TECHNICAL REPORT

Title: Transit Observations with NIRCam: Subarrays, Data Volumes and Readout Modes	Doc #: JWST-STScI-001767 Date: 28 May 2009 Rev:
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1.0 Abstract

In this document, we consider two exoplanets science projects, which are likely to be of top-priority for JWST, and we outline the observations that may be proposed for these projects. These "test case" observations are explored in detail to check if the current capabilities with NIRCam are adequate to carry out these observations, or if additional modes/features are needed. In order to keep the data volume within limits, it should be possible to operate only single SCAs in the short wavelength (SW) and long wavelength (LW) channels both in subarray and full-frame modes. An on-board averaging capability from 2 to 16 frames in powers of 2 is also recommended. Further investigations are needed to determine if additional subarrays will help in grism observations of bright stars in the LW channel. The weak lenses need to be supported for exoplanets transit studies.

2.0 Science Cases

Over the past few years, the study of transiting extrasolar planets has experienced explosive growth. About 60 transiting extrasolar planets have been discovered to date (see http://www.exoplanet.eu for a full and updated list of all known exoplanets). A large fraction of these exoplanets are discovered around bright and closeby stars, but a few exoplanets discovered by HST are around stars as far away as the Galactic bulge (Sahu et al. 2006). These transiting exoplanets include the most extreme cases in several aspects: planets as small as Neptune-size planets (COROT-Exo-7b, Leger et al. 2009), planets close to the habitable zone (Gl 581c, Selsis et al. 2007), and planets with orbital periods of as small as a day or less (Sahu et al. 2006). HST observations of the brighter hosts have led to the detection of atmospheres containing sodium, hydrogen, methane and water in some of these planets (Swain et al. 2008). Spitzer observations have led to the detection of the secondary transits, and temperature gradients in some of these planets (Knutson et al. 2007).

2.1 An earth-like planet around a nearby sun-like star

The discovery of an earth-like planet around a sun-like star will certainly be deemed as a major milestone in the study of extrasolar planets. Many large efforts, including space missions like Kepler, are currently under way to achieve this goal. The discovery will be most interesting if the host star happens to be bright enough so that the molecular signatures from the atmosphere of such a planet can be detected by JWST.

Since bright host stars will be particularly interesting, let us estimate the brightness of the brightest of such objects. The probability of transit for an earth at 1 AU around a G-type star can be expressed as $R_{\odot}/a \sim 7 \times 10^{10}/1.5 \times 10^{13} \sim 0.5\%$. Assuming every star has an earth-like planet, the optimal sample size needed to observe the first earthlike planet around a sun-like star is ~200. Taking the brightness distribution of known stars, the expected brightness of the first sun-like host of an earth-like planet, is V ~ 6. Depending on the efficiency of transit-search programs and the actual abundance of earth-like planets, it is reasonable to expect a few earth-like planets around stars brighter than V ~ 7, which will be high-priority targets for JWST.

2.1.1 Expected Science observations

The expected JWST observations of such an earth analogue will include continuous monitoring of the star before, during, and after the transit. We note that the expected transit duration is ~12 hours for a planet with an orbital period of 1 year around a Sun-like star. Since this is a differential observation, the baseline observations outside of the transit (either before or after) should preferably have higher S/N than the observations during the transit. One way to achieve this would be to observe an equal amount of time during and after the transit, and to use on-chip comparisons. Alternately, observations may spend double the amount of time outside the transit compared to the time spent within the transit. Thus, the observations will last at least ~36 hours (12 hours before, 12 hours during, and 12 hours after the transit), and should preferably be continuous. The likely observations in such a case will be the following:

- Imaging with NIRCam to get high S/N required for accurate radius and inclination angle determination.
- Spectroscopy with NIRSpec to get high S/N spectra for the possible detection of atmospheric features.
- Imaging and spectroscopy with MIRI.

In this document, we will deal with NIRCam observations only. (For NIRSpec-related issues, see the reports by Tumlinson et al. 2009). We immediately face few challenges in carrying out these observations, which are described below.

2.1.2 Observational Challenges

Saturation: The science case can be best served by obtaining very high S/N observations, which would call for the use of a broadband filter, such as F150W. In the SW channel, we note that the time to saturate for a K=15 G2V star using F150W filter is 8.07 sec (Rieke, private comm.). Thus, considering V-K ~ 1.5 for a G-type star, saturation of a G-type star in full-frame mode in this filter will occur at approximately V ~ 17 for the minimum possible pixel-by-pixel reset plus read of 21.2 seconds (an effective integration time of 10.6 sec). Using a 16x16 pixel subarray would allow us to achieve an effective integration time of 2.6 milliseconds (with 2.6 milliseconds for pixel-by-pixel reset plus 2.6 milliseconds for read). This subarray will allow observations of stars which are brighter by 9 magnitudes compared to the full-frame case, and will thus allow observations of stars as bright as V ~ 8. However, this still falls short by about 1 to 2 magnitudes in our goal of observing the brightest host stars. Furthermore, a 16x16 pixel subarray is not ideal to achieve photometric stability required for this project. Using the weak lens WF3, allows us to observe G-type stars as bight as V ~6 (see Beichman et al. 2007 for more details). Additionally, the photometric stability in such a mode is expected to be larger. Use of a weak lens is thus crucial in carrying out such observations in the SW mode.

We note however, that there is no weak lens in the LW channel. In the LW channel, the time to saturate for a K=15 G2V star in F356W filter is 34.6 seconds. So, saturation will occur roughly at V ~ 15 for a G-type star, for the minimum equivalent integration time of 10.6 seconds in full-frame mode. Use of the 16x16 subarray will gain 9 magnitudes, and allow us to observe even the brightest star at V ~ 6, although the photometric stability in this subarray may not be adequate. Another possibility would be to use the grism and an appropriate subarray, but further investigations are necessary to accurately estimate the brightest stars that can be observed using subarrays with the grism in the LW channel.

Data rate/data volume: The second challenge comes from the data rate/data volume requirements. The expected observation cadence with NIRCam for this particular bright-star case will be as follows: 10.6 seconds pixel-by-pixel reset plus 10.6 seconds for pixel-by-pixel read using 2 detectors (SCAs), one for the SW and one for the LW channel. This mode corresponds to a MULTIACCUM pattern where NGROUP=1, NFRAME=1, NSKIP=0 (It would be worthwhile exploring if some additional readout mode would be suitable for this particular case, but we confine ourselves to the available modes in this document). The volume of data expected in this scenario will be 2(SCAs) x 2048 x 2048(pixels) x 16(bits per pixel) x 86400(sec/day)/21.2(sec/exp) ~ 5.47e11 ~ 547 Gbits/day. This estimate is accurate to about 20%, which is adequate for our purpose. For a more accurate estimate of the data volumes (see the report by Friedman, 2008). If the star is fainter, NGROUP can be >1, resulting in a larger data volume by as much as a factor of 2. Since the volume of data that can be downlinked is limited to ~ 250 Gbit/day, and the capacity of the solid state recorder is limited to ~ 500 Gb at the end of mission, the data volume expected from this observation will thus exceed the current limits by a factor of 2 to 4.

Fortunately, since the transit duration is expected to be several-hours long, it is possible to sacrifice some time resolution, and up to 16 frames can be averaged without any impact on the science. Such averaging of data will allow the data volume to drop well below the downlink and solid state recorder limit. Since the exposures are short, even after averaging, cosmic rays are still expected to be too small to cause any concern. We suggest that a capability be added to average the integrations by up to 16 frames in powers of 2.

As noted earlier, use of subarrays will allow the exposure times to be smaller, which in turn, will allow observations of brighter targets without saturation. We note that only one amplifier per SCA can be used in subarray mode (as opposed to 4 amplifiers when the full array is used), so the expected data rate and data volume are 4 times smaller compared to the full-frame mode described above.

In summary, the following extra capabilities are needed to carry out this particular set of observations:

- In the full-frame mode, it should be possible to operate only single SCAs in the SW and LW channels, since operating all the SCAs simultaneously will lead to an increase in the data volume by an additional factor of 5.
- In subarray mode, it should be possible to operate single SCAs in the SW and LW channels for the same reason stated in the prior bullet.
- To keep the data volume within the range that the recorder can handle, it should be possible to co-add (or average) the data, with N_INT_AVERAGE 2 to 16 frames, in powers of 2.
- Weak lenses need to be supported for exoplanet transit studies.
- Advantages of using grim and subarrays in the LW channel need to be further investigated.

2.2 Determining the frequency of hot earths

The frequency of "hot earths" (with radius 1-3 R_{Earth}, from the star) is a key issue at present, for which JWST can be of great help. Our second science goal is to determine the frequency of hot earths in a given population, which as described below, can be best achieved using JWST. We note that the expected transit depth caused by a hot earth ($R \sim 3\ R_{Earth}$) is ~ 0.1%, the expected transit duration is ~ 3 hours, and the expected orbital period is 1 to 5 days. We also note that for the minimum pixel-by-pixel reset plus read time of 21.2 seconds (10.6+10.6), using F150W filter, saturation will be just avoided for stars with V ~17 for a G-type star. This is close to the turn-off magnitude for NGC 6791, making this an ideal target.

A reasonable way to achieve this goal is to monitor a nearby, rich, high-metallicity cluster, such as NGC 6791 ([Fe/H] ~ +0.4). The expected observations will be similar to the SWEEPS program towards the Galactic bulge (Sahu et al. 2006) or the 47-Tuc monitoring program (Gilliland et al. 2001), where a rich stellar field was monitored continuously for about a week. Hot-earths can be detected with 10-sigma detection in such an observational scenario. Monitoring of 2000 to 5000 stars can potentially lead to the detection of ~20 hot earths (where we assume that 10% of the earth-size planets are "hot earths", and 10% of them transit), perhaps further boosted by the higher metallicity of the cluster. The ability to reach to a few Earth radii as the limit for planet size, and to determine the frequency of such planets, would certainly be a worthwhile experiment that is likely to be carried out with JWST.

Other targets for such observations include the Galactic bulge (which has the advantage of having a large metallicity range, where hot earths can be detected around M dwarfs), LMC (which will lead to the first ever detection of extra-galactic planets), and 47-Tuc (which is a metal-rich globular cluster with turnoff at V ~17).

2.2.1 Expected science observations

Since the expected transit duration is ~ 1 to 3 hours, the observations need to be continuous so that no transits will be missed. The observations should be preferably carried out in 2 filters as a guard against false positives. It is clearly necessary to monitor a large number of stars, which would require that all the 10 detectors be used for the monitoring program.

2.2.2 Observational Challenges

First, such observations require stability and flat-field accuracy of ~0.01%, at least in short term (observations carried out over 10 days).

Secondly, the expected data volume will be high. Expected observation cadence for this particular experiment can be assumed to be as follows: 10.6 seconds for pixel-by-pixel reset plus 10.6 seconds for pixel-by-pixel read (corresponding to the MULTIACCUM pattern: NGROUP=1, NFRAME=1, NSKIP=0), using all the SCAs. The volume of data expected in this scenario will be as follows: 10(SCAs) x 2048x2048(pixels) x 16(bits per pixel) x 86400(sec/day) / 21.2(seconds/exp) ~ 2.73e12 ~ 2,730 Gbits/day. The data volume will be increased by up to an additional factor of 2 if NGROUP >1. This exceeds the current data volume limit by an order of magnitude! However, as in the previous case, the transit duration is expected to be a few hours long.

It is possible to sacrifice some time resolution, and up to 16 frames can be averaged without any impact on the science. Thus, the same averaging capability suggested in the previous case will allow the data volume to be within manageable limits. As expected, cosmic rays are unlikely to be of any concern in such a case. Fortunately, the ICDH hardware is capable of co-adding up to 16 frames (in powers of 2) of all the 10 SCAs, although it is unclear if the limit checks performed by the software that operates the ICDH hardware would allow sustained operation in this mode if all the 10 SCAs were used simultaneously (Chris Dailey, private communication). It is clear, however, that the software would allow sustained operation if only 5 SCAs are used. The observations will last for 8 to 10 days, similar to SWEEPS and 47-TUC HST observations, taking alternate exposures in F115W and F150W filters in the SW channel, and F277W and F356W filters in the LW channel.

This observational scenario also calls for an on-board averaging capability of the integrations by up to 16 frames in powers of 2, which will solve the data volume/data rate issue.

Thus, the extra capabilities needed to carry out this particular set of observations are similar to the previous set:

- To keep the data volume within the range that the recorder can handle, an on-board averaging capability is necessary. This can be accomplished with N_INT_AVERAGE = 2 to 16 frames, in powers of 2.

3.0 Conclusions

- The expected data volumes for some transit observations pose challenges for NIRCam, which can be solved by adding capability to carry out onboard sum/average tasks.
- It should be possible to perform operations using a single SCA in SW and LW channels, both in subarray, as well as full-array modes.
- Weak lenses need to be supported for exoplanet transit studies.

4.0 References

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Acknowledgements: We would like to thank Ron Gilliland for help with the science and observational scenarios presented in this document.