand this representation, it is helpful to imagine to be looking directly through the "eyes" of the STR, i.e. along the direction of the boresight (which is thus orthogonal to the diagram's surface and oriented in the direction "entering" into the diagram).
Based on this type of representation, a passage of the Moon through the virtual mission cone is illustrated in Figure 4.

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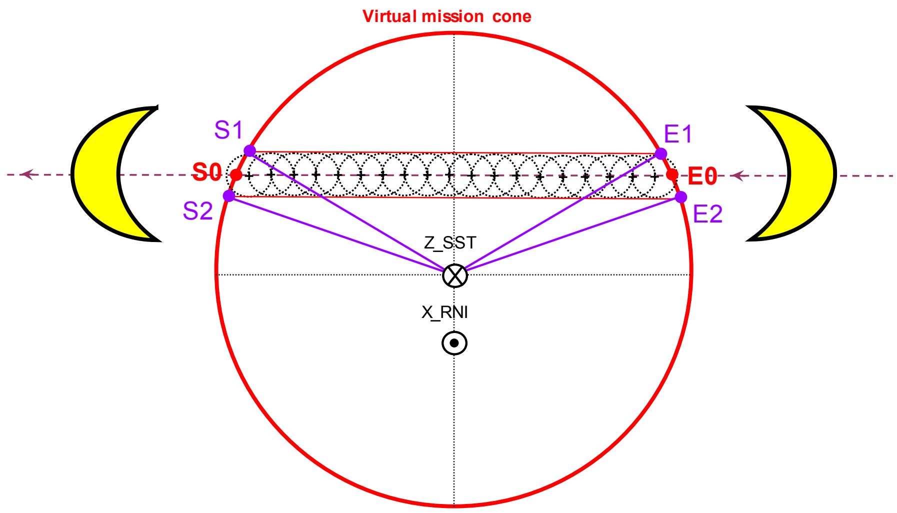

Figure 4: Representation of a Moon passage through the virtual mission cone

In this diagram, the trajectory of the Moon describes a kind of generalized "cycloid" curve. This is due to the motion of the satellite on its orbit, or in technical terms, to the Moon parallax. If the Moon was "infinitely" far, the satellite-Moon vector would be independent of the satellites orbital position, and in such a theoretical case the trajectory of the Moon would simply be the straight "straight" defined by the points E0 and S0.
We call "E" the **entry point of the Moon** into the virtual mission cone, and "S" the **exit point of the Moon** (*exit* is *sortie* in French), independently of the suffixes 0, 1 or 2 for now.
The characterization of these two points is very important to meet the expected objective and operational constraints, as it will be further explained in the next paragraph.

3.4 Problem modelling

Moon direction vector model :
Because of the operational constraints (iii) which requires characterizing during LEOP all Moon passages for the complete mission time-span, we need a model which does not depend on the AOL parameter (i.e. on the knowledge of the orbital position). In other words, we cannot consider the **satellite**-Moon vector to characterize the Moon entry and exit points. Indeed, this would require precise orbit knowledge from a recent restitution, as the along track error diverges very rapidly.
Therefore, the Satellite-moon direction is replaced by the Earth-Moon direction which is accurate: this is equivalent to neglecting the Moon parallax due the radius of MIC's orbit along with the finite distance of the Moon. Hence, it is equivalent to considering that the Moon is infinitely far.
Let us look back at Figure 4. In reality, given the "cycloid"-like nature of the real Moon trajectory in the virtual mission cone, it can enter into the latter by any point belonging to the arc (E1, E2), and similarly it can exit it by any point of the arc (S1, S2). If we define two "middle" points E0 and S0 belonging respectively to (E1, E2) and (S1, S2), the straight line E0 - S0 of the figure represents the trajectory of the Moon resulting from considering the Earth-Moon vector instead of the satellite-Moon vector.
Consequently, the objective of the Moon-glare management strategy requires the accurate characterization of E0 and S0 for every Moon passage.
In terms of numerical error, the Moon parallax value is around 1° for MIC's orbit, and represents the maximum error resulting from our first simplification. This is fully compatible with the Moon-glare management strategy.

Virtual mission cone axis model :
A second simplification was required to model the virtual mission cone. Strictly speaking, we should have considered and calculated the X-axis of the INF as the axis of this cone. However, due to the very nature of the INF

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definition and calculation (cf. §2.1), this was very impractical. Therefore, we defined for this purpose an osculating version of the INF, and the osculating orbital normal was used as the INF X-axis.
In terms of numerical error, there are two aspects to consider. First, the difference between the osculating and the mean orbital's normal (which is important for the science mission) is completely negligible with respect to the Moon-glare slots prediction accuracy requirements. The second aspect concerns the knowledge of the sun-synchronous orbit's plane (which can be defined by its orbital's normal vector). It is obtained by propagating the after-launch accurate orbital parameters with a high-fidelity orbit propagator in order to generate orbit ephemeris data over two years. Unlike the prediction of the AOL parameter (along-track position), the orbital plane prediction remains accurate over such a long time span.

Entry and exit points parameterization :
The Moon entry and exit points need to be parameterized by a date and a "coordinate" parameter.
The dates can be calculated using the previous two models. However, in order to meet the objective of minimizing the mission interruption duration, it is essential to have a measure of "where" the Moon enters and exits the virtual mission cone.
We thus define the key parameter called **Moon pseudo-AOL** (noted **p-AOL**) : it is the angle between the ascending-node vector (of the satellite's orbit) and the vector obtained from the projection of the Moon direction vector onto the orbital plane. This angle must be oriented in the same sense as the AOL parameter.
Due to the definition of the virtual mission cone (in close relation with the INF), and recalling that the INF Z axis is actually directed towards the ascending node, the p-AOL can then be used to parameterize the trajectory of the Moon with respect to the virtual mission cone. This is illustrated in Figure 5. Furthermore, the p-AOL calculation can be made from the Moon direction model and the INF osculating model.

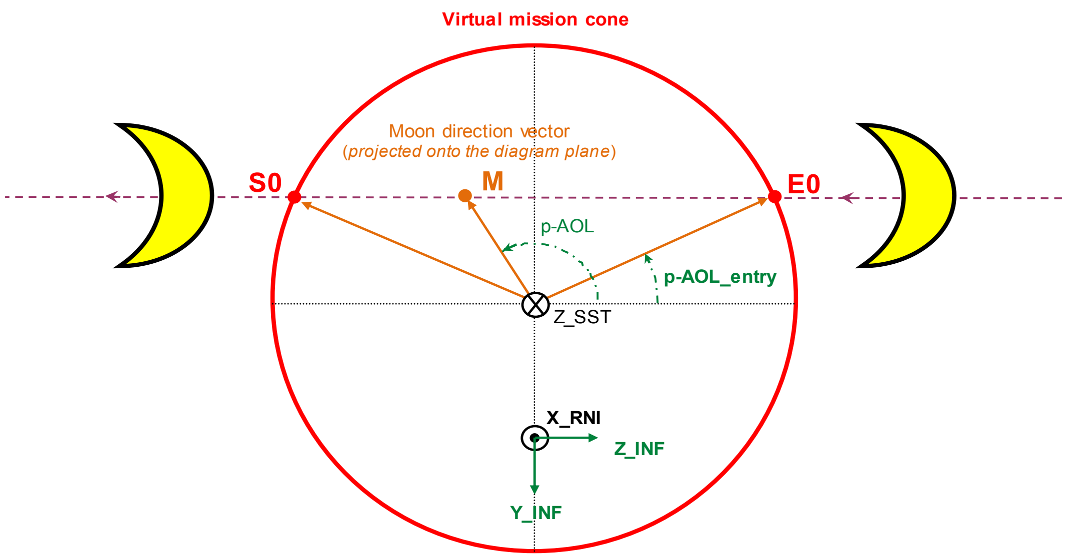

Figure 5: Representation of a Moon passage through the virtual mission cone

To clarify the terminology, the p-AOL has no direct relation with the AOL orbital parameter, but it is critical to determine favorable orbital slots, defined in terms of AOL, for the geocentric to conical-spun slew (and vice versa), hence the term "pseudo".

Interface file :
In order to meet the operational constraint (i) (automatic "withdrawal" and "return" transitions generation), the list of the parameters (date and p-AOL) of all the Moon passages during the entire mission must be defined in a specific interface file that is used both by the mission-planning team (only for the dates), and by the TCG (for the full parameters).

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3.5 Strategy description

For a given Moon passage, the time slot defined by the date of the entry point and the date of the exit point, determines the theoretical minimum mission-interruption period. This is not achievable however, since it would require the capability to instantly “teleport” from the science attitude-law to the conical-spun attitude law for the withdrawal transition (and conversely for the return transition).
Therefore, a more realistic mission-interruption slot should account for the total worst-case duration of the complete slew sequence of both transitions and add it to the theoretical slot. This is indeed the main idea of the Moon-glare management strategy. However, there is a critical part in both slew sequence (withdrawal and return) which makes the problem much more difficult, that is the slew from geocentric to conical-spun, and the opposite slew.
Indeed, because of the tilt of the X axis which is close to 10 deg near the beginning or the end of the respective slews, the Moon will enter into the exclusion cone on some part of the orbit, i.e. within some AOL slot (cf. §2.3), while on the contrary it will be further away from the exclusion cone within another AOL slot.
The objective is therefore to determine these slots. Note that if this was not possible, a very pessimistic solution would be to consider an extended or pseudo virtual mission cone with an augmented angle 30 deg (20 deg for the STR exclusion cone plus 10 deg due to the X-axis tilt). In this case only the dates of the entry and exit points would be needed. This approach leads to an increase of the mission interruption slot of around two days in total (while some Moon passages can be near the border of the virtual mission cone and consequently last only a few hours).

Fortunately, the p-AOL parameter allows to derive such favorable AOL slots. Once such slots are characterized, the slew sequence can then be commanded on one of the last orbits before the Moon entry into the virtual mission cone, i.e. it is a near optimal solution.

AOL slot for the geocentric to conical-spun slew within the withdrawal transition :
For the “withdrawal” transition, the slew between the geocentric to the conical-spun attitude-law must be commanded on a specific AOL slot to guarantee that the tilting phase (setting the “conical” part of the final attitude-law) does not induce STR dazzling.
Let us call SL_start and SL_end respectively the start and the end of this authorized slot. As a matter of fact, a practical slot that answers the absence of the dazzling of STR once the conical part of the target attitude-law is set-up is : [p-AOL-entry - 3/2 PI ; p-AOL-entry - 1/2 PI], which could be described in a way as the half orbit “opposite” the Moon entry point into the virtual mission cone (parameterized by p-AOL-entry). Note that this slot is calculated automatically by the TCG, with the knowledge of the Moon passage parameters from the interface file and of the AOL function of time calculated from the latest restituted orbital parameters.
More precisely, the algorithm must invert the AOL equation to find the accurate date of the slew start by managing inequality of dates modulo the orbital period, because the phasing or the AOL being arbitrary, in the most general case, when the satellite reaches the start of the AOL slot, the Moon has no reason to have reached exactly the entry point at this date : it is somewhere near it, so the algorithm of the TCG searches the last possible orbit to perform the slew before the moon reaches the entry point.

This is illustrated in Figure 6.

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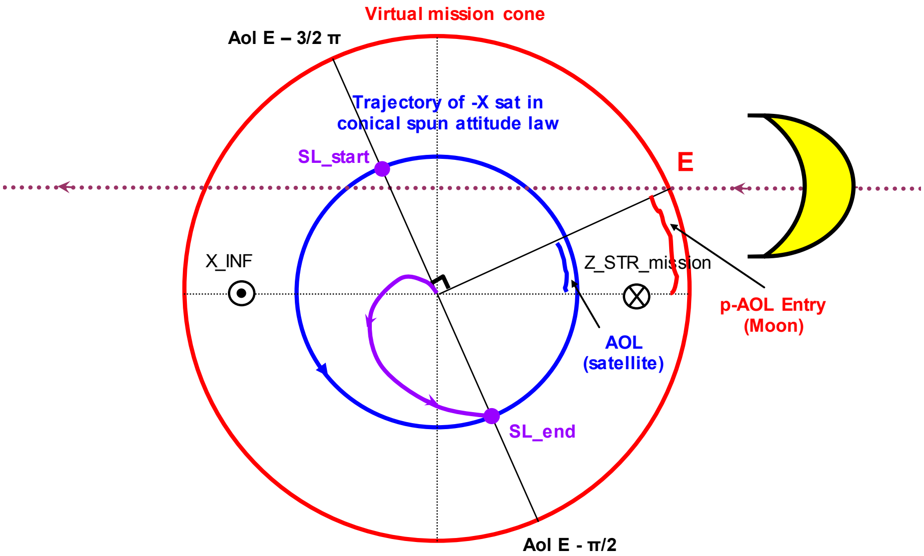

Figure 6: AOL slot for the geocentric to conical-spun slew

Note that on the figure, the blue circle represents the trajectory of the –X sat axis, i.e. the STR boresight direction, as a function of the AOL when the conical attitude law is set up. The purple trajectory represents the evolution of the X axis during the slew. Furthermore, the link between the satellite AOL and the p-AOL of the Moon entry point is highlighted.

AOL slot for the conical-spun to geocentric slew within the return transition :
The logic of the return slot is similar to "withdrawal" case, but in the other direction so to say.
The objective here is to reach-back as soon as possible the Science Mode, without having to waste one day waiting for the Moon to be away enough so that it does not cross anymore the STR exclusion cone whatever the AOL while in conical-spun attitude-law at the start of the return slew-sequence.
However, although the initial design was nearly the symmetric of the withdrawal strategy we had to modify the approach when analysis from the AOCS team (carried-on in parallel) concluded that the de-pointing of the magnetic controlled mode could be in the order of 15 deg. This means that at the very beginning of the first slew, after having switched to the transition mode, the STR could be dazzled. Therefore the virtual mission cone angle is extended of 5 deg in this case, and the start of the AOL slot is "opposite" to the Moon exit point.

4. Flight Results

The LEOP and commissioning phase of MIC, which is summarized in [2], was challenging and very long. Various difficulties had to be faced and overcome. Even after the switch to "routine" operations (which is also quite challenging), much more manual operations, including around Moon periods were required. Nevertheless, as per May 2017, the March and April Moon avoidances have been optimally and fully programmed by the Automatic TCG following the Moon glare management strategy which has been presented.
Analysis of STR telemetry, and in particular of the attitude measurement validity indicator confirmed the fact that the "withdrawal" and "return" strategies were nearly optimum. The following figure shows two images of STR dazzling for illustrative purpose that were taken while the STR was actually (and fortunately) out of the AOCS control-loop

DOI: 10.13009/EUCASS2017-597

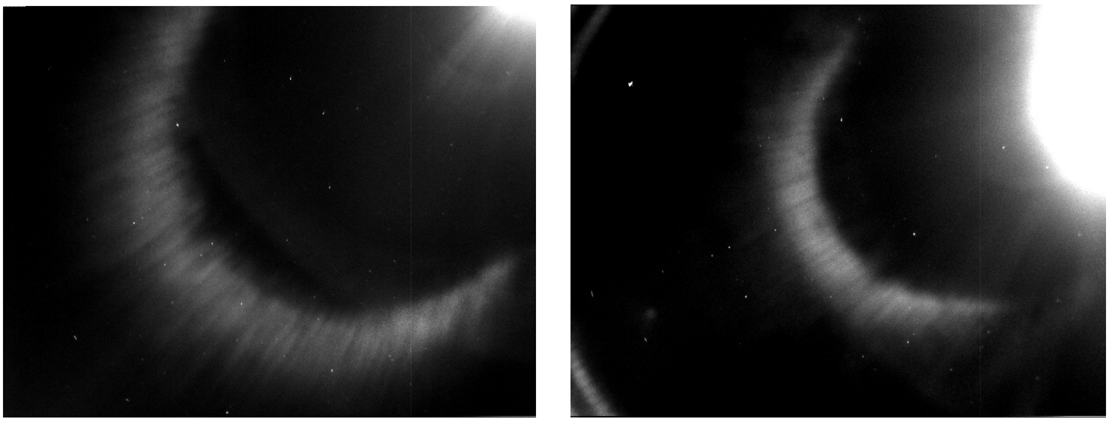

Figure 7: STR dazzling images

Last but not least, it can be noted that a manual procedure for expertise operations based on the Moon-glare management strategy was also set-up and used. It relies on the analysis of the Moon direction's excursion angle with respect to the STR boresight direction to derive the optimum slots for the various slew sequence. This is practical for short term operations as it does not require the knowledge of the p-AOL of entry and exit points. This procedure was initially required by the mission to maximize the feasibility of an hypothetical collision avoidance manoeuvres close to a Moon period. But it was used near a Moon period where the automatic programming could not be used, in order to optimise the last scientific measurement session, and the transitions went smoothly on-board.

References

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