Deep sub-arcsecond wide-field imaging of the Lockman Hole field at 144 MHz

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Recent observations of the radio sky show that the vast majority of sources detected at 144 MHz are unresolved at the typical resolution of a few arcseconds, demonstrating the need for sub-arcsecond-resolution surveys to make detailed studies. At low radio frequencies, high spatial resolution is challenged by the ionosphere and by the propagation delay of radio waves that it induces. If not adequately corrected for, this blurs the images to arcsecond or even arcminute scales. In addition, the required image size to map the degree-scale field of view at low-frequency radio telescopes at sub-arcsecond resolution is far greater than what typical software and hardware are currently capable of handling. Here we present deep degree-scale sub-arcsecond imaging at low radio frequencies. We derive ionospheric corrections in 44 directions on individual sources with sub-arcsecond sub-resolution structures. This has yielded a sensitive 6.6 deg2 144 MHz map with a resolution of 0.38° × 0.30″ and a sensitivity of 25 μJy per beam, near the phase centre. This will allow mapping of the entire northern low-frequency sky at sub-arcsecond resolution.

Endeavours in expanding sub-arcsecond resolution observations to go both deeper and wider have had successes at both 300 MHz (ref. 1) and gigahertz frequencies using very-long baseline interferometry (VLBI). However, the production of contiguous images that span degrees on the sky at sub-arcsecond resolution has not been done at these low frequencies and is still tedious at higher frequencies due to the limited field of view. This is further complicated by a combination of a lack of known compact sources (limiting available calibrators and blind surveying), the long observing times required (limiting survey speed) and the amount of resources required to produce such images.

An ideal instrument for low-frequency sub-arcsecond surveying is the International Low-Frequency Array (LOFAR) Telescope (ILT; van Haarlem et al.). It is most sensitive at frequencies between 120 MHz and 168 MHz and has baselines ranging from 68 m to approximately 2,000 km. This provides a theoretical angular resolution of approximately 0.2″ at 144 MHz. The exact resolution varies depending on the visibility weighting scheme. The international station’s size sets the field of view at 2.1° full width at half maximum at 144 MHz. Over the past decade innovative algorithms have been developed to overcome the ionospheric blurring sufficiently to allow high-quality 6° resolution imaging, and novel computer science approaches have been designed to efficiently process data on large-scale parallel-computing infrastructure. Recently developed pipelines have demonstrated the ability to produce low-frequency sub-arcsecond resolution images of individual sources spanning regions of a few arcminutes. Following this achievement, two major outstanding questions remain on whether calibration of ~10^3 km baselines can be extended reliably to many sources, correcting for ionospheric effects at sub-arcsecond level across the full field of view, and whether we can subsequently image the entire field of view at full resolution.

To address these questions, we use an eight-hour ILT observation of the Lockman Hole field, centred at α=10h45m00s, δ=+58°05′00″, where a wealth of available ancillary data is available (for example, deep optical, near-infrared and far-infrared data). The ionospheric conditions during this observation were typical, based on the 6° image quality. Using this observation, we demonstrate calibrating and imaging of the ILT’s full international station field of view at sub-arcsecond resolution. Figure 1 illustrates the result. This approach provides a general strategy for wide-field high-resolution imaging at low radio frequencies for dense interferometers such as the ILT.

This strategy begins with a direction-independent calibration on a known calibrator source (ILTJ104940+583529) from the Long Baseline Calibrator Survey (LBCS). However, this direction-independent calibration is not sufficient to fully calibrate the field of view, and direction-dependent effects (DDEs) remain. These mainly come from the ionosphere, which varies strongly over time and across the sky. Successfully correcting for these DDEs hinges on two conditions: the direction-independent calibration needs to be approximately valid over the area that is to be calibrated, and there need to be enough bright sources with a sufficient compact structure to allow self-calibration to succeed. The former depends on the isoplanatic patch size and suitable calibrators within them, whereas the latter depends on the amount of compact emission in sources.

Judging the amount of compact emission at sub-arcsecond scales in sources is difficult at a resolution of 6°. To facilitate the selection of DDE calibrator candidates, an intermediate resolution image with an angular resolution of approximately 1° was created.
Fig. 1 | An overview of the field illustrating both the wide-field and high-resolution aspects. The central image shows a 6" image of the covered part of the field. The bottom two panels zoom in on a small portion of the field at 6" (left) and a particular source at 0.3" (right). Surrounding the central image are highlights of various other sources detected in the 0.3" resolution map. Moon image credit: NASA.
If calibration is poor or of insufficient quality on the intermediate and longer baselines, image quality will be poor or the image will appear unfocussed, giving a rough indication of the validity of the direction-independent calibration across the field. Sources that appear as compact at this resolution are also more likely to retain compact emission at sub-arcsecond resolution compared to sources that appear compact at a resolution of 6″. We selected sources that had a peak intensity of 25 mJy per beam or higher in the 1″ image, resulting in a sample of 46 potential calibrators. The data were then phase-shifted to these sources, creating individual data sets, and self-calibrated.

In the direction-dependent self-calibration process, we leverage the fact that the dominant remaining effects are the ionosphere and slowly varying effects, such as errors in the primary beam model. A starting model was automatically generated for each source by imaging it before the first iteration started. Subsequent self-calibration is an iterative process: in each iteration, calibration solutions are obtained that provide an updated model, which in turn can provide better calibration solutions. In the case of dominance by the ionosphere, we can constrain the ‘phase-only’ self-calibration iterations to calibrate for differential total electron content (dTEC), reducing the degrees of freedom by introducing the known frequency dependence of the ionospheric delay as the functional constraint given by equation (1).

$$\phi = -8.44797245 \times 10^9 \times \frac{\text{dTEC}}{\nu}.$$  (1)

Here $\phi$ is the phase in radians and $\nu$ is the frequency in hertz. For every source, now only a single dTEC value per time interval is determined, instead of frequency-dependent phases. This reduces the degrees of freedom by a factor of 48 compared to solving for...
scalar phases at a frequency interval of 1 MHz (a typical solution interval for 6° calibration), substantially increasing the effective signal-to-noise ratio (SNR). This leaves 46 degrees of freedom, one for each calibrator. Following this, long-timescale amplitude corrections were determined to correct remaining amplitude effects. For the ILT an imperfect primary beam model is one of the dominant causes of residual amplitude errors.

Manual inspection of the 46 DDE calibrators concluded that 44 had converged after the dTEC iterations and 41 allowed for subsequent amplitude corrections. The remaining two sources did not have sufficient compact flux for successful self-calibration and were discarded. Figure 2 shows the progression of self-calibration on three sources of varying complexity and distance from the initial LBCS calibrator. The fact that self-calibration converged for 44 directions across the entire 6.6 deg² area confirms that the density of compact sources is high enough to correct direction-dependent effects across the field of view. Furthermore, the fact that a sufficiently accurate starting model for self-calibration could be obtained from a direction-independent-calibrated data set indicates that for similar ionospheric conditions a single correction is likely to be approximately valid over the entire field of view. Finally, the solutions were interpolated into a two-dimensional map of corrections by using radial basis function interpolation. This provides spatially smooth ‘screens’ with calibration solutions for every location in the field.

Imaging the entire field of view is another challenge due to the number of pixels required. We chose a pixel scale of 0.11″ per pixel. Covering the ILT’s field of view then requires a total of 6–7 × 10⁸ pixels. For comparison, the entire Very Large Array (VLA) Fairstein Images of the Radio Sky at Twenty-cm (FIRST) survey covers 10° deg² using roughly 4 × 10⁷ pixels13.

At the time of writing it is not feasible to make a single image at the required size. Therefore, the field was split in 25 facets that were imaged individually. Each facet image covered a 0.69″ × 0.69″ area that could be imaged at a manageable 22,700 × 22,700 pixels. For each facet, the 1″ resolution image was used to subtract sources outside of a central 0.55″ × 0.55″ region. This suppresses imaging artefacts that would arise from undeconvolved emission outside the image boundary. The imaged area extends beyond this subtraction border to account for remaining source structure due to imperfect subtraction. Finally, the inner 0.55″ × 0.55″ regions of the facets overlap each other to avoid gaps in the mosaic. The final mosaic has approximately 83,950 × 83,500 pixels covering 6.6 deg² on the sky.

Imaging was done using WSClean in combination with the newly developed Image Domain Gridding (IDG)14–16. Multi-frequency synthesis was used to account for the large bandwidth, and multi-scale CLEAN was used to account for both extended and compact emission. One of the bottlenecks for imaging is the need to place visibilities measured by a radio telescope on a regular grid in a computationally expensive process called gridding. IDG is a novel approach to gridding that is computationally efficient as it circumvents the need to calculate expensive convolution functions during this process. It simultaneously allows for on-the-fly application of primary beam corrections and other direction-dependent corrections at little extra cost. Each of the facets took between five and seven days of wall-clock time to image. Using both local (ALICE at Leiden Observatory) and national (Spider at SURFsara) computing resources, imaging ran in parallel and the effective wall time was greatly reduced.

A total of approximately 250,000 core hours were required for the data reduction process to arrive at the final image. This was split between calibration and imaging as 34% and 76%, respectively. For the imaging of this data set, this translates to 458 core hours per gigapixel. During calibration data sizes vary greatly, and therefore a general number for that is difficult to give. The image covers a 6.6 deg² sky area at a central angular resolution of 0.38″ × 0.30″ and a central r.m.s. noise level of 25 μJy per beam. This equates to a 1.4 GHz sensitivity of 5 μJy per beam, assuming a spectral index of $\alpha = -0.7$. This depth is comparable to the deepest 1.4 GHz VLA image of the field17.

In the 6° resolution image, 6,103 sources are detected in the ILT covered area using the same eight-hour observation, with a noise level of $\sigma_{\text{rms}} = 70$ μJy per beam. Of these, 5,650 (93%) are unresolved and 453 (7%) are resolved, using the same criterion as the LOFAR Two-Metre Sky Survey (LoTSS).18 Of the 6° unresolved sources, 2,483 (43%) had a high-resolution counterpart detected at SNR $= F_\text{peak}/\sigma_{\text{rms}} > 5$, of which 291 are multi-Gaussian (12%) and 2,192 remain single-Gaussian (88%). The final catalogue was created by cross-matching to the 6° resolution catalogue of the LOFAR Deep Fields survey19,20.

Wide-field low-frequency sub-arcsecond resolution imaging with the ILT opens up important new scientific parameter space with its ability to conduct a blind all-sky sub-arcsecond survey. At this resolution the ILT is also well matched to other telescopes such as e-MERLIN or the VLA. Over the past years the LoTSS has been conducting a sensitive 6° survey of the northern sky21. The data recorded for this survey hold incredible legacy value for a future sub-arcsecond survey. Over 75% of the sky has already been observed for LoTSS, using the same duration, bandwidth and averaging as for the data presented here. Weighted by integration time, per hour of observing, 97% of these data contain international stations; 54% have ≥12 international stations and 84% have ≥10. A considerable amount of data is thus already present in the archive, ready to be processed. Relatively little extra or repeat observing will thus be necessary. The work presented here demonstrates a general strategy for wide-field low-frequency sub-arcsecond imaging and paves the road towards easier pipelined data processing for a new sub-arcsecond low-frequency survey of the northern sky.

Methods

Observation. For this work we used an observation of the Lockman Hole field located at $α = 10h47m00s, δ = 58°05′00″$. This pointing was observed on 2018 July 12 from 11:08:10 to 19:08:10 UTC. In total, eight hours were spent on the target field, which was booked by two 15 min calibrator scans of 3C 196 and 3C 295, respectively. The observing set-up was the standard LoTSS high-band antenna set-up with 48 MHz of bandwidth spanning a frequency range of 120–168 MHz. With the exception of DB609, all 12 other international stations partook in the observation. We will use the term Dutch LOFAR Telescope (DLT) to refer to the core and remote stations.

Calibration and imaging. Calibration of the radio data started from the raw data stored in the Long Term Archive. First the data were processed using the de facto pipelines for calibrating the Dutch stations, PREFACTOR 3.0 and DDF-PIPELINE21,22. Subsequently, a suitable infield LBCS calibrator was selected. From there on, no dedicated pipeline existed. First, direction-independent calibration of the international stations was carried out. An intermediate resolution image at ~1″ was used to select sources for direction-dependent calibration, which were subsequently self-calibrated. Finally, the field was split into ‘facets’ and imaged at the full native resolution.

Direction-independent calibration of the DLT. The PREFACTOR pipeline consists of two workflows for the calibrator scan and target scan, respectively. A more detailed overview of the calibration strategy is given by ref. 22. A short overview of these workflows will be given next.

First, the calibrator workflow determined the following corrections for both Dutch and international stations: a phase offset to align XX and YY polarizations (based on the assumption that the calibrator is unpolarized), a bandpass to translate correlator units to physical units and a clock offset in nanoseconds to synchronize the clocks of each station to the same reference. These solutions were determined on a 4 s time interval and a 48.82 kHz frequency interval. Finally, they were transferred to the target data set and the target workflow determined XX and YY phase solutions for the Dutch stations by calibrating against a sky model from the TIFR GMRT Sky Survey (TGSS)23 on an 8s time interval and a 195.28 kHz frequency interval.

Direction-dependent calibration of the DLT. The DDF-PIPELINE was then run for direction-dependent calibration of the Dutch stations (see refs. 1,24 for a detailed description of this pipeline). First, the direction-independent calibration
was refined by means of self-calibration of the entire Dutch station field of view. Following this, both phase and amplitude calibration solutions were determined in 45 directions across the Dutch field of view, following a facet-based approach. This provided a high-quality 6\'' resolution image of the target field covering the field of view of the Dutch stations.

**Direction-independent calibration of the ILT.** To start calibration of the international stations, we followed the strategy of the LOFAR-VLBI pipeline\(^1\). Calibration solutions from PREFACTOR and DDF-Pipeline were applied, data were combined into 24 manageable 2 MHz chunks of 32 GB and finally a suitable LBCS calibrator was selected within the international station field of view\(^1\). This calibrator source was then split off from the main data set by phase-shifting the visibilities towards this source. After phase shifting, the core stations were all combined into a single 'super station', ST001. The data set was also averaged down to 16 s time and a 195.28 kHz frequency resolution, averaging causes a ~50% intensity loss due to smearing at a distance of ~4'' from the phase centre, which considerably reduces the influence of other sources. ST001 has a field of view of the order of ~4'' as well, further suppressing the effects of other sources on every baseline with this station. Self-calibration was performed using the routine described in ref.\(^2\). This uses DPPP\(^3\) to determine calibration solutions and WSClean\(^4\) for imaging. First, nine 'fast' iterations to solve for remaining amplitude errors due to the slowly varying station values rather than phases. In the slow iterations, DPPP's complexgain mode was done. This determined time, frequency and polarization-dependent amplitude and phase solutions on a 10 min timescale and a 195.28 kHz frequency interval, for the XX and YY polarizations. The starting model for the first phase-only iteration was a point source, due to the lack of more information, with the flux density taken from the low-resolution 6'' image. Such a starting model is likely naive and possibly incorrect, but after each iteration the model was updated and the self-calibration cycle converged to a believable double-lobed source structure. These solutions were then applied to the target field data set as initial direction-independent calibration for the international stations and refined direction-independent calibration solutions for the remote and core stations. The core stations were corrected with the solutions for ST001.

**Intermediate resolution imaging and faceting.** Due to its sheer size, the full field of view could not be covered with a single image at the ILT's native resolution. Therefore the field was split into 25 facets that were imaged separately. To help suppress interference from unresolved sources outside of each facet and to determine suitable candidate sources for direction-dependent calibration, an intermediate resolution image at approximately 1'' was made by tapering the data with a Gaussian taper. The resulting image was 25,000 × 25,000 pixels in size and covered the full field of view. In preparation for high-resolution imaging, 25 data sets (facets) were then split out with their phase centres spread over the field of view in a 5 × 5 grid, with each facet spanning 0.55 × 0.55 deg\(^2\) on the sky, separated by 0.5 deg. For each facet the intermediate resolution map was subtracted outside this 0.55 × 0.55 deg\(^2\) area. The 0.05 deg on each side ensured some overlap between the facets to avoid gaps in the sky coverage. The data were then phase-shifted to each of these phase centres and averaged to 45 time and 48.82 kHz frequency resolution. These were the final 25 data sets that would be imaged at high resolution. The data for each facet were about 250 GB in total size.

**Direction-dependent calibration of the ILT.** Sources that remain bright and compact at 1'' resolution have a better chance of remaining compact down to 0.3'', compared to a selection at 6''. From the intermediate-resolution image, sources with a peak intensity above 25 mJy per beam were selected as candidate DDE calibrators. These were then split off into separate data sets similarly to the LBCS calibrator, but averaged more in time to a 1 min interval. For the brightest sources this balanced well the SNR while retaining the time resolution to correct most of the residual solutions properties. The solutions determined on the LBCS calibrator were pre-applied, and a self-calibration routine similar to that for the LBCS calibrator was subsequently used to self-calibrate these sources, as outlined below.

First, an initial image was made from which a starting model was derived. As the majority of phase-related errors had been corrected on the infed calibrator, it was assumed that the remaining DDEs were dominated by ionospheric smearing. Therefore, in the fast iterations DPPP's tec mode was used to determine dTEC values rather than phases. In the slow iterations, DPPP's complexgain mode was used to solve for remaining amplitude errors due to the slowly varying station beams. Solution intervals for both solves were calculated automatically based on the intensity detected on 800 km baselines\(^5\). The tec iterations converged for 44 sources and the complexgain iterations converged for 41 sources. So-called 'jumps', manifesting as solutions that are offset by a multiple of a specific 'jump' value, were present in the tec solutions. These jumps are a consequence of local \(\chi^2\) minima in the TEC fitting\(^6\). This jump value was subtracted from the offending solution blocks iteratively until no jumps remained. The dTEC values were then temporally interpolated to a smooth screen over the right ascension and declination. A simple approach to convert discrete directions into screens would be a Voronoi tessellation based on the calibrator locations. This would, however, introduce sharp transitions that would negatively impact IDG imaging later on. Therefore, the solutions were interpolated with a multiquadratic radial basis function instead, using SciPy's interpolate.Rbf function. Interpolation was constrained such that at the location of a calibrator the screen solutions matched the original solutions. Similarly, the complexgain solutions were also interpolated to a screen. These two screens were used to apply direction-dependent calibration solutions during the final imaging.

**Final imaging.** Final high-resolution imaging of the data was done using WSClean 2.10.2 in combination with IDG 0.8:master:9faa7c6 in CPU mode. As the IDG algorithm can leverage a graphics processing unit for the gridding calculations, this around the central core of the source was likely an order of 10 times faster. A 22,500 pixel image of each full data set finished four times faster on a 22-core Intel (R) Xeon (R) Gold 6266 system with an Nvidia Tesla V100 compared to an identical system without one. Each of the facets was imaged separately with robust -1 weighting, a 0.11'' pixel size and a 22,700 × 22,700 pixel image size. Multi-scale multi-frequency synthesis clean was used together with spectral fitting using a second-order polynomial (through -fit-spectral-pol 3). Differential primary beam, dTEC and gain corrections were all applied on the fly during imaging. The beam corrections were applied every 10 min, DTEC solutions were applied every minute and gain solutions every hour. This could be done efficiently through the use of IDG. The data were imaged using hardware on the Spider platform at SURFsara and the ALICE cluster in Leiden. Imaging took 5–7 days of wall-clock time per facet on average using 24 cores on a node with two 12-core Xeon Gold 6126 systems running at 2.6 GHz and with 384 GB of RAM. However, effective wall-clock time was greatly reduced due to the availability of many compute nodes, allowing imaging to run in parallel where each compute node imaged a facet independently. From start to finish the entire data reduction procedure consumed approximately 250,000 core hours.

**Source detection and catalogues.** After imaging, source detection was done using PyBDIF 1.9.2\(^1\). Because source detection was done on each facet separately, there will be duplicate detections. Therefore, the catalogues were first merged and then cleaned of duplicate detections. The compact sources and extended sources were treated separately for this. First, we processed the compact sources, starting with a cross-match to the 6'' resolution catalogue of the LOFAR Deep Fields survey with key optical host properties\(^7\). Next, duplicate detections were removed using an internal cross-match within a radius of 0.15'' of the fitted high-resolution position (that is, approximately within the restoring beam of the high-resolution map). The match closest to its facet centre was kept, whereas the others were discarded. Then, a size constraint was introduced. Sources with fitted major or minor axes that were larger than 6'' were discarded as poor fits, as by definition the unresolved sources cannot be larger than the low-resolution restoring beam. Then, an SNR ratio cut was made, constraining the peak intensity to \(\geq \text{SNR}_{\text{peak}}\), where \(\text{SNR}_{\text{peak}}\) is the r.m.s. noise around the source as measured by PyBDIF. Finally, the compact and extended source catalogues were combined into a single catalogue and a final duplicate removal was done. The final catalogue contains 2,483 sources.

**Astrometric corrections.** As phases hold information about source positions, the solution for the source positions is therefore tied to the astrometry available. Therefore during calibration of the LBCS calibrator, we noted that self-calibration had 'recentred' the image near one of the lobes, due to the use of a point-source starting model, introducing a noticeable offset that needed correcting. Therefore, the final image needed to be realigned to a reference. As our reference we used the final calibrated and aligned radio catalogue of Lockman Hole from the LOFAR Deep Field survey.

Offsets to align the high-resolution image to the low-resolution image were determined for each facet separately. First, point sources with SNR: \(\text{SNR}_{\text{peak}}/\text{SNR}_{\text{min}} > 5\) were selected. Second, an isolation constraint for no other sources to be present within 30'' was applied. Astrometric offsets were then determined using the astrometry available on the LBCS calibrator. This could be done efficiently through the use of IDG. The data were imaged using hardware on the Spider platform at SURFsara and the ALICE cluster in Leiden. Imaging took 5–7 days of wall-clock time per facet on average using 24 cores on a node with two 12-core Xeon Gold 6126 systems running at 2.6 GHz and with 384 GB of RAM. However, effective wall-clock time was greatly reduced due to the availability of many compute nodes, allowing imaging to run in parallel where each compute node imaged a facet independently. From start to finish the entire data reduction procedure consumed approximately 250,000 core hours.
radially (bandwidth smearing) and azimuthally (time smearing). Supplementary Fig. 2 illustrates the smearing losses on the longest baseline. Ionospheric disturbances are mostly corrected for in both the direction-independent and direction-dependent calibration processes, but are difficult to remove perfectly as they are limited by the density of direction-dependent calibrators, available SNR, solution intervals and source complexity. The result is similar to atmospheric seeing. Finally, ISS/IPS scrambles astronomical radio signals before they even reach the ionosphere and hence imprint an inherent uncorrectable smearing on the data. The former can technically be resolved with better calibration, but the latter sets a fundamental limit to the effective resolution that can be achieved. The combination of ionospheric seeing and ISS/IPS manifests itself as the broadening of sources near the phase centre, where time and bandwidth smearing is non-existent. If smearing is not accounted for, peak intensity and intrinsic size measurements will be off due to a wrong assumed point spread function. Measuring the most compact sources in the centre of the field, where the resolved bandwidth smearing is negligible, will indicate whether broadening from ISS/IPS is an issue for this compact sources in the centre of the field, where time and bandwidth smearing would need to be taken into account. A substantial reduction in time smearing can be achieved by processing the data at its archived 1 s time resolution.

Flux scale corrections. A correction to the flux scale was necessary, as the reference bandpasses that were used were not tied to any particular flux density scale. For a reliable correction, sources with the same flux density at low and high resolution were needed. A selection was made based on high-singificance sources in the high-resolution image. Compact single-Gaussian sources with SNR > 25 were selected and the median ratio $S_{\text{ILR}}/S_{\text{ILT}}$ was determined. The selection of bright high-SNR and compact sources ensures that no flux density is lost. Smearing effects are mitigated by using the flux density, which should be conserved, instead of peak intensity. The correction factor was determined to be $1.21 \pm 0.19$ from the median flux density ratio. After scaling, the mean ratio is $S_{\text{ILT}}/S_{\text{ILR}} = 0.99 \pm 0.01$ and the median ratio is $S_{\text{ILT}}/S_{\text{ILR}} = 1.00 \pm 0.01$ ($0.82 \pm 1.14$). Both the uncertainty and the values in parentheses reflect the 16th and 84th percentiles, respectively. The distribution of the ratios over all facets after scaling can be seen in Supplementary Fig. 1. A small number of sources have a ratio significantly smaller than unity. These are the most likely sources that have extended emission below the detection threshold. However, this is a small number of outlying sources and has not affected the scaling in a significant way.

The uncertainty in measured flux densities is compounded by two main effects: an uncertainty in the general flux density scale ($\sigma_{\text{cal}}$) and an uncertainty in the scaling factor ($\sigma_{\text{scale}}$). For the former we assume a conservative error of 20% (ref. 11). This was added in quadrature with the other uncertainty to arrive at a total uncertainty in the flux density of $\sigma_{\text{total}} = \sqrt{\sigma_{\text{cal}}^2 + \sigma_{\text{scale}}^2} = 30\%$.

Data availability

A source catalogue and the full-resolution images are accessible through the LOFAR Surveys Key Science Project webpage at https://www.lofar-surveys.org/hdfields.html.

Code availability

The various software and pipelines used in this work are publicly available at https://github.com/lofar-astron/prefactor (PREFACTOR), https://github.com/lofar-astron/LOFAR-VLBI and https://github.com/lofar-astron/LOFAR-Long-Baseline-Calibrator-Survey (LOFAR-LBCS). Code from other parts not using these pipelines is not directly available because it is not part of a complete pipeline, but is available upon reasonable request to the corresponding author.

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Author contributions
F.S. led the paper, reduced the data and produced the images. R.J.v.W. developed the self-calibration routine and helped expand it to international baselines. H.J.A.R. helped scope and write the paper. L.K.M. and N.J. conducted the LBCS survey and developed the LOFAR-VLBI pipeline, which served as the foundation for this work. A.R.O., S.v.d.T. and B.V. maintain WSClean, IDG and were of great help in fixing problems and adding features to the software. J.B.R.O. helped secure resources on SURFsara and provide support for our data reduction on their Spider platform. P.B. led the proposal that obtained the data and contributed to editing of the paper. M.B. is a member of the long-baseline working group and contributed to editing of the paper. T.W.S. contributed towards some of the various data processing pipelines used in this work and produced the deep Lockman Hole 6″ image. C.T. developed the DDFacet software used and produced the deep Lockman Hole 6″ image. A.P.T. is a member of the long-baseline working group and helped determine the flux scale.

Competing interests
The authors declare no competing interests.

Additional information
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