Acquisition with NFIRAOS and IRIS on TMT

David R. Andersen*[a], Jenny Atwood[a], Eric Chisholm[b], Jennifer Dunn[a], Timothee Greffe[c], Tim Hardy[a], Yutaka Hayano[d], Glen Herriot[a], James Larkin[e], Roger Smith[c], Ryuji Suzuki[d], Gelys Trancho[b], Lianqi Wang[b], Shelley Wright[f]

[a]NRC Herzberg Astronomy and Astrophysics, 5071 W. Saanich Rd., Victoria, BC, V9E2E7, Canada; [b]Thirty Meter Telescope Observatory Corporation, Pasadena, California 90807, USA; [c]Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA; [d]National Astronomical Observatory of Japan, 2 Chome-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan; [e]Dept. of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA; [f]Dept. of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA

ABSTRACT

Field acquisition for IRIS and NFIRAOS on TMT poses some unique challenges. The required sky coverage of NFIRAOS is 50% even at the North Galactic Pole which means that the system must necessarily operate with faint guide stars. Furthermore, even for fields with faint guide stars, NFIRAOS and IRIS are required to acquire the guide stars and science field in less than 3 minutes for an average slew. To detect faint stars quickly during acquisition, these stars need to be sharpened by the LGS MCAO system of NFIRAOS before they can be detected on near infrared detectors. We present a trade study of different acquisition options, and show how acquisition has influenced the final design of both NFIRAOS and IRIS. In particular, we discuss the evolution of the IRIS On-Instrument Wavefront Sensor (OIWFS); the detector has switched from a Teledyne H1RG to a Leonardo APD and we have modified the probe tip to better match the detector field of view and minimize vignetting of the IRIS imaging field. We show that acquisition can be achieved for faint targets in the required time using the OIWFS for acquisition.

Keywords: On-Instrument Wavefront Sensing; Acquisition

1. INTRODUCTION

The Infrared Imaging Spectrograph (IRIS) is a cryogenic instrument under development for first-light operation of the Thirty Meter Telescope (TMT)[1]. IRIS is a client instrument of NFIRAOS, which is the first light, Multi-Conjugate Adaptive Optics (MCAO) system for TMT[2,3] (Figure 1). The IRIS science cryostat houses a “wide-field” imager and an integral field spectrograph (IFS) with a 0.84 µm to 2.4 µm wavelength range. Figure 2 presents a functional block diagram of IRIS. It shows that the IRIS imager uses four Hawaii-4RG-10 detectors which yield a total field-of-view (FoV) of 34 x 34 square arcseconds with a plate scale of 4 milliarcseconds (mas). The IFS offers four spaxel scales ranging from 4 mas to 50 mas and is capable of generating up to 14,000 simultaneous spectra within a filled rectangular pattern. Three on-instrument wavefront sensors (OIWFS) are mounted in a separate enclosure atop the science cryostat[4]. These patrol the exterior perimeter of the two arcminute diameter field delivered by NFIRAOS and provide measurements of the tip/tilt, focus (TTF) and plate scale modes invisible to NFIRAOS and its laser guide star (LGS) wavefront sensors (WFS). IRIS mates to NFIRAOS through a support structure which in turn interfaces to a rotator ring. The science cryostat and OIWFS enclosure connect to this rotator, which enables IRIS to provide field de-rotation. The final component of IRIS is the services cable wrap, which routes the cables from the inside the OIWFS and science cryostat to the Nasmyth platform below the instrument and out to either the IRIS electronics cabinet or the TMT facility supplied services. The IRIS instrument completed its Preliminary Design Phase (PDP) in September 2017 and is currently in a Final Design Phase (FDP) which will be complete in early 2021.

*David.Andersen@nrc-cnrc.gc.ca; phone 1 (250) 363-8708

In these proceedings, we will discuss recent updates to the OIWFS and follow that with a discussion of the IRIS acquisition procedures. In section 4, we will summarize the critical design choices that have been made in the past year to enable NFIRAOS + IRIS to acquire scientific targets most efficiently to make the best use of nights at TMT.

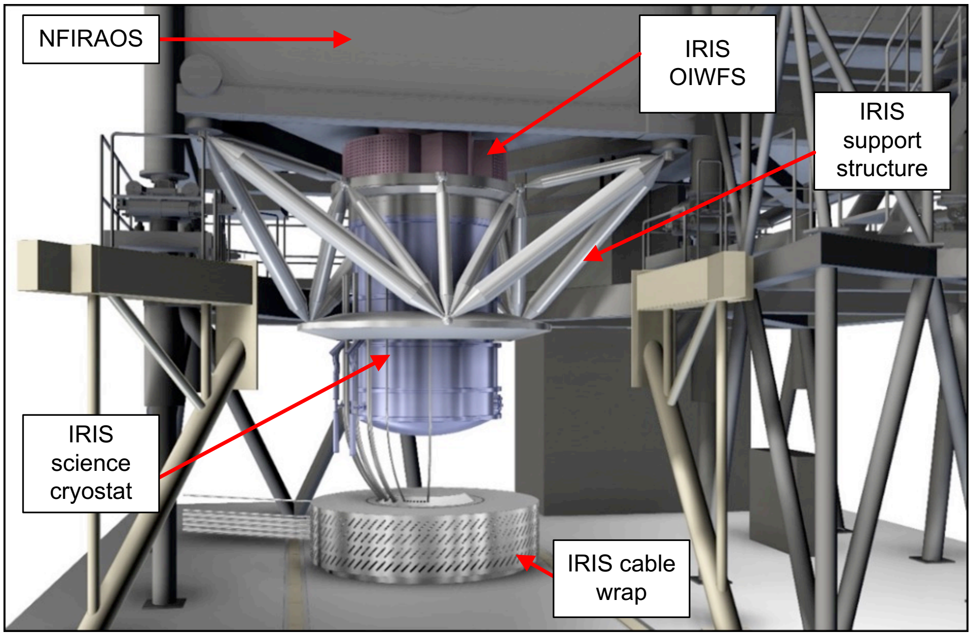

Figure 1. The IRIS instrument shown in-situ mounted to the up-looking port of NFIRAOS. The silver cylinder in the lower portion of the image is the IRIS cable services wrap, which is designed to prevent damage to IRIS cables as the cryostat rotates during operations. For scale, the blue dewar is 1.9 meters in diameter

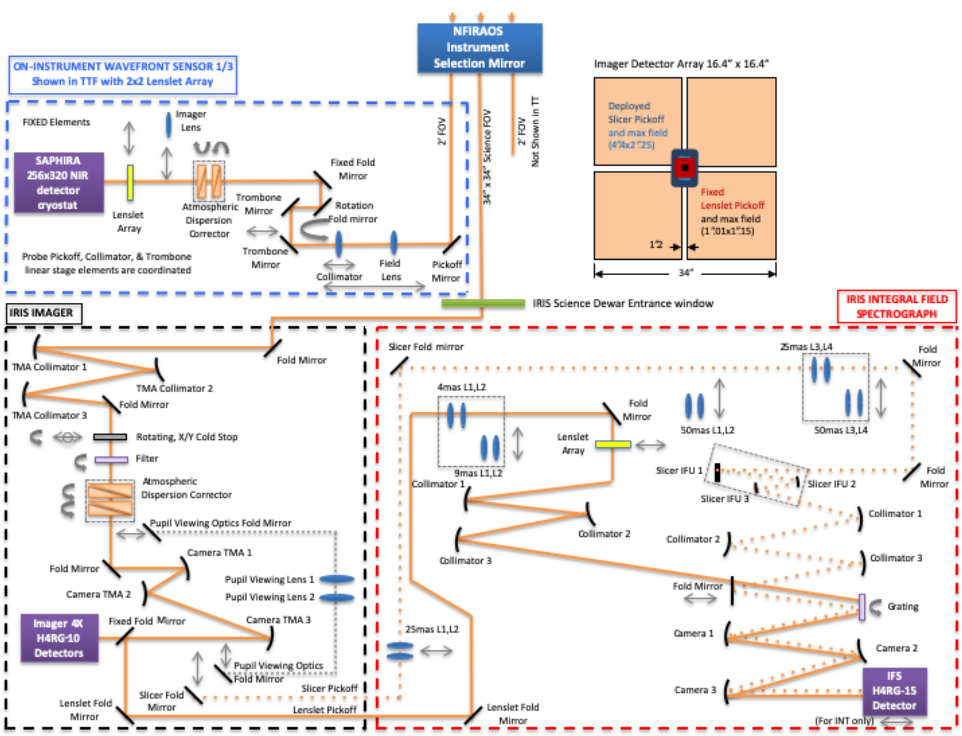

Figure 2. Functional block diagram of IRIS highlighting the OIWFS (blue) housed in a -30° C enclosure, and the IRIS imager (black) and IFS (red) enclosed in the science cryostat.

2. OIWFS DESIGN

The IRIS OIWFS subsystem is critical for sensing tip/tilt, focus and plate scale modes to which the LGS MCAO system is blind. The IRIS OIWFS live in an enclosure cooled to -30° C to match the environment in NFIRAOS. There is an open connection between the OIWFS and NFIRAOS. These OIWFS operate in the near infrared (NIR; 1.1 to 2.3 microns) to take advantage of image sharpening provided by NFIRAOS. In this way, the OIWFS can make use of quite faint stars (J<22) and achieve a sky coverage of ~50% even at the Galactic pole. Three OIWFS probe arms can be configured to sense tip/tilt (TT) or tip/tilt/focus (TTF). The wavelength range is chosen to cover all of J + H + Ks bands to maximize the signal-to-noise of the natural guide star (NGS) detection while cutting off at 2.3 microns to block out most of the thermal infrared light. We set the plate scale to 6 mas/pixel (12 mas/pix in TTF mode) which critically samples a diffraction-limited NGS core. The OIWFS design has evolved since it was last presented[5]; we summarize those changes below.

2.1 Optomechanical Design

The OIWFS optical design is built around R-theta probe arms (Figure *3*). We have modified the opto-mechanical design of these probe arms in response to a concern about vignetting. When the IRIS FOV was increased from 16.4 x 16.4 square arcseconds to 34 x 34 square arcseconds, the probability that useful guide stars would be present near or even in the IRIS Imager FOV increased substantially. Previously, a converter lens and fold mirror were mounted at the tip of the OIWFS probe arm. Since the field lens was further from focus and was designed to accommodate a 5 arcsecond diameter FOV, it would create a substantial vignetting footprint almost 12 arcseconds in diameter. This probe tip assembly has been modified so that the field lens was moved from in front of the pickoff lens to further down the probe arm (Figure 4). As we show in Figure 5, this greatly reduces the potential vignetting of the probe arm over the IRIS imaging field of view. The small rectangular pick-off mirror polished into the probe tip now acts as the field stop limiting scattered light entering the rest of the OIWFS. The details of the rest of the OIWFS design have not changed dramatically. A collimator is still mounted on a small linear stage to compensate for focus errors introduced as the probe arms sweep across the curved NFIRAOS focal plane. Two trombone mirrors and two fold mirrors act as a periscope that preserves the path length as the probe stage moves radially. The periscope is on the axis of rotation of the theta stage. Elements after the 1st fold mirror are fixed.

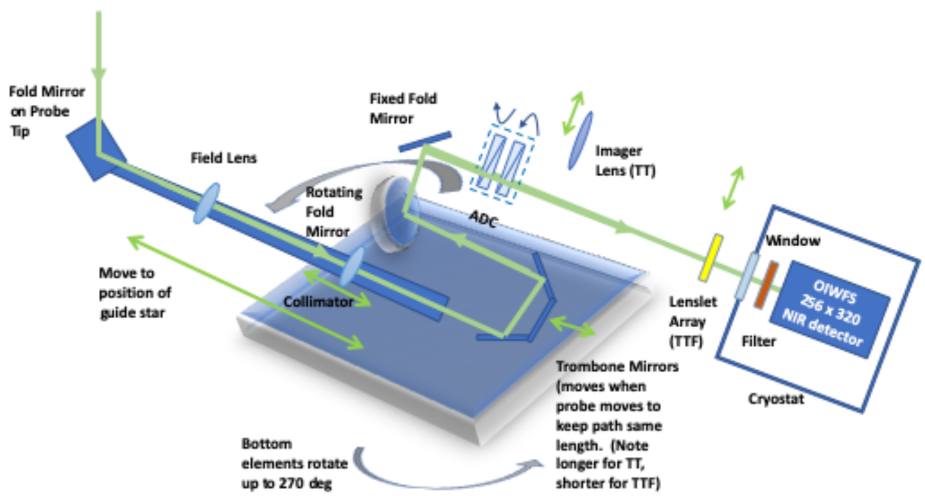

Figure 3: Optical design of tip/tilt and tip/tilt/focus versions of the OIWFS

The elements on the fixed portion of the arm include the atmospheric dispersion corrector (ADC) and an imager lens/lenslet array changer mechanism. When the imager lens is deployed, the OIWFS will be used to image a single star onto the detector (TT mode). When the lenslet array is deployed, four images of the star will be imaged onto the OIWFS detector (TTF mode). Each OIWFS detector sits in a small cryostat that contains a window, a cold baffle and a long-pass filter (J+H+Ks) that limit thermal emission from reaching the detector. We discuss changes to the OIWFS detector in the next subsection.

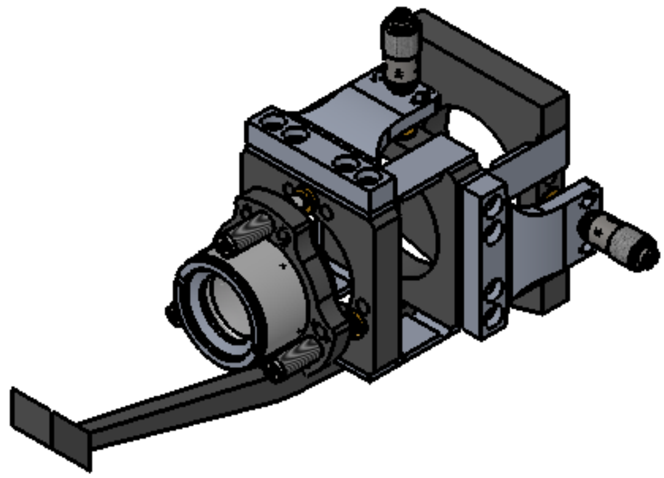

Figure 4: The OIWFS probe tip assembly showing the rectangular fold mirror, and mounts for the field lens. The field lens mounts are 27″ from the center of the fold mirror. This means that vignetting from the field lens mount will only occur when the probes are fully extended close to the center of the IRIS FOV.

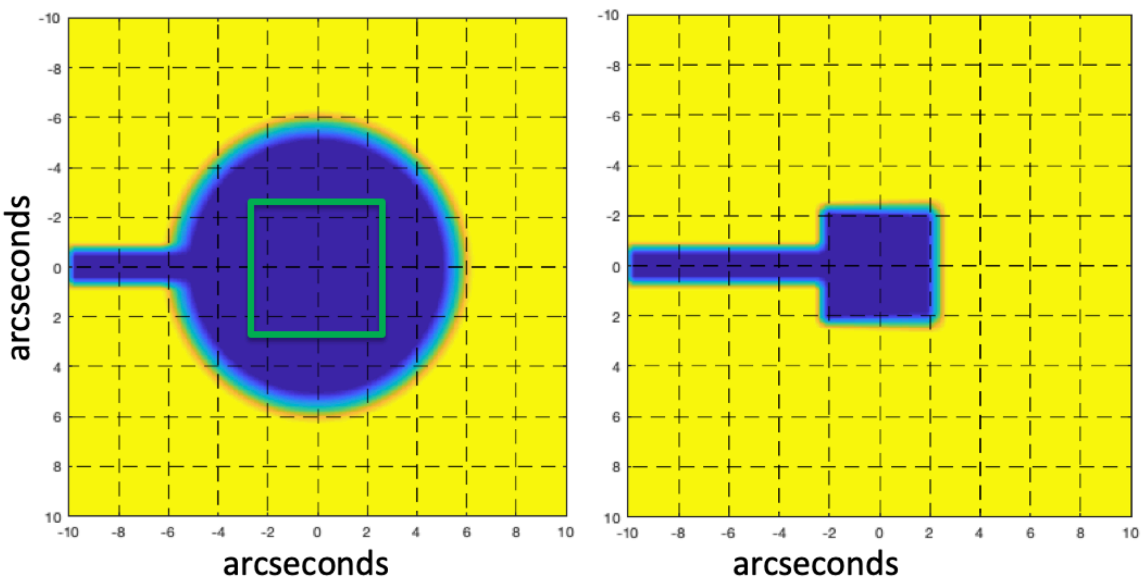

Figure 5: Vignetting of the OIWFS probe tip. Left Panel: Vignetting from the previous OIWFS design in which the field lens was mounted in front of the pick-off mirror (size indicated by the green box). Right Panel: Vignetting of the new pick-off arm in which the field lens has moved 27″ from the center of the fold mirror down the probe arm. The pick-off mirror can possible be further reduced in size depending on the final choice of NIR detector.

The OIWFS mechanical design has been built to meet a demanding combination of requirements on speed, precision and range of motion. The three probe arms must be able to span the 2 arcminute field of regard (~270 mm). A requirement was set that each probe must be able to reach the center of the field (135 mm of travel), and must do so with a precision of 2 mas (4.5 microns). This latter requirement is in place to ensure that IRIS can be used to perform precision absolute astrometry (if the nearest reference star is within the NFIRAOS field of regard and is used as a OIWFS NGS, then the positions of objects falling on the IRIS imager can be determined relative to the OIWFS to high precision) and to ensure that observations of the same field taken at different epochs will have very nearly the same plate scale. Finally, TMT is committed to observing efficiency. There acquisition time requirements between short dithers drives the OIWFS probe arms to move up to 30 arcsec in five seconds. Given the profile of the moves, this translates into a minimum requirement on the top probe speed of 12 arcsec/sec. The redesign of the probe tip has not only mitigated a potential problem with vignetting, it has also removed mass from the end of the probe which increases stiffness and decreases the susceptibility of the probe arm to vibration.

2.2 OIWFS Detector

The other major change in the OIWFS design was the move from a Teledyne H2RG to a Leonardo SAPHIRA NIR avalanche photodiode (APD)[6]. We explored a full trade study between the two detectors. The H2RG had the advantages that it had more pixels so it could support a larger FOV (the previous design had a 5 arcsecond diameter FOV which corresponds to ~830 pixels in diameter). The commercially available SAPHIRA detector only has 256x320 pixels (1.5″x1.9″ FOV) – a future Leonardo APD promises 512x512 pixels (3″x3″ FOV). A larger FOV has benefits if the OIWFS are used to acquire the faint NGS. However, this is almost the only area that favors the H2RG as a high-speed OIWFS detector. To reach the high speeds required of NFIRAOS, the H2RG could only read out a very small window (roughly 8x8 pixels). A real risk existed with the H2RG that lock would be lost during acquisition while the subwindow was decreased in size or during large windshake events. The APD can be read out much faster. Roughly 100x100 pixels can be read out while still meeting a very tight lag requirement (Figure 6). The APD has much better readnoise and well depth which will be very beneficial during operation. The change from H2RG to APD was finalized when it was realized that the APD could be run much quicker than H2RG even for faint stars which means that the OIWFS will be much better able to reject tip/tilt arising from telescope vibrations (Figure 6). The current baseline detector has been changed to the SAPHIRA 256x320 NIR APD, but the OIWFS optics and cryostat can still accommodate a 512x512 NIR APD if it becomes available soon.

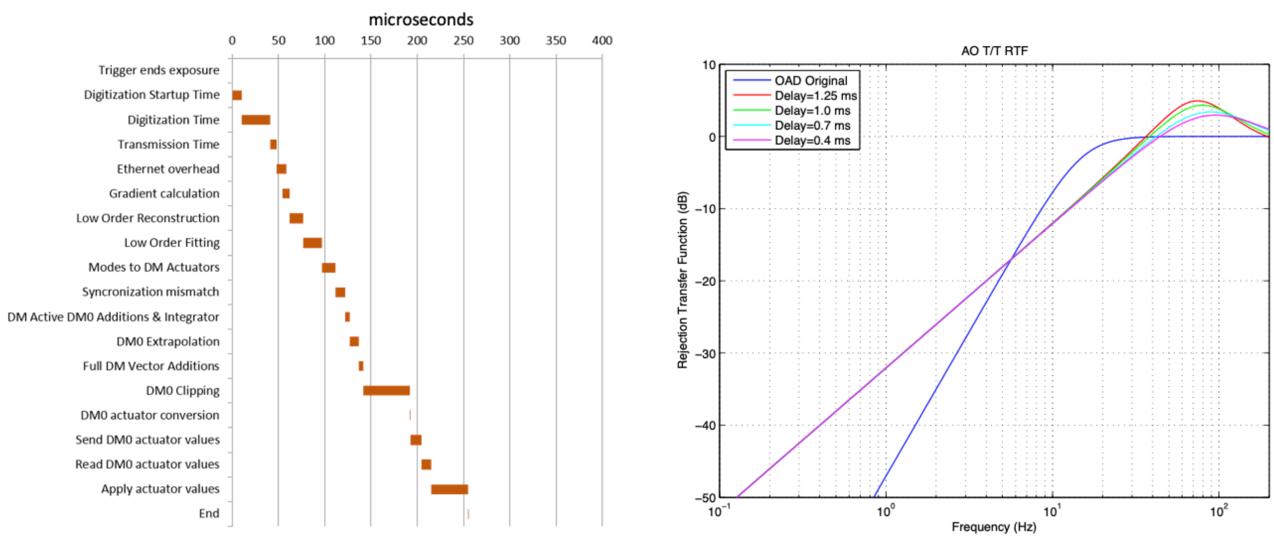

Figure 6: Left Panel – Timing diagram for signals coming from the OIWFS detectors. It will take less than 0.4 ms from the end of a frame to the completion of sending tip/tilt commands to the DM. Right Panel – The rejection transfer function of the baseline requirement (blue) versus what can be achieved using the NIR APD. The bandwidth for rejecting vibration has been greatly increased.

3. IRIS ACQUISITION

IRIS and NFIROS have several different potential cameras that can be used for acquisition. NFIRAOS includes a subsystem dubbed the NFIRAOS Sensor (NSEN; Figure 7). It contains a high-resolution WFS and a diffraction-limited narrow-band commercial SWIR camera. It had also included a commercial SWIR acquisition camera (ACQ) that had a 20 arcsecond FOV with 30 mas pixels. The NFIRAOS team had proposed to remove this functionality from NSEN because other acquisition options existed. IRIS, of course, has a large field imager (34 arcsecond FOV) populated with much more sensitive H4RG-10 detectors which could also potentially be used to acquire field. Finally, the OIWFS probes themselves could be used as acquisition cameras. To make progress on defining the baseline acquisition procedure using these different cameras, we developed a trade study and simulated the various potential acquisition scenarios.

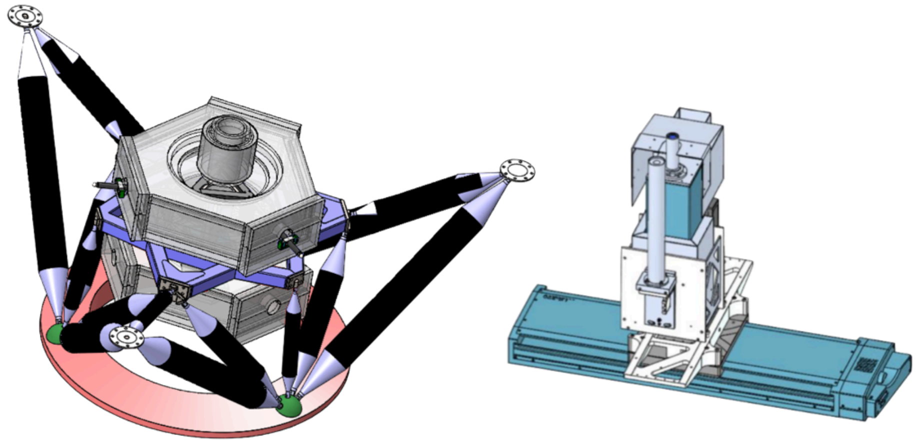

Figure 7: NFIRAOS Sensor (NSEN). NSEN can be mounted on any of the three NFIRAOS instrument ports. It reuses the IRIS support structure and OIWFS enclosure designs. Within the NSEN enclosure is an instrumentation package that can patrol the 2 arcminute NFIRAOS FOV with a high-resolution WFS, diffraction-limited camera and acquisition camera (ACQ).

We evaluated the three acquisition options in terms of probable acquisition times for various use cases and programmatic concerns related to risks and costs. As part of this process, we simulated acquisition frames using the three cameras (Figure 8). We found that for the majority of use cases, the OIWFS would be the fastest acquisition option. Even with the small FOV of the 256x320 NIR APD, if the position uncertainty of the NGS was 1 arcsecond RMS (dominated by telescope pointing error), the OIWFS could dither around an area sufficiently large to have extremely high confidence of finding the target in roughly 7.5 seconds. However, if the pointing error of TMT is much larger than 1 arcsecond RMS, then NSEN ACQ or the IRIS imager will identify the guide star much quicker with lower risk. Furthermore, there was significant concern raised by the IRIS team in attempting to use the IRIS imager as an acquisition camera. If the IRIS Imager H4RG detectors saturated during acquisition, subsequent science observations would be negatively impacted by persistence. The trade study concluded that the baseline at first light, when the telescope pointing would be most uncertain, was to acquire targets using NSEN ACQ. We also concluded that the ability to acquire using the OIWFS should not be ruled out. As part of this trade, we also identified a need to have a physical shutter inside IRIS located optically downstream from the OIWFS that would prevent the IRIS Imager from being inadvertently saturated.

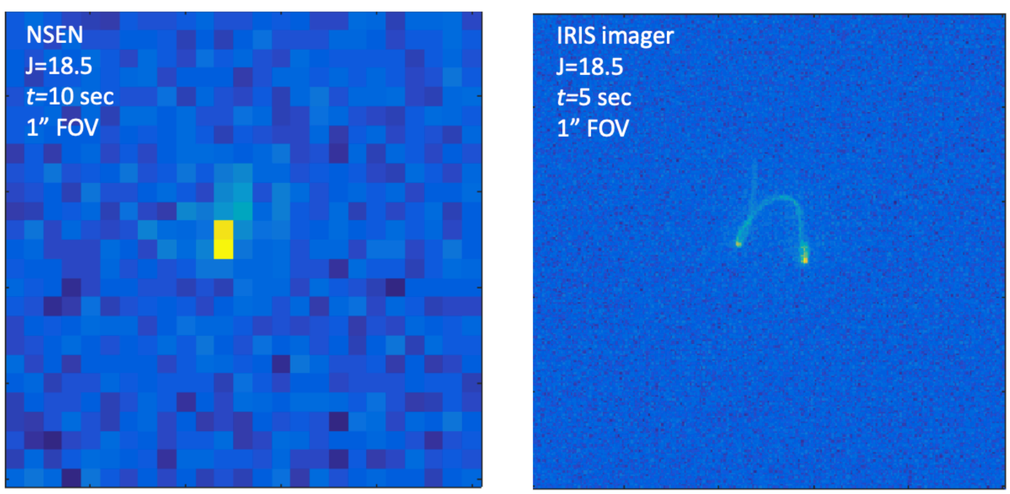

Figure 8: Simulated acquisition frames from the NSEN Acquisition Camera (ACQ; left) and IRIS Imager (right). Simulations were performed using a J=18.5 star which corresponds to the 90th percentile of the brightest guide star in fields meeting the NFIRAOS sky coverage/low order wavefront error budget with stellar densities similar to the North Galactic Pole. ACQ requires a 10 second exposure to detect such a star with sufficient S/N. IRIS could detect the star more quickly, but taking two reads of the full H4RG detectors will take 5 seconds.

Having settled on the baseline acquisition camera, we have defined the corresponding acquisition sequence (Figure 9). Acquiring new targets with TMT+NFIRAOS+IRIS involves many different software systems. The user will command the Executive Software (ESW) to move to the next target. The ESW will command the Telescope Control System (TCS) to slew the telescope to the next target and will communicate with the AO Executive Software (AOESW) and IRIS Control Computer (ICC) to prepare for acquisition. The telescope will be commanded to point to the brightest guide star. Once the slew is complete, the laser will be propagated and NFIRAOS will begin closing high order loops to sharpen the guide star. Meanwhile, NFIRAOS will be directly light to the instrument port that supports NSEN. The NSEN ACQ will take an image. The image will be processed, and the guide star identified. Once the guide star is identified, the telescope pointing will be updated and the telescope will repoint to the science target while NFIRAOS sends light into IRIS. Once the NGS reaches its expected position, the NFIRAOS Pyramid WFS (PWFS) will begin acquisition. Simultaneously, all three OIWFS will be in position and will acquire and lock onto their pre-determined NGS. At this point, all loops are locked and the location of the field should be well-known which gives confidence to open the IRIS shutter while deploying either saturation windows on the IRIS Imager (subwindows on the IRIS OWIFS that are read out and cleared often to prevent saturation) or On-Detector Guide Windows (ODGW) which are subwindows that feed pixels to the NFIRAOS Real-Time Controller to stabilize the delivered focal plane on the IRIS Imager. At this point, acquisition is complete and science observations can begin. TMT is required to complete this process in under 5 minutes from the time one exposure ends to the start of the next exposure.

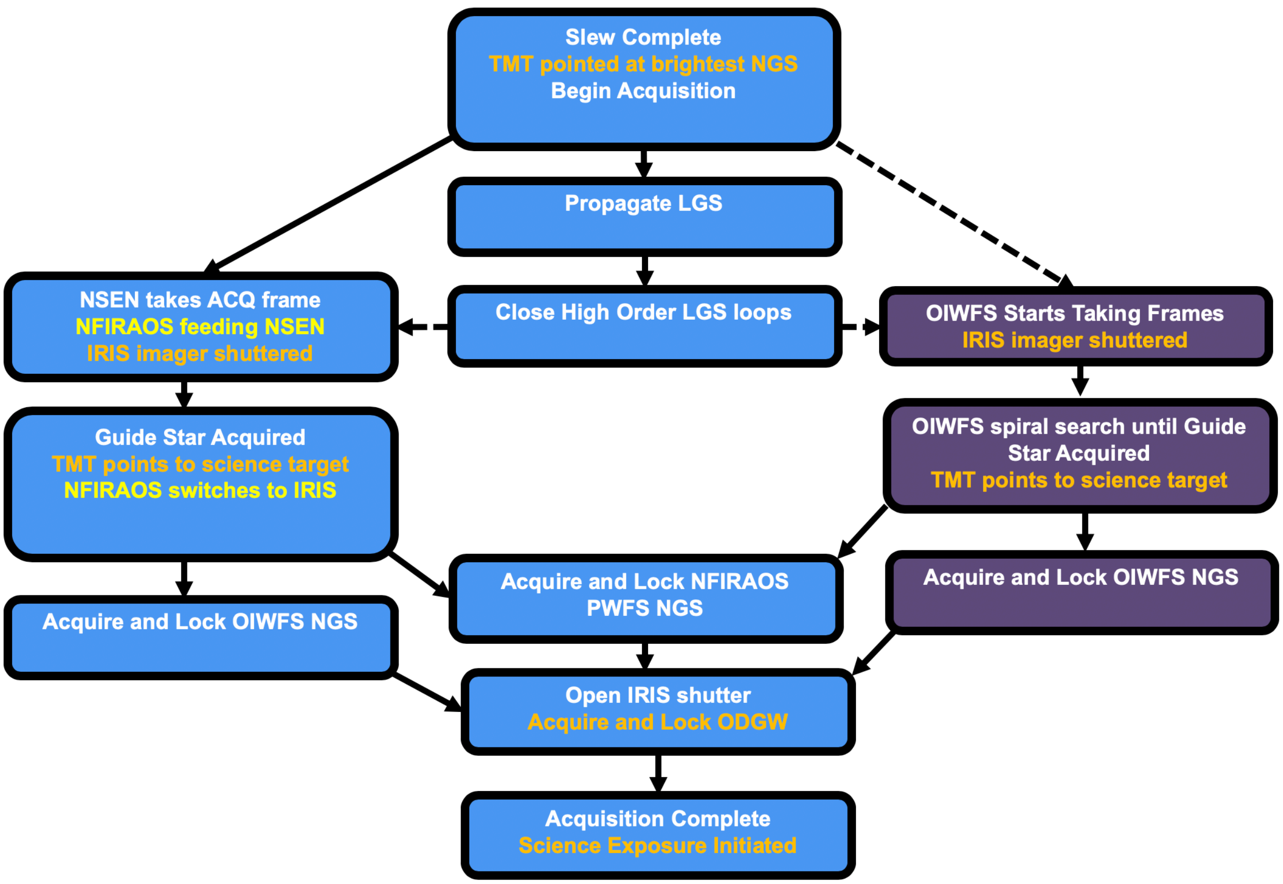

Figure 9: Acquisition flowchart for IRIS. The baseline acquisition sequence using the NFIRAOS NSEN Acquisition Camera is shown in blue. The potential back-up/upgrade acquisition sequence using the IRIS OIWFS camera is shown in purple.

The alternative acquisition scenario is shown in purple in Figure 9. This sequence could potentially be faster if the telescope pointing error is of order 1 arcsecond RMS or better. NFIRAOS is always directing light to IRIS and the IRIS OIWFS performs a spiral search until the NGS is detected. Once detected, the TCS updates its telescope pointing and repoints the telescope to the science target. Subsequent steps are very similar to the baseline sequence described above.

Monte Carlo simulations of the acquisition process have shown that both processes can achieve the 5 minute target to target acquisition requirement.

4. SUMMARY

Minimizing observational overheads such as the time spent acquiring new science targets will be critical to the success of highly in-demand and costly telescopes such as TMT. Acquiring the potentially faint NGS needed to measure tip/tilt/focus and plate scale modes will not always be straight-forward. We have evaluated several different options for acquisition with an eye on minimizing the average time while mitigating the risk that acquisition will be unsuccessful. Time spent studying the different possible NFIRAOS+IRIS acquisition processes on TMT has influenced the design of both instruments. The risk of not being able to identify the guide star in a reasonable time using the OIWFS has caused NFIRAOS to bring back an acquisition camera in NSEN that had been deprecated when it was not clear that it was needed. Concerns over saturation of the IRIS Imager detector during acquisition when the registration of the field to the detector focal plane is uncertain has led IRIS to include a cryogenic shutter that blocks light from the imager while allowing the OIWFS detectors to acquire guide stars. Finally, the OIWFS design was updated. Replacing the H2RG detector with a NIR APD has several advantages, but the combination of being able to read out the entire frame at 800 Hz with practically no readnoise makes the NIR APD a powerful tool during acquisition – even if the size of the OIWFS FOV is curtailed. The probe arms can move quite fast, so combined with fast readout times, the OIWFS with APD can cover more area in less time than the previous H2RG option. Since the OIWFS optics design had to be updated for the different pixel size of the APD, we took advantage of the opportunity and changed the location of the field lens to significantly reduce the potential vignetting of the probe arms if NGS were close to or even within the FOV of the expanded IRIS imager.

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