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JWST TECHNICAL REPORT

Title: Consistent Times and Repetition Factors in ETC and APT		Doc #: JWST-STScI-006013, SM-12 Date: 6 May 2021 Rev: A
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1 Abstract

Users must be able to equate ETC calculations with APT exposure specifications in order to plan successful science exposures. Consistent nomenclature between the ETC and APT enhances usability and reduces the effort required to address help desk calls. We define nomenclature for times and repetition factors in ETC and APT. This updated document includes revised versions of NIR and MIR equations for exposure, measurement, and saturation times, as well as the removal of outdated information.

2 Times

There are multiple ways to define time as a property of JWST observations. Generally, time is divided into two distinct categories, as defined by the JWST efficiency document (JWST-RPT-004166). 1) Exposure (or observing) time, which is "integration time on science and calibration targets" and 2) Observing overhead, which is the time spent on activities that "prevent, delay or interfere with observing time".

This document describes and defines exposure-related times and repetition factors that should be reported to observers by the Astronomer's Proposal Tool (APT) and the Exposure Time Calculator (ETC). The approach emphasizes simplicity over complexity and recognizes that the primary aim of reported times is to inform decisions made by observers to optimize the science output of proposed observations.

3 Repetition Factors

Repetition factors are integers that scale the time for one integration to times for exposures, dither pointings, or instrument specifications. Repetition factors reflect the nesting of operations during observation execution. Most observations defined in APT have the following nesting hierarchy:

- Targets in a target group
    - Tiles in a mosaic (for templates that allow mosaics)
        - Instrument configuration (filter, pupil, grating, etc.)
            - Dither points (primary x secondary points)
                - Exposures (set of integrations)
                    - Integrations (set of groups ending with destructive readout)
                        - Groups (onboard average of one or multiple frames)
                            - Frames (non-destructive single read of all pixels in a detector subarray)

Three templates with small apertures (MIRI Medium Resolution Spectroscopy, NIRSpec IFU Spectroscopy, NIRSpec Fixed Slit Spectroscopy) can all use target groups and use the special "filter first" nesting, which is meant to prevent overuse of limited-lifetime items such as the filter wheel mechanisms:

- Instrument configuration (filter, pupil, grating, etc.)
    - Targets in a target group
        - Tiles in a mosaic
            - Dither points
                - Exposures (set of integrations)
                    - Integrations (set of groups ending with destructive readout)
                        - Groups (onboard average of one or multiple frames)
                            - Frames (non-destructive single read of all pixels in a detector subarray)

These hierarchies become simpler when there is a single target, no mosaic, one exposure specification, no dithers, a single exposure for each exposure specification, and/or a single integration for each exposure.

An ETC calculation is implicitly for a single target, a single tile, and a single exposure specification.

4 Nomenclature

Below is the canonical nomenclature for times and repetition factors. All times have units of seconds. The exposure duty cycle and "X per Y" repetition factors are dimensionless.

The nomenclature for number of repetitions is of the form "X per Y" to make explicitly clear the domain (Y) to which the repetitions (X) applies. Failing to specify the domain leads to ambiguity and confusion. For greater clarity, one may include a "number of" optional prefix, yielding nomenclature of the form "number of X per Y".

"pixel-based time" – Category of times relevant to a single pixel. Measurement and saturation times are pixel-based times.

"array-based time" – Category of times relevant to a detector, or full array. This is also known as "first pixel to last pixel" times. The exposure time is an array-based time.

"exposure time" – The array-based time the detector is operating during a single expose command, including resets but excluding the initial synchronization time and other setup and cleanup. This time includes all integrations in an exposure, but no repetitions per pointing, per tile, or per observation. This is referred to as the "Exposing Duration" in APT. The "Exposure Duration" in APT is equal to the Exposing Duration plus the overhead time for setup and cleanup (e.g., synchronization time, script compilation time, filter wheel moves, end-of-visit overheads, etc.).

"total exposure time" – Total exposure time per specification. In this context a specification is one mosaic tile (for mosaics), one target (for target groups), one source (for MOS spectroscopy), or one observation (for other cases). Total exposure time is the product of exposure time, exposures per dither, and dithers per specification.

"measurement time" – The pixel-based time interval between the first and last reads of a pixel in an integration, multiplied by the number of integrations. This time is directly proportional to the number of incident photons. Here a measurement is a value used to determine the count rate. When a group is the average of multiple frames, the time for a pixel in that group is the average of read times for that pixel in the constituent frames. Measurement time is relevant for determining signal and photon noise in the ETC. This is referred to as the "Photon Collect Time" in APT.

"saturation time" – The pixel-based time interval following the reset of a pixel to the final read of that pixel in an integration. Any additional charge accumulation after the final read is irrelevant due to the reset of the detector at the end of the integration. This time depends only on exposure parameters, not target brightness or instrument throughput. The ETC must use this time (along with knowledge of the target and instrument) to assess and report whether saturation would affect the specified exposure.

"exposure duty cycle" – The pixel-based measurement time divided by the array-based exposure time. This ratio is a measure of the science efficiency within a single exposure. However, the term "efficiency" is explicitly avoided to prevent confusion with the observatory efficiency, which is the ratio between science time and charge duration, as currently reported by APT.

"groups per integration" – Number of groups downlinked to the ground for each integration. This quantity is an explicit parameter in the ETC and most APT templates. Where "groups per integration" is an implicit parameter, APT reports the number of groups. For example, in the NIRSpec BOTS template APT reports that target acquisition will use 3 groups.

"integrations per exposure" – Number of integrations per exposure. This quantity is a useful exposure parameter at the detector hardware level and hence an explicit parameter in the ETC and in many APT science templates. Where number of integrations is not an explicit parameter, APT implicitly sets integrations per exposure to 1.

"exposures per dither" – Number of exposures per distinct dither pointing on the sky for an exposure specification (APT). This quantity is an explicit parameter in some APT templates (e.g., "No. of Exposures" currently in the MIRI MRS template). Where "exposures per dither" is not an explicit parameter, APT implicitly sets exposures per dither to 1. The ETC presently has no explicit concept of "dither".

"dithers per specification" – Number of distinct dither pointings per instrument specification (e.g., filter, pupil, grating). For hierarchical dither patterns (e.g., NIRCam Imaging), "dithers per specification" is the number of primary dither pointings times the number of secondary dither pointings. **In the context of the ETC, a "specification" is one calculation with one instrument setup and one detector setup. In the context of APT, a "specification" is one**

exposure specification. For all mosaics (regardless of nesting order), the domain "per specification" is for one mosaic tile. For target groups, the domain "per specification" is for one target. For MSA spectroscopy, the domain "per specification" is for one source, perhaps observed in multiple MSA specifications. The ETC presently has no explicit concept of "dither".

"composite repetition factors" – Product of individual repetition factors. Valid composite repetition factors are "integrations per dither", "integrations per specification", and "exposures per specification". Because the ETC presently (version 1.6) has no explicit concept of "dither", the "Exposures" field in the ETC Detector Setup tab has an "Exposures" field that corresponds to exposures per specification. These composite repetition factors are useful in cases where individual repetition factors are implicitly set to 1. "Integrations per dither" is particularly useful for APT templates that do not allow multiple exposures per exposure specification.

"total integrations" – Preferred synonym for "integrations per specification".

"input parameter" – Within this document, an input parameter is a quantity that must be specified in order to evaluate total exposure time, measurement time, or saturation time. Depending on the context, users may be able to specify an input parameter or the value may be implicitly set to the only valid value.

5 APT-ETC workflow

The reported total exposure time is one of the key interfaces between APT and ETC. However, it is important to realize that the time interface is implicit. The user does not input a time directly into the ETC or APT. Instead, the following six input parameters fully specify a set of exposures on a source:

- Subarray
- Readout pattern
- Groups per integration
- Integrations per exposure
- Exposures per dither (referred to as "Exposures per specification" in ETC 1.6)
- Dithers per specification (unsupported in ETC 1.6)

Depending on the context, some input parameters may be set implicitly by a tool, or may be combined into a composite repetition factor (e.g., "Exposures per specification" in the ETC).

The ETC and APT provide the following two output quantities for easy comparison:

- **Total exposure time**
- **Total integrations**

Users are advised to check that the reported "Total exposure time" and "Total integrations" are identical in both the APT and ETC.

In an **ETC-first workflow**, users use the ETC to determine an exposure specification that achieves the signal-to-noise ratio needed to accomplish the science goal of a proposal. Then the user manually copies the exposure specification parameters into APT. Some of the exposure parameters are explicitly specified in an APT template (such as the readout pattern, number of groups per integration, and number of integrations per exposure). Others are derived from template parameters (for instance, total integrations).

In an **APT-first workflow**, users use APT to craft a practical observing program. Then the user manually copies the exposure specification parameters into the ETC.

Unfortunately, both workflows are subject to confusion and transcription error; the more realistic approach is to iterate between the two tools. Recent PPS versions include consistent presentation of output parameters in both tools, accompanied by good documentation, to mitigate these issues. Any remaining consistency issues are minor.

6 Purpose of Revision A

Revisions to this document were required to address multiple timing equation issues:

1. *Overly simplified MIRI exposure and measurement times*. The equations in sections 7.1.2 and 7.2.2 have been generalized to account for resets between integrations.
2. *A MIRI measurement time inconsistent with the pipeline for handling of rejected groups when* $n_{groups} < 5$. Additional information has been added for proper handling of short integration ramps in section 7.2.2, as well as breaking up the number of rejected groups into two variables: $n_{pre-reject}$ and $n_{post-reject}$.
3. *Removal of* T_{fffr} *from some NIR equations*. The T_{fffr} variable has been removed from this equation in section 7.3.1 because the fast, full-frame reset occurs prior to the subarray reset, and therefore charge does not accumulate during this time. The T_{fffr} variable was also removed from the equation in section 8.1 for the case of $n_{groups} = 1$ for the same reason.
4. *Updating the "Very Bright Regime" equations for* $n_{groups} = 1$. The equations presented in section 8 are now applicable only for the special case of $n_{groups} = 1$. Previously, this section contained MIRI equations applicable to $n_{groups} < 5$; cases where $n_{groups} > 2$ are now covered in section 7.2.2.

7 Time formulae

This section lists the formulae to be used by APT and ETC to calculate the exposure and measurement times for both the near-infrared and mid-infrared detectors.

7.1 Exposure time

7.1.1 H2RG detectors (NIRCam, NIRSpec and NIRISS)

A general formula for exposure time will be used, as defined in equation 1.4 in JWST-HDBK-015429. The fully generalized formula does have parameters that may never change between detectors and exposure specification, but implementing them all from the beginning may decrease the risk of having to modify the formula later. The complete exposure formula for the H2RG detectors is reproduced below.

$$T_{exposure} = T_{fffr} n_{ints} + T_{frame}\left[n_{resetframes1} + (n_{ints} - 1) n_{resetframes2} + n_{ints}\left(n_{dropframes1} + (n_{groups} - 1)(n_{frames} + n_{dropframes2}) + n_{frames} + n_{dropframes3}\right)\right] \quad (1)$$

where:

T_{fffr} = configurable additional time for the fast row-by-row reset of pixels outside the subarray, which occurs at the end of every integration when an H2RG detector is in subarray mode (this is always zero for full-frame exposures). Note: The T_{fffr} value depends on ASIC configuration, which can be different for each instrument and subarray.

n_{ints} = number of integrations in exposure

T_{frame} = frame time (amount of time between two successive samples of the same pixel in an integration)

$n_{resetframes1}$ = number of reset frames at the beginning of the exposure

$n_{resetframes2}$ = number of reset frames between integrations

$n_{dropframes1}$ = number of dropped frames between the reset at the beginning of each integration and the first read frame

$n_{dropframes2}$ = number of dropped frames between groups (formerly $n_{groupgap}$)

$n_{dropframes3}$ = number of dropped frames after the last group in each integration

n_{groups} = number of groups in one integration

n_{frames} = number of frames that are averaged together to form a group

A "dropped frame" is a frame where photons are collected on-sky but is not saved onboard the spacecraft in order to avoid exceeding data storage limits. These frames may still contribute to the exposure and measurement times, depending on their position along an integration ramp.

7.1.2 Si:As detectors (MIRI)

For practical purposes, the most generalized version of the MIRI exposure time is identical to the NIR exposure time in Eq. (1), with the same variable definitions. However, a handful of the variables in the NIR equation are not applicable to MIRI (MIRI DFM-478). There is no concept of a fast, full-frame reset at the start of an integration (this is practically handled by setting $T_{fffr} = 0$) and there are no dropped frames between the reset and the first read frame ($n_{dropframes1} = 0$), no dropped frames between groups ($n_{dropframes2} = 0$), and no dropped frames at the end of an integration ($n_{dropframes3} = 0$). (In the future, any handling of dropped frames would be controlled by ISIM.) There are currently no resets at the start of an exposure ($n_{resetframes1} = 0$), though this term is accounted for in MIRI DFM-478 should it be added in the future. These simplifications reduce Eq. (1) to:

$$T_{exposure} = T_{frame}[(n_{ints} - 1)n_{resetframes2} + n_{ints}n_{groups}n_{frames}] \quad (2)$$

Should additional complexity be added to the MIRI readout patterns or integrations in the future, the necessary terms from Eq. (1) should be set to non-zero values, and Eq. (2) would be correspondingly more complex.

Note that, for MIRI the frame time depends on both the selected subarray and readout pattern. Rejecting one or more frames during data processing affects measurement time, but not exposure time (see Eq. (5) in Section 7.2.2).

7.2 Measurement time

7.2.1 H2RG detectors (NIRCam, NIRSpec and NIRISS)

The H2RG measurement time is:

$$T_{measurement} = n_{ints}T_{frame}[(n_{groups} - 1)(n_{frames} + n_{dropframes2})] \quad (3)$$

At present, NIRCam is the only NIR instrument that makes use of "frame0," which is where the first frame of the integration (when $n_{frames} > 1$) is saved separately from the first group average. This does not change the exposure time.

Use of frame0 is not currently implemented in the ETC or APT, so the equation below is presented only for potential future implementation in conjunction with other subsystems:

$$T_{measurement} = n_{ints} T_{frame} \left[\left(n_{groups} - 1 \right) \left(n_{frames} + n_{dropframes2} \right) \right] + 0.5 n_{ints} T_{frame} \left(n_{frames} - 1 \right) \quad (4)$$

7.2.2 Si:As detectors (MIRI)

The calibration pipeline does not use all the groups in its processing due to unrecoverable detector effects for all non-target acquisition exposures with MIRI. The number of rejected groups varies with the number of groups in the integration and is equal to the sum of $n_{pre-reject}$ (number of rejected groups at the start of an integration) and $n_{post-reject}$ (number of rejected groups at the end of an integration). The last group is rejected ($n_{post-reject} = 1$) when $n_{groups} > 2$ and the first group is rejected ($n_{pre-reject} = 1$) when $n_{groups} > 3$.

Additionally, $n_{frames} = 1$ and for all MIRI exposures $n_{dropframes2} = 0$.

For MIRI target acquisition exposures, n_{frames} can vary. Also, in target acquisition, only the last group is rejected ($n_{pre-reject} = 0$), and it is always rejected ($n_{post-reject} = 1$).

For convenience, these rules are summarized in the table below:

Term	Non-target acquisition	Target acquisition
n_{frames}	1	1, 4, 8, 16, 32, 64
$n_{dropframes2}$	0	0
$n_{pre-reject}$	1 (when $n_{groups} > 3$)	0
$n_{post-reject}$	1 (when $n_{groups} > 2$)	1

The measurement time for the MIRI detectors for all cases then becomes:

$$T_{measurement} = n_{ints} T_{frame} n_{frames} \left(n_{groups} - 1 - n_{pre-reject} - n_{post-reject} \right) \quad (5)$$

For MIRI target acquisition exposures n_{frames} can vary. Also, in target acquisition only the last group is rejected and it is always rejected ($n_{post-reject} = 1$).

7.3 Saturation time

The time interval following the reset of a pixel to the final sample of that pixel in an integration. Any additional charge accumulation after the final sample is irrelevant due to the reset of the detector at the end of the integration. This time depends only on exposure parameters, not target brightness or instrument throughput. The ETC can use this time along with knowledge of the target and instrument to assess whether saturation would affect the specified exposure.

7.3.1 H2RG detectors (NIRCam, NIRSpec and NIRISS)

For the NIR detectors the last group does not have any drop frames. So, the saturation time is:

$$T_{saturation} = T_{frame} \left(n_{dropframes1} + \left(n_{groups} - 1 \right) \left(n_{frames} + n_{dropframes2} \right) + n_{frames} \right) \quad (6)$$

7.3.2 Si:As detectors (MIRI)

For the MIR detectors $n_{dropframes1} = n_{dropframes2} = 0$, so Eq. (6) reduces to:

$$T_{saturation} = n_{groups} n_{frames} T_{frame} \quad (7)$$

Note that for all non-target acquisition MIRI exposures, $n_{frames} = 1$.

8 Measurement time for $n_{groups} = 1$

When observing bright sources using only 1 group (currently an option only for NIR instruments), the measurement time equations are different as these observations require the use of a bias frame to provide a slope measurement. The larger noise for bias frames is not an issue as the photon noise is the dominant source of noise for such bright sources. The H2RG exposure time formula is not changed in this situation. Currently (PPS 14.14/ETC 1.6), neither the ETC web application nor the Pandeia engine support $n_{groups} = 1$ for any instrument.

Note: The equations below also apply to any pixel for which saturation occurs in the second group, regardless of the length of the integration ramp.

8.1 H2RG detectors (NIRCam, NIRSpec and NIRISS)

For exposures with $n_{groups} = 1$ and $n_{frames} = 1$:

$$T_{measurement} = n_{ints} n_{frames} T_{frame} \quad (8)$$

All $n_{groups} = 1$ integrations are likely to have $n_{frames} = 1$, due to the brightness of the target, but it is possible that this is not always the case. The additional term in Eq. (9) is only added to the first term when $n_{frames} > 1$:

$$T_{measurement} = n_{ints} n_{frames} T_{frame} - 0.5 n_{ints} T_{frame} (n_{frames} - 1) \quad (9)$$

8.2 Si:As detectors (MIRI)

The MIRI measurement time equations for $n_{groups} = 1$ with $n_{frames} = 1$ and $n_{frames} > 1$ are identical to Eq. (8) and Eq. (9), respectively. At present, only MIRI target acquisition readout patterns have $n_{frames} > 1$.

9 Conclusions

This document has defined a complete prescription for the times that may be reported to the users of the APT and ETC for all currently supported options, as well as defining consistent nomenclature for the reported quantities.

10 References

Observation Efficiency Allocations Report, Rev. H, JWST-RPT-004166

JWST NIRSpec Detector Subsystem Flight User's Manual, JWST-HDBK-015429, Rev. T

MIRI FPS Exposure Time Calculations (SCE FPGA2), MIRI DFM-478, M. Ressler