GEMINI FRONTIER FIELDS: WIDE-FIELD ADAPTIVE OPTICS $K$-BAND IMAGING OF THE GALAXY CLUSTERS MACS J0416.1–2403 AND ABEll 2744*

M. Schirmer1, E. R. Carrasco1, P. Pessey1, V. Garrel1, C. Winge1, B. Neichel1,2, and F. Vidal1,3
1 Gemini Observatory, Casilla 603, La Serena, Chile; mschirme@gemini.edu
2 Aix Marseille Université, CNRS, Laboratoire d’Astrophysique de Marseille, UMR 7326, F-13388, Marseille, France
3 Observatoire De Paris, Place Jules Janssen, F-92190 Meudon, France

Received 2014 September 4; accepted 2015 March 6; published 2015 April 24

ABSTRACT

We have observed two of the six Frontier Fields galaxy clusters, MACS J0416.1–2403 and Abell 2744, using the Gemini Multi-Conjugate Adaptive Optics System (GeMS) and the Gemini South Adaptive Optics Imager (GSAOI). With 0″.08–0″.10 FWHM our data are nearly diffraction-limited over a 100″ × 100″ wide area. GeMS/ GSAOI complements the Hubble Space Telescope (HST) redwards of 1.6 μm with twice the angular resolution. We reach a 5σ depth of $K_s \sim 25.6$ mag (AB) for compact sources. In this paper, we describe the observations, data processing, and initial public data release. We provide fully calibrated, co-added images matching the native GSAOI pixel scale as well as the larger plate scales of the HST release, adding to the legacy value of the Frontier Fields. Our work demonstrates that even for fields at high galactic latitude where natural guide stars are rare, current multi-conjugated adaptive optics technology at 8 m telescopes has opened a new window on the distant universe. Observations of a third Frontier Field, Abell 370, are planned.

Key words: galaxies: clusters: individual (MACS J0416.1–2403, Abell 2744) – instrumentation: adaptive optics – techniques: image processing

1. INTRODUCTION

Strong gravitational lensing by massive clusters of galaxies provides us with magnified views of high-redshift galaxies in the young universe. The Hubble Space Telescope (HST) Frontier Fields campaign observes six strong lensing clusters in the 0.43–1.6 μm wavelength range, using the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3). Complementary observations have been obtained with Chandra (PI: Murray, S.), Spitzer (PIs: Soifer, T., Capak, P.), Subaru (Postman et al. 2011), the Very Large Telescope (VLT; Owers et al. 2011), and the AAT (Ebeling et al. 2014).

HST/WFC3 is sensitive to near-infrared radiation shorter than 1.7 μm. This design was chosen (1) to allow for simpler thermo-electric cooling of the detector, and (2) because HST itself contributes significantly to the thermal background and thus would offer only a small gain with respect to ground-based observatories at ≥2 μm. While the Earth’s atmosphere has a suitable observing window between 2.0 and 2.3 μm ($K_s$ band), its turbulence limits the resolution and the depth with classical imaging. Using multi-conjugated adaptive optics (MCAO; Ellerbroek & Rigaut 2000; Ragazzoni et al. 2000), these adverse effects can be overcome for fields as large as one arcminute or more. In theory, diffraction-limited observations are possible, given a sufficient number of bright natural guide stars (NGSs) and a good laser return for the artificial laser guide stars (LGSs). Today, such wide-field diffraction-limited observations can be obtained in the near-infrared at Gemini South with the Gemini Multi-Conjugate Adaptive Optics System (GeMS; Neichel et al. 2014b; Rigaut et al. 2014) and the Gemini South Adaptive Optics Imager (GSAOI; McGregor et al. 2004; Carrasco et al. 2012) camera.

GeMS is the first MCAO system in use at an 8 m telescope. It delivers uniform and nearly diffraction-limited images over a 2′ field at near-infrared wavelengths. GeMS uses five sodium LGSs and needs three NGSs to compensate for tip-tilt and focus, reducing plate-dynamical errors (plate-scale variations). To achieve optimum performance, the NGSs should be positioned as close as possible to an equilateral triangle around the science target. The best constellations (asterisms) are those that cover most of the field. The larger the angular separations between the stars, the lower the plate-scale error will be over the imaged field. Unfortunately, this condition is usually not met at high galactic latitudes where the stellar density is low. With sub-optimal asterisms the point-spread function (PSF) will become larger and non-uniform. Only one sufficiently bright NGS is available for each of our targets, yet we still achieve an image seeing of 100 mas or better.

The focus in the remainder of this paper is on the observations (Section 2), and on various data reduction aspects such as background modeling and astrometry (Section 3). In Section 4, we summarize the properties of the co-added images and describe the data release.

2. OBSERVATIONS

GSAOI is a near-infrared adaptive optics (AO) camera designed to work with GeMS. Its focal plane is formed by a 2 × 2 mosaic of Hawaii-2RG 2048 × 2048 pixel arrays with 2″8–3″0 wide gaps. Images are recorded in a 85″ × 85″ field

---

* Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Science and Technology Facilities Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), and Ministério da Ciência, Tecnologia e Inovação (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina). Based on observations made with ESO Telescopes at the La Silla and Paranal Observatories, Chile.

5 http://www.stsci.edu/hst/nicmos/documents/handbooks/current_NEW/ e04_imaging_6.8.html

6 http://www.gemini.edu/sciops/instruments/gems

7 http://www.gemini.edu/sciops/instruments/gsaoi
of view with a plate scale of 0\arcsec{}0197 pixel\(^{-1}\). The \(K_s\)-band filter in GSAOI has 50% cut-on and cut-off wavelengths of 1.99 and 2.31 \(\mu \text{m}\), respectively. More details about GSAOI can be found on the instrument web page.

The GSAOI pointings for MACS J0416.1-2403, Abell 2744, and Abell 370 are shown in Figures 10, 11, and 12, respectively, in the Appendix. We have overlaid the currently available \textit{HST} data, as well as the areas of highest strong lensing magnification for \(z = 9\) sources as calculated by Richard et al. (2014). In the case of Abell 2744, we cannot cover the area of highest magnification due to the large angular separation of the NGS from the cluster center.

MACS J0416.1-2403 was observed to the planned depth with GSAOI using director’s discretionary time (Program ID: GS-2013B-DD-1). To optimize the observations, the NGS was located outside the GSAOI field of view, but within the patrol field area of GeMS. Due to a setup error (the NGS is a high proper motion star), the images observed during the first two nights were recorded with a southeastern offset of 24\arcsec. As a result, the NGS appears in one of the four arrays. The images recorded during the other three nights have the correct base position.

Regular 3 \(\times\) 3 dither patterns (repeated several times) with a step size of 7\arcsec{} were used to cover the gaps between the arrays. Processing of the data has revealed that this strategy does not allow us to fully suppress background residuals and cross-talk (Section 3). Hence, we switched to random dithers within a 14\arcsec{} wide box for Abell 2744 and Abell 370), resulting in significantly improved background characteristics.

The observing log is presented in Table 1. The targets, dates, number of images, and exposure times are listed in columns 1, 2, and 3, respectively. For the remainder of the Abell 2477 and Abell 370 data, we will use 180 s instead of 120 s to reduce the overhead. Columns 4 and 5 show the average corrected AO FWHM within 1\arcmin{} of the NGS and the natural seeing recorded by the DIMM, respectively. 2014 January 19 was significantly worse with an average AO-corrected seeing of 0\arcsec{}17. Data from that night were included in the low-resolution stack only (see Section 4). Observations for Abell 2744 were started in 2014 September (Program ID: GS-2014B-DD-1, 25% complete by the time of writing). Abell 370 will follow in 2015.

### 3. DATA REDUCTION

Data processing was performed with \textsc{theili} (Erben et al. 2005; Schirmer 2013), following the example in Appendix B of Schirmer (2013). The motivations for the specific treatments for the GSAOI data are presented below.

#### 3.1. Two-pass Background Modeling

To summarize, we have subtracted the median of eight conterminous exposures to remove the background from the image sequences. This corresponds to a floating time window of 22 minutes. Windows of 15–30 minutes yield good background correction as well. Shorter windows (five or less images) cause artifacts near extended objects (insufficient statistics due to masking) and increased noise. Longer windows (e.g., 35–45 minutes) may undersample temporal variations in atmospheric emissivity, increasing the background residuals (see Section 3.3). Due to its comparably small field of view, GSAOI is less sensitive to the latter effect than other near-infrared imagers.

The average background signal is 7490 \pm 440 ADU or 12.58 mag arcsec\(^{-2}\) (VEGA) in the \(K_s\) band. This is close to the long-term average of 12.62 mag arcsec\(^{-2}\), including a thermal contribution of \(\sim 0.7\) mag arcsec\(^{-2}\) from the warm MCAO enclosure (see also Section 3.3).

In the first step of the two-pass background subtraction, the exposures were median combined without masking to get rid of the bulk of the sky signal. During the second step, \textsc{theili} applies SExtractor (Bertin & Arnouts 1996) to the corrected images from the first pass, computing mask images. Without these masks the fainter halos of the cluster galaxies bias the background model toward higher values, causing dark halos in the co-added image.

We have found that the SExtractor masks are too small. A module was added to \textsc{theili} that provides the option of enlarging the masks. It uses an alternative parametrization of the best-fit ellipse to an object’s isophotes. A pixel with image coordinates \(x\) and \(y\) is located inside the ellipse if

\[
C_{xx}(x-x)^2 + C_{yy}(y-y)^2 + C_{xy}(x-x)(y-y) < = R^2, \tag{1}
\]

where \(x\) and \(y\) represent the object’s centroid (first moment), and \(C_{xx}, C_{yy}, \) and \(C_{xy}\) are the SExtractor parameters calculated from the second brightness moments. A choice of \(R \sim 3\) reproduces the outer isophote of a detection.\(^7\) Only for \(R = 8\) or higher did the over-correction of the sky appear in the co-added images. This mask expansion is available in \textsc{theili} as of v2.9.0, with \(R\) referred to as the mask expansion factor. It can be selected during background modeling, collapse correction (see below), and individual sky subtraction. Figure 1 illustrates the effect.

Note that low surface brightness features larger than the dither box (such as intra-cluster light) escape this masking process and are suppressed in the co-added images. This can be avoided by interspersing blank sky fields into the observing sequence.

\(^7\) For details see the SExtractor user manual v2.13, Section 10.1.6.

### Table 1

Summary of the Observing Nights as of February 2015

| Target           | Night (UT) | Exposures | (AO seeing) | Nat. seeing |
|------------------|------------|-----------|-------------|-------------|
| MACS J0416.1-2403 | 2014-01-13 | 40 \(\times\) 120 s | 0\arcsec{}076 | 0\arcsec{}4–0\arcsec{}7 |
| MACS J0416.1-2403 | 2014-01-14 | 37 \(\times\) 120 s | 0\arcsec{}077 | 0\arcsec{}6–0\arcsec{}9 |
| MACS J0416.1-2403 | 2014-01-19 | 34 \(\times\) 120 s | 0\arcsec{}175 | 0\arcsec{}9–1\arcsec{}1 |
| MACS J0416.1-2403 | 2014-01-20 | 37 \(\times\) 120 s | 0\arcsec{}103 | 0\arcsec{}5–0\arcsec{}9 |
| MACS J0416.1-2403 | 2014-01-22 | 16 \(\times\) 120 s | 0\arcsec{}105 | 0\arcsec{}5–0\arcsec{}7 |
| Abell 2744        | 2014-09-07 | 40 \(\times\) 120 s | 0\arcsec{}110 | 0\arcsec{}7–1\arcsec{}2 |
3.2. Reset Anomaly and Background Gradients

GSAOI shows an unstable reset anomaly in array #2 for its medium and faint readout modes, probably due to a bias/dark problem in the detector controller. Every first image in an exposure series is affected by it, as is the image taken immediately after an interruption (e.g., because of the laser being shuttered for air planes or satellites). The anomaly is evident in the data after background subtraction. Figure 2 shows that we can correct it by subtracting a rescaled median model of the affected images. The rescaling factors (between 0.2 and 1.2) were determined manually.

In addition to the reset anomaly, and independent of it, horizontal stripes are found in 84% of the MACS J0416.1-2403 data (and to a lesser degree for Abell 2744). They run parallel to the interface between arrays #2/3 and #1/4 (see Figures 2 and 3). Both the amplitude and the angular extent of the stripes vary between exposures. They affect an identical number of rows in all four arrays. The amplitude is much lower than the reset anomaly, in the worst case reaching 0.2% of the background level (three to four times smaller than the sky noise). For deep co-added images this effect must be corrected for by subtracting an average column profile (collapse correction in THELI). The calculation of the profile includes object masking (see Section 3.1).

3.3. Sky Subtraction

Background modeling with a floating median (Section 3.1) may leave residuals in the data due to undersampled temporal variations of the sky. We correct individual exposures by masking all objects (Section 3.1), using a conservative mask expansion factor of $R = 20$. The masked images are convolved with a Gaussian and subtracted from their originals. For MACS J0416.1-2403, the best results in terms of preserving faint extended galaxy halos while minimizing background inhomogeneities were obtained with a 3″ wide kernel. Abell 2744 required a 6″ kernel due to a few low surface brightness galaxies which were undetected (and thus unmasked) in individual exposures.

The co-added images (normalized to 1 s exposure time) have a mean background level of zero. Without sky subtraction the normalized background value would be $62 \pm 4$ ADU. Effective gains are listed in the FITS headers. Note that due to the dithering of mosaic data, the total exposure time varies across the image. Local noise levels must be estimated using the co-added weight maps.

3.4. Image Persistence and Crosstalk

Saturated objects leave a weak imprint in subsequent GSAOI exposures (image persistence). In the case of MACS J0416.1-2403, the only saturating source is a bright field star (Figure 10), leaving a charge residual of $\sim 0.2\%$. We have

Figure 1. Expansion of object masks to avoid biasing of the background models by faint galaxy halos. Left: part of a GSAOI image after first-pass background modeling. Right: SExtractor mask before (white) and after (black) expansion with $R = 8$, using DETECT_THRESH = 1.2 and DETECT_MINAREA = 20.

Figure 2. Left: the four GSAOI detector arrays (labeled). A reset anomaly (dark extended spot) appears in array #2 at the beginning of each observing sequence. Independently, horizontal striping with a low amplitude occurs in $\geq 80\%$ of exposures, affecting all four detectors. We illustrate the latter by plotting the mean row values along the dashed white line in array #4 both before and after correction (see Figure 3). Right: same exposure after correction for reset anomaly and striping. Note that this is a high contrast display of $12 \times 12$ binned data, exaggerating the effects.
masked these ghosts manually in the weight images as they did not average out entirely due to the repeated dither pattern.

The same star, located in array #1, also causes significant negative cross-talk in one of the four output channels of array #1. Contrary to image persistence, the position of this cross-talk is fixed with respect to the star and thus does not average out. We masked it manually in the weight maps.

Other memory effects exist in some GSAOI arrays. This is particularly noticeable in the low-resolution (0′06 pixel⁻¹) stack of MACS J0416.1-2403 with its high signal-to-noise ratio (S/N) because of the effective 3 × 3 re-binning. Darker spots with a maximum amplitude twice the background noise level (Figure 4) mirror the dither pattern. Only some parts of the arrays are affected, as neighboring sources of similar brightness do not cause ghosting. The origin of this behavior is still under investigation. It is of minor concern as it rarely coincides with images of astrophysical objects. The non-repetitive dither pattern used for Abell 2744 (and Abell 370) fully suppresses this feature.

3.5. Astrometric Calibration With Scamp

THELI uses Scamp (Bertin 2006) for the astrometric calibration, and the discussion below is specific to this context. Nonetheless, our results should provide a useful reference point when solving GSAOI astrometry with other software.

3.5.1. Input Catalogs and Scamp Settings

The setup error described in Section 2 resulted in an offset of 24′′, which is not reflected in the headers of the archival data taken on 2014 January 13 and 14. The CRVAL1/2 header keywords were manually corrected to within ~1′′, i.e., the typical WCS uncertainty in raw GSAOI data. We then loaded SExtractor source catalogs into Scamp (v2.0.1), using a low detection threshold per pixel (DETECT_THRESH = 1.2) to maximize the number of usable sources. A minimum of DETECT_MINAREA = 20 pixels above this threshold was required to form a valid object (rejecting spurious sources, and because GSAOI data are oversampled). This resulted in an average of 11 ± 5 (8 ± 3) detections (mostly galaxies) per array for MACS J0416.1-2403 (Abell 2744). Scamp uses its own internal S/N thresholds for object filtering. A very low setting is required to retain a sufficient number of objects for successful matching with the reference catalog. The final astrometric solution was obtained using a refined median estimate of the relative chip positions and orientations from all exposures in a night (MOSSAC_TYPE = FIX_FOCALPLANE), and a second-order distortion model. We reproduce all of the relevant parameter settings in Table 2. A typical distortion model is shown in Figure 5, revealing a plate scale variation of 3%.

3.5.2. The Need for Secondary Reference Catalogs

Astrometry with GSAOI is non-trivial. First, there is a large discrepancy between the angular resolutions of GSAOI and common all-sky astrometric reference catalogs. A single reference source (stellar or non-stellar) may be resolved into several components by GSAOI. Second, the AO field of view is comparatively small and at high galactic latitude no (or only a few) reference sources are available. Third, GSAOI works in the near-infrared, whereas reference catalogs are mostly based on optical data. This often results in very low densities for the reference catalog in highly reddened areas (2MASS is an exception, but it is comparatively shallow). In our case with mostly extragalactic sources, reference catalogs that are more blue are susceptible to substructures in galaxies, whereas the...
redder science data mainly detect galactic bulges and nuclei. Fourth, GeMS introduces a significant field distortion by means of its optical relay (consisting of two off-axis parabolic mirrors). Fortunately, this distortion is static and, as we show below, it can be measured reliably even for sparse data.

Finally, the distortion correction is imperfect as the wavefront correction is a function of the atmospheric turbulence profile and, e.g., the brightness of the LGS. The latter depends on the laser performance, the alignment of the laser beam transfer optics, and also the atmosphere’s sodium layer (which has a strong seasonal dependence and is replenished by meteor showers). This mostly affects investigations where high-precision astrometry is required. For more details see, e.g., Cameron et al. (2009), Ammons et al. (2013), and Neichel et al. (2014a).

For our purposes, the key to successful WCS matching and sufficiently good distortion modeling are deeper secondary (or even tertiary) reference catalogs (see also Schirmer 2013), ideally constructed from observations at similar wavelengths.

### 3.5.3. External Astrometry

For both galaxy clusters, we tried different reference catalogs constructed from (1) the HST/ACS F814W images (the HST/WFC3 near-infrared data do not fully overlap with the GSAOI pointings), and (2) deep VLT/HAWK-I $K_s$-band observations (PI: Brammer, ESO program ID: 092.A-0472; image seeing $0''29-0''37$). In the case of MACS J0416.1-2403, we also tested an R-band image taken with the Wide Field Imager (WFI) at the 2.2 m MPG/ESO telescope (Grün et al. 2014, ESO program ID: 083.A-9026; image seeing $0''95$). The co-added ground-based data were created with THELI and calibrated against 2MASS (Skrutskie et al. 2006).

Matching was successful for all three reference catalogs. However, calibration against the WFI data caused large residuals (30–70 mas) and we do not consider this further. HST/ACS and VLT/HAWK-I catalogs have provided similar results for MACS J0416.1-2403. For Abell 2744 we could not obtain a good distortion correction for array #2 with the HST/ACS catalog.

It is particularly noteworthy that the VLT/HAWK-I catalog resulted in external residuals of 12–14 mas, whereas for HST/ACS we obtain 6–9 mas. This is not surprising as the HST data have smaller measurement errors for the centroids due to the high angular resolution. However, the nominal Scamp $\chi^2$ values for the VLT/HAWK-I fit have been about 1–6 per image for both clusters, whereas for HST/ACS we have found $\chi^2 = 10–30$ for MACS J0416.1-2403 and $\chi^2 = 30–100$ for Abell 2744. The HST data are significantly bluer (0.8 $\mu$m) than the VLT images (2.2 $\mu$m) and thus more susceptible to substructures in the galaxies. The effect is immediately visible when both reference catalogs are plotted over the GSAOI exposures. The centroids measured in the VLT/HAWK-I data, taken in the same filter as the GSAOI images, align better for a larger number of objects. The higher $\chi^2$ for Abell 2744 is likely the result of a larger fraction of late-type galaxies (spirals and edge-on disks). The GSAOI pointing is further away from the cluster center than for MACS J0416.1-2403 (compare Figures 10 and 11), and thus the effect of sub-structure is perhaps more pronounced.

We base our final external WCS calibration on the VLT/HAWK-I data, which in turn have been calibrated against 2MASS. Note that in v1.0 of the HST data, systematic WCS offsets of $0''17$ and $0''40$ are present for MACS J0416.1-2403 and Abell 2744, respectively. Corrections for the HST headers are as follows:

$$\Delta{\text{CRVAL1}} = +5.0 \times 10^{-5} \text{ (MACS J0416.1)}$$

$$\Delta{\text{CRVAL2}} = -0.6 \times 10^{-5} \text{ (MACS J0416.1)}$$

$$\Delta{\text{CRVAL1}} = -5.8 \times 10^{-5} \text{ (Abell 2744)}$$
3.5.4. Internal Astrometry

The $\chi^2$ did not improve when switching from a second- to a third-order distortion polynomial. The higher-order solution is poorly constrained, given the small number of sources, and significant discontinuities in the pixel scale occurred across array boundaries. Thus we have selected the simpler second-order hypothesis. The internal and external residuals for MACS J0416.1-2403 are shown in Figure 6 and measure 10 and 13 mas, respectively (same for Abell 2744). This is equivalent to half a GSAOI pixel and should be sufficient for most purposes of these particular data sets. The dominating factors limiting the fits are the low source densities and the large measurement uncertainties of the source centroids (0.1–0.3 pixels or 2–6 mas for galaxies).

Astrometric solutions were obtained on a nightly basis. We have also tested a common distortion model for all nights and find it to be inferior. This is because the large angular offsets between the base positions of different nights introduce different distortion patterns as the NGS and LGS configurations move with respect to each other (Neichel et al. 2014a, 2014b; Rigaut et al. 2014). For another test, we have split the nightly sequences into blocks of 30 minutes to sample a variable distortion component caused by flexure due to a changing gravity vector (Neichel et al. 2014a). This effect becomes important when high-precision relative astrometry (on the order of one milli-arcsecond and below) is required across the field (Neichel et al. 2014a, 2014b). We find that for blocks with good AO-corrected seeing (80 mas), the internal residuals decrease from 10 to 6–8 mas, whereas for other blocks the quality of the fit was unchanged or worse. We thus decided to use the more stable nightly fits instead.

It is hard to reach better performance with GeMS at high galactic latitude with few low S/N detections per array, almost all of which are extended, and just a single NGS. In comparison, for dense stellar fields such as NGC 1851 with 500–1000 sources per array and S/N > 10–100, optimal NGS asterisms, and in the absence of dithering, GeMS delivers relative astrometric accuracies of 0.4 mas and better (Rigaut et al. 2012; Ammons et al. 2013; Neichel et al. 2014a).

3.6. Photometric Calibration

THELI normalizes the gains of multi-chip cameras to the array with the lowest gain, i.e., array #2 in case of GSAOI. The co-added images are scaled in ADU s$^{-1}$. The transformation from VEGA to AB magnitudes in the $K_s$-band filter is obtained by adding 1.85 mag.

3.6.1. Transparency

Sky transparency was good, yet somewhat unstable during all observing nights (see Figure 7). The instabilities were caused by a high inversion layer trapping significant amounts of humidity above the observatory. Such conditions may be difficult to recognize at night by observers. Other factors that contribute to the scattering between exposures are errors in the gain determination of the four arrays of 0.5%–1.0% and small differences in their quantum efficiencies. In Carrasco et al.
coefficients. We have neglected a small color term (~0.02 mag) between the GSAOI $K_s$-band filter and the $K$-band filter used for the MKO system (Leggett et al. 2006). The uncertainty of 0.06 mag includes the nominal uncertainty of the fit, contributions from the slightly non-photometric conditions, and the uncertainties of the detector characteristics. For comparison, the only non-saturated star in the area detected by 2MASS has a $K_s$-band magnitude of $15.36 \pm 0.19$ mag (error from 2MASS photometry) after transformation to the MKO system, compared to $15.42$ mag measured in our data.

To verify this calibration, we have re-observed MACS J0416.1-2403, Abell 2744, and a series of standard stars in the $K_s$ band in a photometric night using the Flamingos-2 near-infrared imager at Gemini South. This independent Flamingos-2 calibration falls within $0.02 \pm 0.02$ mag of the 2MASS field photometry. Aperture photometry of common sources in the combined Flamingos-2 and GSAOI data did not reveal an offset.

### 3.6.3. Limiting Magnitude

The depths of the co-added images vary across the field due to the dithered multi-chip data and can be assessed by means of the released co-added weight maps. Another factor that becomes important (compared to classical imaging) is that most of the accessible faint field galaxies in these data have intrinsic sizes smaller than the natural seeing disk ($0.5-0.7$), but larger than the AO-corrected seeing ($0.08$). Therefore, a compact galaxy will benefit more from the AO correction than an equally bright but more extended galaxy. This dependence of the field depth as a function of source FWHM is difficult to model due to the field galaxies’ mostly irregular morphologies, and we ignore it hereafter.

We cannot estimate the depth based on field stars as only a few point sources are found near MACS J0416.1-2403, none of which are near the detection limit. Instead, we use compact (yet extended) galaxies with half-light radii $\leq 0.15$ in the deep medium resolution stack (see Section 4). Based on the distribution of magnitude errors, we measure a 10$\sigma$ detection limit of $K_s = 22.4 \pm 0.2$ mag (VEGA) and extrapolate a 5$\sigma$ limit of $23.8 \pm 0.4$ mag (25.6 \pm 0.4 AB mag). The depth of the intermediate Abell 2744 data has not yet been determined, as only 25% of the data have been taken (and in below average seeing conditions).
4. SUMMARY AND DATA RELEASE

The Gemini Frontier Fields Campaign complements HST observations redwards of 1.6 μm for three galaxy clusters, MACS J0416.1-2403, Abell 2744, and Abell 370. Using GeMS/GSAOI, the first MCAO system in use at an 8 m telescope, near diffraction-limited images on angular scales larger than 1′ are obtained in the Ks band. We make the fully calibrated co-added images and weights publicly available.8 This paper describes the observations and data reduction of the first two clusters observed, MACS J0416.1-2403 (complete) and Abell 2744 (incomplete). Abell 370 is scheduled for observation in 2015.

We release different co-added images resampled to 0″.02, 0″.03, and 0″.06 pixel$^{-1}$ (high-, medium-, and low-resolution stacks). The first preserves the native pixel scale of GSAOI, whereas the other two use plate scales and image geometries identical to the HST data release (their v1.0).

Natural seeing conditions have varied during the observing nights for MACS J0416.1-2403. We provide two different versions for the high- and medium-resolution stacks, optimized for seeing (35% of all exposures) and depth (85%). For the low-resolution stack, only one deep version is provided comprised of all usable exposures, as PSF anisotropies and softer seeing become insignificant. For Abell 2744 all currently available exposures were used. Table 3 summarizes the key properties of the stacked images.

Only one NGS is available for each of the galaxy clusters and GeMS/GSAOI. This results in increasing PSF variations and FWHM as a function of separation from the NGS (Figure 8). The performance variation over the field is well

---

8 http://www.gemini.edu/node/12254
predicted based on numerical simulations, which are available in the Gemini Observing Tool. With an FWHM of $0.07 - 0.10^\prime$ we improve upon HST/WFC3’s angular resolution by a factor of two, albeit over a smaller field of view ($100^\prime \times 110^\prime$; see also Figure 9). We reach a 5$\sigma$ depth for extended sources of $K_{lim} = 25.6$ AB mag. This demonstrates that MCAO at Gemini South works well even for high galactic latitude fields where NGSs are scarce, opening a new window onto the distant universe. We have also shown that current data reduction techniques, developed for classical imaging, are well suited to this type of MCAO data.

4.1. Future Work

In 2015 and 2016, the MCAO system at Gemini Observatory will receive two very significant upgrades. First, new NGS wavefront sensors enable us to guide on $V \sim 17.5$ mag stars (currently $V \sim 15$ mag), which will dramatically increase the sky coverage and the number of targets for which triangular guide star constellations are available. Second, funding has been secured for the purchase of a Toptica (Karpov et al. 2011) laser offering increased LGS brightness, easier maintenance and operation, and lower losses due to simplified beam transfer optics.

We thank Nancy Levenson and Markus Kissler-Patig for granting us directors’ discretionary time, and the anonymous referee for the valuable suggestions. This work utilizes gravitational lensing models produced by PIs Brada, Ebeling, Merten & Zitrin, Sharon, and Williams funded as part of the HST Frontier Fields program conducted by STScI. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555. The lens models were obtained from the Mikulski Archive for Space Telescopes (MAST). The astrometric calibrations of the GSAOI data have been based on secondary reference catalogs derived from VLT/HAWK-I observations, made with ESO Telescopes at the La Silla Paranal Observatory under program ID 092.A-0472.

APPENDIX

The GSAOI pointings for MACS JO416.1-2403, Abell 2744, and Abell 370 are shown in Figures 10, 11, and 12, respectively.

REFERENCES

Ammons, S. M., Bendek, E., Guyon, O., et al. 2013, in Proc. Third AO4ELT Conf., ed. S. Esposito & L. Fini, 96 (http://ao4elt3.sciencesconf.org)
Bertin, E. 2006, in ASP Conf. Ser. 351, ADASS XV, ed. C. Gabriel et al. (San Francisco, CA: ASP), 112
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Cameron, P. B., Britton, M. C., & Kulkarni, S. R. 2009, AJ, 137, 83
Carrasco, E. R., Edwards, M. L., McGregor, P. J., et al. 2012, in Proc. SPIE, 8447, 84470N
Ebeling, H., Ma, C.-J., & Barrett, E. 2014, ApJS, 211, 21
Ellerbroek, B., & Rigaut, F. 2000, Natur, 403, 25
Eiben, T., Schirmer, M., Dietrich, J., et al. 2005, AN, 326, 432
Grün, D., Seitz, S., Brimioulle, F., et al. 2014, MNRAS, 442, 1507
Karpov, V., Protopopov, V., Clements, W., et al. 2011, in Proc. 2nd International Conf. on Adaptive Optics for Extremely Large Telescopes, 52 (http://ao4elt2.lesia.obspm.fr)
Leggett, S. K., Currie, M. J., Varricatt, W. P., et al. 2006, MNRAS, 373, 781
McGregor, P., Hart, J., Stevanovic, D., et al. 2004, Proc. SPIE, 5492, 1033
Neichel, B., Lu, J. R., Rigaut, F., et al. 2014a, MNRAS, 445, 500
Neichel, B., Rigaut, F., Vidal, F., et al. 2014b, MNRAS, 440, 1002
Owers, M. S., Randall, S. W., Nulsen, P. E. J., et al. 2011, ApJ, 728, 27
Postman, M., Coe, D., Ford, H., et al. 2011, BAAS, 43, 227.06
Ragazzoni, R., Marchetti, E., & Valente, G. 2000, Natur, 403, 54
Richard, J., Jauzac, M., Limousin, M., et al. 2014, MNRAS, 444, 268
Rigaut, F., Neichel, B., Boccas, M., et al. 2012, in Proc. SPIE, 84470F
Rigaut, F., Neichel, B., Boccas, M., et al. 2014, MNRAS, 437, 2361
Schirmer, M. 2013, ApJS, 209, 21
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163

http://files.gemini.edu/~software/phase2/release/