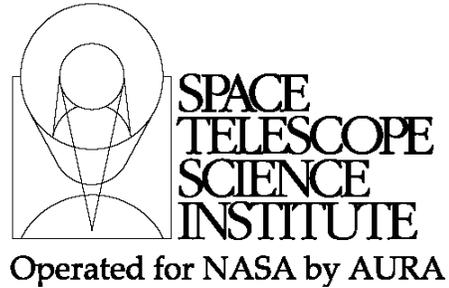




TECHNICAL REPORT



Title: Coronagraphic Operations Concepts and Super-Template Definition for the Astronomer's Proposal Tool	Doc #: JWST-STScI-004141, SM-12 Date: October 27, 2014 Rev: -
Authors: Rémi Soummer, Phone: 410 W. Blair, D. Golimowski, 338-4737 D. Hines, C. Lajoie, M. Perrin, L. Pueyo, J. Stansberry, G. Rieke, M. Rieke, C. Beichman, J. Krist, and the Coronagraphs WG	Release Date: 19 June 2015

NOTE: The coronagraphic super-template discussed in this report is not currently a baselined capability of the JWST S&OC although it is under consideration to be implemented for observing cycle 2.

1 Abstract

This report describes the general operations concepts for coronagraphy, and how they translate into needs for the Astronomer's Proposal Tool (APT). Coronagraphic observations are typically very complex, and the Coronagraphs Working Group (CWG) recommends the implementation of both instrument-level templates and of a higher-level "super-template". This approach accommodates the basic needs for the majority of users and science cases, while preserving sufficient flexibility for customization to accommodate particular science cases. Current unknowns about the observatory performance also motivate this approach, including slew accuracy and thermal temporal evolution, which impact target acquisition (TA), wavefront error, and coronagraphic Point Spread Function (PSF). The overall coronagraphic operations concepts are described in the series of technical reports, of which this is the second. Because of the complexity of the coronagraphic observation concepts these documents will be subject to revision as the development and concepts evolve.

- [TR1] Science Use-Cases for the Preparation of Coronagraphic Operations Concepts and policies JWST-STScI-004140
- [TR2] Coronagraphic Operations Concepts and Super-Template Definition for the Astronomer's Proposal Tool (this report) JWST-STScI-004141
- [TR3] Comparative study of the efficiency of various coronagraphic observations strategies JWST-STScI-004165

Operated by the Association of Universities for Research in Astronomy, Inc., for the National Aeronautics and Space Administration under Contract NAS5-03127

- [TR4] Coronagraphic Exposure Time Calculation JWST-STScI-003862
- [TR5] Coronagraphic Astrometric and Photometric Calibrations JWST-STScI-004166
- [TR6] A Point Spread Functions Library for Coronagraphy JWST-STScI-004167
- [TR7] Coronagraphic pipeline architecture, data products JWST-STScI-004169
- [TR8] Coronagraphic pipeline algorithms JWST-STScI- 004170
- [TR9] Small-Grid Dithers for Coronagraphic Observations JWST-STScI-004142 and JWST-STScI-004172
- [TR10] Coronagraphic policies JWST-STScI-004171

2 Coronagraphic Operations Concept

The Coronagraphs Working Group (CWG) has established a list of coronagraphic science use-cases to guide the definition and development of the coronagraphic operations [TR1]. The use-cases document is intended to provide the foundation for the discussion in the present report and the two reports should be read together.

In order to enable these science use-cases, coronagraphic operations concepts typically include a combination of on-target coronagraphic observations, telescope rolls, and coronagraphic observations of PSF reference stars. Data post-processing is also an integral part of the operations concepts since the subtraction of a reference PSF from the target image is required to reach high-contrast images [TR7, TR8]. Therefore, particular attention is paid to ensure that coronagraphic proposals include adequate reference PSFs [TR10]. In addition, data processing can take considerable advantage of additional reference PSFs from a library [TR6], so this is also taken into account in the definition of the operations concept and templates.

For a given coronagraph/filter combination, the *basic coronagraphic sequence* includes an observation of the "science target" followed by a telescope roll with a second observation of the science target, and then a coronagraphic observation of a PSF reference star. Variants of this *basic coronagraphic sequence* are possible depending on the science use-case. For example, observers may select multiple roll orientations or multiple filters/mask combinations in the case of a survey-type program [TR1]. Based on the careful analysis of the science use-cases, the CWG has constructed a simple set of rules to define the "standard use of coronagraph modes". Additional flexibility can be achieved for expert users or unforeseen applications using the proposed template implementation however such programs would require the submission of additional justification to be evaluated by the Time Allocation Committee (TAC) [TR10].

2.1 Telescope rolls

Unlike HST, JWST has limited roll capability at a given time- 10 deg total (+/- 5 deg off nominal)- but larger rolls can be obtained between different epochs depending on the target position on the sky. Telescope rolls are particularly useful in coronagraphy and they have three applications:

Check with the JWST SOCCER Database at: <https://soccer.stsci.edu>

To verify that this is the current version.

i) Angular Differential Imaging (ADI) aka “*roll deconvolution*” whereby the rolled target observation is used as a self-reference for PSF subtraction. In this case the roll angle must be sufficient to prevent self-subtraction of astrophysical targets of interest (e.g. for point source, the rotation must move the point source by at least one PSF FWHM). This technique is wavelength-dependent (longer wavelengths are associated with larger inner working angles (IWA)). For MIRI at 10.65 micron, a rotation of one λ/D , i.e., the minimum separation to avoid self-subtraction of a point source, is obtained for an IWA of 1.9 arcsec with the typical ± 5 deg roll. At 15.5 microns, this IWA becomes 2.8 arcsec. For all science observations at separations below this IWA, the rolled science target can no be used as a self-reference in PSF subtraction unless the second observation is taken at a roll difference greater than 10 deg (and, therefore, at a significantly later epoch).

ii) Pixel-dithering by rotation of the PSF provides better sampling and increased robustness to detector defects or artifacts. This technique is effective if the astrophysical target is moved by at least one pixel on the detector between rolls. The roll angle required is solely dependent on the pixel size. The IWA corresponding to a rotation by one pixel is 0.6 arcsec for MIRI and 0.4 arcsec, and 0.2 arcsec for the NIRCcam long and short wavelength channels, respectively. For most applications the roll-dither effect improve the data quality; therefore, we recommend that users include the 10 deg roll as part of the default strategy.

iii) Moving astrophysical targets of interest off of PSF structures (e.g. diffraction spikes, or axes of the 4QPM masks) between the two orients. This applies to both disks and planets. This typically requires rolls larger than 10 deg and therefore an observation at a later date. This strategy implicitly provides the pixel-dithering described above.

2.2 Small-Grid Dithers

An additional option [TR9] is a grid of small dithers under fine guidance (e.g. 3x3 dither points each separated by ~ 5 -20 mas). Typically, Target Acquisition is required for each science target, reference star, and after a telescope roll. However, small dithers under fine guidance provide the opportunity to finely sample the PSF without target acquisition. The small-grid dither option is applied after target acquisition to enhance the performance using advanced optimization algorithms commonly used in the community (least-squares or principal component analysis [TR7,8]). The small-grid dithers may be applied to both the target and/or the reference, but for now the CWG recommends implementation only for the reference PSF star.

The small-grid dither is completely optional to enhance the performance. Since this technique is expensive (it multiplies the number of reference PSFs), we expect that the observer will only request this feature when it is scientifically justified. However, since the very small slews under fine guidance have negligible overhead by themselves (few seconds for the slew itself), it will be possible in some cases to select a brighter reference star to minimize the overall “cost” of the program. This is particularly true for MIRI 4QPMs, which are the most sensitive to alignment differences and which will benefit the most from this option. Fortunately, the stellar colors are not strongly dependent on spectral type at the MIRI 4QPM wavelengths therefore reference stars can have a slightly different spectral types from their science targets, which should facilitate finding brighter

Check with the JWST SOCCER Database at: <https://soccer.stsci.edu>

To verify that this is the current version.

reference stars.

2.3 Reference PSFs and PSF library

The coronagraphic pipeline [TR7,8] will provide advanced PSF subtraction algorithms (LOCI, KLIP) to facilitate the interpretation of coronagraphic data. These algorithms leverage large PSF libraries [TR6] that are constructed from observations of reference PSFs from many different coronagraphic programs, as well as PSF observations obtained using a small grid of dithers. For this reason, the CWG recommends a policy to encourage observing reference PSFs. The standard observing template should require the definition of reference PSFs within a program and a scientific justification if the observer chooses not to include them [TR10]. The CWG has identified several use-cases where it is acceptable to not obtain reference PSFs (e.g. in the case of a survey where each star serves both as a target and reference for the other ones).

In order to promote the development of a PSF library to the benefit of the community, the CWG recommends a policy to make reference PSFs public immediately [TR10]. The observer may request a proprietary status for the reference PSFs (e.g. in the case of a survey where each star also serves as reference for the other ones). This request should be included in the proposal and evaluated by the TAC [TR10].

2.4 Time-critical scheduling (back-to-back observations)

Since coronagraphy is very sensitive to changes in the coronagraphic PSF generated by changes in the wavefront, all coronagraphic sequences must be scheduled in a non-interruptible manner. No interruptions (e.g. wavefront sensing activities, momentum management, other observations, etc.) are exempt from this rule. Some programs may be able to accommodate some short interrupts to help with scheduling, e.g. if they only require moderate contrast for particular applications. We defer a study describing the mechanisms for identifying such programs to later time.

3 APT coronagraphic templates description

3.1 Terminology / concepts

For the definition of the terms *Coronagraphic sequence*, *Coronagraphic Suite*, *Coronagraphic Template Form*, *Coronagraphic Super-Template Form*, *Small-Grid dither*, and *Reference PSF library*, see [TR1].

3.2 Template and super-template forms

There will be a single coronagraphic template form per instrument (i.e. one for NIRcam and one for MIRI), which will be used for both science and reference targets. A coronagraphic sequence will typically invoke the instrument-level templates several times. For example, the *basic coronagraphic sequence* includes one instance of template for the target, a second for the target at a different roll orientation, and a third for the reference star.

The observer will use a super-template to assemble each coronagraphic suite in the proposal and organize them into hierarchical containers (suites/sequences/observations), and pre-populate all of the special requirements (e.g. roll orientation or scheduling

constraints). A proposal may contain several coronagraphic suites in addition to ancillary observations that are not part of the coronagraphic templates or super-templates (e.g. a NIRSpec spectrum).

The basic functionality of the super-template is to add (or remove) coronagraphic sequences to assemble a coronagraphic suite, as illustrated in Figure 1. The default coronagraphic sequence is the basic coronagraphic sequence (target, 10 deg roll i.e. +/- 5 deg from nominal, reference), but the super-template allows for customization: i.e. by removing the reference, the +/- 5 deg roll, adding other rolls, adding a small grid dither, or an astrometric calibration. One particular advantage of the super-template implementation is to generate all necessary observations and associated special requirements. This is particularly important for example when multiple filters or instruments are used (see [TR3]) Based on preliminary discussions with the APT team, the preferred implementation for the super-template is a dynamic tool (the *dynamic super-template*), where the information remains dynamically synchronized between the super-template and the instrument-level template. Such a tool would allow users to generate observations using the super-template form, edit the instrument-templates, and then modify the super-template (e.g. adding or removing a target, or filters). The alternate implementation of the super-template is the “*super-template wizard*”, which is called only once to generate the observations. In this case, the user must manually edit the instrument-level templates and special requirements once the observations have been generated because it is not possible to come back to the super-template form. The main drawback to the wizard implementation is that the user may have to regenerate the observations from scratch if some modifications have to be made (e.g. adding or removing a coronagraphic filter). The wizard is an acceptable first implementation of the super-template, however the software development should aim for full implementation of the dynamic super-template.

Since users may specify a standard or a non-standard use of the JWST coronagraphs, the super-template must be able to detect non-standard uses of the coronagraphs and issue appropriate warnings requiring additional justification to submit the proposal [TR10]. This conservative approach guarantees that coronagraphic programs will be properly designed, while preserving flexibility for the large variety of science programs that are possible with the JWST coronagraphs [TR1]. A fully manual mode should be possible by directly editing the APT observations and special requirements. Submission of a proposal with manually generated observations should also require additional justification [TR10]. APT should consider the following as standard observations:

- A coronagraphic suite assembled from *basic coronagraphic sequences*
- For any science target, the coronagraphic sequence should include at least one default +/- 5 deg roll from nominal, or at least one larger roll.
- Self-referenced suites (checkbox selected) corresponding to survey-type programs where some reference PSFs are skipped. This strategy is effective if there are at least 10 targets in the survey, and therefore a minimum of 10 reference PSFs¹.

¹ This rule might be adjusted once actual data from cycle 1 have been analyzed.

- Shared-reference suites (checkbox selected), corresponding to types of surveys where a single reference can be used for a group of target that can be scheduled together, or when the goal is moderate contrast (e.g. T-Tauri stars). This rule is effective if the targets are within 5-deg^2 of each other.

The documentation will provide detailed guidelines about specific use cases for telescope rolls, reference stars, and/or small-dither grids; in particular, it will describe how each observing strategy will impact the final contrast performance and which strategies should be used for typical science cases.

² This rule acts as a placeholder to represent potential schedulability.

Check with the JWST SOCCER Database at: <https://soccer.stsci.edu>

To verify that this is the current version.

4 Implementation notes

4.1 Mockup interface example

Coronagraphic Suite _____

Science Target	Reference PSF	+/-5 deg roll	Astrometric Calibration	MIRI SGD	NIRCam SGD
target#1	PSF#1	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
target#2	PSF#2	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
target#3	PSF#3	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
target#4	PSF#4	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

- self-referenced suite
 shared-referenced suite

NIRCam Options _____

▼ NIRCam	
<input type="checkbox"/>	MASK210R / F210M
<input type="checkbox"/>	MASKSWB / F140M
<input checked="" type="checkbox"/>	MASK335R / F300M
<input checked="" type="checkbox"/>	MASK430R / F430M
<input type="checkbox"/>	MASKLWB / F250M

MIRI Options _____

▼ NIRCam	
<input checked="" type="checkbox"/>	4QPM / F1065C
<input checked="" type="checkbox"/>	4QPM / F1140C
<input checked="" type="checkbox"/>	4QPM / F1550C
<input type="checkbox"/>	Lyot / F2300C

Figure 1 Notional illustration of the functionalities in the super-template interface. The top table describes the coronagraphic suite, the button “add target” adds a line to the table (one line in the table is a coronagraphic sequence). See Reference [TR1] for additional examples of the mock interface, applied to specific science use-cases. The Unlock button represents the option to leave the super template for a fully-manual mode, which requires additional justification.

Check with the JWST SOCCER Database at: <https://soccer.stsci.edu>
To verify that this is the current version.

4.2 Required Capabilities

1. A super-template interface will allow users to define coronagraphic sequences and suites. The super-template interface will provide high-level organization of targets, references, rolls, additional calibration images (e.g. Astrometry), optional dithers requested for different type of coronagraphic suites (self-referenced, shared reference). It will also provide high-level organization of the instruments, coronagraphic masks, and filters requested for each target.
2. There are two instrument-level coronagraphic templates, one for MIRI and another for NIRCcam, which will work for each science and reference target. The instrument-level templates specify the instrument configuration (mask and filter information populated by super-template selections) and the exposure time, etc.
3. Each instrument-level template will allow the user to define the exposure times for target acquisition images as well as science observations. Such flexibility is needed for high dynamic range observations that require multiple exposures with different exposure times and readout settings.
4. The super-template will allow users to add a target to a coronagraphic suite. By default, adding a target will add a *basic coronagraphic sequence* (i.e. a line in the coronagraphic suite table shown in Figure 1, with the +/-5 deg check box selected by default).
5. For each coronagraphic sequence, the super-template will flag science targets and reference stars (e.g. using 2 columns as in the mock design shown in Figure 1). This information is propagated to other systems (e.g. pipeline reduction, removing the proprietary period of reference PSFs unless the self-reference option checked).
6. The default telescope roll angle in the *basic coronagraphic sequence* will be +/- 5 degrees from nominal (i.e. a 10-degree roll) for the science target, and will not be adjustable by the user.
7. Additional roll orientations can be added, with angles specified by the user. Rolls larger than the +/-5 deg will not be linked back-to-back with the rest of the sequence. Hence, schedulability of the selected roll offset must be checked and verified. If possible,, APT will show the range of possible physical orientations for each target to avoid requesting a non-physical roll angle.
8. The super-template interface will support additional calibration images (astrometric/photometric) within the sequence. Most of the additional calibration data may not need to be scheduled using interrupts (e.g. an hours to days delay might be acceptable).
9. The super-template will include a checkbox for an optional small-grid dither pattern of observations that can be activated independently for each target and reference PSF star.
10. Each coronagraphic sequence in a coronagraphic suite will use the same set of instrument/mask/filters. Several coronagraphic suites will be used if the observer wants to use different sets of instrument/masks/filters for different targets. See Figure 1.

Check with the JWST SOCCER Database at: <https://soccer.stsci.edu>

To verify that this is the current version.

11. The super-template will pre-populate the instrument-level templates using all of the mask and filter requests. If a dynamic super-template is implemented, then the dynamic tool will continuously synchronize the super-template and instrument-level templates. In this case, the user may change a filter within a coronagraphic suite using the super-template. In the wizard is implemented, then observations must be generated from scratch using the super-template or edited manually at the observation level.
12. The super-template will automatically generate the set of observations and appropriate special requirements. Every observation within a coronagraphic sequence will be scheduled back-to-back (sequence NON-INT in Commanding terminology) to prevent interruptions from WFS&C activities, momentum dump, other observations, etc.³ Non-interrupts are necessary to minimize changes in the stellar PSF between observations. In several masks and filters are requested within a coronagraphic sequence, then the super-template will provide the most efficient organization of the selected observations, as detailed in [TR3]. The super-template will implement multiple filters differently for NIRCcam (possible to select several filter inside the template) and MIRI (several instances of the template) depending on the design of the instrument-level template.
13. The super-template will include a checkbox to indicate when the coronagraphic suite is self-referenced. This checkbox will allow the user to skip reference PSFs, as long as there are at least 10 targets and 10 reference PSFs. If this box is selected and there are less than 10 reference PSFs⁴ in the program, then the program will be non-standard and the super-template will issue warning and require the user to submit additional justification. If scheduling information can be fed back to the super-template, then the CWG recommends that each group of targets that can be scheduled together should have at least one reference PSF.
14. The super-template will include a checkbox to indicate when the coronagraphic suite is a shared-referenced suite. This strategy is only acceptable for science that requires moderate contrast targets and for targets that can be scheduled together. Selection of this checkbox will generate a warning and a request for justification within the technical justification of the proposal. In doing so, the super-template will discourage observations of a few targets spread all over the sky, which would not make sense. For now, all targets within standard a self-referenced suite must be located within 5 degrees of each other⁵.
15. APT will produce a warning and request additional justification in the case that a template is identified as non-standard. In the case of a dynamic super-template implementation, an “unlock” button will allow users to switch to a fully manual

³ This requirement might be relaxed in the future, once we have a better understanding of the telescope wavefront temporal behavior but for now the position is to force coronagraphic observations to be back-to-back.

⁴ This criterion is for now arbitrary and may be adjusted at a later time.

⁵ this number is used as a placeholder to represent the schedulability of the targets together, and could be replaced later by actual schedulability information.

- mode. In the case of a single-use wizard implementation, APT will check the proposal prior to submission.
16. As described in [TR10], Reference stars will be made public immediately and the public flag must be propagated to DMS. The only exception is for self-referenced suites in which each target can be used as a reference PSF for the other targets.
 17. A specific flag “reference” will be associated with reference PSFs for inclusion in reference PSF libraries. This will interact with other systems (pipeline, DMS etc.)
 18. The mosaic tab will not be needed in APT for coronagraphy and should be removed; this is an obsolete feature in the current version.

4.3 Additional Desirable Capabilities

1. APT could facilitate the selection of reference star based on its spectral type, brightness, separation, schedulability. This is likely beyond the scope of APT at the current time and may be better implemented as a separate tool. In addition to helping the observer to select reference PSF, such a tool could be expanded to report the predicted contrast for each reference star. However, it would require detailed understanding of how slewing impacts wavefront error and stability.
2. Roll-dither could be permitted for reference stars. Roll-dithering will make reference star observations more robust (e.g. if a reference star turns out to be a binary) in cases where the contrast cannot be achieved by re-observing the reference star at a later date. In case of a failed reference PSF (e.g. it turns out to be a binary star), the observer could have the option to request observations of another reference PSF star in order to obtain a good reference PSF. The effectiveness of a re-observation compared with a reference star from the library remains to be studied. Both the +/- 5 deg roll scheduled back to back and larger rolls at later times could also be available for the reference PSF star.
3. APT could automatically update the name of the observation/visit with “reference” where appropriate, to help with readability and avoid the risk of errors.
4. APT could report the total additional exposure time if small-grid dithers are requested.
5. APT could provide more information about the position angles available for each target. This feature would help users choose orients that avoid the spiders.
6. Additional reference PSFs could be added to the coronagraphic sequence, bracketing the science target observation.
7. APT could provide basic scheduling information to indicate which groups of targets within a coronagraphic suite could be scheduled together. This feature would be extremely useful to determine the number of reference PSFs needed within a self-referenced suite for example.

Check with the JWST SOCCER Database at: <https://soccer.stsci.edu>

To verify that this is the current version.