THE SUCCESSFUL RECOVERY OF THE JUICE RIME ANTENNA DEPLOYMENT

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ABSTRACT

On the 14th of April 2023, JUICE spacecraft was successfully lifted into space by an Ariane 5 rocket from Guyana Space Centre in French Guyana. JUpiter ICy moons Explorer is an ESA science mission dedicated to the investigation of the Jupiter and its Galilean moons, and it will be the first spacecraft to orbit a moon of another planet beyond Earth.

Airbus was prime contractor for the design, integration and test of the spacecraft. Spacetech (STI) was in charge of the design, integration and test of the RIME radar antenna.

Following a perfect flight of the launcher, the spacecraft separated from the upper stage. Over the following 36 hours the Launch and Early Operations Phase was completed flawlessly. All systems in JUICE were working nominally, until, on April 17th, JUICE experienced a major setback. The second stage of one of the two booms of the RIME antenna, the ice penetrating radar, failed to deploy.

This paper provides an account of the anomaly investigation that followed and the efforts to deploy the stuck antenna. It describes the design of the antenna, the details of the in-flight anomaly, the root cause analysis and the recovery scenarios that were considered in view of the S/C operational constraints. Finally, the paper recounts how the antenna was recovered, and the deployment was completed successfully, and it concludes with some lessons learned.

1 THE JUICE SPACECRAFT AND THE RIME ANTENNA

The JUICE spacecraft will provide a thorough investigation of the Jupiter system in all its complexity with emphasis on the three potentially ocean-bearing Galilean satellites, Ganymede, Europa and Callisto, and their potential habitability. The JUICE spacecraft carries the most powerful remote sensing, geophysical, and in situ payload complement ever flown to the outer Solar System (Figure 1). The payload consists of 10 state-of-the-art instruments plus one experiment that uses the spacecraft telecommunication system with ground-based instruments. It is important to note that JUICE has a large fixed High Gain Antenna to download the science data back to Earth and this fixed antenna is used as a thermal shield during the 1st part of the mission, when the S/C remain close to the sun. The propulsion includes sets of 10 and 22N thrusters for attitude control, and a 400N Main Engine for large manoeuvres. Finally, JUICE carries two units that proved to be invaluable in the resolution of the RIME antenna anomaly: 2 JMC cameras and one 3-axis High Accuracy Accelerometer (HAA) for a Radio-Science Experiment.

The Spacecraft includes on the Nadir deck the low frequency RIME radar [1], which uses a long 16-meter dipole deployable antenna to measure the thickness of the ice at the surface of the Galilean moons. Other instruments in previous missions like MARSIS in Mars Express have used similar antennas, which proved to be challenging to deploy [2]. The RIME antenna is designed by STI and consists in 2 identical monopoles made out of CFRP tubes, stowed in 4 segments each and arranged around 2 HDRM brackets (Figure 2). The monopoles are referred as Minus Y (MY) and Plus Y (PY), according to its location on the upper deck of the spacecraft. The hinges in between segments are double CRFP C-springs and are referred to as PY1, PY2, PY3 and MY1, MY2 and MY3 starting from the root of the monopole an increasing towards the tip. This antenna features a 5 steps **sequential** deployment:

- NEA1-NEA2 opening each one clamp-band and releasing simultaneously the outer segments of both the MY and PY monopoles,
- NEA4 releasing the middle segment of the PY monopole,
- NEA5 releasing the inner segment of the PY monopole,
- NEA3 releasing the middle segment of the MY monopole,
- NEA6 releasing the inner segment of the MY monopole.

This sequence was selected for 2 reasons:
- the need to release first the monopole in front of the JMC-2 camera (PY) for a better observability,
- the need to release the monopoles one by one to minimize any risk of collision of monopoles due to a possible out of plane movement during release.

2 THE FLIGHT ANOMALY

After the JUICE successful launch on April 14th, 2023, the LEOP phase was conducted flawlessly for 1 day and a half. It included both the Solar Array and the Medium Gain Antenna deployments and allowed starting the Near-Earth Commissioning Phase (NECP) on April 16th. The RIME dipole antenna was the next appendage to be deployed. On April 17th, the RIME antenna deployment operations started in ESOC. Firing of NEA1 and 2 successfully released both clamp-bands and allowed the deployment of the outer segments of both monopoles (opening hinges MY3 and PY3). However, the firing of NEA4 did not lead to any further release of the PY middle segment. The PY2 boom of the RIME antenna was stuck.

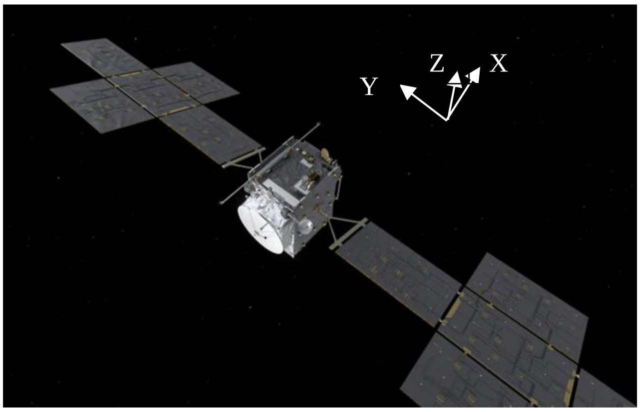
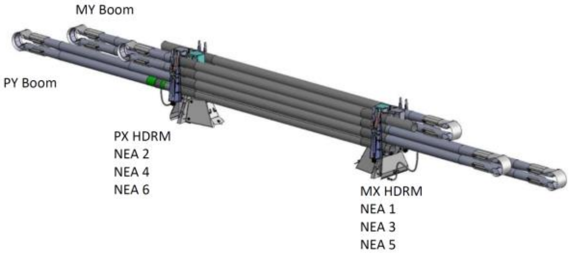
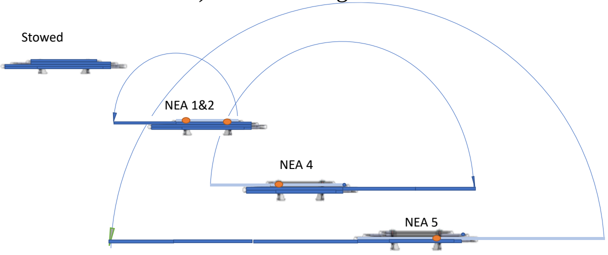


Figure 1. JUICE S/C in the configuration at the time of the anomaly (courtesy of ESA).



a) stowed configuration

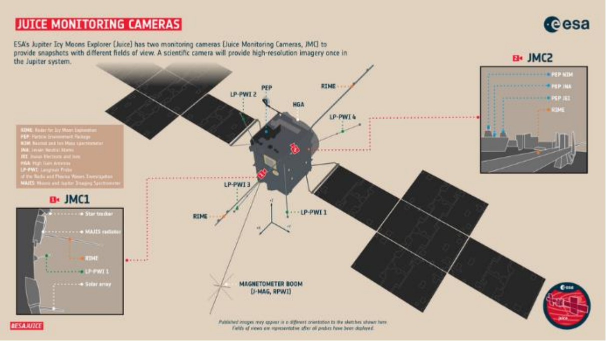


b) sequential deployment of the PY monopole

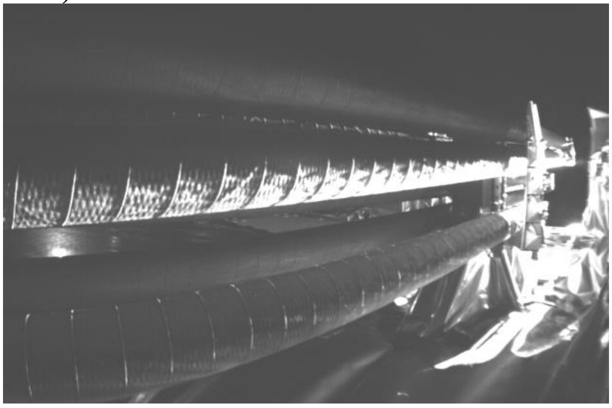
Figure 2. JUICE RIME antenna (courtesy of STI).

There were at the time of the anomaly, a limited number of observables, namely the JMC pictures, that given its field of view only captures images of the minus X half of the antenna, including the MX HDRM, and was showing the middle segment still in stowed configuration, plus a temperature sensor in the PX HDRM recording -80°C (Figure 3).

The HAA data showed that the NEA4 had mechanically operated, since a shock was recorded (Figure 4). Finally, the radar receiver confirmed that the antenna was in short-circuit at 9 MHz.



a) Localisation and FOV of the JMC



b) JMC-2 view after NEA5 firing.

Figure 3. JMC-2 showing a PY monopole stuck middle segment and the MX HDRM bracket.

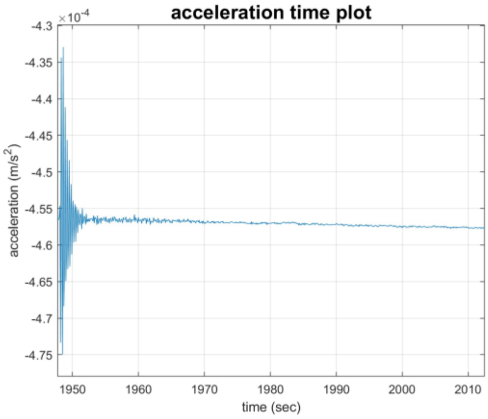


Figure 4: HAA recording during the NEA4 firing. - X channel

3 THE INITIAL ROOT CAUSE ANALYSIS

A team effort was initiated that point to assess the anomaly with participation of the ESA Operations Team, the ESA JUICE Project Team, the Airbus JUICE Project Team, additional mechanisms experts from Airbus, the RIME Antenna Team at STI, and the relevant Payload Team members. A Root Cause Analysis was built-up and exchanged with involved parties on April 18th and some possible root causes were quickly discarded.

3.1 1st RCA iteration

The images of JMC2 showed a nominal release of the outer segment of the PY monopole -MY was hidden behind PY, therefore not visible- and a clear upwards movement of the stowed segments in MX HDRM upon firing of NEA1 and 2. However, no segment deployment was observed after NEA4 release. This was pointing to a problem in PX HDRM - away from camera field of view - but could not initially discard other root causes.

A 1st iteration of the RCA was put in place quickly:

1. NEA4 actuation failure: discarded: NEA4N & NEA4R are in open circuit.
2. NEA4 bolt failed to retract: discarded: based on shock from HAA records.
3. NEA4 associated retainer spring failed to open: open
4. boom stuck in the PX HDRM bracket: open
5. PY2 hinge (facing the sun) weaker than expected: unlikely: creep is gradual and was accounted for in budgets.
6. PY2 hinge damaged during launch: unlikely.
7. Icing impedes release: open
8. Command error: discarded: TC stack rechecked
9. Harness error: discarded: E2E test had validated the sequence in the flight H/W.

The launcher flight data showed only one event with a small exceedance of the predicted loads, at a frequency that was too low to affect the hinges. This allowed to discard also root cause 6 one day later.

Root cause 5 could not be fully discarded yet, but it was considered unlikely as a primary root cause since creep is a gradual phenomenon that would not lead to complete blockage of PY2 hinge only a few days after launch.

3.2 Initial way forward

The original planning called for an early deployment of the RIME antenna to minimize the creep effect on stowed hinges. Indeed, despite the thermal blanket protection (SLI) slow creep phenomenon were expected on sun-illuminated hinges, accelerated at high temperature. This tipped the scales in favour of quick action trying to release the antenna. The most obvious was firing NEA5, the next one in the sequence, to benefit from the push of the kick release spring, and the opening torque of the next hinge PY1. One downside was identified: if successful in freeing up the middle segment of the MY boom, it would lead to simultaneous deployment of the outer and middle segments, which was intentionally avoided by the sequential deployment. However, existing multi-body analysis of the deployment had shown a negligible risk of a collision with the spacecraft (see more details in section 3.4 below). Therefore, the firing of NEA5 was agreed in combination with a slew - a rotation of 45 degrees around Y axis, keeping the sun in the XZ plane and illuminating the Nadir deck of the spacecraft – in an attempt to heat up the PX HDRM, addressing both potential icing effect, and increased friction related to cold temperature. A 25-minute duration was considered safe to avoid excessive heating of sensitive units.

The 25-minute slew plus firing of NEA5 failed to deploy the PY monopole but offered valuable information. JMC2 images showed again clear upward movement in MX HDRM and suggested very limited movement in PX HDRM. This helped to rule out root cause 5 and concentrate on the middle segment being stuck on the HDRM PX bracket. It also showed that a longer duration slew would be required to bring PX HDRM close to ambient temperature since only -40°C were reached.

Moreover, revisiting the thermal analysis of sun illuminated hinges, and the long-term characterization testing of the hinges in stowed configuration, confirmed that there was more time margin than initially assumed. It was safe to take a step back and reconsider options. In this frame, the possibility to use a train of pulses with the 22N thrusters to excite the natural frequency of the suspension of the stowed RIME antenna was introduced and the study of this option was initiated.

3.3 RIME EQM investigations

Following those findings, a more in-depth investigation was carried out in STI with both a rendering software analysing the JMC pictures (Figure 5) and the RIME EQM hardware, concentrating on RCA no's 3&4.

It was then shown by STI that the release pin (preventing the retainer spring to open) can get jammed (Figure 6), when a release bracket is losing its symmetry (Figure 7).

There are several reasons that can lead to this situation:
- harness layout obstructing NEA4 bracket motion,
- marginal tolerance chain,
- brackets interchanged during final assembly leading to an untested configuration,
- unbalanced spring force or friction leading to asymmetric push forces.

One release bracket was found easily jammed on the EQM hardware, with a very low tilt angle. A pulling test was performed and a force of 5 N was necessary to unjam it. ; this amount of force cannot be obtained by any inertial effect (see section 3.4) obtained by shaking the S/C. Conversely, it was decided during the investigation to fire the adjacent NEA6 (dealing with the MY monopole). The resulting shock is sufficient to unjam the release pin. However, it is still difficult to assess the effect of any CTE mismatch.

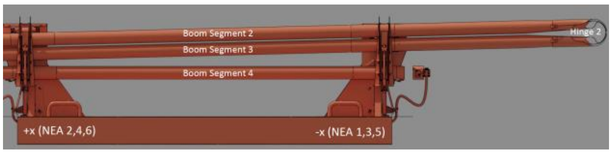
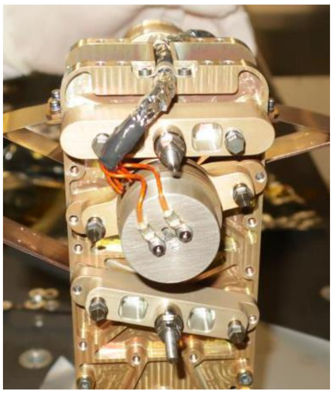


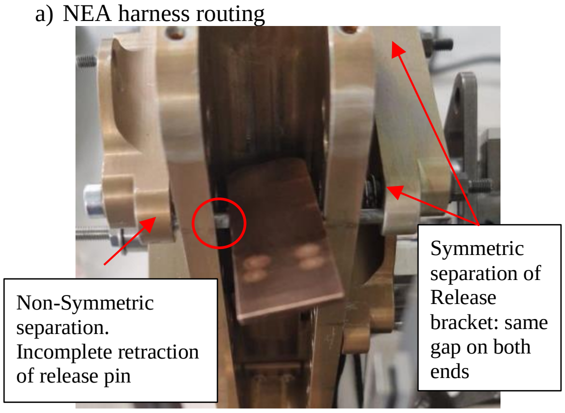
Figure 5: Rendered view of the JMC picture (status after MAGBOOM deployment)

3.4 Multibody simulations

During the development of the RIME antenna, several multi-body simulations were undertaken, mostly to assess the swept envelope and assess the risk of collision with the S/C during the deployment. The modelling campaign also addressed the contingency cases where 2 segments will be released at the same time. It was therefore known at the time of the in-flight anomaly, that a simultaneous release of the 2nd and 3rd segments was considered as safe.



a) NEA harness routing



b) Release pin preventing the retainer spring to open.
Figure 6: View on the anomaly reproduced on the EQM H/W

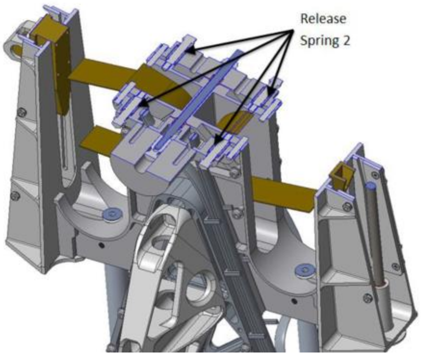


Figure 7: Perspective view of the release bracket

The multi-body models were then re-used to study the partially stowed configuration to:

- Study the dynamic forces inside the RIME assembly under the S/C shaking accelerations,
- Attempt to evaluate a low resonance frequency in the RIME assembly.

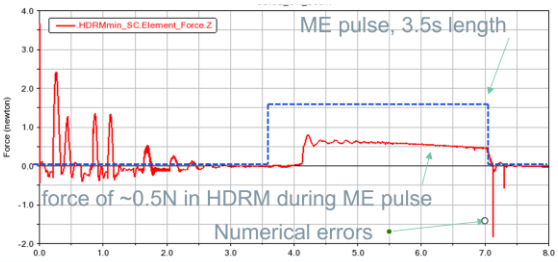


Figure 8: ADAMS multibody model

The following conclusions were drawn:

1. Frequency of the jammed boom is non-linear, starting at 1-2Hz at the beginning of the deployment and converging to 4Hz at „stable" jammed position after several seconds.
2. The influence of Ry acceleration (0.015rad/s2) versus a quiet S/C on the double unsynchronized boom deployment is minimal,
3. A Main Engine (ME) pulse Tz acceleration (in cold) failed on 27.04 and is expected, according to ADAMS to generate a dynamic force of 0.5 N on Px bracket and a dynamic hinge's torque of 0.36 Nm.
4. A 22N Ry pulse train is expected to generate a dynamic force of 0.05 N on Px bracket and a dynamic hinge's torque of 0.036 N.m.
5. observation on the EQM indicated a certain level of friction that would damp any resonance.

3.5 2nd RCA iteration

Both the experimentations on the RIME EQM H/W and the modelling were considered to refine the Root Cause Analysis (Table 1).

4 THE POSSIBLE RECOVERY SCENARIOS

The following recovery methods were considered (more details in Table 2):
-Thermal slews to induce some thermos-elastic settling effects,
- Shaking the S/C either with the Main Engine (used for the various flybys and the Jupiter Orbit Insertion), or with the attitude thrusters [3].
- Release of NEA6 to induce some local shock onto the PX bracket.
However, as the anomaly occurred in the very early phase of commissioning, several units on the Nadir deck were not yet checked-out, which meant the temperature readings of those units were still not available.
S/C shaking (either by the Main Engine or by the attitude thruster around the S/C Y axis) also required a careful assessment of the already deployed appendages, but also the Antenna Pointing Mechanism of the MGA and the SADM. This required more time.
The NEA6 actuation appeared to be our best chance. Various attempts were made on the EQM model (after manual jamming) and local shocks tended to release jam pins but sometimes required multiple attempts.

5 THE S/C OPERATION CONSTRAINTS

Several constraints needed to be considered:
-S/C thermal behaviour: to start a slew in determined thermal conditions, and avoid potentially dangerous cumulative effect it is necessary to wait for 24 hours stabilization time in between 2 slews,
-S/C slew implementation: they are implemented based on ephemerides by the ESOC Flight Dynamic team, which need to be planned one week ahead (design, uplink on the S/C),

-Limitation on the number of ground passes with the ESTRACK network.

These constraints with the S/C operations led to a recovery plan over 2 weeks (Table 2).

6 RECOVERY

After several unsuccessful thermal slews -with increasing durations of 45 and 55 minutes- combined with Main Engine burns, it was decided to plan for the NEA6 firing at the end of a thermal slew, to unjam the release pin at room temperature. To get the PX bracket at room temperature, a longer thermal slew was designed with 72 min dwell time duration.

Firing NEA6 before NEA3 differed from the nominal sequence but it had the advantage of generating a shock on the PX HDRM, without releasing the MY monopole, and therefore avoiding a risky simultaneous release of both monopoles in case of success.

An updated thermal analysis of the RIME antenna under the slew RY 45 deg. was correlated to determine the duration of the extended slew (Figure 9). However, several units sitting on the Nadir deck (namely SWI TRU and PEP JENI) were not necessarily designed to withstand such slew. This required several iterations with these unit suppliers, including:

- Correlation of the thermal model with the short slew,
- Re-run of the correlated thermal model.

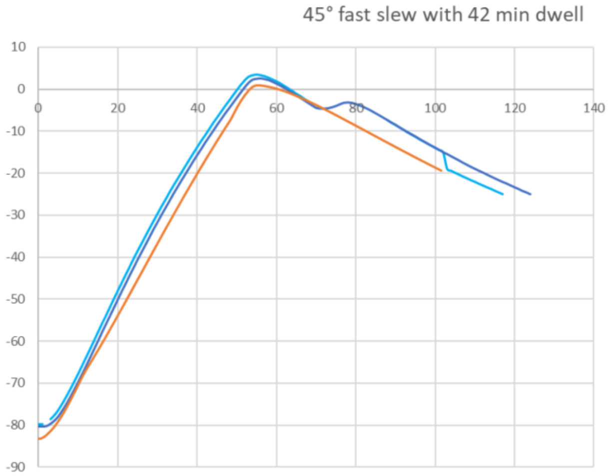


Figure 9: Transient behaviour of the RIME PX bracket during a medium duration slew

On May 12th, the extended duration slew took place, the S/C tilted back to nominal attitude, and a 5 minutes delay was inserted before the NEA6 was fired. The additional delay needed to be short enough before the temperature drops again but long enough to reduce local gradients within the PX bracket. JMC pictures confirmed the successful double unsynchronised deployment of the PY monopole. The situation was almost restored back to nominal, except that the last boom was only hold by its middle bracket now.

The NEA3 was the last one to be fired in order to free up the second boom similarly. At that stage, and as described in this paper, the experience had revealed a failure mode together with a solution being the local shock. But there was no actuator left on this bracket after NEA3. The aim was therefore to maximise chance of success in triggering this last actuator in the best conditions. The initial failure conditions near -80°C had to be avoided. Several hours later, near ambient and stable temperature, the last NEA3 was fired, leading to the successful double unsynchronised deployment of the MY monopole and completing the full deployment of the RIME antenna.

In retrospect, the most likely root cause was validated. The PY2 release pin was indeed unjammed due to the shock of the adjacent NEA6.

The JMC's pictures (Figure 10) were also analysed and compared to the reference multi-body model. The following conclusions were drawn:

- A forward delatch event may have been missed by the camera between T0 + 5s and T0 + 10s,
- Some out of plane motion happened,
- Less energy in the system than predicted from the model (starting from the hinges' characterization on ground prior to integration in the limb)
- Dissipation of this energy in the twist motion of the hinge (out of plane motion) and/or
- Less stored energy than expected due to creep on the MY inner hinge facing the sun.

The predicted swept envelope was thus violated, but no collision with the S/C during the release, neither from the cameras, nor from the correlated multi-body model could be identified.

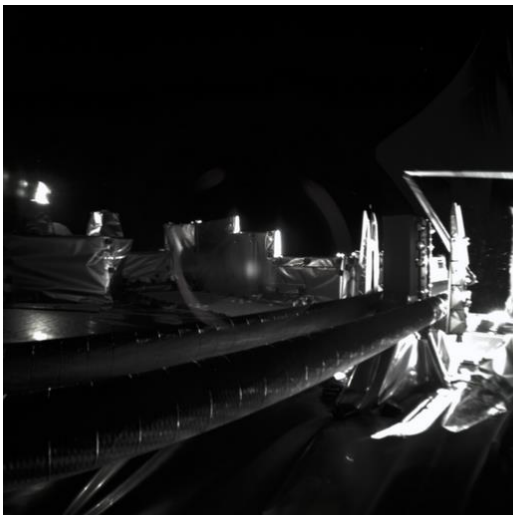


Figure 10: View of the MY monopole during its release featuring an out of plane motion (along Ys/c)

Id	Root cause	Assumption	Evidence	Refutation	Likelihood
3a	Retainer spring did not open - Release pin jammed	Design sensitive to tolerance stacks (but to less extent to CTE mismatch) Loss of symmetry in the dynamic release – either due to a bad tolerance stack or a cold harness.	Compatible with picture from JMC : stack on PX HDRM do not seem to have moved. Investigated by STI on H/W Tolerance stack not mastered at detailed drawing level, thus not reported at metrology check.	Did not happen during the EQM TVAC cold release, but was on a different built	Likely – Can be easily reproduced on ground on the EQM Jamming issue
3b	Retainer spring did not open - Friction on the retainer spring	Never seen on ground	Stack on PX HDRM do not seem to have moved	Did not happen on ground. Cannot be reproduced by STI on ground H/W	Very Low Friction issue
4a	PY2 boom stuck in the PX HDRM bracket – due to hinge roll angle	Reproduction of the on-ground NCR	PY intermediate hinge slightly rotated after clamp band release (NEA2 firing), but may be due to some glare effect in some JMC-2 pictures	extrapolation based on picture indicated boom stuck at pin location	Very Low Friction issue
4b	PY2 boom stuck in the PX HDRM bracket – PY2 boom has a ‘banana shape’ due to high thermal gradient along Xs/c	Was always assumed to remain symmetric on ground.		Very limited lift on PX bracket No apparent ‘banana shape’ on the lower segment not touching the MX bracket. No evidence from JMC-2 pictures processing	Very Low Thermoelastic and friction issues

Table 1: Refined RCA

Id	Recovery	Rationale	Pre-requisites	Constraints	Risks	When?
A	ME pulse (single pulse or train)	Direct acceleration and those deriving from SA oscillations might induce release of stuck condition. Can be repeated, can be combined with D.	ME pulse controller inputs from ADS	Unsynchronized deployment of 2 segments, possibly with S/C out of plane motion	Single pulse: none (nominal use case). Train of pulse: effect on other appendices to be checked.	27.04
B	RY 22N thruster induced excitations	Exciting RIME natural suspension frequency while stowed may contribute to release	Natural frequencies of Solar Arrays, MAG Boom, RIME stowed boom clearly identified. CPS thrusters commissioned. Procedure for thruster chain defined, implemented and validated. Risk assessment for damage to antenna by mechanical team.	Induced kinematic limited, but yet unknown. Might not overcome friction. Minimum appendage deployment (no LPs, no RWI).	Dynamics for RIME release in excited state/rotating SC is confirmed ok SADM oscillating gear stresses confirmed ok.	11.05
C	Proceed with NEA6N/NEA6R actuation	Closest shock source Cannot be repeated. Can be combined with D	May be rendered more effective in combination with Option #D.	One shot. Can induce both boom simultaneous release if sequence not modified. → sequence to be adapted.	Even with adapted sequence it induces double release on both Boom - low risk.	12.05
D	Thermo-elastic effects induce "opening" of the sleeve and/or unlocking of stuck pin(s)/elements	Thermo-elastic effects induce "opening" of the sleeve and/or unlocking of stuck pin(s)/elements	SWI mirror moved to safe position (TBC). JNA de-contamination heater active - OK FD guidance products available (by 2/May)	Slew must be fast. Overall slew duration TBD. SWI OK up to 45 deg elevation if duration <45/55 min - without mirror moved.	Damage to instruments on +Z Face - mitigated by confirmation	02.05

Table 2: Possible recovery scenarios

7 LESSONS LEARNED AND CONCLUSIONS

Several lessons learned have been drawn from this recovery:
1- In retrospect, the issue would have been difficult to detect:
- despite some related RIDS at RIME PDR, the tolerance stack issue is at 3 level down to ESA on detailed drawings not shared,
- "hands on peer reviews in front of the hardware should be promoted, but the EQM strip-down happened during the Covid pandemic and could not be witnessed,
- it is also linked to a distributed procurement due to geo-return requirements,

2- Mechanisms design shall be kept as simple as possible, they should avoid hyperstatic design, leading to high sensitivity to tolerance,

3- The FM units should have been tested in expected thermal conditions, Alternatively, despite qualification covering all temperature ranges, actual deployment shall be made nearer room temperature, when possible,
4- Even when not foreseen as critical, all parts of a mechanism shall not be interchanged between acceptance testing and flight,

5- Plan for as many observables as possible: without the JMC-2 camera (and the rendering software by STI), it would have been extremely difficult to understand the Root Cause,

6- Getting the availability of the RIME EQM H/W was key to reproduce the failure on ground: this understanding is essential for discussing the way forward in a meaningful manner,

7- The availability of past multi-body simulations from 2021 of the early simulations of failure scenarios were key to prescribe the modified NEA firing sequence,

8- Checking that the other units on board stay safe during the various elaborated recovery scenarios (thermal and shaking) took a great deal of effort, not to be underestimated, (also because a minimal number of units had their check-out done at the time of the anomaly),

9- Close coordination and cooperation spirit among all the teams was key.

The on-board cameras do not improve the reliability of the deployment mechanisms. It is however recommended to consider procuring reliable, low-cost miniature cameras for future S/C and having an internal memory to allow a burst mode shooting capability. The interpretation of the pictures is not straightforward, as they can be easily under or over-exposed, depending on the sun orientation and some sub-reflections.

8 ABBREVIATIONS AND ACRONYMS

CFRP: Carbon Fibre Reinforced Plastic
CTE: Coefficient of thermo-elastic
E2E: End-to-End
FCT: ESA Flight Control Team
FD: ESA Flight Dynamic Team
HAA: High Accuracy Accelerometer
HDRM: Hold-Down Release Mechanism
JMC: JUICE Monitoring Camera
LEOP: Low Earth Orbit Phase
MGA: Medium Gain Antenna
NECP: Near-Earth Commissioning Phase
RCA: Root Cause Analysis
RIME: Radar for Icy Moon Exploration radar instrument
NEA: Non-Explosive Actuator
PEP: Particles Experiment Package
SADM: Solar Array Drive Mechanism
SWI: Sub-millimetre Wave Instrument

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- the Airbus and ESA thermal teams, performing on the fly analysis in support of the operations,
- the mechanisms teams, updating the multi-body analysis.

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