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9147-1, Session 1

Instrumentation at Gemini Observatory (Invited Paper)

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The instrument suite at Gemini South has been completely upgraded since our last update in 2012. Since then we have commissioned the Gemini Multi-Conjugate Adaptive Optics System (GeMS) and its associated Gemini South Adaptive Optics Imager (GSAOI); Flamingos-2, our long-slit and multi-object infrared imager and spectrograph; and the Gemini Planet Imager (GPI). We have also upgraded the CCDs in GMOS-S, our multiobject optical imager and spectrograph.
GHOS, a new high-resolution optical spectrograph is in the design phase for possible placement at either Gemini North or South. Under a slightly different process than we have used in the past, we are now in the early competitive stages of developing the next instrument to follow GHOS. We also plan to upgrade the CCDs in GMOS-N later this year. Combined, these instruments and upgrades form the basis for Gemini's continued evolution and improvements into the next decade.

9147-133, Session PSSun

Gemini planet imager observational calibrations I: overview of the GPI data analysis pipeline

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The Gemini Planet Imager has as its science instrument an infrared integral field spectrograph/polarimeter (IFS). Integral field spectrographs are scientificially powerful but notoriously complex in their data reduction. For GPI to achieve its scientific goals of exoplanet and disk characterization, IFS data must be reconstructed into high quality astrometrically and photometrically accurate datacubes in both spectral and polarization modes. Since GPI is a facility instrument, this must be accomplished via flexible software that is usable by the broad Gemini community. This paper describes the data reduction pipeline developed by our team to

meet these needs, which is now publicly available following GPI's on sky commissioning. Other papers in this series describe in detail the steps and algorithms necessary for calibrating GPI data; this paper provides a broad overview of the process as a whole, summarizes the key steps, and presents the overall software framework and implementation.
The GPI data pipeline is written in IDL with a modular architecture that draws on heritage from the Keck OSIRIS pipeline; a compiled version allows use free of IDL license fees. It implements an extensive suite of tasks ("primitives") that can be assembled into reduction recipes to produce calibrated datasets ready for scientific analysis. Angular, spectral, and polarimetric differential imaging are supported, with primitives implementing both noise minimization (i.e. LOCI) and principle components analysis (i.e. KLIP) based methods. Graphical tools automate the production and editing of recipe XML files, an integrated calibration database manages reference files, and an interactive data display tool ("gpitv") customized for high contrast imaging tasks allows exploration and manipulation of data. Quicklook data cubes are produced in real time at Gemini South for inclusion in the Gemini Science Archive, and GPI observers can subsequently use this pipeline to produce and optimize science quality reductions. The GPI data reduction pipeline is open source, available from planetimager.org, and will continue to be maintained and enhanced throughout the life of the instrument.

9147-151, Session PSSun

Automated alignment and on-sky performance of the Gemini planet imager coronagraph

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The Gemini Planet Imager (GPI) is a next-generation, facility instrument currently being commissioned at the Gemini South observatory.
GPI combines an extreme adaptive optics system and integral field spectrograph (IFS) with an apodized-pupil Lyot coronagraph (APLC) producing an unprecedented capability for directly imaging and spectroscopically characterizing extrasolar planets. GPI's operating goal of 10^{-7} contrast requires incredibly precise alignments between the various elements of the coronagraph (two pupil masks and one focal plane mask) and active control of the beam path throughout the instrument.
Here, we describe the techniques used to automatically align GPI and maintain the alignment throughout the course of science observations. We discuss the particular challenges of maintaining precision alignments on a Cassegrain mounted instrument and strategies that we have developed that allow GPI to achieve high contrast even in poor seeing conditions.
Finally we describe the automation that has been created to allow GPI to operate in queue-scheduled mode, which will make it a particularly powerful tool for the whole astronomical community.

9147-183, Session PSSun

Characterization of the atmospheric dispersion corrector of the Gemini planet imager

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At larger zenith angles, the differential atmospheric refraction, or dispersion, becomes important. Atmospheric dispersion is caused by the dependence of the index of refraction on the wavelength of the light. Light rays with shorter wavelength are refracted more than rays with longer the wavelength. This of course implies that for a certain filter bandwidth the star will look elongated, with the red end closer to the horizon and blue end closer to zenith.

An Atmospheric Dispersion Corrector (ADC) uses a double-prism arrangement where the effective prism angle can varied by altering the relative orientation between the two prisms. In doing this one can set the device so that the dispersion it introduces nullifies the vertical dispersion introduced by the atmosphere.

The ADC installed in the Gemini Planet Imager (GPI) was first tested in August 2012 with a telescope simulator while the instrument was in the

laboratory at the University of California Santa Cruz. GPI is now installed at the Gemini South telescope and first light occurred on November 11th 2013. In this paper, we give an overview of the characterization and performance of the ADC unit in the Gemini Planet Imager obtained not only in the laboratory but also on sky, as well as the structure of its control software.

9147-189, Session PSSun

Gemini planet imager observational calibrations IX: least square inversion flux extraction

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The Gemini Planet Imager (GPI) is a high contrast, adaptive optics, lensletbased integral field spectrograph designed to directly image exoplanets and circumstellar disks from 0.9 to 2.5 microns. The light is converged within a microlenslet spot and dispersed in wavelength on a detector to allow for extracting a data cube of a 2D image with a depth in wavelength. The extraction process is highly influential to the extracted cube and can be plagued with overlapping spectra, coherent noise patterns, or shifts in the spectra on the detector. In order to extract dispersed micro-spectra from the detector, we develop an extraction algorithm based on the least squares method. This involves generating reference images of the microlenslet PSF and modeled coherent noise to generate a flux value within each reference image and a correlation matrix of all the reference images to each other. We extract each reference image's contribution to the detector image using a simple matrix inversion. This has the benefit of disentangling spectra-to-spectra and spectra-to-noise overlaps on the detector. With previously developed wavelength calibrations and high-resolution PSFs, we generate reference PSF images positioned at a fixed pixel separation along the spectra to optimally extract the flux from each individual spectra. Furthermore, we generate microphonics reference images with frequencies measured from the detector, to simultaneously separate noise contributions from the spectra to improve low signal to noise spectral extraction. The inversion process is highly sensitive to positional shifts in wavelength calibration primarily due to flexure or temperature fluctuations between instrument servicing. To adapt the fitting process, we vary spectral calibration parameters such as dispersion angle and orthogonal (from the dispersion axis) shift, to find an optimal residual for extraction. After the flux per pixel is extracted, we repeat the extraction process with a parallel shift along the dispersion axis to improve the wavelength resolution. We then interpolate the spectra at a uniform wavelength separation for each lenslet before compiling into a full image data cube. We then compare the performance improvement with other extraction methods.

9147-190, Session PSSun

Gemini planet imager one button approach

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The Gemini Planet Imager (GPI) is an "extreme" adaptive optics coronagraph system and is now on the Gemini South telescope in Chile. This instrument is composed of three different systems that historically have been separate instruments. These systems are the extreme Adaptive Optics system (2 deformable mirrors, including one high-order MEMS system), the Science Instrument (near-infrared integral field spectrograph) and the Calibration System. Each system coordinates actions that require precise timing. The observatory is responsible for starting these actions and has typically done this asynchronously across independent systems. Despite this complexity we are striving to provide an interface that is as close to a one-button approach as possible. This paper will describe the sequencing of these systems both internally and externally through the observatory.

9147-195, Session PSSun

Gemini planet imager observational calibrations VIII: characterization and role of satellite spots

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The Gemini Planet Imager (GPI) combines extreme adaptive optics, an integral field spectrograph, and a high performance coronagraph to directly image extrasolar planets in the near infrared. Because the coronagraph blocks most of the light from the star, it prevents the host star from being measured directly. Instead, satellite spots that are created by the diffraction of light from the occulted star on a grid pattern in the pupil plane mask of GPI can be used to locate the star and extract its spectrum. We describe the techniques to measure the locations and spectra of the satellite spots. We discuss the accuracy of using the positions of the

satellite spots to locate the position of the occulted star for astrometry. We also present measurements of the relative intensities of the satellite spots and our ability to measure the spectrum of the occulted star. In regards to both astrometry and spectrophotometry, we discuss the stability of the satellite spots and the effects of speckle noise, distortion, data cube construction, flexure compensation, atmospheric dispersion, and uncorrected low-order aberrations. Finally, we comment on the use of the satellite spots for both instrument calibration and science.

9147-54, Session 7

Progress on the Gemini high-resolution optical spectrograph (GHOST) instrument

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Nick F. Staszak, Julia Tims, Australian Astronomical Observatory
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Ross Zhelem, Australian Astronomical Observatory (Australia)
The Gemini High-Resolution Optical SpecTrograph (GHOST) instrument is the newest instrument being developed for the Gemini telescopes, in a collaboration between the Australian Astronomical Observatory (AAO), the Herzberg Institute for Astrophysics (HIA) in Canada and the Australian National University (ANU). We describe the general properties of the instrument, including the two-object mode, with R>50,000, the R>75,000 mode with a precision simultaneous reference, and a spectropolarimetry option. A major change to the contract since the 2012 SPIE has been a change of the key subcontractor, with the HIA now taking on the role of the spectrograph subsystem lead. We describe the process of design optimization that utilizes the unique strengths of HIA. Lensletbased image slicing is a key technology for this instrument, enabling R>75,000 with a 1.2" input aperture with a spectrograph has a slit width/ resolution product corresponding to an R4 grating with a 100mm pupil. Since the 2010 SPIE, the AAO has become more experienced with similar lenslet-based image slicing with the KOALA instrument for the AAT. We discuss how this experience mitigates risk for the GHOST project, and also eliminates the need for additional fore-optics for the R>75,000 mode, improving performance. Finally, we outline the updated cost and schedule for the project, and describe the unique scientific role this instrument will have in an international context. Key science topics will span a range from radial velocity follow-up of exoplanet detections through to abundance measurements of gas surrounding the brightest supernovae in the distant Universe.

9147-55, Session 8

The integral field spectrograph for the Gemini planet imager

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Stanford Univ. (United States); Christopher A. Johnson, Evan Kress, Univ. of California, Los Angeles (United States); Quinn M. Konopacky, Dunlap Institute for Astronomy & Astrophysics (Canada); Bruce A. Macintosh, Stanford Univ. (United States) and Lawrence Livermore National Lab. (United States); Kenneth G. Magnone, Univ. of California, Los Angeles (United States); Jérôme Maire, Dunlap Institute for Astronomy & Astrophysics (Canada); Ian S. McLean, Univ. of California, Los Angeles (United States); David W. Palmer, Lawrence Livermore National Lab. (United States); Marshall D. Perrin, Space Telescope Science Institute (United States); Carlos Quiroz, Naru Sadakuni, Gemini Observatory (Chile); Leslie Saddlemyer, NRC - Herzberg Institute of Astrophysics (Canada); Simon Thibault, Univ. Laval (Canada); Sandrine J. Thomas, NASA Ames Research Ctr. (United States) and Univ. of California Observatories (United States); Philippe Vallée, Univ. de Montréal (Canada); Jason L. Weiss, Univ. of California, Los Angeles (United States)

The Gemini Planet Imager (GPI) is a complex optical system designed to directly detect the self-emission of young planets within two arcseconds of their host stars. After suppressing the starlight with an advanced AO system and apodized coronagraph the dominant residual contamination in the focal plane are speckles from the atmosphere and optical surfaces. Since these are diffractive effects their positions in the field are strongly wavelength dependent, while an actual companion planet will remain at fixed separation. By comparing multiple images at different wavelengths taken simultaneously we can freeze the speckle pattern and extract the planet light adding an order of magnitude of contrast. To achieve a bandpass of 20%, sufficient to perform speckle suppression, and to observe the entire two arcsecond field of view at diffraction limited sampling, we designed and built an integral field spectrograph with extremely low wavefront error and almost no chromatic aberration. The spectrograph is fully cryogenic and operates in the wavelength range 1 to 2.4 microns with five selectable filters covering roughly 20% bandpasses. A prism is used to produce a spectral resolution of 45 in the primary detection band and maintain high throughput. Based on the OSIRIS spectrograph at Keck, we selected to use a lenslet-based spectrograph to achieve an rms wavefront error of approximately 25 nm. Over 36,000 spectra are taken simultaneously and reassembled into image cubes that have roughly 192x192 spatial elements and contain between 15 and 35 spectral channels. The primary dispersion prism can be replaced with a Wollaston prism for dual polarization measurements of protoplanetary disks. The spectrograph also has a pupil-viewing mode for alignment and calibration. We present the entire design and implementation of the spectrograph including on-sky performance.

9147-55, Session 8

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9147-65, Session 8

First performance of the GeMS+GMOS system

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During the 2012 commissioning of the Gemini MCAO System (GeMS) in Gemini South Observatory, we briefly explored the performance improvement brought by pairing GeMS with the Gemini Multi-Object Spectrograph (GMOS), compared to GMOS in natural seeing mode. GMOS is a instrument sensitive in the visible band with imaging and spectroscopic capabilities, hence pushing MCAO toward the visible, a mode for which it was not specifically designed.

We report in this paper on the first results obtained with the GeMS +GMOS pair. Several globular clusters were observed in imaging mode only. We have derived performance in term of FWHM and determined the improvement against natural seeing. We also obtain photometric, relative and absolute astrometric precision for the AO enhanced images. We also studied the influence of the NGS constellation on the photometric performance.

Finally, we predict the expected performance for the spectroscopic modes long-slit and integral field spectroscopy, which could be compared with the GALACSI+MUSE system at the Very Large Telescope. We also have looked

at the expected performance of the GeMS+GMOS system once the CCD upgrade, scheduled during 2014, will occur.

9147-135, Session PSWed

Gemini planet imager observational calibrations XI: non-redundant masking on GPI

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The Gemini Planet Imager (GPI) Extreme Adaptive Optics Coronograph (ExAOC) contains an interferometric mode: a 10-hole non-redundant mask (NRM) in its pupil wheel. GPI operates at Y, J, H, and K bands, using an integral field unit spectrograph (IFS) to obtain spectral data at every image pixel. NRM on GPI is capable of imaging with a half resolution element inner working angle at moderate contrast, probing the region behind the coronagraphic spot. The fine features of the NRM PSF can provide a reliable check on the plate scale, while also acting as a neutral density filter for spectral standard calibrators that would saturate the full pupil. NRM can also provide an independent comparison with the astrometric spots created from GPI's gridded apodizer pupil plane masks. Integration and Test NRM images provide a raw (uncalibrated) contrast floor achievable with NRM. We discuss early on-sky performance of GPI NRM, comparing images from integration and tests with the first on-sky images, and discuss the implication for future NRM science on GPI. We discuss using NRM to calibrate the plate scale and to provide an independent check on atmospheric dispersion, with or without an ADC.

9147-279, Session PSWed

Gemini planet imager observational calibrations IV: wavelength calibration and flexure correction for the integral field spectograph

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We present the wavelength calibration for the lenslet-based Integral Field Spectrograph (IFS) that serves as the principal science instrument for the Gemini Planet Imager (GPI). The GPI IFS features a 2.7'' x 2.7'' field of view and a 190 x 190 lenslet array (14.3 mas/lenslet) operating in Y, J, H, and K bands with spectral resolutions ranging from R ~ 35 to 78. Due to variations across the field of view, a unique wavelength solution is determined for each lenslet characterized by a 2D position, the spectral dispersion, and the rotation of the spectrum with respect to the detector axes. The four free parameters are fit using a constrained Levenberg-Marquardt leastsquares minimization algorithm, which compares an individual lenslet's arc lamp spectrum to a simulated arc lamp spectrum. This method enables measurement of spectral positions to better than 1/20th of a pixel on the GPI IFS detector using Gemini's facility calibration lamp unit GCAL, improving spectral extraction accuracy compared to earlier approaches. Using such wavelength calibrations we have measured how internal flexure of the spectrograph with changing zenith angle shifts spectra on the detector. We describe the methods used to compensate for these shifts when assembling datacubes from on sky observations using GPI.

9147-282, Session PSWed

Gemini planet imager observational calibrations III: empirical measurement methods and applications of high resolution microlens PSFs

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The Gemini Planet Imager (GPI) is a newly commissioned instrument that combines an extreme adaptive optics system, an advanced coronagraph,

precision wavefront sensing and a lenslet based integral field spectrograph (IFS) to measure the spectral energy distribution (SED) between 0.9-2.5 µm of young extrasolar giant planets (EGPs) orbiting relatively nearby stars. Each GPI image consists of ~37000 microspectra, simultaneously imaged on the detector, each requiring individual calibration prior to extraction. It has been determined that the required position accuracy of each microspectrum must be better than 0.1 pixels in order to obtain the best quality datacubes. However, depending on the waveband, these spectra are either under- or critically sampled making finding their positions to subpixel precision challenging. This is further complicated by the intrapixel sensitivity of the Hawaii II-RG detectors, which has been observed to decrease by 10-15% towards the edges of the pixels. Lastly, the positions of the microspectra are known to move as a function of instrument position due to internal flexure of the IFS therefore, accurate positions must be determined for each image prior to data extraction.
In this paper, we demonstrate how to obtain high-resolution narrowband microlens PSFs by combining subpixel dithered measurements via methods adapted from high precision Hubble Space Telescope astrometric PSF fitting with the Wide Field Planetary Camera 2 instrument. The dither diversity can be obtained either by combining groups of nearby lenslets that have different phase sampling relative to the detector, or for an individual lenslet by utilizing the internal flexure of the IFS. We then discuss how these narrowband PSFs are used in the GPI data reduction pipeline to determine accurate wavelength calibrations by offering precise locations of the emission line peaks of the arc lamps. The PSFs are also used to characterize the crosstalk between microspectra and are a critical component of advanced spectral extraction techniques. Lastly, we discuss the ability of these PSFs to measure the high order flexure terms. Although this paper focuses on the GPI instrument, the methods demonstrated here are generally applicable to any lenslet-based integral field spectrograph including proposed future instrument concepts for space missions imaging exoplanets.

9147-286, Session PSWed

Gemini planet imager observational calibrations II: detector performance and calibration

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The Gemini Planet Imager is a newly commissioned facility instrument that combines an extreme adaptive optics system, an advanced coronagraph, and an integral field spectrograph (IFS) that will measure the near-infrared spectral energy distribution of young extrasolar planets orbiting relatively nearby stars. Housed in the integral field spectrograph is a Hawaii II-RG science detector with a SIDECAR. The entire IFS is cooled to a temperature of 80 K by two closed-cycle cryocoolers that are mounted onto the side of the cryostat. Variations in vibration induced by the cryocoolers can at times couple into the detector to produce measurable microphonics noise. This paper presents our method to measure and remove microphonics from individual science images via Fourier filtering. We also present a method to remove correlated read noise from the readout electronics that is common among the 32 detector channels. This I accomplished by examining the unilluminated detector pixels lying between the microspectra, then apply the correction to all channels. We also describe our characterization and correction for hot/cold/bad pixels in both spectral and polarimetry modes as well as our persistence correction that follows the model used by the Hubble Space Telescope's Wide Field Camera 3. Lastly, we will describe our correction for nonlinearity.

9147-305, Session PSWed

Gemini planet imager observational calibrations

VII: on-sky polarimetric performance of the Gemini planet imager

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The differential polarimetry mode of the Gemini Planet Imager (GPI) is intended to spatially resolve polarized, scattered light from circumstellar disks. We describe the results of on-sky observations of unpolarized and polarized calibration stars, in both unocculted and occulted coronagraphic modes. In unocculted coronagraphic mode, GPI functions as a conventional polarimeter. Interstellar polarization ("Serkowski") curves as a function of wavelength are constructed for strongly polarized stars. It is expected that the polarization position angle of these stars will be nearly constant with wavelength in the near-infrared, as the peak of stellar Serkowski curves tends to lie in the optical, and we investigate variation in position angle with wavelength. Measured position angles are compared with optical measurements from the literature to determine the accuracy of GPI polarization position angles. Observations of stars identified from the literature to be nearly unpolarized are taken in unocculted coronagraphic mode to determine the accuracy of GPI degree of linear polarization. We also repeat observations of all stars in occulted coronagraphic mode. Nearby, unpolarized stars are identified to have no significant IR excess, and therefore no detectable circumstellar material. The large distance of polarized stars prohibits spatial resolution of potential circumstellar material; therefore, occulted images allow measurement of the pixel-topixel variance in Stokes Q and U as a function both of angular separation from the star and of mean stellar polarization. This is essential in understanding the minimum detectable surface brightness of circumstellar material for all GPI polarization-mode observations. Interstellar polarization has long been known to vary linearly with heliocentric distance, and we therefore probe the significance that this systematic effect will have for disk-hosting stars in occulted coronagraphic mode.

9147-306, Session PSWed

Gemini planet imager observational calibrations V: astrometry and distortion

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Sasha Hinkley, California Institute of Technology (United States); Paul R. Kalas, Univ. of California, Berkeley (United States); James E. Larkin, Univ. of California, Los Angeles (United States); Ben R. Oppenheimer, American Museum of Natural History (United States); Jennifer Patience, Arizona State Univ. (United States); Leslie Saddlemyer, NRC-Dominion Astrophysical Observatory (Canada); Anand Sivaramakrishnan, Space Telescope Science Institute (United States) and Stony Brook Univ. (United States) and American Museum of Natural History (United States)
The Gemini Planet Imager (GPI) will detect and characterize a new population of widely separated (~4-40 AU) exoplanets. In order to understand the dynamical properties of these planets, precise relative astrometry is essential. We present the results of both laboratory and on sky astrometric characterization of the integral field spectrograph (IFS) component of GPI. This characterization includes measurement of the plate scale of the IFS, the position of the detector with respect to north, and optical distortion. Two of these three quantities (plate scale and distortion) were measured in the laboratory using two trasparent grids of spots, one with a square pattern and the other with a random pattern. These grids were designed to sit in the GPI telescope simulator at UC Santa Cruz. Though the separation of the grid spots is known to fairly high precision, we elected not to use this information to measure distortion and instead use a self-calibration method similar to what was performed for HST instruments (e.g., Anderson & King 2003). By rotating each grid through a number of different position angles with slight lateral shifts, a selfconsistent distortion solution is derived. We found in the laboratory that the distortion in the IFS is relatively small, giving an average spot position residual of 0.26 spatial pixels (spaxels). Distortion is corrected in reduced IFS cubes using the results of a 5th order polynomial fit to positional offset vectors found using the pinhole grid. Post distortion corrected residuals are 0.04 spaxels, well below our requirement of 0.1 spaxel residuals. In order to determine the plate scale, we fit for the separation of the pinholes in the regular grid and applied a mm to arc second conversion factor to derive 14.3 +- 0.1 mas/spaxel. This was confirmed using measurements of the artificial star unit inside GPI, which is on a precisely movable stage. On sky, the GPI plate scale is measured using a number of relatively high contrast multiple systems with known positions in arcseconds from other calibrated telescopes and Solar System objects. We have confirmed that the plate scale on sky is 14.3 mas/spaxel. The position with respect to north can also be measured using binaries. Distortion will be verified and remeasured using observation of dense star clusters. However, it is not expected that the Gemini South telescope will induce a significant amount of distortion beyond what is internal to the IFS.
The ultimate goal is to calibrate the IFS such that GPI regularly achieves astrometric precision of ~1 mas. Monte Carlo simulations for the GPI Exoplanet Survey (GPIES) have shown that by achieving this level of astrometric precision will allow for much greater characterization of the orbital properties of discovered planets. In particular, over the three year lifetime of GPIES, we will measure eccentricity limits for all detected planets. These limits will allow us to produce statistically-distinguishable eccentricity distributions for widely separated exoplanets, which will provide important constraints on planetary formation.

9147-307, Session PSWed

Gemini planet imager observational calibrations VI: photometric and spectroscopic calibration for the integral field spectrograph

Jérôme Maire, Dunlap Institute for Astronomy & Astrophysics (Canada); Patrick J. Ingraham, Stanford Univ. (United States); Marshall D. Perrin, Space Telescope Science Institute (United States); Dmitry Savransky, Lawrence Livermore National Lab. (United States); Jason J. Wang, Univ. of California, Berkeley (United States); Jean-Baptiste Ruffio, SETI Institute (United States); Schuyler G. Wolff, Johns Hopkins Univ. (Canada); Christian Marois, NRC - Herzberg Institute of Astrophysics (Canada); Laurent

A. Pueyo, Space Telescope Science Institute (Canada); Sandrine J. Thomas, NASA Ames Research Ctr. (United States); Max Millar-Blanchaer, Quinn M. Konopacky, Dunlap Institute for Astronomy & Astrophysics (Canada); Jeffrey K. Chilcote, James E. Larkin, Jason L. Weiss, Univ. of California, Los Angeles (United States); James R. Graham, Univ. of California, Berkeley (United States); Bruce A. Macintosh, Stanford Univ. (United States); René Doyon, Univ. de Montréal (Canada); Anand Sivaramakrishnan, Space Telescope Science Institute (United States); Alexandra Z. Greenbaum, Johns Hopkins Univ. (United States); Abhijith Rajan, Jennifer Patience, Arizona State Univ. (United States)
The Gemini Planet Imager (GPI) is a new facility instrument for the Gemini Observatory designed to provide direct detection and characterization of planets and debris disks orbiting nearby stars. In addition to its extreme adaptive optics and coronagraphic systems which give access to high angular resolution and high-contrast imaging capabilities, GPI contains an Integrated Field Spectrograph providing low resolution spectra across five wavelength bands between 1 and 2.5µm. High-fidelity spectrophotometry will be essential to study exoplanet structure through the composition and temperature of cooler planetary atmospheres outside the hot inner orbits typical of transiting planets.
In this paper, we describe the sequence of processing steps required for the spectrophotometric calibration of GPI science data, and the necessary calibration files.
Absolute calibration uncertainties and stability are investigated by means of spectrophotometric standard star observations.

9147-312, Session PSWed

The Gemini high-resolution optical spectrograph (GHOST) bench spectrograph preliminary optical design

John Pazder, NRC - Herzberg Institute of Astrophysics (Canada)
The instrument group of the Herzberg Institute of Astrophysics has been subcontracted by the Australian Astronomical Observatory (AAO) to design and build the bench spectrograph for Gemini High-Resolution Optical SpecTrograph (GHOST) instrument. GHOST is the newest instrument being developed for the Gemini telescope and is a collaboration between the Australian Astronomical Observatory (AAO), the Herzberg Institute for Astrophysics (HIA) in Canada and the Australian National University (ANU). The instrument is a fiber feed spectrograph with R>50,000 in two-object mode and R>75,000 in single object mode. This paper outlines the optical design of the bench-mounted spectrograph.
The predicted spectrograph resolution and efficiency for the spectrograph and the design trade-offs explored in the preliminary design phase are presented.

9148-11, Session 3

Galactic astronomy with AO: the study of nearby star clusters (Invited Paper)

Timothy J. Davidge, NRC - Herzberg Institute of Astrophysics (Canada)
During the past two decades AO systems available for astronomical use have progressed from single beacon systems that offer corrections over fields covering a few arcsec to multibeacon systems, such as GeMS on Gemini South, that deliver stable point spread functions over fields in excess of an arcmin on a side.
The development of multi-conjugate AO systems enable surveys of the stellar contents of star clusters in the Galaxy, and the measurement of astrometric information that can be used to probe the structure and mass of the Milky-Way. Clusters are natural targets for AO studies as they contain a wealth of guide stars, and are also natural environments for characterizing images delivered by AO systems. In this talk I will review recent observations of Galactic open clusters and globular clusters

obtained with the GeMS system.
Emphasis will be placed on the investigation of cluster structure, the stellar mass function, and the assembly of the Galactic field population. Finally, the science that might be performed with multi-conjugate AO systems on large telescopes, such as NFIRAOS on the TMT, will also be briefly discussed.

9148-12, Session 3

Supernovae and extragalactic astronomy with laser guide star adaptive optics (Invited Paper)

Stuart D. Ryder, Australian Astronomical Observatory (Australia); Seppo Mattila, Erkki Kankare, Univ. of Turku (Finland) and Tuorla Observatory (Finland); Petri Vaisanen, South African Astronomical Observatory (South Africa)

Optical searches for supernovae (SNe) at intermediate and high redshift find only half the numbers expected on the basis of the measured rate of massive star formation. The missing fraction is even higher in the class of

Luminous Infra-Red Galaxies (LIRGs), which form stars at a rate of tens to hundreds of solar masses per year, and thus ought to play host to ~1 SN per year on average. However optical searches in LIRGs for SNe are hampered by large dust extinction, together with their clumpy nature and large distances (few closer than 50 Mpc). To overcome these difficulties with ground-based telescopes our collaboration has pioneered the use of multi-epoch adaptive optics imaging, with and without laser guide stars, at infrared wavelengths. Observing in the infrared allows us to probe much higher extinctions, at greater spatial resolution, than in the optical. The use of queue-scheduled telescopes is also critical in providing the necessary observing cadence to reduce the risk of missing an SN event in action.
Since 2004 we have used the NAOS-CONICA facility on the VLT; the NIRI-ALTAIR facility on Gemini North; and now the GeMS-GSAOI facility on Gemini South for this work.
Our Gemini North monitoring program of 8 LIRGs from 2008-2010 yielded 4 SN discoveries that would have been missed in optical surveys, and confirmed 2 SNe that were discovered elsewhere. These results have allowed us to place the first empirical constraints on the fraction of SNe that will be missed by future SN searches such as those by SkyMapper, KMTNet, LSST, Euclid, and JWST. Our multi-epoch adaptive optics observations also provide some of the deepest and highestresolution images of the LIRGs themselves, providing insights into the triggering of their starburst activity, as well as the characteristics of their super star cluster populations.

9148-116, Session PSun1

Altair performance and upgrades

Olivier Lai, Gemini Observatory (United States) and Subaru Telescope, National Astronomical Observatory of Japan (United States); Chadwick A. Trujillo, Gemini Observatory (United States); Jean-Pierre Véran, Glen Herriot, NRC - Herzburg Institute of Astrophysics (Canada)

Altair is the facility single conjugate AO system for Gemini North. Although it has been in operation for more than 10 years (and upgraded to LGS in 2007), Altair’s performance is degraded by three main issues: Static noncommon path aberrations, spatial aliasing on centroid offsets from the M2 support structure print-through on the optical surface and vibrations of the telescope and instrument support structure.
Monte Carlo simulations can reproduce the behavior of Altair when including these three effects and they are roughly of the same order of magnitude. Solutions or mitigations are being investigated to overcome these nefarious effects and restore Altair’s performance to its nominal level. A phase diversity approach is being developed to measure and correct for static aberrations. A high accuracy phase map of the M2 print-through has been obtained and is being used to calibrate and/or

filter centroids affected by aliasing. A new real time computer is under consideration, to be able to handle more advanced controllers, especially notch filters to combat vibrations.
In this paper we will report on the various simulations and on-sky results of this rejuvenation of one of Gemini's workhorse instruments.

9148-129, Session PSun2

Laboratory validation of a laser shaping system before guide star projection

Sebastián G. Zúñiga, Univ. Técnica Federico Santa María (Chile); Clémentine Béchet, Pontificia Univ. Católica de Chile (Chile); Benoît Neichel, Lab. d'Astrophysique de Marseille (France); Vincent Fesquet, Vincent Garrel, Gemini Observatory (Chile); Pedro A. Escárate, Univ. Santa María (Chile); Christian Dani Guzmán, Andrés R. Guesalaga, Pontificia Univ. Católica de Chile (Chile)

The multiple laser guide stars for the Gemini South multi-conjugate Adaptive Optics (AO) system (GeMS) is a crucial development that offers wide-field diffraction limited AO correction to the astronomical community. The performance of the AO is strongly dependent on the laser beam power and quality before it is projected to the sodium layer. Calibration and alignment of the laser is a time-consuming procedure carried out before every run. This task is essential for the AO system to work and to obtain good quality of laser guide stars on sky. In order to ensure the best availability and observing time for GeMS, a beam shaping concept to improve the quality of the laser guide stars and also speed-up calibration is currently being developed. The idea is to insert an optical setup with two deformable mirrors right out of Gemini laser box in order to correct the beam distortions in amplitude and phase and ensure an optimal laser field before launching.

The algorithm for this beam shaping concept has been previously presented and is briefly described. It is based on a phase retrieval method from which the phase distortions to be applied by each deformable mirrors are estimated. The first mirror aims to correct the amplitude distortions during propagation in the near-field. The second mirror corrects for the remaining phase aberrations, at a position conjugated to the projecting aperture. New simulations results are now presented in order to enhance the influence of some design parameters like the propagation distance between the deformable mirrors, and the number of degrees of freedom of the mirrors.
Following this description of the method and parameter influence, we show how this method is now implemented on a laboratory bench. This experimental validation is a first step before its implementation on the telescope. The optical set-up includes two deformable mirrors with more than 150 degrees of freedom in total. The experiment is described in details and the results of both amplitude and phase corrections are presented.
We finally discuss the future implementation issues at the Gemini South telescope.

9148-130, Session PSun2

Polarization control optimization of the Gemini south beam transfer optics

Constanza Araujo Hauck, Cristian Moreno, Gemini Observatory (Chile)

The Beam Transfer Optics (BTO) is a sub-system of the Gemini Multi-Conjugate Adaptive Optics System (GeMS). The main purpose of the BTO is to relay the laser light from the laser service enclosure up to the Laser Launch Telescope (LLT), located behind the telescope secondary mirror, where the five laser beams are propagated to the sky. Other functionalities besides relaying the laser light from the laser to the LLT, is the laser polarization control, which is crucial to any AO related system.
The polarization state of the laser output beam influences the photon return flux. It is proven that the backscattering efficiency is higher when exciting the sodium layer with a circular polarized beam than one with linear polarization. For this reason circular polarization of our five laser

beams that exit the LLT is desired for any telescope position.
The paper reviews the current status of the Gemini South Beam Transfer Optics polarization and its control scheme. It reports on the improvements already done on the polarization control and measurement data of the polarization state at different BTO sections. In addition we discuss further optimization and upgrade ideas of the system.

9148-18, Session 5

The Gemini planet imager: first light and commissioning (Invited Paper)

Bruce A. Macintosh, Stanford Univ. (United States); Jeffrey K. Chilcote, Univ. of California, Los Angeles (United States); Daren Dillon, Univ. of California, Santa Cruz (United States); Jennifer S. Dunn, NRC - Herzburg Institute of Astrophysics (Canada); Michael P. Fitzgerald, Univ. of California, Los Angeles (United States); Donald Gavel, Univ. of California, Santa Cruz (United States); James R. Graham, Univ. of California, Berkeley (United States); Alexandra Z. Greenbaum, Johns Hopkins Univ. (United States); Stephen J. Goodsell, Gemini Observatory (United States); Markus Hartung, Pascale Hibon, Gemini Observatory (Chile); Patrick J. Ingraham, Stanford Univ. (United States); Quinn M. Konopacky, Univ. of Toronto (Canada); James E. Larkin, Univ. of California, Los Angeles (United States); Jérôme Maire, Univ. of Toronto (Canada); Franck Marchis, SETI Institute (United States); Christian Marois, NRC-Dominion Astrophysical Observatory (Canada); Ben R. Oppenheimer, American Museum of Natural History (United States); David W. Palmer, Lawrence Livermore National Lab. (United States); Marshall D. Perrin, Space Telescope Science Institute (United States); Lisa A. Poyneer, Lawrence Livermore National Lab. (United States); Laurent A. Pueyo, Space Telescope Science Institute (United States); Fredrik T. Rantakyrö, Naru Sadakuni, Gemini Observatory (Chile); Dmitry Savransky, Cornell Univ. (United States); Rémi Soummer, Anand Sivaramakrishnan, Space Telescope Science Institute (United States); Sandrine J. Thomas, NASA Ames Research Ctr. (United States); James K. Wallace, Jet Propulsion Lab. (United States); Jason J. Wang, Univ. of California, Berkeley (United States); Sloane J. Wiktorowicz, Univ. of California, Santa Cruz (United States); Schuyler G. Wolff, Johns Hopkins Univ. (United States)

The Gemini Planet Imager (GPI) is the first facility extreme-AO highcontrast instrument – optimized solely for imaging of faint companions – on a 8-m class telescope. It combines a high-order MEMS AO system (1500 active actuators), an apodized-pupil Lyot coronagraph, a high-accuracy IR post-coronagraph wavefront sensor, and a near-infrared integral field spectrograph. GPI incorporates several other novel features such as ultra-high quality optics, a spatially-filtered wavefront sensor, and new calibration techniques. GPI had first light in November 2013. I will present results of first-light and performance verification and optimization and show early science results.

9148-19, Session 5

On-sky performance during verification and commissioning of the Gemini planet imager's adaptive optics system

Lisa A. Poyneer, Bruce A. Macintosh, David W. Palmer, Lawrence Livermore National Lab. (United States)

The adaptive optics subsystem of the Gemini Planet Imager has several advanced algorithms and technologies. These include wavefront reconstruction with the Fourier Transform, the spatially filtered wavefront sensor, modal gain optimization on all 2000+ fourier modes, and an LQG controller for tip-tilt vibration correction. We present results of the AO system's performance on-sky during verification and commissioning runs at Gemini South observatory. These results include overall performance,

and a discussion of specific technologies and (as appropriate) their limitations.

9148-19, Session 5

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9148-175, Session 6

On-sky vibration environment for the Gemini planet imager and mitigation effort

Markus Hartung, Gemini Observatory (Chile); Leslie Saddlemyer, NRC - Herzburg Institute of Astrophysics (Canada); Thomas L. Hayward, Gemini Observatory (Chile); Bruce A. Macintosh, Lisa A. Poyneer, Lawrence Livermore National Lab. (United States); Andrés R. Guesalaga, Pontificia Univ. Católica de Chile (Chile); Dmitry Savransky, Lawrence Livermore National Lab. (United States); Naru Sadakuni, Gemini Observatory (Chile); Daren Dillon, Univ. of California, Santa Cruz (United States); James K. Wallace, Jet Propulsion Lab. (United States); Ramon Galvez, Gaston Gausachs, Paul Collins, Andrew Cardwell, Andrew Serio, Fredrik

T. Rantakyrö, Gemini Observatory (Chile); Stephen J. Goodsell, Gemini Observatory (United States)

The Gemini Planet Imager (GPI) entered on-sky commissioning and had its first-light at the Gemini South (GS) telescope in November 2013. GPI is an extreme adaptive optics (XAO), high-contrast imager and integralfield spectrograph dedicated to the direct detection of hot exo-planets down to a Jupiter mass. The performance of the apodized pupil Lyot coronagraph depends critically upon the residual wavefront error (design goal of 60 nm rms with <5 mas RMS tip/tilt), and therefore is most sensitive to vibration (internal or external) of Gemini's instrument suite. Excess vibration can be mitigated by a variety of methods such as passive or active dampening at the instrument or telescope structure or Kalman filtering of specific frequencies with the AO control loop. Understanding the sources, magnitudes and impact of vibration is key to mitigation. This paper gives an overview of related investigations based on instrument data (AO module or from GPI Calibration unit) as well as external data such the accelerometers (permanently) placed at different locations on the GS telescope structure. We report the status of related mitigation efforts, and present corresponding results.

9148-29, Session 7

GPI PSF subtraction with TLOCI: the next evolution in exoplanet/disk high-contrast imaging

Christian Marois, NRC-Dominion Astrophysical Observatory (Canada); Jean-Pierre Véran, NRC - Herzberg Institute of

Astrophysics (Canada); Carlos M. Correia, Univ. do Porto (Portugal)

Exoplanet/Disk imaging requires high level of stellar flux subtraction. The "angular differential imaging" observing technique and the least-squares LOCI algorithm have now become the standard in single band imaging. With the development of new high-order high-contrast adaptive optics integral field units (GPI, SPHERE, P1640, or future instruments for the ELTs), the image subtraction least-squares algorithm needs to be modified to allow the optimal use of polychromatic images, same band/field rotated images and archive data. A new algorithm, TLOCI (for Template LOCI), is presented to achieve this task by "maximizing a companion signal-to-noise ratio" instead of the original LOCI "minimizing of the noise". The TLOCI technique uses an input spectrum and template PSFs to optimize the reference image least-squares coefficients to minimize the flux contamination via self-subtraction (thus maximizing its throughput wavelength per wavelength) of any specific planet (or disk is properly optimized) in the image, while trying to maximize, at the same time, the noise subtraction. The new algorithm has been developed using on sky Gemini Planet Imager data and has achieved impressive contrast. I will present the TLOCI algorithm, its performances, and will discuss the planet spectrum recovery challenge.

9148-143, Session PMon1

The photometric and astrometric performance of LGS MCAO with science-based metrics: first results from Gemini/GeMS observations of galactic globular clusters

Paolo Turri, Univ. of Victoria (Canada); Alan McConnachie, Peter B. Stetson, David R. Andersen, NRC - Herzburg Institute of Astrophysics (Canada); Giuseppe Bono, Univ. degli Studi di Roma "Tor Vergata" (Italy); Giuliana Fiorentino, INAF - Osservatorio Astronomico di Bologna (Italy); Jean-Pierre Véran, NRC - Herzburg Institute of Astrophysics (Canada)

Multi-conjugate adaptive optics (MCAO) can achieve diffraction limited images over a field of arcminutes, and is a central technology of the ELTs. Gemini/GeMS is the first facility-class LGS MCAO system in operation. With this instrument we have taken images in J and Ks bands of the globular cluster NGC 1851 for which we also have HST/ACS observations in the visible. In addition to the principal science of stellar populations analysis, these data allow us to examine the photometric and astrometric

performance of the LGS MCAO system using a large number of point sources (>30000 stars) distributed across the field for which we have a well-calibrated astrometric reference systems (defined by HST/ACS). In this paper we present the deepest near-infrared photometry of NGC 1851, providing high signal-to-noise, colour-magnitude diagrams that reach the lower main sequence. These measurements allow for a new insight into the stellar populations of this globular cluster, as well as initial measurement of its internal dynamics. We analyze the photometric performance of the instrument and the field dependence of the PSF, as well as the geometric distortions produced by the adaptive optics correction. The evaluations of both the photometry and astrometry performances of GeMS are central to predicting and improving the future performance of LGS MCAO systems like NFIRAOS for the Thirty Meter Telescope.

9148-180, Session PMon5

Morphology of distant galaxies with MCAO

Benoît Neichel, Lab. d'Astrophysique de Marseille (France); Marc Huertas-Company, Observatoire de Paris à Meudon (France); Benoit Epinat, Lab. d'Astrophysique de Marseille (France); Damien Gratadour, Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France)

To understand the physical processes taking place in galaxy formation

and evolution and to differentiate between intrinsic and environmental effects, the ability to obtain resolved spectroscopy and images across the objects is a must. Distant galaxies are marginally resolved in seeing-limited conditions and Adaptive Optics (AO) is required. Most of the current extragalactic AO studies are however constrained by the number of targets available to AO correction (the so-called sky coverage), and the need for statistics, that requires observing many objects across the largest possible field. These constraints are now significantly reduced by the new Wide Field AO systems, like GeMS, the Gemini MCAO system.
In this paper, we try to understand the impact of the AO-PSF on the galaxies' morphology analysis accuracy. In a first stage, we use realistic simulated data in order asses the morphological parameters, taking into account partial PSF knowledge. For this, galaxies are modeled based on three level of complexity: (i) combination of simple sersic profiels ; (ii) re-scaling of high resolution images ; (iii) galaxies obtained from cosmological simulation tools. The MCAO PSF is modeled based on accurate AO simulation tools (YAO) scaled on actual observations obtained with GeMS. MCAO PSF are then used to convolve the galaxy models. The morphological analysis is performed on this data, and assumes a given PSF. We study the impact of a partial knowledge of the PSF on the morphological analysis. This allows us to define the critical parameters of the MCAO PSF affecting the analysis accuracy. We then use these simulation results to apply our method on a data set of high-z galaxies observed with GeMS.

9148-188, Session PMon5

On-sky PSF reconstruction with APETy

Rodrigo A. Olguin, ALMA (Chile) and Pontificia Univ. Católica de Chile (Chile); Markus Hartung, Thomas L. Hayward, Gemini Observatory (Chile); Damien Gratadour, Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France); Andrés R. Guesalaga, Pontificia Univ. Católica de Chile (Chile)

PSF reconstruction for AO systems was pioneered by J.P. Veran in 1997 and was successfully demonstrated at CFHT/PUEO. A recent example was presented in the case for the Keck telescope in 2012. Nevertheless, it has been a constant struggle since to implement these technique as observatory standard. APETy (A PSF Estimation Tool for Yorick) has been developed since 2009 and applied for PSF reconstruction for the Near Infrared Coronograph Imager (NICI) at the Gemini South Observatory based on a 85 element curvature AO system. Using on-sky wavefront sensor data, we estimate the seeing (r0) from deformable mirror commands and reconstruct diffraction limited images (52 mas resolution) with an accuracy of 90% when compared to the science images. APETY is publically available via GitHub (https://github.com/dgratadour/APETy) and can be adapted to other systems.

9148-53, Session 13

Tests of high-precision, calibrated astrometry with GeMS and ShaneAO

S. Mark Ammons, Lawrence Livermore National Lab. (United States); Eduardo A. Bendek, NASA Ames Research Ctr. (United States); Olivier Guyon, The Univ. of Arizona (United States); Benoît Neichel, Gemini Observatory (Chile); Donald Gavel, Srikar Srinath, Alexander R. Rudy, Renate Kupke, Daren Dillon, Constance Rockosi, Univ. of California, Santa Cruz (United States); Christian Marois, NRC-Dominion Astrophysical Observatory (Canada); Bruce A. Macintosh, Lawrence Livermore National Lab. (United States); Dmitry Savransky, Cornell Univ. (United States); Raphaël Galicher, Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France)

MCAO systems on large telescopes should deliver the best available relative astrometric precision from the ground, which may be sufficient to detect and measure the masses of exo-earths orbiting nearby brown and red dwarfs (< 30 μas). However, reaching these precisions requires a

better understanding of astrometric systematics such as dynamic optical distortion. We demonstrate the diffractive pupil concept, intended to calibrate changing optical distortion with diffracted light from the target star, on the new ShaneAO instrument, a 16x16 AO system for the Shane 3-meter telescope at Lick Observatory. We insert a small transmissive mask near the woofer DM, which maps optical distortion created by the AO system and the science camera. We use natural, undiffracted reference stars to measure additional low-order optical distortion induced by the primary/secondary. The best simulated precision of the Shane AO system in a Galactic plane sparse field is ~150 μas for a half-hour exposure in H-band. We expect that modeling the anisoplanatic PSF will set the noise floor for the ShaneAO experiment, as with NIRC2 at Keck. In previous results with a seeing-limited experiment at the Nickel 1-meter telescope, we have shown that the diffractive grid reduces the astrometric noise floor by a factor of 2.

Secondly, we use GeMS wavefront sensor telemetry to calculate the distortion induced by the atmosphere and instrument in real time, showing that this distortion is correlated with star motions seen in the GSAOI focal plane. This suggests that distortion residuals uncompensated by the MCAO system in 2-DM mode can be removed in post-processing by subtracting the calculated distortion map from measured star positions in the focal plane.

Motivated by this realization, we pose a new, hybrid system architecture that eliminates atmospheric distortions and retains all the benefits of tomographic AO systems: Medium-field (~1’) LGS ground-layer adaptive optics for 8-30 meter apertures augmented with multiple (~5-10) natural guide star wavefront sensors. The NGS WFSs measure the long-term average of the wavefront at multiple field points using faint stars (V > 18). This information, when combined with fast wavefront sensing telemetry

from laser guide stars, can be used to calculate and subtract the field distortion induced by the atmosphere. This innovation effectively removes the differential tip/tilt jitter (DTTJ) error term, which is dominant over other error terms in sparse fields. For an 8-meter aperture, this hybrid GLAO architecture obtains more precise astrometry on bright stars (~ 20 μas) than MCAO with shorter exposures (< 15 minutes).

9148-54, Session 13

`imaka: a path-finder ground-layer adaptive optics system for the University of Hawaii 2.2-meter telescope on Mauna Kea

Mark R. Chun, Univ. of Hawai’i (United States); Olivier Lai, Gemini Observatory (United States) and Subaru Telescope, National Astronomical Observatory of Japan (United States); Douglas Toomey, Mauna Kea Infrared LLC (United States); Jessica R. Lu, Univ. of Hawai’i (United States); Simon Thibault, Denis Brousseau, Univ. Laval (Canada); Christoph Baranec, Univ. of Hawai’i (United States); Hu Zhang, ImmerVision (Canada)

Astronomical science with ground-layer adaptive optics systems such as astrometry of stars in crowded stellar fields and deep searches for very distant star-forming galaxies pushes the systems to the widest possible fields of view Optical turbulence profiles on Mauna Kea suggest that such a system could deliver corrected fields of view several tens of arcminute in size. We present the status of a wide-field of view ground-layer adaptive optics system for the UH2.2m telescope which will demonstrate these key cases and serve as a path-finder for GLAO systems on larger telescopes and for GLAO with even larger fields of view on modest sized telescopes on Mauna Kea.

9148-58, Session 14

Science results from the Gemini/NICI planetfinding campaign (Invited Paper)

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A. Thatte, Univ. of Oxford (United Kingdom); Adam Burrows, Princeton Univ. (United States); Fraser Clarke, Univ. of Oxford (United Kingdom); Douglas Toomey, Mauna Kea Infrared LLC (United States)
NICI is a dedicated adaptive optics (AO) instrument for the Gemini-South 8.1-m Telescope tailored expressly for direct imaging of exoplanet companions, combining several techniques to attenuate starlight and suppress speckles for direct detection of faint companions to bright stars: (1) Lyot coronagraphy, (2) dualchannel imaging for Spectral Differential Imaging (SDI; Racine et al. 1999; Marois et al. 2005; Biller et al. 2007), and (3) operation in a fixed Cassegrain rotator mode for Angular Differential Imaging (ADI; Liu 2004; Marois et al. 2006; Lafreniere et al. 2007a; Biller et al. 2008). While each of these techniques has been used individually in large planet-finding surveys (e.g. Biller et al. 2007; Lafreniere et al. 2007b), the NICI Campaign is the first time all three have been employed simultaneously in a large survey. From 2008 December to 2012 September, the NICI Planet-Finding Campaign (Liu et al. 2010) obtained deep, highcontrast AO imaging of a carefully selected sample of over 200 young, nearby stars. In the course of the campaign, we discovered four co-moving brown dwarf companions: PZ Tel B (36 ± 6 M Jup, 16.4 ± 1.0 AU), CD–35 2722B (31 ± 8 M Jup, 67 ± 4 AU), HD 1160B (33+12 - 9 M Jup, 81+-5 AU), and HIP 79797C (55^{+20}_{-19} M Jup, 3 AU from the previously known brown dwarf companion HIP 79797B), as well as numerous stellar binaries. Three survey papers have been published to date, covering: 1) high mass stars (Nielsen et al. 2013), 2) debris disk stars (Wahhaj et al. 2013), and 3) stars which are members of nearby young moving groups (Biller et al. 2013). Here we discuss constraints placed on the distribution of wide giant exoplanets from the NICI Campaign, as well as new substellar companion discoveries and disk imaging results.

9148-191, Session PWed1

NGS2: the natural guide star next generation sensor for GeMS

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Gems, the Gemini Multi-Conjugate AO system, has been in regular science operation since 2013. It is performing well, providing typically 80 to 100mas uniform FWHM over a field of 85x85 arcsec covered by its dedicated imager, GSAOI. Performance is limited by noise/servolag consequent to the lower than expected photon return, and by tomographic error. However, the major limiting factor to date is the limiting magnitude of the Natural Guide Star (NGS) Tip-Tilt (TT) wavefront sensors (WFSs). The three NGS WFSs are currently using difficult to align APD quadcell, fed by optical fibres mounted on probes patrolling the two arcmin field of view. This system has proven extremely challenging to align, and the positioning system difficult to calibrate, leading to large acquisition overheads.

We propose to replace this device by a simple 2D visible detector onto which the field is directly imaged, and from which NGS centroids are computed from selectable guide stars. Recent progress in CMOS detectors lead to camera with read out noise of about 1e-, and frame rate of 400Hz for Region of Interest of 512^2 pixels. The new WFS, named Natural Guide Star Next Generation Sensor (NGS^2) is going to be built at the ANU and Gemini, with funds from the Australian Research Council and the Gemini Observatory. It should greatly reduce acquisition time and allow to reach a limiting magnitude of R=18, the initial NGS WFS requirements. It is currently being integrated at Mount Stromlo, ANU, Australia.

9148-197, Session PWed1

Precision astrometry calibration of MCAO systems using a diffractive mask

Eduardo A. Bendek, NASA Ames Research Ctr. (United States); S. Mark Ammons, Lawrence Livermore National Lab. (United States); Dmitry Svaransky, Cornell Univ. (United States); Bruce A. Macintosh, Lawrence Livermore National Lab. (United States); Olivier Guyon, The Univ. of Arizona (United States)

Astrometry will enable efficient detection and characterization of singleand multiple- planetary systems around nearby stars. The results obtained by MCAO systems such as MAD and GeMS open a great opportunity for precision sparse field astrometry. However, dynamic distortions can be in the order of 0.4mas in sparse fields for short-term variations and 1mas over longer times scales. Stability is a critical capability to measure orbits and masses of planets in the Habitable Zone of sun-like stars because their longer period. We propose to overcome this problem at GeMS by inserting a diffractive grid upstream of the MCAO system Deformable Mirrors (DM). This grid creates an array of diffractive spikes on the image plane that allow measuring dynamic distortions providing an stable reference to calibrate short and long term astrometric observations.
The diffractive grid will be constructed on a transmissive optical surface imprinting microscopic dots using photolithography techniques. To have an appropriate sampling we will create diffractive spots every 5” covering the 80” FoV with 16x16 diffractive features. If this system gets funded we plan to deploy this on Gemini South.

9148-217, Session PWed2

Effects of differential wavefront sensor bias drifts on high contrast imaging

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The Gemini Planet Imager (GPI) is a new facility, extreme adaptive optics (AO), coronagraphic instrument, currently being integrated onto the 8-meter Gemini South telescope, with the ultimate goal of directly imaging extrasolar planets. To achieve the contrast required for the desired science, it is necessary to quantify and mitigate wavefront error (WFE). A large source of potential static WFE arises from the primary AO wavefront sensor (WFS) detector’s use of multiple readout channels with independent preamplifiers. Temperature changes within GPI cause drifts in readout channels’ bias levels, inducing an RMS WFE of 1.1 nm and 41.9 nm over 4.44 degrees Celsius, for magnitude 4 and 11 stars, respectively. With a goal of <2 nm of static WFE, these are significant enough to require remedial action. Simulations imply a requirement to take fresh WFS darks every 2 degrees Celsius of temperature change, for a magnitude 6 star; similarly, for a magnitude 7 star, every 1 degree Celsius of temperature change. For sufficiently dim stars, bias drifts exceed the signal, causing a large initial WFE, and the former periodic requirement practically becomes an instantaneous/continuous one, making the goal of <2 nm of static WFE very difficult for stars of magnitude 9 or fainter. In extreme cases, this can cause the AO loops to destabilize due to perceived nonphysical

wavefronts, as some of the WFS's Shack-Hartmann quadcells are split between multiple readout channels. Presented here is GPI's AO WFS geometry, along with detailed steps in the simulation used to quantify bias drift related WFE, followed by laboratory and on sky results, and concluded with possible methods of remediation.

9148-224, Session PWed2

On-sky low order non-common path correction of the GPI calibration unit

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The Gemini Planet Imager (GPI) entered on-sky commissioning phase and had its first light at the Gemini South telescope in November 2013. Meanwhile, the fast loops for atmospheric correction of the Extreme Adaptive Optics systems have been closed on many dozen stars at different magnitudes (I=4-8), elevation angles and a variety of seeing conditions and a stable loop performance was achieved from the beginning on. Ultimate contrast performance shoulders on very low residual wavefront errors (design goal 60 nm rms), and optimization of the planet finding instrument on different ends has just begun to deepen and widen its dark whole region. Laboratory raw contrast benchmarks are in the order of 10^-6 or smaller. In the telescope environment and in standard operations new challenges are faced (changing gravity, temperature, vibrations) that are tackled by a variety of techniques such as Kalman filtering, open-loop models to keep alignment to within 5 mas, and speckle nulling and a calibration (Cal) unit. The Cal unit was especially designed by the Jet Propulsion Laboratory to control slowly varying wavefront errors at the focal plane of the apodized Lyot coronagraph by the means of two wavefront sensors, a 7x7 low order SH and Mach-Zehnder type interferometer for mid-order spatial frequencies. Original design goals aimed for sensing and correcting on a level of a few nm which is extremely challenging in a telescope environment. This paper focuses on non-common path low order wavefront correction as achieved through the cal unit on sky. We will present the obtained results as well as explain challenges that we are facing.

9148-225, Session PWed2

Point spread function reconstruction on the MCAO Canopus bench

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This paper discusses point spread function reconstruction (PSFR) experiments performed on the adaptive optics (AO) bench of the Gemini Multi Conjugate Adaptive Optics (MCAO) System (GeMS) aiming at validating the components of the recently proposed simulation-based laser

guide star (LGS) MCAO PSFR algorithm [Gilles et. al. Appl. Opt. 51, 7443 (2012)]. Since GeMS is a LGS MCAO system, it is an ideal test bed to study PSFR for LGS MCAO on extremely large telescopes (ELTs). Open- and

closed-loop, multi-conjugate experiments were performed with turbulence injected on the ground and high-altitude conjugated deformable mirrors (DMs). High-order wavefront sensor (WFS) telemetry was recorded, as well as on-detector guide window (ODGW) short exposure images serving as diagnostic data.

9148-68, Session 16

Wind layer identification with predictive Fourier control on the ShaneAO 3-meter AO system

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The identification and prediction of time-varying wavefront errors in AO systems will benefit AO for large telescopes with fainter limiting guide star magnitudes and improved temporal bandwidth errors. In a new UCSC-LLNL collaboration, we aim to demonstrate the power of predictive Fourier controllers for AO in the laboratory and on-sky. We have used the Fourier wind identification technique to measure wind velocities at several telescopes, and now characterize the performance gains of predictive Fourier control for the ShaneAO system on the 3-meter telescope at Lick Observatory.

Here, we present identification of the wind direction and velocity using telemetry data from the ShaneAO system, and a laboratory testbed simulating the ShaneAO geometry. Our wind identification system uses a Fourier decomposition technique to identify the correlated movement of the atmosphere from WFS telemetry data; the estimated wind vectors are then fed back to the predictive controller. We test the identification algorithm with ShaneAO telemetry and characterize the performance improvement, with the ultimate goal of reducing the limiting guide star magnitude on-sky. The tests show that the bulk of atmospheric turbulent power appears in correlated wind motion. These tests are the first onsky application of a Fourier-based predictor to a high-order ($d < 10$ cm) astronomical AO system. We see evidence that small subapertures are beneficial for identifying correlated wind motion at fixed wind speed.

We discuss the extension of Fourier-based predictive AO schemes to multi-layer, multi-guide star tomographic AO systems anchored through simulation and analysis of data from the ShaneAO testbed at UCSC. Using GeMS MCAO WFS telemetry, we show with the Fourier wind identification algorithm that tomography cleanly separates wind layers by altitude and boosts the resulting signal-to-noise ratio for the detection of individual wind layers.

9148-240, Session PThu1

Statistics of atmospheric turbulence at Cerro Pachon using the GeMS profiler

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The knowledge of the atmospheric turbulence profile directly above the telescope using the telemetry from wide-field Adaptive Optics (AO) measurements can be extremely powerful to the optimization of the correction performance of the new generation of AO systems. For this purpose, two techniques have been recently developed at the Gemini South MCAO System (GeMS). The first technique is based on a classical SLODAR approach that fits the measured turbulence to theoretical covariance functions calculated from turbulence models such as Kolmogorov or Von Karman. The second method uses the actual slopes of the wavefront sensors which are temporally correlated and deconvolved

via the autocorrelation functions. The latter technique provides not only a turbulence profile, but also the wind speed and direction for each layer from temporal cross-correlation of the wavefront sensors slopes.
The estimation of the vertical and temporal characteristics of the turbulence is aimed at improving the tomographic AO correction possible with GeMS. Beside this goal, the development of the profiler also allows to make a statistical analysis of the turbulence variations at Cerro Pachón, thanks to the telemetry data collected at GeMS over the last three years using this tool. The results of this analysis are presented here.
The data reduction yields to turbulence parameters such as spatial coherence (r0), Cn2 as a function of altitude and the associated wind speed and wind direction.
In this analysis, particular attention is paid to the occurrence of turbulence in the dome of Gemini South. Using a novel technique to separate the estimation of the ground layer wind from internal fluctuations that is based on Taylor's frozen flow hypothesis, the profiler has already demonstrated that it can estimate this dome turbulence that have been previously detected during GeMS runs. Here we investigate this phenomenon in terms of its recurrence and contribution to the total turbulence strength.

9148-241, Session PThu1

Extremely high-resolution ground-layer optical turbulence profile at Mauna Kea

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We present results from a multiple Shack-Hartmann wavefront sensor experiment on the University of Hawaii 2.2-m and Canada-France-Hawaii telescopes on Mauna Kea used to characterize the optical turbulence within the first several hundred meters above the telescope and to test the efficacy of extremely wide-field ground-layer adaptive optics. The wavefront sensors were deployed on 4-5 bright stars spread out over fields of view of 0.5 - 1.0 degrees and sampled the delivered wavefronts at 25Hz with a spatial resolution of about 10cm. Five nights of data were obtained on the UH2.2m and 9 nights were obtain on CFHT under a variety of seeing conditions. We present the optical turbulence profiles extracted via a SLODAR analysis and predictions on the GLAO performance for guide stars spread out over this large field of view.

9148-78, Session 19

Life with quintuplets: transitioning GeMS into regular operations

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The Gemini Multi-conjugate adaptive optics System (GeMS) at the Gemini South telescope in Cerro Pachon is the first sodium Laser Guide Star adaptive optics system with multiple guide stars. It uses five LGSs and two deformable mirrors to measure and compensate for distortions induced by atmospheric turbulence. After its 2012 commissioning phase, it is now transitioning into regular operations. Although GeMS has unique scientific

capabilities, it remains a challenging instrument to maintain, operate and upgrade. In this paper, we summarize the latest news and results.
First, we describe the engineering work done this past year, mostly during our last instrument shutdown in last austral winter covering many subsystems: an erroneous reconjugation of the Laser guide star wavefront sensor, the correction of focus field distortion for the natural guide star wavefront sensor and engineering changes dealing with our laser and its beam transfer optics.
We also describe our revamped software, developed to integrate the instrument into the Gemini operational model, and the new optimization procedures aiming to reduce GeMS time overheads. Significant software improvements were achieved on the acquisition of natural guide stars by our natural guide star wavefront sensor, on the automation of tip-tilt and higher-order loop optimization, and on the tomographic non-common path aberration compensation.
We then go through the current operational scheme and present the plan for the next years. We offered 38 nights in our last semester. We review the current system efficiency in term of raw performances, completed programs and time overheads. We also present our current efforts to merge GeMS into the Gemini base facility project, where night operations are all reliably driven from our La Serena base, without the need for any spotter.
Finally we present the plan for the future upgrades, mostly dedicated toward improving the performance and reliability of the system. Designed and manufactured by our partner the Australian National University (ANU), we will replace at the end of this year our current natural guide star wavefront sensor, based on 3 APD quadcell probes, with a more sensitive focal plane camera. This major upgrade, called NGS2, will allow us to acquire stars up to the magnitude M=18, increase our sky coverage to full coverage in the galactic plane and up to 10% at 50 degrees in galactic latitude while significantly reducing our overhead time.
On a longer term, we are also planning the (re-)integration of our third deformable mirror, lost during the early phase of commissioning. This upgrade presents two different challenges: integrating in the current system a DM from a different manufacturer and revisiting the entire set of software procedures to optimize this DM integration.

9148-82, Session 20

LIFT: analysis of closed loop performance in a laser assisted adaptive optics

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Laser assisted adaptive optics systems rely on Laser Guide Star (LGS) Wave-Front Sensors (WFS) for high order aberration measurements, and rely on Natural Guide Stars (NGS) WFS to complement the measurements on low orders such as tip-tilt and focus. The sky-coverage of the whole system is therefore related to the limiting magnitude of the NGS WFS.
We have recently proposed LIFT, a novel phase retrieval WFS technique, that allows a 1 magnitude gain over the usually used 2x2 Shack-Hartmann WFS. After an in-lab validation, LIFT's concept has been demonstrated on sky in open loop on GeMS (the Gemini Multiconjugate adaptive optics System at Gemini South). To complete its validation, LIFT now needs to be operated in closed loop in a laser assisted adaptive optics system.
The present work gives a detailed analysis of LIFT closed loop operation in a wide field adaptive optics system: magnitude limit, impact of high order residuals, and choice of LIFT tuning parameters (during locking and closed loop regimes). We also discuss the possibility of using LIFT on the scientific detector with no noticeable performance degradation. For this purpose, we simulate a multiconjugate adaptive optics loop representative of a GeMS-like 5 LGS configuration. The residual high orders are derived from a Fourier based simulation. Tip-tilt and focus perturbation includes turbulence and sodium layer altitude variation effects.

9149-79, Session PSThu

AO Operations at Gemini South

Eduardo Marin, Andrew Cardwell, Peter Pessev, Gemini
Conference 9149: Observatory Operations:
Strategies, Processes, and Systems V

Observatory (Chile)
The 8m Gemini South telescope is entering an exciting new era of AO operations, which put it at the forefront of astronomical AO in terms of both wide field AO, and extreme-AO systems. Major milestones achieved were the successful commissioning of GeMS, in 2012, and GPI, in late 2013 and early 2014. Currently we are operating two of the worlds most advanced astronomical AO systems. Gemini, running primarily in queue, must balance the promise of AO with the demands of the community to use non-AO instruments. We discuss the current state of the two AO systems, and their operational models. The preparations that go into planning each AO run, the difficulties in scheduling around non-AO instruments, and the differences between scheduling LGS AO and non-LGS AO are discussed. We also discuss the lessons we have learned from operating these world leading instruments.

9149-87, Session PSThu

Gemini planet imager integration to the Gemini South telescope environment

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The Gemini Telescopes have been operated since 2000 by an international partnership, currently consisting of six countries the United States, Canada, Chile, Australia, Brazil, and Argentina. The Gemini South telescope has a suite of four instruments available to the community, two of which are AO instruments. The Gemini
Planet Imager (GPI) is the latest instrument to be made available to the community. GPI is an Extreme AO instrument with an Integral Field Spectrograph operating in Y, J, H, and K bands. Spectral resolution ranges from R ~ 35 to 78, over a 2.8” x 2.8” field of view with 0.014” spatial resolution. Raw contrast is measured down to 10^-6.
Both the Gemini telescope and the GPI instrument are very complex systems.
Our goal is that the combined telescope / instrument system may be run by one observer operating the instrument, and one operator controlling the telescope and the acquisition of light to the three wavefront sensors in the instrument. This requires a smooth integration and easily operated control interfaces. We discuss the definition of the software and hardware interfaces, their implementation and testing, and the integration of the instrument with the telescope environment.
After an very successful integration first AO corrected science light was obtained on November 11th 2013, the second night of the first commissioning run. It is expected the instrument will be offered for open science in 2014.

9149-36, Session 10

Gemini Observatory’s fast turnaround program

Rachel E. Mason, Markus Kissler-Patig, Andrew J. Adamson, Gemini Observatory (United States); Nancy A. Levenson, Gemini Observatory (Chile); Dennis R. Crabtree, NRC - Herzberg Institute of Astrophysics (Canada); Stephanie Cote, NRC - Herzburg Institute of Astrophysics (Canada)
The standard system for obtaining time on most astronomical facilities involves a delay of many months, if not years, between conceiving an idea and acquiring the supporting data. Gemini currently receives many applications for Director’s Discretionary Time that do not really fit the criteria of being urgent, high-impact, or risky, but which nonetheless

reflect commendable enthusiasm, creativity and eagerness for data among the user community. We are currently developing a scheme to receive and assess proposals, and obtain data, within a matter of weeks. This presentation will explain the considerations, challenges and tradeoffs taken into account in designing the program, and outline the steps remaining to be taken before the program's launch.

9151-159, Session PSThu

GRACES: Gemini remote access to CFHT ESPaDOnS spectrograph through the longest astronomical fiber ever made

Andre-Nicolas Chene, Gemini Observatory (United States); John Pazder, National Research Council of Canada (Canada); Gregory Barrick, Canada-France-Hawaii Telescope (United States); Andre Anthony, Robert Wooff, National Research Council of Canada (Canada); Dave Duncan, National Research Council Canada (Canada); Vladimir A. Reshetov, National Research Council of Canada (Canada); Tom Benedict, Tom A. Vermeulen, Canada-France-Hawaii Telescope (United States); Eder Martioli, Lab. Nacional de Astrofisica (Brazil); Claire Moutou, Lison Malo, Canada-France-Hawaii Telescope (United States); Eric V. Tollestrup, Gemini Observatory (United States); Ricardo Schiavon, Liverpool John Moores Univ. (United Kingdom); Jaehyon Rhee, Oregon State Univ. (United States); Vinicius Placco, Gemini Observatory (United States)

GRACES (Gemini Remote Access to CFHT ESPaDOnS Spectrograph) is an instrument currently under development by the National Research Council of Canada (NRC), the Canada-France-Hawaii Telescope (CFHT) and the Gemini Observatory. It is planned to be commissioned in May 2014, just before the SPIE meeting. It will combine the large collecting area of the Gemini North telescope with the high resolving power and high efficiency of the ESPaDOnS spectrograph at CFHT, to deliver high resolution echelle spectroscopy across the optical region (400 - 1,000 nm). This will be achieved through a 270 m fiber optics feed from the Gemini North telescope to ESPaDOnS. It will be the longest fiber ever used for astronomy.

The making of such a long fiber is challenging, since not only the throughput has to be optimized, but the focal ratio degradation (FRD) has to be minimized. Any curve, bend, turn or twist along the long fiber's path is a potential threat, since the armor cable risks to eventually pinch the fiber. The same is true for any stretching, during the installation or due to repetitive temperature variations during the instrument's lifetime, leading the fiber in a differential motion with respect to the armor cable, causing it to bunch up, and resulting in a significant additional FRD. Fiber Tech E.R. Canada, in collaboration with the NRC, developed a new design for a stale fiber's armor cable. Its stiffness prevents it to pinch the fiber, and the slipperiness of its inside prevents the fiber to bunch during handling and during the expected temperature variations at MaunaKea. The radius of any bend can be as small as half a meter before risking any affect on the fiber. Moreover, currently existing 200m test fibers gave a FRD ~ 17%, even after extensive manipulations, an unprecedented result for such a long fiber.

GRACES will use up to two fibers. In the two fibers mode, one is aligned with the target, and the other is observing a source-free path of the sky (for optimal sky subtraction). The resolution power in that mode will be R ~ 30,000. In the one fiber mode, typically for brighter targets, the expected resolution power is R ~ 50,000. GRACES will use its own slicer bench inside ESPaDOnS, but will send the light into the CFHT's instrument right after it. On the Gemini side, a cassette with the fibers' injectors has been designed to fit inside GMOS-N (Gemini Multi-Object Spectrograph), taking the slot usually used for the IFU module. GMOS-N was demonstrated to be stable enough to use it in a very simple acquisition sequence, and the target centering on the fiber is expected to be as accurate as 0.1".

We will present the details of GRACES design, together with the results of our commissioning, including throughput, sensitivity and measured resolution power.

9151-74, Session 16

The FRD and transmission of the 270-m GRACES optical fiber link and a 50-m high numerical aperture fiber for astronomy

John Pazder, NRC - Herzburg Institute of Astrophysics (Canada); Paul Fournier, Rafal Pawluczyk, Fibertech Optica Inc. (Canada)

We report results of the extensive development work done on the 270m optical fiber link for the GRACES project and a preliminary investigations into a high numerical aperture fiber for astronomy. The Gemini Remote Access CFHT ESPaDOnS Spectrograph (GRACES) is an instrumentation experiment that links ESPaDOnS, a bench-mounted high-resolution optical spectrograph at CFHT, to the Gemini-North telescope with an optical fiber link. A 270-m fiber link with less than 25% Focal Ratio Degradation (FRD) has been developed jointly by HIA and FiberTech Optica for the experiment. A preliminary study has been conducted by HIA into a high numerical aperture fiber (0.26 NA) with the intended application of wide field optical spectrographs fiber fed from the telescope prime focus. The Laboratory test results of FRD, transmission, and stability for the fiber link and the high numerical aperture fiber tests are reported.

9152-37, Session 8

Upgrade and standardization of real-time software for telescope systems at the Gemini telescopes

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The real-time control systems for the Gemini Telescopes were designed and built in the 1990s using state-of-the-art software tools and operating systems of that time. Over the years new systems have been added and the original ones have diverged from the initial designs in an uncontrolled way. Since these systems are basically functional and in use every night there has been no compelling need to standardize them or keep them up to date. Many of these systems are now obsolete and have widely divergent code bases and development environments. As a result, the effort and specialized knowledge required to maintain them is increasing over time.

Gemini is currently engaged in a major upgrade of its facility real-time software systems. The goal is to develop a common real-time software environment and code base which can be used for both our existing systems and those developed in the future. A high priority will be given to the use of existing, well supported software packages in building this environment. Background studies have been performed to evaluate the possible operating systems, tools and techniques which could be employed in this process. Work has started on defining and implementing this environment as well as merging the divergent supporting code bases in preparation for the upgrade work.

This paper reviews the current state of Gemini’s real-time systems and the various scenarios developed for upgrading and stabilizing them.

The results of the background studies are presented along with the final selection of operating systems and development tools for the new realtime environment. The long-term plan for upgrading the systems at both telescopes without impacting ongoing operations is presented along with the progress made so far in implementing the plan.