Non-Redundant Aperture Masking Interferometry (AMI) and Segment Phasing with JWST-NIRISS

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ABSTRACT

The Aperture Masked Interferometry (AMI) mode on JWST-NIRISS is implemented as a 7-hole, 15% throughput, non-redundant mask (NRM) that operates with 5-8% bandwidth filters at 3.8, 4.3, and 4.8 microns. We present refined estimates of AMI’s expected point-source contrast, using realizations of noise matched to JWST pointing requirements, NIRISS detector noise, and Rev-V JWST wavefront error models for the telescope and instrument. We describe our point-source binary data reduction algorithm, which we use as a standardized method to compare different observational strategies. For a 7.5 magnitude star we report a 10-$\sigma$ detection at between 8.7 and 9.2 magnitudes of contrast between 100 mas to 400 mas respectively, using closure phases and squared visibilities in the absence of bad pixels, but with various other noise sources. With 3% of the pixels unusable, the expected contrast drops by about 0.5 magnitudes. AMI should be able to reach targets as bright as M=5.

There will be significant overlap between Gemini-GPI and ESO-SPHERE targets and AMI’s search space, and a complementarity with NIRCam’s coronagraph. We also illustrate synthesis imaging with AMI, demonstrating an imaging dynamic range of 25 at 100 mas scales. We tailor existing radio interferometric methods to retrieve a faint bar across a bright nucleus, and explain the similarities to synthesis imaging at radio wavelengths. Modest contrast observations of dusty accretion flows around AGNs will be feasible for NIRISS AMI. We show our early results of image-plane deconvolution as well. Finally, we report progress on an NRM-inspired approach to

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mitigate mission-level risk associated with JWST’s specialized wavefront sensing hardware. By combining narrow band and medium band Nyquist-sampled images taken with a science camera we can sense JWST primary mirror segment tip-tilt to 10mas, and piston to a few nm. We can sense inter-segment piston errors of up to 5 coherence lengths of the broadest bandpass filter used (~250-500 μm depending on the filters). Our approach scales well with an increasing number of segments, which makes it relevant for future segmented-primary space missions.

Keywords: extrasolar planets, JWST, wavefront sensing, cophasing segmented telescopes, space telescopes, high contrast imaging, high resolution imaging interferometry, AGN, supermassive black holes

1. INTRODUCTION

Non-redundant masking (NRM) in the optical and near-IR on the ground\(^1\) has scored some conspicuous successes, opening up search spaces inaccessible to filled aperture imaging in the near-IR.\(^2-6\) NRM on a stable space platform, notably in the Aperture Masked Interferometry (AMI) mode on JWST-NIRISS\(^7-9\) will open up new scientific vistas (\textit{e.g.}, Figure 1). AMI will be used at longer wavelengths than ground-based JHK bands, so will penetrate through more dust and obscuring material. Ground-based NRM relies on adaptive optics to stabilize the atmosphere, resulting in narrow fields of view. By comparison, NIRISS’ AMI can operate with the entire 2.2’ × 2.2’ on a side detector, and mosaicing can provide far wider fields of view.

In this paper we outline two data acquisition and analysis paradigms that are first steps towards such science: first, the detection of binary point sources, at 9 to 10 magnitudes of contrast, at separations between 75 – 400 mas, and second, imaging the environs of Active Galactic Nuclei (AGNs) at moderate contrast and 100 mas resolution.

We also describe a new wavefront sensing paradigm known as “non-redundant tilting” (NRT),\(^10\) which is inspired by scientific NRM data analysis methods. We present a sketch of the novel Fizeau Interferometric Cophasing of Segmented Mirrors (FICSM) algorithm,\(^11,12\) an efficient, robust, interferometric approach that scales well with an increasing number of segments, while minimizing actuator motion and the number of exposures required. The algorithm requires Nyquist-sampled science detectors and uses filters that can be motivated by core science drivers of the mission. The FICSM algorithm is in principle feasible on several of the imaging cameras on board JWST. On JWST it is robust to initial segment tilts of the order of a few hundred mas, with a capture range of about 5 coherence lengths of the widest of the three science filters it utilizes. Operating at around 4 to 5 μm with a 5% bandpass filter places the capture range at 500 μm (wavefront piston). We note that JWST’s baselined approach to coarse phasing does not possess an operationally worked out backup strategy,\(^13\) whereas the FICSM algorithm can piggy-back off the currently baselined operational strategy for “stacking” JWST primary mirror segments to point in the same direction.\(^10\) Our approach may be useful both for JWST as well as for future segmented mirror space telescopes.

Early numerical and testbed experiments\(^11\) indicate that the FICSM algorithm can leave JWST segments with 0.75 nm rms piston and 4.3 mas rms tip/tilt, giving a total rms wavefront sensing error of about 10 nm. This value is an order of magnitude better than the mission requirement on coarse phasing, and, if this correction is asserted precisely, and gives a final Strehl ratio of 0.985 at 4 μm.

2. A DESCRIPTION OF NRM DATA

Summaries of NRM, optical, and radio interferometry can be found in the literature.\(^14,15\) We assemble some basic descriptions below.

A non-redundant array of subapertures in a pupil mask is implemented with \(N\) holes, \(\{h_1, h_2, ..., h_N\}\), placed so no (vector) baseline between the centers of two holes is repeated. The point-spread function (PSF) delivered by such a pupil mask is formed by several coherent sinusoidal fringe patterns, one from each pair of holes. A fringe formed by holes \(h_i\) and \(h_j\) is quantified by a complex visibility — an amplitude or fringe visibility, which is the degree of modulation of the fringe pattern, and a fringe phase. The fringe phase is measured as an offset of the brightest fringe from image’s centroid, which for an isolated single point source is referred to as the \(G\)-tilt or \(gradient\ tilt\)\(^16,17\) in adaptive optical terminology. Fringe phase is an angular quantity, with \(2\pi\) corresponding to one fringe period in the image plane.
NRM data is often converted to fringe phases and fringe amplitudes by Fourier transforming image plane data. Windowing the image plane data results in averaging or smoothing the visibilities (a simple application of the Fourier convolution theorem). This approach is isomorphic to synthesis imaging in radio astronomy, where the fringe phase and amplitude from each pair of antennae in the interferometric telescope is calculated by a correlator accepting inputs from each antenna. While a radio correlator uses a temporal delay to steer the phase center of the two-dish interferometer, an optical or IR array detector pixel uses an angular offset from the image centroid as a means of effecting steering. At the pixel all incoming electromagnetic fields are summed and squared in the detection of intensity. This is fundamentally the same operation as correlation with the corresponding delay. Once this is recognized, one can consider a focussed image on a focal plane array detector to be an interferogram whose Fourier transform is a two-dimensional function or array of complex visibilities. This function’s domain is the $uv$-plane of the interferometer or telescope, a space of interferometric baselines.

For an arbitrary brightness distribution on the sky a complex visibility is the product of a (complex) Fourier component of the object and a (complex) system visibility. This is more familiar when expressed in the image domain - the ideal recorded image is a convolution of the PSF with the sky brightness distribution. Let us assume that we use an ideal instrument, and that an adaptive optics system has stabilized the pistons of the wavefront over each subaperture. Furthermore, we posit that the wavefront does not possess phase errors on a scale smaller than the hole diameters. Under these conditions, when observing a point source, the fringe phase $\phi_{ij}$ measures the piston wavefront error between the two holes. A closure phase is formed by the addition of three fringe phases created by a triangle of holes, $\{h_i, h_j, h_k\}$, notably $\phi_{ij} + \phi_{jk} + \phi_{ki}$. Although piston wavefront errors change the fringe phases, the closure phases are insensitive to these wavefront errors, and depend only on source structure. Theoretically, any closure phase measured when observing a point source is perforce zero. There are $N(N - 1)/2$ fringe phases, $N(N - 1)(N - 2)/2$ independent closure phases. Recently defined kernel phases generalize the concept of closure phases in high Strehl ratio images. These phases are particular linear combinations of fringe phases that must be zero in a high quality image. The kernel phase approach relaxes the requirement of non-redundancy on the components of the aperture. We note that fringe phases are blind to symmetric structure in the sky. Therefore neither closure phases nor kernel phases are sensitive to symmetric structure in the image. Fringe amplitude information is essential for true imaging.

The stability of a space-based platform improves data quality immensely (with a concomitant increase in cost). One can apply closure phase and squared fringe visibility amplitude fitting to space-based observations of multiple point sources, as is done with ground-based data. However, the stability of space-based aperture masking enables true interferometric imaging rather than just model-fitting, since both fringe amplitudes and fringe phases are highly calibratable using point source calibrators. Ground-based optical/near-IR interferometric data do not yield good fringe amplitude calibration, so in the ground-based case emphasis is placed on phase and closure phase analysis.

Radio interferometric data usually do not yield good phase calibration, which is why synthesized radio telescope beams are constructed using the support of the complex visibility data, by dint of placing delta functions at each point in the $uv$-plane where a complex fringe visibility is measured.

Assuming a single feed per antenna, a snapshot with a multiple-antenna radio interferometer provides fringe data on baselines defined by the vector separations of the antennae. The $uv$-plane coverage of such an observation consists of a set of points (see the example of a 7-antenna coverage in Figure 4). The beam generated by this $uv$ coverage has strong sidelobes. This beam, or point-spread function, differs from that of a conventional optical/IR telescope in that it is zero at the origin of the $uv$-plane, where a zero spacing fringe would exist. A zero spacing fringe is just the total power collected by an optical/IR telescope or single-dish antenna.

Allowing the Earth to rotate the baselines with respect to the sky provides for increased $uv$-coverage. By considering all the fringes measured at a variety of positions, a radio interferometer fills in its coverage to provide a beam with fewer artefacts, but radio fringe data usually lack a zero spacing fringe. Optical/near-IR NRM data always possess the zero spacing fringe. We note that single dish data, which provides zero spacing coverage, is usable in combination with radio interferometric data, so this distinction between radio and optical/IR is not a fundamental one.

The technical problems associated with calibrating fringes in the radio bandpasses are a high level of noise generated by the electronics and detectors, and a lack of instrument stability. The former results in a meaningless...
correlation at zero signal delay between the outputs of two antennae. The astrophysically meaningful correlations between antenna outputs lie in the fine temporal scales of the received signal rather than in the total energy measured at an antenna's feed, so the DC power is discarded. In an optical/IR image, with or without an aperture mask, the total energy the telescope receives from a target is often the most interesting astrophysical quantity. An NRM interferogram's DC power is measurable, and is precisely the complex visibility at zero spacing (although it’s imaginary component is zero).

3. OBSERVING POINT SOURCE BINARIES WITH NRM

NRM observations of binary or multiple point sources rely (in principle) on calibrating the instrument response with a single isolated point source. With such calibration, the *closure phases* of an image prove to be useful variables. A real instrument observing a point source yields the instrumental contribution to all the closure phases measured using the interferometer or pupil mask. These instrumental contributions are then subtracted off from the target’s closure phases, to provide estimates of closure phases of the target.

Models of the sky brightness distribution possessing a limited number of parameters are fit to calibrated closure phases. For example a point source binary is described by three parameters: the vector angular separation \( \mathbf{k} = (k \cos A, k \sin A) \), in radians, where the position angle of the pair is \( A \), and flux ratio \( f \). The complex visibility of this model observed with a pair of holes with baseline \( \mathbf{u} \), in wavelengths, is

\[
V = \frac{(1 + f \exp(-2\pi i k \cdot u))}{(1 + f)}
\]

(we treat the sky and the interferometer as two-dimensional planes, the former requires our targets to be small in angular size). In addition to fitting fringe phases or closure phases, when conditions during an observation are stable enough one can fit the squared visibilities of all measured fringes. These visibility amplitudes may provide additional leverage to improve estimates of model parameters, although in practice they are hard to calibrate well using ground-based near-IR data.

3.1 NIRISS AMI and future space-based NRM

Detailed simulations of space-based NRM data suggest that they will be far more stable (and therefore calibratable) than ground-based data. Pessimistic estimates of thermal instabilities induced by slewing JWST from its coldest to its warmest attitudes are included in the JWST Project's Rev-T wavefront error models. Numerical estimates of binary point source contrast using closure phases and squared visibilities with a two day interval between the calibrator and target, and the models’ worst-case thermal drift of JWST’s structure, indicate a contrast of 12 magnitudes between 75 to 450 mas is achievable under these assumptions. Thus thermal drifts of the telescope wavefront are not expected to be significant obstacles to achieving scientifically interesting contrast. A pointing jitter of 7 mas in each axis was included in this simulation, as well as a center-to-corner pixel relative

Figure 1. The faint point source companion parameter space available to the non-redundant sparse aperture mask in JWST’s NIRISS instrument. It is designed to operate at 3.8, 4.3, and 4.8 µm. The distance scale at the top marked with solar system planets is shown as an angular scale at the distance of Taurus.
quantum efficiency drop from 100% to 80% (with a 5% standard deviation on the corner sensitivity), so these factors are not expected to limit NIRISS AMI point source contrast either. An observing strategy of 9 dither positions located at random within the central pixel appears sufficient to combat the uneven intra-pixel response of typical HAWAII-2RG detectors.\(^9\)

Adding random flat fielding errors with realizations of a zero-mean Gaussian distribution of pixel sensitivities drawn from a sample with a 0.1% standard deviation causes contrast to drop to below 10 magnitudes. The flat field error in each pixel was modelled as being uncorrelated with other pixels. Thus NIRISS AMI performance can be expected to improve with improved flat field knowledge. In the absence of image persistence, the effect of flat field errors could be drastically reduced by matching target and calibrator location to a fraction of a pixel.

### 3.2 The effect of bad pixels on point source contrast in NRM imaging

Bad pixels in the image domain complicate NRM data processing using Fourier methods, unless the detector sampling is fine compared to the Nyquist frequency at the bandpass in question. JWST NIRISS is Nyquist-sampled at 4 µm, so bad pixels within a few tens of pixels of an isolated target star contaminate the Fourier transform of the image with ripples. Isolated bad pixels can be tolerated, and filtered out, but the current JWST flight detectors are plagued with a growing fraction of bad pixels. Furthermore, if bad pixels contaminate adjacent pixels, then even Fourier filtering their effect out becomes difficult.

Given this concern about NIRISS' detectors, we performed a study of the effects of bad pixels on the expected contrast of NRISS NRM. We simulated a 9-point dither pattern in a 256 x 256 subarray of NRISS' HAWAII-2RG detector (at 65 mas/pixel), utilizing the discrete Fourier Transform methods outlined in,\(^26\) with the F430M filter profile at an eleven-fold finer sampling (linearly) than the detector pixel scale. We used the JWST Project Rev-V wavefront errors for NRISS (which are now packaged with the WebbPSF software package,\(^27\) and are freely available). Our pointing model used 15 mas rms errors for target acquisition as well as the dither steps, along with a 5 mas single-axis guiding jitter.

The detector readout simulation incorporates inter-pixel capacitive coupling, which created 5-pixel "plus sign" patterns of bad pixels, and an intra-pixel sensitivity that was on average down 80% at the pixel corner (with a pixel-to-pixel variation of 5%) when compared to a relative quantum efficiency of unity at the pixel center. Uncorrelated pixel-to-pixel flat field errors were distributed about unity with a Gaussian distribution with rms 0.1%.

The observation simulated was of an L=7.5 magnitude star in a 256x256 subarray (with a frame read time of 0.66 s), with 14 consecutive reads between frame resets (NGROUP=14 in JWST terminology), and no pauses between reads. Each frame is saved as a data slice (NFRAME=1).

The peak pixel value was kept below 70000 e\(^-\) in the last read. 9 dithers were executed on a 3x3 grid with 4" steps (~62 NRISS pixels). We further assumed that at each dither position, the central 7x7 pixel box around the brightest pixel was free of bad pixels. 121 integrations were performed at each dither position, with a 3 hour wall-clock-time on target (estimating observatory overheads as best as we could). A similar sequence was simulated for a point source calibrator star.

We varied the fraction of bad pixels from 0% to 5%. The bad pixels were randomly distributed, with 5/6\(^{\text{th}}\) of bad pixels in a “plus pattern”, while 1/6\(^{\text{th}}\) are distributed as individual bad pixels (Figure 2). We assumed, somewhat conservatively, that data in bad pixels are not usable.

Our data analysis procedure starts by masking out bad pixels. Then, using integer pixel shifts only, re-centering all PSFs such that their brightest pixels are co-aligned. We median all these images together to obtain a “clean” PSF representation. Then for each image, we shift the “clean” PSF image by a fraction of a pixel to align it precisely with the image in question, and substitute the particular image’s bad pixels with the corresponding values from the shifted “clean” image. We then apply a fractional shift to all images to precisely register them to a common center, and average all these clean, co-aligned images to obtain a new, and better, “clean” PSF. We repeat the cleaning process (working on the original images once more), with the improved clean PSF to substitute bad pixels in the original images. We then apply the Fourier procedures to extract the closure phases and squared visibilities from each image, then average these quantities for an estimate of the data set’s closure phases and squared visibilities.
Table 1. NIRISS AMI limiting contrast (in magnitude difference) as a function of angular separation (in seconds of arc), in the presence of bad pixels. Target and calibrator observations of a 7.5 magnitude source were simulated with between 0% and 5% of all pixels being unusable. Contrast loss of half a magnitude result from 3% of the pixels being unusable. The bad bixel distribution was modelled on that of a current JWST detector, with approximately 80% of bad pixels occurring in 5-pixel patterns (see text for details of the simulation and bad pixel distribution).

As we improve methods that mitigate against bad pixels, flat field errors, image persistence, and other real-world effects, we expect to improve our estimate of the point-source contrast we can achieve with AMI on JWST-NIRISS.

4. SYNTHESIS IMAGING WITH NRM IN SPACE

NIRISS AMI can be used to detect faint extended structure near a bright point-like active galactic nucleus (AGN). Our target is the unresolved AGN, with a “toy model” bar across it, as might be expected from some models of gas delivery. In order to develop our understanding, we simulated a 9 pixel long bar at the 65 mas NIRISS plate scale (0.585 arcseconds). The integrated flux of the bar was set to be one magnitude fainter than the AGN point source. Each pixel of the bar is approximately 22.5 times fainter than the central pixel on which the AGN falls.

Observations were simulated with an oversampling 11 times finer than the NIRISS detector pixels (on a linear scale). When simulating noise we included pointing jitter during an exposure, intra-pixel sensitivity variations, pixel-to-pixel flat field errors, read noise and photon noise. We then binned the images up to the NIRISS detector pixel scale. This procedure was based on the images created for the binary point source study described above.

We placed the brightest pixel of the target at pixel coordinates (65,65) in a 128x128 array of detector pixels (with (1,1) as the corner pixel). For the noisy case, each exposure is not perfectly centered on a pixel, since we simulated pointing errors. As a result, when we Fourier transform each data frame, the complex visibility array
displays a non-zero phase slope that reflects the lack of perfect target placement in the center of a pixel. We fit this phase slope to the phases of the complex visibility array, and subtract the resultant tilted plane from the phases of the complex visibilities. If we were to transform this zero-phase-slope array of complex visibilities back to the image plane we would have ‘Fourier-shifted’ the image to center it to sub-pixel accuracy on the central pixel of our subarray. However, we do not immediately return to the image plane, but merely record the fringe visibility amplitudes and phases at selected locations in the $uv$-plane.

These fringe amplitudes and phases are similar to radio interferometer data. However, they are easier to work with than radio interferometric fringes because of the expected stability of JWST’s images. We show the $uv$-plane coverage of our extracted visibilities in Figure 4.

We first extracted the 21 independent (or 42 Hermitian) fringe visibilities and phases at the baselines defined by the vectors between aperture mask hole centers. In noisy cases we also recorded the ‘zero spacing’ fringe, which is the ‘DC power’ or total intensity of the images. This minimal extraction discards much useful information in the NRM image. In later experiments we extracted more complex visibilities within each spodge (Figure 4). We also simulated observations at an orthogonal orientation to further improve $uv$-plane coverage, adding baselines that are not measured at a single orientation (Figure 3).

These extracted visibilities were inverse Fourier transformed (returning us to the image plane) using the MIRIAD synthesis imaging package. In radio terminology the inverse Fourier transform of the extracted complex visibilities is the dirty map. We chose the pixel scale of the dirty map to be twice as fine as NIRISS’ detector pixels, so a perfectly reconstructed bar would be 18 pixels long in processed images. We performed the same complex visibility extraction on a simulated observation of a calibrator point source. The point source image (dirty map) was normalized, and used as the beam in MIRIADs implementation of the CLEAN deconvolution routine. We performed the usual CLEAN and RESTORE operations on the target visibility data, to produce clean models and restored maps (Figure 5). The bar is evident in all images, and it is obvious (and unsurprising) that increased $uv$-plane coverage improves the quality of the recovered image, in part by reducing the prominence of sidelobes.

We also present early results from an image plane deconvolution approach to imaging extended structures with space-based NRM, inspired by a prior didactic example. Using the simulations described above, we created noisy exposures with different exposure times by co-adding individual simulated data frames with all the noise sources described above. We deconvolved co-added target images with coadded point source images with statistically similar noise properties and exposure times. No attempt was made to align images to better than a pixel. These results are encouraging in that input target structure is easily discernable in the CLEAN model files shown in Figure 6. Our suggests that sub-pixel dithering could greatly benefit extended object science with NIRISS AMI.

5. FIZEAU INTERFEROMETRIC COPHASING OF SEGMENTED MIRRORS

Many of the largest current and planned next generation telescopes employ segmented primary mirrors. Aligning the separate segments of these telescopes to form a continuous surface (cophasing) is essential for their operation. Existing methods rely on separate dedicated hardware in which certain mirrors in the optical chain must be moved or continuously monitored and actuated. Additional cost and complexity are introduced by dedicated engineering hardware. Furthermore, these methods can introduce a non-common optical path, so the solutions obtained are not optimized for the focus where it matters most: on the science camera.

We present a novel method, Fizeau Interferometric Cophasing of Segmented Mirrors (FICSM) to accomplish the cophasing of segmented mirror telescopes using sparse aperture interferometry. Using the FICSM technique, we show that mirror segments can be measured to interferometric precision using common-path science hardware with a minimal number of exposures. FICSM mitigates critical mission-wide risk for JWST, as our technique is the only operationally sketched alternative to the baseline plans to co-phase JWST’s primary mirror.

The specific scenario developed here is inspired by the use of the AMI’s non-redundant aperture mask, resulting in measurements of seven segments at a time (one for each hole in JWST’s NRM). The tip, tilt, and piston knowledge of these seven segments can be combined with full aperture imaging in the same bandpasses.
Figure 3. Left: The absolute value of the array of complex visibilities derived from JWST-NIRISS’ NRM image, on a square root display stretch. This array is calculated at a single wavelength of 4.6\(\mu\)m. With the 5\% to 8\% bandwidth filters (F380M, F430M, and F480M) the ‘splodges’ will be stretched radially by a small amount, and look slightly elliptical. Gaps in the spatial frequency coverage (uv) coverage are apparent at left. The target’s spatial frequencies in these gaps are not measured by a single observation. Right: The left panel’s single observation complex visibility array is now shown in blue, underneath a second observation (red) taken after JWST has rotated 60\(\degree\). JWST’s orbital motion can induce such a roll — roll during a single visit is likely to be limited to only a few degrees. These two observations now cover most of the uv-plane, and enable good synthesis imaging with almost complete uv coverage. Since each ‘splodge’ of signal at the longest baselines (i.e., at the furthest distance from the center) subtends an angle of approximately 11.5\(\degree\) at the uv plane’s origin, tolerances on the spacecraft roll can be of the order of a few of degrees either way without compromising the science.

Figure 4. From left to right: (1) uv-plane coverage resulting from 21 baselines (along with their Hermitian counterparts) derived from JWST-NIRISS’ NRM image. The units shown in this uv-plane are arbitrary — it is the geometry that is relevant. (2) uv coverage when nine fringes are extracted from each splodge, with the same orientation of the telescope as in the left panel. (3) The addition of nine fringes per splodge after a 90\(\degree\) rotation of the telescope improves uv coverage further. (4) The addition of 41 fringes per splodge and the ‘zero spacing’ or ‘DC’ fringe, becomes more important when noise is added to the simulation.
Figure 5. A simulated JWST NIRISS AMI observation of an AGN with a symmetric bar. CLEAN models (top) and restored images (bottom) of a 0.585 arcsecond bar (9 AMI pixels, 18 pixels in these MIRIAD-generated images), with an integrated brightness one magnitude fainter than the point-like AGN are shown. A square root stretch is used in every panel. The target is symmetric, so both fringe phases and closure phases are blind to its structure. Using stable fringe amplitude information such images can be extracted without ambiguity. The four images were generated using the four sets of fringes with baselines shown in the previous figure. From left to right: (1) One baseline per NRM hole pair results in a beam with strong sidelobes. (2) The improved uv coverage provided by using 9 fringes per NRM hole pair suppresses some of the image artefacts caused by the sidelobes seen at left. (3) Observing with two orthogonal orientations and 9 fringes per NRM hole pair produces a more faithful image. Panels 1 – 3 are noiseless simulations. (4) A 20 minute integration (half at each orientation) with realistic noise. Using 41 fringes per baseline, as well as the ‘zero spacing’ fringe, permits a reconstruction of the faint bar. The latter simulation includes all the sources of noise described in the text. Both target and calibrator images contained pointing jitter of 7mas per axis rms during the observation. A simulated point source observation — noiseless for (1)–(3) — was used to create the beam (PSF), using the same uv coverage as shown in the previous figure. For the noisy simulation in (4) this required an extra minute of integration time (per orientation) on the calibrator. In typical radio interferometric data analysis the beam is generated by using the support of the uv coverage of the target data. We attempted such a strategy, but found that a beam generated from the dirty map of the point source, appropriately normalized, produced far better images. Instrumental noise and instabilities prevent such strategies from being used on radio data.
Figure 6. Deconvolution in image space, using the Clark version of CLEAN as implemented in CASA, of simulated data with increasing exposure times. The output CLEAN models are shown. Two different target orientations were used - a horizontal bar and a vertical bar. The same contrast relative to the central point source as above, and the same bar size (0.585 arcseconds, or 9 NIRISS pixels) were used. The simulated images were the same as those of the previous figure. This initial investigation co-added individual noisy images to create longer exposures times, and better signal-to-noise ratios. Image centering is done only to the brightest NIRISS pixel, so these results will be capable of being improved. From left to right: 1, 3, 10, and 28 exposures coadded to create both the calibrator PSF as well as the target PSF. Each exposure was 2.63 seconds, so the total exposure in each image is, from left to right, 2.63s, 7.89s, 26.3s, and 73.6s. The point source AGN nucleus is 7.5 magnitudes, and the wavelength simulated is 4.5 µm. All images are displayed on an identical square root stretch between 5000 and -200 arbitrary intensity units. Using the NIRISS AMI bandpasses (5-8%) is unlikely to change the results noticeably.

to derive a full solution of the JWST wavefront without employing focus diversity, since the pupil diversity will likely enable unambiguous phase retrieval over the entire mirror. Alternatively, groups of a few (3-4) segments chosen to create non-redundant baselines between them can be defined by imparting a unique common tilt to these segments. The FICSM algorithm can then be applied to each group of segments. Different group PSFs that lie close to but not overlapping each other can be measured in one exposure. This parallelizes FICSM data acquisition, and speeds up telescope commissioning. This parallelized method is the non-redundant tilting (NRT) method of segment cophasing. This segment tilting exercise has been demonstrated at Keck. We note that such groups of segments are likely to be constructed during early phases of JWST’s commissioning, so the FICSM algorithm can be applied to these groups to cophase the segments as they are given a common pointing. This would obviate the necessity of performing a separate dedicated coarse phasing sequence during commissioning. We note that the FICSM algorithm with NRT is feasible with NIRCam’s long or short wavelength channels, as well as MIRI. This enables simultaneous wavefront measurement at multiple field points. The capture range of FICSM is approximately 5 coherence lengths of the widest filter used for piston phasing.

We assumed an initial state of JWST’s primary mirror segments of less than 150 µm piston and 0.5 arcseconds of tilt, and that the requirement on coarse cophasing is that coarsely phased primary mirror should possess a total wavefront error of less than 100 nm rms, as specified in publicly accessible literature at the time of our initial study. Detailed descriptions of the FICSM algorithm are found elsewhere. The essence of the FICSM algorithm follows.
Table 2. Specifications used for simulations

<table>
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<th>Parameter</th>
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<td>Hole Diameter</td>
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<td>Number of Holes</td>
<td>7</td>
</tr>
<tr>
<td>Plate Scale</td>
<td>65 mas</td>
</tr>
<tr>
<td>Narrowband Filter: Central Wavelength</td>
<td>4.05 µm</td>
</tr>
<tr>
<td>Narrowband Filter: Bandwidth (FWHM)</td>
<td>1%</td>
</tr>
<tr>
<td>Broadband Filters: Central Wavelengths</td>
<td>4.30 µm and 4.8 µm</td>
</tr>
<tr>
<td>Broadband Filters: Bandwidth (FWHM)</td>
<td>5% and 8%</td>
</tr>
</tbody>
</table>

Piston and tip/tilt introduce phase distributions and amplitude decreases to the spatial frequency spectrum of the interference fringes produced by an NRM. By measuring these, we can get measurements of both piston and tip/tilt to interferometric precision.

In the broad bandwidth case, both piston and tip/tilt introduce a phase distribution and an amplitude decrease in the complex visibility array. However, in the narrow bandwidth (monochromatic) case, piston introduces only a constant phase, and no amplitude decrease, while tip/tilt leads to a phase distribution and amplitude decrease. In order to distinguish between the two effects, the tip-tilt is measured and removed prior to measuring the piston. This can be accomplished by measuring the phase slope, which can be directly related to the mean tilt on that baseline (the average tilt on the two mirrors that make it).

Piston errors have two effects on the complex visibilities, which occur on different scales. Pistoning a mirror a fraction of a wavelength introduces an approximately constant phase to each frequency associated with that mirror. Since the image is not monochromatic, over larger distances the fringes at different wavelengths move out of phase. This produces a distribution of phase with spatial frequency and a decrease in amplitude. This motivates the separation of the piston measurement into two steps; a coarse measurement based on the shape of the phase and amplitude distributions gives estimates to within a wavelength, which are used in a fine measurement based on the average fringe phase.

To further ensure that the piston measurement is accurate, two broadband images at different observing wavelengths can be used independently to produce two measurements. By comparing these, errors in either step of the piston measurement can be flagged prior to moving the mirrors. The fine piston step will converge to the nearest integer multiple of a wavelength from the coarse value. If the coarse measurement is a few wavelengths from the true value, the fine piston measurements will not agree. The difference between the two measurements can be used to recover the actual piston, albeit with reduced accuracy.

1. An image is taken, with a narrow bandwidth filter
2. The narrowband image is used in a tip/tilt fitting program, to measure tip/tilt
3. The mirrors are adjusted to remove the measured tip/tilt
4. Two images are taken, with broad bandwidth filters at different wavelengths
5. The new images are used in a piston fitting program, where independent measurements are performed on each
6. The piston measurements are compared. If they do not agree, the difference between them and the wavelength difference are used to recover the correct piston
7. The mirrors are adjusted to remove the measured piston
8. The method is repeated once, to remove residual errors.
Figure 7. Residual tilts and piston after fitting with FICSM, from 20 simulated phasing attempts with a JWST-like aperture mask. Noise processes added were: photon noise from $10^9$ photons, 0.1% flat field errors, 0.2 pixels of jitter. In all cases, the residual wavefront errors were well below the requirement from coarse phasing.

Figure 7 shows the efficacy of this method using 30 statistically independent starting points in a numerical simulation. Several types of noise were simulated, including flat field errors, jitter and photon noise. The instrument parameters and filters used are presented in table 2. It is expected that the NRT method discussed briefly above will allow this technique to be used with any of the science cameras on JWST. For this reason, all simulations were performed using current specifications of the JWST NIRCAM instrument, planned aperture mask and NIRCAM filter profiles.

It is important to note that some aspects of the simulated aperture mask differ from those of the actual mask (0.6 m diameter circular holes were used instead of 0.8 m diameter hexagonal holes). The discrepancy in setup for our simulations was motivated by clarity for the images and plots produced; similar outcomes should apply to both cases.

As seen from Figure 7, mirror tilts were reduced from as much as 0.5 arcseconds to give an rms residual tilt of 3.2 mas, corresponding to less than 5% of a single pixel on the camera. Further, the accuracy of the method appears constant in this range. Figure 7 also shows the high accuracy expected from piston phasing with FICSM. Starting from initial pistons of up to 150 microns, the rms residual piston after application of the algorithm was 0.97 nm. However, this has been heavily skewed due to the presence of a few outliers up to 10 nm. These measurements result from disagreement between the measurements in the fine piston step, leading to them being flagged as possibly inaccurate. A further application of the method on any flagged measurements will remove these outliers, leading to an rms residual piston of 0.06 nm.

Notably, even without the removal of these points, the rms total wavefront error was 3.7 nm for these simulations, considerably better than the $\sim$100 nm requirement.

ACKNOWLEDGMENTS
We thank P. A. Lightsey, N. Rowlands and M. Vila for helpful information. This work is supported in part by the National Science Foundation under Grant AST 08-04417, NASA grant APRA08-0117 (NNX11AF74G), JPL grant No. RSA 1330128, Space Telescope Science Institute’s Director’s Discretionary Research Fund, and grants from the Australian Research Council. We also thank Ron Allen, John Hutchings, Doug Johnstone, Jin Koda, and Urvashi Rao for insightful questions and inspiring discussions.

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Visible/infrared spectrometer for EChO  
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J. H. Burge, D. W. Kim, College of Optical Sciences, The Univ. of Arizona (United States)

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C. Re, Univ. degli Studi di Padova (Italy) and Univ. degli Studi di Parma (Italy); R. Roncella,  
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Introduction

A broad range of optical, infrared, and millimeter wave space telescopes and instruments are enabling a dramatically increased understanding of the origin and structure of the universe, the numbers and characteristics of exosolar planets, and other questions of profound astrophysics importance. The same foundational instrument technologies are also providing increasingly detailed solar studies and enabling new lunar and planetary missions. This conference, part of a continuing series of biannual symposia, was structured to provide a broad overview of these concepts and technologies, including performance and early results from recently launched systems, status reports on planned systems, and insights into new technologies and concepts for future systems.

The conference consisted of a total of 96 oral presentations divided among 19 sessions that were conducted over a total of six days. These were supplemented by a one day poster session that included 87 poster presentations.

Currently active and planned missions addressed within the conference included:

- Astrophysics: Current and recent missions included Hubble, Spitzer, AKARI, and Herschel. Planned missions under active development included GAIA, JWST, WFIRST, EUCLID, EChO, and several Explorer class missions.

The Conference explored the current state of the art of space telescope and observatory concepts, technologies from the visible through the infrared to millimeter wave. The meeting elicited ideas responsive to current risks and opportunities. Papers were presented that addressed multiple topic areas, including the following:

- Optical, IR, and millimeter wave astronomical space telescopes and instruments including their on-orbit performance:
  - Concepts and technologies for exoplanet detection and characterization
  - Approaches to increasing insight into dark matter and dark energy and the origin, evolution, and structure of the universe
- Innovative telescopes and instrumentation for solar system studies:
  - Solar astrophysics
  - Structure and evolution of the constituent bodies, large and small, of the solar system
- Highly innovative space telescope and instrument concepts
- Smaller and more affordable mission concepts:
  - Technology demonstrations
  - Expanded performance of space telescopes against additional science questions
Life cycles and costs that support student involvement while producing valuable science

- Enabling subsystem and component technologies for space telescopes, such as:
  - Innovative real time metrology and wavefront sensing and control
  - Technologies and architectures for achieving high thermal stability of large telescopes
  - New detector and sensor technologies
  - Enhanced spectrometers
  - Coating technologies

- Approaches that leverage results and programs in other areas:
  - Balloon and sounding rocket astronomical observatories and instruments
  - Synergism with science missions in other spectral regions
  - Earth observation concepts and technologies

- Systems engineering for space telescopes, to include:
  - System modeling of telescopes and space observatories and simulations of their performance
  - Ground fabrication, integration, and testing of telescopes, instruments, and complete telescope structures and observatories

Mark C. Clampin
Giovanni G. Fazio
Howard A. MacEwen
Jacobus M. Oschmann, Jr.