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Abstract: In the context of space missions, where science is the most important goal, careful planning and detailed commanding are fundamental. The planning and commanding phases are activities whose complexity depends on the instrument characteristics, environmental constraints and scientific goals. The purpose of this work is to describe in detail these activities for the Jovian Infrared Auroral Mapper (JIRAM) on board the Juno spacecraft, a NASA mission to Jupiter. To maximize the scientific return, we fully employ the flexibility offered by the JIRAM operational modes to efficiently plan observations of various Jovian targets, in spite of the harsh Jovian radiation environment and the spinning state of the Juno spacecraft. Moreover, the JIRAM observations are limited by the challenging pointing and timing scheme of the mission, which impose constraints on both the observation planning and instrumental commanding.

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09 January 2019

Dear Editor,

We wish to submit a new manuscript entitled “Juno/JIRAM: Planning and Commanding activities”. We confirm that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere. The purpose of this work is to describe in detail the activities of planning and commanding for the JIRAM instrument, on board the Juno spacecraft, a NASA mission to Jupiter. The paper should be of interest to readers in the areas of space instrumentation development and ground segment.

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Thank you for your consideration of this manuscript.

Sincerely

Raffaella Noschese

Juno/JIRAM: Planning and Commanding activities

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Abstract

In the context of space missions, where science is the most important goal, careful planning and detailed commanding are fundamental. The planning and commanding phases are activities whose complexity depends on the instrument characteristics, environmental constraints and scientific goals. The purpose of this work is to describe in detail these activities for the Jovian Infrared Auroral Mapper (JIRAM) on board the Juno spacecraft, a NASA mission to Jupiter.

To maximize the scientific return, we fully employ the flexibility offered by the JIRAM operational modes to efficiently plan observations of various Jovian targets, in spite of the harsh Jovian radiation environment and the spinning state of the Juno spacecraft. Moreover, the JIRAM observations are limited by the challenging pointing and timing scheme of the mission, which impose constraints on both the observation planning and instrumental commanding.

1 INTRODUCTION

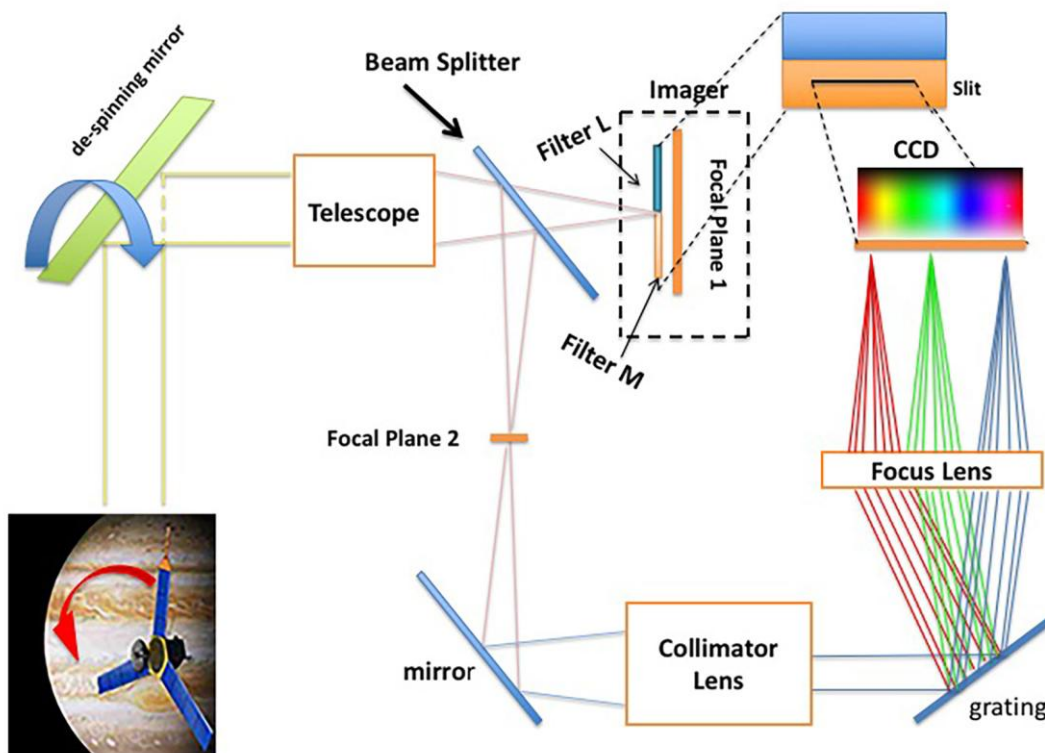
JIRAM [1] is an imager/spectrometer onboard the NASA Juno spacecraft (S/C) [2]; the probe, launched on August 5th, 2011, arrived at Jupiter on July 4th, 2016, after a cruise of five years that included a flyby of the Earth-Moon system. JIRAM's main scientific goal is the Jovian atmosphere in order to determine its composition, to

48 explore the dynamics and chemistry of the auroral regions and to study the hot spots
 49 through the troposphere; secondary goals, contingent on the existence of any
 50 fortuitous observing opportunities, include the observation of the three innermost
 51 Galilean moons (Io, Europa and Ganymede).
 52 Since Juno is a spinning spacecraft, JIRAM was built with a de-spinning mirror
 53 designed to compensate for spacecraft rotation. A similar device was not implemented
 54 in the previous deep space spectrometers from which JIRAM derives its heritage,
 55 such as the Cassini VIMS-V, the Rosetta and Venus Express VIRTIS and Dawn VIR-
 56 MS instruments, which were operating aboard 3 axis-stabilized spacecraft. Juno is
 57 nominally rotating at 2 rpm, namely 12deg/s; the de-spinning mirror allows the target
 58 scene to remain stable in the instrumental Field-of-View (FOV) for up to 1.1 s.
 59 In this paper we describe the planning and commanding processes implemented by
 60 the JIRAM team to successfully operate at Jupiter and obtain groundbreaking
 61 scientific observations. A brief description of the JIRAM instrument is reported in
 62 Section 3 (more details are reported in [1]). A description of the JIRAM observations
 63 and of the associated planning strategy is reported in Sections 4 and 5. In Section 6
 64 the timelines for the most relevant targets observed during the mission detailed. Data
 65 volume estimation, an important operational constraint of the mission, is discussed in
 66 Section 7.

68 2 JIRAM INSTRUMENT DESCRIPTION

69 2.1 JIRAM INSTRUMENT

70 The JIRAM instrument [1] uses a dual-channel infrared (IR) imager and an imaging
 71 spectrometer sharing a common telescope and de-spinning unit (see Figure 1)
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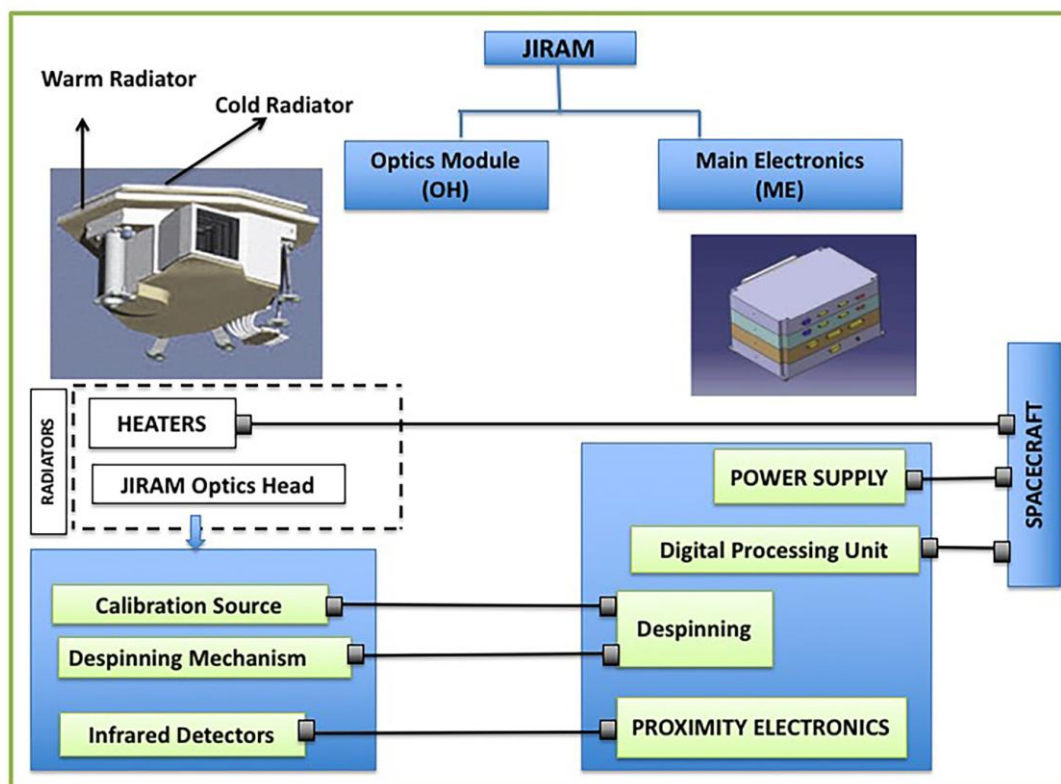
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76 Figure 1 JIRAM optical scheme. The de-spinning mirror rotates in the reverse direction of the rotation of the
 77 spacecraft to stop the image. The light, after entering the telescope, is splitted by 30 % on the focal plane 1
 78 (imager) and the 70% on the Focal plane 2 (spectrometer). Regarding the spectrometer, the beam is deflected
 79 (mirror) and collimated on the grating; the grating separates the beam into different wavelengths and a then
 80 focalized on focal plane 2.

81
 82 Such a configuration maximizes the scientific return in each phase of the mission by
 83 ensuring an equitable share of available resources, such as power and data rate. The
 84 JIRAM instrument makes use of its capabilities to perform:

- 85 ➤ spectral imaging of the planet in the 2.0-5.0 μm interval of wavelengths
 86 with a spectral resolution better than 10 nm and
- 87 ➤ simultaneous imaging in the L (spectral range 3.3–3.6 μm) and M (spectral
 88 range 4.5–5.0 μm) bands.

89 The two different channels composing the instrument front–end have a common Main
 90 Electronics Module (ME) and power supply (see Figure 2).



91
 92
 93 Figure 2: General block diagram of JIRAM. The instrument is constituted by the Optics Head (OH), the Electronic
 94 Unit and internal harness connecting the two units.

95
 96
 97 The ME contains the electronics that drive the Focal Plane Arrays (FPAs) and
 98 compensating mirror. It performs the acquisition of the science and housekeeping
 99 data, stores the data, performs data compression, and serves as an interface between
 100 the instrument and the spacecraft.

101 Both imager and spectrometer channels use the same HgCdTe detector type with a
 102 format of 270×438 pixels, 38- μm pixel pitch, 2 million e- full-well capacity. Data
 103 are recorded in a subset of these pixels (256×336 for the spectrometer and 256×432
 104 for the imager).

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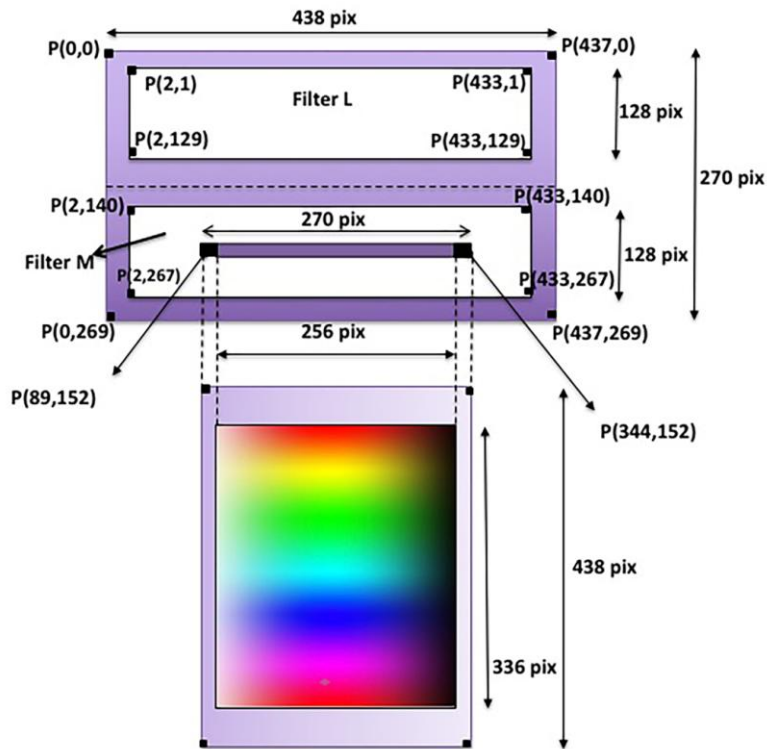


Figure 3: Layout of the JIRAM Detectors. Top panel: imager FOVs projected above the detector frame. Bottom panel: spectrometer channel detector. The position of the spectrometer FOV within the M channel FOV is shown in the top panel.

The JIRAM detectors are passively cooled down to operational temperatures of 80-90 K through a thermal harness connected to an external radiator. The detectors' optimal scientific performance (dark current) is guaranteed for $T \leq 95$ K. The compression algorithm does not work correctly at temperatures higher than 105 K due to increased noise. However, at these temperatures, the signal-to-noise ratio is typically too low to be scientifically useful. There are temperature limits, which, if reached, disable the usage of Calibration Lamps (170 K), Detectors (200 K), Motor Mirror (200 K), and Digital Processing Unit (DPU) (373 K). If the DPU temperature exceeds the limit, a SAFE ME transaction request will be sent to the spacecraft, commanding JIRAM to power off.

Focal planes are housed in two separate mechanical structures designed to:

1. maintain the correct alignment with respect to the optical bench,
2. thermally isolate the instrument housing with respect to the optical head mechanical structure and
3. hold the order-sorting filters on the spectrometer (SPE) detector and the L and M filters on the imager (IMG) detector.

The two filters of the imager are designed to address distinct scientific goals. The L-band filter is used primarily to study the Jovian aurora and environmental radiation ([3], [4], [5]), and to determine the infrared albedo of satellite surfaces. Images taken

135 through the M-band filter are used to study morphology and dynamics of Jupiter's
136 troposphere ([6], [7], [10]). Data from the JIRAM spectrometer, albeit more limited in
137 spatial coverage, enable one to investigate Jupiter's atmospheric composition ([7]
138 [8]), to determine the distribution, concentration and temperature of H_3^+ ions in the
139 Jovian system [12] and to measure the surface temperature of Io [9]

140 **2.2 JIRAM MODES**

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142 The onboard application software implements a number of system states (modes) as
143 shown in Figure 4.

144 Each state is dedicated to the performance of specific actions. The transition from one
145 state to another is commanded by the S/C by means of dedicated telecommands (TC).

146 The states and their meaning for the application program are described below:

- 147 • Initialization mode (INI) is executed at the start-up or after any reset, when all
148 preliminary operations for the nominal setting are executed.
- 149 • Software Maintenance mode (SWM) is commanded from INI to allow direct
150 access to the onboard RAM and EEPROM memories that can be modified and
151 checked to allow SW patching and parameter modification.
- 152 • Safe mode (SAF) is the entry state of the application program from the boot
153 program. After the completion of the runtime environment and variable
154 initialization, the application program will immediately communicate a mode
155 change event to the S/C. All mandatory services are available (except some
156 TCs of private services linked to the software maintenance and science
157 operation). Periodic housekeeping (HK) is generated and sent to the S/C.
- 158 • Stand-by mode (STBY) is entered after switch on and when it is needed to
159 change from one mode to another; the only performed activity is the periodic
160 HK acquisition.
- 161 • Science mode (SCI) is the only mode in which the acquisition of science data
162 occurs. The Science mode includes a number of sub-modes, organized in
163 subgroups (for more details, see paragraph 5.3).
- 164 • Calibration mode (CAL) allows the instrument to perform the calibration
165 sequence: the calibration sources are ON and the mirror motor is commanded
166 to a fixed position.

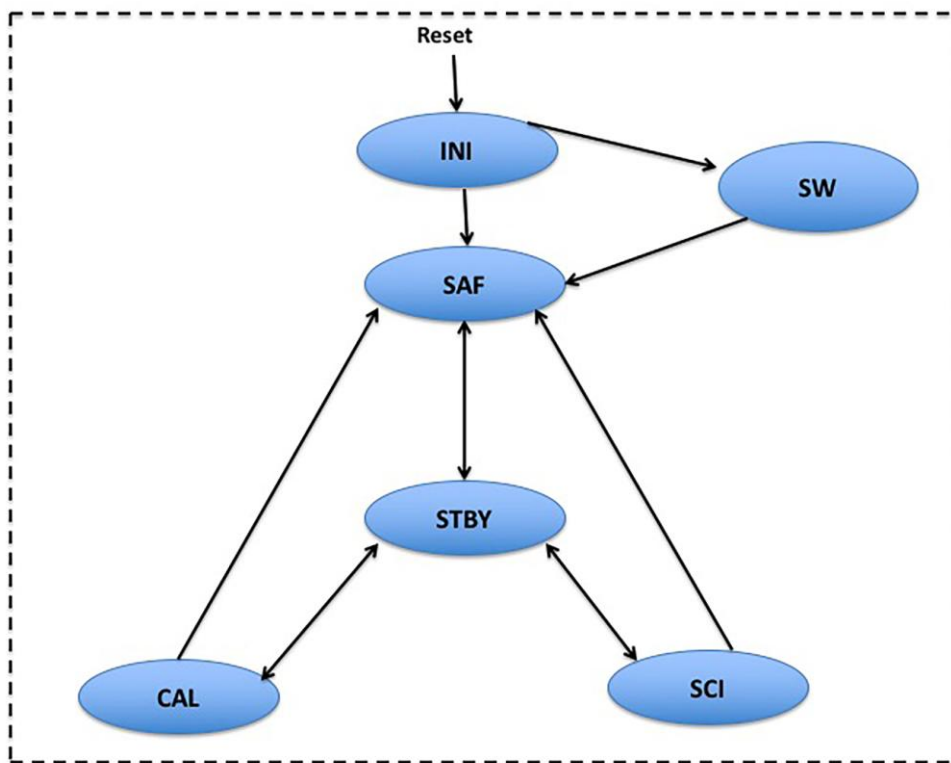


Figure 4: JIRAM operational modes and related transitions.

3 JIRAM PLANNING & COMMANDING DESCRIPTION

3.1 JIRAM SCIENCE PLANNING STRATEGY

Each orbit of the mission is divided into two planning sequences: a perijove sequence and an apojove sequence. Perijove sequences begin roughly one day prior to perijove and end one day before apojove. Apojove sequences pick up where the preceding perijove sequence leaves off and runs up until about one day before the following perijove. The JIRAM observation windows typically start 18 hours before perijove (PJ) and end 23 hours later. When Jupiter or its satellites are not in the FOV, JIRAM can be used for measuring background radiation.

Among Juno's various science investigations, JIRAM is a relatively straightforward instrument to operate. For example, there are no keep-out zones to which the instrument is subject that constrain when it can take data. And because it takes data in the near- to mid-infrared, JIRAM can take good data of science targets such as Jupiter and Io even when they are not illuminated by the Sun. The availability of resources such as power and data volume do not preclude simultaneous operations of JIRAM with any of Juno's other instruments. The main factors that constrain the operability of JIRAM relate to the instrument's thermal environment, the Jovian radiation environment and, being body-mounted to a rotating spacecraft, spacecraft pointing. As mentioned above, the instrument performance is guaranteed at detector temperatures <95 K. However, in practice, temperatures never greatly exceed this value by more than a few degrees K and does not effectively limit when JIRAM can

195 successfully obtain data. Likewise, the radiation does not limit the planning of data
196 acquisition. At times radiation does degrade science data. But predicting precisely
197 when radiation will impact observations to an unacceptable degree is difficult in the
198 unpredictable Jovian radiation environment. Therefore, the JIRAM team does not
199 attempt to plan around this.

200 It is spacecraft pointing and the orbital trajectory which mostly limit the data that
201 JIRAM acquires. Being a spinning spacecraft, Juno maintains a constant attitude
202 during a given perijove; changing attitudes at perijove is expensive from both an
203 operational and resource standpoint. The bulk of Juno's Jupiter flybys are
204 implemented in the GRAV attitude, which keeps the high-gain antenna pointed
205 roughly at the Earth to enable ranging throughout the encounter. Other flybys
206 incorporate a slight tilt to allow the Microwave Radiometer (MWR) instrument to
207 observe the nadir point on Jupiter as the S/C rotates. Other custom orientations have
208 been implemented as well. The principal difference from the perspective of JIRAM is
209 the persistence of Jupiter in the JIRAM FOV.

210 When Juno arrived at Jupiter in July 2016, its orbit was roughly aligned along the
211 dawn-dusk line and with a perijove latitude slightly north of the equator. As the
212 spacecraft trajectory has evolved, the perijove latitude has shifted northward and the
213 tilt of the orbit relative to the orbital plane of Jupiter has increased. The result is that
214 Juno and JIRAM make ever quicker passes over the north pole of the planet with less
215 time to observe, while the spacecraft provides an excellent platform to observe the
216 south pole of Jupiter as Juno recedes away and towards apojoive. This leads to greater
217 coverage in the south compared to the north, as the number of footprints in Figure 6
218 suggests.

219 For each orbit JIRAM tries to observe Jupiter's auroras, to track and monitor the polar
220 vortices and their evolution, and image Jupiter's moon Io to study the evolution of its
221 volcanoes. In most cases, scientific objectives are not overlapping. For example,
222 taking images of a satellite does not affect the observations of aurorae and
223 atmosphere, because usually moons are visible in different time windows (some hours
224 before or after perijove). In a few cases, the scientific team has to decide which
225 scientific goal has precedence; this is the case, for example, when Juno is over
226 the poles and one would like to observe the aurora or the cyclones, but can't do both at
227 the same time, or in the rare cases when a moon opportunity happens at the same time
228 that Jupiter is in the field of view. In this case, we follow the primary objectives of the
229 Juno mission. Moon observations, for example, have lower priority because such
230 science is not the primary goal of Juno.

231 232 233 234 235 **3.2 PLANNING & COMMANDING PIPELINE**

236
237 The JIRAM planning team participates in regular Science Planning Working Group
238 (SPWG) meetings, which are held monthly, to discuss and prioritize possible science
239 objectives for future sequences.

240 For each PJ, a Science Activity Plan (SAP), which specifies the instrument activities
241 to occur during that interval of time and the resource distribution between the
242 instruments, is generated and reviewed at the SPWG meeting. The JIRAM operations
243 team then generates a Spacecraft Activity Sequence File (SASF), which contains the
244 detailed commanding for instrument operations that is consistent with the SAP.

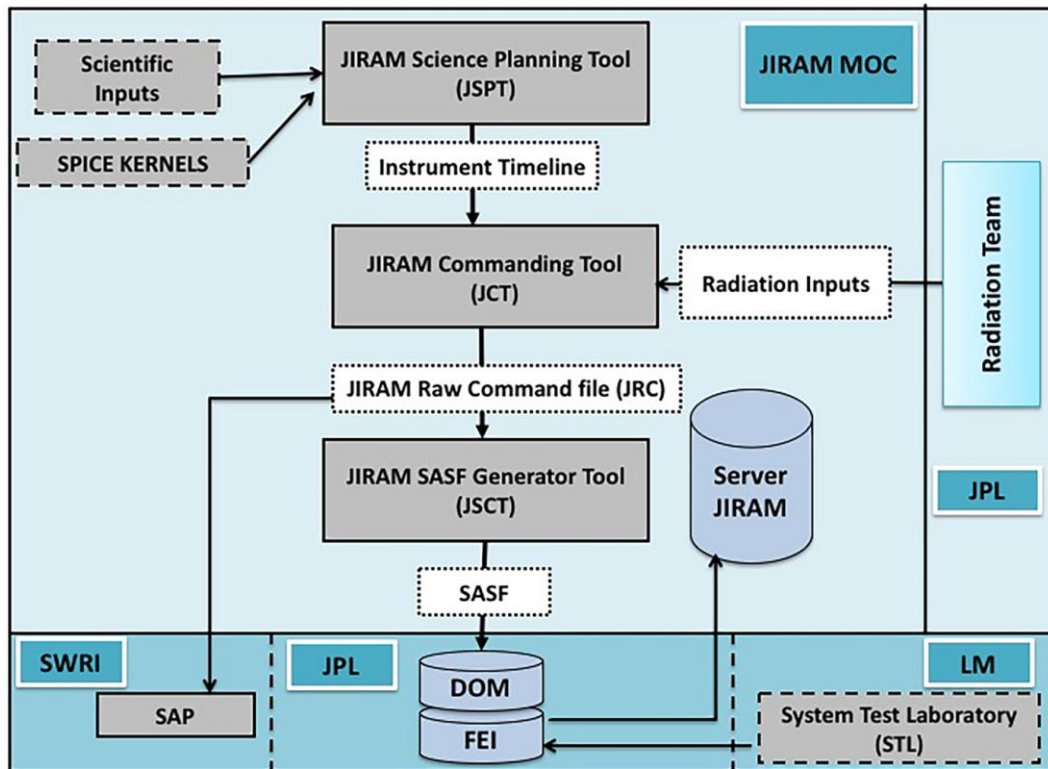
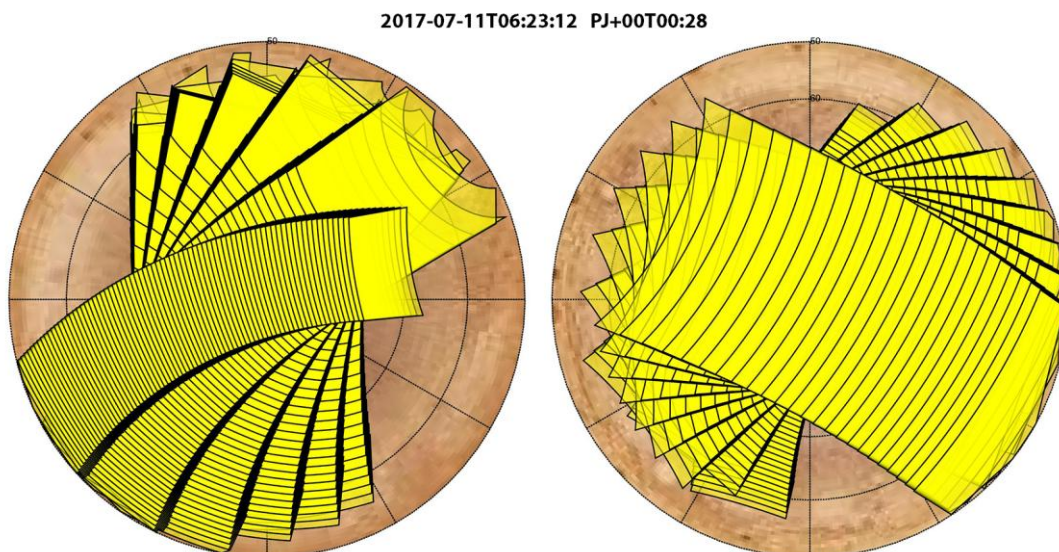


Figure 5: Planning & Commanding Pipeline. The image shows the uplink ground segment (JSPT, JCT, JSCT) and all bodies involved: SWRI for SAP, LM for STL, JPL for DOM, FEI and Radiations input; the tools of the ground segment of JIRAM were developed by JIRAM team in Matlab and have all a graphical interface.

In order to correctly plan and execute each sequence of science observations and allow for a variety of science targets and operational constraints, a complete Planning & Commanding Pipeline (see Figure 5) has been developed.

The first step of this chain involves the JIRAM Science Planning Tool (JSPT), the purpose of which is to allow the scientific team to visualize the observation opportunities during a given perijove and to plan the JIRAM observations based on the predicted trajectory (as encoded in the SPICE kernels), working on a common platform.



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261 Figure 6: Simulation of Orbit 7- Imager filter L. Left: the coverage of the North Pole; right : the coverage of the
262 South Pole. The overlapped yellow strips represent the predicted FOVs.

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266 The JSPT produces the time sequence of the JIRAM instrument activities and
267 displays (in 2D and 3D) Juno's ground track on to Jupiter, as well as JIRAM's FOV
268 (both imager and spectrometer) to verify the coverage (see Figure 6).

269 The next step is to process automatically process the output of the JSPT and the
270 observation requests from the Radiation Monitoring team [5] with the JIRAM
271 Commanding Tool (JCT) that implements procedures and algorithms, allowing the
272 generation of the parameters used to configure the instrument. In particular, it takes
273 into account both mission and instrument constraints:

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- flight rules,
- data volume,
- data rate and
- hard partition size.

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280 Nominal inputs to the Commanding Tool are the instrument timelines generated by
281 the JSPT and validated within the Science Activity Plan file (SAP) at Southwest
282 Research Institute (SWRI). The outputs of the JCT are the science parameters used to
283 set the instrument and formalized in the JIRAM Raw Command file (JRC). The JRC
284 file is then translated automatically into Spacecraft Activity Sequence File (SASF)
285 format with the JIRAM SASF Generator Tool (JSGT) and delivered to the Distributed
286 Object Manager (DOM) at JPL. Before the command sequence is transmitted to the
287 S/C, the syntax and consistency of the content are checked and then integrated with
288 the command sequences from Juno's other subsystems. The command sequence is
289 then tested by Lockheed Martin (LM) on the System Test Laboratory (STL) against
290 S/Cflight rules and for conflicts between subsystems.. The STL data are manually
291 retrieved with a client-server application, "File Exchange Interface" (FEI), or queried
292 by the JPL ground reception time. These data can also be automatically retrieved as
293 soon as they are available through a subscription service. The check of the STL data
294 allows us to verify commanding.

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3.3 SCIENCE PLANNING CYCLE

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298 The sequence development process typically starts 8-9 weeks before a given PJ.
299 Science sequence development generally begins with "Pass 1", which lasts
300 approximately two weeks and begins 4-5 weeks before sequence execution. Prior to
301 this, the engineering team works through the engineering issues for that sequence. It
302 is also during this period that the SPWG convenes to discuss the science activities in
303 the sequence under development. It is in "Pass 1" that the SAP is officially approved
304 and all subsystems generate their individual SASFs; "Pass 1" ends with the review of
305 the STL run on the merged sequence product. After this period begins the "Pass 2"
306 phase, which starts with the opportunity to correct any commanding errors uncovered
307 during the "Pass1" phase. "Pass 2" generally lasts another two weeks and concludes
308 with the uplink of the full background sequence. It is worth noting that if no problems
309 arise during "Pass 1", "Pass 2" is bypassed, and the sequence is uplinked either during
310 the nominally scheduled window or a few days prior.

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314 4 SCIENCE OBSERVATIONS

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316 During a single orbit, JIRAM can perform a sequence of different science

317 observations depending on the details of the trajectory.

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319 4.1 JUPITER SCIENCE OBSERVATIONS

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321 For each orbit, the science team identifies the target areas to observe and optimizes

322 the tilt angle to command for each acquisition in order to have the best coverage of

323 the targets, the operational mode and the exposure time to be used, depending on the

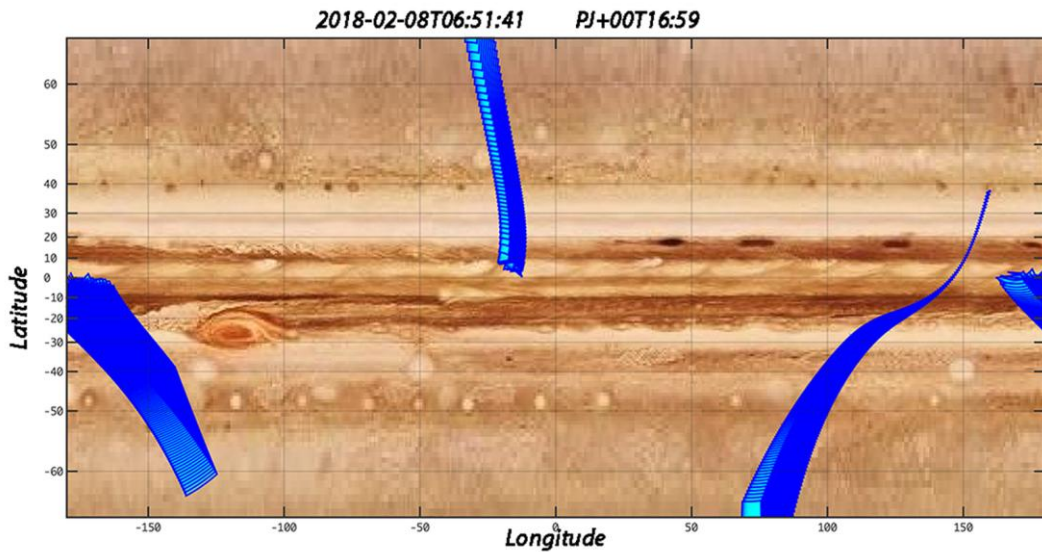
324 target to be studied. As stated above, the angular range of the de-spinning mirror

325 limits the maximum exposure time to 1.1s.

326 The tilt angle, defined as the angle between the nadir direction and the direction to

327 the target of interest in the sense of Juno's rotation, can be set as follows:

- 328 1. '0' tilt: the images are acquired with nadir pointing; i.e. the tilt angle is set to
- 329 0 deg with respect to nadir point (see simulation Figure 7 and Figure 8a)



330

331

332 Figure 7: Observation PJ11 '0' tilt , simulated with JSPT,the blue strips are produced overlapping the predicted
333 FOVs during the single orbit at each S/C revolution.

334

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- 336 2. Fixed tilt : the images are acquired by setting the mirror at a fixed angle with
- 337 respect to the nadir position.

- 338 3. Variable tilt (Figure 8b): in this case the combination of the movement of the
- 339 S/C together with the variation of the tilt angle allows an extended coverage

340 of the targets; this mode is used to scan both the polar and auroral areas.

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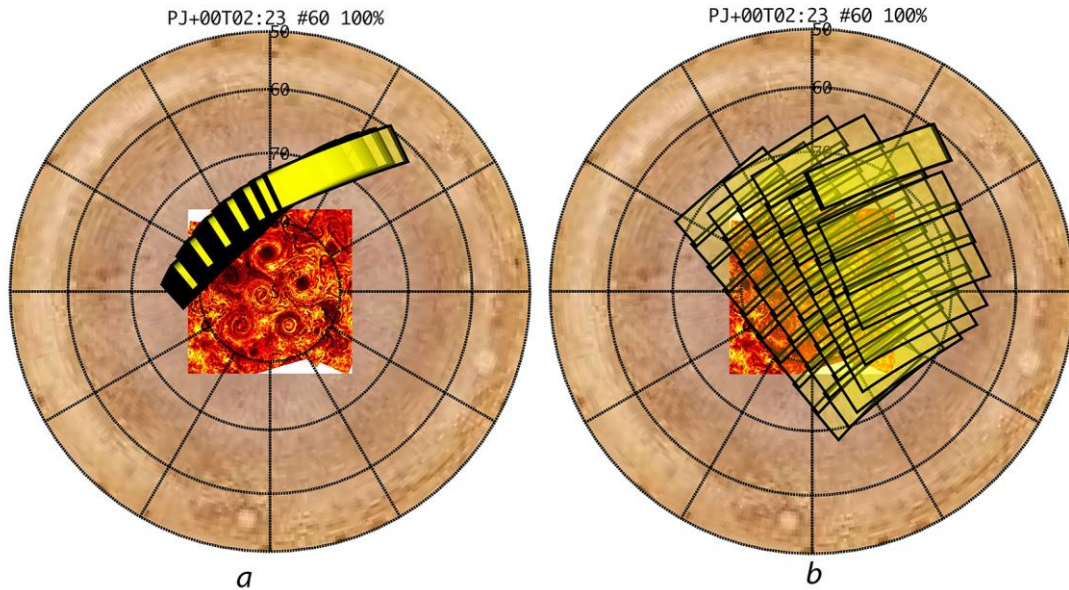


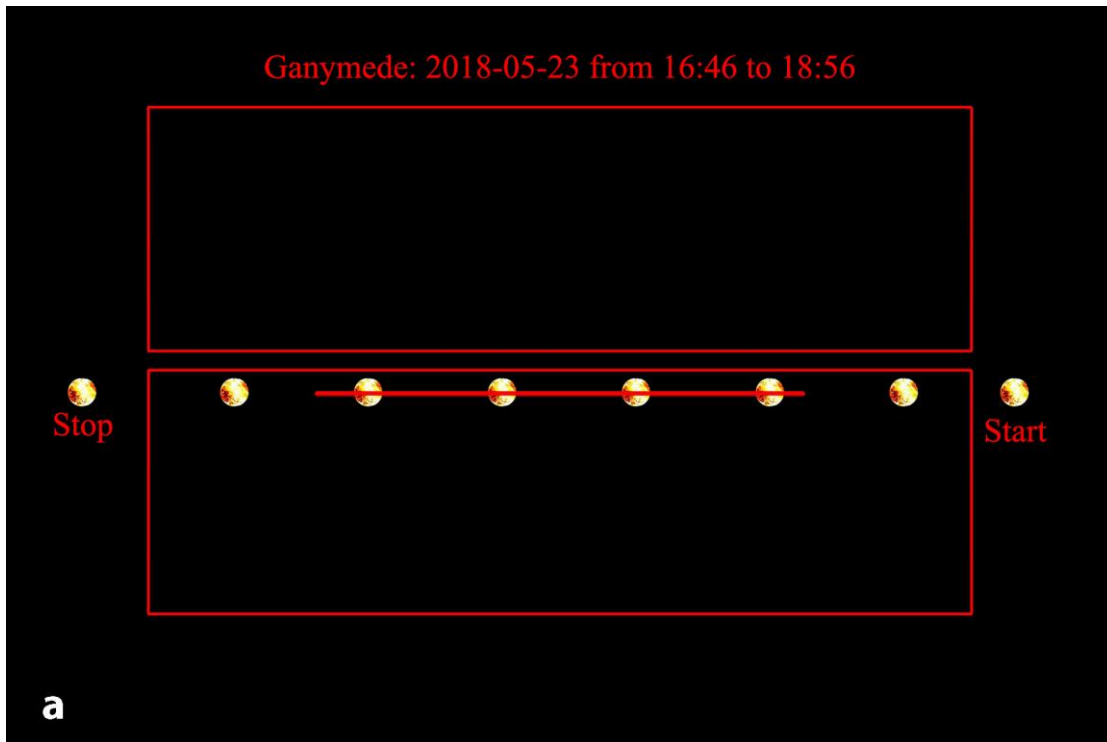
Figure 8: Simulation with JSPT, South Pole observation PJ13 Respectively a) with 0 tilt and b) with variable tilt. The overlapped yellow strips represent the predicted FOVs. The JSPT shows the apparent position of the polar cyclones observed by JIRAM during the first orbits [10]. This is a very useful capability during the planning process.

4.2 SATELLITE SCIENCE OBSERVATIONS

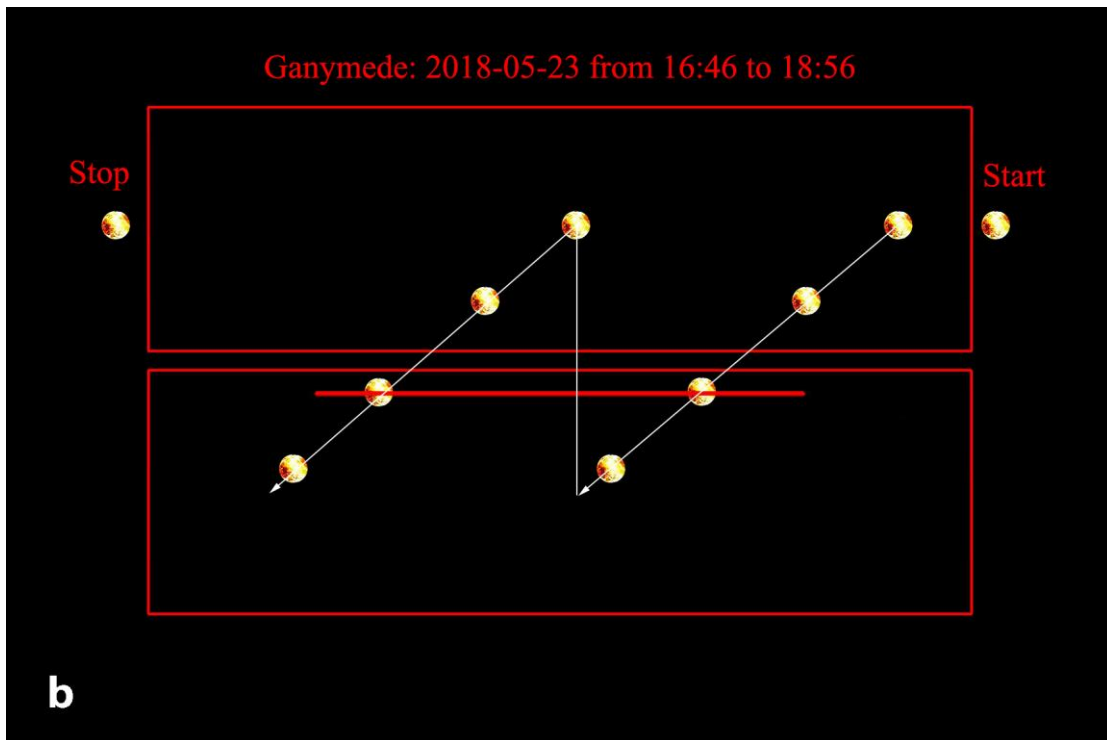
Occasionally, the trajectory around Jupiter allows serendipitous observation of the Galilean moons.

In such cases, we perform scans by manipulating the tilt angle in order to simultaneously acquire the targets with one or both filters of the imager and with the spectrometer. In Figure 9 is shown a simulated example of an observation of Ganymede, produced with JSPT and obtained with the following procedure. Since JIRAM's FOV is restricted to observations along the spin plane of Juno, JSPT uses SPICE software and the related mission kernels to estimate the time when the moon will be in a favorable position for the observation (i.e., when the moon crosses the spin plane of Juno). Then, the JSPT tool uses the same SPICE kernels to estimate the proper tilt angle needed to acquire the moon. This tilt is usually on the order of 90° , and the moon is often seen from above or below the poles. Even if the actual time of the observation has an uncertainty of about 30 seconds (we don't know in advance the orientation of the spacecraft, but we know that every 30 seconds the FOV of JIRAM will explore all the angles in the Juno spin plane). In summary, the JSPT's output is a time interval for the observation and a proper tilt angle for a given spacecraft orientation. In addition, JSPT is also used to evaluate the possibility to add a small additional tilt angle, slightly above or below the sub-spacecraft point on the target, in order to acquire spectra from different locations on the moon ("spectral cubes"). Since the moon is usually quite far from the spacecraft, these additional tilt angles are of the order of few minutes of arc.

375 As an example, Figure 9a shows the images of Ganymede acquired both with the
 376 spectrometer and the M filter of the imager ([10], [12]), while the Figure 9b shows the
 377 Ganymede observations managing the tilt in order to observe it also with both
 378 channels (L+M+ SPE).
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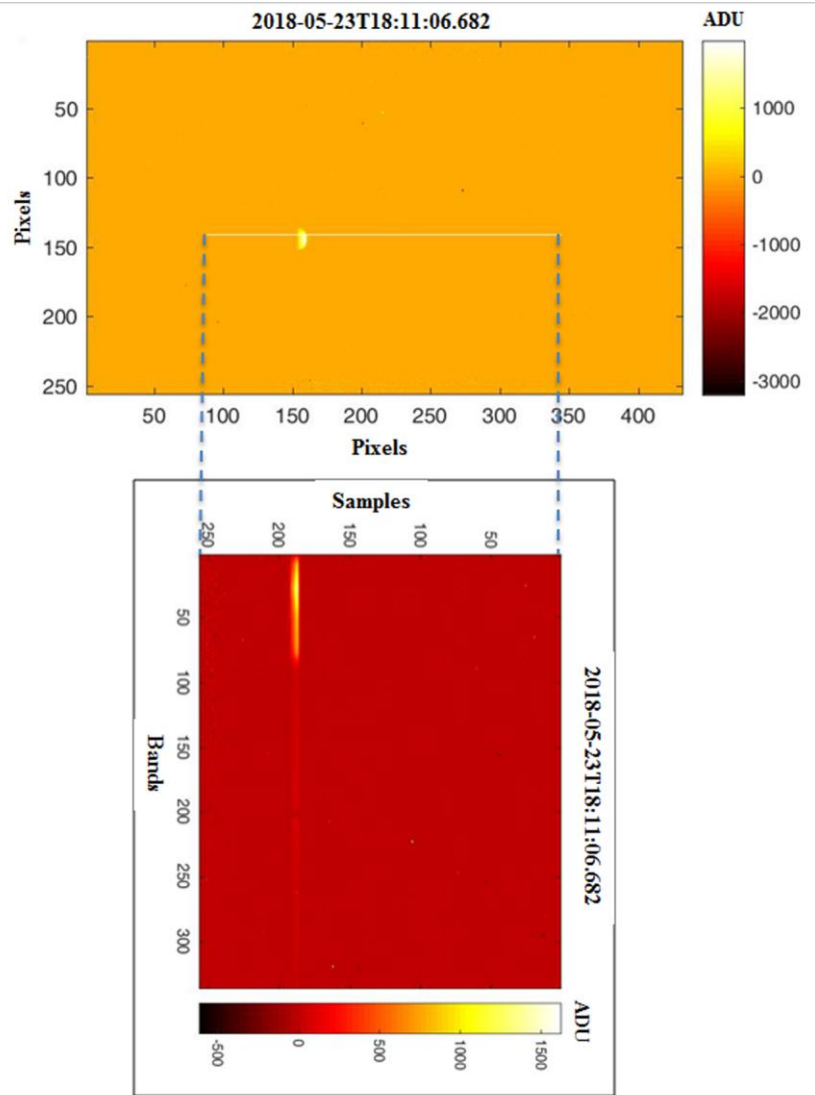
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Figure 9: In Figure 'a' is reported a simulation of Ganymede prior to PJ13 with fixed tilt; in this case JIRAM acquires Ganymede with spectrometer and filter M. Using an appropriate variation of the tilt angle JIRAM can acquire Ganymede with both Imager (filter M and L) and spectrometer, as you can see in the Figure 'b'. Please note that in both images the satellite enters in the JIRAM FOV from right side (Start) and exits from left one

389 (Stop). In the Figure 9a the acquisitions are centered on the spectrometer while in the figure 9b we can see the
 390 apparent movement of the satellite in the JIRAM FOV generated by means of the mirror angle variation.
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 395 Figure 10: Ganymede observation, during PJ13, acquired by both the JIRAM Imager and Spectrometer. In the
 396 image are shown the simultaneous acquisitions of the Imager (top) and Spectrometer (down). Top: the M filter
 397

401 4.3 RADIATION SCIENCE OBSERVATIONS

402
 403 JIRAM is one of the first instruments to be used to monitor the environmental
 404 radiation at Jupiter; extremely harsh radiation intensities (>10 MeV) that characterize
 405 Jupiter's background conditions can affect the images acquired by JIRAM because of
 406 the potential for the detectors to detect penetrating charged particles.
 407 This background radiation can degrade the quality of the standard observations. On
 408 the other hand, the amount of "hits" registered can be useful for estimating the levels

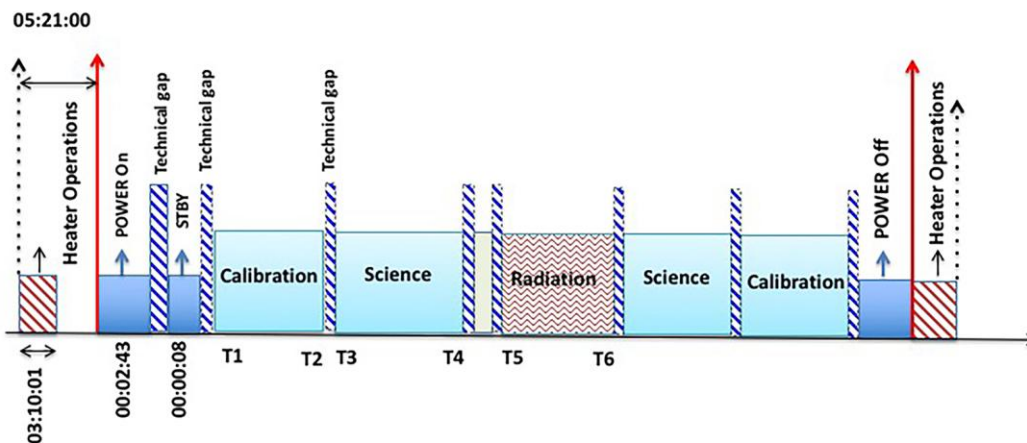
409 of radiation encountered. The analysis of the images contaminated by the radiation is
 410 discussed in [4].

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 414 **4.4 POINTING CALIBRATION OBSERVATIONS**

415
 416 During the first science orbit (JM0001), JIRAM was turned on for the first time after
 417 the insertion maneuver around Jupiter. In detail, JIRAM observed Aldebaran (α Tau)
 418 and the Hyades in order to perform the geometrical calibration of the instrument.
 419 Aldebaran was observed on 20 July 2016 by JIRAM, using an increasing offset of
 420 0.0094169 deg (about $\frac{3}{4}$ pixel) for each image. These offsets were predicted by using
 421 the Juno reference trajectory (SPK kernel), the predicted SC orientation (CK kernel)
 422 and the Juno and JIRAM frame definition (frame kernels) [14]. The analysis of these
 423 observations was important because it allowed the JIRAM team to evaluate the
 424 difference between the reconstructed geometry (obtained with reconstructed kernels)
 425 and the predicted geometry for these observations. Examining these differences in
 426 each of the obtained images allowed the team to determine the Aldebaran centroid in
 427 the M band during this observation sequence. A significant outcome of this analysis
 428 was an improved knowledge of the pointing orientation of JIRAM.
 429 Considering that Aldebaran is a very easy target, and the centroid is estimated
 430 by using ~ 10 pixels, we found that the position of the star in the images corresponds
 431 to the expected one, so the final error on the pointing is less than 1 pixel, once the
 432 improved knowledge of the JIRAM orientation is taken into account.

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 436 **5 JIRAM GENERIC TIMELINE**

437
 438 Figure 11 shows a generic operations timeline that includes the science and radiation
 439 blocks, described in section 5, and also some technical blocks necessary for the
 440 execution of the sequence. The timeline for JIRAM is a sequence of TCs
 441 appropriately timed to achieve the scientific objectives defined during the planning
 442 phase.



443
 444
 445 Figure 11: Generic Timeline

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5.1 TECHNICAL BLOCKS

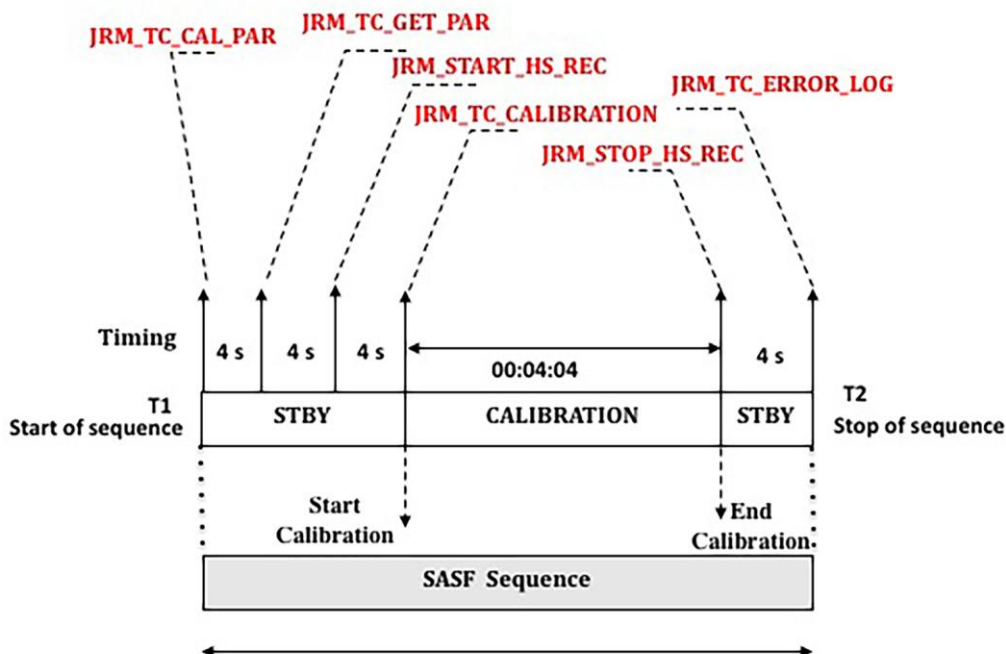
450
451

452 The Heater operations are a set of TCs to ensure the electronics and optical head
453 temperatures are greater or equal to their turn-on temperatures before turning JIRAM
454 on. These TCs are active 320 minutes before the power on.

5.2 CALIBRATION BLOCKS

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456

457 The Calibration is inserted in the timeline immediately after the Power On and before
458 Power Off, to verify that there are no changes in the radiometric and spectral
459 response, defective pixels of the instrument. The Calibration Block consists of a
460 sequence of TCs (see Figure 12):
461



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Figure 12: Calibration Sequence specifics and format.

- 467 • “JRM_TC_CAL_PAR” sets the parameters necessary to acquire images and
468 spectra.
- 469 • “JRM_TC_GET_PAR” is a TC that enables the download of the copy of the
470 instrument parameters inserted in the EEPROM.
- 471 • “JRM_START_HS_REC” enables the data recording
- 472 • “JRM_TC_CALIBRATION” starts the calibration phase
- 473 • “JRM_STOP_HS_REC” disables the data recording
- 474 • “JRM_TC_ERROR_LOG” enables the download of the related possible
475 errors.

476

477 The calibration procedure provides a standard sequence of 6 measurements described
 478 in Table 1. The details of each of these steps are as follows:
 479 1 - the detectors look at the internal calibration unit where the calibration sources are
 480 in the “off” state; the integration time is set in the “JRM_TC_CAL_PAR” and it is 6
 481 ms for the imager and 140 ms for the spectrometer.
 482 2 – the detector is acquired with an integration time of 20 μ s
 483 3 – one of the calibration sources is turned on and powered at a previously defined
 484 current level; same integration time as step 1
 485 4 - the same calibration source is turned on and powered at another previously defined
 486 current level which is higher than that in step 3 to produce a different level of signal;
 487 integration time as in step 1
 488 5 – repeat of step 1
 489 6 – repeat of step 2.

490 Calibration Cycle:

<i>Step</i>	<i>Phase</i>	
#1	Internal Background	493
#2	Readout Noise	494
#3a	Cal Source Stabilization	495
#3b	Cal Source Gain 1	
#4a	Cal Source Stabilization	
#4b	Cal Source Gain 2	
#5	Internal background	
#6	Readout noise	

496
497 Table 1: JIRAM Calibration cycle
498
499

500 During each cycle (30 sec) JIRAM performs two acquisition (OFF-NADIR and
 501 NADIR see Figure 13) for each of the previous steps but only half of the collected 12
 502 acquisitions are sent to the ground.

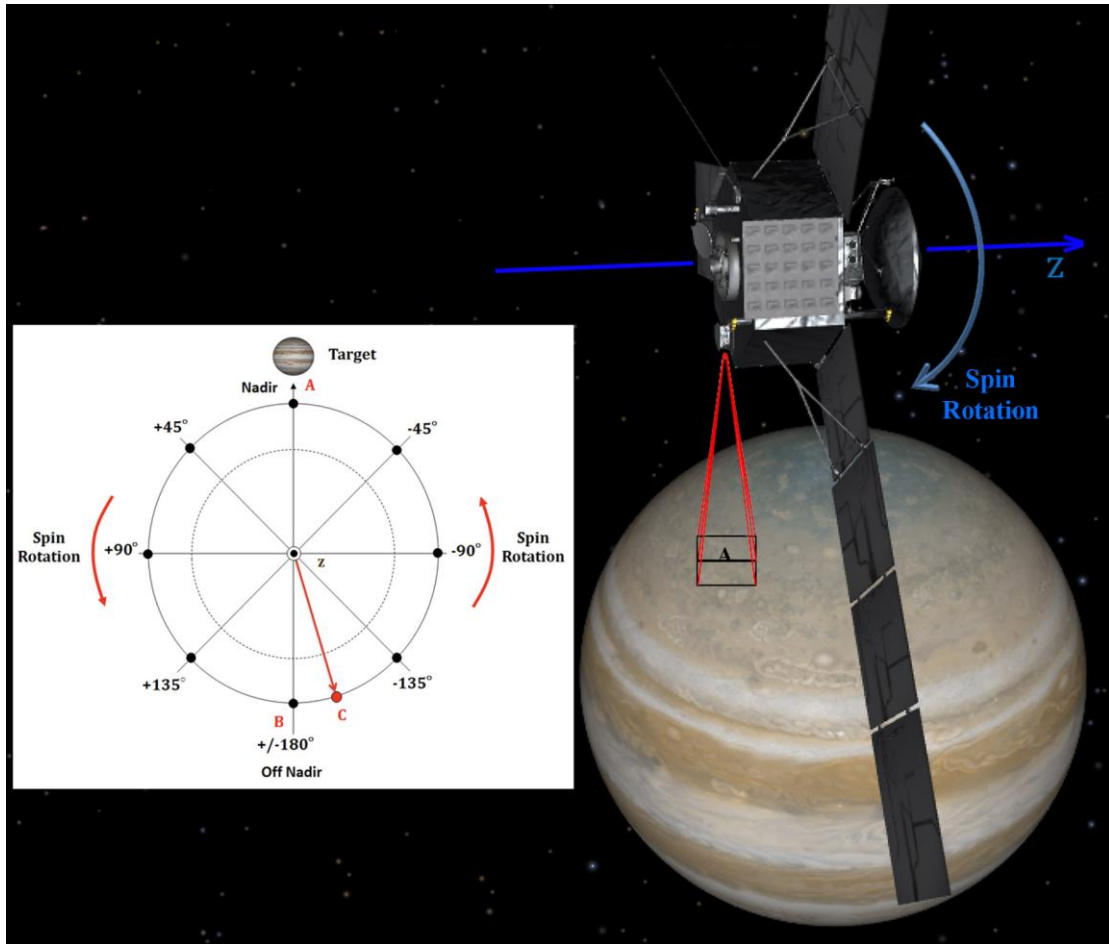


Figure 13: JIRAM(JRM) schematic observation geometry. The small image shows the position of the two acquisitions (A and B) performed in the nominal cycle of operation. The point “C” shows a generic position (see section 5.3.4). The inner panel shows the position, on Jupiter, of the acquisition “A” and the S/C spin rotation.

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During the first step JIRAM acquires the background OFF-NADIR that is stored in the Buffer_A, and after 15 seconds the Readout Noise (RN) in the Buffer_B; the Readout Noise is subtracted if subtraction is enabled.

For the second step, the OFF-NADIR acquisition is not used; only the RN is sent to the ground.

For step 3b and 4b, the acquisition of Source 1 and Source 2, respectively, are stored on Buffer_A, and the RN is subtracted if it is enabled.

Steps 5 and 6 are the same as for step 1 and 2.

A scheme of the various combinations is reported in Figure 14.

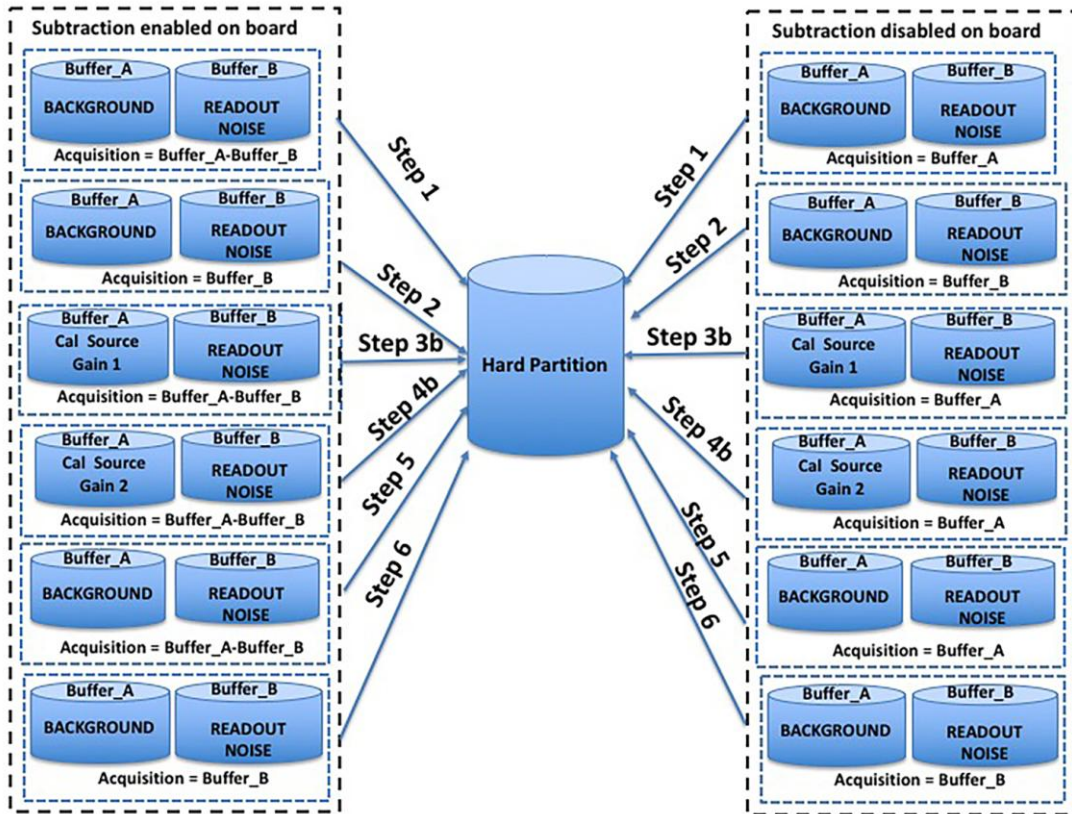


Figure 14: Details of the calibration cycle in case is enable or disable the subtraction on board.

5.3 SCIENCE BLOCK

In Science mode, the instrument performs a Science Session according to the parameters received in STBY. The Science Block includes the following sequence of TCs (Figure 15):

- “JRM_TC_SET_PAR” changes the default value of the onboard parameters
- “JRM_TC_SCI_PAR” sets the parameters that determine how the imager and spectrometer data are acquired: number of acquisitions, exposure time, operational modes, etc.
- “JRM_START_HS_REC” enables data recording
- “JRM_TC_SCIENCE” starts the science phase
- “JRM_TC_ERROR_LOG” enables the download of any potential related errors
- “JRM_STOP_HS_REC” disables data recording.

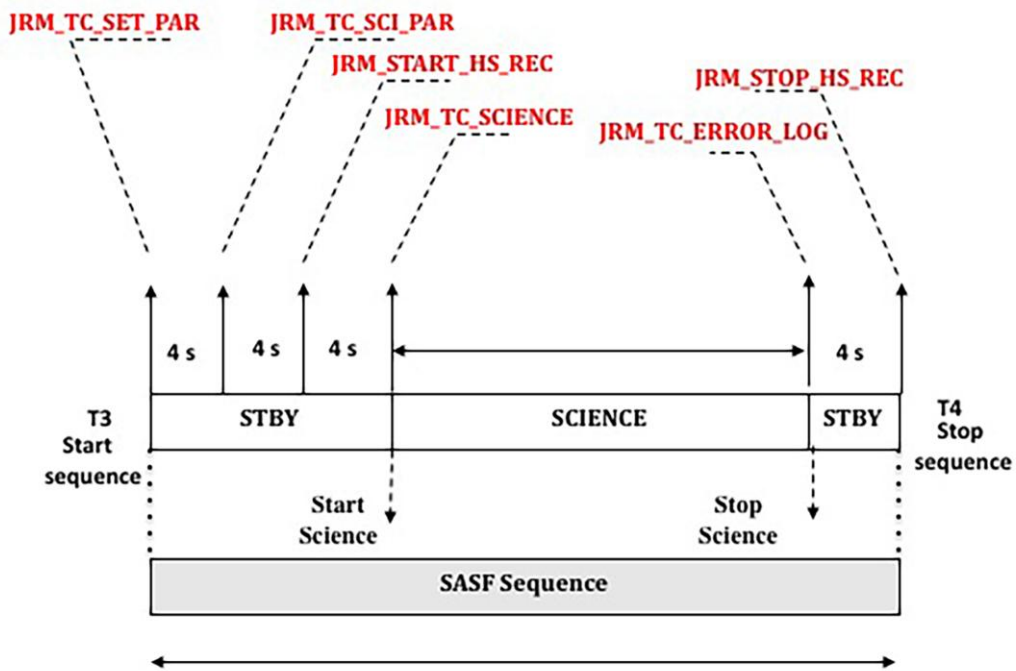


Figure 15: The figure shows the format of the science block: the TCs and the wait time required between successive TCs.

JIRAM can remain in SCI mode for a long time, depending on the parameters defined in JRM_TC_SCI_PAR. After this time it autonomously returns to STBY mode.

5.3.1 JIRAM SUBMODES

As mentioned in section 2.2, the Science mode is composed of several sub-modes that include both the imager and the spectrometer acquisitions.

For the Imager the possible sub-modes are:

I0	Imager is off
I1	acquires the entire focal plane (filter L and M)
I2	acquires only the part of focal plane with filter M.
I3	acquires only the part of focal plane with filter L

Table 2: Operational modes for Imager

For the Spectrometer the possible sub-modes are:

S0	Spectrometer is off
S1	acquires the entire focal plane

S2	spectral binning over 4 pixels.
S3	spectral binning over 16 pixels.

Table 3: Operational modes for Spectrometer

S2 and S3, whose main characteristic is to reduce the required data volume, have been tested but never used in flight during any routine observations, as the allocated data volume has always been sufficient to meet the needs of the observing plan.

5.3.2 JIRAM Spacecraft Dynamics

A key step in planning the science observation is evaluating the duration of the acquisition. This involves utilizing Spacecraft Dynamics (SD), information provided by the spacecraft to its subsystems, which encodes attitude information. JIRAM receives SD every 2 seconds from the S/C, through the LSSL. The JIRAM instrument needs only three of the many parameters provided through SD for the correct start and duration of the acquisitions: the “Nadir Spin Phase Validity Flag”, the “Nadir Spin Phase” and the “Spin Rate”.

➤ Nadir Spin Phase Validity Flag:

Depending on this flag, JIRAM software will use either the real spin phase of the S/C or an internally calculated one for the acquisition start. If the spin phase is invalid, JIRAM software uses the last valid value received for the spin phase and estimates its current value through the actual spin rate and onboard time (refreshed every two seconds via Juno).

➤ Spin Rate:

It is used by JIRAM software to calculate the duration of each image acquisition cycle (the default is 30 seconds), and it is also used to calculate the exact time to start the acquisitions (for both off-nadir and nadir acquisitions).

➤ Nadir Spin Phase:

It is necessary to calculate the exact moment at which to start each acquisition. Knowledge of the “angular distance” to the nadir position and the time necessary to reach the nadir is necessary to correctly calculate the start time for each acquisition.

After booting JIRAM will wait for the first transition and begins to send HK data every 2 sec. If the S/C time, provided by Spacecraft Dynamics, is available in the first transition, JIRAM will use it; otherwise the instrument will use an internal time (starting from 0). As soon as the S/C time is recovered, JIRAM is automatically re-synchronized.

5.3.3 JIRAM Acquisition Description

During the Science Block, JIRAM executes two acquisitions during each S/C rotation and stores them in two buffers; the first acquisition is set to -180° (off-nadir) relative

596 to the direction to the target, the second is set to 0° (nadir) with respect to the target
597 direction (see Figure 13).

598

599 The acquisitions can be as follows:

- 600 • Background: in this case the scanning mirror points at the calibration lamps
601 that are switched off during the Science observation
- 602 • Readout Noise (RN)
- 603 • Dark: the scanning mirror points to the center of the field of view while
604 JIRAM looks at deep space.
- 605 • Nadir Observation: the observation is executed while the JIRAM FOV is
606 pointed at the target.

607

608 The observation mechanism is characterized as follows:

609

- 610 1. If the background repetition is set to a value ≥ 2 in the “JRM_TC_SCI_PAR”,
611 the acquisitions can be planned in two modes that can vary accordingly to the
612 background subtraction settings.

613 If the subtraction is enabled, JIRAM performs a first acquisition, background,
614 stored in Buffer_A and a second acquisition, RN, stored in Buffer_B. Then it
615 performs a subtraction between buffers A and B. Finally, JIRAM sends the
616 data to the hard partition to await transmission to the ground. Since this
617 particular acquisition is dedicated to the collection of the background, for the
618 sake of simplicity, we refer to it as First Acquisition (FA hereafter).

619 For the next set of rotations, until a new FA is acquired, JIRAM performs as a
620 first acquisition the background, stored in Buffer_A, and the target
621 observation, in Buffer_B; in this case, the subtraction is done between
622 Buffer_B and Buffer_A. This sequence is identified as Science Acquisition
623 (SA hereafter).

624 If the subtraction is disabled, JIRAM will perform always the two
625 observations but the subtraction between the buffers is not performed (see
626 Figure 16).

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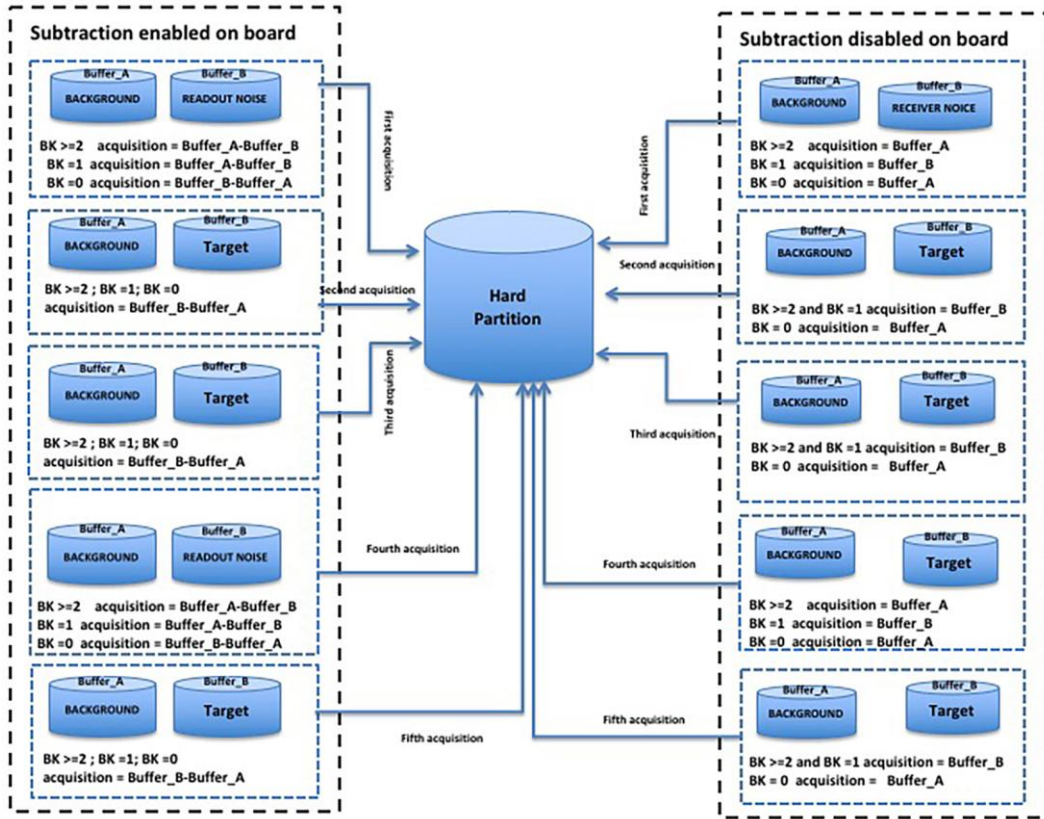


Figure 16: The acquisition dynamics for the possible case of the the background acquisition and in the cases where subtraction is disabled or enabled.

1. When the background repetition is set to a value of “0”, the background is not sent to the ground (no FA sequence); only science is performed (see Figure 16.)
2. If the background repetition is set to a value of “1”, there are no science acquisitions (no SA sequence); only background is sent to the ground (FA sequence) (see Figure 16).

5.3.4 JIRAM anomaly cases

Two anomalies may occur:

- 1) The S/C stops sending Spacecraft Dynamics information; in this case JIRAM uses the last ones received until the link with S/C is restored.
- 2) The Spacecraft Dynamics were never sent to JIRAM; this compromises the estimate of the spin rate of the S/C. In this case, JIRAM will perform a default science observation that consists of 120 acquisitions in mode I1_S3 (see table2 and 3) with an assumed duration of 30 sec per acquisition.

As of this writing, neither anomaly has occurred during operations.

653 Moreover, the acquisition duration can be set in order to disable the Spacecraft
654 Dynamics; in this situation, the S/C spin rate will be evaluated starting from values set
655 by the operator.

656 When the science TC starts, the first acquisition executed by JIRAM must be in
657 position “B” (see Figure 12); if JIRAM is in position “C”, this means that it has
658 already rotated beyond position “B”, so it is necessary to wait until the instrument
659 returns to position B.

660 The following equation calculates the duration of a generic Science block:

$$661 \text{ Science_Duration_Sec} = \text{Spin_Rate} * (N_{acq} + 1) + \text{Technical_Time} + \text{Tilt_Time} \quad (1)$$

662 Where:

663 $N_{acq} + 1$ = number of acquisitions, taking into account the most unfavorable case,
664 namely, that JIRAM is in position “C” (see Figure 13)

665 **Technical_Time** = the time necessary to perform the TCs when JIRAM is in
666 standby before going into science mode (see Figure 11)

667 **Tilt_Time** = $(N_{acq} - 1) * (\text{Spin_Rate} / 360^\circ) * \text{tilt}$ = the amount of time

668 required for the spacecraft to rotate from the nadir position to the planned observation
669 orientation

670 5.3.5 RADIATION BLOCKS

671 Radiation science is performed with a set of 3 images, one image for each science
672 block (see Figure 17) observing inside the instrument.

673 In particular, all of the acquisitions are commanded to following specifications:

- 674 ➤ one second of exposure time,
- 675 ➤ de-spinning mirror tilted into the instrument calibration source but with the
676 calibration source OFF (a completely dark frame, not looking out into deep
677 space),
- 678 ➤ acquired filter M and L, even if interest is only for filter L and for
679 spectrometer,
- 680 ➤ onboard RN subtraction,
- 681 ➤ no compression.

682

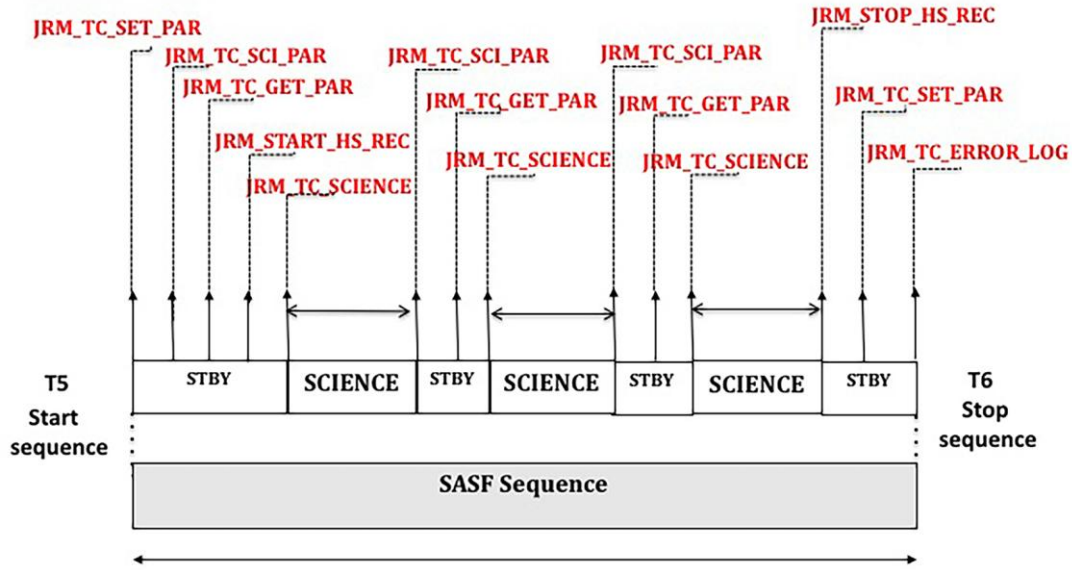


Figure 17: Science Radiation Sequence: JIRAM specifics and format.

6 DATA VOLUME ESTIMATION

During the planning phase, a key step is represented by the correct estimation of the data volume (DV) produced by the observations to avoid conflicts with other instruments or, in the worst case, the loss of scientific data.

It is necessary to consider the size of the instrument-specific Hard Partition (537 Mbit), where the data are stored during the observations, and the total storage capacity of the Soft Partition (4000 Mbit), where the data are transferred once JIRAM receives the TC “JRM_STOP_HS_REC” and where they remain until the downlink process occurs.

The formulas to estimate the DV are:

$$SCI_DV_bits = N_{acq} * 16 * \left[I \left(36 * N_p + \frac{pixels * 432}{I_Comp_Factor} \right) + S \left(36 * N_p + \frac{pixels * 336}{S_Comp_Factor} \right) \right] \quad (2)$$

$$CAL_DV_bits = N_{acq} * 6 * 16 * \left[I \left(36 * N_p + \frac{pixels * 432}{I_Comp_Factor} \right) + S \left(36 * N_p + \frac{pixels * 336}{S_Comp_Factor} \right) \right] \quad (3)$$

Where

I = 0 in operational mode I_0

I = 1 in operational mode I_1, I_2, I_3

S = 0 in operational mode S_0

S = 1 in operational mode S_1, S_2, S_3

N_{acq} : acquisition number

N_p = number of packets

$N_p = 3$ in operational mode I_2, I_3, S_2, S_3

716 $N_p = 6$ in operational mode I_1, S_1

717

718 pixels =

719 ➤ 256 in I_1, S_1

720 ➤ 128 in I_2, I_3

721 ➤ 64 in S_2

722 ➤ 16 in S_3

723

724 The data compression is possible in order to reduce the data volume. Lossy
725 compression is possible on imager data. The lossy compression reduces the images'
726 data volume by a factor of 6. Lossless compression can be applied to spectra. The
727 lossless compression would produce a compression of a variable factor that depends
728 on the data itself. The average value is about 1.5. During routine operations,
729 compression is disabled for both channels because, in practice, allocated data volume
730 has always been sufficient. In each activity, the instrument produces about 2 Gbits of
731 science packets and HK packets of 1824 bits in size; the activity cycle is expressed in
732 seconds and can be changed from the default value that is set to 10 sec.

733

734 **7 DISCUSSION**

735

736 Imaging Jupiter in the infrared from a spinning spacecraft immersed in the harsh
737 Jovian radiation environment is challenging at best. The JIRAM operations team has
738 developed and implemented a successful and robust operations strategy that has
739 allowed Juno to return infrared observations of the Jovian system of unprecedented
740 quality and detail. This strategy allows the team to construct observation timelines
741 that are robust to a 2.5% uncertainty in the spin rate of the spacecraft. This strategy
742 and the action of the despinning mirror are key to obtaining stable images and spectra.
743 It also allows the JIRAM team to incorporate radiation monitoring sequences into the
744 observation timeline. Software built by the JIRAM operations team allows the team
745 to plan future observation sequences, manage data volume and account for instrument
746 flight rules and generate detailed command sequences that are used to operate
747 JIRAM. It is these streamlined operations capabilities, in addition to the durability
748 and capability of the instrument itself, that will be needed to insure continued
749 successful operations at Jupiter.

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756 the US authors, NASA. A special thank you is for Leonardo S.p.A who assisted us
757 during these years. This paper is dedicated to the memory of Angioletta Coradini
758 (1946-2011), Principal Investigator of JIRAM, who passed away before she could see
759 the results achieved with JIRAM.

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Table

<i>Step</i>	<i>Phase</i>
#1	Internal Background
#2	Readout Noise
#3a	Cal Source Stabilization
#3b	Cal Source Gain 1
#4a	Cal Source Stabilization
#4b	Cal Source Gain 2
#5	Internal background
#6	Readout noise

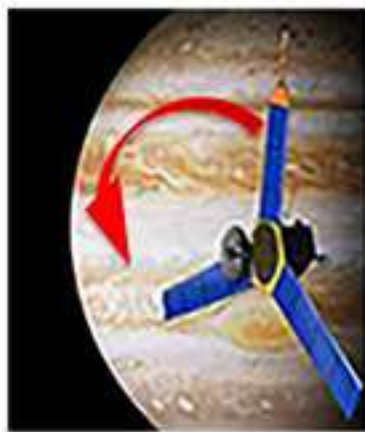
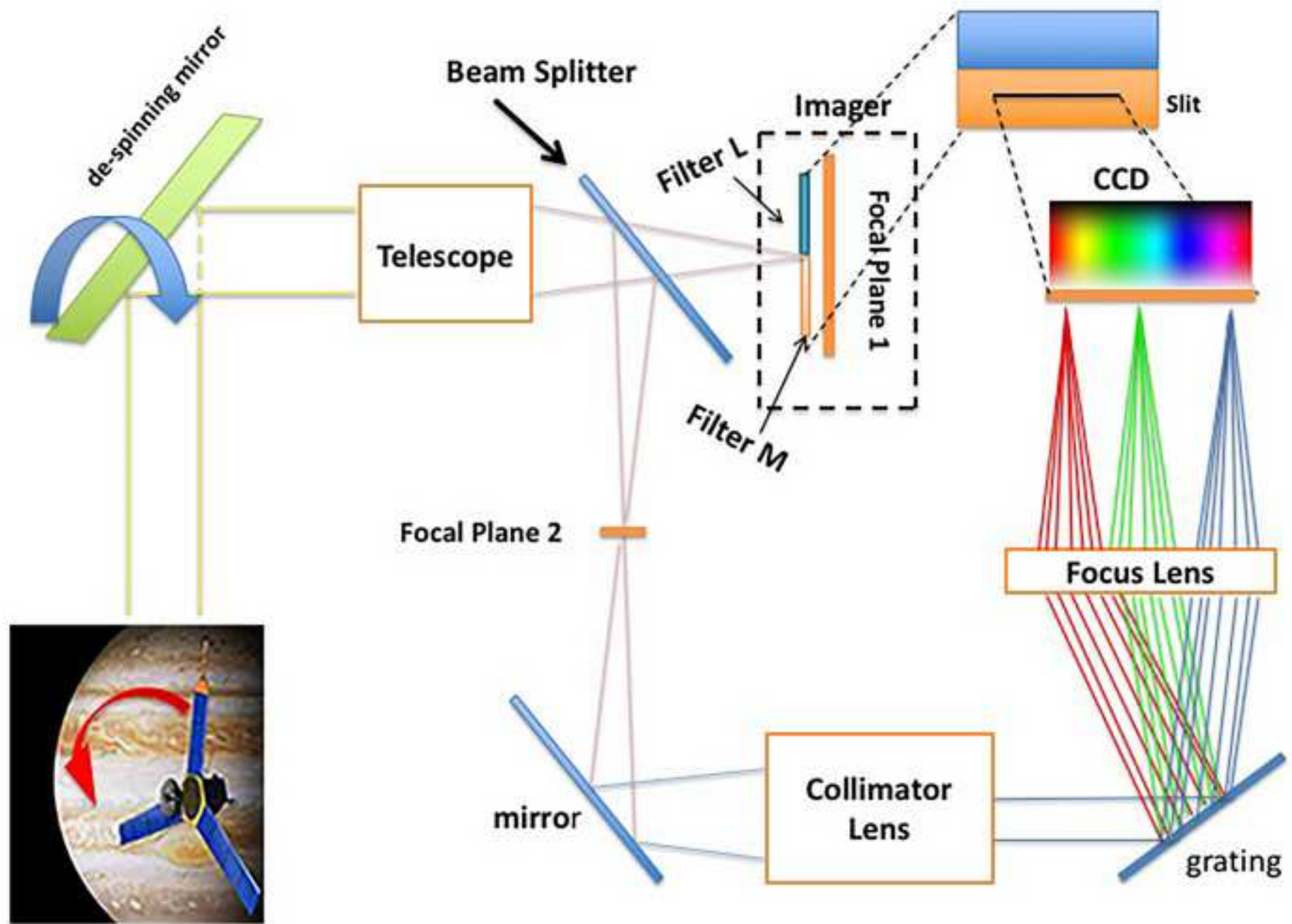
Table

I0	Imager is off
I1	acquires the entire focal plane (filter L and M)
I2	acquires only the part of focal plane with filter M.
I3	acquires only the part of focal plane with filter L

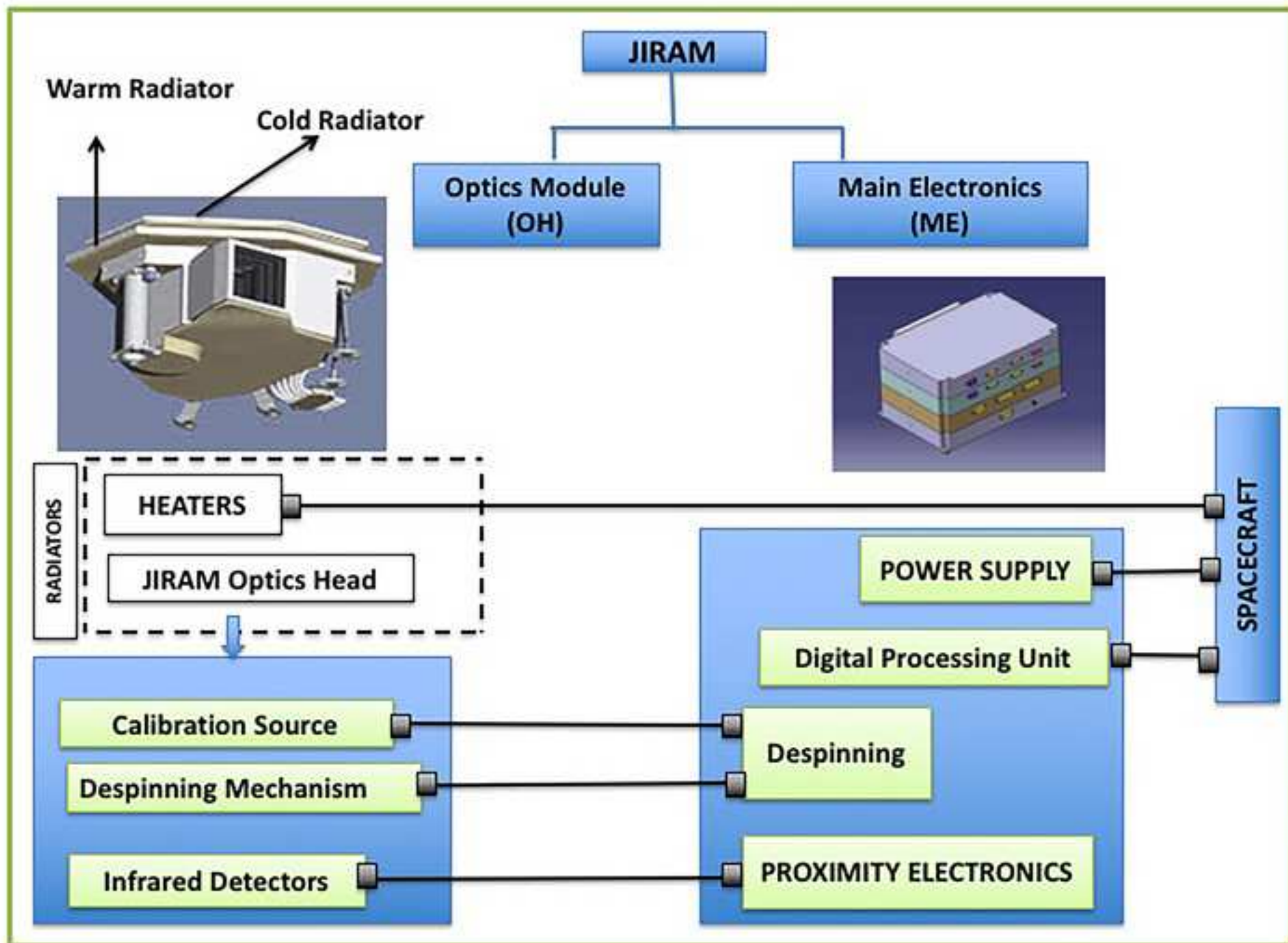
Table

S0	Spectrometer is off
S1	acquires the entire focal plane
S2	spectral binning over 4 pixels.
S3	spectral binning over 16 pixels.

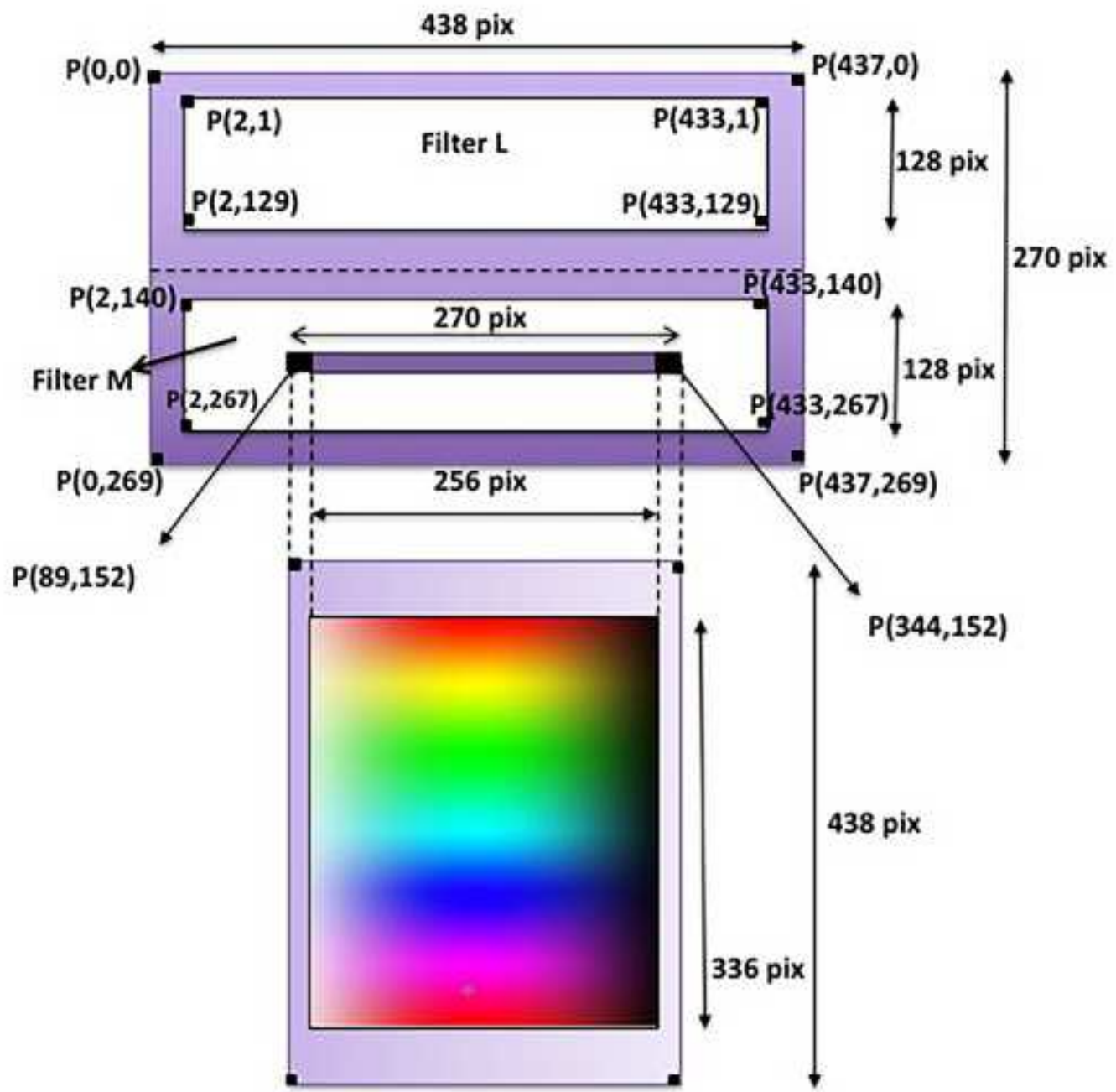
Figure



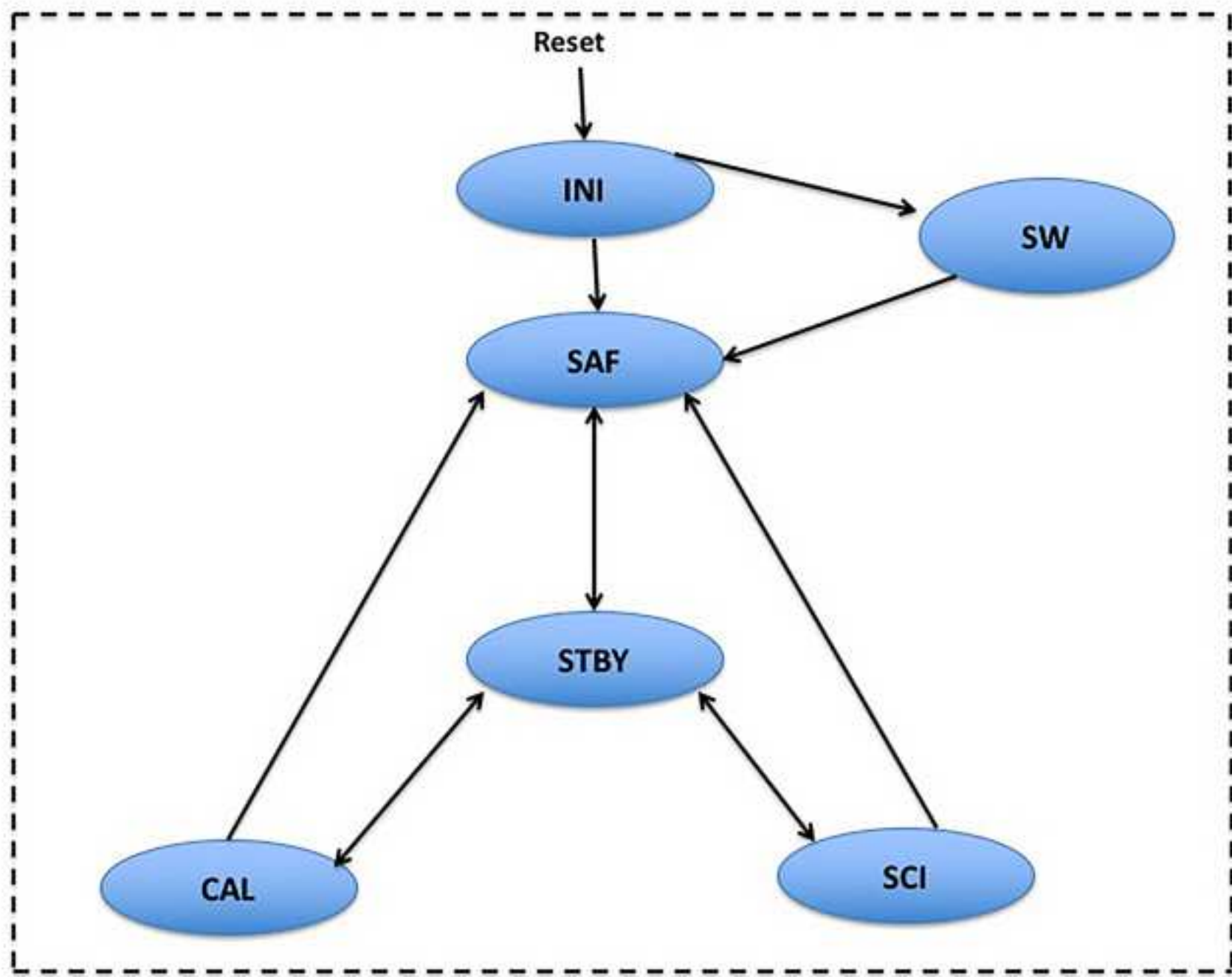
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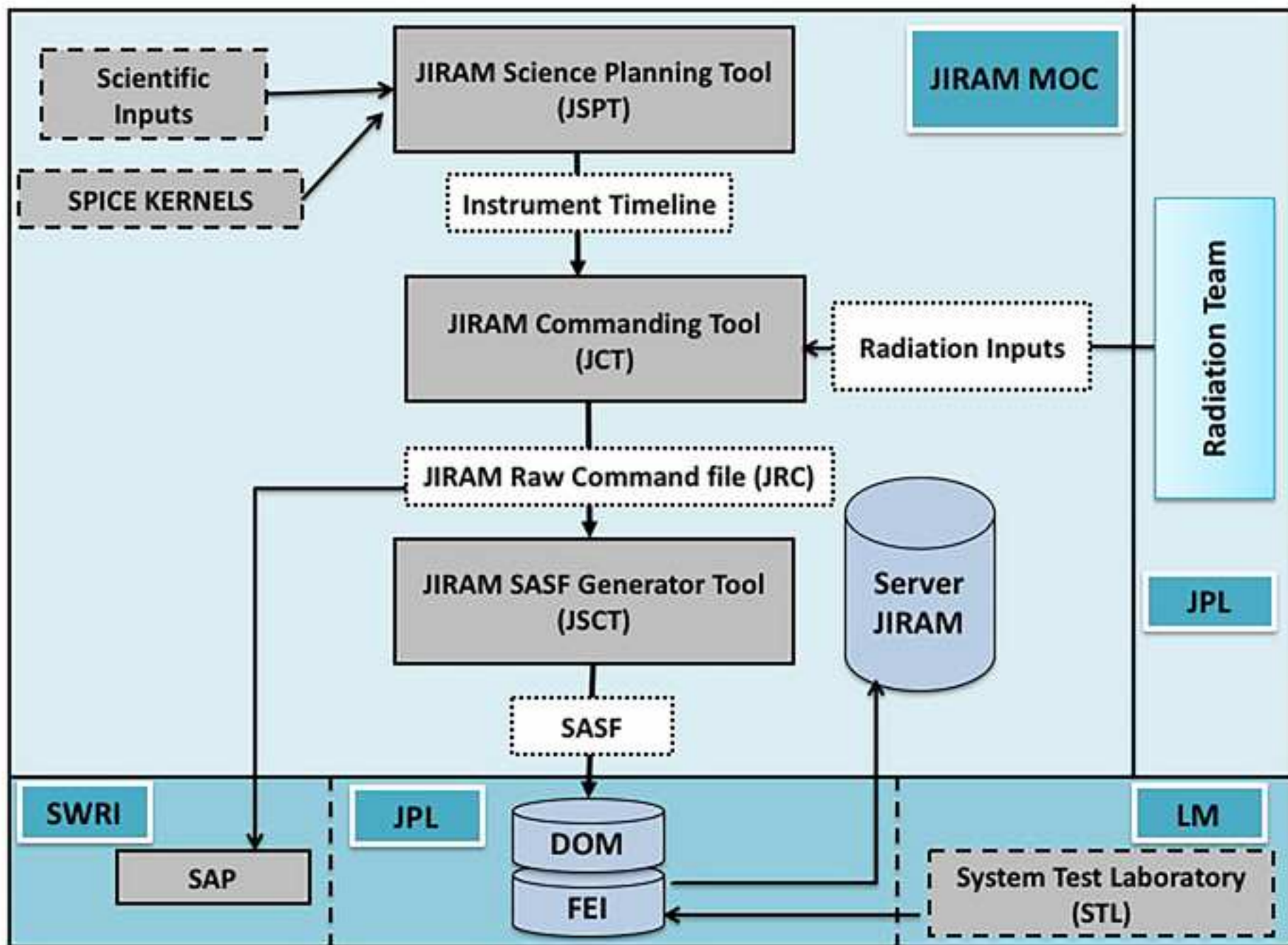
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Figure

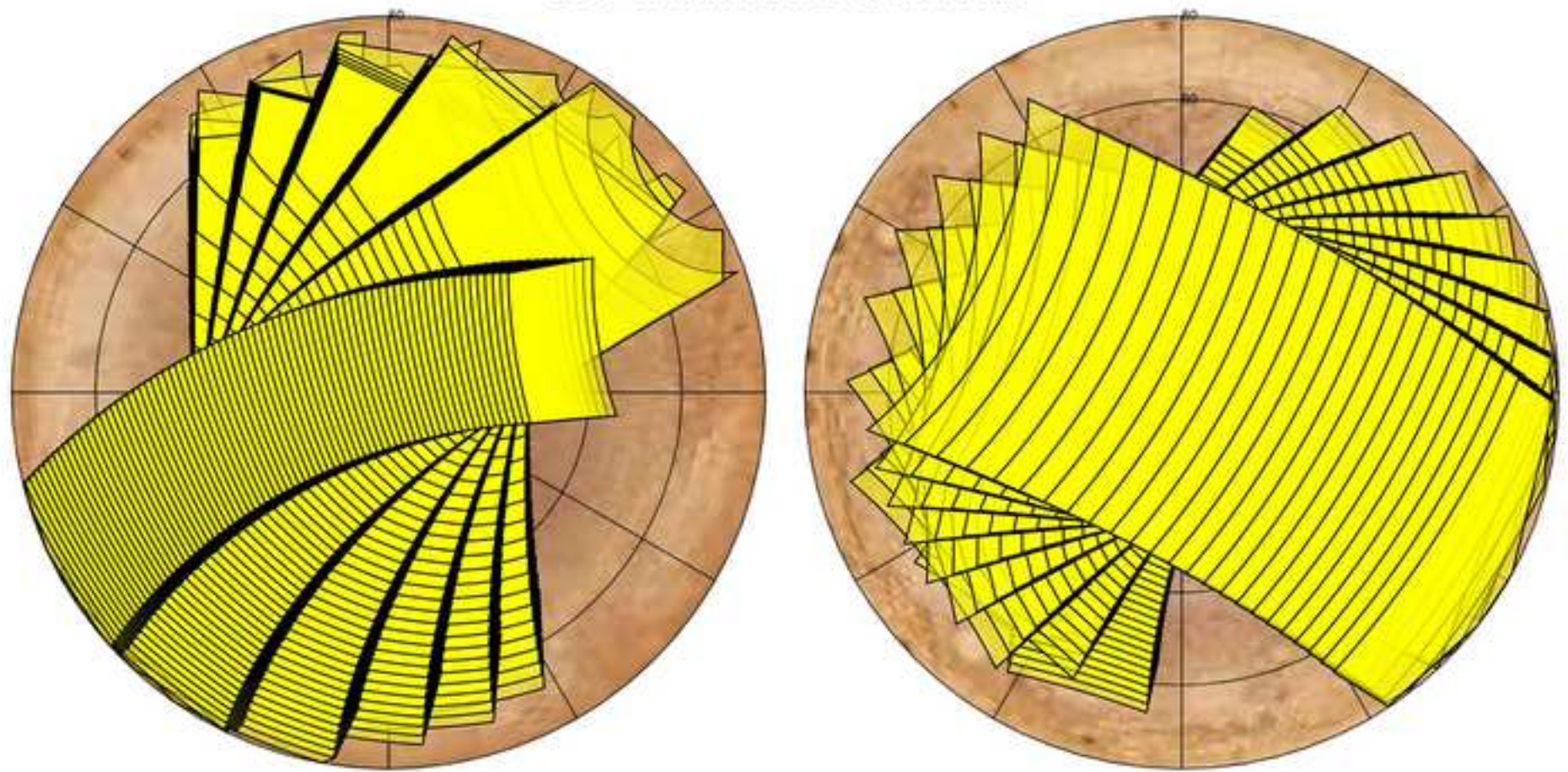


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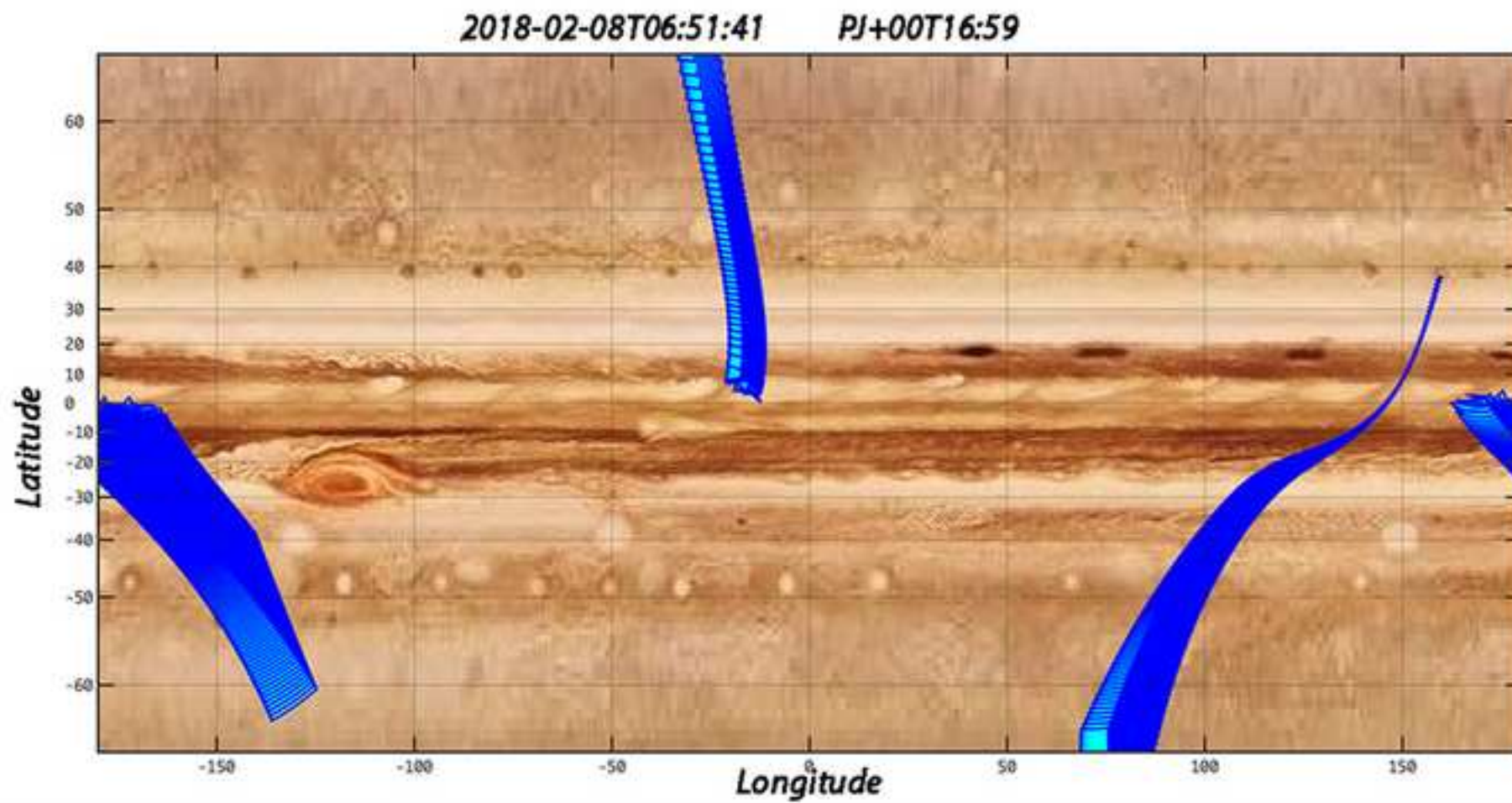


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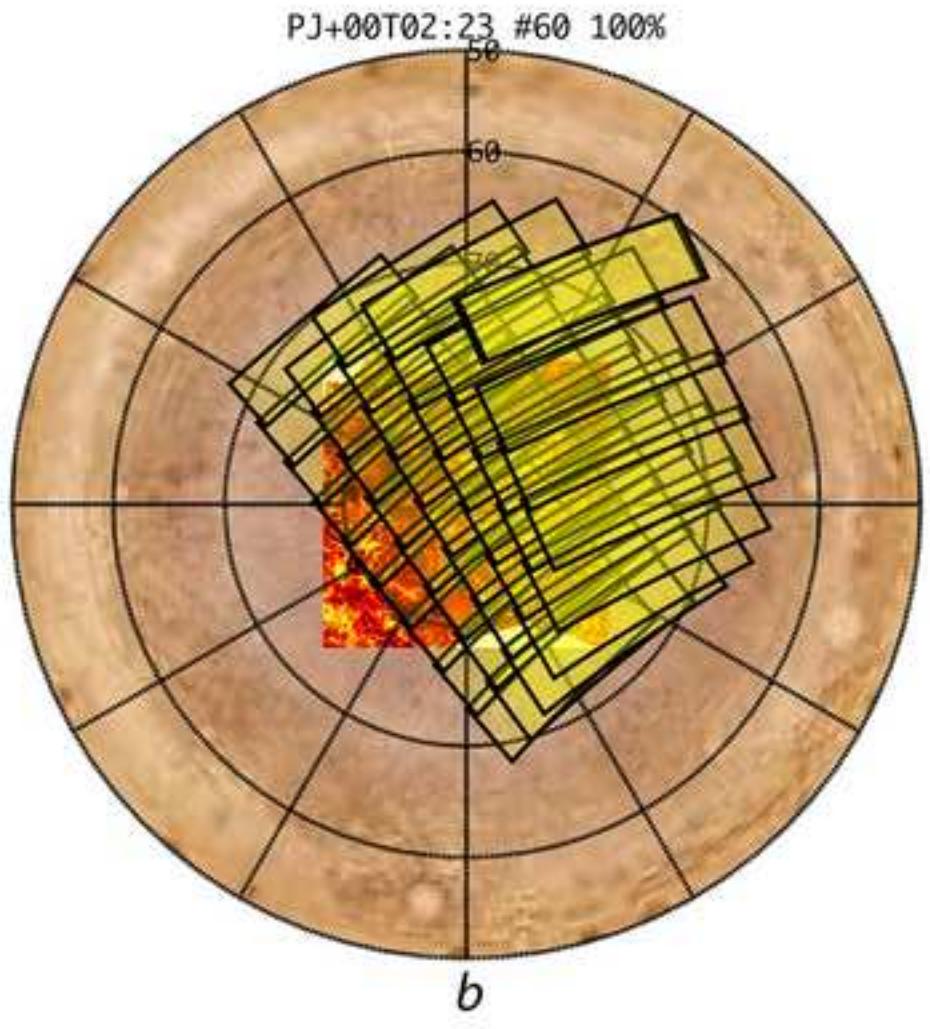
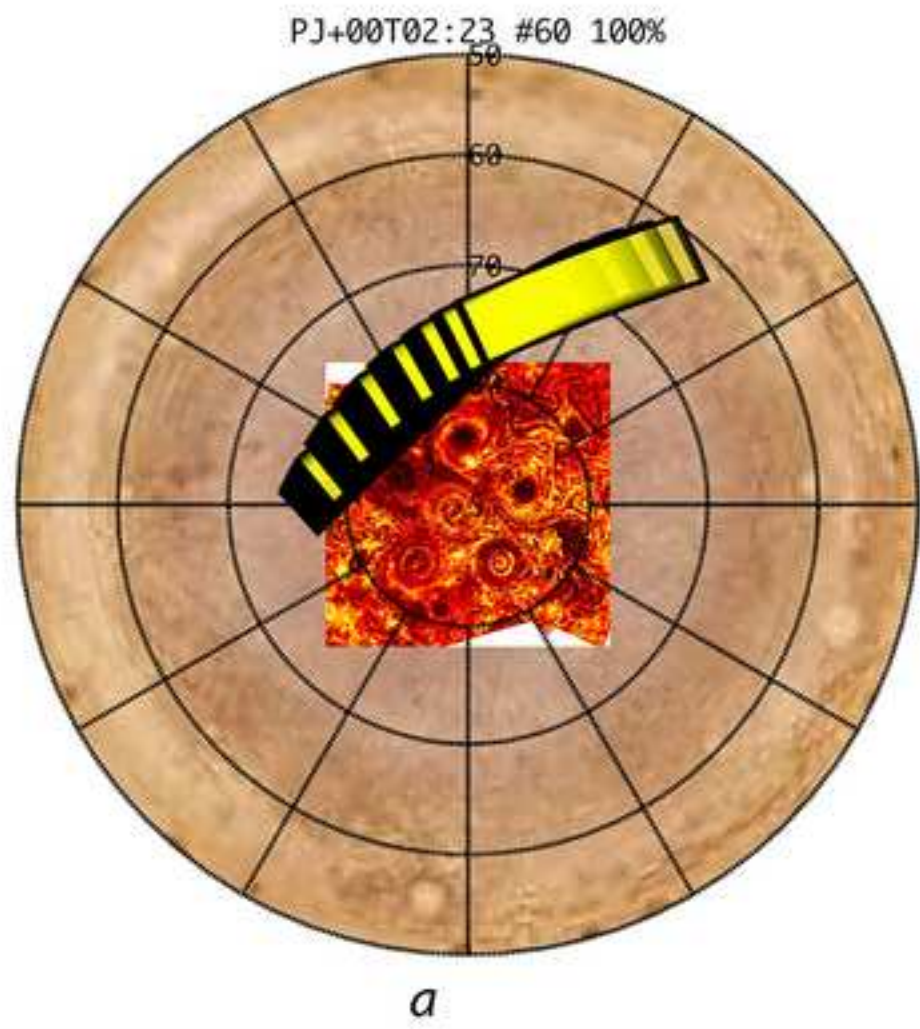
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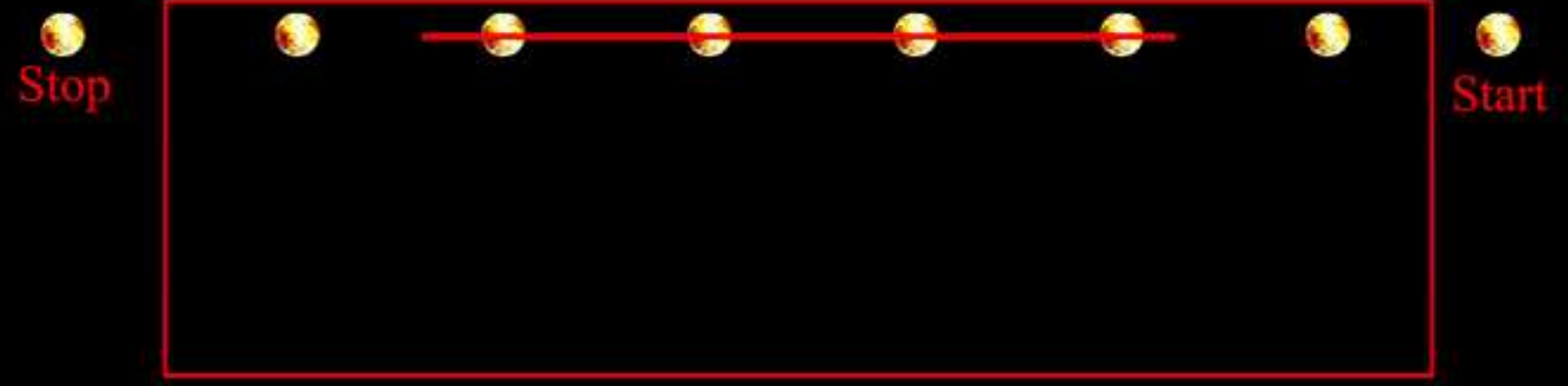
Figure



Figure



Ganymede: 2018-05-23 from 16:46 to 18:56

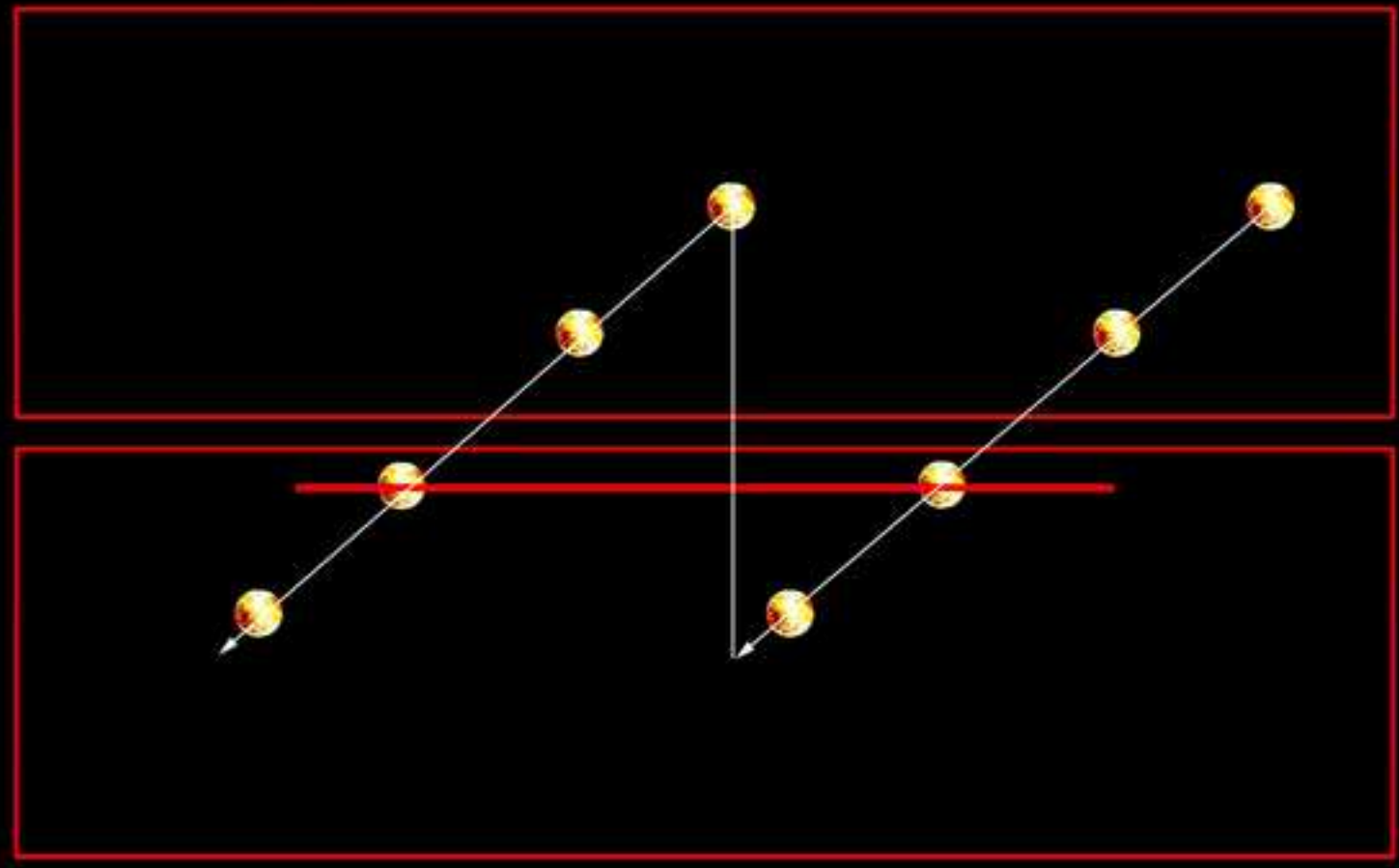


a

Ganymede: 2018-05-23 from 16:46 to 18:56

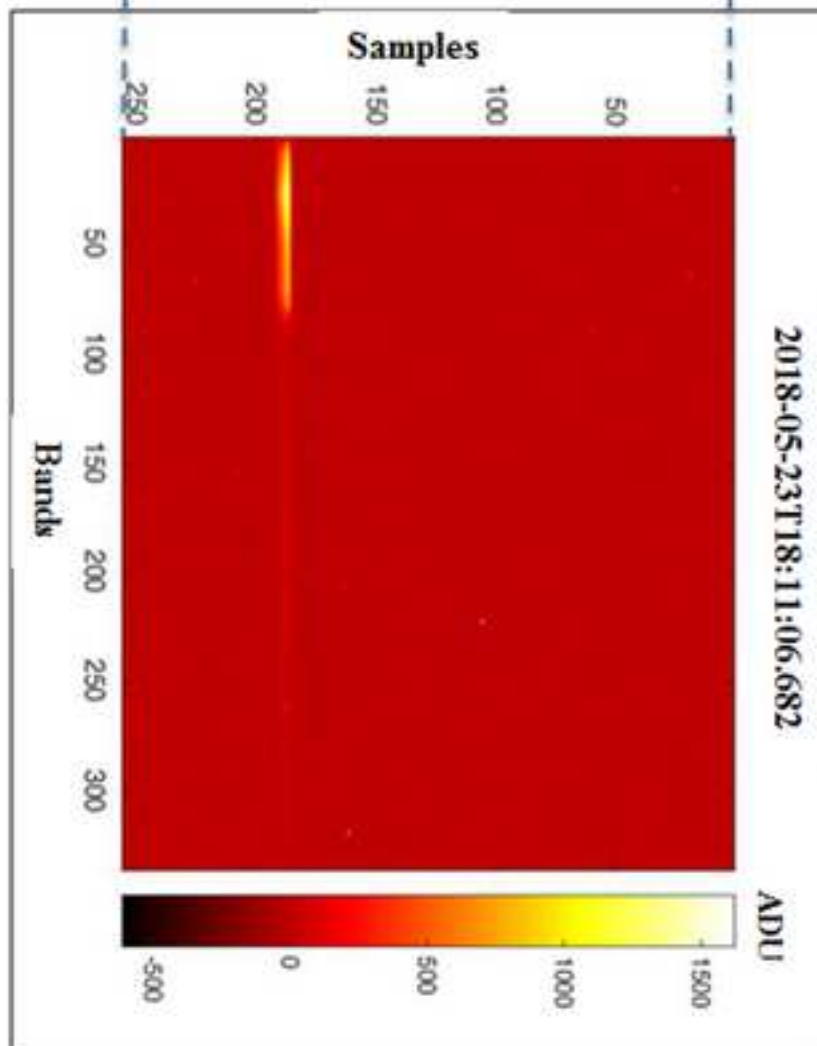
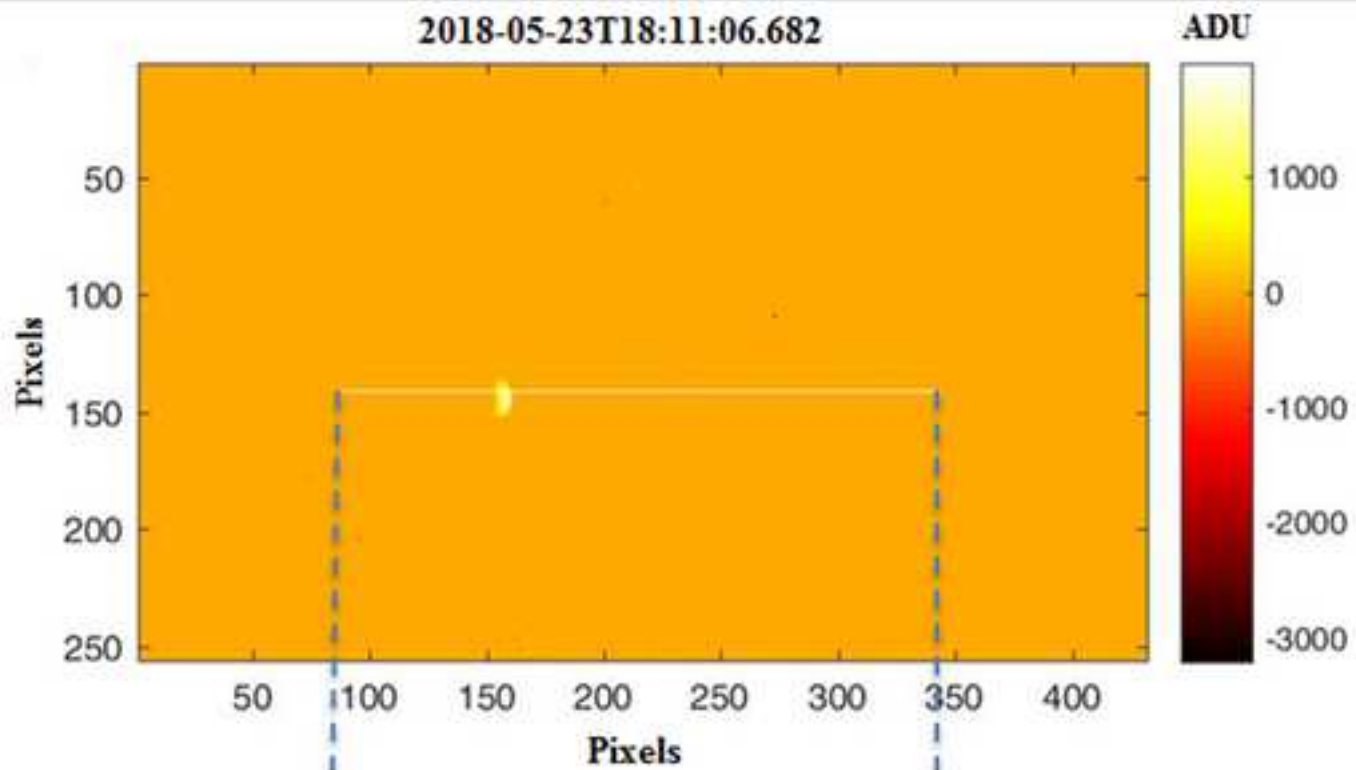
Stop

Start

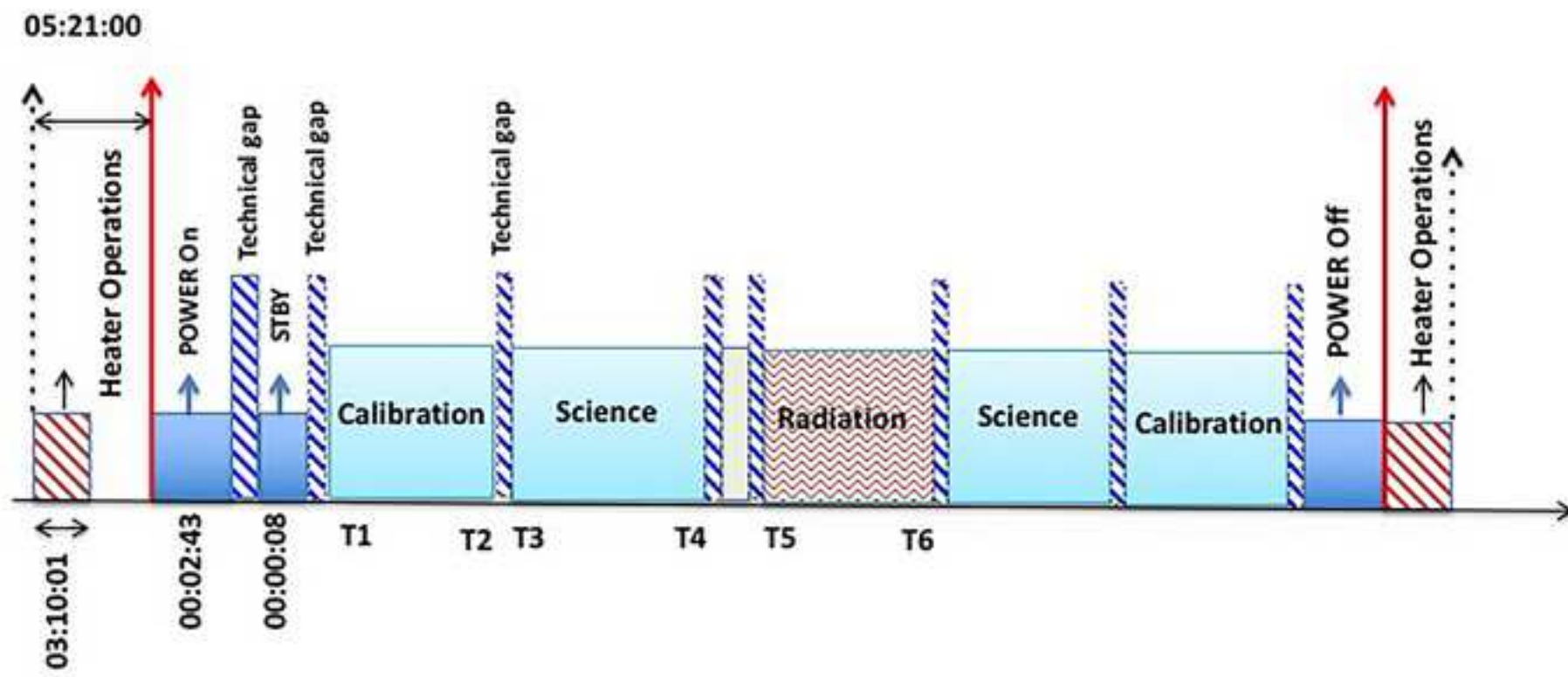


b

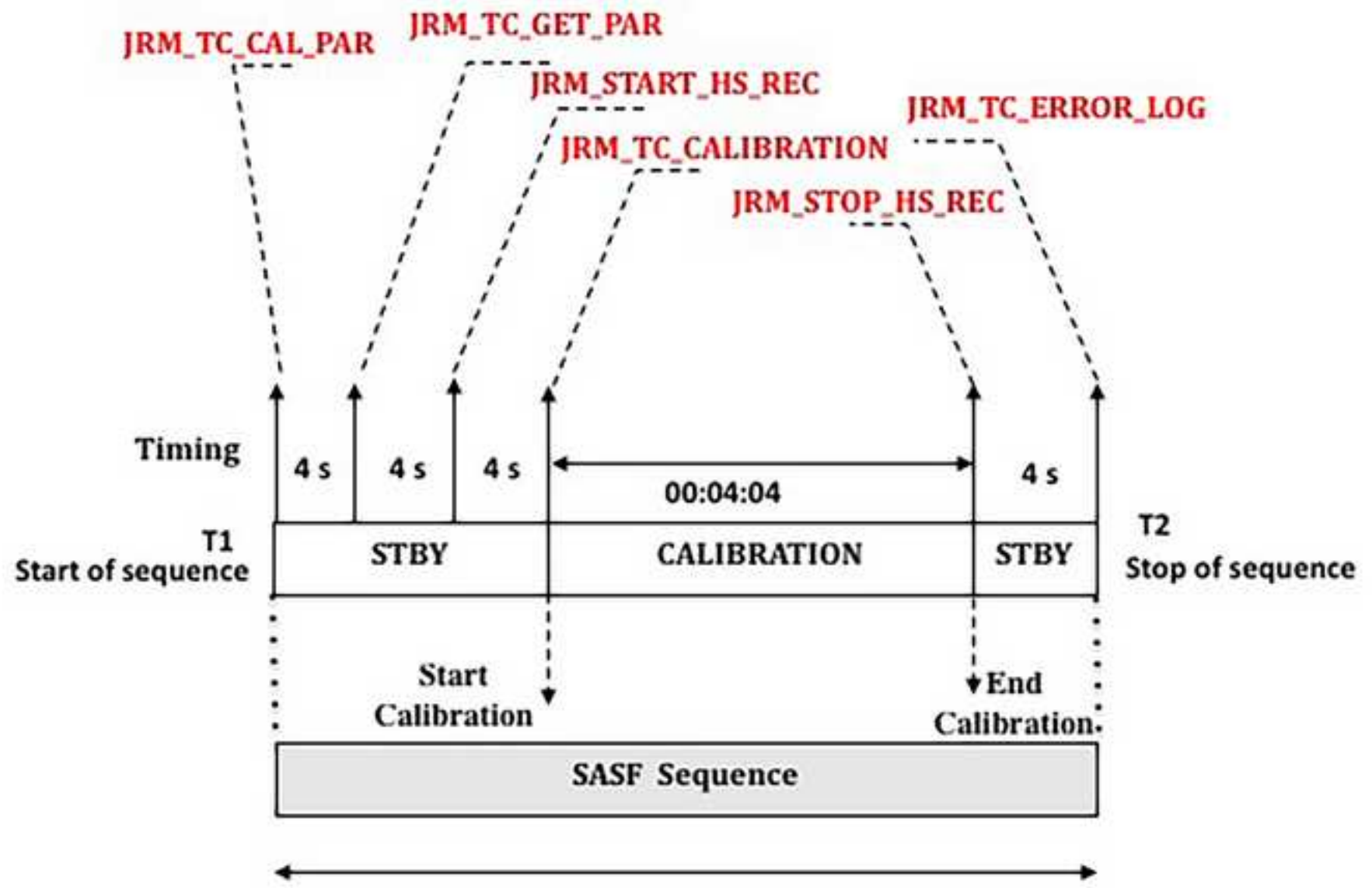
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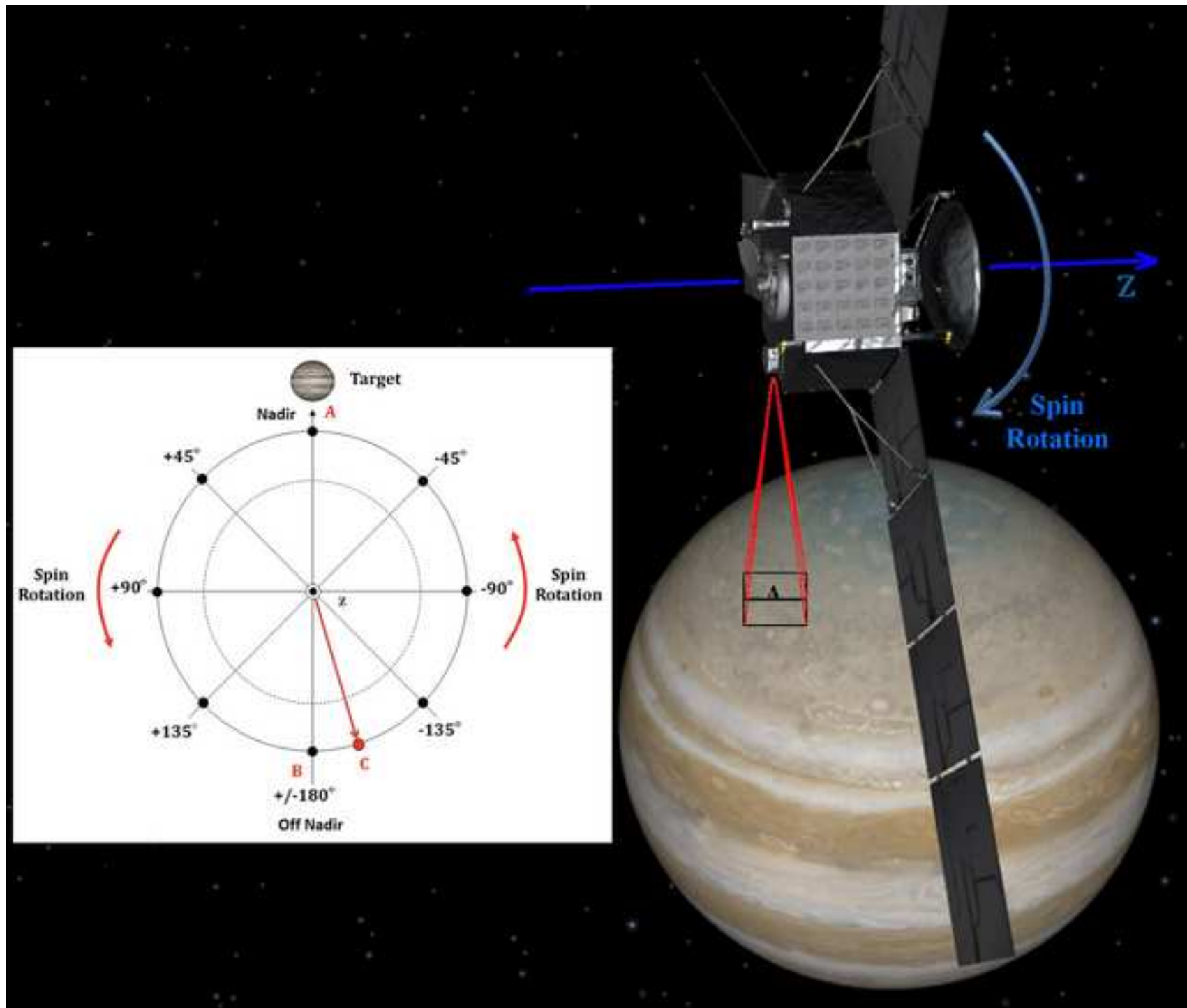
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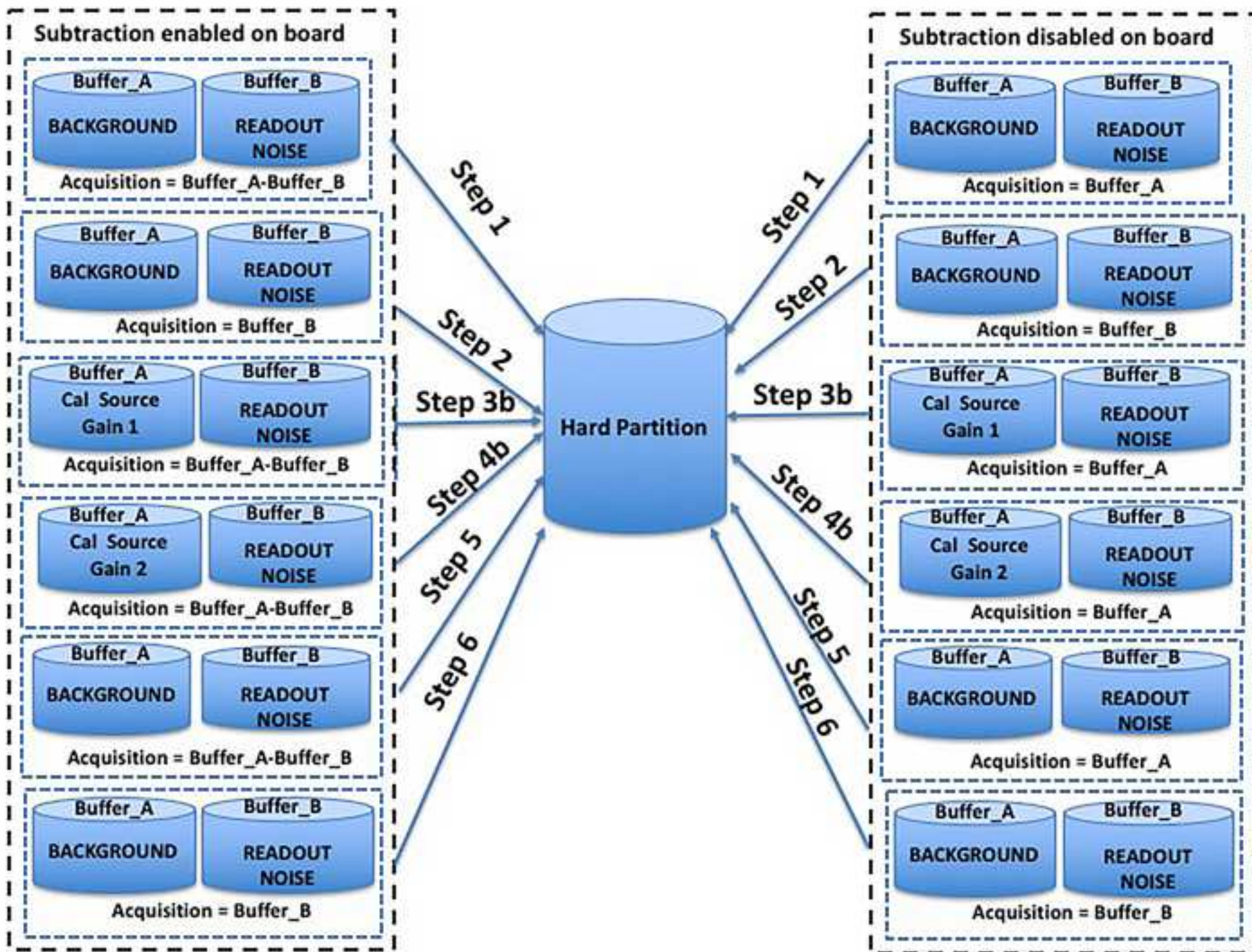
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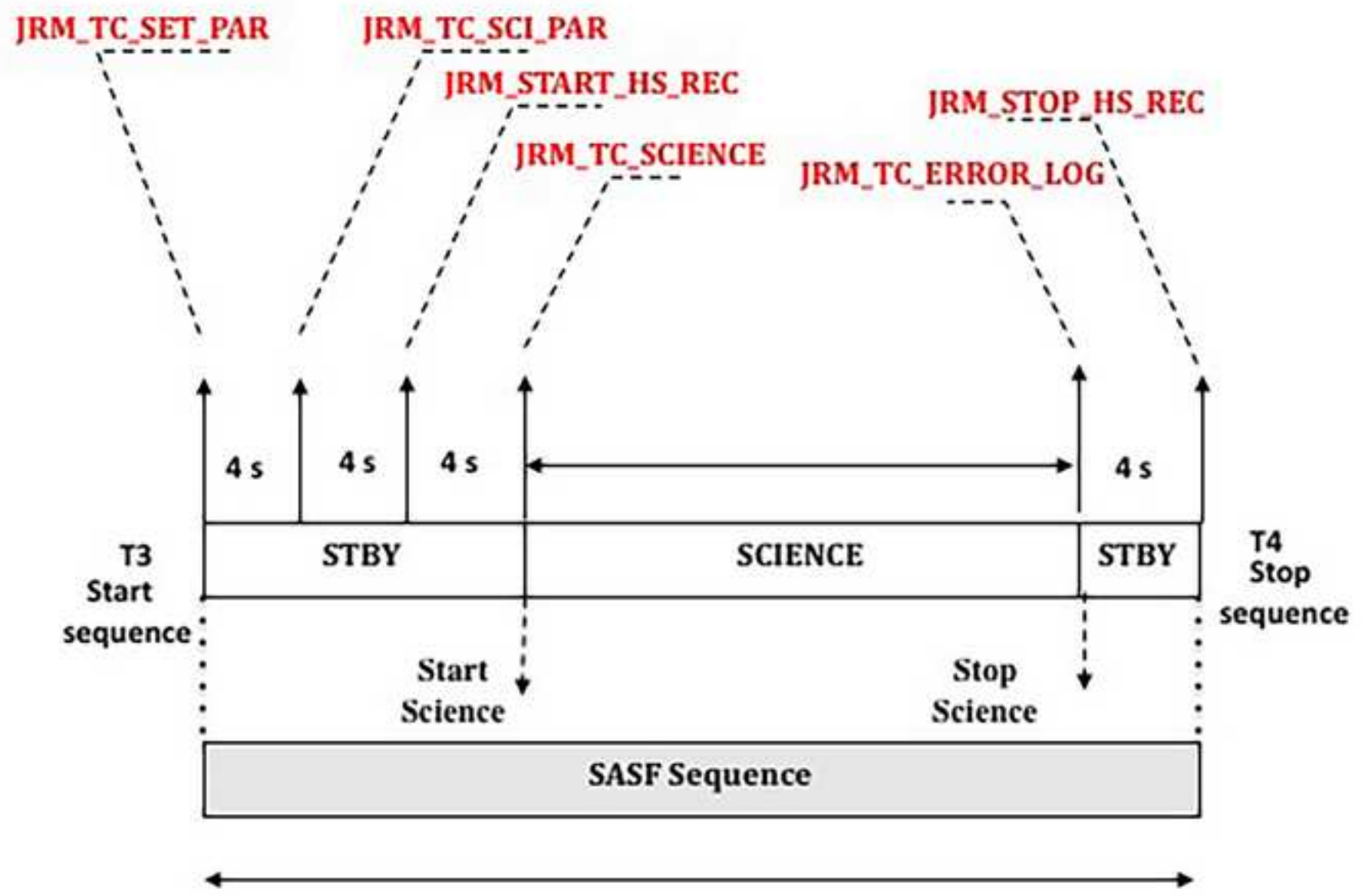
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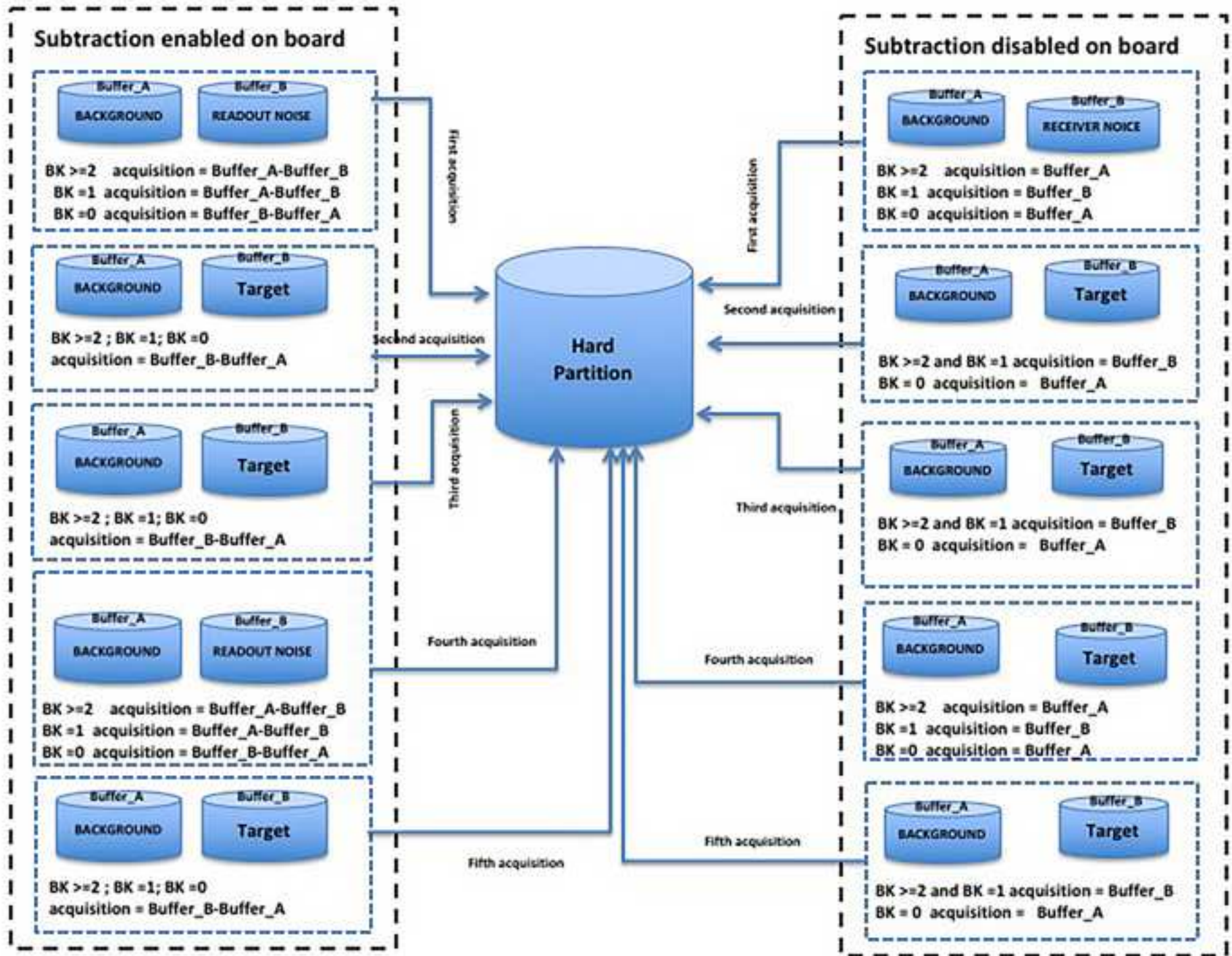
Figure



Figure



Figure



Highlights

- We describe in detail the activities of planning and commanding for JIRAM.
- We describe the observation strategy to construct robust observation timelines.
- We describe the timing of JIRAM science observation.