Submission: LOFAR2.0 Large Programmes — Full proposal

The International LOFAR Two-metre Sky Survey (ILoTSS)

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Abstract

The International LOFAR Two-metre Sky Survey (ILoTSS) will extend and build on the highly successful LoTSS survey to be the first wide-area, high resolution (0.3″) extragalactic radio survey and, more generally, the deepest wide-area survey for typical radio sources. The science goals are extensive, and we highlight some here. This survey will robustly characterise the whole AGN population, including the emerging low-luminosity population, and resolve all jets on kpc scales, which is essential for understanding the AGN physics, their galaxy-scale feedback and for separating the AGN and star formation contributions. In the local Universe, the study of nearby galaxy halos will determine the role of cosmic ray transport in stellar and galactic feedback, while at higher redshift ILoTSS will characterise the AGN and star formation activity in more than a million quasars out to $z \sim 6$, and map the growth of the earliest black holes ($z > 6$). Due to its 0.3″ resolution, ILoTSS will be a gravitational lens finding machine, with >5000 new radio-loud lens systems expected, enabling unique tests of high-z galaxy populations and cosmology. The ILoTSS source counts will be used to independently constrain the cosmological parameters, and to determine the radio source count dipole at high significance, which may have dramatic implications for the cosmological principle. We are also proposing to complete LoTSS, for legacy value and to provide the first low-frequency high-resolution study of the Milky Way, probing the detailed physical structure of the ISM in addition to discovering new pulsars. Finally, ILoTSS will open up new discovery space in cosmic magnetism and the time-domain Universe, and provide insights on exoplanet-induced emission, their periodicity and the space weather conditions for over 100 stellar systems. The potential and full range of science cases for international baseline resolution data is evolving in real-time as community expertise with these datasets grows, and so the legacy value of our programme is expected to extend well beyond any science case we can propose now. ILoTSS is designed to overlap with the *Euclid* sky area in order to maximise the multi-wavelength information at matched resolution, and will include full polarisation and time variability information across 7,600 deg^2. The proposed ILoTSS survey (in addition to finishing the remaining 10% of the LoTSS survey, which is <10% of our time request) can be conducted with 8,500 observing hours, resulting in 30 PB of archived data products.

Keywords

surveys, radio continuum, radio polarimetric, image processing

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International LOFAR Telescope

1. Science goals

The case for surveying the sky at international baseline (IB) resolution is clearly outlined in the LOFAR2.0 white paper, and ILoTSS is the logical extension to the extremely successful LoTSS survey (>250 publications, ∼8,000 citations) to fully exploit the capabilities of LOFAR2.0 for the benefit of the whole astronomical community. The LOFAR IB have only recently begun to be fully exploited (e.g. [1, 2]), providing new insights into AGN evolution ([3], [4], [5]) and their interaction with the surrounding environment ([6]); gravitational lensing ([7]); and nearby galaxies ([8]). However, our understanding of the scientific potential is still rapidly evolving as the capabilities of the instrument are better exploited and the scientific community grows. We emphasise that such high resolution survey imaging is a capability of LOFAR that will remain unique for the foreseeable future and, coupled with other optical/IR surveys at comparable resolution, it is natural that such a survey, once publicly available, will be an invaluable resource that will enhance many scientific studies. To maximise legacy value and utility of the survey, the area has been carefully chosen to encompass both the WEAVE-LOFAR and *Euclid* sky areas. WEAVE-LOFAR will provide a million optical spectra of LoTSS sources, increasing the number of spectra for AGN by a factor of 100. While in the ILoTSS overlap region, *Euclid* will map 750 million galaxies in optical and infrared at a matching resolution of 0.2-0.3″, with associated multiband ground based surveys to determine their photometric redshift. The next sections summarise the key science cases while acknowledging that some of the most impactful results will likely come from new discoveries due to the substantial new parameter space that ILoTSS will probe (e.g. star/exoplanets in LoTSS).

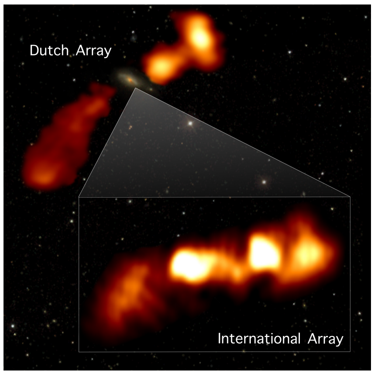

Figure 1: 3C293 images showcasing the ILT ability to reveal emission on extended and sub-galactic scales [9].

1.1. AGN and galaxy evolution

The deep, high angular resolution radio data of ILoTSS, coupled with superior ancillary imaging with *Euclid* and supporting ground-based surveys for host galaxy identification and characterisation, will extend the capabilities of LoTSS out to significantly higher redshifts for the study of the evolution of AGN and star-forming galaxies. The ILoTSS sky area of 7,600 deg^2 ideally complements both lower-redshift low-resolution LoTSS studies and smaller dedicated deep-fields at high resolution (e.g. LUDO LOFAR2.0 proposal). The angular resolution of the ILT will allow morphological detection of jets/lobes and identification of AGN cores, enabling the separation and simultaneous measurement of AGN activity and star formation for the first time for large samples of sources $\gtrsim 10^{23}$ W/Hz out to cosmic noon at $z \sim 2$.

1.1.1. Radio AGN physics, lifecyles & environmental impact

LOFAR has allowed us to significantly expand our knowledge of the physical conditions of AGN jets through detailed studies of single objects (e.g. [10, 11, 4]). However, its strength has been in building large samples of radio AGN and making possible a step change in our understanding of their properties [12], lifecycles [13] and their environmental impact [14]. A limiting feature of LoTSS so far is the 6″ resolution of the Dutch array, resulting in a characteristic physical size of the resolved radio-AGN of around 50 – 100 kpc [15], however ILoTSS will resolve *all* sources on kpc scales. In LoTSS this affects our ability to study the impact of the radio AGN on the host galaxy ([14, 16]), as well as biasing the morphological classification of the resolved subset of the population [12] and preventing us from studying in bulk the high-energy physics of compact regions such as jets and hotspots, which give key information on particle acceleration mechanisms, on restarting activity and the evolution and intermittency of jet power. The use of LOFAR IB in a (so far) limited number of studies has shown how powerful they are at tracing complex structure in the central regions of radio galaxies. Restarted activity is common, and high-resolution low-frequency imaging not only shows the new jets in detail (Fig. 1) but also allows us to identify the turnover in the spectra which traces the presence of free-free absorption by a gas rich nuclear medium inside which the jets have to expand [9, 17]).

The high resolution of ILoTSS will allow us to obtain large samples of the emerging low-luminosity, physically small radio AGN population [19], which are important for understanding jet feedback on galaxies, rather than the more widely studied cluster scales. Since physical size provides a proxy for age, only with high angular resolution can we characterise the ages of the whole AGN population, with implications for their jet powers, lifetime distributions and duty cycles [15]. Thus, ILoTSS will allow us to extend studies of AGN lifecycles across cosmic time, and to measure the bulk of the jet kinetic luminosity function across a wide redshift range for radio-loud AGN (c.f. [15]) which will demonstrate how the importance of radio-AGN feedback evolves across cosmic time back to (and possibly beyond) the peak epoch of star formation.

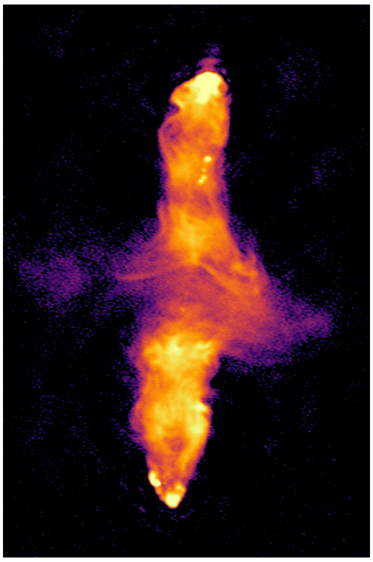

Figure 2: ILT image of 3C 34 at 0.3", showcasing its sensitivity to compact, diffuse and filamentary emission, enabling matched-resolution analysis with facilities at other wavelengths [18].

A key strength of ILoTSS is that it will provide unbiased, sensitive, high-resolution imaging in total intensity and polarisation over an area wide enough to provide large samples of *rare* objects (e.g. powerful FRIIs, galaxy-scale jets, restarting sources & remnants [20], and polarized sources). We expect to image up to 500,000 radio-loud AGN in the 7,600 deg^2 survey area, spanning $\sim$10 decades of radio luminosity and covering a wide range of host galaxy masses, environments and redshifts. The combination of high resolution and excellent ancillary optical data (Legacy, WEAVE-LOFAR, *Euclid*, UNIONS) will mean an extremely high host galaxy identification rate, thus enabling accurate inference of host galaxy and host cluster/group environment masses, giving a picture of the environmental impact and life cycles of the radio AGN populations that will be unsurpassed for a generation. The ILoTSS resolution will also be well matched to multi-wavelength data from e.g. e-MERLIN, JVLA, ALMA, *HST*, *JWST* & *Chandra* ([18], Fig. 2).

1.1.2. Evolution of AGN and star-forming galaxies

ILoTSS will enable us to characterise the nature of the low-frequency emission from more than a million quasars [21], and crucially to resolve their emission. Furthermore, using both morphological information and brightness temperatures [2, 22], we will determine the proportions associated with AGN activity and star-formation. With a few thousand quasars in each of 100 bins across redshift ($0 < z < 6$) and quasar absolute magnitude (0.0001 $L*$ to 10 $L*$) space, ILoTSS will determine the interplay between black hole accretion and star formation, and measure the integrated black hole accretion rate in a manner unbiased by dust extinction. ILoTSS will also be crucial for detailed (sub-galactic-scale) characterisation of the relationship between radio luminosity and star-formation rate (using star-formation rates uncontaminated by AGN activity), as well as how this depends on host galaxy properties, and whether/how it evolves across cosmic time (c.f. [23]). This is not only critical for a detailed understanding of the physical processes driving the relation, but also to allow radio luminosity to be calibrated as a dust-independent star-formation tracer out to the highest redshifts.

High redshift radio sources: With LoTSS-DR2 we have recently been able to make the first statistical constraints on the low-frequency radio properties of the $z > 5$ quasar population [24]. The combination of resolution and sensitivity of ILoTSS promises to further transform our understanding of high-redshift AGN, enabling significant detections of the majority of jet activity in the $z > 5$ quasar population. With the large statistical samples of $z \sim 6$ to 8 quasars (of order 100) that will be discovered in the ancillary *Euclid* data, statistical analysis using ILoTSS will allow us to map out the growth of the earliest black holes and to reveal the underlying star-formation activity within the quasar host galaxy population. Furthermore, the 0.3″ resolution will enable studies of the resolved ($\gtrsim$2 kpc) jet properties [25] and their feedback effects on the protocluster medium and in building the most massive galaxies [26], in combination with complementary optical and sub-mm observations [27].

1.1.3. Nearby Galaxies

Low-frequency synchrotron emission provides unique information on the state and structure of the galactic ISM, revealing ongoing star formation, properties of cosmic rays (CRs) and magnetic fields [e.g. 28]. The 0.3″ resolution of ILoTSS will disentangle the dense HII regions and other compact objects, reveal the CR injection sites, the clumpiness of the ISM [29], regions of strong thermal absorption and ionization [30]. Unique information on star formation activity will be available through the detection and characterization of young supernovae and supernova remnants [31]. For spectral index analyses, ILoTSS can be combined with the e-MERLIN LeMMINGs survey [32], which has data for 280 galaxies with similar resolution at 1.5 GHz.

Studying CR transport in galaxies is crucial to understanding how CRs migrate from their injection sites, how they are confined to the ISM structure, where and why CR transport is faster, enabling galactic outflows. At 0.3″ resolution we can trace CR transport around individual HII complexes on a scale of 20 pc in the Local Volume galaxies, something not yet achieved in external galaxy studies. The models of CR advection and diffusion in the ISM are available [30, 33, 34] and can be constrained by the distribution of synchrotron emission and spectra. In-band spectra, together with LLoCuSS data, will finally enable detailed physical modelling of processes shaping galaxy spectra at low frequencies [see, e.g. 28, 35].

Using LoTSS, we have demonstrated that the local radio-infrared correlation tracks the physics of galactic star formation [e.g. 36]. With the resolution of ILoTSS we are able to go down below the diffusion length of the CR (about 100 pc) and investigate the conditions of the turbulent ISM that cause the putative breaking of this relation at small scales [37].

1.2. Cosmic Magnetism

ILoTSS RM Grid: A Faraday rotation measure (RM) Grid enables a wide range of science, such as radio AGN physics [38], magnetism of galaxies and their circumgalactic medium [39], discovery of new pulsars [40], Milky Way magnetism [41], and studies of the cosmic web [42]. The unique RM precision of the LoTSS DR2 RM Grid [43] has enabled the detection of weak magnetic fields in cosmic web filament, using $\sim$1000 RMs with redshifts [44].

For the ILoTSS survey, we expect an increase by at least a factor of $\sim$1.5 in the areal source density compared to LoTSS due to the enhanced sensitivity of 30 uJy/beam [46]. The expected increase from imaging at $0.3''$ is less well understood, but has the potential to be truly groundbreaking (by overcoming depolarization effects). Polarization imaging at $0.3''$ has recently been demonstrated (Fig. 3, [45]), and we have pioneered the mosaicing of polarization data with LOFAR (by cross-calibrating the absolute polarization angles and ionospheric RM variations between fields before mosaicing) [47]. These techniques are essential to achieve the full sensitivity of the ILoTSS survey over a contiguous wide area, thus enabling the robust cross-correlation of the RM Grid with cosmic web structure (as identified by *Euclid*, in addition to potential direct detection of filament synchrotron emission from ILoTSS or LLoCuSS). Thus, an ILoTSS RM Grid covering a large, and contiguous, fraction of the extragalactic sky has the potential to be the leading RM Grid survey into the SKA era for cosmic web science, due to the unique combination of low RM uncertainty, moderate to high areal RM density and unrivaled host galaxy redshift information.

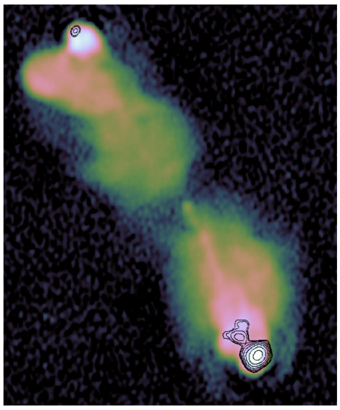

Figure 3: ILT Stokes I (colour) and polarized emission (contours) at $0.3''$ [45]. Only the SW hotspot is detected at $6''$, with new polarized emission detected in the NE hotspot at $0.3''$.

Faraday tomography of the ISM: Observations with the HBA revealed a plethora of structures in Galactic polarized synchrotron emission [48, 47], whose exact origin is still not fully understood. These structures are present everywhere across the northern sky as shown by the LoTSS survey in the outer [47] and inner Galaxy [49]. Moreover, the observed morphological features show a striking correlation with the neutral interstellar phases, traced both by HI emission and interstellar dust [e.g. 50, 48]). The observed link must be related to the full complexity of the magneto-ionic interstellar medium which can be traced by Faraday tomography [51].

For ILoTSS, the survey sensitivity for Faraday tomography of $\sim 25\ \mu\mathrm{Jy\ PSF^{-1}\ RMSF^{-1}}$ will enable the study of faint diffuse polarized emission at $3'$, which encodes information about the regions where synchrotron emission and Faraday-active material are mixed. This is an improvement by a factor of 3 in sensitivity compared to the current LoTSS survey.

1.3. Gravitational Lensing

The depth, uniform noise and angular resolution of ILoTSS will turn LOFAR into a gravitational lens finding machine because the median lensed image separations are $\sim 1''$ ([52] and Fig. 4). The increased depth of ILoTSS is needed to detect the faintest of the multiple images from each system, which is vital for confirming their lensing nature directly from the survey data. We expect to identify > 5000 new radio-loud lensed objects, an increase of a factor $10 - 100$, and in addition ILoTSS will assist *Euclid* lens searches, which will discover more lenses in total, because the joint survey will be an important means of rejecting false positives.

The brightest of the radio-loud lensed objects can be followed-up with e-MERLIN/EVN to investigate the mass distributions on mas-scales, providing a unique probe of the properties of dark matter [53, 54]. Also, given the wide-bandwidths that are available with ILoTSS, it will be possible to investigate the ISM of the lensing (deflector) galaxy population through detecting differential free-free absorption and differential polarisation/Faraday rotation between the different lensed images [55]; this would determine the electron density and magnetic fields within the lenses. Third, the lensing magnifications will increase the effective depth of the survey to $\lesssim 10\,\mu$Jy, probing weak radio jets at the 10^{23} W Hz^{-1} level at $z \sim 2$, and thousands of galaxies with star-formation rates of $\gtrsim 5$ M$_\odot$ yr^{-1} [56].

There are $\sim$200 known radio-quiet lensed quasars, and LoTSS detected 75% that are within the DR2 area. *Euclid* is expected to detect $\sim$1,000 lensed quasars in the area of ILoTSS, with its high angular resolution helping constrain mass models of the lensed objects and the nature of the quasar host galaxies (obscured and unobscured), revolutionising this field. We expect ILoTSS will have the sensitivity to detect most of these quasars, which can be combined with the *Euclid* imaging to determine the radio power and test models for the emission mechanisms at about an order of magnitude lower than the ILoTSS detection limit. Finally, given the 0.3″ resolution and typical magnifications of 10, ILoTSS will be effectively imaging objects at a resolution of about 200 pc at redshift 2. This will uniquely probe models for radio emission mechanisms and structure formation, in combination with the stellar and molecular gas distributions from ancillary multi-wavelength datasets [57, 58, 59].

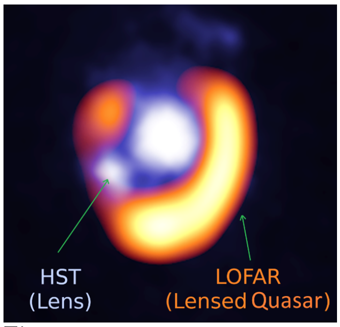

Figure 4: ILT image of a lensed quasar and lensing galaxy from HST [52].

1.4. Galaxy clusters

With ILoTSS the study of galaxy clusters, and the sources within them, will move into the high angular resolution domain. In combination with the LLoCuSS data, we will map the spatial and spectral structure of the diffuse cluster emission, such as radio relics and halos. There are indications that diffuse cluster sources are very filamentary in nature, which may be related to the properties of the underlying MHD turbulence and to the intermittent nature of the turbulent energy flux (see [60, 61]). In order to study the physics of magnetic fields, particle acceleration and transport in these rare objects (~ 10 relics and ~ 40 halos known per 1,000 square degrees), it is important to study the fine spatial structure up to $\sim$3 kpc at z=0.2 (or $\sim$1″). Moreover, diffuse radio sources appear to be connected to radio galaxies [e.g. 62]. In order to study the causal connection, one has to observe clusters at high resolution and at low frequencies, since the filaments connecting radio galaxies and diffuse sources are often quite steep. In addition, we will study the morphologies of the embedded cluster sources, ranging from radio AGN tails to BCGs and "jellyfish" galaxies [63]. In the center of clusters, the 0.3″ resolution (i.e. $\lesssim$3 kpc) offered by ILoTSS will allow detailed studies of AGN feedback up to $z \sim 2$ [64]. These efforts will be substantially aided by the eROSITA all-sky data.

1.5. Cosmology

The distribution of galaxies, as probed in the radio, allows us to measure cosmological parameters and test the principles of cosmology. We have demonstrated this with LoTSS, measuring how galaxies cluster [65, 66] or align [67] and constraining the evolution of the halo mass function and corresponding bias factor [68, 69]. Radio surveys observe to higher typical source redshift than optical surveys, and benefit from the large areal coverage and lack of dust attenuation.

To-date the precision of our results has been hindered by the overall depth, sky coverage and the variations in the sensitivity of LoTSS over wide areas. This has effectivly limited our source samples to AGN and excluded the fainter star-forming galaxies. Furthermore, the comparatively low resolution of LoTSS is mismatched with optical/IR surveys which limits cross-correlation studies between multi-wavelength datasets (e.g. *Euclid*), hinders our ability to resolve multiple radio sources in a given dark matter halo, and prohibits weak lensing measurements. The tighter grid and much higher resolution of ILoTSS will allow us to address each of these shortcomings. Importantly, we are able to exploit the different systematics compared to other wavelength surveys to provide invaluable cross-checks and independently constrain the cosmological parameters and the evolving relationship between radio sources and the underlying environment. The improved depth and sky coverage of ILoTSS over our current analysis [69] will improve the precision on the clustering strenght σ_8 by a factor of ~ 1.7, better than all currently available late universe measurements.

Additionally, the cosmological principle predicts that the proper motion of the Solar system [71] should lead to a source count dipole at all frequencies [72]. Recent results show that there is close to a 5σ tension in the amplitude of the radio source counts dipole compared to the prediction based on the CMB [73, 74, 75, 76]. If confirmed, this would have dramatic consequences for the cosmological principle and imply that an anisotropic universe model could be more likely [77]. ILoTSS has the potential to confirm or refute the tension indicated by the current data. While the Completing LoTSS will also better constrain the dipole signal when the low galactic latitude regions are included in the analysis [78]. For example, comparing an incomplete LoTSS survey to the usable sky coverage of a complete LoTSS, we can improve the precision to within 3% (from ∼10%) and the localization to <3° (from ∼5°).

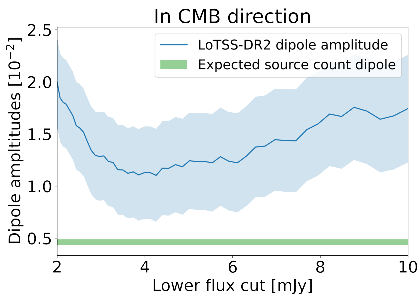

Figure 5: LoTSS-DR2 measurement of the source count dipole amplitude (blue line with 68% confidence level [70]). The green line is the expectation from the CMB dipole. If real, the excess will be detected by ILoTSS at $> 5\sigma$.

1.6. Transient and variable source populations

ILoTSS will be a treasure trove for transient and variable studies. It will probe the time domain through comparison with LoTSS, by making use of the extensive overlap between neighboring ILoTSS pointings (each region of the sky will be measured on 6 different dates) and by exploring the time variable properties in a given 8 hr observation [79]. Such searches will allow us to constrain long (>1 year) or shorter (∼seconds to ∼days) period events 4 or 3 orders of magnitude deeper than current state of the art surveys respectively. Using LoTSS DR1, we have placed the deepest constraints on transient rates to date at low radio frequencies and found one unidentified transient source of duration $O(10)$ sec [80]. Using the full ILoTSS dataset, with 2 minute snapshot images, we expect to find $\sim$50 of these transient sources. The commensal transient survey with ILoTSS is part of a wider campaign outlined in the LORAX proposal (LOFAR2.0 Observations of Radio Astrophysical eXplosions). Few low frequency transient events are known, thus ILoTSS will be crucial to probe new parameter space to discover new events and their origins (e.g. [81, 82]). ILoTSS will detect extreme events such as tidal disruption event afterglows and γ-ray bursts [83], characterize the variable AGN population and continue LOFARs high-impact star/exoplanet work [84, 85, 86, 87, 88].

1.6.1. Star/exoplanet systems

Emission at $\lesssim 200\,\mathrm{MHz}$ from stellar systems encodes the conditions of the outer stellar corona, is sensitive to star-planet interactions [89], and is pertinent for evaluating the exoplanet space weather (with consequences for the emergence and sustainability of life). In 25% of LoTSS we have already discovered 19 M-dwarfs [89, 88], and have confirmed detections of exoplanetary systems both for individual targets and on a statistical basis [90]. These remarkable discoveries have opened up a whole new way of finding and characterising exoplanets, in addition to demonstrating the potential of LOFAR to discover objects at the brown dwarf/exoplanet boundary that are too cold and/or distant to have been found in infrared surveys [86]. ILoTSS will detect 130$\pm$30 stellar systems (or twice this including coronally-active stars), but critically, through the overlap between pointings, it will give insights on the periods of all detections which is vital to assess the star-planet interaction hypothesis [84].

1.7. Milky Way

Finishing LoTSS (a large fraction of which contains the Milky Way disk) will allow, for the first time, detailed low-frequency high-resolution studies of the processes that govern the spatial, chemical, and dynamical structure of the ISM. In particular, stellar outflows and their environments will be studied by systematically searching for non-thermal emission from jets in massive young stellar objects, and using high-resolution maps of planetary nebulae to understand the role of AGB and post-AGB winds in shaping them. Furthermore, the LoTSS maps of the Galactic plane will allow for detailed integrated and spatially resolved spectral studies of individual supernova remnants (SNR), whose low-frequency spectrum can potentially distinguish between different particle acceleration models [91, 92]. In addition, the discovery of new SNR is likely [93] given that our surface brightness limit will be $\sim$10x lower than current studies [94]. Importantly, at 150 MHz the effect of Galactic scattering is such that point sources have an angular size of $\sim 1''$ [95, 96]. Therefore, imaging at 0.3$''$ in different lines-of-sights allows us to probe, for the first time, structure in the warm ionized medium. We aim to achieve these science goals in collaboration with the LOFAR 2m Galactic Plane Survey (L2GPS) team.

We will also continue our collaboration with the Pulsar KSP, using LoTSS imaging to find (and precisely locate) new pulsars, particularly slow pulsars and millisecond pulsars, which are challenging to detect in dedicated pulsar searches (LOTAAS; [97]). To date, the LoTSS-guided targeted pulsar survey has discovered 3 new pulsars, 2 of which are binary millisecond pulsars and 40 known pulsars [40]. Another 7 pulsars recently discovered by other telescopes, which lacked accurate sky positions, were blindly rediscovered, showing the success of these targeted pulsar searches. The full coverage of the Galactic plane will be valuable for all pulsar studies.

2. Observational requirements

Technical Justification Table (please provide additional clarifications and justifications, as necessary)	
Total observing time required	8,658 hrs
Typical time per target	8.0 hrs
Total number of observations per target (including calibrators)	1 target observation. Two 10min calibrator scans within 24hrs of each target observation shared between projects.
Are there parallel observations planned with other observing facilities?	No.
Are there any mandatory stations needed for the observations (e.g. Superterp, International stations, list of customized stations)?	Yes. The most important conditions are $\geq$11 international stations and preferably RS210, RS310, RS508/RS509 to allow full resolution imaging and stable calibration.
Are there date constraints for your observations (e.g., specific dates, LST, cadence)?	No but we want to finish LoTSS within year 1 so it can be publicly released. This is mainly regions at galactic latitude $< 20^{\circ}$.
Are there time constraints for your observations (day, night, no twilight)?	No but the HBA (like the LBA) is heavily influenced by the ionosphere so avoiding sunrise/sunset and days with particularly poor ionosphere is preferable.
Are combined data products requested in the setup (e.g., beam formed + interferometer)?	No. We request pre-processed (average, flagged, compressed) visabilities.
Noise-level you wish to achieve for your observations	0.03 mJy/beam at $0.3''$ resolution
Expected maximum data rate from COBALT to CEP?	6.0 GB/s
Do you request any processing offered by the ILT?	Yes we are keen to exploit any processing (particularly LINC and RAPTHOR) offered by the ILT that helps with the calibration and imaging of the full international array.
Do you need to store raw data products in the LTA?	No our data can be averaged to 1s and 16ch/sb before storage in the LTA.
Do you request your data to be stored at a specific site?	No but we would like it split equally between sites where there is good access to compute - presently SURF and Juelich but we would welcome processing opportunities at Poznan and future LTA sites.
Do you have access to external processing facilities?	Yes we have access to substanstial compute with a track record of securing millions of CPU-hours on JUWELS (Juelich), Spider (SURF) and Hertfordshire (LOFAR-UK)
Are you open to co-observing (LBA, HBA) with other programmes?	Yes we would like to optimse observing efficiency by coobserving with all other projects with spare HBA bandwidth.

The primary aim of ILoTSS is high sensitivity 0.3″ resolution mapping (Fig. 6) of 7,600 square degrees of the extragalactic sky (absolute galactic latitude $>$ 23.0° and declination $>$ 20°) in a region fully overlapping with *Euclid*, WEAVE-LOFAR and the deeper region of the proposed LLoCuSS LOFAR2.0 LBA survey. ILoTSS will be the deepest wide-area radio wavelength survey for typical radio sources (Fig. 9). As shown in Figs. 7 and 8, the existing LoTSS grid spacing of 2.58° is too coarse to meet this objective, due to time-averaging and bandwidth smearing as well as the FWHM of the international stations beam. More specifically, mosaicing wide-area LoTSS images at 0.3″ resolution would result in maps with at least a factor of 6 sensitivity variations that are extremely impacted by smearing but, more realistically, as stable calibration of a region requires sufficient apparent flux, large regions of the sky can not be imaged at this resolution using LoTSS data alone. Through ILoTSS we will build new pointings into the existing LoTSS grid (placing a new pointing between each pair of neighbouring LoTSS pointings), thus making optimal use of the vast existing LoTSS dataset (∼15,000 hrs of observations) whilst rectifying this severe limitation. As shown in Fig. 8, ILoTSS will enable us to image large contiguous areas at the full resolution of the ILT at almost uniform sensitivity. Furthermore, the extra data will provide a factor of two improvement in sensitivity compared to LoTSS which will double the source density when mapping at 6″ resolution (from ∼800 sources per square degree to ∼1,600).

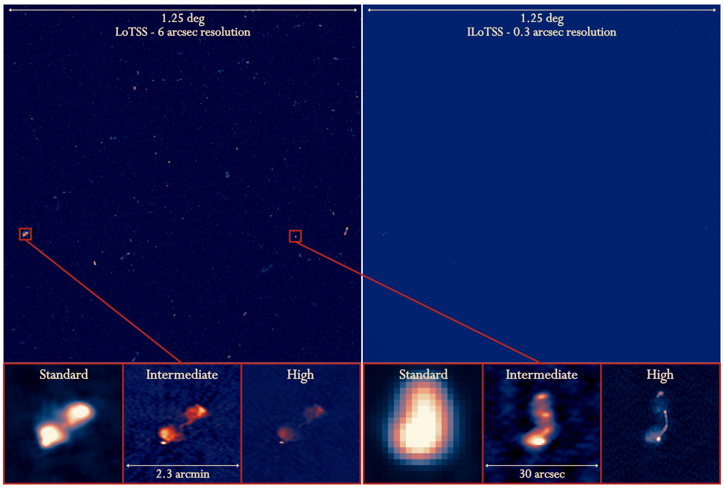

Figure 6: Left: LOFAR HBA image with 6" resolution and 100μJy/beam sensitivity. Right: Wide-field international baseline image from the same dataset; here the resolution is 0.3 asec and the sensitivity improves to 35μJy/beam due to extra collecting area ([2]). The cutouts show 2 sources at LoTSS (6″), intermediate (1″) and international baseline resolution (0.3″). Full images are available on https://home.strw.leidenuniv.nl/~sweijen/lockman_aladin.php

As part of this proposal we also request to complete LoTSS and to repeat LoTSS pointings within the ILoTSS footprint that were taken in the earliest LOFAR cycles where there were less than 11 international stations available (see Fig. 8). The number 11 has been chosen as below this number the calibration is unstable and the resolution is compromised (if we were instead to choose 10, the number of observations required for these repeats only decreases by 5). Of course, the repeated observations will directly contribute to the new ILoTSS tier of the survey whereas the remaining LoTSS pointings are outside the ILoTSS footprint. However, completing LoTSS will not only allow for a final LoTSS data release covering the entire hemisphere and the completion of key science goals that are yet to be accomplished with LoTSS (i.e. Galactic science and high precision radio source dipole measurements) but it will also enable 0.3″ imaging of large parts of the sky outside the ILoTSS footprint and will form the foundations of any future expansion of ILoTSS.

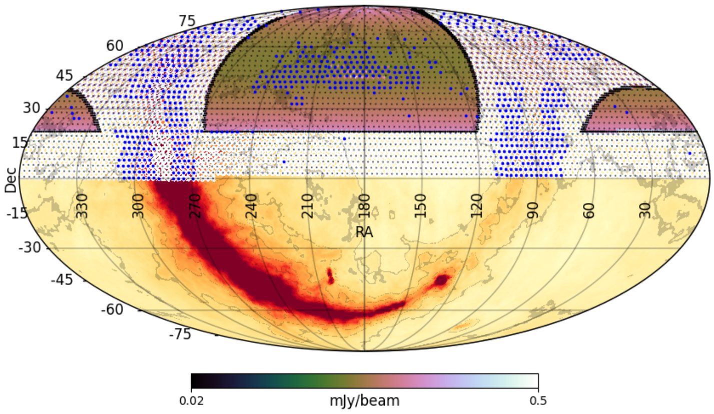

Figure 7: The ILoTSS anticipated sensitivity extrapolating from achieved 0.3″ imaging sensitivity (e.g. [2]) and including known declination dependencies due to the station beam projection. The highly sensitive (30μJy/beam) regions outlined in black are the regions with both ILoTSS and LoTSS coverage whilst the lower sensitivity (up to 0.5mJy/beam) regions are where only LoTSS data exists. The blue markers show the remaining and repeat LoTSS observations that we aim to conduct.

In total we request to observe 534 pointings (1230 hrs) to complete LoTSS, 202 pointings (404 hrs) to repeat pointings within LoTSS that have less than 11 international stations (necessary for stable calibration and imaging performance) and 3512 new pointings spaced between each LoTSS pointing with absolute Galactic latitude $> 23.0°$ and declination $> 20°$ - these new pointings will form ILoTSS (7024hrs). Thus the total time request is 8,658 hrs split between 4248 pointings (4 of which will be observed simultaneously). We note that in this proposal we have included all pointings required to complete LoTSS because this is the top priority for our first year of operations. However, we emphasise that 318 of the 534 pointings (∼700 hrs) required to finish LoTSS are also requested as part of the L2GPS proposal and we have full data sharing between the two projects thus reducing our effective time request. We also envisage that 500-1,000 hrs of data can be obtained by co-observing with other large programs (or single cycle proposals) that observe objects within or near our proposed area and have spare HBA bandwidth (e.g. LUDO, ExLOO, LoDMaX, nearby galaxies).

Our preference is to complete LoTSS within the first year of LOFAR2.0 operations so it can be publicly released, ensuring that its full legacy value and scientific potential can be realised. Furthermore, as LoTSS is processed at 6″ resolution using a well-established pipeline (DDF-pipeline) and infrastructure, these are low-risk observations for early LOFAR2.0 operations. We also hope to gather several hundred square degrees of contiguous ILoTSS data in year 1 allowing us to start to refine the automation, performance and deployment of pipelines on various compute facilities and fully demonstrate the feasibility of ILoTSS. After year 1 we aim to observe at a rate of at least 1,000 square degrees per year and to build up contiguous areas of ILoTSS until the survey is complete. Building contiguous areas allows us to do the mosaicing right away and release to the community final data products for the observed region.

2.1. Observational setup

The observational setup for the ILoTSS pointings is the same as that that has been successfully used for LoTSS except that we opt to use HBA-dual rather than HBA-dual-inner. This change in our strategy is because the ILoTSS grid is tight enough for the smaller beam and the international stations already present the issue of dealing with different beams for different stations (commonly

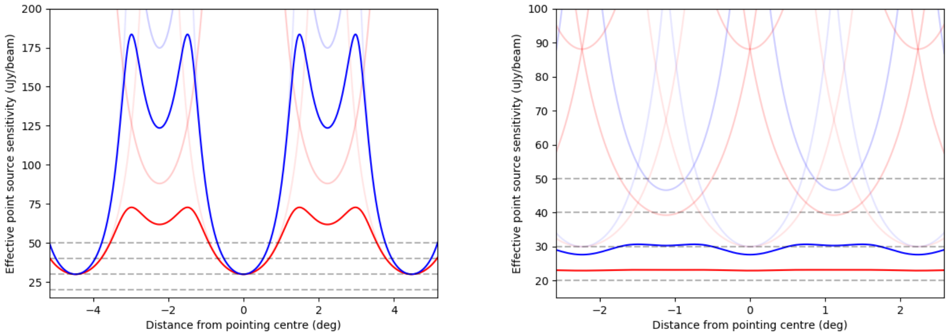

Figure 8: The individual pointing and mosaic effective point source sensitivity for the LoTSS grid (2.58° separation) and the proposed ILoTSS grid separation (1.29° separation) when assuming the international station field of view at 150 MHz (FWHM of 2.7°) and 0.3″ resolution imaging are shown on the left and right respectively (note different x-axis and y-axis limits). The mosaic response is shown with the dark red and blue lines which show the sensitivity accounting for, or not accounting for, time- and bandwidth-smearing respectively. The semi transparent red and blue lines show the individual pointing contributions, again with and without smearing respectively. Whilst 0.3″ resolution imaging with the LoTSS grid is somewhat possible, the sensitivity variations over a region are approximately a factor of 6 and are primarily due to smearing effects.

used LOFAR software now supports different beams). Furthermore, our initial tests with HBA-dual (through ILoTSS preparation project LC20_008) did not reveal any unforeseen issues and, in line with expectations, offer better sensitivity of the central region compared to HBA-dual-inner (we do not yet have sufficient statistics for a definitive number but of order 20%). Otherwise, as with LoTSS, we plan to conduct 8 hr observations, with 48 MHz bandwidth (120–168 MHz) on each of the four simultaneously observed target pointings. Continuous 8 hr observations, where possible, are preferable in order to simplify the analysis of the linear polarization data (i.e. to avoid the data-intensive task of correcting for global polarization angle offsets between observations [46]). The inclusion of international stations in our observations is critical and the data must be stored at high resolution (16 ch/sb and 1 s) in the LTA to avoid time or bandwidth smearing.

We envisage archiving the data after RFI flagging, averaging and dysco compression. The volume of each pointing is approximately 5.5 TB, making the total data volume of the proposed survey to be stored in the LTA 23 PB. We do not require specific calibrator observations associated with each target observation but instead request at least two 10 min calibrator observations within 24 hrs of a target observation. These calibrators can be shared between projects. For consistency, and because of the larger pointing grid separation, we request that the observations to complete LoTSS are still conducted with HBA-dual-inner.

We anticipate that an 8 hr HBA-dual 120-168 MHz integration at optimal elevation with the full ILT at a resolution of 0.3″ will have a sensitivity of 30 μJy/beam at the pointing centre. This is consistent with the results of [2] and applies to both wide-field and postage stamp style imaging in regions where the noise is not limited by dynamic range. When imaging individual pointings at lower resolutions of 1″ or 6″ we anticipate reaching 60 μJy/beam and 80 μJy/beam in line with the results of [98] and [99]. During mosaicing with the tight ILoTSS grid, the noise levels will further decrease and we expect uniform noise levels over large areas of 30 μJy/beam, 50 μJy/beam and 60 μJy/beam when imaging at resolutions of $0.3''$, $1''$ and $6''$ respectively. With this setup ILoTSS can be observed at a rate of a square degree per observing hour.

In Sec. 4 we detail the technical challenges associated with ILoTSS as well as the anticipated data processing strategy.

2.2. Co-observing possibilities

In ILoTSS we shall make use of all 976 subbands which we will split equally between 4 ILoTSS pointings that are simulatanouesly observed. We are aware of other programs where the full bandwidth will not be exploited for the science aims of that program (e.g. all proposals with spare HBA bandwidth such as LUDO, ExLOO, LoD-MaX, nearby galaxies). Given that ILoTSS is a wide area survey, many of the targets of these science programs fall within the ILoTSS footprint, and, where possible, we aim to establish data sharing agreements with other programs and make use of spare bandwidth by observing ILoTSS pointings. This will require coordinated observing at a later date but will help boost observing efficiency and scientific output of LOFAR2.0. Furthermore, through LoTSS we established a co-observing program for single cycle LOFAR1.0 proposals and we wish to offer this opportunity again with LOFAR2.0.

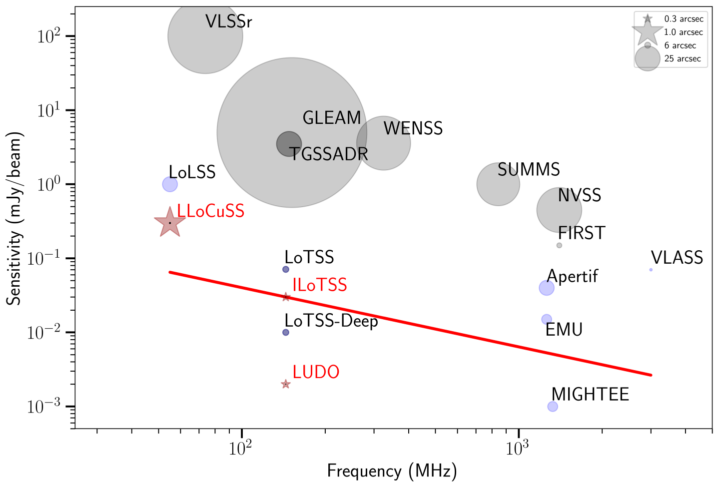

Figure 9: The rms, frequency and resolution (proportional to the size of the markers) of ILoTSS in comparison to existing (grey), ongoing (blue) and proposed (red) surveys. Most of the surveys are wide area (> 1000 square degrees) but the LUDO, LoTSS-Deep and MIGHTEE deep surveys (about 20 square degrees) are included to show state of the art depth. The red line shows the equivalent sensitivity to radio sources with typical spectral indices of -0.8.

3. Description of team and programme

3.1. Team structure, communication and membership

Our project to create ILoTSS and finish LoTSS is the continuation and major expansion of an existing project. It will therefore initially continue to be carried out within the construct of the LOFAR Surveys Key Science Project, in close collaboration with the LOFAR Magnetism Key Science Project. All members of these existing key science projects (over 400 people) will have access to ILoTSS data. Furthermore, after advertising our proposal, over 130 individuals (online membership list) expressed strong interest in contributing to ILoTSS through aspects such as scientific research, computing, pipeline development, processing, observing, group coordination, publicity and synergies with other experiments. These members form the base of our ILoTSS team which we shall continue to expand, both in members, expertise, and in the number of external collaborations (e.g. we already have MoU with Apertif, eBOSS, *eROSITA*, WEAVE-LOFAR and *Euclid*), to ensure that we continue to meet technical challenges and exploit scientific opportunities. Our base group is split over 21 countries, 62 institutes with 59.5% preferring the pronouns He/Him, 33.6% She/Her, 2.6% They/Them whilst 3.4% prefer not to say. This group consists of 36.2% researchers/associate professors, 13.8% full professors, 11.2% PhD students, 35.3% Postdoctoral researchers, 3.5% other where 55% have permanent positions.

Our collaboration is entirely open to all researchers in LOFAR member countries and interested parties can join upon request. In many cases membership will also be granted to researchers in other countries to broaden our expertise whilst striving for good age and gender balance and being inclusive of minority populations. We also have a policy of allowing external scientists to conduct research with our data and data products if it does not conflict with our ongoing or planned research activities within the collaboration. Finally, our target user base is the international astronomical community and we strive to make our data products and software freely accessible with low barriers of entry as well as being well documented and as versatile as possible to facilitate full scientific exploitation by the broad community (see Sec. 5).

Our team has well established publication policies (e.g. SKSP-policy and MKSP-policy) and all members must follow the principles outlined in the IAU code of conduct. Our team interacts with regular collaboration meetings that focus on e.g. project-wide events, particular scientific topics, key results or technical challenges. Furthermore, we have a general bi-weekly meeting for any project discussion, busy-weeks for technical/scientific challenges, bi-monthly project management meetings, and an approximately biennial large collaboration wide hybrid conference where all aspects of the project and research are discussed.

The collaboration is organised into distinct scientific and technical working groups, so that our scientific programmes are led by world experts, our coordination groups ensure excellent oversight of key scientific synergies, and our technical developments are organised yet creative.

Science Working Groups

- Evolution of AGN and star-forming galaxies *(P. Best, L. Morabito)*
- Low-redshift AGN and AGN physics *(R. Morganti, M. Hardcastle)*
- High redshift radio sources *(K. Duncan, G. Miley)*
- Nearby Galaxies *(K. Chyży, J. Conway, V. Heesen)*
- Galactic radio sources *(G. White, M. Haverkorn)*
- Cosmological studies *(D. Schwarz, C. Hale)*
- Magnetism *(S. O'Sullivan, C. Horellou, V. Heesen)*
- Gravitational Lensing *(N. Jackson, J. McKean)*

- Clusters and cluster halo sources *(G. Brunetti, M. Brüggen, R. van Weeren)*
- Exoplanets and stellar systems *(H. Vedantham, J. Callingham)*

Coordination Groups

- WEAVE-LOFAR *(D. Smith)*
- Transients *(A. Rowlinson)*
- *Euclid (Lingyu Wang, H. Röttgering)*
- *L2GPS Galactic plane survey (M. Arias, K. Rajwade, M. Hajduk)*

Technical Working Groups

- Pipeline development *(C. Tasse, M. Hardcastle, L. Morabito, R. van Weeren, F. Sweijen, R. Timmerman, J. Petley, T. Shimwell, A. Drabent)*
- *Observing (A. Botteon, W. Williams, T. Shimwell)*
- Data processing *(M. Hardcastle, A. Drabent, T. Shimwell)*

3.2. Scientific and technical expertise

Our co-PIs Shimwell & O'Sullivan lead the LoTSS survey and magnetism working group which are critical aspects of ILoTSS. Our team has worked closely together for several years and has a wide range of expertise for all stages necessary to enact this survey: preparing observations (extensive operation of LOFAR via expert user support); efficient bulk processing of data (e.g. [100, 101, 102, 103]); complex but robust state of the art direction-dependent calibration and imaging algorithms (e.g. [104, 105, 106]), including international station calibration (e.g. [107], [2]); catalogue generation; cross-matching with multi-wavelength data for science-ready value-added catalogues ([108, 109]); dissemination of the final data products; science exploitation. We have together achieved four successful public data releases (LoTSS [105, 109, 110], LoTSS Deep Fields [106, 111, 112, 113], LoLSS [62]), and the second data release of LoTSS [99], [108]). LoTSS DR2 is the largest-ever radio source catalogue, with 4.4 million sources spanning 26% of the sky; 200 TB of data are public including many image products and calibrated uv-data [99]. LoTSS-DR2 is also the largest-ever cross matched radio-optical catalogue with counterparts identified for 85% of the detected radio sources [108]. Our team has produced over 250 publications (Publication library, including three A&A special issues (LoTSS, LoTSS Deep Fields, ILT sub-arcsec imaging) and numerous works in the highest profile astronomical journals. Our works span not only the Stokes I image products but also the time and polarisation nature of the emissions. Finally, we have an excellent track record for obtaining funding for scientific research (members awarded e.g. VENI, VIDI, ERC starting, consolidator & advanced) and securing vast computational capacity (we presently use up to 1,000 cores at a given time and store over 2 PB of data through grants at Jülich (CHTB00), Hertfordshire (ST/V002414/1), SURF (2019.056) and others and are able to increase our capacity).

Our team will work in close coordination and collaboration with the ILT, telescope operators and other LOFAR2.0 programs, to help ensure sufficient technical development, smooth operations and efficient robust data processing for the benefit of all telescope users. For example, we envisage joint compute and storage proposals with other LOFAR2.0 programs and the ASTRON SDCO to secure sufficient resources to scientifically exploit the allocated telescope time. We have dedicated highly-experienced personnel to run the observing program and assist the telescope operators. We also intend to make full use of all services the ILT are able to offer (e.g. LINC, RAPTHOR, User Pipeline Execution, ADEX) and to contribute to these developments through whatever forums are established to coordinate with other LOFAR2.0 programs and ASTRON/ILT developers. As previously highlighted, our team has vast experience in each of these areas and whilst we have identified some team members who will dedicate substantial time to processing, pipelines and observing (see Table above) we note that far more members are keen to help these aspects - from the 130 base team members 22%, 9%, 22% and 19% are keen to assist with pipeline development, computing/storage, observing, and processing respectively.

3.3. Career development opportunities

Early and mid-career researchers form the majority of our base team and the wider SKSP/MKSP membership. Of course a key ambition of our project is to provide development and leadership opportunities to enrich the careers of project members, particularly those at early or mid career level who are given priority to lead research projects. Our PIs and a substantial fraction of our scientific (45%), coordination (85%) and technical (90%) group leaders are early or mid career researchers and have clear leadership roles in our collaboration. Importantly though, the scientific output of our collaboration is completely dominated by young researchers with 35%, 30% and 25% of our publications led by postdocs, PhD and young faculty respectively. This highlights the scientific opportunities our collaboration provides for young researchers who lead essentially all our major scientific studies. These scientific and leadership opportunities have resulted in many (> 20) young researchers in our collaboration securing permanent jobs in astronomy and/or substantial research grants directly related to LOFAR surveys work (including VIDI, VENI, ERC starting, consolidator & advanced). Our collaboration and its leadership group continuously evolve and our shared ambition is to ensure our teams are balanced (e.g. career level, gender, regional) and at every opportunity we shall seek to improve this balance.

In our team we also have particular emphasis on supporting those whose efforts make the survey possible through e.g. software, processing, observing. Presently this group is recognised through a builders list that provides the opportunity to join and contribute to collaboration publications. Furthermore, we strive to ensure this group are given priority to lead research projects in areas of their interest as well as actively recognising their contributions in conference talks, press releases and by referencing and summarising technical aspects in publications.

3.4. Coordination with other large LOFAR2.0 programs

This proposal is submitted following discussions on scientific synergies, efficient observing, shared technical development and mitigation of scientific overlap between the teams of the Nearby galaxies, LoDMaX, COSMOS, ExLOO, LUDO, LLoCuS, ILoTTS, LORAX and L2GPS. Our team aims - in close collaboration with ILT/ASTRON and other LOFAR2.0 programs - to (i) deliver an optimised survey that accounts for the science interests of proposers as well the wider LOFAR community, (ii) coordinate work on analysis methods, processing pipelines, data storage and computing infrastructure and telescope commissioning to ensure the shared ambition of producing science ready products is realised and publicly available, (iii) keep team membership open to all interested astronomers in LOFAR countries and, upon special request, from other countries whilst striving for good age and gender balance and being inclusive of minority populations, (iv) produce science papers following shared principles in a publication policy that outlines routes for conflict mitigation, strengthens career development and leadership opportunities for young members and credits those that play important roles in producing the surveys, (v) optimise the accessibility of complementary surveys at other wavelengths, and (iv) coordinate public engagement and press events. A coordinating team will be setup up consisting of the PIs and/or nominated representatives, of the various proposals.

4. Observing, data processing and management plan

Our proposal relies on observing and imaging 23 PB (split over several thousand observations) of data at resolutions ranging from several arcmin to 0.3″. This allows us to optimise surface brightness sensitivity and point source sensitivity both of which are required to achieve our varied scientific goals. Furthermore, we aim to do this in all polarisations (requiring images at ≥ 480 frequencies to mitigate bandwidth depolarisation) and to study the time dependence of the emission (up to 1s). Below we outline our observing, processing and data management plan.

4.1. Observing process

Through W. Williams, A. Botteon and T. Shimwell we have run LoTSS as a user-shared support project since 2017. We have carried out over 10,000hrs of HBA observations and assessed their quality (through observatory provided inspection plots and by processing through pipelines such as LINC or DDF-pipeline). These previous observations are almost identical to the proposed observations and the same observers will spearhead the observing process for ILoTSS. Should a change of personal be required due to unforeseen availability issues then new observers will be trained within our team and in collaboration with the observatory to ensure a smooth transition.

4.2. Data processing

4.2.1. Required tools and development

Pioneering studies such as [1, 2, 45], have paved the way for this ambitious proposal and demonstrate that 0.3″ resolution imaging is possible with existing pipelines and components that are a mixture of those offered in the proposal call (LINC, WSCLEAN, DP3 [114, 115]) and those presently used for studies with LoTSS or comparable datasets (e.g. DDF-pipeline, Facet-selfcal, Long-baseline pipeline, DynSpecMS, DDFacet, kMS [116, 117, 118, 119]). The results achieved to date include those from [2] who used 250,000 CPU-hours to map the full ILT field of view (6.6 square degrees) at 0.3″ resolution and obtained a sensitivity of 30μJy/beam (Fig. 6). Alternatively, [1] demonstrated a more postage stamp style approach where a number of target sources in a field could be examined at 0.3″ resolution at the cost of about 30,000 CPU-hours per 100 sources. Using such an approach polarisation studies are feasible and [45] have already demonstrated the detection of polarised emission at 0.3″ resolution with the HBA (Fig. 3). Finally, in [98] we demonstrated imaging at an intermediate resolution of 1″ where the full field of view can be processed in 50,000 CPU-hours (i.e. 5 times less than [2]).

Despite these studies a pipeline that requires negligible user interaction and routinely produces high-quality ILT-resolution images of wide fields in a tolerable time frame does not yet exist. Hence development is required prior to bulk processing the vast ILoTSS and LoTSS datasets at full resolution. Our team already develops with ASTRON and our plan is to continue to collaboratively build upon what the ILT can offer to ensure that robust 0.3″ resolution imaging pipelines are available to all LOFAR2.0 users. As such it is not yet possible to definitively say what software packages will be in the final pipelines used for ILoTSS but we anticipate using all imaging related packages offered in the proposal call and coupling this with other software developments by our team as well as co-development with the ILT and/or partners. As detailed in Sec. 5 we endeavor for all our software developments to be open-access.

4.2.2. Required compute and storage

Even though the software and pipelines are rapidly evolving we can estimate the compute resources required for this project. For a single field we anticipate a minimum of 50,000 CPU-hours and a maximum of 125,000 CPU-hours will be required for full wide-field imaging at $0.3''$ resolution. These numbers are motivated by reproducing the work of [2] which would now take 125,000 CPU-hours compared to the original 250,000. Here the speed improvements achieved so far are due to improved efficiency of visibility gridding and the application of facet imaging in WSCLEAN. Further areas for efficiency improvements have already been identified in the application of solutions and profiling to find other areas is ongoing. Postage stamp imaging is likely to remain far cheaper computationally and we estimate that 100 sources per field can be achieved in less than 20,000 CPU-hours hours compared to the present requirement of about 30,000 CPU-hours. Here bottlenecks in the processing have been identified and improvements will be made to the removal of off-axis sources whilst innovative approaches that make use of DDFaect/kMS to simultaneously produce and calibrate a given number of postage stamp images across a field of view have been demonstrated and are ready for extensive testing.

Our team has extensive experience utilising large facilities including the LTA sites at Jülich and SURF as well as the super computers in Hertfordshire that have fast access to some LTA sites (download speeds from SURF to Hertfordshire reach 500MBytes/s). For example, presently, we use up to 1,000 cores at a given time and are able to increase such capacity (note that e.g. producing LoTSS-DR2 took 10 million CPU-hours). At the moment, the majority of our processing occurs on SURF (1 million CPU-hours per year through NWO grant 2019.056), Jülich (1 million CPU-hours per year through grant CHTB00), Hertfordshire/LOFAR-UK (7 million CPU-hours per year though STFC grant ST/V002414/1). Our main archiving areas are presently in Leiden (500TB), SURF (2PB) and Hertfordshire (500TB) and from these sites we are able to make our data products available to both our collaboration and the wider astronomical community (e.g. LoTSS-DR2 repository; LoTSS-DR2 release). At each of these sites there is substantial room for growth, with opportunities to access UK SKA computing resources in addition to LOFAR-UK resources at Hertfordshire, whereas our allocations at SURF and JUWELS are both very small compared to similar level scientific projects at these sites (often 10-50 million CPU-hours). The new large Italian LOFAR Computing cluster (72 nodes totaling 2592 cores) will also be available for ILoTSS. We are also looking for opportunities to deploy processing in Poznań but this has not been necessary for present projects. For the entire ILoTSS we anticipate needing approximately 300 million CPU-hours split over 5 years and 30PB of storage gradually accumulated during this period (which we hope to store in the LTA). Whilst these numbers are large (7 times more cpu than we presently use and about equal storage to LoTSS) they are not prohibitive given the compute accessible to the collaboration. Furthermore, many of our scientific aims can be achieved with far fewer CPU-hours, e.g. postage stamp maps rather than full wide field maps would require a factor of 5 less resources whereas producing $1''$ maps would be 2-3 times less. Producing these less expensive products would be a step towards producing full field of view $0.3''$ resolution images and would not be wasted compute. For example, if we were to take an approach of first producing postage stamp maps then we would derive direction dependent calibration solutions in a number of directions at full resolution: such solutions could later be used to produce full wide field of view images and thus compute is efficiently used.

4.2.3. Required data processing services

We can provide substantial compute for ILoTSS but are also keen to utilise and help develop services offered by the ILT such as additional compute; executing LINC and RAPTHOR (if they produce the desired data products); and in optimising the efficiency of ILT software. We also envisage that the User Pipeline Execution (UPE) services (see "LOFAR2.0 Large Programme Proposals Data Management Capabilities") would be very useful for ILoTSS as we seek to refine processing using both ILT-supported and externally developed tools (i.e those used for LoTSS that we are adapting for full ILT-resolution imaging, namely DDFacet, kMS, DDF-pipeline). As detailed later, the LTA is another service of great importance and we hope to store 30 PB there.

4.3. Data product management

4.3.1. Archiving and legacy value

We aim to produce calibration solutions and associated products that when applied to the pre-processed (flagged, averaged, compressed) data products produce the final calibrated images. We believe this is the most efficient way of archiving our data as it requires the least data transport and offers the most flexibility for further processing – both for tailored reprocessing for specific science aims or because of improvements in calibration and imaging techniques. An alternative is to store the processed data and calibration solutions (it is not possible to have calibrated data for a whole wide field as different calibration solutions apply for different parts of the field and thus the calibration solutions should be applied during imaging) but given that we will not average our data due to time and bandwidth smearing limitations the storage size is the same. The calibration solutions and associated products that are required to create the fully calibrated images are about 10% of the size of the uv-data. Additionally, we will archive several PB of image products (including polarisation and several resolutions of total intensity) and associated catalogues. In line with the "LOFAR2.0 Large Programme Proposals Data Management Capabilities" document we hope to store all of these data in the LTA regardless of where they are generated. These will then be VO-compliant, support FAIR data management principles and will be discoverable through ADEX.

All the data that we collect as well as the data products we derive will be valuable legacy products for future users. Our source catalogues and images will likely have the broadest reach because they are the easiest to work with. However, these products are also inflexible and do not allow a user to tailor our data to their science. Hence our intention is to allow for the data to be reimaged in whichever way a user would like, as such an approach has proved invaluable for LoTSS. Examples of projects that have post-processed large amounts of LoTSS data to include: searching for transient sources (reimaging at 8 second cadence, [80]); searching for very low surface brightness structures (remove sources and image at very low resolution, [120]); discovering and characterising star/planet interactions (reimaging Stokes V at different cadences, [88]); and charactersing faint diffuse emission from AGN, clusters or galaxies (optimise calibration for target, remove contaminating sources, reimage, [45]). We understand that these products are large (i.e. the products are the pre-processed data, calibration solutions, images (IQUV) and catalogues and we anticipate these occupy about 8TB per pointing or 30PB for the entire 7,600 square degree survey). However, without storing this large amount of data many important scientific opportunities would be lost forever. Publicly releasing our entire dataset is very important and our data release strategy is detailed in Sec. 5.

5. Publication and dissemination plan

In year 1 we aim to collect all remaining LoTSS data and produce a final LoTSS (6″) data release of the entire northern sky. Existing LoTSS data release publications have accumulated over 1,200 citations and the final data release will facilitate a huge number of studies whilst also completing important outstanding aims of LoTSS (i.e. cosmological, galactic, full-sky legacy). Simultaneously we aim (year 1) to publish the ambitions and setup of ILoTSS as well as presenting a demonstration of the feasibility of the project for a wide range of applications (e.g. 0.3″ imaging, polarisation, time variability). This article will help iron out processing procedures, enable us to thoroughly characterise the quality of our dataproducts and critically examine all aspects of our survey strategy - this will assist the focusing of resources on aspects where development is most necessary. Over the following years we shall publish $\sim$3 further ILoTSS data releases (roughly evenly spaced over the duration of the project). Here the first would cover several hundred square degrees, the second several thousand and the third the entire ILoTSS region. As we have so successfully done with LoTSS, each data release will be appropriately split (e.g. polarisation, Stokes I, time variability, multi-wavelength) into enough articles to ensure that all aspects of the survey are fully characterised so that they can be properly exploited by the wider community.

To achieve low barriers of accessibility to science usable data release products we shall build upon the foundations we have laid with LoTSS where our science products are arguably the most widely used and easily accessible that LOFAR has produced to-date. For example, through the LoTSS-DR2 data release webpage we have available a range of science-ready products that are fully documented in publications. Users can access our full polarisation images and catalogues ([43], [88], [99]) as well as our multi-wavelength cross matched catalogue ([121] which contains optical identifications and source properties (including redshifts we dervied from auxillary data) for all sources where it was possible to do so. Users can also make use of other products such as images optimised for surface brightness ([120]) or cutout uv-datasets with optimised calibration for targets of interest (over 1500 objects including galaxies, clusters, AGN, stars, see e.g. [122]). Finally, as we hope to build upon with ILoTSS, we have released large uv-datasets and associated calibration solutions through the DICE project (Horizon 2020 Grant no. 101017207). These products are widely used for projects that require tailored calibration, different imaging, or the examination of variability and polarisation. We thus have extensive experience in making our products accessible and a comparable range of products will be produced for ILoTSS to ensure that catalogues (radio and cross matched), images and data can all be fully exploited. Inspired by our LoTSS experience we also hope to be able to provide a space for legacy products derived from ILoTSS studies (i.e. calibrated cutout datasets and images used in publications).

We aim to publicly release all products associated with data releases through the LTA. A critical part of this is the pre-processed data and in line with present LOFAR procedures we anticipate that the proprietary period for these data will be a year, although we would waive this period for any proprietary data contained in a data release. Final images, catalogues and calibration solutions would also be available through the LTA. These products would only become public at the time of a given data release so that their characteristics are fully described to potential users. However, before their public release the collaboration members and external collaborators may require access to products and we aim to facilitate that through the LTA.

The data releases will form a tiny fraction of our publications as many of our team members focus their efforts on the vital scientific exploitation of the data. As described in the Sec. 1, each science working group has clear ambitions to produce world-leading results. The science groups meet regularly and group leaders manage active and planned projects to avoid and rectify any overlap between projects. The group leaders are committed to ensuring excellent opportunities and priority for young and mid career scientists to develop as researchers and to lead key projects. Furthermore, they shall protect the scientific interests of those that contribute so much to the ILoTSS technical operations and provide them with important scientific opportunities. As with LoTSS, and thanks to the new parameter space that ILoTSS is exploring (Fig. 9), we anticipate that over 90% of our publications will be scientific studies of single objects or samples. ILT resolution data already exists (primarily through LoTSS) and high resolution studies are already being conducted by our team for science demonstration and to build experience. As expertise grows the frequency of publication is increasing ([52, 123, 124, 26, 125, 18]). Finally, besides large data releases we will release data products to interested parties if there are no conflicts with other projects, thus allowing a constant flow of data products to the wider community.

Another important aspect is the release of software and pipelines to ensure that they can be used on other facilities or by other LOFAR users. Our team's contributions towards LINC and RAPTHOR will be coordinated with ASTRON but presently these packages are developed on the the GitLab and are freely available. Other pipelines and software packages such as DDF-pipeline, longbaseline-pipeline, DDFacet & kMS are all developed on GitHub and publicly available through OSI-approved licenses. We have also made these packages available in Singularity and Docker containers allowing them to be easily deployed on different compute clusters.

The key form of disseminating scientific and technical results from ILoTSS is through peer-reviewed publications in reputable journals that are appropriate for the subject matter. For example, in LoTSS we have published in journals including Nature, Nature Astronomy, Science, Science Advances, MNRAS, ApJ, A&A. We expect ILoTSS results to be published in a similar array of journals. Results and progress will also be presented at relevant conferences that allow our team members to appropriately highlight scientific or technical aspects of the project. These are in addition biennial collaboration conferences that focus on results, ambitions and progress with ILoTSS. Besides this, we do not envisage key conferences where our results must be presented but instead anticipate that our team will present at a wide range of different conferences that have focuses including: general radio, multi-wavelength, science specific (e.g. AGN, clusters, cosmology, magnetism, transients, etc.), future instruments/science, astronomical software, data intensive astronomy and astronomy schools. Of course, for large relevant conferences we shall seek to ensure that ILoTSS is represented. Finally, for key results and achievements we expect our team to issue press releases to reach a wider audience. As we have done with LoTSS, the press release is led by the lead scientists on a particular project and is coordinated with various institutes that have interests in that project. We shall also pursue other public engagement opportunities, for example building upon our LOFAR galaxy zoo where citizen scientists made an astonishing 957,374 classifications of LoTSS sources (see [121]). From our experience with LoTSS we have found our results are very well picked up by the community (over 8,000 citations of LoTSS results, numerous successful international press releases, and 13,711 distinct users of our galaxy zoo) and this gives us faith in our methods of dissemination.

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