Results of KCWI "Nod & Shuffle" Observing Mode Testing with ESI

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SUMMARY

To study the feasibility and efficiency of KCWI "nod-and-shuffle" mode operations using the existing telescope control and guiding systems on Keck II, we carried out tests on ESI during engineering time in August 2011. Based on these tests, we find that the current guiding system works well for nod-and-shuffle mode observations only for the case in which the guide star remains on the guider field of view at all times, a restriction which would greatly limit the ability of KCWI to achieve optimal sky subtraction. Employing larger nods that move the guide star off the guider field of view, as will be required for observations of extended objects with KCWI, requires regular and laborious manual intervention by the OA in order to pause and resume guiding, and thus introduces substantial operational overhead that leads to a correspondingly significant loss of science time. Furthermore, the need to pause and resume guiding makes it hard to accurately reposition the guide star at the exact same spot as it was in at the start of the exposure sequence, thus introducing small spatial offsets between sub-exposures within a given nod-and-shuffle sequence and degrading the effective spatial resolution of the observations. Tests of Keck II nodding repeatability demonstrate that the telescope offsets accurately and should therefore be capable of reliably bringing the guide star to the predicted location after completing a nod move. It is possible that modifications to the Keck II telescope and guider control software can substantially reduce overhead and deliver significant improvements in KCWI operational efficiency; however, detailed discussion of such changes is postponed for a later design note.

BACKGROUND

The success of KCWI will depend critically on the quality of the sky background subtraction. To achieve optimal sky subtraction, KCWI will employ a "nod-and-shuffle" observing mode in which observations of the source (target) field are interleaved with observations of a suitable sky (background) region, with both the source and sky spectra being stored on-chip until readout. This observing mode requires performing multiple telescope offsets between the source and sky fields in the course of a each exposure. This raises several questions about the ability of Keck II to support such observations:

1. If the nod moves the guide star off the guider field of view, will guiding resume when the reverse nod executes?
2. Is open loop tracking sufficiently good that exposures of the sky field can be unguided?
3. What operational overheads are incurred in carrying out "nod-and-shuffle" mode observations?
4. How accurately can the Keck II telescope offset between fields separated by various angular distances?

In the following sections we describe the planned KCWI observing model, review recent tests performed with ESI designed to test this model, and discuss the implications of these tests. Future work will recommend changes to the telescope and guider software which could enhance KCWI operational efficiency.

EXISTING AND PROPOSED OBSERVING MODELS FOR KCWI

Existing CWI Observing Model

According to the KCWI instrument development team, the baseline plan is for KCWI to adopt an observing style similar to that currently employed on the CWI instrument at Palomar (P. Morrissey, private communication). The overall CWI sequence was described as follows:

1. 1/2 length exposure on sky
2. full length exposure on source
3. loop alternating between full length sky and source exposures
4. 1/2 length exposure on sky

During the loop in step 3, the detailed sequence was described as follows:

1. Command guider to slew to field 1
2. Wait 10s for slewing/settling
3. Begin guiding
4. Open shutter, expose 120s on field 1, close shutter
5. Shuffle charge (fraction of a second)
6. Stop guiding
7. Wait 5s for guider command buffer to empty
8. Slew to field 2
9. Wait 10s for slewing/settling
10. Begin guiding
11. Open shutter, expose 120s on field 2, close shutter
12. Shuffle charge
13. Stop guiding
14. Wait 5s for guider command buffer to empty
15. Loop back to step 1

Here, field 1 is the source field (with the science target) and field 2 is the sky (background) field.

Proposed KCWI Observing Model

Based on the CWI model, we composed an ESI shell script to simulate the CWI observing process at Keck. The corresponding shell script is reproduced in its entirety in Appendix A. Its operation can be summarized as follows:

1. Set up guiding on source field
2. Nod to sky position
3. Wait for telescope/guider to settle
4. Open shutter, expose 60s on sky, close shutter
5. Nod back to source position
6. Wait for telescope/guider to settle
7. Open shutter, expose 120s on source field, close shutter
8. Nod to sky position
9. Wait for telescope/guider to settle
10. Open shutter, expose 120s on sky, close shutter
11. Repeat previous 6 steps 4 more times (5 times total)
12. Nod back to source position
13. Wait for telescope/guider to settle
14. Open shutter, expose 120s on source field, close shutter
15. Nod to sky position
16. Wait for telescope/guider to settle
17. Open shutter, expose 60s on sky, close shutter
18. Return to source field
19. Read out CCD

This observing sequence yields 600 s on source and 600 on sky.

ESTIMATION OF OBSERVING EFFICIENCY WITH KCWI BASED ON TESTS WITH ESI

During ESI engineering time on 2011-Aug-31 (HST), we carried out a series of tests using the cwi_sequence script and logged the results to analyze operational overheads. Each observing sequence consisted of 5×60 sec sub-exposures on the source field and 4×60 sec + 2×30 sec on the background field. Parameters were varied as summarized in the following table:

Sequence	Scenario	Nod (E,N)	Nod off guider FOV?	Pause before nod?	Guide on sky?
2	1	10,10	No	No	Yes
3	2	0,-30	Yes	No	No
4	3	0,-30	Yes	Yes	No
5	4	0,-30	Yes	Yes	Yes
6	4	0,-30	Yes	Yes	Yes

Table 1. CWI observing sequence input parameters

Please note that sequence 1 was a test sequence which is not of interest and is thus not included in the table or the discussion to follow. Below, we review the results of the remaining sequences.

Scenario 1: On-chip nod

This sequence involved only a small nod of 10" east and 10" north in order to keep the guide star on the guider field of view at all times; it was thus intended to characterize the performance of the system under near-optimal conditions which involved no interruption of guiding. Results are shown in Table 2.

Results	Value
Start time (HST)	22:25:21
End time (HST)	22:36:11
Elapsed time	650 sec
Exposure time	600 sec
Time to nod from source to sky	4 sec
Time to nod from sky to source	4 sec
Overhead (actual)	50 sec
Fractional overhead (actual)	8.3%

Table 2. Results from sequence 2

Note that the overhead quoted above includes CCD erase time (13 sec) plus time for telescope nodding and settling; however, CCD readout time is ignored because we assume that telescope slews and other activities will occur during that time and thus that it will not be wasted. Inspection of the resulting ESI image indicates that the telescope was moving during some of the exposures. Follow-up investigation determined that this was due to a missing pause in the `gotobase` command which returns the telescope to the starting position. Whereas the command to nod the telescope to the sky position included a 4-second pause to allow the telescope to settle, the `gotobase` command lacked this pause and thus started the on-source exposure prematurely, resulting in telescope motion during the exposure. The ESI `gotobase` command has since been fixed to add a suitable pause. As a result, the correct overhead should have been somewhat longer than tabulated above.

Scenario 2: Off-chip nod without guider intervention

The intention of this test was to determine whether the guider would pause while the star was off the field of view, and then resume once the telescope returned to its original location. This sequence involved a nod of 30" south, which was larger than in sequence 2 and thus moved the guide star off the guider field of view. In practice, we found that the guider software interrupted guiding once the star moved off the field of view, and did not resume once the corresponding reverse nod brought the star back onto the guider field of view. We thus abandoned this test due to the loss of guiding, since this is not a workable mode of operation. We will not consider scenario 2 further.

Scenario 3: Off-chip nod without guiding on sky

Sequence 4 employed the same 30" nod size as sequence 3, moving the guide star off the guider field of view. However, in this case we inserted a pause in order to allow the OA to stop guiding before executing the nod. Guiding remained "off" during the on-sky exposure so that we could determine the quality of the open loop tracking. After nodding back to the source field, we paused again to allow the OA to set up and resume guiding at approximately the same location as before. In practice, we found that the unguided portion of the exposure showed poor image quality, indicating that the open-loop telescope tracking was not sufficient to maintain good tracking over a 60 sec exposure.

Results	Value
Start time (HST)	23:06:57
End time (HST)	23:21:48
Elapsed time	891 sec
Time to nod from source to sky	14 sec
Time to nod from sky to source	33 sec
Exposure time	600 sec
Overhead (actual)	291 sec
Fractional overhead (actual)	48.5%

Table 3: Results from Sequence 4

Measured overheads are significantly higher in this mode than in the on-chip nodding mode. This results from:

- the need to pause guiding prior to nodding off the guider field of view;
- the need to resuming guiding after nodding back to the source position; and,
- the need to recenter the guide star after returning to the source position due to drift that occurs during unguided sky exposures.

Scenario 4: Off-chip nod with guiding on sky

As with sequences 3 and 4, the last two sequences used a 30" nod size and thus the guide star moved off the guider field of view during nods. This scenario differs from scenario 3 in that guiding was employed both on the source field and the sky field. There is no functional difference between sequences 5 and 6; sequence 6 is simply a repeat of sequence 5 and was completed more quickly because of greater attentiveness by the observer during execution of the script. Image quality was good throughout the exposures since guiding was enabled both on-sky and on-source.

Results	Sequence 5	Sequence 6
Start time (HST)	23:24:28	23:41:11
End time (HST)	23:40:08	23:56:18
Elapsed time	940 sec	907 sec
Time to nod from source to sky	21 sec	25 sec
Time to nod from sky to source	39 sec	25 sec
Exposure time	600 sec	600 sec
Overhead (actual)	340 sec	307 sec
Fractional overhead (actual)	56.7%	51.2%

Table 4: Results from Sequences 5-6

As shown in the tables, overheads are higher in this mode than in the preceding scenarios because of the need to set up guiding on the sky field as well as on the source field.

Idealized Model

The results from the tests above allow us to construct an idealized model of the CWI-like observing process and to draw conclusions about the resulting efficiency of observing in various modes.

Operation	Time [sec]	Comments
CCD erase	13	May be more or less for KCWI
Nod on chip	4	Includes time for telescope to settle after move
Nod off chip	14	Includes time to stop guiding
Start guiding	11	Additional overhead on top of nod

Table 5: Predicted overheads for various operations

With these ideal overheads determined, we can estimate the predicted overheads for the various observing scenarios explored above. We assume that each exposure sequence will include time for CCD erase, 6 nods from source to sky, and 5 nods from sky to source; we presume that the final nod from sky back to source will occur during CCD readout and will thus not add any overhead to the exposure sequence. The following table shows the resulting predicted overheads.

Scenario	Nod	Guiding on sky?	On-chip nods	Off-chip nods	Guiding setups	Predicted overhead	
						Total [sec]	Fractional
1	On chip	N/A	11	0	0	57	10%
3	Off chip	No	0	11	5	222	37%
4	Off chip	Yes	0	11	11	288	48%

Table 6: Predicted total overheads for various observing scenarios

Discussion

The efficiency of observing in CWI-like modes at Keck critically depends on what happens with the guide star during the exposure. Due to the 13 second overhead involved in erasing the ESI CCD, please note that lowest achievable overhead of an exposure sequence is 2.2% (assuming zero time lost to nodding and guiding).

If the guide star remains on the guider in both the source and sky positions (scenario 1), then guiding can continue uninterrupted throughout the nod sequence and the overhead involves only the time required to nod the telescope and allow it to settle, which requires about 4 seconds per nod. The resulting predicted overhead is about 10% of the exposure time[1], still a relatively small value. However, the on-chip nodding mode limits the size of the nod throw to no more than size of the guider field of view (approximately 4 arcmin under ideal conditions), and this will not be adequate to support KCWI observing of extended objects which are expected to require nod throws of up to a degree (P. Morrissey, private communication).

If the nod throw is sufficiently large that it moves the guide star off the guider field of view, then guiding must be manually paused before the nod occurs or else the guider will fault. We tested both the case in which the telescope remains unguided while observing the sky region (scenario 3) and the case in which guiding is enabled on the sky region (scenario 4). The need to pause guiding prior to the nods, and to manually re-start guiding, increases the operational overhead substantially: in the case of no on-sky guiding (scenario 3), predicted overhead is at least 37% of the exposure time (and probably more if the guide star

1 Note that the derived overheads assume that the standard exposure time is 60 sec per nod. If the standard current CWI exposure time of 30 sec were used instead, the overheads quoted above would double, reaching 96% in the case of scenario 4.

requires re-centering due to drift). When guiding both on source and on sky (scenario 4), predicted overhead reaches 48%.[2]

The above analysis establishes that the present guiding system on Keck telescopes can only operate KCWI efficiently in the special case of on-chip nodding. In the more general case for which nods take the guide star off the field of view, substantial losses of telescope time will result.

NODDING ACCURACY

A valid concern raised by the KCWI science team was the accuracy and repeatability of telescope nods. If the nods are repeatable to high accuracy then the telescope should be able to resume guiding without manual intervention once the telescope returns to a field with a guide star. To quantify the nodding repeatability, we performed a short on-sky test with ESI on the night of 2011-Aug-31. The test procedure was as follows:

1. Point the telescope south on the meridian, so that north corresponds to the positive elevation axis, and east to the negative azimuth axis.
2. Select a star and have the Observing Assistant center the star at the REF pointing origin of ESI (pixel position x=512, y=256).
3. Turn off guiding.
4. Execute a telescope move in either the north/south or east/west direction.
5. Immediately execute the opposite move.
6. Re-enable guiding to provide a measurement of the guide star location.

Nods of various sizes (logarithmically spaced from 10" to 1 degree) were made along the east/west (azimuth) or north/south (elevation) axes. Results of this test are tabulated below.

Trial	Nod size		Starting position		Ending position		Offset		
	east ['']	north ['']	x [px]	y [px]	x [px]	y [px]	x [px]	Y [px]	r [px]
1	10	0	512	256	509	254	-3	-2	3.6
2	0	10	512	256	511	254	-1	-2	2.2
3	36	0	512	256	511	254	-1	-2	2.2
4	0	36	512	256	512	256	0	0	0.0
5	100	0	512	256	513	256	1	0	1.0
6	0	100	512	256	511	256	-1	0	1.0
7	360	0	512	256	513	255	1	-1	1.4
8	0	360	512	256	512	256	0	0	0.0
9	1000	0	512	256	512	255	0	-1	1.0
10	0	1000	512	256	512	256	0	0	0.0
11	3600	0	512	256	513	255	1	-1	1.4
12	0	3600	512	256	514	256	2	0	2.0

Table 7: Results of on-sky nod testing

[2] In order to ensure that all observations of the source field were spatially coincident (thus preventing an increase in the effective PSF of the on-source images due to offsets in the sub-exposures), we should have had the OA record the original location of the guide star and then, each time we returned to the source field and set up guiding, had the OA enter these coordinates to force the guide star back to the original location. In this case, one would also need to allow the guider time to complete one or more guider correction iterations in order to ensure that the star was at the original location before resuming the integration. Carrying out this revised procedure would have increased the quoted overheads by perhaps 20%.

The offsets shown in the final column are small with an average less than 1.4 pixels in radius (less than 0.5" based on the ESI guider plate scale of 0.233"/pixel), indicating that the nods are highly repeatable in both axes.[3] Given that the typical guide box size for Keck observations is 10", this repeatability should be more than adequate to bring the guide star within the guide box after a nod.

CONCLUSIONS

The tests described in the preceding sections establish the following:

- Current guider software deployed on Keck instruments can support reasonably efficient operation of KCWI only if the nod size is restricted to values small enough to keep the guide star on the guider field of view at all times.
- For nod sizes large enough to move the guide star off the guider field of view, the current Keck guide software requires guiding to be paused and later resumed, at a high cost to observing efficiency.
- The efficiency of operating in scenario 3 (unguided operation while observing the sky background region) is only marginally better than in scenario 4 (guiding while observing the sky background region) because the subsequent telescope drift which occurs during unguided mode necessitates time-consuming re-centering of the guide star upon return to the sky field.
- Unguided exposures lasting more than a few seconds are subject to smearing due to the poor open-loop tracking on Keck II. As a result, unguided sky images acquired with KCWI will be smeared, and thus the quality of background subtraction may suffer.

The results compel us to consider whether changes to the Keck guider software and the telescope control system can substantially improve the quality and quantity of data produced by KCWI. A separate document will present suggested modifications to the Keck guider and telescope control software that will achieve these goals.

[3] We note that the *smallest* nods are actually the *least* repeatable, which is counterintuitive.

APPENDIX A: CWI_SEQUENCE SCRIPT

The following shell script (`/home/esieng/scripts/cwi_sequence`) was employed in the on-sky tests of the CWI observing mode with ESI.

```
#!/bin/csh -f
#+
# cwi_sequence -- obtain CWI-style exposure sequence with ESI
#
# Purpose:
#     Use ESI to acquire an exposure in the style of CWI and log the
#     results to assess the overheads involved in KCWI operation.
#
# Usage:
#     cwi_sequence
#
# Arguments:
#     None
#
# Key variables:
#     The following variables control operation of the script:
#     - pause_on_sky: if set to 1, pause for guiding setup
#                 when moving to sky field
#     - pause_on_obj: if set to 1, pause for guiding setup
#                 when moving to source field
#     - pause_before_nod: if set to 1, pause before nodding
#                 to allow guiding to be turned off
#
# Output:
#     To stdout
#
# Procedure:
#     - Set up guiding on source field
#     - Nod to sky position (on guider)
#     - Waitfor telescope/guider to settle
#     - Open shutter, expose 60s on sky, close shutter
#     - Nod back to source position
#     - Waitfor telescope/guider to settle
#     - Open shutter, expose 120s on source field, close shutter
#     - Nod to sky position
#     - Waitfor telescope/guider to settle
#     - Open shutter, expose 120s on sky, close shutter
#     - Repeat previous 6 steps multiple times
#     - Nod back to source position
#     - Waitfor telescope/guider to settle
#     - Open shutter, expose 120s on source field, close shutter
#     - Nod to sky position
#     - Waitfor telescope/guider to settle
#     - Open shutter, expose 60s on sky, close shutter
#     - Return to source field
#     - Read out CCD
#
# Exit values:
#      0 = normal completion
```

```
#      1 = wrong number of arguments
#
# Example:
#     1) Execute cwi-style observing sequence with log to file
#     cwi_sequence_1.log:
#           > script cwi_sequence_1.log
#           > cwi_sequence
#-
# Modification history:
#     2011-Aug-31 GDW   Original version
#-----------------------------------------------------------------------

set pause_on_sky = 1
set pause_on_obj = 1
set pause_before_nod = 1

@ fulltime = 60
@ halftime = $fulltime / 2
@ niter = 4

@ nod_e = 0
@ nod_n = -30

# set up for long exposure (which we will terminate prematurely)...
tint 1000

# print header info...
set t = `timestamp`
echo  "[$t] ---------- START ----------"
echo  "[$t] Params: "
echo  "[$t]   fulltime     = $fulltime"
echo  "[$t]   halftime     = $halftime"
echo  "[$t]   niter        = $niter"
echo  "[$t]   nod_east     = $nod_e"
echo  "[$t]   nod_north    = $nod_n"
echo  "[$t]   pause_on_sky = $pause_on_sky"
echo  "[$t]   pause_on_obj = $pause_on_obj"
echo  "[$t] Set up guiding on source field"
markbase

# start with nod to sky position...
echo  "[$t] Nod to sky position (on guider)"
echo  "[$t] Waitfor telescope/guider to settle"
if ( $pause_before_nod) then
      set t = `timestamp`
      echo  "[$t] Pausing for nod..."

      beep 2
      set ans = $<
      set t = `timestamp`
      echo  "[$t] Resuming after nod..."
endif
en $nod_e $nod_n

if ( $pause_on_sky ) then
```

```
      set t = `timestamp`
      echo  "[$t] Pausing for guiding setup on sky..."

      beep 2
      set ans = $<
      set t = `timestamp`
      echo  "[$t] Resuming after guiding setup on sky..."
endif

# acquire HALF exposure on sky...
set t = `timestamp`
echo "[$t] Open shutter, expose $halftime sec on sky, close shutter"
echo "[$t] Expose $halftime on sky"
goi &
waitfor -s esi exposip=t
sleep $halftime

# start loop...
@ i = 1
while ( $i <= $niter )

      # nod to source position...
      set t = `timestamp`
      echo "[$t] Starting iteration $i of $niter"
      echo "[$t] Nod back to source position"
      echo "[$t] Waitfor telescope/guider to settle"
      modify -s esi pause=t
      if ( $pause_before_nod) then
            set t = `timestamp`
            echo  "[$t] Pausing for nod..."

            beep 2
            set ans = $<
            set t = `timestamp`
            echo  "[$t] Resuming after nod..."
      endif
      gotobase

      if ( $pause_on_obj ) then
            set t = `timestamp`
            echo  "[$t] Pausing for guiding setup on obj..."

            beep 2
            set ans = $<
            set t = `timestamp`
            echo  "[$t] Resuming after guiding setup on obj..."
      endif

      # FULL integration on source...
      set t = `timestamp`
      echo "[$t] Open shutter, expose $fulltime sec on source field, close
shutter"
      echo "[$t] Expose $fulltime on object"
      modify -s esi resume=t
      sleep $fulltime
```

```
      # nod to sky...
      set t = `timestamp`
      echo "[$t] Nod to sky position"
      echo "[$t] Waitfor telescope/guider to settle"
      modify -s esi pause=t

      if ( $pause_before_nod) then
            set t = `timestamp`
            echo  "[$t] Pausing for nod..."

            beep 2
            set ans = $<
            set t = `timestamp`
            echo  "[$t] Resuming after nod..."
      endif
      en $nod_e $nod_n

      if ( $pause_on_sky ) then
            set t = `timestamp`
            echo  "[$t] Pausing for guiding setup on sky..."

            beep 2
            set ans = $<
            set t = `timestamp`
            echo  "[$t] Resuming after guiding setup on sky..."
      endif

      # FULL exposure on sky...
      set t = `timestamp`
      echo "[$t] Open shutter, expose $fulltime sec on sky, close shutter"
      echo "[$t] expose $fulltime on sky"
      modify -s esi resume=t
      sleep $fulltime

      # increment counter...
      @ i++

end

# final FULL exposure on source...
set t = `timestamp`
echo "[$t] Nod back to source position"
echo "[$t] Waitfor telescope/guider to settle"
modify -s esi pause=t
if ( $pause_before_nod) then
      set t = `timestamp`
      echo  "[$t] Pausing for nod..."

      beep 2
      set ans = $<
      set t = `timestamp`
      echo  "[$t] Resuming after nod..."
endif
gotobase
```

```
      if ( $pause_on_obj ) then
            set t = `timestamp`
            echo  "[$t] Pausing for guiding setup on obj..."

            beep 2
            set ans = $<
            set t = `timestamp`
            echo  "[$t] Resuming after guiding setup on obj..."
      endif

set t = `timestamp`
echo "[$t] Open shutter, expose $fulltime sec on source field, close shutter"
echo "[$t] expose $fulltime on object"
modify -s esi resume=t
sleep $fulltime

# nod to sky...
set t = `timestamp`
echo "[$t] Nod to sky position"
echo "[$t] Waitfor telescope/guider to settle"
modify -s esi pause=t
if ( $pause_before_nod) then
      set t = `timestamp`
      echo  "[$t] Pausing for nod..."

      beep 2
      set ans = $<
      set t = `timestamp`
      echo  "[$t] Resuming after nod..."
endif
en $nod_e $nod_n

# HALF exposure on sky...
set t = `timestamp`
echo "[$t] Open shutter, expose $halftime sec on sky, close shutter"
echo "[$t] expose $halftime on sky"
modify -s esi resume=t
sleep $halftime

# return to source field...
set t = `timestamp`
echo "[$t] Return to source field"
modify -s esi pause=t
if ( $pause_before_nod) then
      set t = `timestamp`
      echo  "[$t] Pausing for nod..."

      beep 2
      set ans = $<
      set t = `timestamp`
      echo  "[$t] Resuming after nod..."
endif
gotobase
```

```
# readout detector...
set t = `timestamp`
echo "[$t] Read out CCD"
tint 1
modify -s esi resume=t
echo "[$t] ---------- END ----------"

exit
```