Nod-and-Shuffle Observation Outline

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INTRODUCTION

KCWI will utilize the so-called nod-and-shuffle technique to achieve the scientifically desired 10^{-4} sky subtraction accuracy. Descriptions of the detector shuffling implementation, telescope nodding control, and the nod-and-shuffle mask system can be found elsewhere. This note is intended to detail the process of nod-and-shuffle observations to help clarify and identify any functionality and modes of operation that need to be tested, modified, or added to the Keck TCS, MAGIQ guider system, and KCWI software and communication architecture.

The basic premise of a nod-and-shuffle is shown in Figure 1. In the simplest case, two fields are specified: a **target** field that contains an object of interest, and a **background** field that is chosen as it is deemed to be empty. A mask is inserted to block light from falling on 2/3 of the detector, leaving the central 1/3 uncovered (this reduces the available spectral bandpass by a factor of 3). The telescope is pointed at the target field, instrument shutter is opened and the exposure is started (Figure 1a). After some predefined time T, that is short compared to the characteristic timescales over which sky brightness changes (on the order of 100s), the shutter is closed. The collected charge is shuffled under one side of the mask and the telescope is nodded to the background field (Figure 1b). The shutter is reopened for another integration period. After the same time as before, the shutter is closed, charged shuffled by 1/3 of the detector back to the initial position and the telescope returned to pointing at the target field (Figure 1c). This cadence is repeated until the total integration time on both fields has reached the desired length, usually 20-30 minutes (the value depends on

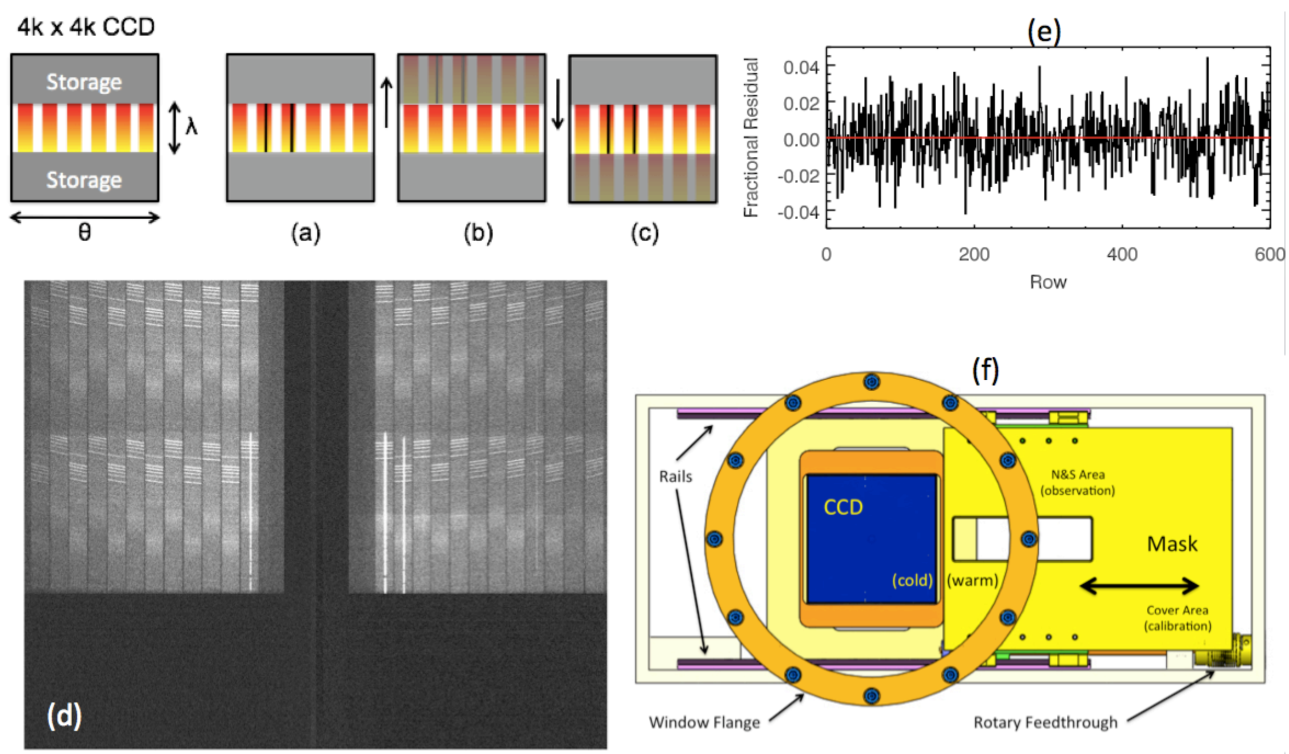

Figure 1. Nod-and-Shuffle. Figures (a)-(c) show the motion of charge on the CCD during a shuffle, which coincide with a telescope nod; the telescope is pointing at the target in images (a) and (c), while it is trained on the background in (b). Panel (d) is a resulting image from CWI, Plot (e) shows the resultant subtraction accuracy, while panel (f) is a CAD rendering of the mask implementation for KCWI.

the length of exposure necessary to become sky-background, rather than detector read-noise, limited). At this point the detector is read out; the resultant image contains both the target and background spectra. Figure 1(d) is an example of a nod-and-shuffle spectrum collected with CWI. The two spectra are obtained nearly contemporaneously, with photons collected by each going through the same optical elements and incident on the same physical detector pixels. This approach minimizes the effect of instrument systematic effects (e.g., vignetting within the system, pixel-to-pixel response variations). This approach allows for very accurate sky subtraction, evidence of which is seen in CWI (Figure 1e).

For some types of observations of faint and diffuse objects (e.g., cosmic web, reionization bubbles), it is difficult to determine a priori whether a particular background field is truly empty. In those cases multiple background fields will be chosen, separated by distances larger than the expected characteristic sizes of the objects being observed (typically a few arcminutes). This would be done to mitigate the impact of structure present in any single field. This requirement adds complexity to the design and to the preparation and observing processes.

A full N+S campaign will involve multiple exposures, typically on the same target, though the observer will typically choose to adjust the target location within the instrument field-of-view between exposures. This adjustment will likely be a small dither, usually a fraction of slit or a rotation the instrument position angle to alter the object spatial sampling. An identical dither may or may not be applied to the background fields, or a different set of background fields may be chosen for each target pointing.

It is expected that primary targets for nod-and-shuffle observations will be low surface brightness objects that cannot be easily detected with short integrations. As such, the telescope will be pointed using blind offsets and pointing offsets will be used to execute the nod part of the nod-and-shuffle. As these observations are most likely to be performed during highly coveted dark time, it is paramount that the observing procedure be streamlined.

PRE-OBSERVING PREPARATION

A full nod-and-shuffle exposure is defined when the following quantities are specified:

1. IFU position angle
2. KCWI spectrograph settings (slicer, gratings, filters)
3. Tracking guider position angle
4. Tracking guider astronomical filter
5. Chopping frequency / single integration time
6. Total exposure time
7. For the primary target:
    a. Sky coordinates, possibly as an offset from a nearby brighter star
    b. Pixel coordinates of a guide star within the guider FOV (possibly integration time and ROI)
8. For each background field:
    a. Offset from the primary target
    b. Pixel coordinates of a guide star within the guider FOV (possibly integration time and ROI)

There is significant overhead involved in preparing a N+S observation and the observer is responsible for preparing the guide star data prior to the run (?). Ideally, each field used in an observation would be visited and the observer would be allowed to verify coordinate accuracy. Such a visit could occur during twilight, if the target is available, or, possibly, during bright time, or an engineering night. If a mode of operation is chosen in which the pointing information is verified well in advance of the observations, the feedback returned to the observer from such a procedure will need to be defined.

NOD-AND-SHUFFLE PROCEDURE

shows the series of steps for a sample single N+S exposure, it attempts to detail the communication between KCWI hardware and software and its MAGIQ and TCS counterparts. Assumptions are made that the locations of the guide stars have been verified and that the tracking guider and K-mirror are active. It would be useful for the telescope operator and the observer to have prior images of the guider field for each pointing. The procedure described in the table takes a half-length integration of the background field to bookend the full exposure to better trace the changing sky-brightness; this technique is akin to the trapezoidal integration rule used in calculus. Figure 2 is graphical representation of this exposure pattern.

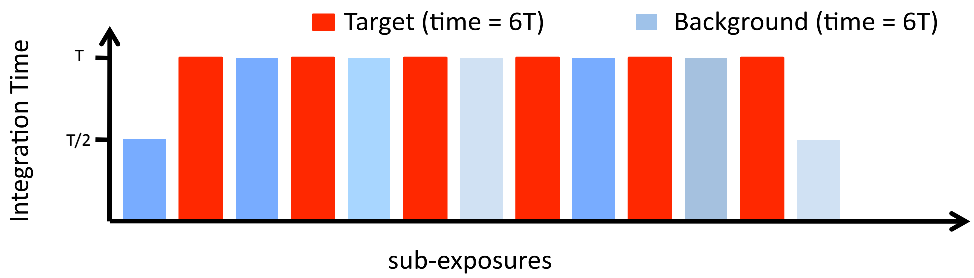

Figure 2: Graphical representation of the "trapezoidal rule" nod-and-shuffle pattern

A few things of note about the N+S implementation sequence:

- The state of the instrument is the same at the start and end of the N+S script, meaning the N+S exposure can be repeated immediately, or a small dither applied to the target field and next script can be ran quickly, provided the existing script generating GUIs have this functionality

- The script keeps track of the pixel coordinates of the guide stars and the offsets to the target and background fields. This seems preferable to having all those coordinates stored in the MAGIQ or TCS system. A possible caveat here is a case in which the guider system corrects for instrument (including K-mirror) and guider axis misalignment. That is, for observations that stay on a single target the initial guide star pixel coordinates are updated to reflect guidestar trajectory or offset. If that is the case, either the same correction will have to be available to the N+S script, or the guider will store and access the guide star coordinates for each field, or the guider will update the coordinates provided by the script to reflect current values.

- The final fits image contains pointing information for every subexposure (RA, Dec, Airmass, etc., guider pointing coords, any other useful guider information, perhaps star fluxes, seeing, and so forth); they also contain instrument info (e.g., detector temperatures, pressures, motor encoder readings, plus other information, as defined in another note).

Table 1: Nod-and-shuffle step-by-step prescription

Step #	Action	Who Directs?	Notes
1	Ensure spectrograph settings are as desired	Op. and Obs.	
2	Go to primary target field	Op.	
3	Ensure guide star location, start guiding	Op. and Obs.	
4	Start N+S script	Op. or Obs.	
5	Collect spectro information into hdr file	Script	Most subsystems probed
6	Tell MAGIQ to stop guiding	Script	
7	Request TCS offset to first bg field (BG1)	Script	star coordinates, maybe int. time and ROI?
8	Wait for telescope to settle	Script	Open loop? Does the TCS return anything?
9	Send BG1 guide star info to MAGIQ	Script	The script keeps track of the star coordinates, dithers and offsets (?)
10	Tell MAGIQ to start guiding	Script	
11	Wait for guiding to stabilize	Script	Open loop? Does MAGIQ return anything?
12	Collect MAGIQ + TCS info into hdr file	Script	What information is available?
13	Open shutter, integrate for T/2, close shutter	Script	
14	Shuffle charge UP on CCD	Script	
15	Tell MAGIQ to stop guiding	Script	
16	Request TCS offset back to target field	Script	
17	Wait for telescope to settle	Script	?
18	Send target star info to MAGIQ	Script	
19	Tell MAGIQ to start guiding	Script	
20	Wait for guiding to stabilize	Script	
21	Collect MAGIQ + TCS info into hdr file	Script	
22	Open shutter, Integrate time T, close shutter	Script	
23	Shuffle charge DOWN on CCD	Script	
24	Tell MAGIQ to stop guiding	Script	
25	Request TCS offset to the next bg field (BGn)	Script	
26	Wait for telescope to settle	Script	
27	Send BGn guide star info to MAGIQ	Script	
28	Tell MAGIQ to start guiding	Script	
29	Wait for guiding to stabilize	Script	
30	Collect MAGIQ + TCS info into hdr file	Script	
31	Open shutter, integrate T or T/2, Close shutter	Script	T/2 only if this is the last BG exposure
32	Shuffle charge UP on CCD	Script	
33	Tell MAGIQ to stop guiding	Script	
34	Request TCS offset back to target field	Script	
35	Wait for telescope to settle	Script	
36	Send target star info to MAGIQ	Script	
37	Tell MAGIQ to start guiding	Script	
38	Wait for guiding to stabilize	Script	
39	Go to step 21 if not last BG exposure	Script	
40	Read out detector, write FITS data+header	Script	
41	Return	Script	Note that the return state is the same as the initial state.

REQUIREMENTS IMPOSED ON TCS SYSTEM, MAGIQ GUIDER SYSTEM AND KCWI CONTROL

The determination of what tasks are to be performed on what hardware, and the process distilling the set of requirements for the various subsystems will take a several iterations between the WMKO and CIT teams.

To start off with:
KCWI Host must be able to command telescope offsets to the TCS.

TCS must raise a flag/bit when a move has been completed and pointing has settled, otherwise the offset move and settling times must be determined and included as an open loop delay in the scripts.

KCWI Host computer must be able to access guidance pixel information, with knowledge of star flux, seeing data, and sky background data, if available, desired.

KCWI Host computer must be able to access pointing information from the TCS. This includes RA, Dec, offsets, airmass, alt, az, and others (TBD).

KCWI Host must be able to set the guide star pixel coordinates on the MAGIQ guider. Ability to set integration time, tracking box, or region of interest information is desired.

MAGIQ system must inform KCWI host when guiding has stabilized, otherwise the stabilization time must be determined and included as an open loop delay in the scripts.

QUESTIONS

Does the MAGIQ guider record sky brightness measurements? Would that be useful in any way?

REFERENCES

Adkins, MAGIQ
Cuillandre "va-et-vient"
Sembach+Tonry "nod-and-shuffle"