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Report on the ESO workshop

VLTI and ALMA Synthesis Imaging Workshop

held at ESO Headquarters, Garching, Germany, 9–12 January 2023

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Supported by the EU-funded Opticon RadioNet Pilot (ORP), the VLTI and ALMA Synthesis Imaging Workshop was held at ESO Headquarters on 9–12 January 2023. The hybrid format of the workshop allowed one hundred registered participants from six continents to gather, bringing with them a wide range of expertise: theorists, observers and data scientists. The need for such a broad range of skills originates in the workshop's focus on interferometric image-reconstruction algorithms applied to data from instruments across the optical/infrared and millimetre/radio domain, allowing the diverse communities to build synergies and explore innovative techniques applicable to both regimes. The three-day workshop was organised into six topics, each followed by discussion. Four distinguished lecturers established a shared understanding of data analysis processes (including data characteristics, handling and reduction) and presented innovative techniques employing artificial intelligence used by the two communities. Traditional imaging methods, as well as techniques for morphology fitting and other popular tools and methods, were presented and discussed by keynote speakers. Given the nature and goals of the workshop, most of the speakers were invited. ORP supported a number of speakers as well as students to allow growth within a young community in the rapidly evolving area of image analysis.

Motivation

The Very Large Telescope Interferometer[1] (VLTI) and the Atacama Large Millimeter/submillimeter Array[2] (ALMA) are two leading facilities employing synthesis imaging. Their data require extensive processing and analysis to align and combine the signals from multiple telescopes so as to produce high-quality images. Both observatories deliver high-resolution imaging of celestial objects and multi-wavelength observations. VLTI and ALMA data alone have provided breakthroughs in astronomy, widening our knowledge of the Universe in regards to several hot topics, such as the formation of stars and extra-solar planets, the distribution of molecular gas in the Universe, the evolution of galaxies, and the high-redshift Universe. Over the past five years interest has grown within the scientific community in employing VLTI and ALMA data to derive high-impact results (for example, Bohn et al., 2022).

Because of the low information content of interferometric data, the generation of images is a complicated and, in some cases, poorly defined procedure. VLTI images are typically reconstructed by minimising a cost function that includes both the data and some prior information on the object brightness distribution. ALMA data are characterised by a higher sampling of the uv plane compared to the VLTI, given the larger number of interferometric elements. ALMA's strategic design and location and its ability to track phases more accurately than the VLTI allow for a higher information content in the images. Nonetheless, images are reconstructed by converting the calibrated visibility data, often with iterative deconvolution algorithms to remove artefacts and to enhance the resolution of the final image. Challenges in image deconvolution include preventing thresholding in the deconvolution algorithm, continuum subtraction, the detection and deconvolution of extended emission, separating point-like sources from diffuse emission, and weak signal detection.

The VLTI and ALMA Synthesis Imaging Workshop[3] emphasised strengthening the links between the optical/infrared and radio/millimetre communities, with the aim of improving and exploring algorithms which allow imaging enhancements in both wavelength regimes, and which can be applied to multiple facilities. With this scope, sessions were structured around subject areas, including image deconvolution and enhancement, artificial intelligence, astrophysical parameter estimation and feature extraction, data visualisation and exploration, analysis and interpretation. It is worth mentioning that assessing the quality of the images is highly relevant to bench-marking image reconstruction algorithms. However, so far no systematic studies have been conducted on the selection of a robust metric for quality assessment, and no studies have been conducted that include similar algorithms applied to both optical/infrared and radio/millimetre data sets.

In the optical/infrared regime, experience of using Bayesian imaging techniques has been accumulated (for example, Buscher, 1994; Baron, Monnier & Kloppenborg, 2010; and see Thiébaut & Young, 2017 for a review), and they are now routinely applied. In the radio/millimetre, only the maximum entropy method of Cornwell & Evans (1985) has been employed within the 'tclean' task in the Common Astronomy Software Applications package (CASA; Casa Team et al., 2022). Other Bayesian estimation methods for imaging are advancing, and some packages based on artificial intelligence applied to ALMA (for example, Di Mascolo et al., 2023; Delli Veneri et al., 2023; Tychoniec et al., 2022) show promising results and are suited to the new generation of ALMA (Guglielmetti et al., 2022). One of the goals of this workshop was to explore the usability of such techniques in situations with very sparse sampling of spatial frequencies (for example, Arras et al., 2022), which is typically the case with optical interferometry observations, but also extends to the radio and millimetre, where the challenges lie mostly in reaching a high image dynamic range. In addition, developing procedures for speeding up the deconvolution algorithm is essential, especially for future facilities such as the Square Kilometre Array (Dewdney, 2009) and the forthcoming ALMA upgrade (Carpenter et al., 2023).

The objectives of the workshop were met. Collaboration was fostered among communities addressing similar problems and employing similar techniques, yet having limited practical overlap. The exchange of recent technical and scientific advances was facilitated, promoting knowledge-sharing and cross-pollination of ideas. Lively discussions about collaborative initiatives were encouraged, leading to the identification of opportunities for joint efforts and endeavours. The groundwork for collaborative progress and mutual benefit in the field of synthesis imaging was laid and algorithms applicable to both regimes were identified.

Introduction to the VLTI and ALMA

The VLTI and ALMA observe in the wavelength ranges of about 0.002–0.013 millimetres and 0.3–8.6 millimetres, respectively.

The VLTI is composed of four 8.2-metre Unit Telescopes, supplemented by 1.8-metre movable Auxiliary Telescopes, at Paranal Observatory. The maximum distance (baseline) achievable by the Unit Telescopes is about 130 metres, while the Auxiliary Telescopes support a 200-metre longest baseline. These longest baselines allow us to detect astronomical objects with milliarcsecond resolution. The fields of view of the Unit and Auxiliary Telescopes are 30 arcminutes and 4 arcseconds, respectively. Adaptive optics technology is used to correct for atmospheric distortions, resulting in clearer and sharper images.

ALMA is equipped with 54 12-metre and 12 7-metre antennas located on the Chajnantor plateau in the Atacama Desert. The plateau has an extension of about 10 square kilometres, and the 12-metre antennas are sited on 'pads' — individual antenna stations that provide power, signal and network connection in addition to a stable foundation — such that they can be moved into different configurations. The dimensions of the most extended and most compact configurations are 16 kilometres and 160 metres, respectively. The longest baseline allows a resolution as sharp as 20 milliarcseconds to be achieved at a wavelength of 1.3 millimetres. The fields of view of the 12-metre and the 7-metre antennas are about 19 arcseconds and 33 arcseconds, respectively, at a wavelength of 1 millimetre. Mosaicking is used to achieve uniform sensitivity over larger regions. Atmospheric distortions are calibrated with water vapour radiometers that measure the amount of water in the line of sight, and a technique known as fast-switching phase referencing to mitigate the atmospheric phase fluctuations (atmospheric phase correction).

Complexities of image analysis

According to the Rayleigh criterion, the angular resolution, θ, of an imaging system (i.e., its ability to distinguish objects on the sky separated by some angular distance) is directly proportional to the observed wavelength (λ) and inversely to the antenna's diameter (D), such that $\theta \sim 1.22\ \lambda/D$. Therefore, for a given telescope size, higher resolutions are obtained in the optical/infrared regime than at millimetre/radio wavelengths. To obtain images at higher angular resolution, signals from several telescopes are

Figure 1. The VLTI is located on top of Cerro Paranal, in the Chilean Atacama Desert. The 8.2-metre UTs are visible at the image centre. On the right of the UTs, the 1.8-metre ATs are in their characteristic spherical dome shells. The ATs are movable and can be relocated on 30 different observing stations. To perform interferometry, the signals from the several telescopes are combined with varying array configuration and number of telescopes.

combined through interferometry, emulating a telescope with a larger diameter (aperture synthesis). Coherence theory, i.e. a statistical description of the electromagnetic radiation, is used to analyse the degree of correlation between pairs of measurements. Note that for N telescopes, there are N(N–1)/2 of those measurements, one for each baseline. The spatial coherence (correlation) of the signals illuminating telescope pairs is given by the van Cittert–Zernike theorem that provides a relation between the sky brightness and the spatial coherence function. Specifically, the geometrical (or time) delay of the signals from the pair of antennas is compensated for before reaching the correlator using a technique known as delay tracking. The correlator is a device capable of multiplying together the signal voltages produced by the antennas and time-averaging the signal, thereby producing the interferometer fringe pattern. The correlator output is proportional to the complex visibility function, which is the Fourier transform of the sky brightness integrated over the sky. Calibration procedures are applied to estimate the complex amplitude of the visibility function, which contains both the amplitude and the phase information of the correlation between the antennas. The amplitude of the complex visibilities is proportional to the brightness of the object being observed, while the phase is related to the position of the object in the sky. In the main, point sources of known flux density and position are used during the observation to allow the determination of the instrumental parameters for calibrating the visibility measurements.

Since the van Cittert–Zernike theorem provides the mathematical relationship between the detected complex visibility and the brightness distribution of the celestial source, this pivotal theorem forms the basis of Fourier synthesis imaging. It uses the inverse Fourier transform of the calibrated complex visibilities (in units of Jy, in the case of ALMA) to produce an image of the source brightness distribution (flux density per unit solid angle, or beam volume in the case of ALMA). An array of several antennas (or telescopes) measures the visibility function for each baseline. The sampling of the visibility function is limited by the number of antennas or telescopes, the observing time and the pervasive presence of noise in the measurements[a]. The inverse Fourier transform of the sampled (and noisy) visibility function provides an image I^D (the dirty image) that is corrupted by the instrumental point spread function, known as the dirty beam[b]. The sky brightness distribution, which is affected by the antenna's primary beam, can theoretically be obtained by deconvolving I^D from the dirty beam. However, to control image formation, the sampling function is traditionally (density) weighted and tapered to constrain the shape of the dirty beam. While tapering implies smoothly weighting down the highest spatial frequencies to suppress sidelobe effects, the density weigthing is employed, for example, to optimise the density

Alma Observatory, Guy Wenborn

Figure 2. ALMA is located on the Chajnantor Plateau in Chile's Atacama Desert. At the bottom-center of the image, one can see a set of the fifty-four 12-m atennas. To the left, in the bottom-center, the Atacama Compact Array (ACA) is composed of twelve 7-m antennas and four 12-m antennas. Triangular antenna stations are visible in the image. Each of the 192 available stations can house an antenna, allowing for several array configurations.

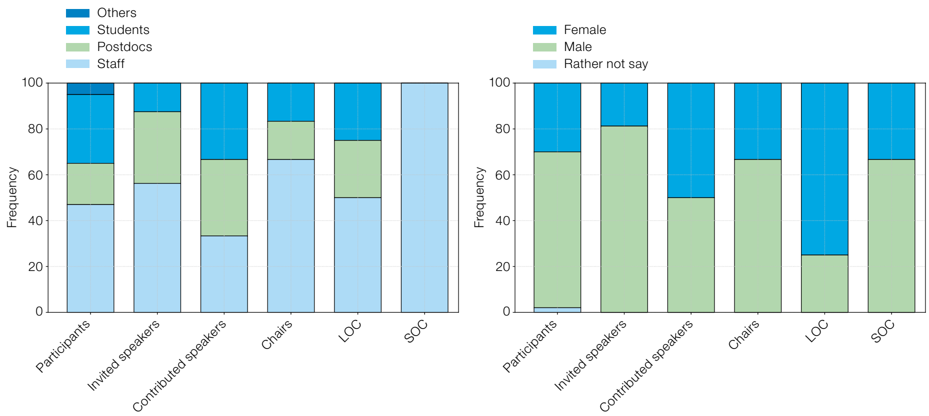

Figure 3. Demographic distributions of the career stage (left) and gender (right) between participants, invited and contributed speakers, Chairs, LOC and SOC.

of sparse sampling (long baselines) with respect to the dense sampling at the short baselines contributing to I^D. This uniform weighting scheme allows one to achieve an improved angular resolution compared to employing no density weights (a natural weighting scheme). Often tapering occurs at schemes in between these two extremes. Gridding is frequently used to calculate I^D as discrete representations in image pixels. The visibility measurements (sampled and weighted) are interpolated to a regular grid employing the Fast Fourier Transform algorithm, providing an estimate of I^D (the dirty map). The ill-posed problem in image reconstruction is summarised by the measurement equation $\tilde{I}^D = B * I + n$, where B, I and n are the dirty beam, the true sky representation and the additional noise, respectively. Additional imaging intricacies include, for example, the heterogeneous sensitivity of the instruments to point sources and extended emissions, chromatic aberration, azimuthal smearing, and position-shift as a result of distortion across the field of view.

Sparse sampling complicates the imaging process because of gaps in the visibility measurements. For this reason, VLTI measured visibilities are used to derive closure phases, combinations of phase differences between three or more telescope elements of the array. The closure phases are used as constraints in the image reconstruction process with the aim of improving image accuracy and quality.

The interpretation of aperture synthesis data is a complex process, in which the uncertainties associated with image reconstruction are always present. Sparse sampling, instrumental responses and the pervasive presence of noise affect the data. The inverse problem of extracting astrophysically interesting information from the observed sky brightness is ill-posed, in the sense that the solution is not unique, or is not stable under perturbations in the data. Perturbation caused by noise can create large deviations in the solution being sought.

Major theme

On the first day of the workshop, proceedings were led by two keynote speakers, Urvashi Rao Venkata and Jean-Philippe Berger, who delivered an extensive retrospective of image reconstruction methods. Their presentations aimed to foster mutual understanding and facilitate the development of expertise in synthesis imaging within the two communities.

Because of the significant influence this groundbreaking research and its developments have had on various scientific domains, artificial intelligence was allocated two specialised sessions. Each of these sessions commenced with a keynote introductory talk aimed at offering a comprehensive grasp of machine learning and information field theory. Both Giuseppe Longo and Torsten Enßlin demonstrated the evolution of the field over the past decade and emphasised the importance of developing data scientists as an invaluable and essential resource for addressing contemporary astronomical challenges. Further themes included traditional reconstruction methods, advanced statistical methodologies, model fitting and tools at the interface between the data and imaging.

Half-day sessions comprised talks followed by 30–60-minute moderated discussions that all participants were invited to contribute to. The participants engaged in a hybrid format, and a dedicated Slack workspace facilitated further discussions, exchanges of ideas, and sharing of material. Synergies between different teams were forged and plans for collaborative surveys were developed.

Summaries of talks and highlights from sessions

Five sessions were organised over three days on a comprehensive range of topics.

Machine learning (ML) applications on the VLTI and ALMA were shown to successfully reconstruct high-resolution images from sparse and incomplete measurements. The CASSINI-Automap technique exploits the compressibility of a signal with neural networks. The networks are designed with adaptive activation functions to find an optimal mapping system between the infrared interferometric data and the reconstructed images. The ORGANIC method utilises generative adversarial networks for the reconstruction of objects from VLTI data. This class of deep learning models is used to learn the underlying distribution of the object being imaged from the interferometric data, while an input astrophysical prior is used for regularisation. DeepFocus is a high-performance and deep-learning pipeline, whose strength is shown when applied to ALMA cubes. By integrating images captured at different frequencies, DeepFocus effectively speeds up the deconvolution process and performs source detection and characterisation. It is capable of obtaining sharper and more detailed images of objects at different spatial frequencies. The ML algorithms have the potential to enhance the quality and fidelity of object reconstruction in interferometric imaging, enabling better understanding and analysis of astronomical data.

ML was shown to be used mostly as a supervised algorithm to infuse knowledge of the astrophysical object into the image reconstruction using mainly synthetic datasets generated from astrophysical simulations. A striking advantage resides in the increase in computation speed with respect to other methods.

Following this session, participants delved into traditional imaging techniques along with the latest developments in these historical methods: POLCA, OImaging, CASA, GILDAS, SQUEEZE are well-established numerical methods and integrated into user-friendly tools. Aspects of these techniques have been found to have usability in both regimes and to allow for the sharing of information and knowledge between communities, as OImaging can be customised for the use of ALMA, opening the doors for further implementations with other algorithms.

The subsequent half-day was specifically allocated to model fitting, an image reconstruction approach tailored for highly sparse data. During this session, various forward modelling algorithms were discussed, including PMOIRED, uvmultifit, RHAPSODY, and other techniques designed to address the challenges posed by interferometric data. These methodologies enable precise fitting of models to the data, offering valuable insights and enhanced reconstruction capabilities for sparse datasets. Also in this case, discussions revealed the potential for algorithms applicable to both observatories. The remaining day was fully reserved for information field theory (IFT), an artificial intelligence methodology to recover field-like quantities from finite and noisy data. IFT is based on Bayesian inference in the context of field theory. The Numerical Information Field Theory (NIFTy) library was shown to be a powerful computational tool, designed to handle and analyse numerical data within the IFT framework. This valuable resource provides a comprehensive set of functionalities to enable signal processing, including data manipulation, numerical operations, and advanced statistical modelling. Several presentations followed, on a large variety of applications: VLBI, ALMA, GRAVITY and direction- and time-dependent self-calibration. IFT came out as a strong candidate for a general algorithm applicable to VLTI and ALMA data.

The last day session was dedicated to popular tools (such as TP2VIS) and new methods. The TP2VIS software package is designed to effectively merge and analyse data from different observational techniques to achieve a more comprehensive view of astronomical sources. A very interesting assessment of imaging quality and parametric modelling for ALMA data showed valuable insights for VLTI data as well. The workshop concluded with applications of advanced statistical techniques to ALMA data. In a serendipitous search of high-*z* quasars in ALMA cubes, multiple algorithms are used and evaluated to detect and differentiate faint spectral lines employing a blind search technique. Moreover, the use of SupReMo enables the study of the early evolution of galaxy clusters using sparse data; supported by multiwavelength observations, SupReMo reconstructs the cluster properties, such as mass, velocity dispersion, and density profile, with the goal of improving our understanding of cluster evolution. Lastly, a regularised maximum likelihood approach to continuum data highlighted the significance of employing Graphics Processing Unit (GPU) for ALMA image deconvolution. The advancement of machine learning has played a pivotal role in fostering the development and applications of GPUs in astronomical data analysis. GPUs are known to improve the speed of image processing thanks to their performance in several concurrent calculations and to memory optimisation when handling large datasets. The first published application of GPUs on ALMA imaging is from Delli Veneri et al., 2023. The application of GPUs to VLTI data for image reconstruction is not a novelty (see Baron & Kloppenborg, 2010).

Main conclusions and ways forward

The workshop was successful in bringing together two communities working on related topics, but with few connections. The meeting exposed some methods used by one community which could be used by the other, with artificial intelligence techniques playing a significant role. For instance, regularised maximum likelihood has been used for 20 years in optical interferometric image reconstruction and provided popular imaging tools in multiwavelength astronomy. During the workshop, an efficient regularised maximum likelihood approach applied to ALMA continuum observations was presented. The technique made use of GPUs for fast image reconstruction. Prior information

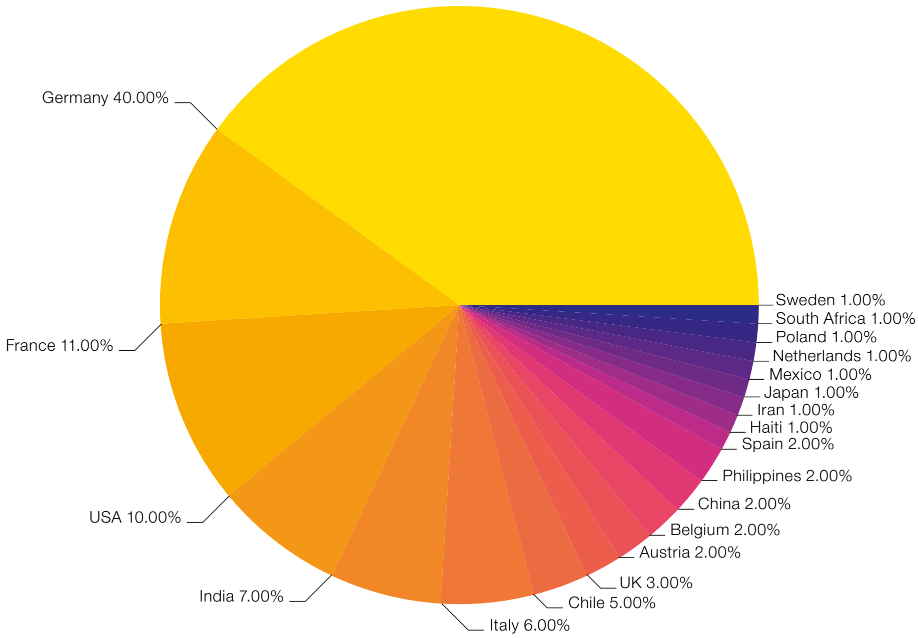

Figure 4. Geographical representation of attendees, highlighting the international diversity of the conference.

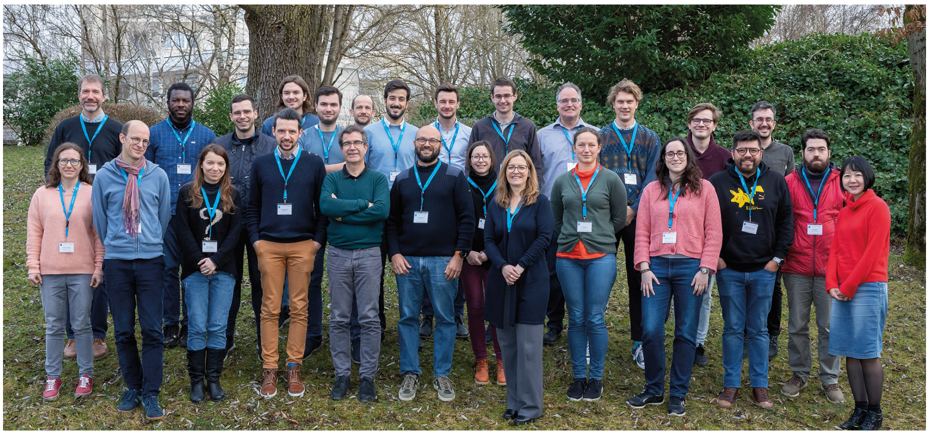

Figure 5. Participants at the VLTI and ALMA Synthesis Imaging workshop.

was incorporated in the image reconstruction process as a regularisation term to improve quality and reliability. The maximum likelihood approach has the advantage of providing a point estimate and its uncertainty, but in a parameter space of moderate size. Conversely, IFT (a Bayesian based technique) has the advantage of expanding the solution to a multi-dimensional parameter space and it is applicable to large data volumes. IFT computes the volume under the estimated parameters from which the covariance matrix is estimated to provide a robust uncertainty quantification. The IFT approach has been successful in radio imaging and can potentially be applied to optical data. Dissemination of ideas and methods can be achieved by fostering data format unification or developing data converters. These efforts would streamline the exchange of reference datasets and enable straightforward comparison of results. The advent of machine learning techniques requires large learning and control datasets and having fewer data formats ensures that datasets can be re-used in that context. Fewer data formats also make sure data challenges can be easily organised.

Demographics

The Scientific Organising Committee aimed at having a fair representation from the two communities in terms of speakers and genders, as well as including a wide range of techniques and research methodologies developed for aperture synthesis and their impact on scientific results. The cross-disciplinary programme was designed to combine insights and expertise from different communities to address the complex problem of image analysis and explore new paths to generate innovative solutions. For each of the six sessions, a reviewer led the discussions to promote a climate of creative collaboration and to support open-minded exploration of ideas. A well-balanced participation, including senior scientists, postdocs and students, was designed. Female participation and contributions reflected the overall demographic of the field — 31% of the participants, 20% of invited speakers, 30% of session chairpersons — and the distribution of speakers between young researchers, postdocs and staff was well balanced (see Figure 3). The attendees exhibited a diverse demographic composition, spanning five continents, with the following percentages (see Figure 4):

- 69% Europe (Germany, France, Italy, UK, Austria, Belgium, Spain, the Netherlands, Poland, Sweden)
- 13% Asia (India, Japan, Iran, China, Philippines)
- 12% North America (US, Haiti, Mexico)
- 5% South America (Chile)
- 1% Africa (South Africa)

The workshop had a high level of participation during each session, with 100 participants in total (Figure 5). Most of the in-person participants came from European countries, the extremes overall being 40% from Germany and 1% from Japan. The workshop was held in the second week of January, limiting face-to-face international participation. However, the hybrid format of the workshop allowed for a level of global participation that enriched the overall discussion and networking opportunities. We attribute this success both to the compelling nature of the subject matter, which draws researchers at all career stages, and to the generous support that kept the cost of attendance relatively low.

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Links

[1] VLTI webpage: https://www.eso.org/sci/facilities/paranal/telescopes/vlti.html
[2] ALMA webpage: https://www.eso.org/sci/facilities/alma.html
[3] Workshop website: https://www.eso.org/sci/meetings/2023/VLTI-ALMA-IW.html

Notes

[a] Earth's atmosphere may introduce phase errors, especially at longer wavelengths. ALMA mitigates this effect by employing atmospheric calibration and phase referencing. Other sources of random noise limiting the accuracy of the amplitude and phase information are thermal noise, shot noise, environmental noise, quantum noise, digitisation and crosstalk in addition to systematics.
[b] The dirty beam considers the source as a point of unit amplitude at the phase tracking centre and the visibility function is unity everywhere.