On *Roman* WFI Parallel Observations during Coronagraph Instrument primary operations

James E. Rhoads, Thomas Barclay, Sangeeta Malhotra, Julie McEnery, Joshua Schlieder, Neil Zimmerman, Robert Zellem on behalf of the *Roman* project science team.

Motivation

The Roman Wide Field Instrument provides closed-loop guiding to the observatory whenever the Coronagraph is in use. The full-field Wide Field Instrument (WFI) images taken during Coronagraph Instrument operations will yield approximately 90 days of scientifically valuable deep imaging observations over tens of square degrees.

The approach outlined in this document follows the standard principle of parallel observing: Maximize science return but do no harm to the primary instrument's observing program. This principle constrains the choice of fields, filters, exposure time, and cadence for WFI parallel observations.

In all, we expect the WFI parallels to yield dozens of deep field observations, with typical on-target times of a few hours to a few days, distributed widely over the sky.

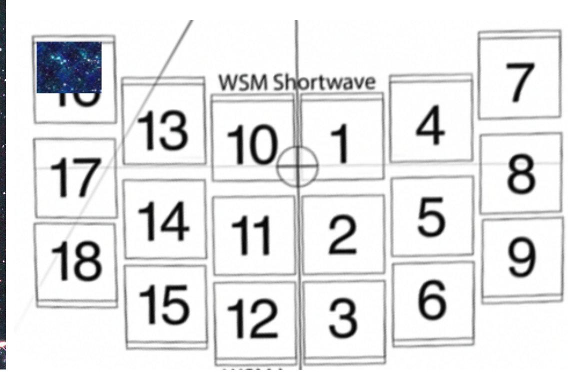


Figure 1: Left: The CANDELS Ultra-Deep Survey (left) is comparable in wavelength, color information, and spatial resolution to expected Roman WFI Parallel fields. [Photo credit: NASA, ESA, A. Riess (STScI and JHU), D. Jones and S. Rodney (JHU), S. Faber (University of California, Santa Cruz), H. Ferguson (STScI), and the CANDELS team.]
Right: The 4' x 5' size of the CANDELS Ultra-Deep Survey is superposed on the Roman WFI field of view. WFI parallels will cover tens of WFI fields at a depth comparable to CANDELS.

Executive Summary

The planned approach is to divide observing time equally among the F106 (Y), F129 (J), F158 (H), and F184 (F) imaging filters in each parallel field, to the extent possible.

These four filters, along with F146 (W), are the only elements that may be used for guiding while the Coronagraph Instrument is prime during initial Roman operations, because the WFI guiding performance is expected to be best in these five elements. The WFI grism and prism guide using a different algorithm that identifies the edges of bright star spectra, and this is anticipated to result in less precise attitude control than the approach used in imaging mode. Because the bluer filters (F062 (R) and F087 (z)) are substantially undersampled, their guiding performance may also be poorer. The F213 (K) filter is expected to yield poorer attitude control because its background count rate is substantially elevated by the thermal emission of the observatory.

The F146 filter is an available option but we are not including it in the initial WFI parallel observations plan because parallel opportunities come in sets of four observing time “blocks”, and the color information offered by the other four filters will support a more diverse set of science applications than ultradeep observations in a single broad filter.

The suitability of the F062, F087, F213, Prism, and Grism elements for parallel observations will be reassessed based on realized, on-orbit performance. If some or all of these elements are found suitable to support the objectives of the Coronagraph’s observations, this plan may be revised.

Policies for Proposers

WFI parallel observations will follow the strategy summarized in this document. Roman General Investigator (GI) Program proposals can request support for the scientific analyses of parallel data. Such proposals should be robust to the inherent uncertainties in parallel observing. The filter mix (YJHF) and total observing time (~ 90 days) can be taken as secure. The total solid angle covered and resulting depth should be treated as notional. And, target fields must be treated as “generic” targets whose exact positions on the sky will remain unknown at the time of proposal submission.

GI proposals may *not* request modifications of the baseline parallel observing strategy. General Astrophysics Survey proposals to obtain additional data in parallel fields would be welcome on the same basis as any other GAS proposal seeking to augment existing Roman survey plans with further observations. There may be additional considerations in scheduling such observations, since the precise locations of the parallel fields will not be known prior to the Cycle 1 deadline.

Coronagraph Instrument Operations shape WFI Parallel Opportunities

The boundary conditions placed on parallels include:

- Only F106 (Y), F129 (J), F158 (H), F184 (F), & F146 (wide) are allowed.
- Filter changes can occur only when Coronagraph Instrument changes target or roll angle.
- Dithering opportunities are highly constrained.
- Opportunity durations & field placement are dictated by the Coronagraph Instrument program.
- Individual WFI exposures are limited to ≤ 300 seconds (to avoid situations where a Coronagraph Instrument observation has finished and WFI is integrating long afterwards).

Some of these conditions may be relaxed in the future, if on-orbit performance of the observatory shows that such relaxation does not impact the quality of coronagraphic observations.

The normal Coronagraph Instrument observing sequence includes a bright reference star and a target star. The reference star is used for PSF subtraction of the target star via reference differential imaging. Rolled measurements of the two objects are used for angular differential imaging. Thus, for each coronagraph target, there are four WFI parallel target fields, which we'll refer to as TA (short for science Target at roll angle A), TB (short for science Target at roll angle B), RA (short for Reference star at roll angle A), and RB (short for Reference star at roll angle B).

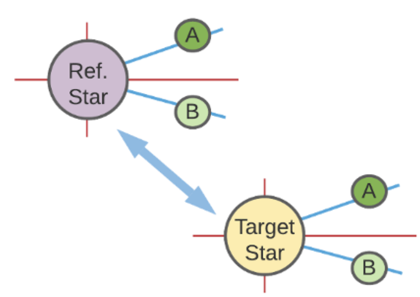
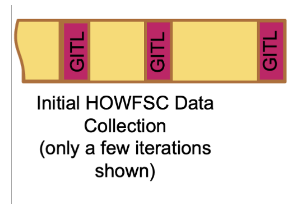
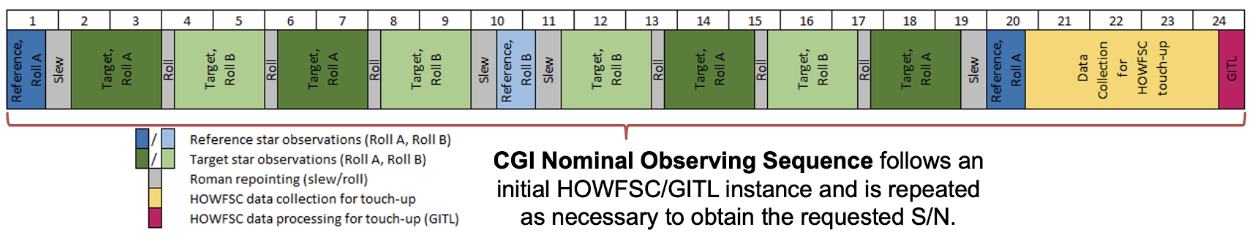


Figure 2: Illustration of a typical Coronagraph Instrument operations concept. The observation is a double-differential experiment, using both target-reference differencing and angular roll differencing to aid with starlight suppression.

Typically, science observations will span one or more calendar days per target. This will be preceded by several hours spent on the reference star, “digging the dark hole” (more formally, performing High Order Wavefront Sensing and Control). The primary observing sequence continues to split time between the Target star (75-80%) and Reference star (20-25%). This sequence will be built up of 1-day scheduling units (see fig. 3).

Figure 3: Illustrative timeline of a coronagraph observation, beginning with initial high-order wavefront sensing and control observations (HOWFSC, also known as “digging the dark hole”; right panel), and continuing with the primary observation sequence (lower panel). “Digging the hole” is done entirely on the reference star, at a single roll angle, and is expected to take ~ 2-50 hours. Thereafter, the primary observation sequence alternates two roll angles on the science target, interspersed with reference star observations and touchups of the high-order wavefront sensing.

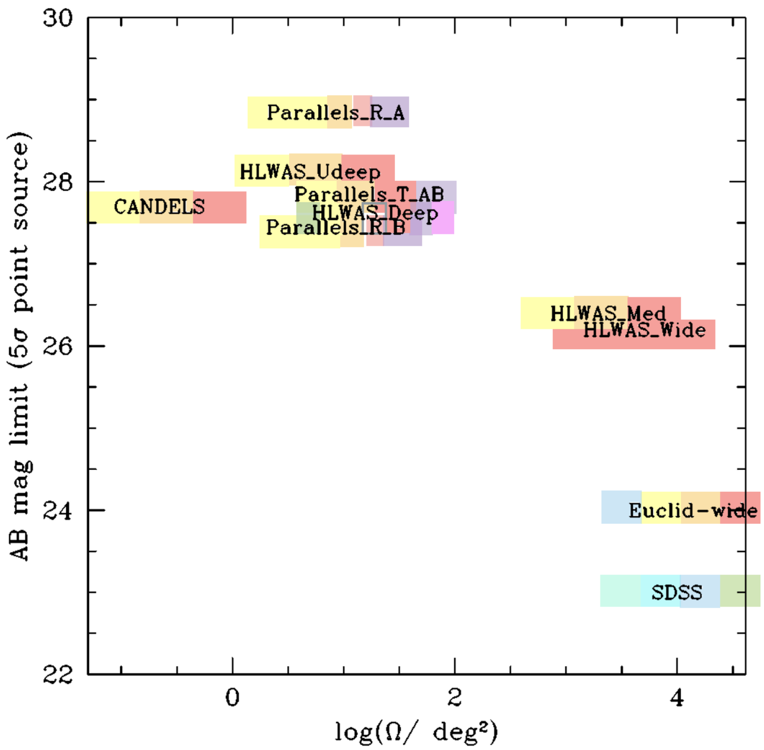




The timeline illustrated in Figure 3, combined with the recommended parallel observing strategy, would yield for each 24 hour “unit” of Coronagraph instrument observations, 2 hours’ integration time in each of four filters at positions TA and TB, plus approximately one hour in a single filter at position RB. Position RA would receive 2-50 hours in a single filter from the initial HOWFSC observations, plus 1 hour per cycle (in any available filter) from reference star observations. Each additional cycle after the first would yield a few more hours on target RA from HOWFSC touch-up observations.

Representative depths corresponding approximately to these integration times are shown in Figure 4 and in Table 1.

Figure 4: This figure compares the parallels to some other well-known surveys (past, ongoing, and planned-with-Roman). The representation of parallels here is indicative, but far from final.



Wavelength range and diversity is crudely indicated by colored boxes highlighting survey names. (Color info: K – magenta, F184 – purple, H – red, J – orange, Y – yellow, z – green, R – blue, Bluer-than-R – Cyan)

To produce this figure, we assumed 2 hours/filter for Parallels_T_AB, and 12 hours for Parallels_R_A.

Parallels_R_A could be up to ~ 0.75 or even 1 mag deeper in its deepest filter, and will be shallower than plotted in other filters. This follows from the observing timeline above.

Table 1: Illustrative 5 sigma limiting sensitivities for parallel fields. Depths are scaled from Table 1 of the “Roman High Latitude Wide Area Survey Definition Committee Recommendations” as reproduced in Appendix C of the ROTAC final report.
There will be variation from field to field depending on final integration times, filter mix, and zodiacal background. Each combination of field and filter is divided into the matched-filter-fitting photometry depth expected both for a point source, and for an extended source with 0.3” half light radius.

Field type	F106 (Y)		F129 (J)		F158 (H)		F184 (F)		F146 (Wide)	
	Point	0.3”	Point	0.3”	Point	0.3”	Point	0.3”	Point	0.3”
TA/TB (2 hrs)[a]	27.9	26.6	27.8	26.5	27.7	26.5	27.3	26.2	28.5	27.3
RA (initial,12 hrs)[b]	28.9	27.6	28.8	27.5	28.7	27.5	28.3	27.2	29.5	28.3
RA/RB (1 hr)[c]	27.5	26.2	27.4	26.1	27.3	26.1	26.9	25.8	28.1	26.9

Table notes:
[a.] For fields “TA” and “TB”, the parallels to the Coronagraph Instrument *science* target, the nominal plan would include all of F106, F129, F158, and F184 at the stated depths.
[b.] For reference star parallel field “RA” initial observations, which are parallel to the initial high-order wavefront sensing and control (“digging the dark hole”), the stated depths assume 14 hours (50 ksec) of observation which would be taken in *only one filter*. The ability to change filters during this process is still under discussion. Additionally, the number of hours available could be smaller or larger by a factor of ~ 2, changing the resulting depths by +- 0.37 magnitudes.
[c.] For each of fields “RA” and “RB” during the main observing loop, one filter would be available to the stated depth for each 24 hour increment of the main observing loop.

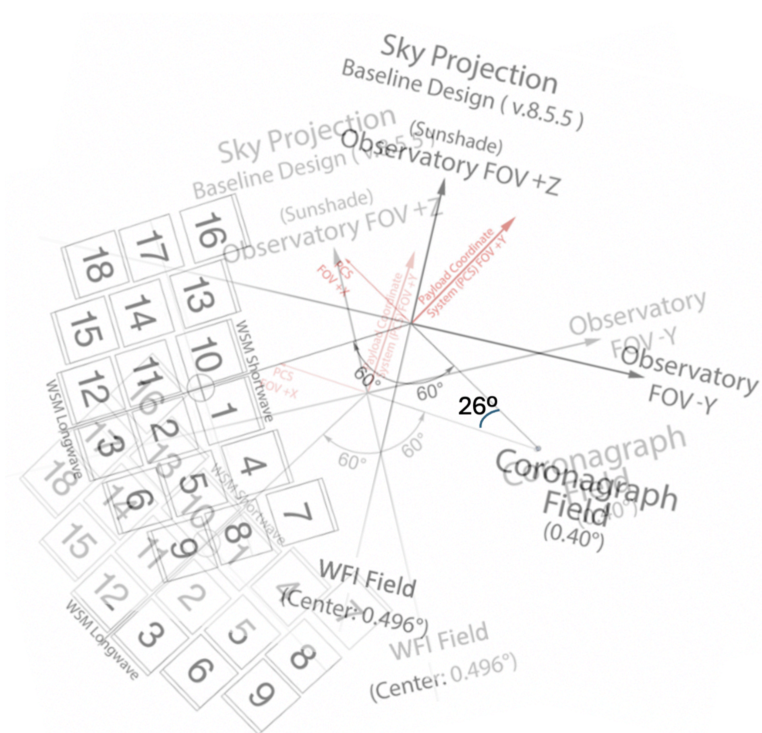


Figure 5: Geometry of WFI parallels to Coronagraph Instrument observations with a ±13° A-B roll pattern. There is significant overlap between the WFI fields at the two rolls, adding up to about 290 square arcminutes per A-B pair, or about 28% of the 1011 square arcminute WFI footprint. Each A-B pair therefore comprises about 1440 square arcminutes at single depth, and 290 square arcminutes at double depth.

Dithering

High quality deep-field WFI observations would normally be dithered on multiple scales. The Roman WFI, like most HST and JWST instruments, is undersampled by a factor of about 2 relative to the Nyquist frequency expected for its diffraction limit. Dithering can recover information that would otherwise be lost to this undersampling; and additionally can help mitigate the effects of bad pixels and detector gaps.

Parallel observations preclude full control of dithering. Realized observations may provide some measure of effective subpixel dithering (i) in regions where the roll A and roll B observations overlap; (ii) in multi-day observations *if* CGI adopts a roll strategy based on specifying Sun angles; and (iii) if some amount of effective dithering is provided by small variations in roll angle and/or differential aberration (see Appendix).

However, Cycle 1 Roman proposals should not plan for science that critically depends on the recovery of spatial information on subpixel scales from parallel data.

Appendix: Dithering Options for WFI Parallels

Parallel observations preclude full control of dithering, but two valuable options remain for Roman: Roll dithering, and effective dithering due to differential velocity aberration.

Roll dithering:

When executing an A-B-A-B roll chopping pattern for Coronagraph Instrument observations, it is possible to use slightly different position angles for each "A" position and each "B" position, provided that the position angle remains constant between roll maneuvers.

WFI pixels are offset from the Coronagraph Instrument position by angles θ ranging from 0.484° to 1.14° (with the nominal WFI center lying about 0.776° from the Coronagraph Instrument field). A roll of angle φ_{rad} radians will shift a pixel at separation θ by an amount $\delta = \varphi_{rad}\,\theta$.

Putting this into convenient units of arcminutes of spacecraft roll and pixels of WFI offset, we have $\delta_{pix} = k\,\varphi_{amin}$ where the range of separations $0.484^\circ < \theta < 1.14^\circ$ yields 4.61 pixels/arcminute < k < 10.85 pixels/arcminute.

The Coronagraph Instrument's largest FOV radius is 1.4" for 825nm 10% bandpass imaging mode. At 1.4" radius, a 1 arcminute roll corresponds to a 410 μarcsec shift, equivalent to 0.02 EXCAM pixels or about 5e-3 of the diffraction limited PSF size. The preliminary assessment of the Coronagraph Instrument scientist at GSFC (Neil Zimmerman) is that position angles can vary by several arcminutes (or more) between different "A" roll observations without impact on the Coronagraph Instrument science.

We note that a single 24-hour observing block, with a four-filter parallels plan, will still not yield any dithering in a single filter, though a more complex attempt to recover spatial information from observations in multiple filters where roll dithering accompanies filter changes may be possible. Roll dithers become a very powerful tool once multiple 24-hour observing blocks occur for the same coronagraph target.

Fixed Sun Angle Dithering:

Additionally, the Coronagraph instrument has both PA-fixed and roll-fixed options. PA-fixed means that the on-sky position angle is repeated over multiple observing blocks. Roll-fixed means that the Sun angle is instead held (approximately) constant. The Roll-fixed option will result in a ~ 1 degree roll between each subsequent Coronagraph observing block. This offsets the WFI position by 0.5 arcminutes at the corner closest to the Coronagraph field, and 1.1 arcminutes at the corner furthest from the Coronagraph field. This effectively dithers each subsequent block, with the side effect of reducing overlap between subsequent blocks from ~100% to ~98% of the WFI field.

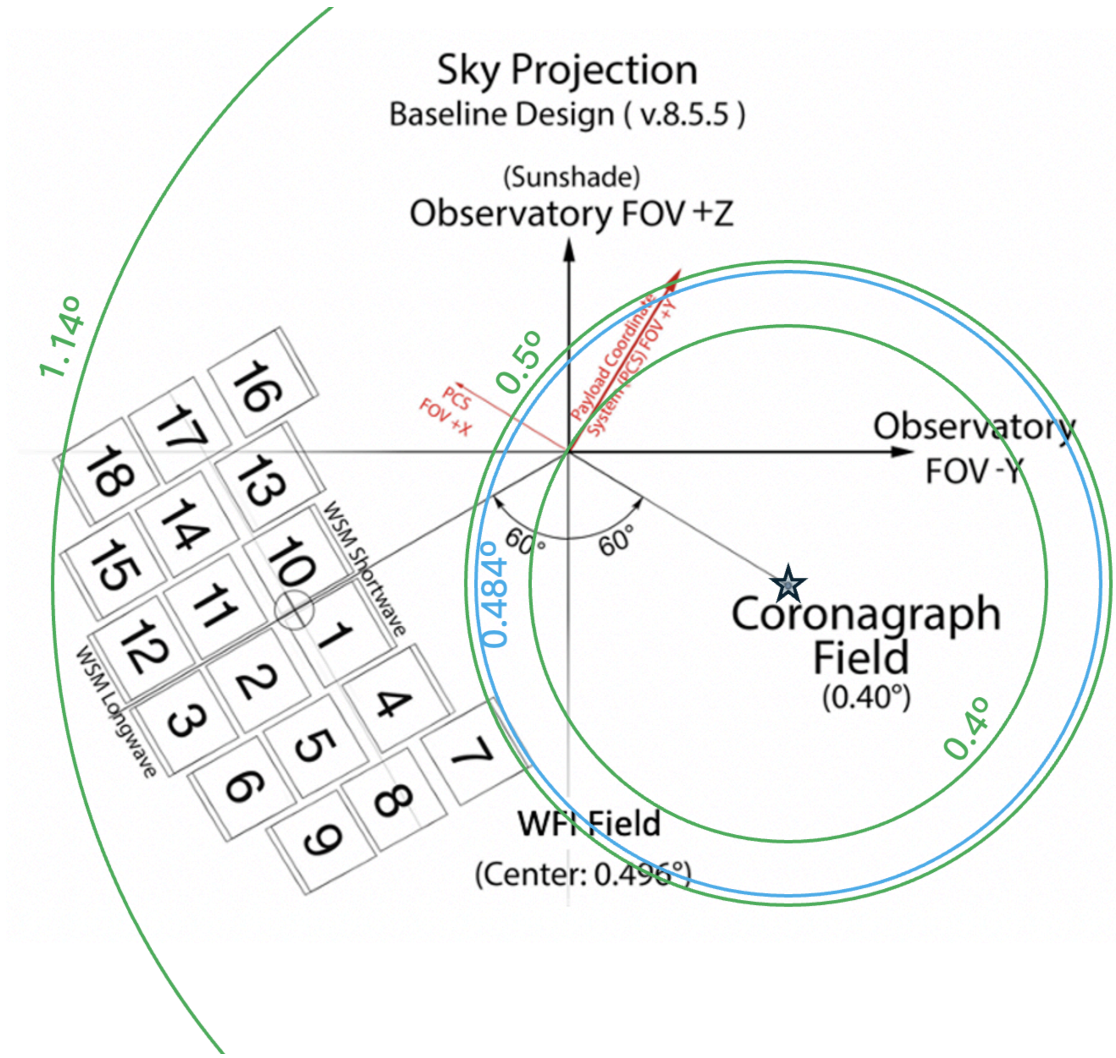


Figure A1: Supplemental figure showing the range of angular offsets between the center of the Cononagraph Instrument field and the near and far corners of the WFI field, useful for understanding effective dithering from both roll variations and differential aberration.

Differential Velocity Aberration:

Velocity aberration, for nonrelativistic motions, moves the apparent position of an object on the sky by an aberration angle A = v / c * sin(θ) closer to the projection of the spacecraft's velocity vector on the celestial sphere, where v is the spacecraft's speed and θ is the angle on the celestial sphere between source and the spacecraft's projected velocity vector. For a spacecraft at L2, the effect is dominated by motion around the sun (30 km/s) with very small corrections for the spacecraft's halo orbit motion around L2 (~ 0.4 km/s), and the total effect is up to ~ 21".

However, aberration affects both our science targets and guide stars, so only differential aberration across the field of view matters. Helpful expositions of differential aberration can be found in WISE technical memo WSDC-D-T034 (J. W. Fowler & H. L. McCallon 2011), and in STScI Instrument Science Report OSG-CAL-97-06 (C. Cox, 1997).

For an extended field of view, the differential of A = v / c * sin(θ) acts as a change to the instrument plate scale and field of view: $dA/d\theta = (v/c)\, cos(\theta)$, so a field of size φ is changed by $\Delta\varphi = \varphi\, dA/d\theta = \varphi\, (v/c)\, cos(\theta)$, and the field is changed by a factor of $(\varphi + \Delta\varphi)/\varphi = 1 + (v/c)\, cos(\theta)$. With (v/c) ~ 10^{-4}, this changes the 12,264 x 24,528 pixel WFI field size by about ±1 pixel on the narrow axis and ± 2 pixels on the long axis.

To understand the implications for WFI parallels, we need one more differential of the effect: How much does it change between *different* observations of a coronagraph target + WFI parallel field?

Aberration means that the WFI field position must shift slightly on sky to keep the coronagraph target in the center of the Coronagraph Instrument field. We assume in this discussion that the spacecraft roll is kept fixed. For the separation of the Coronagraph Instrument and WFI fields of view, 1740" < $\Delta\alpha$ < 4100" (see fig. A1), and the shifts are 0.17 cos(θ) – 0.41 cos(θ) arcsec. The spacecraft's direction of motion changes by about 1 degree per day. So, two visits separated by Δt days will result in a shift of (0.17 to 0.41 arcsec) X Δcos(θ) ~ (0.17 to 0.41 arcsec) sin(θ) Δθ ~ (0.17 to 0.41 arcsec) sin(θ) Δt / 57, where the 57 is degrees per radian. So, for a target observed near the orbital poles, the outermost point of WFI will shift by 0.5 pixel on sky when revisit occurs after 7.5 days; and the innermost point will shift by 0.5 pixel when revisit occurs after 18.5 days.

For targets not observed perpendicular to the direction of motion, these effects get smaller by a factor of sin(θ), and may be too small to matter.