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TECHNICAL REPORT

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Title: How to Implement a JWST Coronagraphic Observation Sequence in APT	Doc #: JWST-STScI-004707, SM-12 Date: November 30 2015 Rev: June 22, 2016
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1 Abstract

Observing extrasolar planets and debris disks with JWST will require the use of the coronagraphic masks on the NIRCam and MIRI instruments. The most basic coronagraphic observations have a relatively well-defined sequence consisting of a science target observation, a roll dither, and a reference PSF observation. However, manually implementing such a sequence in APT is non-trivial. Here we provide the background necessary to understand the basic coronagraph sequence, how JWST's pointing restrictions impact coronagraph observations, and provide an example of how to implement an APT program to observe a debris disk with a NIRCam coronagraph.

2 Introduction

JWST's coronagraphic capabilities for NIRCam and MIRI will enable the search for and study of planets orbiting other stars (exoplanets) as well as circumstellar disks. Here we summarize how to schedule a coronagraphic observation sequence in APT. We note that this summary is in the context of APT v24.1.2. We expect this guide to evolve as APT is updated.

This guide was written in conjunction with the JWST coronagraph SODRM documentation (TR JWST-STScI-004706), which details the APT implementation of each SODRM program described in the Coronagraph Science Use Case Document (TR JWST-STScI-004140). Here we provide a broad description of how to craft a JWST coronagraph program; we direct the reader to the SODRM document for program specific details.

3 The basic coronagraph observation sequence

To understand how to implement coronagraph observations with APT, we must first discuss the basic sequence that will be programmed. The basic coronagraphic observation sequence (defined in TR JWST-STScI-004141) consists of 3 observations: a science target observed at two rolls (for pixel dithering and roll diversity at large separations) and the observation of a reference star at a single roll angle for PSF subtraction. This is the baseline observational strategy for all JWST coronagraph observations (see TR JWST-STScI-004141). There exist exceptions to this baseline (e.g., the self-referenced survey use case described in TR JWST-STScI-004140) but we do not expect those to be prevalent in early JWST cycles. Further, to maximize contrast we need to minimize wavefront changes, so we should make observations within a given coronagraph sequence non-interruptible. The most basic coronagraph observation sequence is a non-interruptible sequence of 3 observations:

1. Science target, MIRI, 4QPM, F1065, -5° roll
2. Science target, MIRI, 4QPM, F1065, +5° roll
3. Reference PSF target, MIRI, 4QPM, F1065

where we have assumed we're using MIRI with the 4QPM coronagraphic mask and the F1065 filter. The ±5° roll between observations 1 and 2 simply signifies that we will attempt to schedule observations with a ~10° Position Angle (PA) offset to create a "roll dither," with the goal of mitigating bad pixels and allowing the astrophysical scene to rotate with respect to the coronagraph PSF. In the sequence above, we have not performed a roll dither to mitigate bad pixels on the reference star, as this is not expected to significantly impact observations, but is an option the user may want to add.

Variations on this basic sequence could add additional filters, such as the following non-interruptible sequence of 6 observations:

1. Science target, MIRI, 4QPM, F1065, -5° roll
2. Science target, MIRI, 4QPM, F1140, -5° roll
3. Science target, MIRI, 4QPM, F1065, +5° roll
4. Science target, MIRI, 4QPM, F1140, +5° roll
5. Reference PSF target, MIRI, 4QPM, F1065
6. Reference PSF target, MIRI, 4QPM, F1140

Note that as per the CWG study on coronagraph efficiency (TR JWST-STScI-004165) we are choosing here to sequentially expose in each filter before any spacecraft maneuvers in order to minimize overheads. The MIRI 4QPM masks and the NIRCam wedge masks have axes that occult part of the science target. Thus for many objects, it is likely that the user may want to perform a second larger roll (e.g., ~30°) to complete the field of view, such as:

1. Science target, MIRI, 4QPM, F1065, -5° roll
2. Science target, MIRI, 4QPM, F1065, +5° roll
3. Reference PSF target, MIRI, 4QPM, F1065
4. Science target, MIRI, 4QPM, F1065, +25° roll
5. Science target, MIRI, 4QPM, F1065, +35° roll
6. Reference PSF target, MIRI, 4QPM, F1065

Here observations 4 and 5 act as a roll dither pair. Note that, as we will discuss below, a 30° roll cannot be performed on any single date with JWST. Thus, observations 1-3 are a non-interruptible sequence and observations 4-6 must be their own non-interruptible sequence, scheduled on a separate date. Because the wavefront may have drifted significantly between the first and second set of observations, the second set of observations requires its own PSF reference star.

Additional complexities could include multi-instrument observations, small grid dithers of the reference star to improve PSF subtraction, full-frame imaging, full-frame images read out strategically for astrometry, and the lack of a reference star for self-referenced surveys. Some of these features are not easily implementable in the current version of APT, so we leave a detailed discussion of these additional observing strategies to future documentation. More information can be found in TR JWST-STScI-004140.

4 JWST's pointing restrictions and the impact on schedulability

To understand how to schedule a coronagraphic observation sequence, it is beneficial to understand the pointing restrictions of JWST, and how that limits a target's visibility and range of accessible roll angles. JWST is limited to observing at solar elongations between 85 and 135°. This creates a field of regard "stripe" over the surface of the celestial sphere within which targets can be observed, as shown in the left panel of Figure 1. As JWST orbits the Sun, this stripe rotates around the ecliptic pole such that the entire sky is traced out. As shown in the right panel of Figure 1, this creates three different zones of visibility: 2 small continuous viewing zones at the ecliptic polar caps (red), 2 larger zones that have a single annual visibility block (green), and the large swath of sky that provides 2 semi-annual visibility blocks (blue). The visibility of a target therefore depends on its ecliptic latitude.

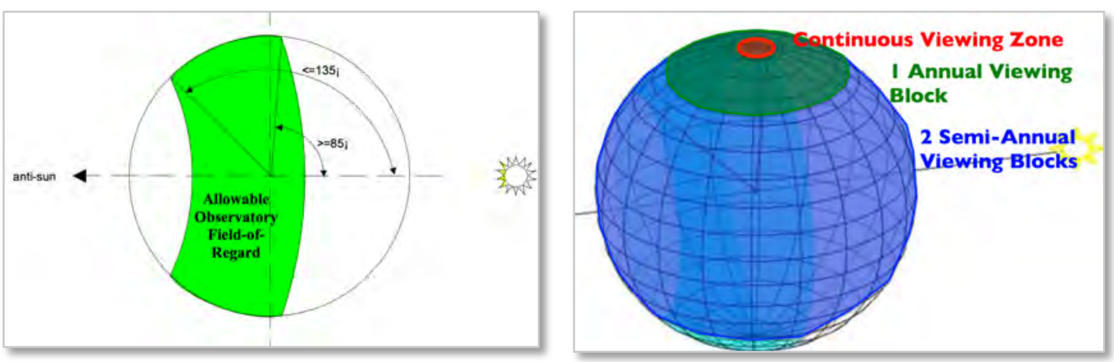


Figure 1 ***Left:*** **JWST's allowable range of solar elongations creates a field of regard "stripe" on the celestial sphere.** ***Right:*** **As JWST orbits, the field of regard rotates over the celestial sphere, such that a target's visibility depends on ecliptic latitude.**

The ecliptic latitude of the target and solar elongation of the observation, which changes with time, will determine the roll angle of JWST on the sky when pointing at the target. JWST can also roll about the optical axis. Limits on the roll angle allowed for a given pointing have been loosely described as ±5° about the optical axis, such that ~10° of roll range is accessible at any point in time (hence, the ~10° roll dither described in the previous section). However, the actual pointing restrictions of JWST are in terms of a solar avoidance angle, and are not in terms of the optical axis roll angle. As a result, the range of optical axis roll angles is a function of solar elongation, with ±3.5° allowed at a solar elongation of 85° and ±7° allowed at solar elongation of 135°.

Combining the roll angle restrictions with visibility restrictions produces visibility plots like those shown in Figure 2. Here we show the solar elongation required to observe the target (black line), the allowed solar elongations (red and orange), and the allowed roll angles (blue, labeled "V3 PA") vs time for 3 targets with different ecliptic latitudes (the initial date on the x-axis is arbitrary and TBD). The top panel shows a target at high ecliptic latitude, in the single visibility block zone. The middle panel shows a target at modest ecliptic latitude, representative of the majority of JWST's targets, and the bottom panel shows a target near the ecliptic.

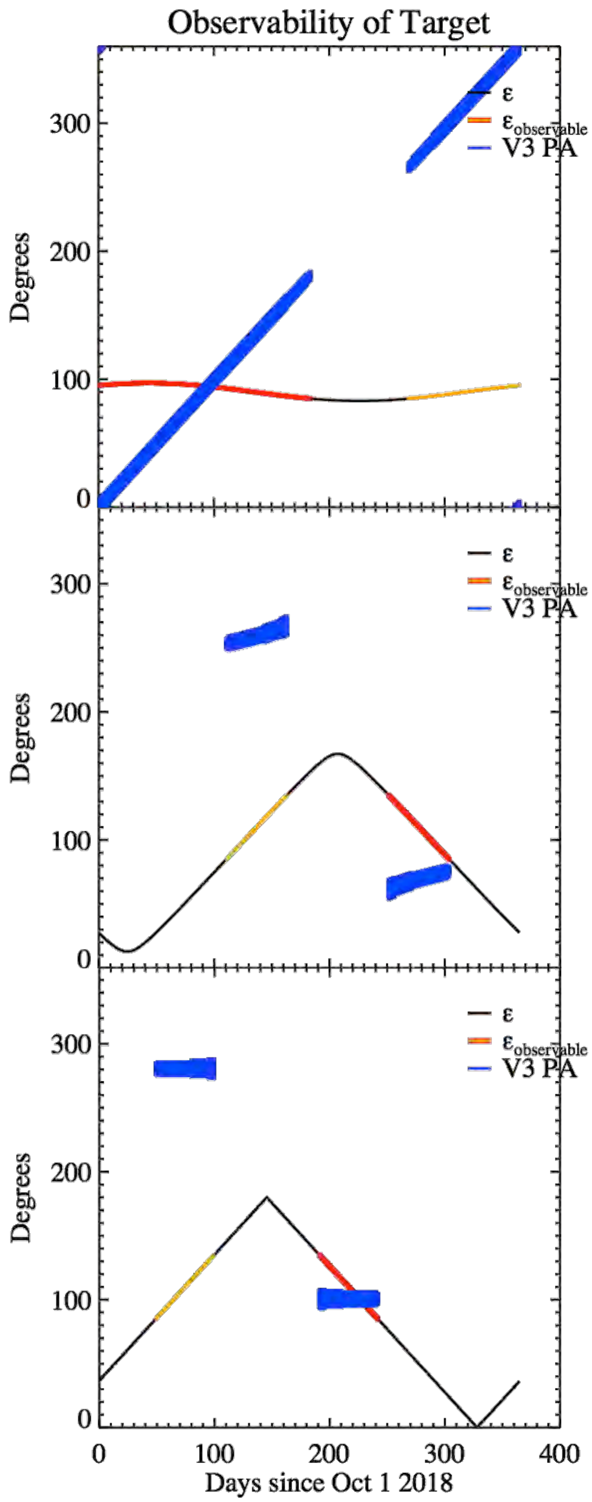


Figure 2 ***Top:*** **A target a high ecliptic latitude with a single annual visibility block.** ***Middle:*** **A typical target at moderate ecliptic latitude with two visibility blocks per year.** ***Bottom:*** **Targets near the ecliptic have limited PA ranges.**

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

As the top panel in Figure 2 shows, targets with high ecliptic latitudes are observable for the majority of the year and are observable over a wide range of roll angles/PAs. On any given date a relative roll between 7 and 14° is allowed, depending on the solar elongation, as illustrated by the thickness of the blue curve. To obtain PA offsets larger than ~14°, one must schedule observations on 2 separate dates. If one's goal is to, e.g., image a disk in its entirety using a wedge mask, one could easily schedule 2 observations on separate dates with a relative roll offset ~90°.

Targets near the ecliptic (bottom panel) have the most restricted visibility. Only the small 7—14° range of roll angles around the optical axis are allowed, as well as a 180° rotation between the two observation blocks. Because of the geometry of the coronagraphic masks, a 180° rotation is usually not beneficial. For targets such as this, JWST is limited to observing at the orientation that nature provides and one simply cannot observe the full scene with some coronagraphic masks. Note that the range of roll angles is larger at larger solar elongations, as discussed previously and illustrated by the thickness of the blue curve. So if one wants the largest roll dither possible of 14°, one should choose to observe at a large solar elongation, but this is available only for a small amount of time.

Finally, as shown in the middle panel, targets at modest ecliptic latitudes (the majority of targets) have observable blocks of allowed roll angles that are curved and can span ~20° or more due to rotation on the sky. The degree of curvature in a single observation block depends on the ecliptic latitude; it may be possible to schedule relative roll offsets ~30° in a single observation block for some targets, but not for others.

The curved observation blocks shown in the middle panel of Figure 2 leads to important subtleties when scheduling an observation. Because they are not symmetric, the sign of a relative roll offset matters if scheduling is limited to a given year. For example, for the target shown in the middle panel of Figure 2, one can move from the first observation block to the second via a relative roll of just +145°, but moving in the negative direction takes a relative roll of -170°; the magnitude of relative roll offsets allowed depends on the direction of the offset. **The PA offset special requirements in APT consider the sign/directionality of the roll, so understanding this asymmetry is helpful to creating schedulable observations**. Currently there is no option in APT to specify only the magnitude of a PA offset, and disregard the direction.

The range of relative roll offsets remains fixed, though. For the target shown in Figure 3, positive roll offsets between +145 and +195° are allowed. Negative roll offsets between -220 and -170 are allowed. As previously mentioned, we are typically interested in the roll ±180°. So to achieve the largest roll offset ±180° for this target, we would request a roll offset of either +145° or -220°.

5 JWST visibility tool

To produce the plots shown in Figure 2, we used a JWST visibility tool written in Python. This tool calculates the allowed position angles of JWST's optical axis for a given target as a function of time. As shown in Figure 3, one can also provide the coordinates of a companion (or the semi-major axis of a circumstellar disk in this case) and the tool will plot the location of the companion on the detector. This allows one to determine whether the companion (or major axis) will be aligned with the NIRCam wedge mask or the MIRI 4QPM axes.

This tool is fairly simple, but has proven to be very valuable when creating coronagraphic observation plans, as it allows the user to easily visualize what orientations are possible for a given target. This tool is currently under development and is expected to be released mid-2016. This document assumes this tool will be available to users, and we describe how to implement a basic coronagraph sequence given information like what is shown in Figure 2.

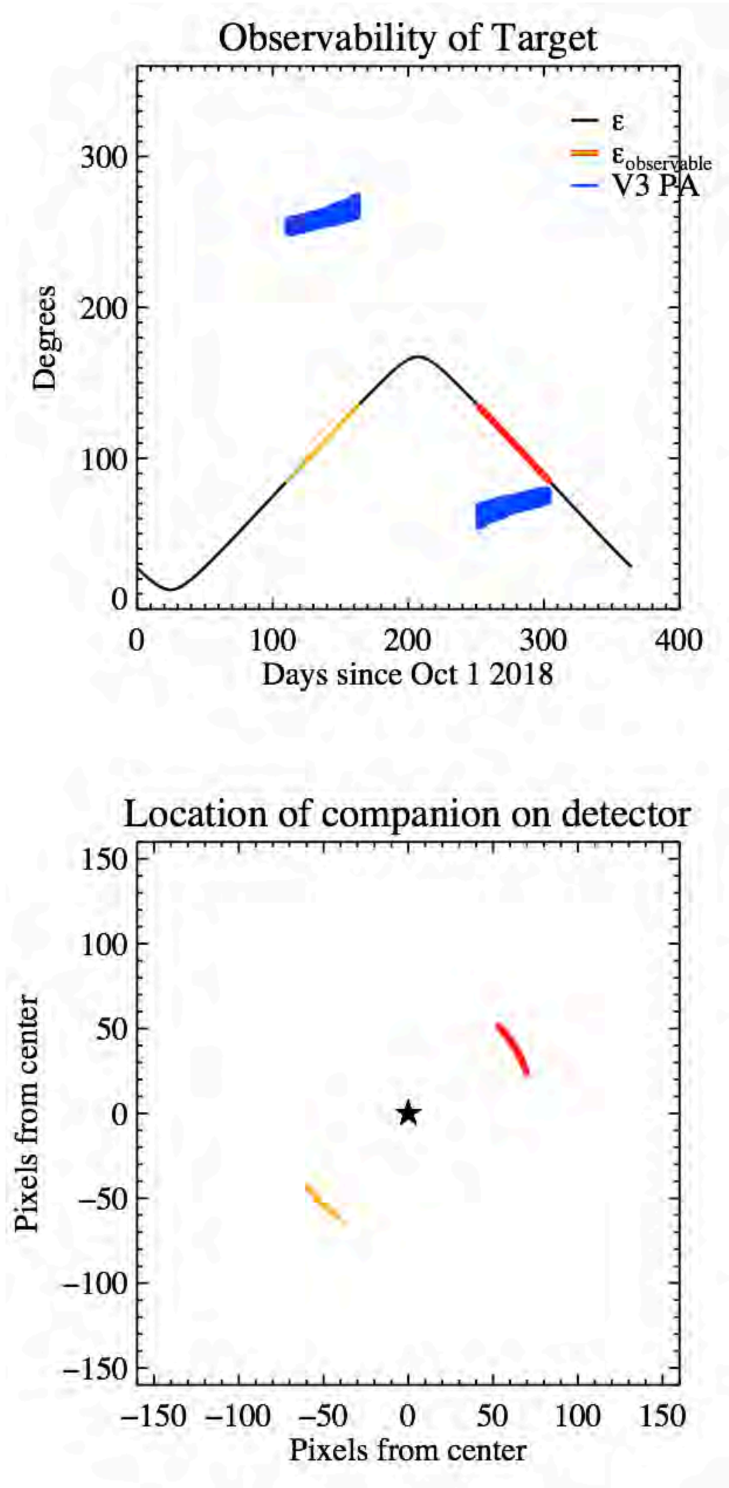


Figure 3 Output of the JWST visibility tool for AU Mic: accessible PA vs time (top) and major axis of disk on the detector (bottom).

6 Example: APT program to observe a debris disk

Suppose we wanted to observe the edge-on debris disk around AU Mic with the NIRCam 210 wedge. Figure 3 shows the possible roll angles of the disk, which we calculated using the JWST visibility tool. The lower panel shows the orientation of the major axis on the detector. Given that the disk plane can't be aligned with the wedge, we need not worry about the wedge occulting the disk and do not need to specify an absolute roll angle.

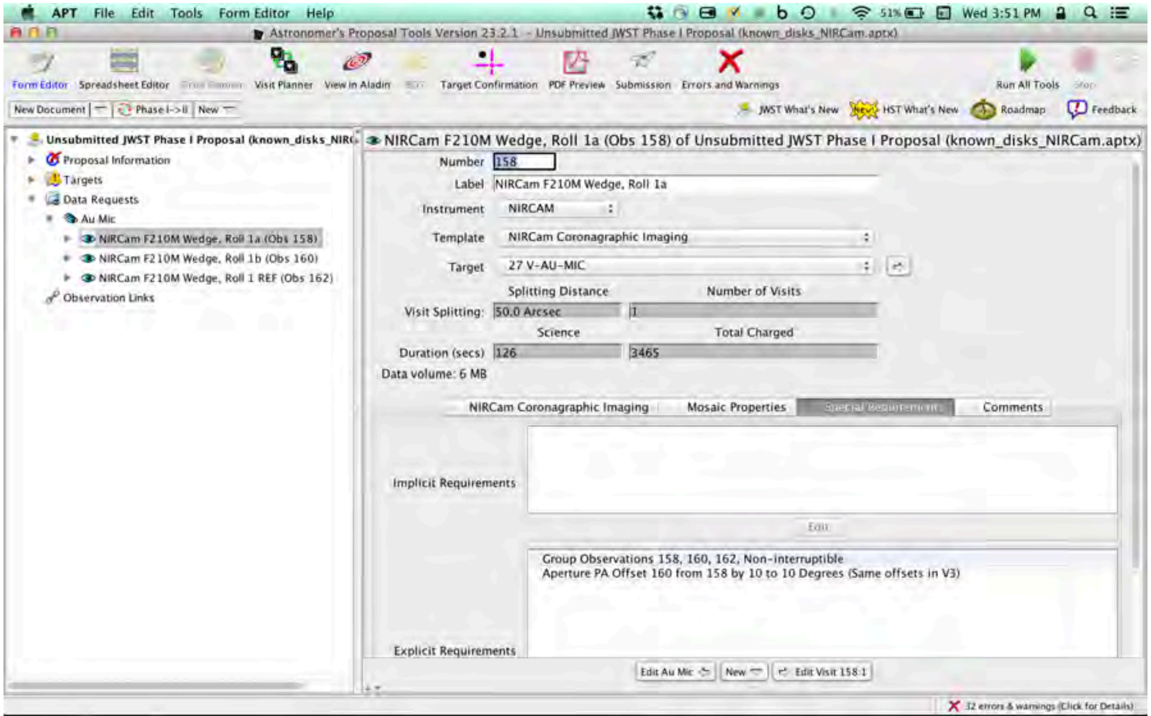
6.1 A single coronagraph sequence

To create an APT program to observe AU Mic with a JWST coronagraph, we would add AU Mic to our target list, create a new observation using the NIRCam instrument with the NIRCam Coronagraphic Imaging template, and select AU Mic as our target. Under the NIRCam Corongraphic Imaging tab, we'd select MASKSWB for use with the 210 filter. We'd then add a filter, select the F210M and an appropriate exposure time.

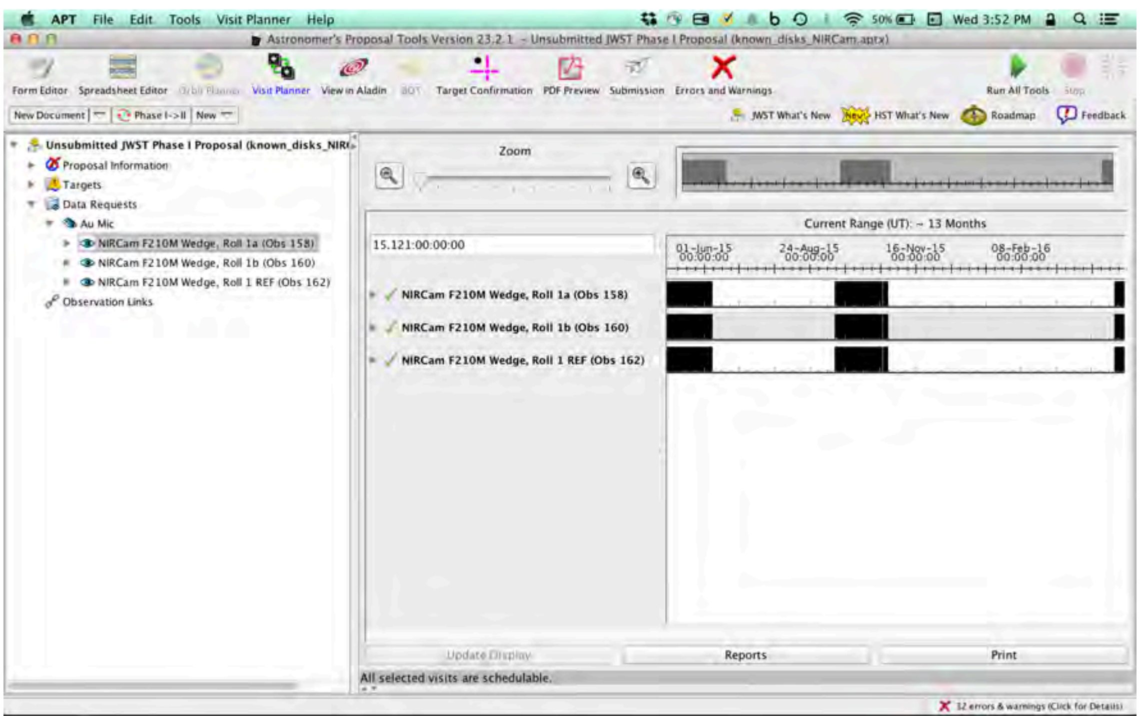
To add the roll dither observation, we'd duplicate the first observation and rename it. Consider this the 2nd observation. Under the special requirements tab, we'd add a PA offset link from the previous observation of ~10°. Because we did not specify the absolute orientation of the first observation, APT is allowed to pick any set of observations that satisfies the PA offset requirement; the sign of the ~10° PA offset does not matter in this case. Note that we could have picked a PA offset range of 13-14 degrees to demand as large of a dither as possible, or a PA offset range of 7-14 degrees to maximize the chances of schedulability (see discussion of PA range in Section 4).

To complete the basic coronagraph sequence, we will also need a 3rd observation of a reference star for PSF subtraction. To add this, we'd duplicate one of the existing observations and change the target to our reference star. We would need to modify the exposure time and make sure that no undesired special requirements were copied over during duplication. Finally, we would need to make all 3 observations a non-interruptible sequence to ensure that the wavefront changes as little as possible between observations. To do so, we'd add a Group/Sequence Observations Link under the special requirements tab of any of the 3 observations, select the 3 observations from the "Observation list," and check the "Sequence" and "Non-interruptible" boxes. The Form Editor view of our APT file should look like the following.

We note that by default, users should check the "Sequence" box to make a non-interruptible sequence, as opposed to a non-interruptible group, and should specify the order of observations as desired. The user would determine the order by either minimizing overheads (e.g., filter changes before spacecraft maneuvers), or by minimizing wavefront changes. It is important to remember that **for a non-interruptible sequence, APT determines the order of the sequence by the observation "Number" (given at the top of the coronagraph template), NOT the ordering of observations in the observations folder of the left panel**. Not specifying the coronagraph observations as a sequence means that APT could potentially modify the order of the coronagraph sequence.



After updating the display in the visit planner, we'd see the following observation plan.



6.2 Multi-roll coronagraph sequences

Now, suppose we want to observe *the full scene* around AU Mic using the 210 wedge. We would need to make observations at another larger roll angle, such that the wedge has been rotated significantly—the two sets of rolls can then be median combined to remove most of the obscuration from the wedge. Let's say that we desire ~30° of roll compared to the first set of observations. If we were to add a 4th observation, with a PA offset special requirement of 30° relative to the first observation, and include it in our non-interruptible sequence, we'd find that APT is unable to schedule these observations. This is because, as shown in Figure 3, a single observation block does not span 30° in roll angle.

So we must make the 4th observation on a separate date. Removing it from the non-interruptible sequence and attempting to reschedule again results in an error, though. As Figure 3 shows, this is because even when allowing for separate dates, the roll angles between the two observable blocks are much larger than the desired 30°.

There appears to be no way to schedule this observation with a relative roll angle of ~30°, either in the positive or negative direction. However, given the geometry of the coronagraphic masks, we are usually interested in the relative PA offset ±180°. As Figure 3 shows a relative roll angle of +145° should be schedulable for this target (also see Figure 4). This roll angle would provide 35° of roll relative to a 180° offset, enabling the complete coverage of the disk that we desire.

Unfortunately, changing our large PA offset special requirement to +145° from our first observation again results in an error. This time the schedulability error is a bit subtler. Given that APT is scheduling the 2nd observation at +10° with respect to the 1st observation simultaneously, if the first observation is in the first observing block, then a PA offset of +145° with respect to the first angle will not quite reach the second observing block. The roll angle between the 1st and 4th observations needs to be at least 10° larger, or ~155°. Indeed, updating the PA offset link for our 4th observation to 155° solves the problem. Alternatively, we could have specified the 4th observation as ~145° with respect to the 2nd observation. Figure 4 provides a visualization of these scheduled visits.

We also want a roll dither with respect to the 4th observation. Given that we have probably forced the observations to be scheduled such that the 4th observation is near the lower limit of the second observable block for this target, as shown in Figure 4, a 5th observation with -10° PA offset with respect to the 4th observation would result in an error. Thus, we add a 5th observation that has a +10° PA offset with respect to the 4th observation. Figure 4 illustrates the final roll angles at which APT is likely scheduling our observations, as shown by green dots. PA offsets are also labeled in green.

Finally, we should add a PSF reference star observation for observations 3 and 4, and make observations 4 – 6 non-interruptible.

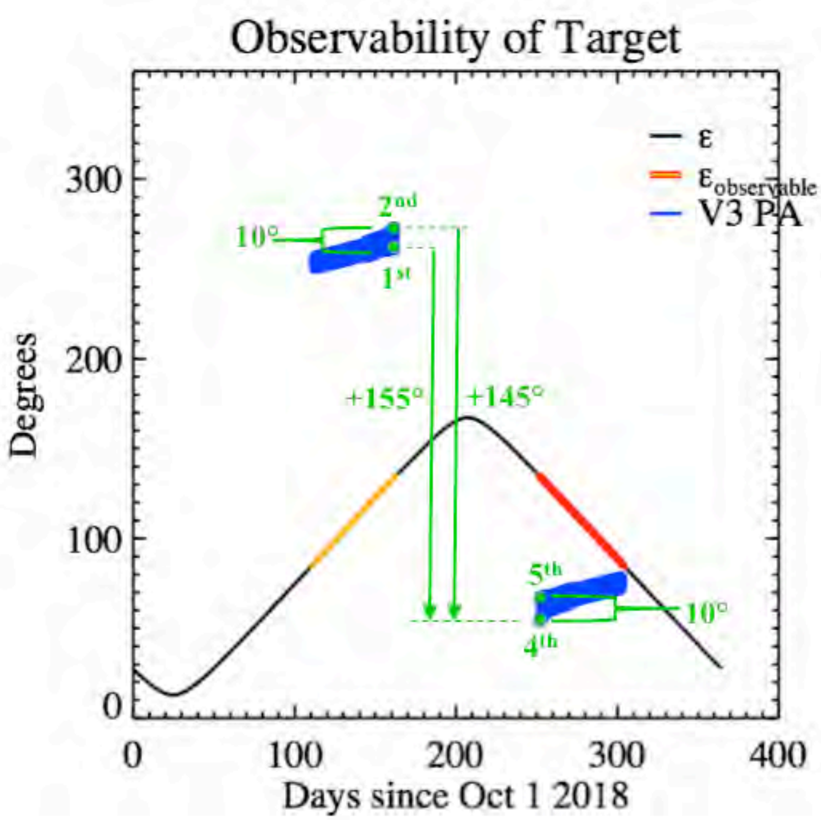


Figure 4 Depiction of the final coronagraph sequence for AU Mic, consisting of a 10° dither pair (Obs. 1 & 2), and a second dither pair at +155° with respect to the first observation (Obs. 4 & 5).

6.3 An algorithm for the scheduling of multi-roll coronagraph sequences

The above example shows that manually programming a multi-roll coronagraph sequence is a non-trivial process that requires an understanding of the roll angles accessible by JWST for a given target. In light of this, we offer the following "algorithm" that can be used to manually program a multi-roll sequence. Here we assume that the user requires roll dithers of angle α and a larger roll offset of angle θ. We assume that $\theta > 15°$ and $\alpha <$ 14°. Because of the asymmetry in the visibility windows, this algorithm may not work in every case.

1. Create a basic 3-observation, non-interruptible coronagraph sequence, as described in Section 6.1 above, following the form:

   Obs. 1: Science Target

   Obs. 2: Science Target @ PA offset = +α° wrt Obs. 1 (for dither)

   Obs. 3: Reference star

2. Create another 3-observation, non-interruptible sequence of the form:

   Obs. 4: Science Target

   Obs. 5: Science Target @ PA offset = +α° wrt Obs. 4 (for dither)

Obs. 6: Reference star

3. Add a PA offset special requirement to Obs. 4, with respect to Obs. 1, with an allowed range of angles of [θ°, 180–θ°].
4. If the above is not schedulable, switch the range of PA offsets on Obs. 4 wrt Obs. 1 to [θ–180°,–θ°].

Figure 5 shows the allowable PA ranges for Obs. 4 and 5 in solid blue and black-dashed lines, respectively, for a single example of Obs. 1 and Obs 2, shown in red solid and dashed lines, respectively.

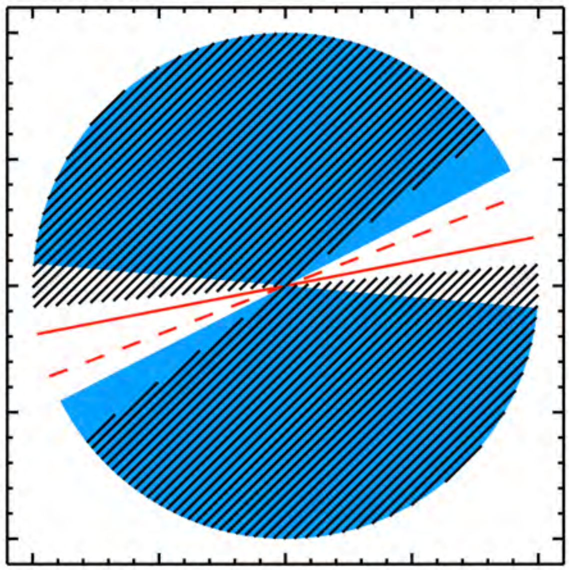


Figure 5 Illustration of allowed ranges of Obs 4 and 5 given the above algorithm. Obs 1 and 2 are shown as solid and dashed red lines, respectively, separated by +α°. Obs 4 (blue shaded region) is allowed to be scheduled from [θ°, 180–θ°] or [θ–180°,–θ°]. Obs 5 (black dashed region) is rotated by +α° wrt Obs 4. If the user does not constrain the PA of Obs 1, the entire diagram would rotate correspondingly.

6.4 Multi-filter or multi-instrument coronagraph sequences

When scheduling multi-filter or multi-instrument observations, it is important to consider the special requirements necessary to maintain proper PA positioning. For example:

1. If one desires to perform multiple NIRCam filters with a given coronagraph mask, APT allows this to be done within a single observation using the NIRCam coronagraph template. No modification to PA special requirements is necessary.
2. If one desires to observe with the NIRCam SWB and 210 round masks interleaved, the user will only need a single epoch for the 210 round mask. Further, while the 210 round mask will need a roll dither special requirement, the absolute orientation does not matter, so it will not need to be linked to the PA of the SWB PA.

3. If one desires to observe with the NIRCam SWB and LWB interleaved, the user will need to either A) create separate 2-epoch PA special requirements separately for the SWB and LWB, or B) use a Same PA special requirement to link each LWB to the previous SWB observation.
4. If one desires to observe with the NIRCam wedge masks and the MIRI 4QPM masks interleaved, then one would need to perform the same steps as described in the previous example.

7 Conclusions

The guidelines above should provide users with the understanding required to program a basic coronagraph observation sequence. Programming a single, basic 3-observation coronagraphic sequence with no constraints on target PA is straightforward. Including PA constraints requires knowledge of the allowed PA for any target and adds a layer of complexity to schedulability. Further, programming multi-roll coronagraph sequences for full sky coverage of a science target is a challenging, non-trivial process. To aid in this, we have provided a scheduling algorithm for multi-roll coronagraph sequences. We find that the JWST visibility tool is extremely useful in planning such observations, and may be useful to the general JWST user base.