Expanding e-MERLIN with the Goonhilly Earth Station

I. Heywood1, H.-R. Klöckner1,2, R. Beswick3,4, S. T. Garrington3,4, J. Hatchell5, M. G. Hoare6, M. J. Jarvis7, I. Jones8, T. W. B. Muxlow3 and S. Rawlings1

1Subdepartment of Astrophysics, University of Oxford, Denys-Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK
2Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
3e-MERLIN / VLBI National Radio Astronomy Facility, Jodrell Bank Observatory, The University of Manchester, Macclesfield, Cheshire, SK11 9DL, UK
4Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK
5Astrophysics Group, CEMPS, University of Exeter, Stocker Road, Exeter, EX4 4QL, UK
6School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, UK
7Centre for Astrophysics Research, STRI, University of Hertfordshire, Hatfield, AL10 9AB, UK
8Goonhilly Earth Station Ltd, Goonhilly Downs, Helston, Cornwall, TR12 6LQ, UK

Abstract. A consortium of universities has recently been formed with the goal of using the decommissioned telecommunications infrastructure at the Goonhilly Earth Station in Cornwall, UK, for astronomical purposes. One particular goal is the introduction of one or more of the ∼30-metre parabolic antennas into the existing e-MERLIN radio interferometer. This article introduces this scheme and presents some simulations which quantify the improvements that would be brought to the e-MERLIN system. These include an approximate doubling of the spatial resolution of the array, an increase in its N-S extent with strong implications for imaging the most well-studied equatorial fields, accessible to ESO facilities including ALMA. It also increases the overlap between the e-MERLIN array and the European VLBI Network. We also discuss briefly some niche science areas in which an e-MERLIN array which included a receptor at Goonhilly would be potentially world-leading, in addition to enhancing the existing potential of e-MERLIN in its role as a Square Kilometer Array pathfinder instrument.

1. Introduction

The Goonhilly Earth Station (GES; lat = 50.0504 N, lon = 5.1835 W) is home to three large (∼30-metre) parabolic antennas which were originally built for telecommunications. GES was in fact the world’s first satellite communication station, its original parabolic antenna being used to receive the first transatlantic television broadcast via the Telstar satellite approximately half a century ago.

Since most satellite communication and international telecommunication needs are now met using a combination of much smaller dishes and undersea cables, several of which terminate at the Goonhilly site, the satellite operations using the large dishes at Goonhilly were ceased in 2008. The Consortium of Universities for Goonhilly Astronomy (CUGA1) consisting of the universities of Exeter, Hertfordshire, Leeds, Manchester and Oxford) has recently formed in order to use the existing infrastructure at Goonhilly for astronomical purposes. One such application is the connection of one or more of the large parabolic antennas into the e-MERLIN array.

In this short article we present some simulations to demonstrate the improved performance of an e-MERLIN which includes an antenna at Goonhilly. We also discuss some scientific applications which would be ideal for such an instrument. This article is also a follow-up to a previous paper which discusses the benefits of the inclusion of the 25-metre parabolic antenna at Chilbolton Observatory (Heywood et al., 2008).

The e-MERLIN array, which is described in more detail in Section 2, serves as the UK’s Square Kilometre Array (SKA) pathfinder facility. It has a unique science scope due to its “intermediate” baseline lengths (i.e. occupying the gap between those of the EVLA and VLBI networks such as the VLBA and EVN). Its scientific exploitation can thus potentially strongly influence the eventual placement of the dishes in Phase-I of the SKA (SKA1; Garrett et al., 2010). Goonhilly may be particularly important in this respect as it enhances the resolution of e-MERLIN enough to allow the exploration of specific SKA Key Science aspects which are certain to require such intermediate baseline lengths, but for which there is little

1 http://www.ast.leeds.ac.uk/~mgh/CUGA.htm
2. e-MERLIN

The e-MERLIN array, operated by the University of Manchester at Jodrell Bank Observatory, is a radio interferometer consisting of seven radio telescopes situated around the UK, with a current maximum baseline of approximately 217 km. Upgrades to the original MERLIN array include new receivers and a high-bandwidth fibre link to transport the data back to a new digital correlator.

The upgraded system allows e-MERLIN to deliver micro-Jansky sensitivity with up to 4 GHz of instantaneous bandwidth at L- (1.3 - 1.8 GHz), C- (4 - 8 GHz) and K-band (22 - 24 GHz), with an angular resolution of 10 - 150 milliarcseconds.

The locations of the existing e-MERLIN telescopes are shown by the white markers on Figure 1 and also marked on this map in yellow are the locations of the GES and Chilbolton Observatory. Note that Jodrell Bank hosts two antennas: the 76-metre Lovell Telescope and the 25-metre Mark-II. The extra long baselines formed by connecting an antenna at Goonhilly to each of the existing e-MERLIN telescopes should be immediately apparent.

The surface accuracy of the Lovell telescope precludes its inclusion in K-band observations, and similarly the telescope at Defford cannot be used because of the spacings of its mesh reflector.

Note that even if both the Lovell and Mark-II telescopes are included in an e-MERLIN observation there is still one spare correlator input which could be fed by an additional antenna.

3. Extra baselines and improved uv-coverage

The GES has three large antennas on site: Goonhilly-1 (or “Arthur”; 25.9 m diameter), Goonhilly-3 (or “Guinevere”; 29.6 m diameter) and Goonhilly-6 (or “Merlin”, no relation; 32 m diameter). We assume that the proposed extension of e-MERLIN would initially involve the use of Goonhilly-1 at L- and C-bands, and the eventual use of Goonhilly-3 at C- and K-bands.

In an interferometric observation each baseline as projected on the sky measures a single Fourier component of the sky brightness distribution at a particular observing frequency. A single correlation product between two antennas is the atomic unit of an interferometric observation, a “visibility”, and this complex number and its conjugate occupy distinct points in the uv-plane. The longest baseline of an array occupies the outermost region of the uv-plane and provides the highest resolution. Similarly the shortest baseline samples the largest spatial scales and occupies the inner-most region. The shortest baseline also determines the spatial scale at which objects begin to get “resolved out”.

In addition to increasing the sensitivity via an increase in collecting area, adding more antennas to an array increases the range of spatial scales it can sample by virtue of the extra baselines which are created, thus adding more points to the uv-plane coverage. Earth-rotation increases the uv-coverage further by changing the projection of the baselines on the sky with time, causing the baselines to trace arcs on the uv plot. Multi-frequency synthesis can also be used to increase the spread of measurements in the uv-plane, by observing over a broad bandwidth, which manifests itself as a radial spread in the uv plot.

We can demonstrate the improved uv-plane coverage that the introduction of Goonhilly would bring by simulating an e-MERLIN observation with an additional antenna at the location of Goonhilly-1. This is accomplished by generating a set of simulated visibilities. The antenna table is constructed using the locations of antennas from an actual e-MERLIN observation with an additional entry for the Goonhilly-1 antenna.

We simulate a full earth-rotation L-band observation with 256 channels between 1.2 and 1.712 GHz for three representative declinations, and an antenna elevation cut-off of 8 degrees is also imposed.

Simulations are performed using the sm tool within the CASA package.
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Fig. 2. Four full synthesis $uv$-coverage plots for the e-MERLIN array with a frequency range of 1.2 to 1.712 GHz, for four source declinations as indicated on each panel. The extra baselines provided by the Goonhilly station are shown in red.

Figure 2 shows the $uv$-plane coverage of the e-MERLIN array with the inclusion of the Goonhilly antenna. This figure is constructed by plotting the resulting $u$ and $v$ coordinates from the simulated visibilities at four representative declinations and colouring in red any baseline that is formed with the Goonhilly-1 antenna.

These plots clearly demonstrate the increased and improved spatial frequency sampling and resolution advantages of an extended e-MERLIN array. Of particular note is the upper panel showing the declination = 0 case. When observing the celestial equator with an interferometer the baseline tracks are in a purely E-W direction, generally resulting in undesirable N-S structure in the dirty beam (or point-spread function). Any N-S extension of the array itself goes some way to alleviating this problem.

Note that for the simulations presented here we include the Mark-II but not the Lovell Telescope. Generally only one of these two telescopes is included in the interferometer, and inclusion of the Lovell instead of the Mark-II would make little difference to the $uv$-plane coverage as the telescopes are located very close to one another. The main effect the Lovell Telescope has when included in e-MERLIN (at L- and C-band) is to form a series of very sensitive baselines due to its 76-metre diameter, increasing the sensitivity of the array by a factor of 2–3.

Although the inclusion of the Lovell has implications for wide-field observing due to its comparatively small field-of-view, the proposed e-MERLIN Legacy Surveys will generally benefit from its inclusion, and such programmes especially those targeting faint objects at high resolution, would be enhanced greatly by the very sensitive long-baseline formed by Goonhilly and the Lovell (Klöckner et al., 2011, in prep.)

4. Improved beam shapes

The visibilities used to generate the $uv$ plots in the previous section are imaged with natural weighting to determine the dirty beam (i.e. point-spread function) of a given
Table 1. Major axis, minor axis and position angle of the Gaussians fitted to the central lobes of the naturally-weighted dirty beams for full-track observations at four declinations at L-band. These effectively correspond to the resolution of the array. Also included in the table are the ratios of the major to minor axis for each scenario. The closer this number is to unity the more circular the beam, and Goonhilly provides vastly more circular beams for low—Dec— observations. (eM = the existing e-MERLIN array; eM+G includes Goonhilly-1).

| Declination (and array) | B_{maj} (arcsec) | B_{min} (arcsec) | PA (deg) | B_{maj}/B_{min} |
|------------------------|------------------|------------------|---------|-----------------|
| \( \delta = -20^\circ \) (eM) | 0.685 | 0.159 | 12.72 | 4.33 |
| \( \delta = -20^\circ \) (eM+G) | 0.352 | 0.118 | 163.482 | 2.98 |
| \( \delta = 0^\circ \) (eM) | 0.393 | 0.166 | 22.28 | 2.37 |
| \( \delta = 0^\circ \) (eM+G) | 0.195 | 0.116 | -29.65 | 1.68 |
| \( \delta = +30^\circ \) (eM) | 0.225 | 0.186 | 23.45 | 1.21 |
| \( \delta = +30^\circ \) (eM+G) | 0.135 | 0.120 | 134.39 | 1.13 |
| \( \delta = +60^\circ \) (eM) | 0.200 | 0.183 | 0.74 | 1.09 |
| \( \delta = +60^\circ \) (eM+G) | 0.133 | 0.126 | -1.06 | 1.06 |

As mentioned previously, the baselines during a declination = 0 observation move through the uv-plane in a purely E-W direction as can be seen in Figure 2. This generally results in unfavourable N-S sidelobes in the dirty beam, and increasing the N-S extent of e-MERLIN by including Goonhilly mitigates this problem significantly.

5. Applications

Here we briefly discuss some e-MERLIN science cases for which the enhanced performance of the instrument would be particularly valuable.

5.1. Strong gravitational lenses (primarily L-band)

The concomitant advent of an efficient means of finding strongly-gravitationally-lensed systems (HERSCHEL; Negrello et al., 2010) and a means of following these up at high spatial resolution (e-MERLIN; Deane et al. 2011, in prep.) opens up some fascinating new possibilities. Goonhilly provides e-MERLIN with “HST-like” resolution even at L-band where the lensed radio sources are typically brightest. As emphasised by Dalal & Kochanek (2002) and Vegetti & Koopmans (2009), such resolution is sufficient and necessary to adequately probe the dark matter distribution of quad-system gravitational lenses down to sub-galactic scales. Critically, the new HERSCHEL / e-MERLIN method will target lensed sources that are intrinsically extended enough to avoid microlensing effects, but compact enough to be noticeably perturbed by small-scale substructure in the dark matter. By measuring the mass fraction in sub-structure in a large sample of new gravitational lenses, e-MERLIN with Goonhilly could prove to be the current-generation facility best-suited to testing the predictions of the CDM model on mass scales well below that of the Milky Way satellites.

5.2. European VLBI (primarily L- and C-band)

Forming baselines between the existing e-MERLIN telescopes and Goonhilly will also improve the overlap between e-MERLIN and the European VLBI Network, which has a minimum baseline length of \( \approx 270 \) km (Effelsberg - Westerbork). Combined EVN+MERLIN observations are currently routine, where the shorter baselines of MERLIN are required to resolve larger scale structure. Adding a Goonhilly receptor to the e-MERLIN array will introduce overlaps in baseline lengths between these two arrays. Goonhilly would also increase the western extent of the EVN. For a more detailed discussion of this aspect see the article by Klöckner et al. (2011, in prep.).
Fig. 3. Simulations of observations of a CO disk at a redshift of 4.023. Simply to illustrate the channelised source morphology, the left-hand column shows thumbnail images of a selection of numbered channels from the input model, which is the molecular gas disk of a simulated galaxy at $z = 4.023$ as described by the S3-SAX simulation. The four, large colour frames show the frequency-averaged cube emission for the input model (upper-left), an ALMA Band 4 observation of CO(7-6) (upper-right), a current e-MERLIN observation of CO(1-0) at K-band (lower-right) and a second e-MERLIN observation but with the Goonhilly antenna included (lower-left). Each simulated observation has 24-hours of on-source time, and colour scales run linearly from the minimum to the maximum pixel value. Contour levels are $(-4, -2, 2, 4, 8, 16, 32...) \times 0.01 \text{ mJy per beam}$ for the three simulated images and $(-4, -2, 2, 4, 8, 16, 32...) \times 0.01 \text{ mJy per pixel}$ for the input model. This figure shows that the resolution provided by an e-MERLIN array which includes a Goonhilly antenna is sufficient and necessary to resolve and recover the disk orientation in a typical $z \sim 4$ massive galaxy.

5.3. Massive star formation (primarily C- and K-band)

To understand the complex dynamics driven by gravity, rotation, radiation and magnetic fields during the process of massive star formation high resolution probes of both the infalling molecular material and outflowing ionized gas are needed. ALMA will provide the required sensitivity to molecular gas at a resolution of around 10–100 mas which corresponds to 30-300 AU at a typical distance of 3 kpc for the nearest samples. Only e-MERLIN can provide the matching resolution and sensitivity at cm wavelengths to probe the ionized jets and winds that are an integral part of the star formation process.

Significant progress will be made only through joint high resolution studies of a common sample which necessitates e-MERLIN with Goonhilly being able to observe equatorial objects also accessible to ALMA. Furthermore, most massive star formation takes place in the inner Galaxy (e.g. Urquhart et al., 2008) and representative samples require observations in the range $-20^\circ < \text{Dec} < +2^\circ$. Most of the best examples of jets from massive protostars are found in this region (e.g. Carrasco-Gonzalez et al., 2010; Gibb et al., 2003) and only e-MERLIN with Goonhilly can provide the factor of ten increase in resolution over current studies to probe the inner regions where the flows are being driven and collimated.
5.4. Resolving molecular gas disks at high redshift (primarily K-band)

The $^{12}$CO molecule is the best proxy for molecular hydrogen and its J(1-0) transition ($\nu_{\text{rest}} = 115.27$ GHz) is redshifted in to the K-band of e-MERLIN at $z=4$. High-redshift detections of molecular gas typically target systems which are undergoing vigorous episodes of AGN activity (e.g. quasars) or star-formation (e.g. sub-mm galaxies). ALMA will be the natural choice of instrument to target the higher-order transitions in such galaxies however it is incapable of observing the lowest-order transition which provides the most robust estimate of the total mass of molecular gas.

The $S^3$-SAX simulation (Obreschkow et al., (2009) and references therein) makes strong predictions about the cosmological evolution of molecular gas disks. We can demonstrate the advantage of adding Goonhilly to this array by selecting a massive object at $z = 4.023$ from the $S^3$-SAX database$^6$ and simulating a line observation on the celestial equator. Galaxies are extracted from the simulation catalogue within a random volume of space defined by the field-of-view of a 25-metre antenna along the spatial axes and the maximum K-band bandwidth along the redshift axis. A model sky cube is then generated (Levrier et al., 2009) for the most massive galaxy within this volume showing the CO(1-0) emission from its molecular disk, redshifted to 22.948 GHz, covered by 32 channels of 21.4 MHz each. For comparison we also simulate an ALMA observation of the CO(7-6) emission ($\nu_{\text{rest}} = 806.89$ GHz) which is redshifted into Band 4 of ALMA at 160.63 GHz. A selection of numbered channels from the CO(1-0) cube are shown in the left-hand column of Figure 3 to illustrate the morphology of the source.

These two model datacubes are then inverted to generate three sets of visibilities, namely for an e-MERLIN observation both with and without Goonhilly, and an ALMA observation using a current proposed layout for its most extended configuration. On-source time in all cases is 24 hours, and noise is added accordingly. The simulations are performed in spectral-line mode and imaged with uniform weighting for maximum resolution. The final, deconvolved, frequency-averaged images are presented in Figure 4. Clockwise from the upper-left these are the input model, the ALMA simulation, the e-MERLIN simulation and the e-MERLIN simulation including Goonhilly. Please refer to the caption for contour and colour-scale details.

One of the fundamental requirements for ALMA is excellent image fidelity and ALMA faithfully recovers the disk structure in our simulation. The current six-element e-MERLIN array barely resolves the source and because of the beamshape it mis-informs as to the disk alignment. The image produced by e-MERLIN including Goonhilly comfortably resolves the gas disk. For the three simulated cases this would be the most valuable observation in terms of constraining the gas kinematics by spatially and spectrally resolving this lowest CO transition in this high-redshift object. Note that the resolution of an expanded e-MERLIN array at K-band would exceed that of ALMA for any frequency below Band 7.

Even for galaxies which are barely resolved (e.g. $\geq 3$ independent points) it is possible to derive a crude rotation curve from the red- and blue-shifted measurements either side of a mean. Such observations can be combined with models for gas kinematics in clumpy disks to derive estimates of gas and dark-matter masses in distant $z\sim 1.5$ galaxies (e.g. Daddi et al., 2010). An expanded e-MERLIN array may well be the best facility for extending such studies to $z\sim 4$ since obtaining such high spatial resolution with ALMA would require targeting of CO at impractically high-order J-transitions.

Note also that high-redshift CO is another area in which an extended e-MERLIN would be a unique pathfinder instrument for influencing the design of the SKA. New and upgraded cm-wave facilities such as the EVLA (e.g. Riechers, 2010), Greenbank Telescope (e.g. Harris, 2010) and eventually MeerKAT (Heywood et al., 2011, these proceedings) are becoming increasingly important for studies of the low-order transitions of CO at high-z.

A realisation of the SKA with e-MERLIN-like baselines will be capable not only of detecting and resolving such galaxies, but doing so with extremely high detection rates via the survey speed offered by the extreme sensitivity and wider field of view (due to the smaller dish sizes).

6. Conclusions

Introducing one of the 30-metre class antennas at the Goonhilly Earth Station into e-MERLIN would double the already superb resolving power of the array by increasing the maximum baseline from 217 km to 441 km.

During the course of an observation an interferometer samples a range of spatial scales governed by the baselines between antennas as projected onto a sky plane perpendicular to the observing direction (thus defining the uv-coverage), and including Goonhilly results in significant improvements in this aspect. Of particular note is how the increased N-S extent of the array improves its performance during low-declination observations. The point-spread function of an aperture synthesis observation is essentially the Fourier transform of the uv-coverage, and the improved uv-coverage when Goonhilly is included results in correspondingly lower PSF sidelobes.

An antenna at Goonhilly also increases the overlap in baseline lengths between e-MERLIN and the EVN, and would also increase the E-W extent of the latter (Klöckner et al., 2011, in prep.).

We have highlighted some science cases where a Goonhilly-enhanced e-MERLIN would be an extremely powerful instrument, including resolving molecular gas at high-redshift with resolution exceeding that of all but the highest ALMA bands, and follow-up observations of newly-discovered strong gravitational lens sys-
systems. The latter is particularly noteworthy as an expanded e-MERLIN may well be the best contemporary facility for testing the predictions of the CDM model on small mass-scales.

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