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Aperture masking behind AO systems

Michael J. Ireland^{a,b,c}

^aDepartment of Physics and Astronomy, Macquarie University, NSW 2109, Australia;

^bAustralian Astronomical Observatory, PO Box 296, Epping, NSW 2121, Australia;

^cMQ Research Centre in Astronomy, Astrophysics and Astrophotonics, Macquarie University, NSW 2109, Australia

ABSTRACT

Sparse Aperture-Mask Interferometry (SAM or NRM) behind Adaptive Optics (AO) has now come of age, with more than a dozen astronomy papers published from several 5-10m class telescopes around the world. I will describe the reasons behind its success in achieving relatively high contrasts (1000:1 at λ/D) and repeatable binary astronomy at the diffraction limit, even when used behind laser-guide star adaptive optics. Placed within the context of AO calibration, the information in an image can be split into pupil-plane phase, Fourier amplitude and closure-phase. It is the closure-phase observable, or its generalisation to Kernel phase, that is immune to pupil-plane phase errors at first and second-order and has been the reason for the technique's success. I will outline the limitations of the technique and the prospects for aperture-masking and related techniques in the future.

Keywords: aperture mask interferometry, sparse aperture masking, extrasolar planets, adaptive optics, optical interferometry

1. INTRODUCTION

The calibration of Adaptive Optics (AO) images has long been a key limitation in achieving the full diffraction limit of large telescopes. The photon-noise limit for diffraction-limited imaging gives >10 magnitudes contrast at $5\text{-}\sigma$ for 10 minute exposures on $K\sim 10$ magnitude stars where a companion is buried in the airy-ring of a 10m class telescope Point-Spread Function (PSF). However, PSFs have not been able to be calibrated nearly this well, meaning that imaging at the full diffraction limit has been restricted to moderate contrasts (<4 magnitudes): the regime of binary star science. Even in the case of binary stars, precision astrometry has been difficult, because this also requires precise PSF calibration.

Sparse Aperture-Mask interferometry is a technique borrowed from calibration of seeing-limited observations^{1,2} that enables a more precise calibration of the PSF at the diffraction-limit. It has been used since 2004 behind adaptive optics systems, mostly to enable high-contrast diffraction-limited imaging and precise binary astrometry.³⁻⁵ This technique involves placing a binary mask in the pupil-plane of the telescope, where the majority of the mask is opaque. These masks as commissioned have consisted of arrays of holes where the vector separation between any two holes is unique. The terms Non-Redundant Masking (NRM) or Sparse Aperture Masking (SAM) have both been used, partly reflecting origins in US publications (NRM) or European publications (SAM). As will be seen in Section 2, SAM is technically more correct because all holes of non-zero size are redundant, but NRM is possibly a more descriptive term.

In this paper, I will review SAM as it applies behind AO systems, attempting to repeat little of what has come before, and also attempting to minimise overlap with other papers presented at this conference.^{6,7} I will give a background to SAM in section 2, then I will discuss the general problem of phase errors in AO imaging in section 3. I will discuss the calibration of kernel/closure phase in section 5, and how these calibrated observables can be used for high-contrast imaging and astrometry in sections 6 and 7. Finally, I will conclude and discuss the future of SAM in the context of the next generation of telescopes and AO systems in section 8.

E-mail: michael.ireland@mq.edu.au

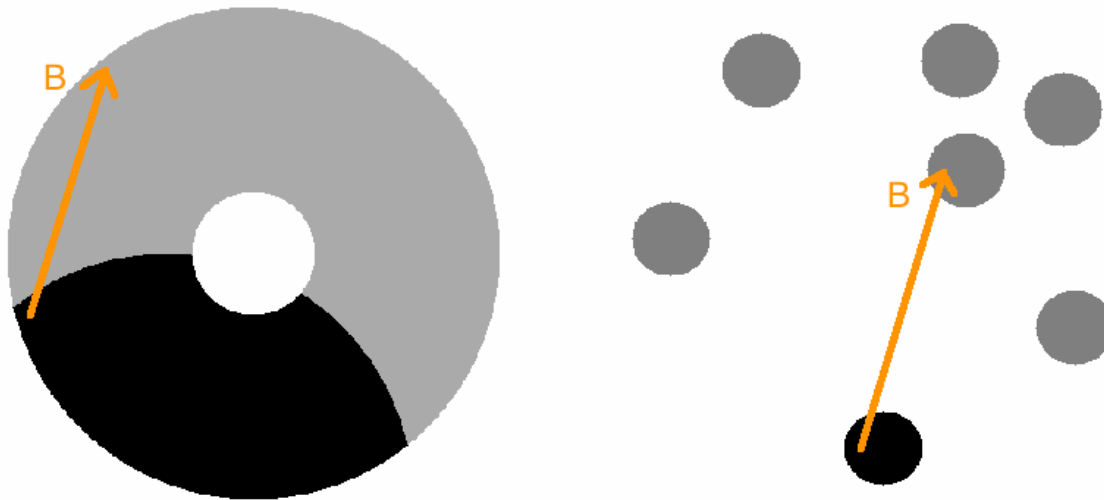


Figure 1. An illustration of the support function S (in black) for a baseline vector $B = (u, v)$ on a typical circular pupil with obstruction (left) and a sparse aperture mask (right). The sparse aperture is clearly less sensitive to large scale phase errors.

2. SPARSE APERTURE MASKING BACKGROUND

Sparse aperture-masking is a form of high-resolution imaging where the amplitude and phase of the Fourier transform of the image are considered the primary observables, and the information contained in the Fourier domain is as carefully controlled as possible. Consider images formed by a complex pupil-plane aperture function $P(x, y)$. The Fourier-transform of the image formed by this pupil is the auto-correlation of the aperture-function:

$$F(u, v) = \int P(x + u, y + v)P^*(x, y)dxdy \quad (1)$$

For this to make sense dimensionally, if x and y have units of meters, u and v also have units of meters, and spatial frequency is converted to cycles per radian by dividing by wavelength. For a simple aperture function P that is simply zero where light is blocked and $\exp(i\phi(x, y))$ for some aberration function ϕ , we can simplify this integral to:

$$F(u, v) = \int \exp(i[\phi(x + u, y + v) - \phi(x, y)])S(x, y)dxdy, \quad (2)$$

where the support function S is 1 where baselines exist within the pupil, and 0 elsewhere (see Figure 1 and 2).

Historically, mask holes have been made even smaller than in Figure 1, in order to match the coherence length in speckle imaging.² The structure function in speckle imaging was roughly Kolmogorov, meaning that the majority of the phase aberrations was on large spatial scales. In this case, given sufficient flux, a non-redundant aperture-mask meant that the phase was nearly constant (and certainly didn't wrap) in the integral of Equation 2, producing high fringe contrast. This provided a clear advantage over full pupil imaging. The problem with speckle imaging through an aperture-mask was that there were very few science targets for which sufficient signal-to-noise could be obtained within an atmospheric coherence time. SAM with AO has pushed to fainter magnitude limits, meaning larger sub-aperture diameters. The combination of larger sub-aperture diameters with AO correction of the large spatial scale aberrations means that the advantages of SAM are no longer so clear, and have to be examined in detail.

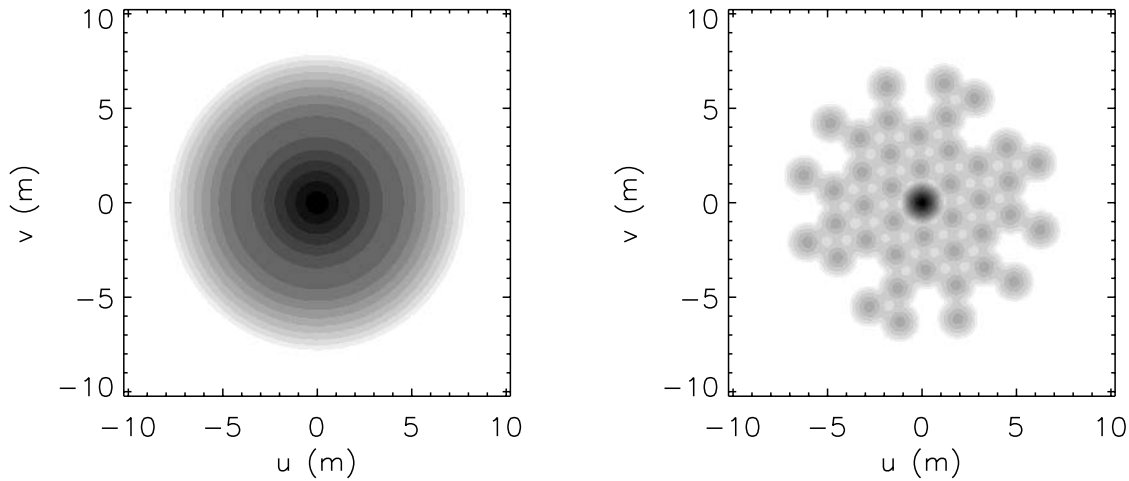


Figure 2. The autocorrelations of the aperture functions illustrated in Figure 1.

3. PHASE ERRORS IN AO IMAGING

Fourier amplitudes are roughly proportional to Strehl ratio, so change with changing Strehl and are difficult to calibrate. They are discussed briefly in the interferometry session of this conference.⁶ In this paper, we will consider Fourier phase only. We can consider phase in Equation 2 more carefully by approximating the argument of F to first order in ϕ :

$$F(u, v) = \int S dx dy + i \int \Delta_{u,v} \phi S dx dy, \text{ where} \quad (3)$$

$$\Delta_{u,v} \phi(x, y) = \phi(x + u, y + v) - \phi(x, y) \quad (4)$$

$$\text{Arg}(F(u, v)) = \left(\int \Delta_{u,v} \phi S dx dy \right) / \left(\int S dx dy \right) + O(\phi^3). \quad (5)$$

In the case of a finite field of view, the image Fourier transform F becomes discrete. We can then replace Equation 5 with a sum:

$$\psi_k = \sum_{j=1}^{N_P} a_{k,j} \phi_j \quad (6)$$

Here ψ_k is a Fourier phase, meaning an argument of $F(u, v)$ for a discrete Fourier pixel (u_k, v_k) . ϕ_j is similarly a pupil-plane phase for pupil location (x_j, y_j) . For a 2-dimensional aperture, there are always at least twice as many elements ψ_k as there are elements ϕ_j . To see why, consider the most redundant aperture, a fully filled shape, in this case a circle. For an aperture with diameter D pixels that includes the longest baselines in the pupil (the aperture edge), there are $\pi D^2/4$ free pupil-plane phases, and $\pi D^2/2$ measured Fourier phases. The factor of 2 in Fourier plane phases is due to the complex Fourier amplitude at $(-u, -v)$ being the complex conjugate of a Fourier amplitude at (u, v) . An annular aperture, or any other *sparse aperture*, has the same number of Fourier phases but fewer pupil phases.

This means that, to first order, at least half the phase information measured in the Fourier transform of an image is *independent of phase aberrations*. This extremely powerful piece of information has not been explicitly used in AO imaging, however it is beginning to be now following on from the concept of *kernel phase* outlined by Martinache (2010).⁸ The technique is conceptually simple - the range of the matrix $A = \{a_{k,j}\}$ forms a subspace R in the Fourier-phase vector space $V = \{\psi_1, \psi_2, \dots, \psi_{N_F}\}$. The orthogonal complement of R in V is the set

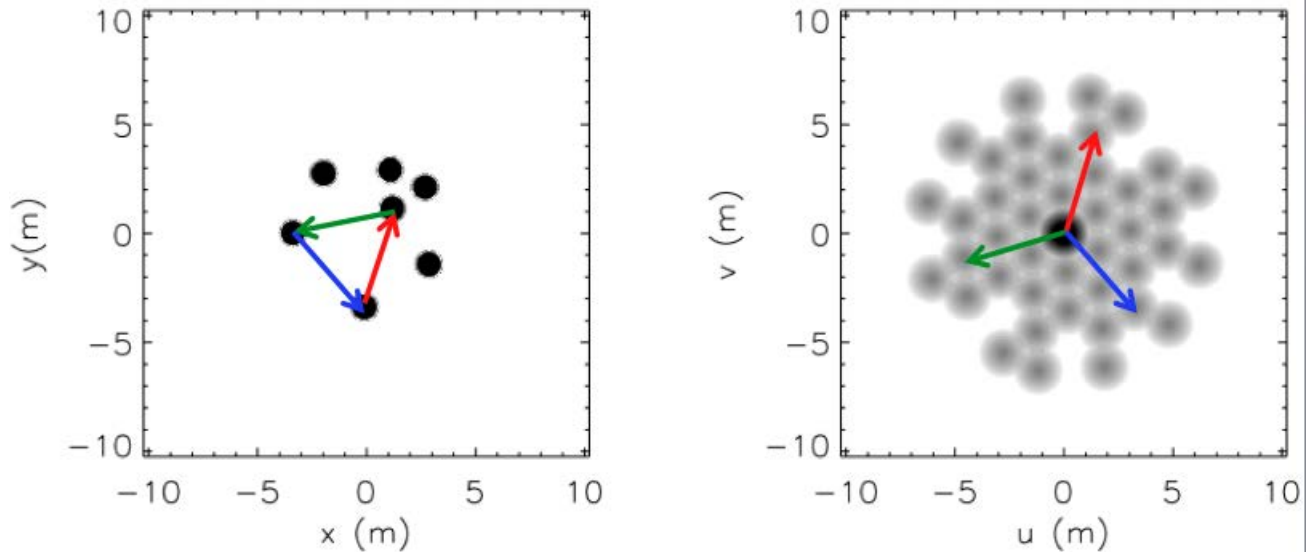


Figure 3. Left: The same pupil as in the right hand panel of Figure 1, with a closing triangle highlighted. Right: The locations of the Fourier phases corresponding to this closing triangle. A closure-phase is formed by the sum of the Fourier phase at these locations.

of *kernel-phases* K , consisting of linear combinations of Fourier phases that are independent to first order of pupil-plane phases ϕ_j . By projecting the Fourier phases ψ_k onto the subspace K using standard linear algebra techniques, we arrive at a set of $N_F - N_P + 1$ kernel phases (the “+1” comes from piston⁸).

Kernel-phase is closely related to techniques based on bispectrum phase,⁹ and indeed any paper that fits to bispectrum phase¹⁰ is essentially fitting to kernel-phase. Although each bispectrum-phase is a kernel-phase, there are many more bispectrum phases than kernel-phases, meaning that it is difficult to be statistically robust when fitting to bispectrum phase. In this context, kernel-phases can be thought of as linearly independent linear combinations of bispectrum phases. The advantage of the bispectrum is that it can be used when phase itself is not a robust observable – i.e. when there is a significant probability in each frame of data that a Fourier amplitude is zero within errors. In this case, the complex bispectrum is averaged. The advantage of kernel-phase over bispectrum phase is that the problem of computing an using the covariance matrix is tractable (to be described in Ireland 2012, in prep).

4. CLOSURE-PHASE AND LOW-STREHL DATA

Rather than attempting a full kernel-phase analysis, SAM data has typically been analysed by approximating the phase across each sub-aperture as being constant. With n subapertures, this gives $n(n-1)/2$ discrete Fourier phases, $(n-1)(n-2)/2$ Kernel-phases, and $n(n-1)(n-2)/6$ *closure-phases*. The concept of a closure-phase is illustrated in Figure 3 for the example of the 7-hole mask. Sampling the Fourier plane in 3 locations and adding up the phases gives a closure-phase, which is just one example of a kernel-phase. Just like in bispectrum speckle interferometry, rather than computing phase directly for single exposures, we can compute closure-phase by computing the *triple-product* corresponding to each closure-phase. Averaging the triple product is a convenient way to give a low weight to images with low Fourier amplitudes, and also to solve the phase wrapping problem. The argument of the triple product is the closure-phase. For modern telescopes, this is only particularly useful for low-Strehl data using the CONICA camera, where a fast acquisition mode called a *cube* mode is available.

Even where phase is a good observable in single exposures, there is an advantage to using an aperture-mask over imaging with a fully-illuminated pupil. This is clear from Figure 1: if there are dominant large-scale aberrations, the third-order phase errors in Equation 5 will contribute much more to the kernel-phase for the fully-illuminated pupil when compared to the sparse aperture mask. This advantage of a sparse aperture-mask is especially useful for low-Strehl data typical of a laser-guide star system. Defocus in particular can be large if

the slow wavefront sensor is not able to adequately track the changing height of the sodium layer. The ability of aperture-masking to enable diffraction-limited resolution for this kind of data has been used successfully in the studies of brown dwarf binaries[CITATION].

5. PHASE CALIBRATION

In principle, the kernel- and closure- phase techniques do not require calibration, in a similar manner to raw adaptive optics images not requiring calibration. In the case of laser-guide star observations, calibrator stars are typically not used, because of the overheads associated with taking data on a calibrator, the relatively noisy data and contrast requirements that are relatively easily met. However, for most SAM data, the systematic closure-phases caused by third-order pupil-plane phase errors need to be calibrated. The standard method of calibration is inspired by speckle and long-baseline interferometry, where a single unresolved calibrator star is observed, so that the closure- or kernel-phases from this star can be subtracted from the target. Early SAM observations ensured that the AO WFS magnitude and the infrared magnitude was similar between target and calibrator. This requirement has since been relaxed – as long as the AO WFS has a good background (i.e. so that there isn't a brightness-dependent static aberration), calibration benefits from higher Strehls and higher photon-limited signal-to-noise.

An ideal calibrator is one that is co-located with the target and observed simultaneously. As this is not possible, many calibrators can be observed, and an optimal linear combination of calibrators used to minimise the closure- or kernel- phase residuals. These techniques are described in other references^{6,11} and will be expanded in an upcoming publication (Ireland 2012, in prep).

6. HIGH-CONTRAST IMAGING

So far, we have discussed kernel- and closure- phases as arbitrary observables. In order to determine the structure of the target, we need to be able to fit to the data. The forward model is simple to compute for kernel- and closure-phase – a Fourier transform is taken of a model image and the kernel- or closure-phase computed, and a χ^2 value computed. Code such as MACIM¹² can then minimise χ^2 and find the best fitting image. *However*, not all images give a signal in Fourier-phase. In particular, any point-symmetric target has only 2 possible values of Fourier-phase: 0 or 180 degrees. In general, creating images from phase data alone is a difficult process, but in the high-contrast regime, where there is an unresolved source containing the majority of the flux, the situation is simplified. A model image I can be decomposed into its point-symmetric and point-antisymmetric components:

$$I_s = (I_0 + I_{180})/2 \quad (7)$$

$$I_a = (I_0 - I_{180})/2. \quad (8)$$

Here I_a is the antisymmetric image, and I_s is the symmetric image. I_{180} is the image rotated by 180 degrees, and I_0 is the true image. Fitting to phase alone gives I_a only. As this has negative flux, there is a minimum possible I_a to produce image positivity. However, with phase data alone, adding more than this minimum I_a is possible without modifying the fit.

In practice, imaging from phase data needs care, and model-fitting for simple targets (such as a star and one or more faint companions) is preferred. The contrast limit to high-contrast imaging using aperture-masking has several causes:

- Photon- or background-noise. This is typically only a dominant error for LGS data (K magnitudes around 12 or fainter) or for L-band or longer wavelengths. Locking an adaptive optics loop requires on order 10^4 photons per second per sub-aperture. The contrast limit is approximately the square-root of the number of photons collected per sub-aperture. If we approximate the number of infrared photons through a broadband filter to be the same as the number of AO wavefront sensor photons, then a signal-to-noise of 10^3 is obtained in only 100s whenever the AO loops are locked.

- Sub-aperture phase noise. Equation 5 is only valid to first-order, with residuals that are third-order in pupil-plane phase ϕ over the sub-aperture. This causes both an unbiased closure-phase error, and a closure-phase bias whenever aberrations differ between a target and a calibrator. Carefully calibrated data has demonstrated approximately 6 magnitudes of contrast in 15 minutes of on-sky time at $5\text{-}\sigma$, with contrast improving as square-root time.
- Dispersion-related phase noise. For broad-band filters, the combination of atmospheric dispersion and differing airmasses or spectra cause closure-phase systematics. This effect can be largely removed by careful calibration, or choosing narrower bandwidth filters (or an IFU).
- Subaperture piston noise. Given that the exposure times used in SAM are typically much longer than the atmospheric coherence time, time-variable piston causes non-zero closure phases. For bright, well-calibrated data, the contrast limits to SAM (about 1000:1) are generally consistent with simulations that include these effects.

7. PRECISION ASTROMETRY

Given that fitting to closure- or kernel-phase is unbiased (i.e. calibration errors are equally likely to give positive or negative phases) and ensemble averages give well defined error bars, SAM is a fantastic technique for computing precision orbits of binary stars. An example of this precision is shown in Figure 4, with more detail given in several refereed papers.^{10,13,14} When astrometric targets are observed in a group with interspersed calibrators, approximately 8 minutes of observing time at Keck is required for one astrometric data point, including all overheads.

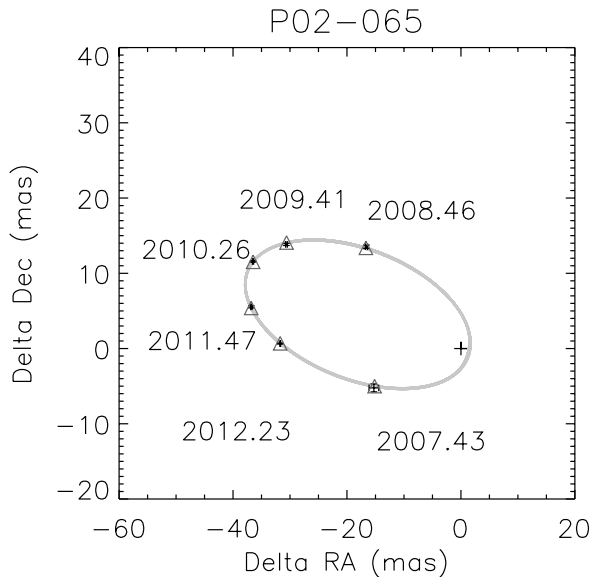


Figure 4. An orbit for the young binary star [PBB2002] 160517.9-202420. Typical residuals are $100\mu\text{as}$, with a combination of K-band and CH4S (1.55 micron filter) data from Keck plotted. The smallest separation measured is 16 mas in K-band, corresponding to $0.35\lambda/D$. Contrast is ~ 0.4 magnitudes (thanks to A. Kraus for access to the data in advance of publication).

8. CONCLUSIONS AND FUTURE WORK

Sparse Aperture Masking (SAM) has been a successful technique to achieve the full diffraction-limit of large telescopes. Precisely calibrated data can be obtained through the kernel-phase observable, which includes closure-phase observables as a subset. The contrast obtained by this technique is approaching the limits imposed by the performance of adaptive optics systems and the photon-noise limit (around 7 magnitudes for 1 our on sky). The

use of SAM with IFUs promises to both remove dispersion-related phase noise, and give spectral properties of targets with a single observation. SAM will continue to be the preferred technique for binary astrometry at the diffraction limit of the current and next generation of large telescopes, especially for moderate Strehl ratio data expected to be typical of LGS AO systems.

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- 8447 05 **Overview of deformable mirror technologies for adaptive optics and astronomy (Invited Paper)** [8447-5]
P.-Y. Madec, European Southern Observatory (Germany)
- 8447 06 **TMT DMs final design and advanced prototyping results at Cilas** [8447-6]
J.-C. Siquin, A. Bastard, CILAS (France); C. Boyer, Thirty Meter Telescope Observatory Corp. (United States); S. Cornette, R. Cousty, CILAS (France); B. Ellerbroek, Thirty Meter Telescope Observatory Corp. (United States); X. Gilbert, B. Gourdet, R. Grasser, D. Groeninck, C. Guillemard, CILAS (France); G. Herriot, NRC Herzberg Institute of Astrophysics (Canada); A. Iannacone, A. Jeulin, A. Moreau, H. Pagès, CILAS (France); L. Wang, Thirty Meter Telescope Observatory Corp. (United States)
- 8447 07 **Low-cost unimorph deformable mirror with high actuator count for astronomical adaptive optics** [8447-7]
J. Ma, Y. Liu, Univ. of Science and Technology of China (China); C. Xu, Nanjing Institute of Astronomical Optics & Technology (China); H. Rong, B. Li, J. Chu, Univ. of Science and Technology of China (China)
- 8447 08 **The actuator design and the experimental tests of a new technology large deformable mirror for visible wavelengths adaptive optics** [8447-8]
C. Del Vecchio, G. Agapito, C. Arcidiacono, L. Carbonaro, INAF - Osservatorio Astrofisico di Arcetri (Italy); F. Marignetti, E. De Santis, Univ. degli Studi di Cassino (Italy); V. Biliotti, A. Riccardi, INAF - Osservatorio Astrofisico di Arcetri (Italy)

SESSION 3 QUANTITATIVE ASTRONOMY AND SCIENCE WITH AO I

- 8447 0A **Adaptive optics observations of the galactic center young stars (Invited Paper)** [8447-10]
S. Yelda, A. M. Ghez, Univ. of California, Los Angeles (United States); J. R. Lu, Institute for Astronomy, Univ. of Hawai'i (United States); T. Do, Univ. of California, Irvine (United States); L. Meyer, M. R. Morris, Univ. of California, Los Angeles (United States)
- 8447 0B **Adaptive optics for high contrast imaging (Invited Paper)** [8447-11]
M. Kasper, European Southern Observatory (Germany)
- 8447 0C **Quantitative solar system science with AO systems (Invited Paper)** [8447-12]
F. Marchis, SETI Institute (United States); J. Berthier, IMCCE, Observatoire de Paris, Avenue Denfert-Rochereau (France); M. H. Wong, Univ. of California, Berkeley (United States)

SESSION 4 LASER SYSTEMS

- 8447 0D **Progress in laser guide star adaptive optics and lessons learned (Invited Paper)** [8447-13]
P. Wizinowich, W. M. Keck Observatory (United States)
- 8447 0E **An overview of guidestar laser technologies (Invited Paper)** [8447-14]
D. T. Gavel, Univ. of California Observatories (United States)
- 8447 0F **RFA-based 589-nm guide star lasers for ESO VLT: a paradigm shift in performance, operational simplicity, reliability, and maintenance** [8447-15]
A. Friedenauer, TOPTICA Photonics AG (Germany); V. Karpov, D. Wei, MPB Communications Inc. (Canada); M. Hager, B. Ernstberger, TOPTICA Photonics AG (Germany); W. R. L. Clements, MPB Communications Inc. (Canada); W. G. Kaenders, TOPTICA Photonics AG (Germany)
- 8447 0G **Towards a practical sodium guide star laser source: design for > 50 watt LGS based on OPSL** [8447-16]
J. D. Berger, J. L. A. Chilla, S. Govorkov, J. F. P. van Nunen, A. Y. Lepert, Coherent, Inc. (United States)
- 8447 0H **Simulations of pulsed sodium laser guide stars: an overview** [8447-17]
R. Holzlohner, European Southern Observatory (Germany); S. M. Rochester, Rochester Scientific, LLC (United States) and Univ. of California, Berkeley (United States); D. Bonaccini Calia, European Southern Observatory (Germany); D. Budker, Univ. of California, Berkeley (United States) and Rochester Scientific, LLC (United States); T. Pfrommer, European Southern Observatory (Germany); J. M. Higbie, Bucknell Univ. (United States)

SESSION 5 PROJECT STATUS II

- 8447 0I **GeMS: first on-sky results (Invited Paper)** [8447-18]
F. Rigaut, Gemini Observatory (Chile) and Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); B. Neichel, M. Boccas, Gemini Observatory (Chile) C. d'Orgeville, Gemini Observatory (Chile) and Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); G. Arriagada, V. Fesquet, S. J. Diggs, C. Marchant, G. Gausachs, W. N. Rambold, J. Luhrs, S. Walker, E. R. Carrasco-Damele, M. L. Edwards, P. Pessev, R. L. Galvez, T. B. Vucina, C. Araya, A. Gutierrez, A. W. Ebbers, A. Serio, C. Moreno, C. Urrutia, R. Rogers, R. Rojas, C. Trujillo, B. Miller, D. A. Simons, A. Lopez, V. Montes, H. Diaz, F. Daruich, F. Colazo, Gemini Observatory (Chile); M. Bec, G. Trancho, M. Sheehan, Giant Magellan Telescope Organization Corp. (United States); P. McGregor, P. J. Young, M. C. Doolan, J. van Harmelen, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); B. L. Ellerbroek, Thirty Meter Telescope Observatory Corp. (United States); D. Gratadour, LESIA - Observatoire de Paris (France); A. Garcia-Rissmann, European Southern Observatory (Germany)
- 8447 0J **ESO adaptive optics facility progress report (Invited Paper)** [8447-19]
R. Arsenault, P.-Y. Madec, J. Paufique, P. La Penna, S. Stroebele, E. Vernet, J.-F. Pirard, W. Hackenberg, H. Kuntschner, L. Jochum, J. Kolb, N. Muller, M. Le Louarn, P. Amico, N. Hubin, J.-L. Lizon, R. Ridings, J. A. Abad, G. Fischer, V. Heinz, M. Kiekebusch, J. Argomedo, R. Conzelmann, S. Tordo, R. Donaldson, C. Soenke, P. Duhoux, E. Fedrigo,

B. Delabre, A. Jost, M. Duchateau, M. Downing, J. R. Moreno, R. Dorn, A. Manescau, D. Bonaccini Calia, M. Quattri, C. Dupuy, I. M. Guidolin, M. Comin, R. Guzman, B. Buzzoni, J. Quentin, S. Lewis, P. Jolley, M. Kraus, T. Pfrommer, European Southern Observatory (Germany); R. Biasi, Microgate S.r.l. (Italy); D. Gallieni, A.D.S. International S.r.l. (Italy); C. Bechet, Ctr. de Recherche Astronomique de Lyon (France); R. Stuik, Leiden Observatory (Netherlands)

8447 OK **Tests of open-loop LGS tomography with CANARY (Invited Paper)** [8447-20]

T. J. Morris, A. G. Basden, Durham Univ. (United Kingdom); F. Vidal, Observatoire de Paris (France); A. P. Reeves, Durham Univ. (United Kingdom); E. Gendron, Observatoire de Paris (France); R. M. Myers, Durham Univ. (United Kingdom); Z. Hubert, Observatoire de Paris (France); E. J. Younger, Durham Univ. (United Kingdom); A. Longmore, UK Astronomy Technology Ctr. (United Kingdom); M. Cohen, Observatoire de Paris (France); N. Dipper, P. Clark, Durham Univ. (United Kingdom); D. Henry, UK Astronomy Technology Ctr. (United Kingdom); G. C. Rousset, Observatoire de Paris (France); S. P. Todd, UK Astronomy Technology Ctr. (United Kingdom); F. Chemla, Observatoire de Paris (France); D. C. Atkinson, UK Astronomy Technology Ctr. (United Kingdom); J.-M. Huet, Observatoire de Paris (France); B. Stobie, C. J. Dickson, UK Astronomy Technology Ctr. (United Kingdom)

8447 OL **Image quality and high contrast improvements on VLT/NACO** [8447-21]

J. H. V. Girard, J. O'Neal, European Southern Observatory (Chile); D. Mawet, European Southern Observatory (Chile) and Jet Propulsion Lab. (United States); M. Kasper, European Southern Observatory (Germany); G. Zins, IPAG, Univ. Joseph Fourier, CNRS (France); B. Neichel, Gemini Observatory (Chile); J. Kolb, European Southern Observatory (Germany); V. Christiaens, Univ. de Liège (Belgium) and European Southern Observatory (Chile); M. Tourneboeuf, Univ. Católica de Chile (Chile)

SESSION 6 QUANTITATIVE ASTRONOMY AND SCIENCE WITH AO II

8447 OM **Science with ESO's Multi-conjugate Adaptive-optics Demonstrator - MAD (Invited Paper)** [8447-22]

J. Melnick, E. Marchetti, P. Amico, European Southern Observatory (Germany)

8447 ON **Results from the commissioning of the Gemini South Adaptive Optics Imager (GSAOI) at Gemini South Observatory** [8447-23]

E. R. Carrasco, M. L. Edwards, Gemini Observatory (Chile); P. J. McGregor, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); C. Winge, Gemini Observatory (Chile); P. J. Young, M. C. Doolan, J. van Harmelen, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); F. J. Rigaut, B. Neichel, Gemini Observatory (Chile); G. Trancho, Giant Magellan Telescope Organization Corp. (United States); E. Artigau, Univ. de Montréal (Canada); P. Pessev, F. Colazo, Gemini Observatory (Chile); J. Tigner, Univ. of Victoria (Canada); F. Mauro, Univ. de Concepción (Chile); J. Lührs, W. N. Rambold, Gemini Observatory (Chile)

8447 OO **High-contrast imaging in the Hyades with snapshot LOCI** [8447-160]

K. M. Morzinski, Steward Observatory, The Univ. of Arizona (United States); B. A. Macintosh, Lawrence Livermore National Lab. (United States); L. M. Close, Steward Observatory, The Univ. of Arizona (United States); C. Marois, NRC Herzberg Institute of Astrophysics (Canada); Q. Konopacky, Dunlap Institute for Astronomy and Astrophysics (Canada); J. Patience, School of Earth & Space Exploration, Arizona State Univ. (United States)

8447 OP **Theoretical limits on bright star astrometry with multi-conjugate adaptive optics using a diffractive pupil** [8447-25]

S. M. Ammons, Lawrence Livermore National Lab. (United States); E. A. Bendek, Steward Observatory, The Univ. of Arizona (United States); O. Guyon, Steward Observatory, The Univ. of Arizona (United States) and Subaru Telescope (United States); B. Macintosh, D. Savransky, Lawrence Livermore National Lab. (United States)

SESSION 7 WAVEFRONT SENSING I

8447 OQ **Advances in detector technologies for visible and infrared wavefront sensing (Invited Paper)** [8447-26]

P. Feautrier, Institut de Planétologie et d'Astrophysique de Grenoble, UJF-Grenoble I, CNRS-INSU (France) and First Light Imaging (France); J.-L. Gach, Observatoire Astronomique de Marseille-Provence (France) and First Light Imaging (France); M. Downing, European Southern Observatory (Germany); P. Jordan, e2v technologies (United Kingdom); J. Kolb, European Southern Observatory (Germany); J. Rothman, CEA-LETI-Minatec (France); T. Fusco, ONERA (France); P. Balard, Observatoire Astronomique de Marseille-Provence (France) and First Light Imaging (France); E. Stadler, Institut de Planétologie et d'Astrophysique de Grenoble, UJF-Grenoble I, CNRS-INSU (France) and First Light Imaging (France); C. Guillaume, Observatoire de Haute-Provence (France) and First Light Imaging (France); D. Boutolleau, First Light Imaging (France); G. Destefanis, N. Lhermet, CEA-LETI-Minatec (France); O. Pacaud, M. Vuillermet, A. Kerlain, SOFRADIR (France); N. Hubin, J. Reyes, M. Kasper, O. Ivert, European Southern Observatory (Germany); W. Suske, A. Walker, M. Skegg, e2v technologies (United Kingdom); S. Derelle, J. Deschamps, C. Robert, N. Vedrenne, ONERA (France); F. Chazalet, SHAKTI (France); J. Tanchon, T. Trolhier, A. Ravex, Absolut Systems (France); G. Zins, P. Kern, T. Moulin, O. Preis, Institut de Planétologie et d'Astrophysique de Grenoble, UJF-Grenoble I, CNRS-INSU (France)

8447 OR **Measured performance of the prototype polar coordinate CCD array (Invited Paper)** [8447-27]

S. M. Adkins, W. M. Keck Observatory (United States)

8447 OT **The AOLI low-order non-linear curvature wavefront sensor: a method for high sensitivity wavefront reconstruction** [8447-29]

J. Crass, P. Aisher, Institute of Astronomy, Univ. of Cambridge (United Kingdom); B. Femenia, Instituto de Astrofísica de Canarias (Spain) and Univ. Politécnica de Cartagena (Spain); D. L. King, C. D. Mackay, Institute of Astronomy, Univ. of Cambridge (United Kingdom); R. Rebolo-López, Instituto de Astrofísica de Canarias (Spain) and Consejo Superior de Investigaciones Científicas (Spain); L. Labadie, I. Physikalisches Institut, Univ. zu Köln (Germany); A. Pérez Garrido, Univ. Politécnica de Cartagena (Spain); M. Balcells, Isaac Newton Group of Telescopes (Spain), Instituto de Astrofísica de Canarias (Spain), and Univ. de La Laguna (Spain); A. Díaz Sánchez, Univ. Politécnica de Cartagena (Spain); J. J. Fuensalida, Instituto de Astrofísica de Canarias (Spain) and Univ. de La Laguna (Spain); R. L. Lopez, Instituto de Astrofísica de Canarias (Spain); A. Oscoz, J. A. Pérez Prieto, Instituto de Astrofísica de Canarias (Spain) and Univ. de La Laguna (Spain); L. F. Rodríguez-Ramos, Instituto de Astrofísica de Canarias (Spain); I. Villó, Univ. Politécnica de Cartagena (Spain)

- 8447 0U **Natural guide star adaptive optics systems at LBT: FLAO commissioning and science operations status** [8447-30]
S. Esposito, A. Riccardi, E. Pinna, A. T. Puglisi, F. Quiros-Pacheco, INAF - Osservatorio Astrofisico di Arcetri (Italy); C. Arcidiacono, INAF - Osservatorio Astronomico di Bologna (Italy); M. Xompero, R. Briguglio, L. Busoni, L. Fini, J. Argomedo, A. Gherardi, G. Agapito, INAF - Osservatorio Astrofisico di Arcetri (Italy); G. Brusa, D. L. Miller, J. C. Guerra, K. Boutsia, LBT Observatory, The Univ. of Arizona (United States); P. Stefanini, INAF - Osservatorio Astrofisico di Arcetri (Italy)
- 8447 0V **LINC-NIRVANA Pathfinder: testing the next generation of wave front sensors at LBT** [8447-121]
A. R. Conrad, Max-Planck-Institut für Astronomie (Germany); C. Arcidiacono, INAF - Osservatorio Astronomico di Bologna (Italy); H. Baumeister, Max-Planck-Institut für Astronomie (Germany); M. Bergomi, INAF - Osservatorio Astronomico di Padova (Italy); T. Bertram, J. Berwein, Max-Planck-Institut für Astronomie (Germany); C. Biddick, Large Binocular Telescope Observatory (United States); P. Bizenberger, M. Brangier, F. Briegel, Max-Planck-Institut für Astronomie (Germany); A. Brunelli, INAF - Osservatorio Astronomico di Padova (Italy); J. Brynnel, Large Binocular Telescope Observatory (United States); L. Busoni, INAF - Osservatorio Astrofisico di Arcetri (Italy); N. Cushing, Large Binocular Telescope Observatory (United States); F. De Bonis, Max-Planck-Institut für Astronomie (Germany); M. De La Pena, Large Binocular Telescope Observatory (United States); S. Esposito, INAF - Osservatorio Astrofisico di Arcetri (Italy); J. Farinato, INAF - Osservatorio Astronomico di Padova (Italy); L. Fini, INAF - Osservatorio Astrofisico di Arcetri (Italy); R. F. Green, Large Binocular Telescope Observatory (United States); T. Herbst, R. Hofferbert, F. Kittmann, M. Kuerster, W. Laun, D. Meschke, L. Mohr, A. Pavlov, J.-U. Pott, Max-Planck-Institut für Astronomie (Germany); A. Puglisi, INAF - Osservatorio Astrofisico di Arcetri (Italy); R. Ragazzoni, INAF - Osservatorio Astronomico di Padova (Italy); A. Rakich, Large Binocular Telescope Observatory (United States); R.-R. Rohloff, J. Trowitzsch, Max-Planck-Institut für Astronomie (Germany); V. Viotto, INAF - Osservatorio Astronomico di Padova (Italy); X. Zhang, Max-Planck-Institut für Astronomie (Germany)
- 8447 0W **Science readiness of the Gemini MCAO system: GeMS** [8447-32]
B. Neichel, Gemini Observatory (Chile); F. Rigaut, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); A. Serio, G. Arriagada, M. Boccas, Gemini Observatory (Chile); C. d'Orgeville, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); V. Fesquet, C. Trujillo, W. N. Rambold, R. L. Galvez, G. Gausachs, T. B. Vucina, V. Montes, C. Urrutia, C. Moreno, S. J. Diggs, C. Araya, J. Lührs, Gemini Observatory (Chile); G. Trancho, M. Bec, Giant Magellan Telescope Organization Corp. (United States); C. Marchant, F. Collao, E. R. Carrasco, M. L. Edwards, P. Pessev, A. Lopez, H. Diaz, Gemini Observatory (Chile)
- 8447 0X **First closed-loop visible AO test results for the advanced adaptive secondary AO system for the Magellan Telescope: MagAO's performance and status** [8447-33]
L. M. Close, J. R. Males, D. Kopon, V. Gasho, K. B. Follette, P. Hinz, K. Morzinski, Steward Observatory, The Univ. of Arizona (United States); A. Uomoto, T. Hare, OCIW (United States); A. Riccardi, S. Esposito, A. Puglisi, E. Pinna, L. Busoni, C. Arcidiacono, M. Xompero, R. Briguglio, F. Quiros-Pacheco, J. Argomedo, INAF - Osservatorio Astrofisico di Arcetri (Italy) (Italy)

- 8447 0Y **Results from the PALM-3000 high-order adaptive optics system** [8447-34]
J. E. Roberts, Jet Propulsion Lab. (United States); R. G. Dekany, Caltech Optical Observatories (United States); R. S. Burruss, Jet Propulsion Lab. (United States); C. Baranec, Caltech Optical Observatories (United States); A. Bouchez, Giant Magellan Telescope Organization Corp. (United States); E. E. Croner, S. R. Guiwits, D. D. S. Hale, Caltech Optical Observatories (United States); J. R. Henning, Palomar Observatory, California Institute of Technology (United States); D. L. Palmer, M. Troy, T. N. Truong, Jet Propulsion Lab. (United States); J. Zolkower, Cornell Univ. (United States)

SESSION 9 ADVANCES IN AO CONTROL I

- 8447 0Z **Vibration mitigation in adaptive optics control (Invited Paper)** [8447-35]
C. Kulcsár, P. Massioni, L2TI, Institut Galilée, Univ. Paris 13 (France); G. Sivo, L2TI, Institut Galilée, Univ. Paris 13 (France) and ONERA (France); H.-F. Raynaud, L2TI, Institut Galilée, Univ. Paris 13 (France)
- 8447 10 **Distributed control of large deformable mirrors (Invited Paper)** [8447-36]
D. G. MacMartin, California Institute of Technology (United States); R. Heimsten, T. Andersen, M. Owner-Petersen, Lund Univ. (Sweden)
- 8447 11 **Design of frequency-based controllers for vibration mitigation at the Gemini-South telescope** [8447-37]
A. Guesalaga, Univ. Católica de Chile (Chile); B. Neichel, F. Rigaut, Gemini Observatory Southern Operations Ctr. (Chile); J. Osborn, D. Guzman, Univ. Católica de Chile (Chile)
- 8447 12 **On the rejection of vibrations in adaptive optics systems** [8447-38]
R. Muradore, Univ. degli Studi di Verona (Italy); L. Pettazzi, E. Fedrigo, R. Clare, European Southern Observatory (Germany)

SESSION 10 WAVEFRONT SENSING II

- 8447 13 **Comparison of LGS wavefront-sensing with pyramid, yaw, and quad-cell types wavefront sensors** [8447-39]
E. Gendron, D. Gratadour, LESIA, Observatoire de Paris, CNRS, UPMC, Univ. Paris Diderot (France)
- 8447 14 **Wavefront sensing and correction with the Gemini Planet Imager** [8447-40]
S. Thomas, Gemini Observatory (United States); L. Poyneer, D. Savransky, Lawrence Livermore National Lab. (United States); B. Macintosh, NRC Herzberg Institute of Astrophysics (Canada); M. Hartung, Gemini Observatory (United States); D. Dillon, D. Gavel, UCO Lick Observatory (United States); J. Dunn, NRC Herzberg Institute of Astrophysics (Canada); K. Wallace, Jet Propulsion Lab. (United States); D. Palmer, Lawrence Livermore National Lab. (United States); R. De Rosa, Univ. of Exeter (United Kingdom)
- 8447 15 **Focal-plane wave front sensing strategies for high contrast imaging: experimental validations on SPHERE** [8447-41]
J.-F. Sauvage, T. Fusco, C. Petit, L. Mugnier, ONERA (France); B. Paul, ONERA (France) and Lab. d' Astrophysique de Marseille (France); A. Costille, IPAG (France)

- 8447 16 **Retrieving the telescope and instrument static wavefront aberration with a phase diversity procedure using on-sky adaptive optics corrected images** [8447-42]
L. Jolissaint, aquilAOptics (Switzerland); L. M. Mugnier, ONERA (France); C. Neyman, W. M. Keck Observatory (United States); J. Christou, Gemini Observatory (United States); P. Wizinowich, W. M. Keck Observatory (United States)
- 8447 17 **Design of a truth sensor for the GMT laser tomography adaptive optics system** [8447-43]
M. A. van Dam, Flat Wavefronts (New Zealand); R. Conan, The Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); A. H. Bouchez, Giant Magellan Telescope Organization Corp. (United States); B. Espeland, The Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia)

SESSION 11 AO DISTURBANCES MODELING AND CHARACTERIZATION I

- 8447 18 **Turbulence modeling and estimation for AO systems (Invited Paper)** [8447-44]
A. Beghi, A. Cenerede, A. Masiero, Univ. degli Studi di Padova (Italy)
- 8447 19 **Mesospheric sodium structure variability on horizontal scales relevant to laser guide star asterisms (Invited Paper)** [8447-45]
T. Pfrommer, European Southern Observatory (Germany); P. Hickson, The Univ. of British Columbia (Canada)
- 8447 1A **Lunar scintillometer to validate GLAO turbulence distribution measurements** [8447-46]
K. Newman, M. Hart, E. Bendek, Ctr. for Astronomical Adaptive Optics, The Univ. of Arizona (United States); E. Bustos, Cerro Tololo Inter-American Observatory (Chile)
- 8447 1B **Estimation of vertical profiles of wind from MASS measurements** [8447-47]
M. V. Kornilov, Lomonosov Moscow State Univ., Sternberg Astronomical Institute (Russian Federation)

Part Two

SESSION 12 AO DISTURBANCES MODELING AND CHARACTERIZATION II

- 8447 1C **Vibrations in AO control: a short analysis of on-sky data around the world** [8447-48]
C. Kulcsár, L2TI, Institut Galilée, Univ. Paris 13 (France); G. Sivo, L2TI, Institut Galilée, Univ. Paris 13 (France) and ONERA (France); H.-F. Raynaud, L2TI, Institut Galilée, Univ. Paris 13 (France); B. Neichel, F. Rigaut, Gemini Observatory (Chile); J. Christou, Gemini Observatory (United States); A. Guesalaga, Univ. Católica de Chile (Chile); C. Correia, J.-P. Véran, NRC Herzberg Institute of Astrophysics (Canada); E. Gendron, F. Vidal, G. Rousset, LESIA, Observatoire de Paris, CNRS, Univ. Paris Diderot (France); T. Morris, Durham Univ. (United Kingdom); S. Esposito, F. Quiros-Pacheco, G. Agapito, INAF - Osservatorio Astrofisico di Arcetri (Italy); E. Fedrigo, L. Pettazzi, R. Clare, European Southern Observatory (Germany); R. Muradore, Univ. of Verona (Italy); O. Guyon, F. Martinache, Subaru Telescope, National Astronomical Observatory of Japan (United States); S. Meimon, J.-M. Conan, ONERA (France)

- 8447 1D **Tolerancing the fabrication errors of static optical elements for ELT-size wide-field AO systems** [8447-49]
J.-P. Véran, J. Pazder, G. Herriot, D. Andersen, NRC Herzberg Institute of Astrophysics (Canada)

SESSION 13 PROJECT STATUS IV

- 8447 1F **Subaru laser guide adaptive optics system: performance and science operation** [8447-52]
Y. Minowa, Y. Hayano, H. Terada, T.-S. Pyo, S. Oya, M. Hattori, Subaru Telescope, National Astronomical Observatory of Japan (United States); M. Shirahata, Japan Aerospace Exploration Agency (Japan); H. Takami, National Astronomical Observatory of Japan (Japan); O. Guyon, V. Garrel, S. Colley, M. Weber, T. Golota, Subaru Telescope, National Astronomical Observatory of Japan (United States); M. Watanabe, Hokkaido Univ. (Japan); Y. Saito, Tokyo Institute of Technology (Japan); M. Ito, Univ. of Victoria (Canada); M. Iye, National Astronomical Observatory of Japan (Japan)
- 8447 1G **'Imaka: working towards very wide-field of view AO** [8447-2]
M. Chun, Univ. of Hawai'i, Hilo (United States); O. Lai, J.-C. Cuillandre, Canada-France-Hawaii Telescope Corp. (United States); H. Richer, The Univ. of British Columbia (Canada); D. Toomey, Mauna Kea Infrared LLC (United States); D. Salmon, Canada-France-Hawaii Telescope Corp. (United States); R. Carlberg, Univ. of Toronto (Canada); D. Andersen, NRC Herzberg Institute of Astrophysics (Canada); D. Burgarella, Observatoire Astronomique de Marseille-Provence (France); K. Ho, Canada-France-Hawaii Telescope Corp. (United States); J. Pazder, NRC Herzberg Institute of Astrophysics (Canada); E. Bertin, Institut d'Astrophysique de Paris (France)

SESSION 14 AO FOR ELTs

- 8447 1I **The Giant Magellan Telescope adaptive optics program** [8447-54]
A. H. Bouchez, Giant Magellan Telescope Organization Corp. (United States); D. S. Acton, Ball Aerospace & Technologies Corp. (United States); G. Agapito, C. Arcidiacono, INAF - Osservatorio Astrofisico di Arcetri (Italy); F. Bennet, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); V. Biliotti, M. Bonaglia, R. Briguglio, INAF - Osservatorio Astrofisico di Arcetri (Italy); G. Brusa-Zappellini, Steward Observatory, The Univ. of Arizona (United States); L. Busoni, L. Carbonaro, INAF - Osservatorio Astrofisico di Arcetri (Italy); J. L. Codona, Steward Observatory, The Univ. of Arizona (United States); R. Conan, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); T. Connors, O. Durney, Steward Observatory, The Univ. of Arizona (United States); B. Espeland, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); S. Esposito, L. Fini, INAF - Osservatorio Astrofisico di Arcetri (Italy); R. Gardhouse, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); T. M. Gauron, Smithsonian Astrophysical Observatory (United States); M. Hart, P. M. Hinz, Steward Observatory, The Univ. of Arizona (United States); S. Kanneganti, Smithsonian Astrophysical Observatory (United States); E. J. Kibblewhite, The Univ. of Chicago (United States); R. P. Knox, Steward Observatory, The Univ. of Arizona (United States); B. A. McLeod, Smithsonian Astrophysical Observatory (United States); T. McMahon, M. Montoya, Steward Observatory, The Univ. of Arizona (United States); T. J. Norton, M. P. Ordway, Smithsonian Astrophysical Observatory (United States); C. d'Orgeville, S. Parcell, P. K. Piatrou, Research School of Astronomy and Astrophysics, The

Australian National Univ. (Australia); E. Pinna, INAF - Osservatorio Astrofisico di Arcetri (Italy); I. Price, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); A. Puglisi, F. Quiros-Pacheco, A. Riccardi, INAF - Osservatorio Astrofisico di Arcetri (Italy); J. B. Roll, Smithsonian Astrophysical Observatory (United States); G. Tranco, Giant Magellan Telescope Organization Corp. (United States); K. Uhlendorf, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia); V. Vaitheeswaran, Steward Observatory, The Univ. of Arizona (United States); M. A. van Dam, Flat Wavefronts (New Zealand); D. Weaver, Smithsonian Astrophysical Observatory (United States); M. Xompero, INAF - Osservatorio Astrofisico di Arcetri (Italy)

- 8447 1J **TMT adaptive optics program status report** [8447-55]
B. L. Ellerbroek, Thirty Meter Telescope Observatory Corp. (United States); S. M. Adkins, W. M. Keck Observatory (United States); D. R. Andersen, J. Atwood, National Research Council Canada (Canada); A. Bastard, CILAS (France); Y. Bo, Technical Institute of Physics and Chemistry (China); M.-A. Boucher, National Research Council Canada (Canada); C. Boyer, Thirty Meter Telescope Observatory Corp. (United States); P. W. G. Byrnes, K. Caputa, National Research Council Canada (Canada); S. Chen, Institute of Optics and Electronics (China); C. Correia, National Research Council Canada (Canada); R. Cousty, CILAS (France); J. T. Fitzsimmons, National Research Council Canada (Canada); L. Gilles, Thirty Meter Telescope Observatory Corp. (United States); J. Gregory, MIT Lincoln Lab. (United States); G. Herriot, National Research Council Canada (Canada); P. Hickson, The Univ. of British Columbia (Canada); A. Hill, J. Pazder, National Research Council Canada (Canada); H. Pagès, CILAS (France); T. Pfrommer, The Univ. of British Columbia (Canada); V. A. Reshetov, S. Roberts, National Research Council Canada (Canada); J.-C. Sinquin, CILAS (France); M. Schoeck, Thirty Meter Telescope Observatory Corp. (United States) and National Research Council Canada (Canada); M. Smith, J.-P. Véran, National Research Council Canada (Canada); L. Wang, Thirty Meter Telescope Observatory Corp. (United States); K. Wei, Institute of Optics and Electronics (China); I. Wevers, National Research Council Canada (Canada)
- 8447 1K **Dual-channel multiple natural guide star wavefront sensor for the E-ELT multiconjugate adaptive optics module** [8447-56]
E. Diolaiti, INAF - Osservatorio Astronomico di Bologna (Italy); L. Schreiber, INAF - Osservatorio Astronomico di Padova (Italy); I. Foppiani, M. Lombini, INAF - Osservatorio Astronomico di Bologna (Italy)
- 8447 1L **Wavefront sensor design for the GMT natural guide star AO system** [8447-57]
S. Esposito, E. Pinna, F. Quiros-Pacheco, A. T. Puglisi, L. Carbonaro, M. Bonaglia, V. Biliotti, R. Briguglio, G. Agapito, INAF - Osservatorio Astrofisico di Arcetri (Italy); C. Arcidiacono, INAF - Osservatorio Astrofisico di Bologna (Italy); L. Busoni, M. Xompero, A. Riccardi, L. Fini, INAF - Osservatorio Astrofisico di Arcetri (Italy); A. Bouchez, Giant Magellan Telescope Organization Corp. (United States)
- 8447 1M **TMT NFIRAOS: adaptive optics system for the Thirty Meter Telescope** [8447-58]
G. Herriot, D. Andersen, J. Atwood, P. Byrnes, NRC Herzberg Institute of Astrophysics (Canada); M.-A. Boucher, INO (Canada); C. Boyer, Thirty Meter Telescope Observatory Corp. (United States); K. Caputa, C. Correia, J. Dunn, NRC Herzberg Institute of Astrophysics (Canada); B. Ellerbroek, Thirty Meter Telescope Observatory Corp. (United States); J. Fitzsimmons, NRC Herzberg Institute of Astrophysics (Canada); L. Gilles, Thirty Meter

Telescope Observatory Corp. (United States); P. Hickson, The Univ. of British Columbia (Canada); A. Hill, D. Kerley, J. Pazder, V. Reshetov, S. Roberts, M. Smith, J.-P. Véran, NRC Herzberg Institute of Astrophysics (Canada); L. Wang, Thirty Meter Telescope Observatory Corp. (United States); I. Wevers, NRC Herzberg Institute of Astrophysics (Canada)

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C. Plantet, ONERA (France); B. Neichel, Gemini Southern Observatory (Chile); S. Meimon, T. Fusco, J.-M. Conan, ONERA (France)

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C. d'Orgeville, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia) and Gemini Observatory (Chile); S. Diggs, V. Fesquet, B. Neichel, W. Rambold, Gemini Observatory (Chile); F. Rigaut, Research School of Astronomy and Astrophysics, The Australian National Univ. (Australia) and Gemini Observatory (Chile); A. Serio, C. Araya, G. Arriagada, R. Balladares, Gemini Observatory (Chile); M. Bec, Giant Magellan Telescope Organization Corp. (United States); M. Boccas, C. Duran, A. Ebberts, A. Lopez, C. Marchant, E. Marin, V. Montes, C. Moreno, E. Petit Vega, C. Segura, Gemini Observatory (Chile); G. Trancho, Giant Magellan Telescope Organization Corp. (United States); C. Trujillo, C. Urrutia, P. Veliz, T. Vucina, Gemini Observatory (Chile)
- 8447 1R **Photon returns test of the pulsed sodium guide star laser on the 1.8 meter telescope** [8447-63]
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- 8447 1S **Advanced control of low order modes in laser guide star multi-conjugate adaptive optics systems** [8447-64]
C. Correia, J.-P. Véran, G. Herriot, NRC Herzberg Institute of Astrophysics (Canada); B. Ellerbroek, L. Wang, L. Gilles, Thirty Meter Telescope Observatory Corp. (United States)
- 8447 1T **Ensemble Transform Kalman Filter, a nonstationary control law for complex AO systems on ELTs: theoretical aspects and first simulations results** [8447-65]
M. Gray, B. Le Roux, Lab. d'Astrophysique de Marseille, Aix-Marseille Univ., CNRS (France)

- 8447 1U **Evidence that wind prediction with multiple guide stars reduces tomographic errors and expands MOAO field of regard** [8447-66]
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- 8447 1V **Experimental comparison of tomographic control schemes using the ONERA WFAO facility** [8447-67]
A. Parisot, ONERA (France) and Lab. d'Astrophysique de Marseille (France); C. Petit, ONERA (France); T. Fusco, ONERA (France) and Lab. d'Astrophysique de Marseille (France); J.-M. Conan, ONERA (France)

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- 8447 1X **How ELTs will acquire the first spectra of rocky habitable planets** [8447-69]
O. Guyon, Subaru Telescope, National Astronomical Observatory of Japan (United States), Steward Observatory, Univ. of Arizona (United States), and College of Optical Sciences, Univ. of Arizona (United States); F. Martinache, Subaru Telescope, National Astronomical Observatory of Japan (United States); E. Cady, Jet Propulsion Lab. (United States); R. Belikov, NASA Ames Research Ctr. (United States); K. Balasubramanian, D. Wilson, Jet Propulsion Lab. (United States); C. Clergeon, Subaru Telescope, National Astronomical Observatory of Japan (United States); M. Mateen, College of Optical Sciences, The Univ. of Arizona (United States)
- 8447 1Y **The Subaru coronagraphic extreme AO project: first observations** [8447-70]
F. Martinache, Subaru Telescope, National Astronomical Observatory of Japan (United States); O. Guyon, Subaru Telescope, National Astronomical Observatory of Japan (United States) and The Univ. of Arizona (United States); C. Clergeon, V. Garrel, Subaru Telescope, National Astronomical Observatory of Japan (United States) and Observatoire de Paris-Meudon (France); C. Blain, Univ. of Victoria (Canada)
- 8447 1Z **The SPHERE XAO system SAXO: integration, test, and laboratory performance** [8447-71]
C. Petit, J.-F. Sauvage, ONERA (France); A. Sevin, LESIA (France); A. Costille, IPAG (France); T. Fusco, ONERA (France); P. Baudoz, LESIA (France); J.-L. Beuzit, IPAG (France); T. Buey, LESIA (France); J. Charton, IPAG (France); K. Dohlen, LAM (France); P. Feautrier, IPAG (France); E. Fedrigo, European Southern Observatory (Germany); J.-L. Gach, LAM (France); N. Hubin, European Southern Observatory (Germany); E. Hugot, LAM (France); M. Kasper, European Southern Observatory (Germany); D. Mouillet, IPAG (France); D. Perret, LESIA (France); P. Puget, IPAG (France); J.-C. Siquin, CILAS (France); C. Soenke, M. Suarez, European Southern Observatory (Germany); F. Wildi, Observatoire de Genève (Switzerland)
- 8447 20 **Project 1640: the world's first ExAO coronagraphic hyperspectral imager for comparative planetary science** [8447-72]
B. R. Oppenheimer, American Museum of Natural History (United States); C. Beichman, California Institute of Technology (United States); D. Brenner, American Museum of Natural History (United States); R. Burruss, E. Cady, Jet Propulsion Lab. (United States); J. Crepp, L. Hillenbrand, S. Hinkley, California Institute of Technology (United States); E. R. Ligon, T. Lockhart, Jet Propulsion Lab. (United States); I. Parry, Institute of Astronomy, Univ. of Cambridge (United Kingdom); L. Pueyo, Johns Hopkins Univ. (United States); E. Rice, American Museum of Natural History (United States); L. C. Roberts, Jr., J. Roberts, M. Shao,

Jet Propulsion Lab. (United States); A. Sivaramakrishnan, R. Soummer, Space Telescope Science Institute (United States); G. Vasisht, F. Vesceles, J. K. Wallace, C. Zhai, Jet Propulsion Lab. (United States); N. Zimmerman, Max-Planck-Institut für Astronomie (Germany)

8447 21 **Extremely fast focal-plane wavefront sensing for extreme adaptive optics** [8447-73]
C. U. Keller, V. Korkiakoski, Leiden Observatory (Netherlands); N. Doelman, TNO Science and Industry (Netherlands); R. Fraanje, R. Andrei, M. Verhaegen, Delft Ctr. for Systems and Control (Netherlands)

8447 22 **On advanced estimation techniques for exoplanet detection and characterization using ground-based coronagraphs** [8447-74]
P. R. Lawson, Jet Propulsion Lab. (United States); L. Poyneer, Lawrence Livermore National Lab. (United States); H. Barrett, College of Optical Sciences, The Univ. of Arizona (United States); R. Frazin, Univ. of Michigan (United States); L. Caucci, College of Optical Sciences, The Univ. of Arizona (United States); N. Devaney, National Univ. of Ireland, Galway (Ireland); L. Furenlid, College of Optical Sciences, The Univ. of Arizona (United States); S. Gładysz, Fraunhofer Institute (Germany); O. Guyon, Steward Observatory, The Univ. of Arizona (United States) and Subaru Telescope, National Astronomical Observatory of Japan (United States); J. Krist, Jet Propulsion Lab. (United States); J. Maire, David Dunlap Institute, Univ. of Toronto (Canada); C. Marois, NRC Herzberg Institute of Astrophysics (Canada); D. Mawet, European Southern Observatory (Chile); D. Mouillet, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); L. Mugnier, ONERA (France); I. Pearson, College of Optical Sciences, The Univ. of Arizona (United States); M. Perrin, Space Telescope Science Institute (United States); L. Pueyo, Johns Hopkins Univ. (United States); D. Savransky, Lawrence Livermore National Lab. (United States)

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L. Wang, B. Ellerbroek, Thirty Meter Telescope Project (United States)

8447 24 **Modeling anisoplanatism in the Keck II laser guide star AO system** [8447-76]
M. P. Fitzgerald, G. Witzel, Univ. of California, Los Angeles (United States); M. C. Britton, the Optical Sciences Co. (United States); A. M. Ghez, L. Meyer, B. N. Sitarski, C. Cheng, E. E. Becklin, Univ. of California, Los Angeles (United States); R. D. Campbell, W. M. Keck Observatory (United States); T. Do, Univ. of California, Irvine (United States); J. R. Lu, Institute for Astronomy (United States); K. Matthews, Caltech Optical Observatories (United States); M. R. Morris, Univ. of California, Los Angeles (United States); C. R. Neyman, W. M. Keck Observatory (United States); G. A. Tyler, the Optical Sciences Co. (United States); P. L. Wizinowich, W. M. Keck Observatory (United States); S. Yelda, Univ. of California, Los Angeles (United States)

8447 25 **Size of the halo of the adaptive optics PSF** [8447-77]
S. Gladysz, Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (Germany); M. Le Louarn, N. Yaitskova, European Southern Observatory (Germany); A. Garcia-Rissmann, European Southern Observatory (Germany) and Lab. Nacional de Astrofísica (Brazil); L. Kann, J. D. Drummond, R. L. Johnson, D. Roskey, Air Force Research Lab. (United States)

- 8447 26 **A Fresnel propagation analysis of NFIRAOS/IRIS high-contrast exoplanet imaging capabilities** [8447-78]
C. Marois, J.-P. Véran, C. Correia, National Research Council Canada (Canada)

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- 8447 27 **Aperture masking behind AO systems (Invited Paper)** [8447-79]
M. J. Ireland, Macquarie Univ. (Australia), MQ Research Ctr. in Astronomy, Astrophysics and Astrophotonics, Macquarie Univ. (Australia), and Australian Astronomical Observatory (Australia)
- 8447 28 **Adaptive optics point spread function reconstruction project at W. M. Keck Observatory: first results with faint natural guide stars** [8447-80]
L. Jolissaint, aquilAOptics (Switzerland); C. Neyman, W. M. Keck Observatory (United States); J. Christou, Gemini Observatory (United States); P. Wizinowich, W. M. Keck Observatory (United States)
- 8447 29 **Tip/tilt point spread function reconstruction for laser guide star multi-conjugate adaptive optics** [8447-81]
L. Gilles, Thirty Meter Telescope Observatory Corp. (United States); C. Correia, J.-P. Véran, NRC Herzberg Institute of Astrophysics (Canada); L. Wang, B. L. Ellerbroek, Thirty Meter Telescope Observatory Corp. (United States)
- 8447 2A **Temporal convergence of phase spatial covariance matrix measurements in tomographic adaptive optics** [8447-218]
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E. Pinna, F. Quirós-Pacheco, A. Riccardi, R. Briguglio, A. Puglisi, L. Busoni, INAF - Osservatorio Astrofisico di Arcetri (Italy); C. Arcidiacono, INAF - Osservatorio Astrofisico di Arcetri (Italy) and INAF - Osservatorio Astrofisico di Bologna (Italy); J. Argomedo, INAF - Osservatorio Astrofisico di Arcetri (Italy) and European Southern Observatory (Germany); M. Xompero, INAF - Osservatorio Astrofisico di Arcetri (Italy); E. Marchetti, European Southern Observatory (Germany); S. Esposito, INAF - Osservatorio Astrofisico di Arcetri (Italy)
- 8447 2C **Optimization of adaptive optics correction during observations: algorithms and system parameters identification in closed-loop** [8447-84]
C. Béchet, M. Tallon, É. Thiébaud, Univ. Lyon 1, Ctr. de Recherche Astronomique de Lyon, CNRS, Ecole Normale Supérieure de Lyon (France)
- 8447 2D **Calibration strategy of the AOF** [8447-85]
J. Kolb, P.-Y. Madec, M. Le Louarn, N. Muller, European Southern Observatory (Germany); C. Béchet, Ctr. de Recherche Astronomique de Lyon (France)

- 8447 2E **A high-performance FPGA platform for adaptive optics real-time control** [8447-86]
H. Zhang, Z. Ljusic, G. Hovey, J.-P. Veran, G. Herriot, National Research Council Canada (Canada); M. Dumas, Lyrtech RD Inc. (Canada)
- 8447 2F **Design and implementation of the PALM-3000 real-time control system** [8447-87]
T. N. Truong, Jet Propulsion Lab. (United States); A. H. Bouchez, Giant Magellan Telescope Organization Corp. (United States); R. S. Burruss, Jet Propulsion Lab. (United States); R. G. Dekany, S. R. Guiwits, California Institute of Technology (United States); J. E. Roberts, J. C. Shelton, M. Troy, Jet Propulsion Lab. (United States)

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- 8447 2G **VLT deformable secondary mirror: integration and electromechanical tests results** [8447-88]
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- 8447 2I **Global wavefront sensing for extremely large telescopes** [8447-90]
R. Ragazzoni, INAF - Osservatorio Astronomico di Padova (Italy); M. Bergomi, INAF - Osservatorio Astronomico di Padova (Italy) and Univ. degli Studi di Padova (Italy); A. Brunelli, M. Dima, J. Farinato, D. Magrin, INAF - Osservatorio Astronomico di Padova (Italy); L. Marafatto, Univ. degli Studi di Padova (Italy); V. Viotto, INAF - Osservatorio Astronomico di Padova (Italy)
- 8447 2J **An interferometric wavefront sensor for high-sensitivity low-amplitude measurements** [8447-91]
N. A. Bharmal, R. M. Myers, A. G. Basden, A. P. Reeves, Durham Univ. (United Kingdom)
- 8447 2K **A phase-shifting Zernike wavefront sensor for the Palomar P3K adaptive optics system** [8447-92]
J. K. Wallace, S. Crawford, F. Loya, J. Moore, Jet Propulsion Lab. (United States)
- 8447 2L **Fast computer-free holographic adaptive optics** [8447-93]
G. Andersen, F. Ghebremichael, R. Gaddipati, P. Gaddipati, HUA Inc. (United States)

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- 8447 2M **The wavefront correction control system for the Advanced Technology Solar Telescope** [8447-94]
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- 8447 2N **Adaptive optics real time processing design for the advanced technology solar telescope** [8447-95]
K. Richards, National Solar Observatory (United States)
- 8447 2O **The Robo-AO software: fully autonomous operation of a laser guide star adaptive optics and science system** [8447-96]
R. L. Riddle, Caltech Optical Observatories (United States); M. P. Burse, Inter-Univ. Ctr. for Astronomy and Astrophysics (India); N. M. Law, Dunlap Institute for Astronomy and Astrophysics, Univ. of Toronto (Canada); S. P. Tendulkar, C. Baranec, Caltech Optical Observatories (United States); A. R. Rudy, National Central Univ. (Taiwan); M. Sitt, Stanford Univ. (United States);
A. Arya, Mississippi State Univ. (United States); A. Papadopoulos, Aristotle Univ. of Thessaloniki (Greece); A. N. Ramaprakash, Inter-Univ. Ctr. for Astronomy and Astrophysics (India); R. G. Dekany, Caltech Optical Observatories (United States)
- 8447 2P **Recent development in real time control system of Subaru LGSAO-188** [8447-97]
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- 8447 2Q **SPARTA for the VLT: status and plans** [8447-98]
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- 8447 2R **FPGA-based real time controller for high order correction in EDIFISE** [8447-99]
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- 8447 2S **An AO real-time control solution for ELT scale instrumentation and application to EAGLE** [8447-100]
A. Basden, N. Dipper, R. Myers, E. Younger, Durham Univ. (United Kingdom)
- 8447 2T **Operation of the adaptive optics system at the Large Binocular Telescope Observatory** [8447-101]
D. L. Miller, J.-C. Guerra, Large Binocular Telescope Observatory (United States); K. Boutsia, Large Binocular Telescope Observatory (United States) and INAF-Roma (Italy); L. Fini, J. Argomedo, INAF - Osservatorio Astrofisico di Arcetri (Italy); C. Biddick, Large Binocular Telescope Observatory (United States); G. Agapito, C. Arcidiacono, R. Briguglio, INAF - Osservatorio Astrofisico di Arcetri (Italy); G. Brusa, Large Binocular Telescope Observatory (United States); L. Busoni, S. Esposito, INAF - Osservatorio Astrofisico di Arcetri (Italy); J. Hill, Large Binocular Telescope Observatory (United States); C. Kulesa, D. McCarthy, Steward Observatory, The Univ. of Arizona (United States); E. Pinna, A. T. Puglisi, F. Quiros-Pacheco, A. Riccardi, M. Xompero, INAF - Osservatorio Astrofisico di Arcetri (Italy)

- 8447 2U **Pupil rotation compensation for LINC-NIRVANA** [8447-102]
M. Brangier, A. R. Conrad, T. Bertram, X. Zhang, J. Berwein, F. Briegel, T. M. Herbst, Max-Planck-Institut für Astronomie (Germany); R. Ragazzoni, INAF - Osservatorio Astronomico di Padova (Italy)
- 8447 2V **FOAM: the modular adaptive optics framework** [8447-103]
T. I. M. van Werkhoven, L. Homs, Leiden Observatory (Netherlands); G. Sliepen, AlbaNova Univ. Ctr. (Sweden); M. Rodenhuis, C. U. Keller, Leiden Observatory (Netherlands)
- 8447 2Y **First laboratory validation of LQG control with the CANARY MOAO pathfinder** [8447-106]
G. Sivo, L2TI, Institut Galilée, Univ. Paris 13 (France) and ONERA (France); H.-F. Raynaud, L2TI, Institut Galilée, Univ. Paris 13 (France); J.-M. Conan, ONERA (France); C. Kulcsár, L2TI, Institut Galilée, Univ. Paris 13 (France); É. Gendron, F. Vidal, LESIA - Observatoire de Meudon (France); A. Basden, Durham Univ. (United Kingdom)
- 8447 2Z **Performance of LQG-based control for AO: a numerical analysis** [8447-107]
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- 8447 31 **Infinite impulse response modal filtering in visible adaptive optics** [8447-109]
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- 8447 32 **On application of constrained receding horizon control in astronomical adaptive optics** [8447-110]
M. V. Konnik, J. De Doná, J. S. Welsh, The Univ. of Newcastle (Australia)
- 8447 33 **Analysis and experimental demonstration of adaptive optics based on the modal control optimization** [8447-111]
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- 8447 34 **Mitigation of transient meteor events in sodium layer by TMT NFIRAOS** [8447-112]
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- 8447 3F **Status of the Raven MOAO science demonstrator** [8447-124]
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- 8447 3M **ERIS adaptive optics system design** [8447-132]
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- 8447 3O **Optical calibration and testing of the E-ELT M4 adaptive mirror** [8447-134]
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- 8447 3Q **Optical designs of the LGS WFS system for GMT-LTAO** [8447-136]
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- 8447 3R **Design and predicted performance of the GMT ground-layer adaptive optics mode** [8447-137]
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- 8447 3S **The Giant Magellan Telescope phasing system** [8447-138]
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- 8447 3U **Optical design of a Cassegrain mounted AO relay for Imaka** [8447-142]
J. Pazder, NRC Herzberg Institute of Astrophysics (Canada)

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- 8447 3W **Dimensioning and performances of an AO system for the SALT** [8447-144]
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- 8447 3X **System analysis and characterization of the FFREE bench** [8447-145]
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- 8447 3Y **Holographic combination of low-resolution Shack-Hartmann sensor and holography-based modal Zernike wavefront sensor** [8447-146]
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- 8447 40 **Tomographic reconstructor for multi-object adaptive optics using artificial neural networks** [8447-148]
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- 8447 43 **Residual tip-tilt motion of LGS in monostatic scheme** [8447-151]
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- 8447 44 **Adaptive optics for laser space debris removal** [8447-152]
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- 8447 4J **Vibration control for the ARGOS laser launch path** [8447-168]
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- 8447 4K **A sodium guide star adaptive optics system for the 1.8 meter telescope** [8447-169]
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- 8447 4M **Improving stability, robustness, and performance of laser systems** [8447-171]
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Telescope Organization Corp. (United States); C. Marchant, F. Collao, E. R. Carrasco, M. L. Edwards, P. Pessev, A. Lopez, H. Diaz, Gemini Observatory (Chile)

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- 8447 51 **A test bench for ARGOS: integration of sub-systems and validation of the wavefront sensing** [8447-186]
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- 8447 52 **A prototype phasing camera for the Giant Magellan Telescope** [8447-187]
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- 8447 54 **Design and test results of the calibration unit for the MOAO demonstrator RAVEN** [8447-189]
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