The NuMOIRCS Project: Detector Upgrade Overview and Early Commissioning Results

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ABSTRACT

In 2014 and 2015 the Multi-Object InfraRed Camera and Spectrograph (MOIRCS) instrument at the Subaru Telescope on Maunakea is underwent a significant modernization and upgrade project. We upgraded the two Hawaii2 detectors to Hawaii2-RG models, modernized the cryogenic temperature control system, and rewrote much of the instrument control software.

The detector upgrade replaced the Hawaii2 detectors which use the Tohoku University Focal Plane Array Controller (TUFPAC) electronics with Hawaii2-RG detectors using SIDECAR ASIC (a fully integrated FPA controller system-on-a-chip) and a SAM interface card. We achieved an improvement in read noise by a factor of about 2 with this detector and electronics upgrade.

The cryogenic temperature control upgrade focused on modernizing the components and making the procedures for warm up and cool down of the instrument safer. We have moved PID control loops out of the instrument control software and into Lakeshore model 336 cryogenic temperature controllers and have added interlocks on the warming systems to prevent overheating of the instrument.

Much of the instrument control software has also been re-written. This was necessitated by the different interface to the detector electronics (ASIC & SAM vs. TUFPAC) and by the desire to modernize the interface to the telescope control software which has been updated to Subaru's "Gen2" system since the time of MOIRCS construction and first light. The new software is also designed to increase reliability of operation of the instrument, decrease overheads, and be easier for night time operators and support astronomers to use.

Keywords: MOIRCS, NuMOIRCS, Subaru Telescope, Hawaii2, TUFPAC, Hawaii2-RG, Lakeshore, Alpha Particles

1. INTRODUCTION AND MOTIVATION

The Multi-Object InfraRed Camera and Spectrograph (MOIRCS) instrument[1,2] at the cassegrain focus of the 8.2 meter Subaru Telescope operated by the National Astronomical Observatory of Japan (NAOJ) saw first light in September 2004. MOIRCS operates as both a JHK imager using two 2k x 2k HAWAII2 detectors providing a 4 by 7 arcminute field of view at a pixel scale of 0.117 arcseconds per pixel and as a multi-object spectrograph utilizing a separate Dewar for a cryogenic slit mask exchanger system which allowed installation of 23 different slit masks which can be exchanged in a few minutes by the robotic slit mask exchange mechanism.

MOIRCS was the first near-infrared MOS instrument offered for open use on an 8 meter class telescope. As a result, it has been a popular instrument on Subaru. MOIRCS has been used for wide variety of science, from

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solar system objects to distant galaxies. Some of its science highlights include identification of the most distant galaxies,[3–7] the discovery and characterization of proto-clusters at the cosmic-high noon era,[8–12] and a survey of the low-mass brown dwarfs in star-forming regions.[13–16] Using the data from MOIRCS nearly 200 papers have been published to the refereed journals, including 3 Nature papers.[4,17,18]

Detector technology has advanced since the time of the MOIRCS design. Newer Hawaii2-RG detectors are now available. When combined with newer readout electronics, it became possible to significantly improve the sensitivity (primarily the read noise) and the cosmetics of the detector. A project was begun in 2011 to update the MOIRCS detectors and readout electronics. New detectors and electronics also enable the possibility of new operational modes. In particular "up the ramp" sampling and on chip guiding.

Because the cost of the telescope and enclosure are a "sunk cost", the scientific productivity of an observatory are strongly influenced by the quality of the instrumentation used on the telescope.[19] When combined with the high cost of new instrumentation, upgrading an instrument can be a far more cost effective way to boost scientific output of an observatory than replacing that instrument with something new. In a study of the scientific output of instrumentation at the two 10 meter W.M. Keck Observatory telescopes, Ref. 19 found that "instruments which have not undergone significant upgrades achieve a peak [in productivity] between five to eight years after commissioning." He also finds that upgrades to instruments can maintain their productivity, so that rather than dropping after 6-8 years of life, the instrument can maintain a "plateau" of productivity over an additional 5-10 years*. With this in mind, a project to upgrade MOIRCS was begun in 2011. Funding support was though a KAKENHI (23224005) Grant-in-Aid for Scientific Research (S) thorough the Japan Society for the Promotion of Science (JSPS) (PI: Nobuo Arimoto).

In this paper, we describe the upgrades to the instrument's temperature control system in §2, the new instrument control software in §3, including a discussion of further upgrades made possible by the new hardware and software in §3.1, and a brief summary of the ongoing commissioning in §4 of the upgraded instrument. A detailed description of the upgrades to the detectors and their control electronics is available in Ref. 20 also in this proceedings.

2. TEMPERATURE CONTROL SYSTEM

In addition to the detector and readout electronics upgrade, it was decided to improve the temperature control system on MOIRCS. The existing system used two Lakeshore model 340 temperature controllers to modulate heaters mounted near the detectors to maintain them at an operational temperature of 77 K. The Dewar is initially cooled by a liquid nitrogen automatic pre-cool system (APS[21]) and the temperature is maintained by two two-stage closed cycle Sumitomo Heavy Industries RDK-408S cryocoolers, one connected to the main Dewar (which contains the detectors, camera optics, filter wheels, and collimator optics) and one connected to the carousel Dewar which contains the cryogenic slit mask carousel and the slit mask exchange mechanism.

The optical bench in the main Dewar of MOIRCS floats in temperature at 100-120 K $\pm$5 K. It is connected to the first stage of the main Dewar cryocooler.

To warm up the main Dewar to ambient, a pair of resistive heaters were mounted on the optical bench. These heaters were controlled from two separate 100 W power supplies mounted on the exterior of the instrument. Each output of the power supplies was controlled via serial commands issued by a warm up script running on both of the instrument control computers.

This warm up script was designed to automatically shut off the heaters when the temperature reached a target (presumably near ambient), however in practice this process was not reliable. The script would often overshoot the target temperature placing the instrument at risk of overheating and potentially damaging the interior components if the system became too hot. As a result, the main Dewar warm up process required that observatory personnel monitor the system during a warm-up and be prepared to shut off the heaters manually to mitigate the risk to the instrument.

The warm up heater power supplies were also configured to provide power to a warm-up heater located in the carousel Dewar which could be used to warm up the carousel or to bake the carousel getter. A relay, controlled

*See Ref. 19 for a detailed discussion of the meaning of "productivity" in this context.

by activating power on a particular port on a switched remote power strip, could be used to toggle the output of the power supplies between the main Dewar heaters and the carousel heaters.

The risk imposed by the unreliable shut off of the main Dewar heaters and the complexity of the system led us to redesign the temperature control system with the primary goal of making main Dewar warm-up process safer for the instrument and to make it truly automatic, so that no constant monitoring was required.

The new control system is based around two Lakeshore model 336 cryogenic temperature controllers. These have direct network interfaces which removed the need for a serial connection to one of the control computers on the instrument or to a terminal server. Each Lakeshore model 336 has two heater outputs (configured to provide a maximum of 100 W and 50 W respectively) and two auxiliary outputs which send an analog signal which can be used to control the output of an external power supply.

We connected the 100 W heater output of each Lakeshore to the detector module (which contains the detector, ASIC electronics, and detector focus mechanism, see Ref. 20 for more details on the detector upgrades) and the 50 W output to the detector mounting plate itself. Each 100 W module output on the Lakeshores was configured to maintain a temperature of 76 K while the 50 W detector outputs were programmed to maintain a temperature of 77 K. This meant that the larger thermal mass of the module would pull the temperature of the detectors down slightly through the thermal coupling of the mounting and allow the PID control loop of the 50 W detector output to hold the detectors at a precise 77 K temperature.

Only at one place we add an additional software control loop to the temperature control system: During the instrument precool with liquid nitrogen, the detectors must remain warmer than the optical bench to prevent condensation onto the detector surfaces. However, their temperature must be ramped down in a controlled fashion to avoid overpowering the detector and the module heaters. While the Lakeshore controller does provide temperature ramping functionality, it does not allow to track another temperature with a certain offset. We therefore implemented a simple control loop which updates the detector and module setpoints every five minutes to 10 K above the optical bench temperature during precool. Once the precool is completed and the coldheads are turned on, they become effective cryopumps. At that point it is safe to ramp to temperature of the detectors and modules down to their operation temperatures of 77 K and 76 K respectively.

To control the main Dewar warm up process we used the two additional analog outputs of the Lakeshores to modulate the output of an Agilent Technologies N5747A power supply connected to the main Dewar heaters. The warm up process does not need to be tightly controlled. We empirically determined, based on experience from the original control system, that providing 100 W (the maximum rating) to each of the resistive heaters led to a warm up rate of 4-5 K/hr which was our maximum allowed target (that rate was based on documentation from the original instrument builders). Thus a true PID control loop for this output was unnecessary and the "warm up heater" mode of the Lakeshore analog control was sufficient because it could be turned on to a particular setting (percent of maximum power) and the output could be linked to a particular temperature sensor in the main Dewar and the Lakeshore would automatically turn off the heaters once a maximum allowed temperature was reached. Our experience with other Lakeshores suggested that this Lakeshore based control would be much more reliable (and thus safer for the instrument) than the software based control loop we had been using.

The carousel heater is configured in a very similar fashion to the main Dewar heater. Because it heats a smaller thermal mass, we use a smaller power supply (a model N5743A), but it is otherwise controlled identically to the main Dewar and has the same safety systems configured to prevent over heating.

3. INSTRUMENT CONTROL SOFTWARE

Initially we had hoped to modify the existing instrument control software (TLECS; Ref. 22) to control the new detector control electronics (SAM and ASIC, see Ref. 20 for more details). After further examination, however, we chose to rewrite most of the instrument control software. This was motivated by several factors.

First, due to schedule and budget constraints, we chose to use the Teledyne provided control software rather than build a customized controller. The system runs in a Windows based computer connected directly to the readout electronics via USB connection. The Teledyne software provides a socket interface for external control via a supported command set. The interface for the previous control electronics (TUFPAC) had the control software sending commands to both start and end the exposure, while the command set for the new controller handled the timing internally and only required a single command to start the exposure. As a result the basic sequencing of the exposure commands would change meaning that altering the existing software would include modifications to the sequencer and not just a command translator as we had hoped.

Second, the old instrument control software was built to interface with the Subaru's first generation telescope control software. The current second generation telescope control software uses a different Python based interface to the instruments. MOIRCS was using an additional software layer to provide compatibility between the old system and the new. Because of a desire to phase out the old interface (to minimize effort needed to support that software), there was motivation to upgrade the MOIRCS instrument control software to use the new Python based interface.

Thirdly, the control system for the instrument mechanisms other than the detectors used a software package called Cassegrain Instrument Automatic Exchanger (CIAX). This package was already well along on an upgrade to a new version[†] with significant changes to the API. The existing instrument control software would have to be modified if we wanted to use the upgraded CIAX control software.

Based on the above points, it was decided that modifying the existing instrument control software would involve comparable effort to writing a new instrument control software package from scratch because almost all of the components of the old software would need modification. We thus opted to write new software.

The new instrument control software runs on a single instrument control computer located in the summit control building and communicates with hardware via network connections: a TCP socket interface to the detector control computers mounted on the instrument, a standard TCP connection to the Lakeshore temperature controllers, and using a Digi terminal server to communicate with most other hardware components via serial communications protocol (e.g. RS232).

One advantage of the new instrument control software over the old is that it has a simpler architecture. It runs on only a single computer rather than being installed on multiple computers. It queries instrument status and telescope status values in real time as needed rather than storing them in an SQL database and querying the database for information. This eliminates one of the control computers needed. The architecture of the control software is shown in Fig. 1.

The user controls the instrument from the telescope control system (Gen2) interface (seen at the upper right of Fig. 1) which is common to all facility instruments at Subaru. The g2cam software is the interface between Gen2 and the instrument. It is simply a set of Python functions and methods which map to Gen2 commands which the user can invoke as part of their "OPE" file which they prepare in advance of an observing run.

For non-detector components, the functions and methods in g2cam call CIAX to query status (via http requests) or to command the sub-components (via a UDP command). The CIAX software provides a standardized interface (via HTTP and UDP calls) to the various hardware components and it abstracts away their individual command protocols (e.g. RS-232, RS-485, etc.).

To control the detector, the functions and methods in g2cam use the socket interface to communicate with the Teledyne software running on one of two detector computers (one for each Hawaii2-RG detector). Much of the detailed detector control logic and FITS file handling are called by the g2cam python code, but are implemented in C.

To minimize heat dissipation in the dome, we chose small, relatively low power consumption computers (Intel NUCs) to be the detector computers mounted on the instrument itself. These machines run Subaru's standard Cent-OS Linux install and they host a Windows virtual machine to run the Teledyne detector control software. This allows us to sandbox the Windows machines for additional security and to keep backups of them using our standard backup system for our Linux computers.

Observers can also view instrument specific status via a GUI which is part of the instrument control software. The GUI is written in Python using a Qt based graphical user interface. The GUI runs on the instrument computer, but can be viewed from other machines using an ssh connection and X forwarding or a VNC connection to the instrument computer.

[†]https://github.com/ciax/ciax-xml

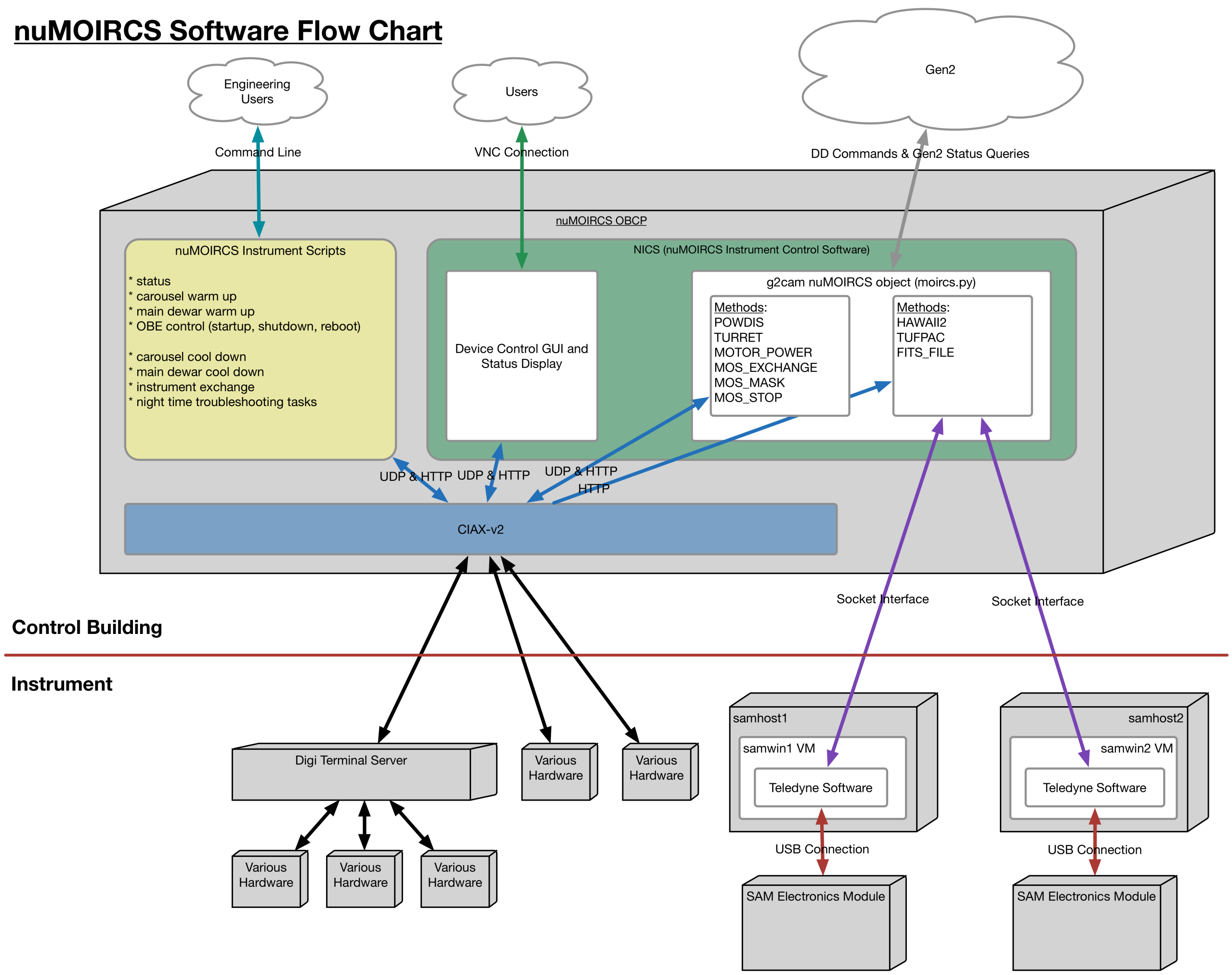

Figure 1. Graphical overview of the MOIRCS instrument control software. See text for details.

There is also a web based instrument ”dashboard” which monitors all of the processes which need to be running for the instrument to operate, presents their status, provides web access to the log files being generated by each program, and gives the user the ability to start, stop, or restart any of those software programs.

We have also developed a small number of engineering scripts which run on the instrument computer which can be used for engineering tasks such as initiating a main Dewar warm up, a carousel Dewar warm up (used to install new slit masks in the carousel), or for putting the instrument in a safe state before the instrument is to be mounted or dismounted from the telescope itself.

3.1 FUTURE SOFTWARE UPGRADE POSSIBILITIES

Support for some software features were deferred until after initial commissioning in order to simplify the initial development and to save resources (budget and schedule). These features are discussed below and can be added in software in the future, requiring no hardware modifications.

3.1.1 ON CHIP GUIDING

The Teledyne provided socket interface for detector control does not support use of the on chip guiding feature. This is not critically important to operations at the current time because the Subaru cassegrain port includes a separate guide camera system which is what MOIRCS has used up to this point. However, support for on chip guiding is desirable because one possible use of the instrument in the future would be with the ULTIMATE-Subaru project which would add ground layer AO capabilities for Subaru telescope with Adaptive Secondary Mirror. Current plans for ULTIMATE-Subaru would require space in the cassegrain port currently occupied by the guide camera, so an on chip guiding system would be advantageous if MOIRCS is to be used in conjunction with ULTIMATE-Subaru.

A potential upgrade path would include implementing on chip guiding by replacing the socket interface with our own software (which would use a lower level, more powerful interface to the detector). A side benefit to replacing the Teledyne software with our own detector control software would be that we could remove the dependency on the Windows operating system. Subaru uses Linux systems for nearly all of its control computers, so we have a expertise and infrastructure supporting Linux, but not Windows. Removing the Windows dependency would reduce the risk and effort associated with supporting an unusual (for Subaru) computer system. In addition, if we replace the Teledyne software with our own detector control software, we may be able to reduce the overheads associated with taking images.

3.1.2 DETECTOR CONTROL OVERHEAD

The new electronics have a 32 channel readout while the old system was 4 channel. This should enable much faster readouts of the chip and lower the overhead between images. The previous system had typical overheads in excess of 30 seconds (under typical observing settings) while the new system overhead has been measured to be about 15 seconds. This improvement is quite significant for imaging operations in which typical exposures are tens of seconds.

In addition, while the old system offered coadds to add frames in the controller (which had lower overhead than taking multiple frames and writing them out as FITS files), the new system does not support this feature. Replacing the Teledyne software with our own detector control software should enable us to investigate and optimize the timing, hopefully reducing overhead times even further and improving the overall system efficiency.

3.1.3 UP THE RAMP READOUT MODE

The "up the ramp readout mode" is supported by the Teledyne socket interface, but we have not propagated that support through our instrument control software to the user. This mode was not available with the previous detector system, so none of the high level instrument control scripts included this option and would have to be modified to offer it to the user. We opted not to add this option in order to save development time and because it has not been in high demand, however this is a relatively straightforward software upgrade which is available to us in the future with the new control system.

4. EARLY COMISSIONING RESULTS

During lab testing of the new detectors we found that there were a large number of clusters of pixels on the detector saturated in each image. Their locations were variable, and they could affect even after coadding multiple frames. This behavior was only seen when the detectors were installed in the instrument and had not been seen when the detectors were in our test Dewar. We eventually concluded that these were alpha particle impacts on the detector which originated from the anti-reflection coating on the last lens surface in the optical system. To mitigate the alpha particle impacts, we installed a pair of blocking filters (one in front of each detector) to absorb the particles (see Ref. 20 in this volume for more details).

Early commissioning nights in late 2015 and early 2016 were focused on testing and debugging the new instrument control system software and confirming the basic operation of both imaging and spectroscopy modes.

The read noise was measured to be 14 and 15 electrons in the two channels. This is roughly a factor of two improvement over the old detectors and readout electronics (see Ref. 20 in this volume for more details).

In May 2016, observations to measure the overall system throughput (Fig. 2) were made. The results show a noticeable improvement in total throughput over the old instrument. While the amount varies with wavelength and by detector, we found improvements in throughput ranging from a few percent to over 40 percent (see Fig. 3).

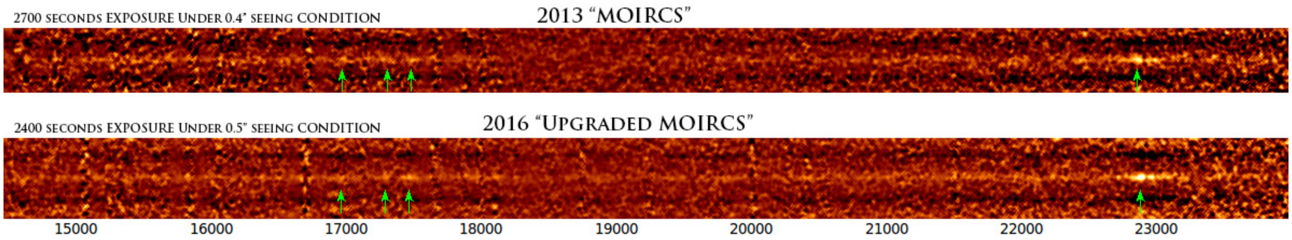

Figure 2. Spectra of the same target taken by the old MOIRCS system and the new upgraded MOIRCS.

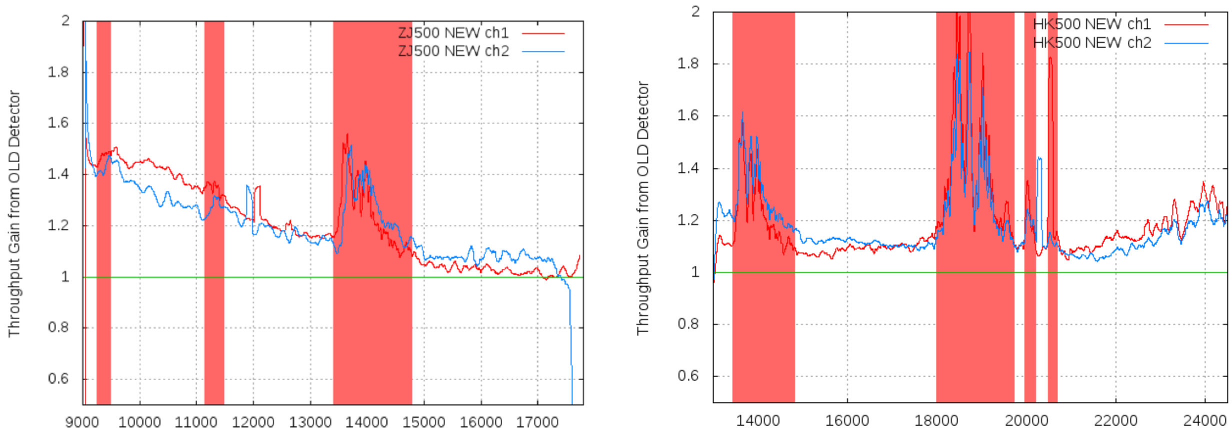

Figure 3. Ratio of the throughput of the new system to the throughput of the old system. The values for the old system are somewhat influenced by a QE variation across the detector, so the curve shown here is for a representative location on the detector.

REFERENCES

[1] Ichikawa, T., Suzuki, R., Tokoku, C., Uchimoto, Y. K., Konishi, M., Yoshikawa, T., Yamada, T., Tanaka, I., Omata, K., and Nishimura, T., "MOIRCS: multi-object infrared camera and spectrograph for SUBARU," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Proc. SPIE* **6269**, 626916 (June 2006).

[2] Suzuki, R., Tokoku, C., Ichikawa, T., Uchimoto, Y. K., Konishi, M., Yoshikawa, T., Tanaka, I., Yamada, T., Omata, K., and Nishimura, T., "Multi-Object Infrared Camera and Spectrograph (MOIRCS) for the Subaru Telescope I. Imaging," *PASJ* **60**, 1347–1362 (Dec. 2008).

[3] Oesch, P. A., Bouwens, R. J., Illingworth, G. D., Labbé, I., Smit, R., Franx, M., van Dokkum, P. G., Momcheva, I., Ashby, M. L. N., Fazio, G. G., Huang, J.-S., Willner, S. P., Gonzalez, V., Magee, D., Trenti, M., Brammer, G. B., Skelton, R. E., and Spitler, L. R., "The Most Luminous z ˜ 9-10 Galaxy Candidates Yet Found: The Luminosity Function, Cosmic Star-formation Rate, and the First Mass Density Estimate at 500 Myr," *ApJ* **786**, 108 (May 2014).

[4] Finkelstein, S. L., Papovich, C., Dickinson, M., Song, M., Tilvi, V., Koekemoer, A. M., Finkelstein, K. D., Mobasher, B., Ferguson, H. C., Giavalisco, M., Reddy, N., Ashby, M. L. N., Dekel, A., Fazio, G. G., Fontana, A., Grogin, N. A., Huang, J.-S., Kocevski, D., Rafelski, M., Weiner, B. J., and Willner, S. P., "A galaxy rapidly forming stars 700 million years after the Big Bang at redshift 7.51," *Nature* **502**, 524–527 (Oct. 2013).

[5] Bunker, A. J., Caruana, J., Wilkins, S. M., Stanway, E. R., Lorenzoni, S., Lacy, M., Jarvis, M. J., and Hickey, S., "VLT/XSHOOTER and Subaru/MOIRCS spectroscopy of HUDF.YD3: no evidence for Lyman α emission at z = 8.55," *MNRAS* **430**, 3314–3319 (Apr. 2013).

[6] Ono, Y., Ouchi, M., Mobasher, B., Dickinson, M., Penner, K., Shimasaku, K., Weiner, B. J., Kartaltepe, J. S., Nakajima, K., Nayyeri, H., Stern, D., Kashikawa, N., and Spinrad, H., "Spectroscopic Confirmation of

Three z-dropout Galaxies at z = 6.844-7.213: Demographics of Lyα Emission in z ˜ 7 Galaxies," *ApJ* **744**, 83 (Jan. 2012).

[7] Richard, J., Stark, D. P., Ellis, R. S., George, M. R., Egami, E., Kneib, J.-P., and Smith, G. P., "A Hubble and Spitzer Space Telescope Survey for Gravitationally Lensed Galaxies: Further Evidence for a Significant Population of Low-Luminosity Galaxies beyond z = 7," *ApJ* **685**, 705–724 (Oct. 2008).

[8] Shimakawa, R., Kodama, T., Tadaki, K.-i., Hayashi, M., Koyama, Y., and Tanaka, I., "An early phase of environmental effects on galaxy properties unveiled by near-infrared spectroscopy of protocluster galaxies at $z > 2$," *MNRAS* **448**, 666–680 (Mar. 2015).

[9] Kubo, M., Yamada, T., Ichikawa, T., Kajisawa, M., Matsuda, Y., and Tanaka, I., "NIR Spectroscopic Observation of Massive Galaxies in the Protocluster at z = 3.09," *ApJ* **799**, 38 (Jan. 2015).

[10] Koyama, Y., Smail, I., Kurk, J., Geach, J. E., Sobral, D., Kodama, T., Nakata, F., Swinbank, A. M., Best, P. N., Hayashi, M., and Tadaki, K.-i., "On the evolution and environmental dependence of the star formation rate versus stellar mass relation since z 2," *MNRAS* **434**, 423–436 (Sept. 2013).

[11] Tanaka, M., Toft, S., Marchesini, D., Zirm, A., De Breuck, C., Kodama, T., Koyama, Y., Kurk, J., and Tanaka, I., "On the Formation Timescale of Massive Cluster Ellipticals Based on Deep Near-infrared Spectroscopy at z ˜ 2," *ApJ* **772**, 113 (Aug. 2013).

[12] Howard, A. W., Marcy, G. W., Bryson, S. T., Jenkins, J. M., Rowe, J. F., Batalha, N. M., Borucki, W. J., Koch, D. G., Dunham, E. W., Gautier, III, T. N., Van Cleve, J., Cochran, W. D., Latham, D. W., Lissauer, J. J., Torres, G., Brown, T. M., Gilliland, R. L., Buchhave, L. A., Caldwell, D. A., Christensen-Dalsgaard, J., Ciardi, D., Fressin, F., Haas, M. R., Howell, S. B., Kjeldsen, H., Seager, S., Rogers, L., Sasselov, D. D., Steffen, J. H., Basri, G. S., Charbonneau, D., Christiansen, J., Clarke, B., Dupree, A., Fabrycky, D. C., Fischer, D. A., Ford, E. B., Fortney, J. J., Tarter, J., Girouard, F. R., Holman, M. J., Johnson, J. A., Klaus, T. C., Machalek, P., Moorhead, A. V., Morehead, R. C., Ragozzine, D., Tenenbaum, P., Twicken, J. D., Quinn, S. N., Isaacson, H., Shporer, A., Lucas, P. W., Walkowicz, L. M., Welsh, W. F., Boss, A., Devore, E., Gould, A., Smith, J. C., Morris, R. L., Prsa, A., Morton, T. D., Still, M., Thompson, S. E., Mullally, F., Endl, M., and MacQueen, P. J., "Planet Occurrence within 0.25 AU of Solar-type Stars from Kepler," *ApJS* **201**, 15 (Aug. 2012).

[13] Yasui, C., Kobayashi, N., Saito, M., and Izumi, N., "Low-metallicity Young Clusters in the Outer Galaxy. II. Sh 2-208," *AJ* **151**, 115 (May 2016).

[14] Yasui, C., Kobayashi, N., Tokunaga, A. T., Saito, M., and Tokoku, C., "Short Lifetime of Protoplanetary Disks in Low-metallicity Environments," *ApJL* **723**, L113–L116 (Nov. 2010).

[15] Scholz, A., Jayawardhana, R., Muzic, K., Geers, V., Tamura, M., and Tanaka, I., "Substellar Objects in Nearby Young Clusters (SONYC). VI. The Planetary-mass Domain of NGC 1333," *ApJ* **756**, 24 (Sept. 2012).

[16] Geers, V., Scholz, A., Jayawardhana, R., Lee, E., Lafrenière, D., and Tamura, M., "Substellar Objects in Nearby Young Clusters (SONYC). II. The Brown Dwarf Population of ρ Ophiuchi," *ApJ* **726**, 23 (Jan. 2011).

[17] Zanella, A., Daddi, E., Le Floc'h, E., Bournaud, F., Gobat, R., Valentino, F., Strazzullo, V., Cibinel, A., Onodera, M., Perret, V., Renaud, F., and Vignali, C., "An extremely young massive clump forming by gravitational collapse in a primordial galaxy," *Nature* **521**, 54–56 (May 2015).

[18] Collins, C. A., Stott, J. P., Hilton, M., Kay, S. T., Stanford, S. A., Davidson, M., Hosmer, M., Hoyle, B., Liddle, A., Lloyd-Davies, E., Mann, R. G., Mehrtens, N., Miller, C. J., Nichol, R. C., Romer, A. K., Sahlén, M., Viana, P. T. P., and West, M. J., "Early assembly of the most massive galaxies," *Nature* **458**, 603–606 (Apr. 2009).

[19] Kulkarni, S., "Instruments on Large Optical Telescopes – A Case Study," *PASP, in prep.* (2016).

[20] Fabricius, M., "Detector upgrade of Subarus multi-object infrared camera and spectrograph," *Proc. SPIE* (2016).

[21] Omata, K., Nishimura, T., Colley, S., Cook, D., Gorman, W., Magrath, B., Ramos, L., Kleinman, S., Tokoku, C., Konishi, M., Yoshikawa, T., Tanaka, I., and Suzuki, R., "Automatic pre-cooling system for large infrared instruments," in [*Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation*], *Proc. SPIE* **7018**, 70182E (July 2008).

[22] Yoshikawa, T., Omata, K., Konishi, M., Ichikawa, T., Suzuki, R., Tokoku, C., Katsuno, Y., and Nishimura, T., "T-LECS: The Control Software System for MOIRCS," in [*Astronomical Data Analysis Software and Systems XV*], Gabriel, C., Arviset, C., Ponz, D., and Enrique, S., eds., *Astronomical Society of the Pacific Conference Series* **351**, 678 (July 2006).