LOFAR-UK

Proposal to STFC PPRP

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Summary

LOFAR is a next-generation software-driven telescope currently funded and under construction in The Netherlands by ASTRON. Operating in the poorly explored 30–240 MHz frequency range, with an unprecedented field of view and multiple beams, it will open up a completely new phase of radio astrophysics. In addition to this, it is the only fully-funded pathfinder for the low-frequency component of the *Square Kilometre Array*, one of just two future astronomical facilities in the Reseach Councils UK Large Facilities Roadmap.

LOFAR-UK is a consortium of fourteen UK Universities (plus RAL and the ATC), with the goal of joining the LOFAR project by siting antennae stations in the UK and transporting the data for correlation in The Netherlands via high-speed internet. In return for this contribution to the project we have developed strong involvement, and in some cases overall leadership, of some of the key scientific projects of this major new radio facility. LOFAR-UK has been in existence for 2+ years already and has generated an extremely broad interest, far beyond the traditional radio astronomy groups, and has raised sufficient funds to purchase an initial LOFAR station for siting in the UK. This proposal, in concert with other major funding bids, is for resources to expand the LOFAR-UK network to four stations, making us a major partner in this ground-breaking European project. Without this, current significant UK activities within LOFAR will have to be scaled back.

The LOFAR project is itself being augmented not only by stations in the UK, but also in Germany, France, Sweden and maybe also Italy, Poland, Austria. Thus the project is evolving towards a pan-European, low-frequency radio network, designated **E-LOFAR**.

This proposal is submitted on behalf of LOFAR-UK, which is a consortium of representatives from:

Liverpool John Moores University, The Open University, The University of Cambridge, The University of Cardiff, The University of Durham, The University of Edinburgh, The University of Glasgow, The University of Hertfordshire, The University of Manchester, The University of Oxford, The University of Portsmouth, The University of Southampton, Aberystwyth University, University College London /Mullard Space Science Laboratory, and The Rutherford-Appleton Laboratory

1 Science Case

1.1 Introduction

LOFAR, the **Lo**w-**F**requency **Ar**ray, is a next-generation software-driven radio telescope operating between 30 and 240 MHz. This low frequency radio band is one of the few largely unexplored regions of the electromagnetic spectrum. The sensitivity and angular resolution offered by LOFAR will be two to three orders of magnitude better than existing telescopes at these frequencies, and as such it will open up this new window on the Universe. LOFAR will have an enormous field of view, offering survey mapping speeds orders of magnitude in excess of other radio telescopes, and facilitating semi-continuous monitoring of more than half of the entire sky at the lowest frequencies. LOFAR will impact on a broad range of astrophysics, from cosmology to solar system studies: it will conduct the first studies of the Epoch of Reionisation, carry out the deepest ever large–sky radio source surveys, revolutionise the study of transient radio phenomena, make measurements of ultra-high energy cosmic rays via radio emission from air showers, and investigate the radio signatures of solar and interplanetary activity. In addition, history teaches us that exploring new frequency windows has always led to unexpected discoveries.

The core of the LOFAR array is currently under construction in the Netherlands by ASTRON. The Dutch LOFAR will consist of between 36 and 50 stations (depending on Dutch finances), each containing 96 low-band (30-80 MHz) and 48 high-band (120-240 MHz) antennae. These simple antennae will be sensitive to a large fraction of the sky, and by *beamforming* at each station can be made to 'look' in any direction on the sky. Only data transport and correlator computing limitations limit the number of beams available: the current LOFAR design allows for, e.g., 8×4 MHz beams, or a smaller number with larger bandwidth (greater sensitivity) up to a maximum of 32 MHz. The LOFAR 'Core Station 1' (CS1) has been operational since the fourth quarter of 2006; during 2007 the first official sky maps from CS1 have been publically released, and LOFAR has detected its first pulsar and solar bursts (see **www.lofar.org** for more details).

Although LOFAR is a Dutch project being led by ASTRON, in recent years there has been a growing European involvement, driven by the need to add stations far from the main core in order to improve angular resolution. LOFAR-UK is a project aimed at cementing UK participation in LOFAR via the operation of four stations within the UK, as part of a European expansion (E-LOFAR) already including Germany, France and Sweden, with other European countries (Italy, Poland, Ukraine, Austria) likely to join. LOFAR-UK ground stations will allow the highest angular resolution LOFAR observations, reaching sub-arcsecond scales at the highest LOFAR frequencies. This is important to accurately localise the detected radio sources and allow cross-matching of these with sources detected in other wavebands. In addition, deep LOFAR observations quickly become confusion-limited, and so an increase in angular resolution translates directly to an increase in the sensitivity to which the array will be able to probe. A long-baseline science case for LOFAR is available at **www.lofar.org/conference_meetings/LOFAR_LOBAS_Science.pdf**.

A full science and technical case for UK involvement in LOFAR has been developed and is presented in the LOFAR-UK White Paper, available at **www.lofar-uk.org**. Here, we summarise the main UK science goals for LOFAR, the extent of the UK's leadership and influence in the project, and the benefits to UK astrophysics.

1.2 Science objectives for LOFAR and LOFAR-UK

The original Dutch science case for LOFAR identified 4 Key Science Projects (KSPs):

- The Epoch of Reionisation
- Low Frequency Surveys of the Radio Sky with LOFAR
- Radio Transients and Pulsars
- Ultra-High Energy Cosmic Rays

In addition, two further International KSPs have been approved following the involvement of international partners in the LOFAR project:

- Solar and Heliospheric Physics
- Cosmic Magnetism

These LOFAR KSPs will be allocated considerable quantities of guaranteed time observations with LOFAR during its first few years of operation. Although there will also be open-time observations (beginning at a moderate level but rising as the KSP guaranteed time falls), these Key Science Projects offer by far the greatest potential scientific return from the instrument. The installation and operation of four LOFAR-UK stations will enable leading UK involvement in all of these KSPs, as discussed below.

1.3 The Epoch of Reionisation

According to the present view of the early Universe, atoms of hydrogen were first formed about a million years after the Big Bang when the primordial matter cooled to a temperature of about 3000K. The Universe then became dark and it cooled further due to the general Hubble expansion. These "Dark Ages" came to an end many hundreds of millions of years later, when UV and X-ray radiation from the first stars and black holes (active galactic nuclei; AGN) then ionised the hydrogen again, and later radiation from galaxies and quasars kept the bulk of the Universe highly ionised up to now. The time at which 50% of the Universe was ionised is termed **the Epoch of Reionisation (EoR)**. Identifying and studying this epoch is of great astrophysical importance as it will reveal when the first sources of light in the Universe, since the Big Bang, turned on. Current observational constraints on the EoR, for example from the Wilkinson Microwave Anisotropy Probe (WMAP; 32) and from the Gunn-Peterson trough in quasar spectra (e.g. 4), suggest that reionisation started somewhere around redshifts $z \lesssim 12$, and was mostly completed by at least $z \gtrsim 6$. Little else is currently known about when, and especially *how* the reionisation happened. When did reionisation occur? How rapidly did the IGM change from being mostly neutral to mostly ionised? What were the sources of ionisation, and how did they affect the global progression of the reionisation? How did reionisation affect subsequent galaxy formation? These are all crucial questions for our understanding of this major event in the history of the Universe.

LOFAR will probe the reionisation epoch at redshift z_r by searching for the redshifted 21-cm signal that arises from neutral hydrogen in the intergalactic medium (IGM). In the redshift range $6 < z < 11$, the 21-cm hyperfine line of neutral hydrogen will fall within the LOFAR high frequency band. Provided that the spin (excitation) temperature of the transition has decoupled from the CMB temperature (which is expected to happen through 'Lyman-α pumping' by the earliest sources of UV radiation preceding the EoR, e.g. 25; 20), the 21cm line will be observable at wavelengths $\lambda \geq 21 \times (1 + z_r)\mathrm{cm}$, but not at wavelengths below that. This leads to a step in brightness temperature, the magnitude of which depends only on the cosmic baryon density and the reionisation redshift; for $z_r \approx 10$ it will occur at a frequency around 130 MHz and will have an amplitude of 10-20mK. In principle, LOFAR will be able to detect such a signal after only a few hundred hours of observing.

The 21-cm signal from HI around the reionisation epoch will reveal the spatial distribution of the bulk of the baryonic component of the early Universe (cf. Figure 1). This provides a unique test of structure formation models, since the baryons are expected to trace the dark matter. The HI signal is predicted to show structure down to very small angular scales (0.1 arcmin or less): halos and filaments will appear in emission in 21-cm prior to reionisation, while the lower density IGM should be seen in absorption at early times, and in emission later (after it has been heated by X-rays). The low surface brightness of the signal means that it may only be possible to detect it over receiver noise if it is smoothed over scales of a few arcminutes on the sky, however. For this reason, it is predominantly the central core ($\lesssim$ 5 km) of the LOFAR array, containing around half of the Dutch stations, that will be effective for measuring angular structure in the signal from the reionisation epoch.

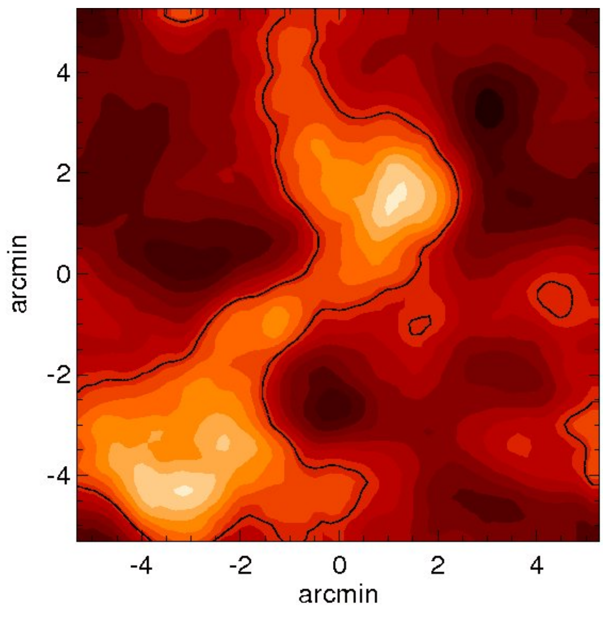

Figure 1: Simulated radio map of redshifted 21–cm emission against the CMB at $z = 8.5$, on the scale of $20h^{-1}$ (comoving) Mpc, for a typical LOFAR beamwidth (from 33). The baryons reveal the underlying filamentary structure of the dark matter.

The detection of the EoR is a major technical challenge because the raw signal from the sky is dominated by contaminating foreground signals (unresolved radio sources, Galactic and extragalactic radio recombination lines, polarised Galactic synchrotron emission) and confusion noise which collectively exceed the EoR signal by 5 orders of magnitude (e.g. 27; 16). Thus, although the addition of international baselines to LOFAR is not essential for the detection of the reionisation signal *per se*, they will play a very important role in the identification, localisation and spectral characterisation of these foreground signals. The most promising approach for removing the foreground is to chop the signal in frequency, for individual patches of the sky, taking advantage of the (measured) smooth spectra of the contaminating sources, which distinguishes them from the relatively large frequency variations of the 21cm signal (25; 16).

The cosmology community in the UK is well placed to make a substantial contribution to interpreting and exploiting LOFAR data on the EoR, because of the extensive expertise in cosmological simulations of large-scale structure formation, galaxy formation, and radiative transfer. The 21-cm data should be able to constrain many properties of high-redshift galaxy formation that are currently poorly-known, such as the ubiquity and initial mass function (IMF) of zero-metallicity population III stars, the presence (or not) of a substantial population of very early X-ray sources, and the escape fraction of ionising photons from small galaxies. To accomplish this it will be vital to have a suite of high-resolution numerical simulations which include all of the relevant physics of galaxy formation, radiative transfer and gas heating and cooling, to investigate how rival models may be distinguished. Several UK universities have a proven track-record in performing such simulations and theoretical modelling, and UK involvement in the LOFAR project would enable UK scientists to play a leading role in the interpretation of the LOFAR EoR data.

It should be noted that other experiments such as the PAST and MWA instruments in China and Australia, respectively, also have the goal of detecting the EoR signal. However, LOFAR's capabilities to *image* the re-ionisation epoch, and hence compare it with detailed simulations, are unparalleled.

1.4 Deep Extragalactic Surveys

Low Frequency Sky Surveys with LOFAR is the key project which has attracted the most widespread interest amongst UK researchers. LOFAR will carry out unprecedentedly deep and sensitive surveys of the entire 2π steradians of the northern sky at frequencies of 30, 60, 120 and 200 MHz, together with deeper surveys at 120 and 200 MHz over approximately 250 square degrees (hereafter referred to as 'LOFAR-deep'), reaching the confusion limit of ≈6 μJy rms at 200 MHz. For the typical spectral index of distant radio sources ($\alpha \sim 1$, where $S_\nu \propto \nu^{-\alpha}$), the 200 MHz 'LOFAR-deep' survey will have a sensitivity equivalent to $1\sigma \sim 1\mu$Jy at 1.4 GHz. Such depths have not yet been approached, requiring, in principle, a year or so of exposure with telescopes like the VLA or the GMRT, and then only over $\lesssim 1$ deg^2. The survey speed of LOFAR will outstrip even the EVLA by at least a factor of ~ 50, and will not be bettered until the SKA is operational. These surveys will detect tens to hundreds of millions of galaxies (cf. Figure 2).

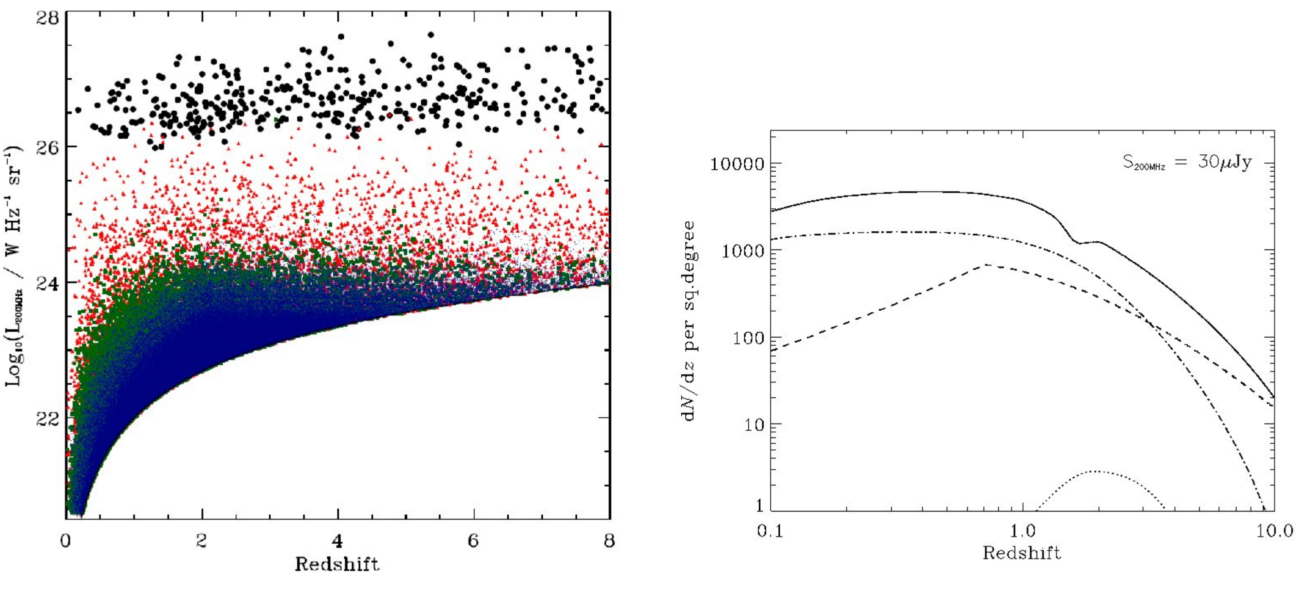

Figure 2: *Left:* A simulated $L_{200\mathrm{MHz}} - z$ (radio luminosity versus redshift) plane for 1 deg^2 of the 'LOFAR-deep' survey, to an approximate flux density limit of $S_{200\mathrm{MHz}} = 30\mu$Jy. The model splits the LOFAR population into four sub-populations (23): starbursts (blue); radio-quiet quasars (RQQs; green), Fanaroff & Riley (11) class I (FR I) radio galaxies (red); and FR II radio galaxies (black; in this case calculated for 100 deg^2). This survey will provide volume-limited samples of AGN (RQQ, FR I and FR II) out to very high redshift, and also detect most of the luminosity density in starbursts out to $z \sim 2$ and the most extreme starbursts to much higher redshift. *Right:* The number of sources per square degree in the deep LOFAR survey, split into the various sub-populations. Solid line – star-forming galaxies; dot-dashed line – RQQs; dashed line – FR Is; dotted line – FR IIs. The survey is dominated by the star-forming galaxies. [NB. The slight kink in the star-forming galaxies curve is an artefact of the two-population modelling of the evolving star-forming population.]

The vast improvement in both sensitivity and angular resolution that LOFAR will offer over previous radio surveys means that a very broad range of scientific topics can be addressed, including: probing galaxy evolution by studying radio–selected star forming galaxies across a wide range of cosmic epoch; detecting the most distant radio galaxies in the Universe; determining the role of radio-loud AGN in galaxy and cluster evolution; constraining the physics and energetics of radio sources, and their evolution; investigating the large-scale structure of the Universe through radio source clustering; searching for and analysing strong gravitational lens systems; dark matter and dark energy studies through weak lensing and target selection for baryon acoustic oscillation surveys; detailed studies of local starburst galaxies; exploring new parameter space for serendipitous discovery.

Due to the relatively small size of the Dutch astronomical community, they have strong scientific interest in only a subset of these goals. On the premise that there will be four LOFAR-UK ground stations, UK scientists have already been welcomed into the Surveys KSP, both at Board level (Best and Jarvis), and in the broader science team. They are helping to design both the format and the sky areas of the surveys that LOFAR will carry out, and the UK can expect to play a leading role in many areas of the scientific analysis. Furthermore, in modern astronomy, it is often the combination of datasets from different international facilities which results in the most significant breakthroughs. In particular, the combination of deep optical and/or near-infrared observations with the LOFAR survey data will provide redshift estimates for tens of millions of radio sources detected. Studies of the local Universe have demonstrated that the shift from 2D to 3D tends to transform hints on key issues in galaxy formation and cosmology (e.g., 10) to firm measurements, e.g., how local galaxies trace the dark matter and hence $\Omega_{\rm M}$ (e.g., 29). UK researchers are currently involved in preparing or undertaking many complementary surveys of the LOFAR survey regions at a wide variety of other wavelengths (UKIDSS and other WFCAM surveys; VISTA; PanSTARRS; Westerbork, GMRT and eMERLIN deep radio surveys; XMM-Newton; Spitzer SWIRE; SCUBA-2; Herschel; Swift; etc). Combining these with the LOFAR survey data will both greatly increase the scientific potential of the LOFAR surveys, and give leadership to UK scientists.

Areas of LOFAR surveys of particular interest to UK scientists, where the UK currently shows strong scientific leadership, are:

Starforming galaxies in the deepest radio surveys: Due to the massive increase in sensitivity of LOFAR over previous telescopes, the most numerous extragalactic sources will no longer be the radio-loud AGN, but rather starburst galaxies. A 200 MHz LOFAR-deep survey to a 30μJy flux density limit will detect galaxies with star formation rates of $10 M_{\odot}$ per year out to redshift $z \approx 2$, the epoch at which the cosmic star formation history is believed to have peaked. Objects with more extreme star formation rates of $100 M_{\odot}$ will be detectable out to $z \sim 6$. Combining the LOFAR radio data with deep optical and near-IR data will enable detailed measurement of the cosmic evolution of the global-average star formation rate density (using a sensitive, dust-insensitive indicator over large sky areas). More crucially, it will also investigate how the relationship between star formation rate and galaxy mass evolves with redshift (so-called 'down-sizing', e.g. 8), and how this depends on large-scale environment, through the key galaxy formation epoch. To this end, the LOFAR data will also be compared with surveys of star-forming galaxies at other wavelengths, in particular: (i) the SCUBA-2 Cosmology Survey, which aims to map 20 square degrees of sky at 850μm – LOFAR observations will allow the host galaxies of essentially all of the sub-mm sources to be identified and localised (cf. 21), and provide rough redshift estimates for these sources via the radio to sub-mm flux ratio; (ii) the Spitzer SWIRE Legacy Survey, which has imaged over 50 square degrees in seven infrared bands between 3.6 and 160μm; (iii) surveys with the Herschel satellite, due to be launched in 2008, which will carry out deep infrared surveys between 60 and 500μm – again, LOFAR's high angular resolution will be essential to identify the host galaxies. Finally, LOFAR can be used to carry out blind searches for high-redshift star forming galaxies through their gigamaser emission, and will extend study of the very tight but poorly understood radio–infrared correlation to lower radio frequencies and luminosities.

Radio–loud AGN and their influence on galaxies and their larger-scale environment: In recent years it has become crystal clear that AGN play a key role in galaxy evolution, and feedback from these systems is essential to explain even the most basic features of the local galaxy population, such as its luminosity function. Low luminosity radio-loud AGN have been argued to play the dominant feedback role at low redshifts (9; 6). It has been shown that for massive elliptical galaxies, the time-averaged energetic output of recurrent radio activity is sufficient to balance the radiative energy losses from their hot gas haloes, so this process does indeed offer a feasible feedback mechanism (5). The LOFAR-deep survey, in combination with deep optical and near-infrared data (e.g. PanSTARRS and UKIDSS DXS) will enable such studies to be extended to $z \sim 2$, allowing both the radio source duty cycle as a function of galaxy mass, and the radio-AGN heating rate, to be measured as a function of epoch. LOFAR will also enable more comprehensive investigation of the mechanisms by which AGN energy may be transferred to the surrounding environment, through detailed studies of low-luminosity galaxy-scale radio sources out to $z \sim 0.5$, and (because of its low frequency of operation) by characterisation of the energy distribution of low energy electrons in both the radio lobes and the jet hotspots. LOFAR's low frequency will also enable it to search for radio emission in the 'radio-quiet' outer cavities and bubbles seen in the intracluster medium of some cluster of galaxies, and thought to be associated with previous radio outbursts. In this way, LOFAR will help to determine the duty cycle of the radio-AGN activity of the brightest cluster galaxies, and the role of these in re-heating the cooling intracluster gas. The LOFAR-deep survey will contain about 250 Abell-richness clusters between $0.5 < z < 1.5$, enabling such studies to be extended to early cosmic epochs.

Powerful radio galaxies within the Epoch of Reionisation: The LOFAR-deep survey area is large enough to virtually guarantee objects at $z \gtrsim 7$ (cf. Figure 2), even if the decline if the space density of radio sources at high redshift is an order of magnitude higher than currently predicted. Such objects would allow detailed studies of the interstellar medium through redshifted 21 cm absorption studies at the end of the reionisation epoch (cf. 7). These $z \gtrsim 7$ objects will be blank in the deep optical and near-IR observations which exist to sufficient depth over many tens of square degrees that other blank–field radio sources will be rare.

Cosmology with the LOFAR sky surveys: LOFAR will play a key role in cosmological studies, in a number of different ways. The radio surveys are expected to contain of order 100,000 strong gravitational lens systems; the ease of identifying these will increase with angular resolution, but it is likely that between 50 and 100 would be found straightforwardly (e.g. 22). Strong lens systems provide a unique opportunity to probe the internal dark-matter substructures in $z \sim 0.5$ galaxies, for comparison with cold dark matter simulations of galaxy formation. Radio lens systems have the advantages that: (i) the sources are bigger than optical quasars, and so are less influenced by micro-lensing by stars in the lens galaxy; and (ii) they can probe the inner regions of the lensing galaxy (ie. study the steepness of the central stellar cusp, and central black hole) where optical lenses are undetectable. The larger-scale dark matter distribution can also be probed with LOFAR using weak gravitational lensing, at the angular resolution provided by UK stations. Weak lensing affords measurements of the overall density of dark matter and dark energy (e.g. 19), and small-scale structure on the scale of tens of kpc through higher-order (flexion) weak lensing statistics (1). The large survey areas projected for LOFAR will make its lensing results competitive with the next generation of optical lensing surveys (e.g., Pan-STARRS). Finally, the radio sources in the LOFAR-deep surveys can be used to provide a target spectroscopic sample for Baryon Acoustic Oscillation studies at $z \gtrsim 1$, to determine the dark energy component of the Universe. The main advantage of the radio selection for these studies is that the radio sources are likely to have emission lines, allowing their redshifts to be obtained in relatively short spectroscopic observations.

Low frequency observations of nearby galaxies: The central regions of starburst galaxies are generally heavily obscured at optical wavelengths by large reservoirs of dust and gas which fuel the ongoing star-formation. Observations at radio wavelengths are one of the few ways in which the on-going physical processes can be studied. Radio observations of nearby starburst galaxies with LOFAR can be compared with e-MERLIN observations at similar angular resolution, but significantly higher frequency; this will enable the free-free absorption of the foreground ionised gas within these galaxies to be mapped against the background radio continuum on linear scales of a few parsecs, as well as allowing the individual compact radio sources (supernovae, supernova remnants, compact HII regions) to be studied in detail. LOFAR will also allow the study of the radio lobes around X-ray binaries producing jet flows (so-called microquasars) in other nearby galaxies.

1.5 Radio Transients and Pulsars

The very wide field of view of LOFAR, particularly in the low frequency band, makes it ideal for the discovery and monitoring of variable radio sources. LOFAR will be able to both scan a large fraction of the sky daily *and* localise new transients with arcsec accuracy, by a stepwise ramping up of baselines from core to full array, and frequency from 30 to 240 MHz. It may well become the most productive source for the discovery of new transients, following the likely demise of the all-sky monitor (ASM) on-board the RXTE mission within two years. LOFAR has the capability to study variable sources on temporal scales from microseconds to years (14).

The UK has a strong history and interest in variable radio sources, and with two of the Transients Key Project Board members (Fender, Stappers) now located at UK Universities, LOFAR-UK anticipates a clear and productive working relationship with the Dutch LOFAR Transients KSP team. The UK can also bring considerable additional benefits to the transients project, in particular due to their access to the RoboNet Telescopes (the Liverpool and Faulkes telescope) which are able to acquire transient sources such as Gamma Ray Bursts within one minute of an alert being generated. Observational support for UK involvement will also include observations of new transients with e-MERLIN and X–ray follow up with SWIFT (via UCL/MSSL).

There are many science areas within the Transients Key Project in which the UK LOFAR community has interest and expertise. These include the following.

X-ray binaries and microquasars: these are systems in which accretion of material from a more or less 'normal' companion star onto a collapsed relativistic object (neutron star or black hole) results in an enormous release of gravitational potential energy in the form of both radiation and powerful relativistic synchrotron-emitting jets. Clear patterns of behaviour in the radio band have been linked to changes in the luminosity and 'state' (geometry and radiative efficiency of the accretion flow) of the accretor (e.g., 13). Studying such objects not only provides us with valuable insight into the physics of accretion and jet formation, but has been shown to be scaleable to accretion onto Active Galactic Nuclei (e.g., 26). LOFAR will discover new X-ray binary transients in the radio band, and carry out daily monitoring of known X-ray binaries (including those discovered by LOFAR itself), providing a unique resource. The international baselines provided by the UK will be primarily of use in imaging the transient radio structures associated with relativistic ejection events. UK expertise in the variable radio counterparts of X-ray binaries (also known as 'microquasars') includes phenomenological models of disc-jet coupling, and theory and modelling of outbursts and jet formation.

AGN outbursts and variability: LOFAR will open up a new window for studying radio-emission from AGN in the time domain. Some AGN are highly variable on short timescales (sometimes less than days), due to processes that are physically associated with the accretion/jet process. It is now thought that AGN jets play a crucial role in regulating the growth of massive galaxies and galaxy clusters, and variability is an essential tool to probe these jets close to their origin. LOFAR's sub-mJy sensitivity on day time-scales will enable, for the first time, the study of the variability of faint AGN jets known to exist in 'radio-quiet' AGN such as Seyfert galaxies, radio-quiet quasars and low-luminosity AGN (LLAGN), as well as hundreds of more distant and powerful radio-loud objects. X-ray studies of AGN have led to the identification of characteristic time-scales of variability, which scale with black hole mass and inversely with accretion rate (26). LOFAR will determine if similar scalings hold in the radio for thousands of AGN, allowing definitive tests of how jet sizes scale with mass and accretion rate; this will provide the key physical parameters for models of how jets affect the galactic and intergalactic environments. LOFAR will also be sensitive to transient extragalactic sources which are impossible to find using conventional radio telescopes. For example, it has long been suspected that the 'quiescent' supermassive black holes harboured by every galaxy should occasionally flare up as they tidally disrupt, and then accrete, material from a star that has wandered too close. These accreting black holes (i.e. AGN) will emit in the radio and LOFAR might detect a few tens of these events each year. This would revolutionise this whole area of research.

Gamma-ray bursts: Gamma-ray bursts (GRBs) are short flashes of gamma rays, detected at the rate of about one per day from random directions, that instantaneously outshine every other gamma-ray source in the sky including the Sun. They are often followed by "afterglow" emission at longer wavelengths, from X–rays through to radio wavelengths. The radio afterglows offer a crucial indicator of the physical parameters of the blast wave, providing constraints on the energetics of the explosion itself and the density and structure of the circumburst medium with which it interacts (e.g., 35). The afterglow evolves on a much longer timescale at low radio frequencies than in the optical and X-ray regimes (indeed, the radio light curve does not peak until months or years after the burst), offering both a "slow-motion" view of events, and the possibility to track the evolution of GRBs for years after they have ceased to become visible in the optical. This will enable the study of afterglows that were missed in the optical, and therefore allow a statistical assessment of whether the faintness of these "dark bursts" was intrinsic, or due merely to survey incompleteness. The long baselines provided by UK LOFAR stations will be particularly important in this respect, to provide high positional accuracy for the bursts. The radio component is also relatively insensitive to the geometry of the relativistic fireball (15); this makes it possible to detect the more isotropic radio emission from GRBs whose high energy emission is confined to a beam that, in the majority of cases, lies out of our line of sight. LOFAR will thus provide an unbiased census of GRB beaming statistics, and a measure of their true rate. Finally, UK researchers have developed very advanced numerical simulations of the coalescence of neutron-star-neutron-star or neutron-star-black-hole systems (e.g., 30), which are thought to be the progenitors of the short-duration GRBs; detailed LOFAR observations will enable testing and refinement of these models.

Pulsars: Pulsars are steep spectrum objects whose pulsed flux density usually peaks in the 100–200 MHz range, where LOFAR has unprecedented sensitivity. LOFAR will measure the low-end of the pulsar luminosity function significantly better than any previous survey, thus constraining the massive star population and supernova rate in the Galaxy. A LOFAR pulsar survey of the Milky Way visible from Northern Europe will find $\approx$1500 new pulsars, almost doubling the total number of pulsars known and better determining the period distribution of pulsars, which is an important ingredient in understanding supernova physics and the physics of neutron stars. In addition, there may be a large population of pulsars that are only visible at frequencies near or below 100 MHz because the pulsar emission cone width increases at lower frequencies, and LOFAR will be in a unique position to detect these, providing an improved understanding of the emission process. LOFAR high sensitivity will also greatly increase the population of pulsars for which individual pulses can be studied in detail; micro-structure and sub-pulses tend to be stronger at low frequencies, and the study of these offers powerful constraints on theoretical models of the pulse emission process. Pulsars also offer excellent probes of the ionised component of the interstellar medium through scintillation, dispersion measure, and Faraday rotation studies. Finally, due to its sensitivity, LOFAR will be able to detect extragalactic pulsars in at least 20 other galaxies, thus investigating how the bright end of the pulsar distribution depends upon galaxy type and star formation history.

Transient Radio Emitting Neutron Stars:

In recent years there been a significant increase in the number of neutron stars which emit radio emission transiently. These new classes of sources provide a rich group which can best be discovered with telescopes with large instantaneous fields of view like LOFAR. The Rotating Radio Transients, RRATs (McLaughlin et al. 06) are characterised by bright individual bursts of duration 2–30 milliseconds which repeat on timescales ranging from 4 minutes to 3 hours, with radio emission typically being detectable for < 1 s per day making them particularly difficult to detect with conventional radio telescopes. It has been shown that there may be as many RRATs as radio pulsars and thus discovering the size of the population and its relationship to the radio pulsars is essential for understanding the total number of neutron stars in the Galaxy and the radio emission mechanism.

PSR B1931+24 is a prototype of the "sometimes a pulsar" sources (Kramer et al. 2006). It was thought to be a normal radio pulsar but was seen to turn off for an extended period of time (10's of days) and then turn on again. It was then noted that during these off periods that its spin-rate decreased more slowly confirming for the first time the idea that particle loss during radio emission results in an extra torque on radio pulsars. A handful of such sources have now been recognised but their transient nature indicates again the value of a LOFAR radio sky monitor for discovering new sources. Moreover the frequeny monitoring of the known sources which will be possible with LOFAR can accurately identify periods when the source turns on and/or off which are vital to understand the switching phenomena and to allow for follow-up at other wavelengths, in particular X-rays.

Another new class of sources are the Magnetars. Until recently they were thought to only emit at high energies, but both XTE J1810-197 (Camilo et al. 2006) and 1E 1547.0-5408 (Camilo et al. 2007) have now been shown to emit at radio wavelengths. In both cases it is thought that the pulsed radio emission is triggered by outbursts in X-rays. The radio emission of both sources is unusual when compared with normal radio pulsars in that it shows a very flat spectrum. The transient nature of the radio emission makes LOFAR an ideal instrument for detecting more of these sources even when/if there is no X-ray monitor available. The physics of the pulsed radio emission and its relationship with that of the normal radio pulsars is of import as it has been claimed on theoretical grounds that the extreme magnetic fields of these sources should enhibit the production of radio emission.

Short duration radio bursts of extragalactic origin:

It has long been proposed that exotic events, such as the merger of two neutron stars or evaporating black holes, at cosmological distances might produce short radio bursts. However it is only recently that a short duration radio burst has been clearly identified as being at a distance of the order of a few hundred megaparsecs. Lorimer et al (2007) discovered the 30-Jy burst in archival pulsar survey observations of the Small Magellanic Cloud. They found that it has a duration of less than 5 milliseconds and based on its very high dispersion measure showed that it is located well beyound the SMC. They also show that there may be hundreds of similar events occuring every day! While these are still small number statistics this high rate is extremely interesting for LOFAR. The very large field of view utilised by both the radio sky monitor and the pulsar surveys mean that LOFAR will have a high probability of detecting a number of these sources each day if the rate is as high as predicted. The brightness of the source means that it will still be detected even in the 1-second images of the radio sky monitor, while the higher time resolution data accumulated for the pulsar survey observations will be sensitive to the weaker bursts. Detecting more of these bursts with LOFAR will allow the detailed study of these intriguing bursts which may probe some of the most extreme physical environments.

Extrasolar planets, and SETI: Extrasolar planets is one of the most dynamic and exciting areas of astrophysics, engaging both astronomers and the general public. New discoveries as to the structure and formation of extrasolar planets are being made at a rapid rate, and LOFAR will make important advances in this field. Based on extrapolations from the solar system (most notably Jupiter), and using parameters appropriate for the known extrasolar planetary systems, LOFAR should be able to detect the magnetospheres of extrasolar planets. This will offer a unique chance to investigate the magnetic field strengths of extrasolar planets, planetary rotation (which may be very difficult to access via any other means), possibly the presence of moons orbiting the planet, and also stellar parameters such as the stellar wind mass-loss rate and wind velocity on which the level of radio emission depends. LOFAR could also be used to search for new detections of extrasolar planets (cf. 12; 17).

LOFAR would also have the sensitivity to detect human-like radio signals from nearby stars with planetary systems. These would have the form of narrow spectral features with Doppler shifts due to both the orbital (around the star) and rotational (spin on axis) motions of the planet, as well as possible modulations in strength. Finding such a signal in the LOFAR data-stream is a major technical challenge; even if no signal is detected, a LOFAR SETI initiative would provide important training for the SKA.

1.6 Ultra-High Energy Cosmic Rays & Neutrinos with LOFAR

Ultra-high energy cosmic rays (UHECRs) are predominantly protons and heavy nuclei with energies far exceeding those in terrestrial particle accelerators. The mechanism by which these particles are accelerated to such high energies is not known, but candidates include AGN, Gamma Ray Bursts, the decay of unknown massive particles often predicted in Grand-Unified Theories (GUTs), or topological defects arising during the period of inflation after the Big Bang. These UHECRs can be studied at low radio frequencies because when they impact the atmosphere they produce a particle shower of secondary charged particles, which are then deflected in the Earth's magnetic field and produce coherent radiation at frequencies below about 100 MHz. These radio signatures from cosmic rays were first detected over forty years ago (see 34, for an historical overview); the unprecedented size of the LOFAR array makes this a very powerful instrument for advancing these studies.

LOFAR has a unique opportunity to detect ultra-high energy neutrinos. Although the spectrum of charged cosmic rays has been measured over 14 orders of magnitude (e.g. 31), no diffuse cosmic neutrino spectrum has yet been observed. Unlike cosmic rays, neutrinos are undeflected by magnetic fields and so will point back to their source. They also travel cosmological distances unattenuated. When a neutrino interacts in matter and produces a shower, that results in Cerenkov radiation; at wavelengths longer than about 10 cm, the signal is coherent. There exist media (ice, salt, sand) that occur naturally in large volumes and are transparent at that frequency. The GLUE experiment was the first to search for ultra-high energy neutrinos by viewing the sandy surface of the moon (the regolith) with a radio antenna (18). LOFAR, with its antennas pointed at the moon, offers the opportunity to extend the search for cosmogenic neutrinos into a higher energy regime, and with greatly improved sensitivity, than is possible with existing and proposed detectors. The UK has expertise in the simulation of neutrino interactions and the associated radio signal, through their participation in the ANITA radio high-energy neutrino experiment. This expertise will be applied to the neutrino-moon interactions that LOFAR has sensitivity to, with a view to probing predictions of the neutrino flux to 10^{22} eV and identifying any sources, should a flux be observed.

1.7 Solar and Heliospheric Physics with LOFAR-UK

The Sun is a powerful emitter at radio wavelengths, not only during intense bursts of activity related to phenomena such as solar flares and coronal mass ejections (CMEs), but also during times when it is considered quiet at other wavelengths. The radio domain provides a particularly sensitive diagnostic tool for accelerated particles on the Sun because even weak disturbances, such as the tiny events thought to be related to coronal heating, can give rise to detectable radio signatures via coherent plasma emission. LOFAR's high angular resolution (a few arcseconds in the low frequency bands), enhanced sensitivity and time resolution, and its ability to perform radio imaging spectroscopy, scanning rapidly in many frequencies and following dynamic sources as they propagate through the corona on (sub)second timescales, makes for a solar radio instrument far superior to any previous. A major advantage of LOFAR will be the opportunity to examine phenomena for which radio signatures occur preferentially at low wavelengths, such as coronal shock waves and radio noise storms.

LOFAR will enable the study of accelerated particles, from very weak to very energetic events, and will allow the processes involved in energetic and dynamic phenomena such as solar flares and coronal mass ejections to be investigated from their origins on the Sun as they propagate out through the solar atmosphere and into interplanetary space. Flares and CMEs are challenging physical phenomena to be understood in their own right, and are also of interest as they are major drivers of interplanetary disturbances and can affect the Earth's space environment. LOFAR's multi-beam capability will also give it a unique view of the large-scale structure of the solar wind as it expands through interplanetary space. By observing the apparent variation in intensity of many astronomical radio sources caused by variations in the solar wind, LOFAR will be able to track CMEs and to image solar wind density and velocity structures in near real-time; this will provide the ideal complement to STFC-supported missions such as STEREO, Venus Express and Bepi-Colombo.

The UK has large, internationally-leading, solar and heliospheric physics communities that are active in theory, modelling and data analysis from gamma-rays to radio wavelengths, of phenomena occurring below the solar photosphere, through the solar atmosphere, into the solar wind and on to the atmospheres and surfaces of the planets. These communities host considerable expertise in radio methods and are well-placed to take advantage of LOFAR to study the genesis of solar disturbances and their effect on the Earth and the other inner planets. The Solar and Heliospheric Physics Key Science Project for LOFAR is an international

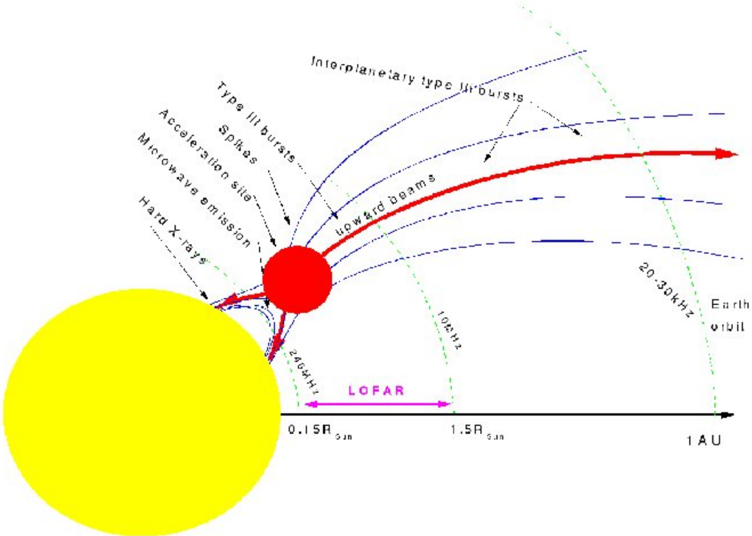

Figure 3: The approximate location of different types of solar radio emission, in the context of the flare magnetic geometry

project being managed by German, UK and French scientists, and so the UK can be expected to play a leading role.

Some specific scientific areas in which there is strong UK interest in using LOFAR are the following.

Solar Flares: Solar flares are the largest energy release events in the solar system. They are complex, extremely energetic and often dynamic phenomena. Among other things they produce immense bursts of energetic electrons, the source and acceleration of which is not well-understood. The primary diagnostics for these accelerated electrons are hard X-rays and radio waves. LOFAR observations will: offer unique insight into the production of non-thermal particle distributions in the corona; enable the study of flare electrons in large-scale magnetic structures that are difficult to see at other wavelengths; determine the starting locations and propagation paths of the near-relativistic electrons producing type III and other coherent radio bursts; diagnose local plasma conditions by studying how the burst spectra change as a function of time and position. The LOFAR frequency range corresponds to plasma densities of 10^7 to $7 \times 10^8\,\mathrm{cm}^{-3}$, present between about 1.15 to 2.5 solar radii (cf. Figure 3).

Coronal Mass Ejections: CMEs are studied to determine the physical processes that precede and cause them, their intrinsic properties and their consequences, and also to determine how to identify the most geo-effective events. They have been imaged at radio frequencies (e.g., 2) at heights below two or three solar radii (corresponding to LOFAR frequencies) but with comparatively few events analysed so far, little is known of their origins or consequences. LOFAR, combined with imaging and spectroscopy at other wavelengths, will allow investigation of: the trajectories of CMEs; their effects on the surrounding corona; the physical structure (density, field strength) and driver of the CMEs; the relations between CMEs and flares; the relation between CMEs and shock waves seen in the corona and in interplanetary space.

Coronal Shock Waves: LOFAR observations of plasma emission from electrons accelerated at outward-propagating shocks (type II bursts; 36), will enable the physical properties (density, magnetic field strength) of these shocks to be determined. Are these shock waves launched by, e.g., a piston of moving matter, or a pressure pulse? How are they associated with flares or CMEs? What are their propagation characteristics and their effects on the surrounding corona and other solar structures? Type II radio bursts preferentially occur at low wavelengths (typically $<150\,\mathrm{MHz}$) and, consequently, comparatively few have been studied to date; thus, the potential for discovery with LOFAR is very high. These investigations will augment the pre-eminent UK effort in the detection and analysis of MHD waves at X-ray, EUV and optical wavelengths.

Non-flaring active region energy release: The corona of an active region evolves continuously under the action of sub-photospheric driving, and it is believed to sustain a permanent population of non-thermal electrons. Small micro-flares occur every few minutes when there are active regions on the disk (24), and the quasi-continuous occurrence of even smaller events has been proposed as the mechanism that maintains the hot corona (28). High brightness temperature radio noise storms are a signature of accelerated electrons in the corona lasting for hours or even days. The origins of these noise storms are not understood. Noise storms preferentially occur at low frequencies and so LOFAR is ideal for their study. LOFAR will address fundamental issues in solar coronal physics, such as: how is the accelerated population of electrons produced and maintained?; how is energy partitioned between heating and particle acceleration?; what is the role of nano-flares in coronal heating and in the 'gradual' evolution of active regions?

Radio scintillation observations of the 3D solar wind: The solar wind is the medium by which solar disturbances, such as coronal mass ejections and fast solar wind stream interaction regions, are conveyed to the Earth and the other planets. Current instruments – and currently planned instruments – can only give a partial view of solar wind structure. LOFAR has the collecting area, sampling rate, and angular resolution to enable it to be used as a multi-beam interplanetary scintillation (IPS) telescope, providing a high-resolution view of density and velocity structures in the solar wind from inside the orbit of Mercury to beyond Earth orbit. As well as providing valuable supporting data for the STEREO mission, this will address questions such as: how do structures within coronal mass ejections interact?; how does this affect the interaction between the mass ejection and the background solar wind?; how do stream interaction regions develop, and how important is this in determining the geo-effectiveness of mass ejections?; how does large-scale structure in the solar wind evolve in the inner solar system? how do small-scale structures (turbulence) in the solar wind evolve with increasing distance from the Sun, and how rapidly is energy transported between scales? LOFAR will also provide a new view of the interaction between the solar wind and the inner planets, providing important supporting data for the Venus Express and Bepi-Colombo missions.

Ionospheric diagnostics: LOFAR operates at low frequencies, where radio propagation is significantly affected by the terrestrial ionosphere. In particular, geographically-confined ionospheric features could lead to significant differences in radio propagation characteristics above different parts of the extended array. The UK has a large base of expertise in ionospheric radio studies, and this will be built on to provide accurate ionospheric diagnostics for LOFAR, optimising its performance in all its modes of operation.

1.8 Cosmic Magnetism

Magnetic fields fill interstellar and intracluster space, and play a vitally important role in many aspects of astrophysics, from the onset of star formation to the evolution of galaxies and galaxy clusters. Despite their importance, little is still known about the origin, structure and evolution of magnetic fields. When were the first magnetic fields generated in the Universe? Are they primordial, or was their generation associated with early structure formation? How did magnetic fields evolve as galaxies evolve? These are all unanswered questions.

Radio emission offers the best probe of astrophysical magnetic fields. The intrinsic polarisation of a radio source yields information about the orientation and degree of ordering of the magnetic field. Faraday rotation of the polarisation vector as the radio wave passes through the magnetised medium between the radio source and the observer gives a view of the magnetic field along the line of sight. However, magnetic field strengths are typically weak, so only the nearest or brightest objects have so far been studied. LOFAR's high sensitivity will permit these studies to be extended into much weaker field regimes, such as galaxy haloes, galaxy clusters, and the intergalactic medium. LOFAR's multichannel spectropolarimetric capabilities will be essential in this aim, as they will enable accurate measurements of rotation measures and intrinsic polarisation position angles in a single observation in a single (up to 32MHz) frequency band.

Science goals for the Cosmic Magnetism KSP include: Faraday tomography of the interstellar medium in the Milky Way and in the disks and central regions of nearby galaxies; studying the extensions of galaxies into their halos or intergalactic space, due to the effects of interactions and galaxy winds; tracing the full extent of magnetised halos in galaxy clusters; studying, and clarifying the origin of, magnetic fields in the intracluster medium of galaxy clusters; measuring the magnetic fields in galaxies out to $z \sim 2$.

The Cosmic Magnetism KSP is German-led, but with strong UK involvement. The UK has considerable expertise in this area, both on galactic and extragalactic scales. In addition to the scientific results that LOFAR will produce, studying the weak magnetic fields that LOFAR will see will enable UK researchers to develop the technical and scientific analysis tools that will be essential for polarisation studies with the SKA, which will be able to probe to significantly deeper depths.

1.9 LOFAR-UK as a stand-alone array

There will be times when some or all beams from the international LOFAR stations will not be correlated with those of the Dutch LOFAR stations, either because they are not required (e.g. when EoR observations are carried out using only the Dutch core stations), or because of limitations of the correlator. In these circumstances, beams from individual LOFAR-UK stations can be used independently, or may be correlated with the other international stations (and any unused Dutch stations) as a sparsely-sampled array.

Solar Physics with individual LOFAR-UK stations: Although the angular resolution of an individual LOFAR station will be low, it will be able to operate as a very sensitive, high temporal resolution and high frequency resolution solar radio spectrograph, greatly increasing the capabilities for solar activity monitoring. Spectrographic observations are essential to make sense of the solar radio emission in the full-LOFAR solar imaging observations, because a variety of radio bursts have been classified according to their form in spectrograms and these, in turn, have been related to various physical phenomena. Moreover, several very interesting fine structures have been seen in recent spectrogram data. LOFAR acting as a very sensitive spectrograph will very likely reveal much more information on the detailed spectral behaviour of solar radio emissions, and thus on the details of the particle accelerations and plasma process involved. Continual solar spectroscopic monitoring would also allow burst-trigger-mode observations, whereby the entire LOFAR array could be triggered to observe the Sun at relatively short notice if an interesting burst is detected in the radio spectrograms.

Heliospheric Physics with individual LOFAR-UK stations: The UK has considerable experience in indirect imaging of the interplanetary medium using scintillation techniques. This has proven effective in monitoring the solar wind, providing alerts for the possible onset of geomagnetic activity, and determining the connections between solar activity and interplanetary weather. Such data have direct relevance to satellite and spacecraft operations, the commercial operation of high-latitude electric power grids and radio communication. To date, near real-time monitoring of the solar wind has been hampered by the lack of suitable radio telescopes on the ground, capable of measuring the scintillation levels of several hundred compact extragalactic radio sources per day. Each LOFAR station has the sensitivity, collecting area and bandwidth to perform these scintillation measurements; indeed, a single LOFAR station is far superior to any low frequency array currently in operation worldwide. Measurements of density structures can be performed by a single stand-alone UK LOFAR station. With more than one UK station, or including German and French stations, intensity correlation analyses will reveal the motion of the scintillation pattern over the ground and therefore high-precision measurements of the velocity and direction of the solar wind.

Pulsar observations with individual LOFAR stations: Individual LOFAR stations have sufficient sensitivity to be able to do very interesting monitoring observations of some known pulsars and other transient radio emitting neutron stars. Stand-alone LOFAR-UK stations could be used to perform regular timing observations of a few dozen radio pulsars which are known to glitch; seeing how often neutron stars suffer glitches, and how the rotation rate recovers thereafter, is one of the keys to understanding the equation of state of the super dense material of a neutron star. LOFAR-UK stations could also be used to monitor two new interesting classes of radio emitting neutron stars: the RRATs and the intermittent pulsars. RRATs are characterised by infrequent bright single pulses (typically a few/hr), and regular monitoring may greatly improve the number of pulses detected and thus better determine the nature of the sources. Intermittent pulsars are seen to emit radio waves for a period of a few days to years and then turn off for similarly long periods. Intriguingly during the off periods they exhibit different spin properties to when they are on, thus providing a unique probe of the emission mechanism itself. The monitoring capabilities of a LOFAR station are ideally suited for providing better statistics on the repetition on–off timescale, and observing exactly what happens at the moment when the on–off or off–on transition occurs.

Correlating E-LOFAR stations for early long-baseline surveys: The $u-v$ plane coverage of an international array of 8-10 telescopes will be sufficient to make reasonable images at $1''$ resolution. This offers the opportunity to carry out pilot high-resolution surveys, allowing optimisation of long-baseline observing strategies in advance of the full-scale surveys with the whole E-LOFAR array. In just a few beam-months, it should be possible to survey the 1.4-GHz FIRST survey (3) area to a flux limit of a few mJy at 200 MHz. The correlation requirement would be relatively modest because the FIRST survey dictates exactly where the sources are: only a small area around each source need be correlated, greatly reducing requirements on channel width and integration time. Ionospheric calibration would be done by observing only in fields around bright (>200-mJy) point-source calibrators. As well as the technical advantage of carrying out such pilot surveys, such a survey would push into new parameter space for the study of radio source populations, and thus have a valuable early scientific contribution. For example, the entire FIRST survey could be examined for strong gravitational lenses.

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2 Technical Case

LOFAR is the first of the next generation of radio telescopes in which a single, or few, large dishes are replaced by large numbers of small receptors coupled to sophisticated signal transport and processing hardware and software. These receptors are grouped in so called stations and these stations are distributed with decreasing density from a dense core out to international baselines. Significant processing power at each of the stations is used to combine the signals from the receptors to form a number of phased array beams on the sky. Beamforming at the station level is required to reduce the raw digitized data rate per station from 0.5 Tb/s to approximately 2 Gb/s. The signals from these beams can then transported to a central processing facility (CEP) using optical fibre connections. At CEP the signals from all the stations are correlated with each other. After correlation the signals are calibrated and imaged using a large computing cluster. The design and implementation of LOFAR has been led by ASTRON in The Netherlands. We here provide a summary of the various LOFAR components.

2.1 The Antennae

LOFAR is optimised to operate in the frequency range from 30–240 MHz. To achieve this wide range of observable frequencies two different receptors are used; the Low Band Antennae (LBAs) and the High Band Antennae (HBAs). The LBAs cover the range 30–80 MHz and the HBAs 120–240 MHz with the gap between the frequencies designed to avoid the FM band. The LBAs (Figure 4) are simple dipoles and there will be 96 of them in each station. The HBAs consist of a tile of 4×4 antenna elements that are beamformed together using an analogue beamformer, and there are between 48 and 96 tiles in each station.

Figure 4: *Top:* The LBAs of the first LOFAR station in the field. Also visible is the container where the receiving and the local station processing hardware (Figure 5) is located. *Below:* Six close-packed HBA tiles in the field, with a single HBA antenna element in the foreground.

2.2 The Receiver System

The receiver system at each station (Figure 5) is able to select from one of three inputs, either HBA or LBA with a third input for future extensions with a third antenna type. Once an antenna is selected the signal from both polarisations is filtered and amplified. An analogue-to-digital converter converts the analogue signal into a 12-bit digital signal at a sampling rate of either 160 or 200 MHz. Using the first three Nyquist zones of both sampling rates means that all frequency ranges between 0-300 MHz can be observed.

After sampling the chosen band is split into 512 subbands using a polyphase filterbank. A polyphase implementation is used so as to reduce the spectral leakage and thus greatly improve the robustness to strong interfering signals. Depending on the sampling rate the channel width is now 195 or 156 kHz and either 164 or 205 channels can be chosen from the 512 to make up a total of 32 MHz of bandwdith per polarisation. This maximum transported bandwidth is matched to the current capacity of the fibre infrastructure and CEP. To form the so-called station beams, the antenna signals are combined using the appropriate weights fed to independent beamformers for each subband. A Local Control Unit (LCU) generates the weights and also performs statistical analysis of the subands to monitor system health. As each subband is treated independently it is possible, in theory, to have each given separate weights and thus effectively pointing to different locations in the sky. However limitations in the LCU effectively limit this to 8, thus allowing us to form 8 different beams, each of 4 MHz, on the sky.

Stations are also equiped with transient buffer boards (TBB) making LOFAR unique in that it can effectively look back in time. The TBB consists of a large amount of RAM in which either the raw 100 MHz bandwidth data from each antenna or a selection of subbands is buffered. The buffer can store up to 1 second of raw data or many 10's of seconds of channel data. Using either internal or external triggers, these buffers can be frozen

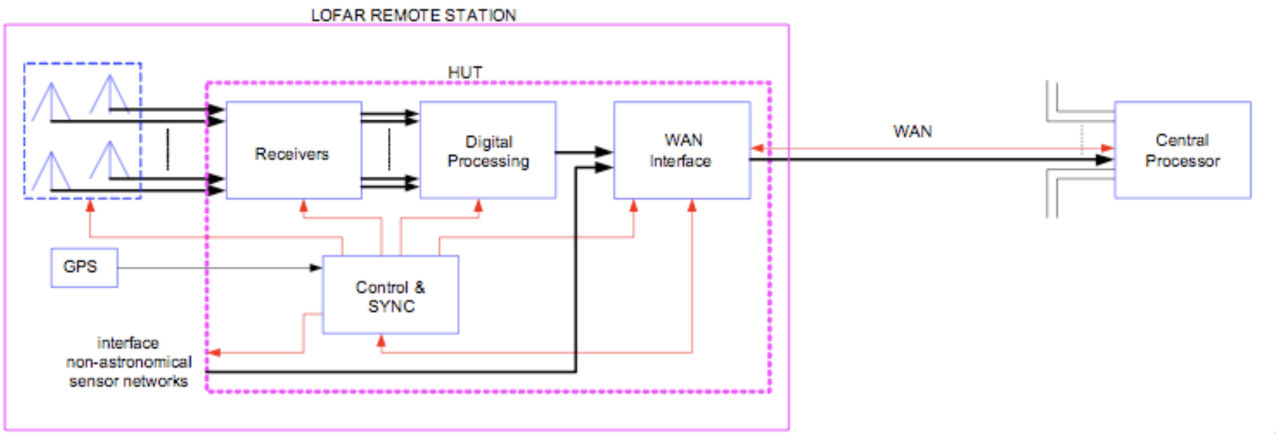

Figure 5: A block diagram showing the main components of a LOFAR station.

and an image of the sky made at the time of the trigger. The TBBs are essential for the Cosmic Ray Key Science Project and enable exciting new science for the Transient Key Science Project.

2.3 Stations and LOFAR Layout

LOFAR can effectively be divided into three separate regions, the core, baselines less than 100 km, and the international stations with baselines longer than 100 km. In each region the density of stations decreases and the stations have a slightly different form. The core will consist of 18–25 stations (depending on Dutch finances) located within a radius of approximately 3 km. A further 18–25 stations will be contained in the region between 3 and 100 km from the core. These 36–50 stations will form the Dutch component of the array, and constitute between 60–80% of the total E-LOFAR collecting area in 2011 (see section 4).

Each of these stations will contain 96 LBA elements and between 48 and 96 HBA elements. On the baselines within the Dutch core ($\lesssim 3$ km) each HBA station will consist of 48 antenna split into two sub-fields, this configuration maximises the number of short HBA baselines. On intermediate length baselines upto 100 km from the core of the array the HBA stations will consist of 48 antennas in a single field, whilst on longest baselines, including all international stations 96 HBA antenna elements will be used. This distribution of the collecting area of HBAs will maximise the sensitivity on the longest baselines whilst also providing additional HBA baselines at low spatial frequencies. Both of these factors will aid both the imaging and calibration capabilities of the HBA array.

2.4 Central Processing Facility

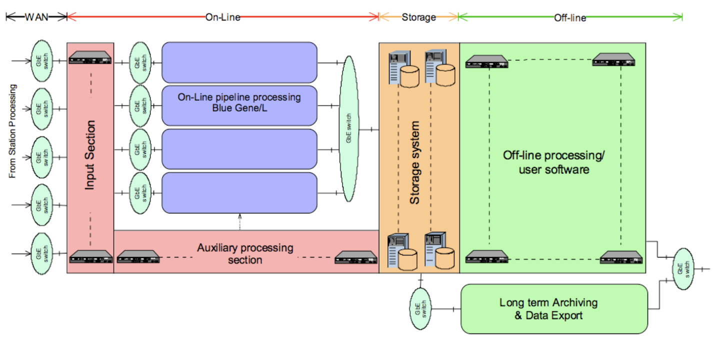

Figure 6: Overview of the LOFAR central processor hardware consisting of 4 different clusters integrated with the Blue Gene/L computer.

The Central Processor hardware (Figure 6) will be used to process the data from the stations in real time. The system is capable of correlating a minimum of 77 stations at the maximum bandwidth of 32 MHz with a maximum input data rate of approximately 400 Gb/s. The input section is responsible for data validity, synchronizing output data streams and preparing the data for correlation, including doing the fine scale geometric corrections. The 27 Tflop Blue Gene/L performs either the correlations which are subsequently calibrated and later imaged, or it forms so-called tied-array beams which are used for timeseries studies such as pulsar searching. In the imaging application the 195 or 156 kHz bands are further decimated using another polyphase filter to reduce the bandwidth to approximately 1 kHz. The correlation matrix for each channel and all stations is then calculated. The correlator is extremely efficient achieving 98% of the theoretical peak performance.

In parallel to Blue Gene/L there is an auxiliary processing cluster which may work on all or a subset of the data. This is a more general purpose cluster which will be used for calculations like, on-line ionospheric and system calibration and RFI detection and mitigation. This system will also be responsible for generating the real-time images that will be used, for example, by the Transients Key Science Project for transient detection.

An on-line storage area is used to store the intermediate data products for of the order of one week. These data products are then processed to the users specifications using the off-line processing cluster. This is a multi-purpose cluster which will be running anything from imaging algorithms, transient detection pipelines, to pulsar search algorithms. The products of this analysis will then be permanently archived.

As LOFAR is essentially the first (close to) 'all digital' radio interferometer, software is clearly a critical part of the overall project and a lot of effort has gone in to defining LOFAR Common Software (LCS) and setting up a software development team at ASTRON which is well integrated with LOFAR software development thoughout The Netherlands.

2.5 LOFAR

2.5.1 LOFAR - The Netherlands

The core of LOFAR will be situated in the northern regions of The Netherlands. Following recent reviews with The Netherlands, the Dutch portion LOFAR array will initially consist of at least 18 closely packed Core stations and 18 more remote stations with The Netherlands. Note that in order to optimise the survey speed and imaging capability of the instrument, the Dutch stations will have 48 LBAs and 48 HBAs. The international stations, however, will have 96 LBAs and 96 HBAs (ie. twice the sensitivity, but a smaller field of view). This is as recommended for calibration purposes by the LOFAR Calibration Advisory Group, led by Wim Brouw.

Beyond The Netherlands considerable interests in the LOFAR project has been made by several European countries, not least the UK. At present, Germany has the largest involvement having already constructed a LOFAR station at Effelsberg. Plus they have already placed orders for a further three stations with several more planned. Within the current procurement round France have ordered their first station which will be situated at Nançay, and are planning to augment this with several future stations. These will be all co-located in Nançay, forming a LOFAR 'super-station'. Within Sweden, funding has recently been secured for a single LOFAR station. This will be located in Onsala and will be the most northerly LOFAR station. In Italy a similar level of funding is being sort for a single station. In addition, there is strong interest in funding and hosting up to three further international LOFAR stations in Poland.

Within the UK, the initially procurement a single LOFAR station is underway within the first round of international station orders. This procurement and entry into the project allows the UK to engage in a leadership role within the LOFAR project at an early stage. Following the successful rollout and installation of the UK's first station, procurement and installation of a further three stations will follow. The construction and operations of these four LOFAR stations will place the UK amongst the largest country contributors to LOFAR project.

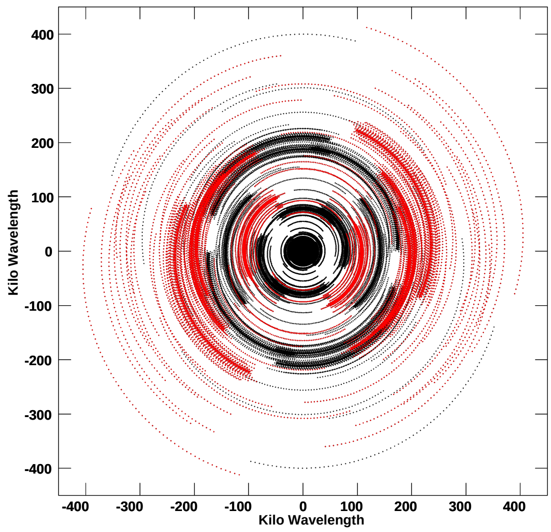

Figure 7: Simulated single frequency (100 MHz) *u*-*v* coverage of currently funded LOFAR array plus international stations in the UK, Germany, France and Sweden. Baselines involving UK stations are shown in red.

2.5.2 LOFAR-UK

The LOFAR-UK consortium intends to operate a total of four LOFAR stations on UK soil. The sites for the four potential LOFAR-UK stations are Chilbolton (RAL), Edinburgh, Lord's Bridge (University of Cambridge) and Jodrell Bank Observatory (The University of Manchester).

With respect to the other LOFAR sites, both within The Netherlands and the rest of Europe, the locations of the potential UK sites offer considerable benefits to the high resolution imaging capabilities of the whole instrument. In particular the UK sites provide baseline lengths of between 400 and 600 km to the LOFAR core stations in Holland which naturally compliment the baseline lengths provided by other international stations. Crucially the baselines between the individual UK stations fill a significant portion of the *uv* plane which is otherwise very sparsely covered (see figure 7). As a result, the contribution of multiple UK LOFAR stations significantly enhance the high resolution imaging capabilities of LOFAR, with particular benefits for high resolution imaging science.

2.5.3 Technical experience & training

LOFAR, both as a scientific instrument and technical project, is a ground-breaking forerunner of future radio astronomical projects such as the SKA. One significant benefit to the UK radio astronomy community of hosting multiple LOFAR stations, will be in the form of technical experience gained from installation and operation of these stations.

These benefits are multi-fold. Firstly, the installation and operation of several LOFAR stations within astronomical institutes in the UK will provide invaluable technical experience of the first of the next generation of radio telescopes. This will help to facilitate UK's technical involvement in future radio astronomy projects and help to provide the experience required to secure technical leadership. Secondly, by virtue of the UK's involvement within the LOFAR project, the wide scientific astronomical community will gain vast experience in terms of data handling, reduction and interpretation using the first of the next generation of radio interferometers.

2.6 LOFAR host observatories

The sites chosen for LOFAR stations are required to fulfill certain criteria relating to the site itself, the surrounding environment, and the data connection and support infrastructure available. These criteria are designed to result in a smooth operation of LOFAR stations, whilst also ensuring that the operation of the site produces the best possible science returns, both individually and as part of the whole array.

The overall environment surrounding LOFAR stations needs to relatively free from radio frequency interference, consequently it is preferable for sites to be located away from major towns and cities. In order to host a LOFAR station the site needs to be minimum area of 75 by 150 m for the the astronomical detector fields, which need flattening to within a few centimetres rms. In addition to the two fields of dipoles, station based processing and control electronics must be situated adjacent to the detector elements. This equipment requires the installation of services and crucially an optical fibre path for subsequent data transfer from the detectors. The full data transport requirements for each LOFAR station are $\sim$3 Gb/s between the remote LOFAR station and the correlator processing which will be based in The Netherlands at the Groningen supercomputing centre. Whilst the LOFAR station hardware is designed to require minimal technical operational support, following the initial installation and commissioning phases, a small level of technical support and preventative maintenance will be required. In order for the expertise required to be available at each of the proposed UK sites, along with the any necessary facilities, it is significantly advantageous for UK LOFAR sites to be hosted at, or close to, existing radio astronomical facilities where these skills and facilities already exists.

2.6.1 UK host sites

The Jodrell Bank and Lords Bridge sites are natural choices for UK LOFAR stations, for a number of reasons. These locations have a long history of radio astronomical facilities, and thus extensive local technical expertise. Land has been donated to the LOFAR-UK project at these sites by the University of Manchester and the University of Cambridge, respectively. The sites have recently been RFI surveyed by the LOFAR team, and initial findings show that in both cases the interference environment is better than other LOFAR sites in Holland.

Critically each LOFAR station, once in full operation, will be producing up to 3Gb/s of data which will need to be transferred to the CEP in Groningen for correlation. Consequently the provision of fast internet connections from each of the LOFAR-UK sites is essential. At Jodrell Bank, a fibre connection directly onto the SuperJanet-5 fibre network is already in existence and is currently being upgraded to a 12 Gb/s as part of the

EU-funded EXPReS project. Using this link, e-VLBI have already demonstrated sustained data transfer rates of up to 1 Gb/s from Jodrell Bank to The Netherlands for correlation. This link is will provide ample bandwidth for both e-VLBI and LOFAR applications. The Lords Bridge site, near Cambridge, currently requires an enhanced connection in order to handle the large data rates required by a LOFAR station. Whilst the site is situated close to e-MERLIN dark fibre the most cost effective solution will be to connect the Lords Bridge site by fibre directly to Cambridge allowing access to the SuperJanet-5.

The Chilbolton Observatory site, close to STFC Rutherford Appleton Laboratory, also offers excellent potential to host a LOFAR-UK station. In addition, the majority of facilities required to support the establishment of a LOFAR station are present. The only notable short-coming is the lack of a connection to dark fibre. Connection to dark fibre is thought to be a more cost effective method of providing data transport than using the Chilbolton Observatorys connection to the BT fibre network. The South East England Development Agency (SEEDA) are very enthusiastic about the location of a LOFAR station in this part of the country and may provide financial support to assist in data connectivity.

Funding towards a Scottish LOFAR station has been sought through the "Scottish Universities' Physics Alliance 2" bid to Scottish Funding Council. The currently-favoured location for a Scottish LOFAR station is about 10 km south of Edinburgh, close to the Edinburgh Technopole Science Park, on land owned by the University of Edinburgh. Investigations of precise site locations are still on-going, but the availability of a 10 Gb/s fibre connection from this science park, connecting directly into the SuperJanet 5 fibre network, make this an ideal choice. The nearby location of the STFC's UK Astronomy Technology Centre also means that technical support would be locally available. A Scottish LOFAR station would provide the longest possible UK baselines, and also a different subtended angle relative to the main LOFAR core, providing improved coverage of the *uv* plane.

2.6.2 Selection of the first LOFAR-UK site

Between 2005–2007, LOFAR-UK has raised the sum of £600k in contributions from thirteen different collaborating institutions, which we will use to purchase and operate the first LOFAR-UK station.

As a result, the LOFAR-UK consortium has agreed with ASTRON to purchase one LOFAR station in the first round of procurement, corresponding to delivery, installation and commissioning in 2008Q4. The LOFAR-UK Management Committee have investigated in detail the merits of each of the three proposed sites within England (the Edinburgh site is not well enough advanced at present) and have found that there is essentially nothing to choose between them scientifically. Given the importance of financial efficiency, the decision for the location of the first LOFAR-UK site will take place in April 2008, at which time we will have a clearer picture of the status of various regional funding bids.

2.7 Data transport

The anticipated data rate from a LOFAR station outside the central core is $\sim$2 – 3 Gb/s, based on a total bandwidth of 32 MHz, which can be divided in up to 8 beams, in each of 2 polarisations, with 12-bit sampling, and allowing up to 512 Mb/s for formatting and framing overheads along with control and monitoring data. For LOFAR within the Netherlands, the data will be transmitted from each station across a dedicated Wide Area Network using Gigabit Ethernet protocols to the central processor. Connecting stations from outside this dedicated WAN will require additional work and resources.

For remote stations in the UK, we expect that the LOFAR station data can be transmitted across the Super-Janet 5 (SJ5) network, which has trunk data rates and access points at 10 Gb/s, to interconnect with the Geant network (the EC-funded network which connects the various European research networks) for transmission to Amsterdam. Subsequent transmission to the LOFAR central processing facility will be handled by Surfnet in the Netherlands. A similar route is currently being used for regular e-VLBI experiments, where data from radio telescopes at Jodrell Bank, Cambridge (via radio link to Jodrell Bank), Torun (Poland), Medicina (Italy), Westerbork (Netherlands) and Onsala (Sweden) are transmitted at data rates of up to 950 Mb/s to the EVN data processor at JIVE (located in Dwingeloo, in the Netherlands) for real-time correlation there. Data are transmitted using standard IP protocols across national research networks and Geant. Scientists and engineers at Jodrell Bank Observatory, the MERLIN/VLBI National Facility and the High Energy Physics group at the University of Manchester have played important roles in the development of e-VLBI and are engaged in a number of research projects to develop the technique and capabilities still further. Currently, data transmission from Jodrell Bank also makes use of the UKLight connection from Manchester to Amsterdam, provided by Janet(UK). The last two years have seen a rapid development of this e-VLBI capability, with sustained data rates climbing from 32 Mb/s to 950 Mb/s, and an EC-funded project EXPReS is currently tasked with making routine 1 Gb/s real-time operations a routine procedure for the European VLBI Network. Sustaining continuous transmission across production networks at these rates is a real challenge and a very active area of research in terms of processing and throughput bottlenecks, data protocols and switching and routing techniques.

Issues for data transport from LOFAR-UK stations include the initial connection from the station to the SJ5 network, and consideration and optimisation of the data rate and management of the data flow across SJ5 and Geant to Amsterdam. For the Jodrell Bank site, a 2.5 Gb/s connection to Manchester already exists, funded through e-MERLIN and a PPARC grant for e-VLBI, with operational costs currently met by MERLIN. Equipment is currently being installed to upgrade this connection to 10 Gb/s. For the Cambridge site, there may be options to make use of the e- MERLIN dark fibre connection to connect with national trunk fibre networks and then SJ5. Other sites will require fibre rental or new optical fibre cables to be installed over distances of up to a few kilometres.

The nature of the data flow from a LOFAR-UK station needs to be considered in detail, this will be the be investigated with Workpackage D2 of this project. While the 12-bit sampling depth is a specification for the LOFAR core and stations in the Netherlands, and may be appropriate for the combination of stations where there are considerable correlated interfering signals present, it may be possible to reduce this sampling depth at remote stations where the interfering signals are much more independent. In addition, it may be possible to increase the amount of local signal processing in order to reduce the transmitted data rate. In the end, this comes down to issues of cost: for the LOFAR core, it is cheaper to transmit larger volumes of data and do the processing centrally, while for the most distant stations it may be more cost effective to do more processing locally and reduce the data rate. As data transmission becomes cheaper and easier, it will be possible to increase the data rate, number of beams and sampling depth, even for the remote stations.

2.8 Data calibration and dissemination

One of the key technical challenges for LOFAR is that of calibrating the data from the different stations. Although the antennas are co-planar at any particular station, the Earth's curvature means that widely-spaced stations will necessarily point in different directions, and will therefore see the sky slightly differently. This difference needs to be accurately accounted for via instrumental calibration of each individual station, if post-calibration dynamic-range limitations are to be avoided. This issue is particularly pronounced for the long-baseline international stations. Furthermore, the low frequency of operation of LOFAR means that observations will be highly susceptible to disturbances in the ionosphere. An accurate model of the ionosphere above each LOFAR station must be developed, in order to calibrate each station independently of every other. For the longest baselines (e.g. to the UK) this is a severe challenge because each station sees an ionosphere that's essentially independent of the ionosphere above the LOFAR core. The size of the isoplanatic patch can also become smaller than the size of each 'station beam', requiring a set of calibration sources for each of the (up to 8) independent beams.

Both data calibration and data dissemination are critical to the successful operation of LOFAR as a science instrument and as an SKA pathfinder. Software development is obviously central to solving this problem, and the experience of many astronomical projects is that this is typically the hardest part of a programme to reliably cost and then to deliver on schedule. The LOFAR project has put heroic efforts into setting up integrated software teams and a LOFAR Common Software (LCS) infrastructure, and they are confident that all the necessary software will be in place for the operation of the LOFAR core. It is clear, however, that the succesful comissioning and operation of long baselines will require additional software development effort and LOFAR-UK and LOFAR have agreed work packages which can be led in the UK to provide this additional effort. This will be investigated in work packages D3 (Data Calibration) and D4 (Data Products).

3 LOFAR in the context of the SKA and UK radio astronomy

The UK has hosted world-leading groups and individuals throughout the history of radio astronomy. It was in the UK that novel techniques like astronomical phased arrays and aperture-synthesis interferometry were invented and these technology breakthroughs led to fundamental discoveries like pulsars, quasars and quasar jets. Nobel prizes have resulted from such studies.

Low-frequency radio surveys conducted at Cambridge over the past five decades have produced some of the most important and well–studied radio source samples which will only finally be superseded with the operation of LOFAR. In the same period, the Jodrell Bank observatory at Manchester has been at the cutting edge of the development and operation of long-baseline and low-frequency radio interferometers, culminating in the creation and operation of the world's largest permanently connected interferometer, MERLIN, soon to be upgraded to eMERLIN.

UK astronomers have also been central to the planning for the Square Kilometre Array (SKA) - the next-generation radio astronomy facility - since its inception. This instrument forms a cornerstone of the STFC planning 'Roadmap', and is one of just two future astronomical facilities on the Research Councils UK Large Facilities Roadmap. The start-up of the EC Framework 6 (FP6) SKA Design Study (SKADS) and its FP7 follow-on (PrepSKA) has seen the UK adopt a global leadership position in the SKA, and this in turn has led to major investments by UK universities including the set-up of a new radio astronomy group in Oxford, and the movement of the International SKA Project Office to the new Turing Building in Manchester.

The SKADS proposal is led by the UK and Holland and unifies significant activity in several other EC countries (France, Germany, Italy, Portugal, Spain) as well as international partners, most critically in Australia and South Africa, the two remaining possible host countries for the SKA. STFC itself leads PrepSKA which expands this partnership to all interested countries in the world. If the UK is to maintain its current international leadership position, it must expand its technical and scientific radio astronomy expertise by seriously participating in SKA pathfinder experiments that will deliver world-leading science results ahead of SKA 'first light' around 2015.

LOFAR is by far the most innovative and ambitious 'SKA Science Pathfinder', test-bedding some of the key technologies for SKA, and delivering early science over a restricted (c.f. SKA) low-frequency range. It is the only SKA pathfinder project being developed in Europe, is led by the Dutch, and now includes a serious participation from Germany. Looking forward to SKA, and UK and European leadership thereof, there are obvious political reasons why the UK should join the LOFAR project at at least the same level as the German LOng-Wavelength (GLOW) consortium.

UK astronomers have long recognised the scientific importance of joining LOFAR, and this led to the formation of the LOFAR-UK consortium in 2005. Technically, the digital electronics and software basis of LOFAR was the inspiration for the 'all–digital' SKA concept for the low ($\lesssim 1$ GHz) frequency band being developed by UK groups as part of STFC-funded SKADS programme. Full involvement in the LOFAR project will therefore not only achieve involvement for UK astronomers in a world-leading science facility operating in the immediate future, but also allow the UK to build up important hands-on technical experience in 'next generation' radio astronomy. Many of the key challenges for LOFAR now, and the SKA in the future, are different to those that were faced by instruments like the VLA and MERLIN. LOFAR stations will be able to form beams 'looking in many directions at once' which whilst scientifically exciting, generates new challenges which are especially demanding on the longest baselines, like those from the Dutch core to the UK. Many of these challenges must be met by implementing novel solutions for data transport, data calibration and the distribution of useable data products.

It is worth noting that all of the leading institutions in the STFC-funded e-MERLIN and SKADS programmes are members of, and strongly support, LOFAR-UK, viewing it as an essential part of the UK strategy for radio astronomy facilities on the pathway to the SKA. It is also worth noting that the LOFAR-UK consortium contains many more active institutes than those directly involved in e-MERLIN and SKADS, reflecting the broadening of the 'radio astronomy' community necessary as we enter the SKA era. The two southern-hemisphere locations shortlisted for the SKA (Western Australia and South Africa) mean that its construction will not render LOFAR scientifically redundant: LOFAR and early phases of the SKA are envisaged to operate in tandem, providing full–sky surveys and transient monitoring. As the largest contributors to the SKADS project are the Netherlands and the UK, it seems natural that these countries collaborate closely on the LOFAR project, and Dutch astronomers have already been very welcoming of such participation. The total cost of UK involvement in LOFAR is small compared to the likely UK and global investment in radio astronomy over the next two decades, but will offer a unique opportunity to obtain hands-on experience both on a technical and on a scientific level.

4 LOFAR-UK and E-LOFAR

As noted earlier in Sections 2 and 3, the installation and operation of LOFAR stations in the UK is part of a wider effort to develop LOFAR into a European facility with pan-European baselines, or E-LOFAR.

Fig 8 below indicates the location of existing, funded and proposed international LOFAR stations within the UK, Germany, France and Sweden, as well as the Dutch core. In Section 2 we already demonstrated how the baselines to the UK stations would enhance the angular resolution and imaging capability of the telescope as a whole.

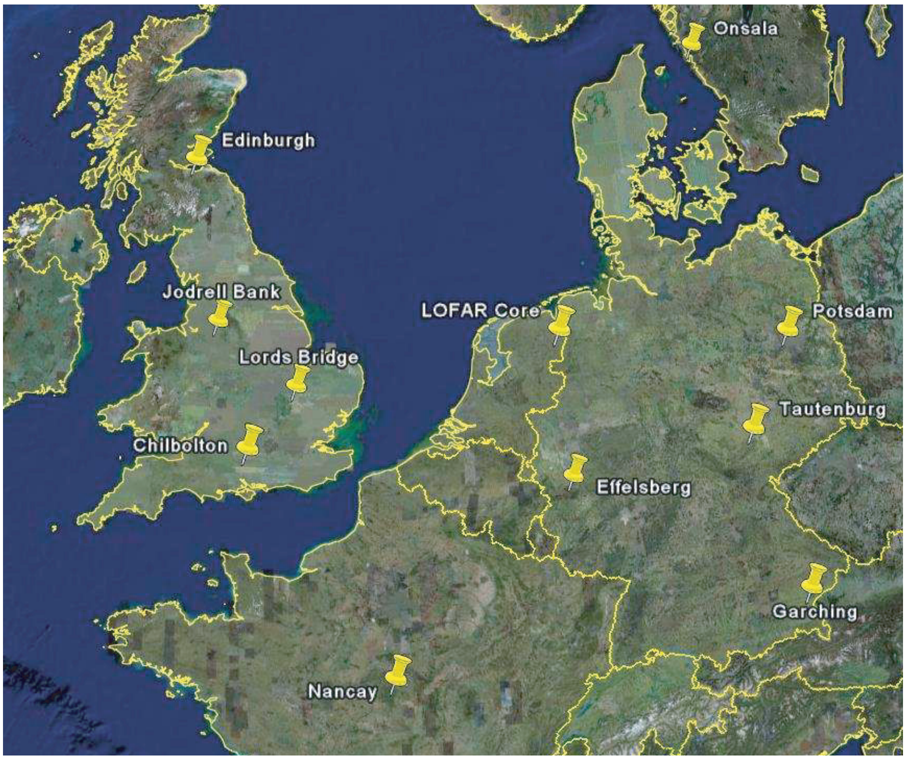

Figure 8: Locations of existing, funded and proposed international LOFAR stations with the UK, Germany, France and Sweden. Note there is probably at least one more station funded within Germany.

Table 4.1 below indicates how, if all funding plans are successful, the share of collecting area (=sensitivity) will be distributed between the partners by 2010, by which time the two major procurement rounds will be completed. It should be noted that the estimated 14% collecting area in the UK is achieved at about 2.5% of the total LOFAR project cost, and is currently facilitating a disproportionately large degree of scientific leadership.

4.1 Four LOFAR-UK stations

There are several reasons to aim for four LOFAR-UK stations, both political and technical.

Politically, UK has established significant leadership in the LOFAR project (see both below and Scientific Justification) which has been based upon our committment, from early on, to try to place a significant amount of the collecting area in the UK. This has always been discussed at the level of four stations. As can be seen in table 4.1 this puts us at a comparable fractional level of collecting area to the German consortium, GLOW, and not at the level of the 'tertiary' partners (e.g. France, Sweden and possibly Italy, Ukraine, Austria etc). *In this note that there exists a verbal agreement between LOFAR-UK and ASTRON that we will have to scale down our involvement and leadership in LOFAR in the event that we are limited to fewer stations.*

It is further important to note that the four-station LOFAR-UK concept is only possible because of the large degree of external, non-STFC, funding we have already secured or are currently bidding for. In the context of E-LOFAR, it is likely that in the longer-term funding will be sought from FP7 and/or other centralised European routes – the larger the LOFAR-UK contribution to the LOFAR, the larger fraction of such funding we can expect to attract.

Technically, the UK baselines are very important for the highest angular resolution studies with LOFAR (see Technical Case, Fig 7). Not only the NL-UK baselines, but the intra-UK baselines fill in an important region in baseline space (the *uv*-plane). This will significantly improve the imaging fidelity. In addition, at any times when the UK-only stations may be correlated, four stations provides far better imaging (six baselines) than three (three baselines). In addition to collecting area, significant parts of our personnel work packages (notably WP-D3 and D4, see next section) contribute directly to the core LOFAR and E-LOFAR efforts and further enhance our stake within the project (this has all been coordinated directly with ASTRON). On top of all this we are of course contributing to the overall leadership of the project.

	2008	2009	2010
ASTRON (NL)	96 (50%)	960 (62.5%)	1728 (62%)
GLOW (DE)	96 (50%)	384 (25%)	480 (17%)
LOFAR-UK	0	96 (6.3%)	384 (14%)
FlOW (Fr)	0	96 (6.3%)	96 (3.4%)
SLOW (Sw)	0	0	96 (3.4%)

Table 1: Evolution of E-LOFAR until 2010. For each country and year are listed the total number of antennae of each type (LBA and HBA), and the fraction of the total collecting area of the telescope. If funding is successful, by 2010 approximately one third of the array will be sited in the UK and Germany. Note that stations in NL will have 48 of each type of antennae, whereas those on international baselines will have 96.

4.2 UK leadership within E-LOFAR

As outlined in Section 1, the return for this significant contribution of LOFAR-UK to the array will be strong involvement, and often leadership, of some of the key science areas. While the organisation of the Key Science Projects (KSPs) varies slightly from project to project, all have a board with a restricted membership (< 10, often < 5). These board members will be the decision-making body for the KSP, and largely responsible for prioritising projects within the KSP. Below the board level, there will be 'ordinary' and 'associate' members who have some, more limited, data rights.

In return for the UK's committment to try and build four LOFAR stations, as well as significant contributions to the scientific and technical manpower efforts, we have been awarded significant roles within all of the KSPs.

4.2.1 Surveys

Within the Surveys KSP two UK scientists (Best [Edinburgh], Jarvis [Hertfordshire]) have been appointed to the board, and ~ 10 additional scientists accepted as ordinary members, from Durham, LJMU, Manchester, Cambridge, Southampton, Portsmouth, Hertfordshire and Oxford.

4.2.2 Transients

Two of the three current board members of the Transients KSP (Fender [Southampton], Stappers [Manchester]) are now working at UK universities, as a result of job movemements since the creation of the KSP. In addition, scientists from Hertfordshire, LJMU, Portsmouth and UCL/MSSL have been accepted into the project, to provide a very strong UK influence.

4.2.3 Solar and Heliospheric Physics

One UK representative (Khan [Glasgow]) has been appointed to the four-man board of this KSP, with more accepted as ordinary members, including scientists from Aberystwyth and Southampton.

4.2.4 Epoch of Reionisation

UK representatives, from Cambridge, Durham and Edinburgh, have been accepted into this KSP, although the level is still under negotiation.

4.2.5 Cosmic Rays

UK representatives, from UCL and RAL, have been accepted into this KSP, although the level is still under negotiation.

4.2.6 Cosmic Magnetism

UK representatives, from Cambridge and The Open University, have been accepted into this KSP, although the level is still under negotiation.

In summary, currently the UK has a very strong influence within LOFAR, comparable to that exercised by the German consortium, GLOW, which has already purchased four stations. We wish to maintain this strong position.

4.3 Further European evolution of E-LOFAR

It is anticipated by ASTRON, and all the current E-LOFAR partners, that LOFAR will continue to expand across Europe as access to high speed internet connections widens. Beyond the currently funded projects (NL, Germany, UK, Sweden, France), serious interest has been expressed in Italy, Poland, Austria and The Ukraine. It is clear that E-LOFAR is the major European-based radio project for the coming decade. Within LOFAR-UK we have been working very closely with the German, French, Italian and Swedish LOFAR consortia.

Furthermore, a funding request has been put to RadioNet FP7, to cover the formation of the E-LOFAR board, with representatives from at least ten European nations. The PI of this PPRP proposal (Fender) is also PI of the RadioNet proposal, ensuring UK leadership in the expanding E-LOFAR.

4.4 ASTRON endorsement

The following is a letter of endorsement for this proposal from the ASTRON director.

ASTRON

NETHERLANDS FOUNDATION FOR RESEARCH IN ASTRONOMY

Prof. R. Fender
School of Physics and Astronomy
University of Southampton
UK.

Dwingeloo, 4 January 2008

Dear Rob,

I understand that you and a consortium of other researchers are planning to submit a proposal to STFC, requesting significant funding for the construction of LOFAR antenna stations in the UK and the wider participation of the UK astronomical community in LOFAR.

ASTRON wishes to express its strong support of this initiative. LOFAR will be a transformational instrument, opening up a new region of the electro-magnetic spectrum with unprecendent sensitivity and angular resolution. In addition, the technology deployed permits large scale cosmological surveys to be conducted and for the nature of the transient radio sky to be studied properly for the first time. In addition, the instrument is expected to play a major role in investigations of the quiet and active sun, including coronal mass ejections, solar flares and shocks in the solar carona. Undoubtedly, these are all areas where we would expect the UK community to make a promininent and important scientific contribution. It is also clear, that the UK community has expertise to offer in the area of data distribution, calibration and analysis. Discussions on how these activities can be integrated are already advanced; the detailed implementation still needs to be fully explored.

ASTRON intends to reserve access to a part of the total observing resources (telescope time) for scientists from communities and groups in recognition for making significant enhancements to the integral LOFAR facilities, such as are proposed by the LOFAR:UK consortium. ASTRON expects that parties bringing additional LOFAR stations to the array will also share in the operational burden and costs associated with the integrated exploitation, with, again, appropriate recognition for their contribution in the form of privileged access to part of the observing resources.

The placement of antennas outside of the Netherlands will significantly enhance the scientitfic potential of the LOFAR telescope, in particular antennas in the UK would increase the angular resolution by a factor of 10, permitting cosmic radio sources to be imaged with sub-arcsecond imaging. Currently, four LOFAR stations are funded for construction in Germany, and the first international station is already operating at Effelsberg. Funding for additional stations in Sweden and France is confirmed. Interest in other European counties (e.g. Poland and Austria) is also becoming serious.

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ASTRON

This is exactly the right time for the UK to become fully involved in the E-LOFAR project – timely participation of the the UK community will ensure that they will fully capaitalise on the undoubted expertise they can bring to the project. I wish you every success in this endeavour!

Best regards,

Prof. Michael A. Garrett
General Director, Stichting ASTRON

5 Management

5.1 Work Breakdown Structure

The work breakdown structure (WBS) for LOFAR-UK is presented in Fig 9. At level 1 the WBS breaks down into two clear major subsystems

- **Management / Development / Commissioning Personnel.** This system provides the essential infrastructure for the successful operation and exploitation of the LOFAR-UK stations.
- **Installation / Comissioning of LOFAR stations.** The installation of the hardware which constitutes the four-station LOFAR-UK array.

In the following text we outline these subsystems at the Work Package level (level 2); detailed breakdowns and costings are provided in Annex A.

5.1.1 Development / Commissioning Personnel

We are requesting four work packages related to personnel support for LOFAR-UK, in the areas of Project Management (WP-D1), Data transport (WP-D2), Calibration (WP-D3) and Data Products (WP-D4).

WP-D1 Management The management of LOFAR-UK has evolved since the inception of the project in 2004. Section 5.4 and Fig 5.4 illustrate the structure as envisaged in a STFC-funded model. This work package covers the overall management, station level management and public outreach aspects of the LOFAR-UK proposal.

The major additional component not currently in place would be a Project Manager (PM) who would be employed at the 50% level. The PM would report to both the Project PI / co-PI and also to the LOFAR-UK partners and international partners. In addition to this, we request fECs for the Principal Investigator (PI, Fender), the co-PI (Rawlings), as they will have an essential role in taking overall responsibility for the project.

We further request a small amount of fEC support for the station managers at each of the four LOFAR-UK station sites:

- Chilbolton (Davies)
- Edinburgh (Best)
- Jodrell Bank (Garrington)
- Lord's Bridge (Alexander)

Finally, we request a small amount of fEC support for a publicity officer, to coordinate the public outreach aspects of LOFAR within the UK. We propose Dr Alastair Gunn at JBO/University of Manchester as the Publicity Officer. Dr Gunn has acted as the outreach officer for RadioNet, and EC-funded initiative, pulling together all the major European radio astronomy observatories (24 partners from 10 countries), since 2003. He plays a significant role in outreach activities at JBO, including most recently a spectacular sound and light show projected on the Lovell Telescope, to celebrate its 50th anniversary.

WP-D2 Data Transport The data transmission network is a key part of the LOFAR project, both within the Netherlands and for the international partners. Each LOFAR station (outside the core) has a maximimum observing bandwidth of 32 MHz in each of two polarisations and which can be divided into a maximum of 8 simultaneous beams. The total raw data rate from a LOFAR station is approximately 2 Gb/s and allowing for overheads and additional monitor and control signals, the required bandwidth is approximately 2.5 Gb/s. The network connections must be capable of sustaining this data rate for long periods and with low error rates.

In the UK, we plan to use the new lightpath facility on the SuperJanet 5 network, offered by UKERNA for connections from the nearest SJ5 point of prescence (PoP) to an interconnection with the Geant network operated by Dante, which provides a peering connection to SURFnet in the Netherlands. The LOFAR project have offered to provide the data connections from Amsterdam to the Central Processor in Groningen.

Each LOFAR-UK station will need a connection to a SJ5 10 Gb/s PoP, with a capacity of at least 1 Gb/s initially and 3 Gb/s eventually.

Sustaining data rates of this order for real-time transmission to a central processor is challenging. Over the last few years, this challenge has been tackled by the European VLBI Network, which is now able to carry out

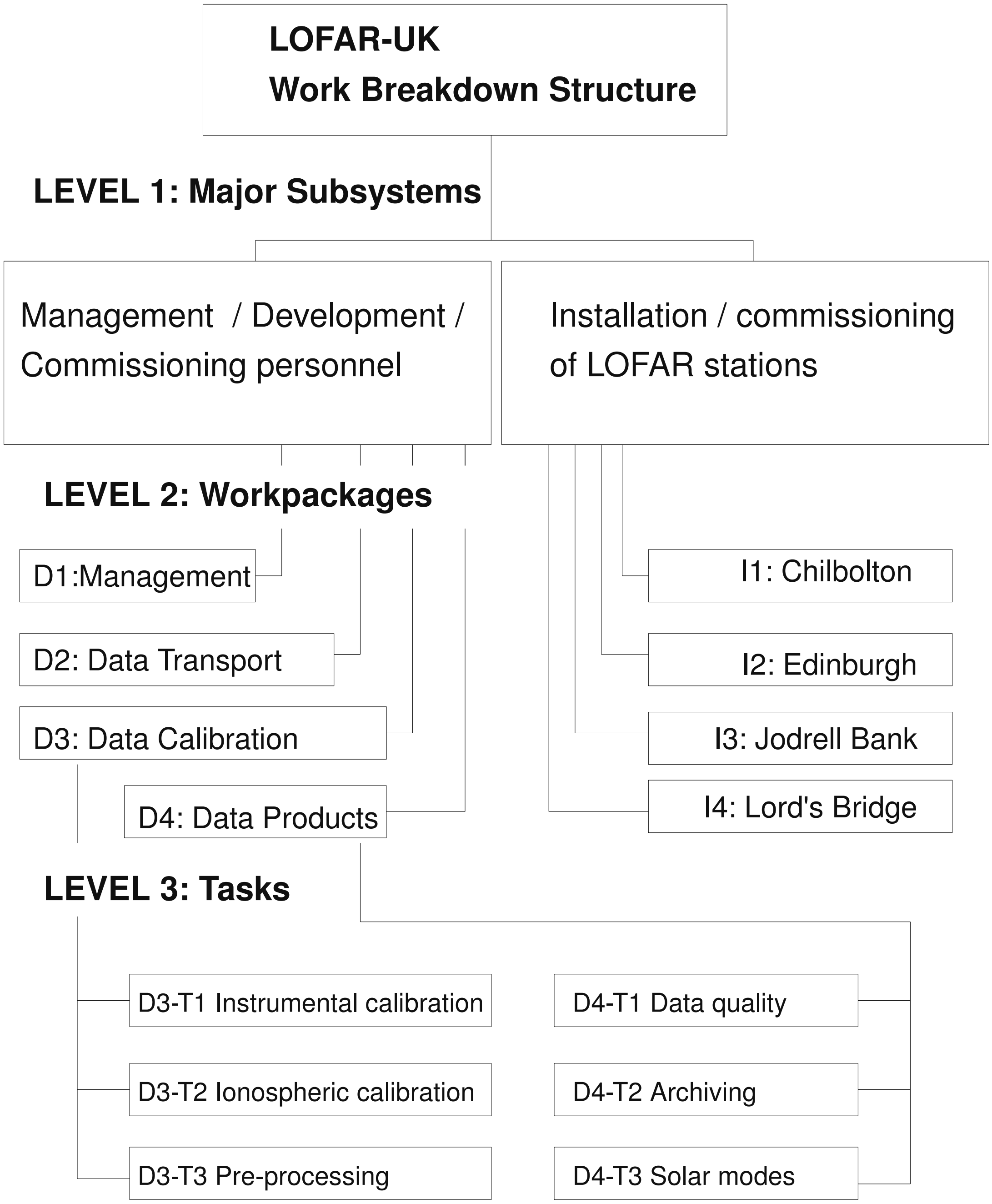

Figure 9: Work Breakdown Structure (WBS) for LOFAR-UK

real-time correlation (e-VLBI) from six radio telescopes across Europe, sending data at rates close to 1 Gb/s to the correlator at Jive in the Netherlands.

In the UK, staff at Jodrell Bank Observatory and the University of Manchester have played a key role in e-VLBI and developed strong collaborations with the high energy physics community who have similar requirements for LHC data transport. Particular contributions include: first demonstration of > 500 Mb/s e-VLBI traffic between the UK and the Netherlands, development of UDP transmission protocols for e-VLBI, diagnosis of bottlenecks in system hosts and the networks.

We plan to capitalise on this e-VLBI experience and use the expertise of staff involved in e-VLBI. This first task will be to gain familiarity with tranmission requirements and protocols for LOFAR. This will include an investigation of techniques to reduce bandwidth requirements for LOFAR-UK stations for initial operations (reduced RF bandwidth, reduced number of bits). Significant liaison with LOFAR-UK sites, UKERNA (SJ5), Dante (Geant) and LOFAR will be required to establish lightpath connections from each LOFAR-UK site to Amsterdam. Technical tasks will include tests to check capacity of these links; investigate throughput, rates of packet loss, duplication and re-ordering. This work package includes taking responsibility for continued operational monitoring of these links.

WP-D3 Data Calibration One of the founding aims of the LOFAR-UK consortium was to spread expertise in radio astronomy beyond the few existing centres in the UK. With this in mind, LOFAR-UK technical effort will be spread amongst the smaller UK radio astronomy groups with relevant local expertise. The PDRAs involved will work closely with the main LOFAR project by making extended trips to work alongside the core software team in the Netherlands. They will also develop close links with higher-frequency radio calibration development work undertaken for eMERLIN at Manchester and UCL, and under the auspices of the PrepSKA and RadioNet projects within Cambridge, Manchester and Oxford. The expertise developed in long-baseline calibration of LOFAR will also be invaluable for our international partners in E-LOFAR.

This work package breaks into three tasks:

- Instrumental calibration (WP-D3-T1) led by Glasgow
- Ionospheric calibration (WP-D3-T2) led by UCL
- Pre-processing (WP-D3-T3) led by Herts

These tasks are all essential if LOFAR long baselines to the UK are to be usable for the highest possible fraction of time at the widest possible range of frequencies and the widest possible field of view. LOFAR-UK aims to employ three software developers (i.e. expert C++, Python, HPC programmers) to form a UK team that will deliver UK-led software packages as part of the integrated LOFAR Common Software (LCS). They will work closely with the LCS team in ASTRON. If the LOFAR-related HEFCE/SEPNET bid is successful, the core 'software developer' work will be supplemented by two years of dedicated LOFAR-project work extending the scope of the ionospheric calibration work. These 'in-kind' contributions to the LOFAR project will count towards maximising the LOFAR science return to the UK from the LOFAR-UK programme.

WP-D4 Data Products In addition to requesting support for the construction of LOFAR-UK arrays, we request here support for the involvement of UK scientists in the creation and archiving of the key LOFAR data products. The UK has a long tradition in this area via its involvement in many astronomical surveys and has significant expertise to provide the LOFAR project. Furthermore, we must also prepare for the use of the LOFAR-UK stations in stand-alone mode (see Section 1.9). In summary, this work package is key to ensuring the UK scientists gain the maximum scientific return on our investment into the LOFAR project.

This work package is broken down into three tasks:

1. The construction of reliable source catalogues from the calibrated long-baseline radio maps. This task will be lead by the ATC Edinburgh under the supervision of Rob Ivison and will exploit key UK knowledge recently developed as part of the ALMA and EVLA projects. The main issue to resolve is the detection and characterization of extended sources in the presence of a varying PSF. This effort will obtain equal matching funds from the SUPA-2 bid.
2. The construction of a series of related science databases and web-based user-friendly interfaces. This task will be shared between the IfA Edinburgh and the ICG Portsmouth and leverages the UK's long-standing expertise in the design and maintenance of scientific databases, e.g., UKIDSS, SuperCOSMOS, VISTA, SDSS, etc. This package will be co-supervised by Phil Best and Bob Nichol, and will receive considerable matching funding ($> 50\%$) from the SUPA-2 and SEPNET bids (see Section 6.2.2) as well as

university departmental support. The three key goals of this work are to: *(i)* Establish a catalogue-based database in the UK to service our scientific community and in collaboration with the Dutch, enhance the present user interface of the astro-WISE system; *(ii)* Design and implement a database for the stand-alone operation of LOFAR-UK arrays in collaboration with the UK scientists; *(iii)* Work with our international partners to develop a general LOFAR archive for all data LOFAR products being compatible with the Virtual Observatory initiative. Finally, this database team will work closely with the LOFAR Publicity Officer to help design and maintain the LOFAR-UK public website.

3. The development of algorithms for LOFAR solar data. This task is being led by the University of Glasgow under the supervision of Lyndsay Fletcher and will be done in close collaboration with the LOFAR Solar Key Science Project in Potsdam. The UK has much expertise in this area of research and the use of the LOFAR-UK arrays for solar observations is an excellent use of the UK hardware when in stand- alone mode. In particular, solar radio spectrograms are an obvious use during daylight hours, but automated algorithms need to be developed in order to maximise the science coming out of these observations. This effort will obtain equal matching funds from the SUPA-2 bid.

The tasks identified above will be carried out in collaboration with the full LOFAR project and represents work presently under-staffed by the Dutch LOFAR team. They have requested our help on these work packages and this work will be counted as "in-kind" contributions to the LOFAR project. Furthermore, it allows the UK to take leadership roles in key areas of science and ensure our scientists have the best access to the data products they require.

The requested STFC funds for this work package will leverage considerable matching funds from other agencies and universities. For example, all staff and PDRA support has 50% matching from other sources, while computer hardware required for the LOFAR databases will be provided through university contributions or the SEPNET bid (total of up to $\pounds 230$k).

5.1.2 Installation of LOFAR stations

We propose to purchase, install, commission and operate full (ie. 96 high-band and 96 low-band antennae) LOFAR stations at four sites within the UK. These sites are Chilbolton, Edinburgh, Jodrell Bank and Lord's Bridge (see Fig 10). More technical information on the stations is provided in the Technical Justification (section 2).

The installation and commissioning process involves a combined effort between ASTRON staff, local labour and institute technicians. Ground preparation is expected to take approximately four to eight weeks. ASTRON staff expect commissioning tests to take three weeks.

At the three sites in England detailed studies have been carried out into the feasibility of station installation. This includes:

- Radio Frequency Interference (RFI) tests performed by a team from ASTRON. All sites passed with average RFI conditions 'better than the average in The Netherlands' and acceptable for a station.
- Detailed costing of installation to specifications provided by ASTRON. The detailed figures are presented in Annex A, and can be broken down further if required
- Land and administrative approval has been sought and given at all three sites, i.e. the operating institution is fully in support of the siting of a LOFAR station on their land

In the event of a successful outcome of the SUPA2 bid the same procedures will be carried out ASAP for the proposed Edinburgh site.

Detailed breakdown of installation costs are provided in Annex A.

5.2 Overall project schedule

In December 2007 LOFAR:UK agreed with ASTRON the purchase of the first LOFAR:UK station. This is part of the first of two major LOFAR purchasing rounds. This station is expected to be delivered in 2008Q3, and installed and commissioned by 2008Q4. We propose to run this station during 2009 with a data transport rate of 1 Gb/sec (around 40% of maximum) to The Netherlands. Note that final selection of the first LOFAR-UK site will take place in April 2008.

The second round of LOFAR station purchasing will occur around the same time (2008Q4), at which point LOFAR:UK will order three more stations, contingent upon funding (both from STFC and elsewhere), to be delivered, installed and commissioned by 2009Q4. We would run the entire LOFAR:UK network at 1 Gb/sec in

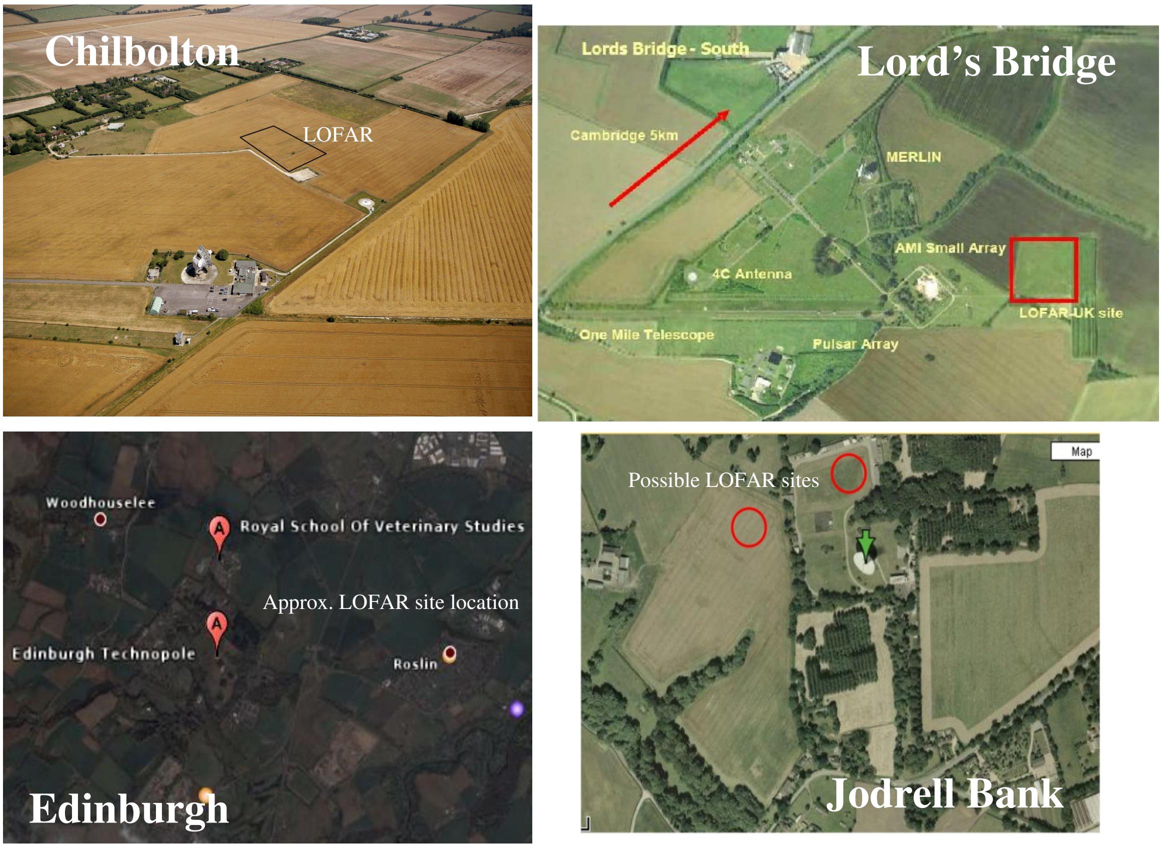

Figure 10: The four potential LOFAR-UK sites. All three sites within England have been thoroughly tested for Radio Frequency Interference (RFI) and have had detailed installation and data transport cost estimates.

2010, and increase data transport to 3 Gb/sec in 2011. *Currently there are no further purchasing rounds anticipated* – therefore purchases at a later date may be expected to be at a higher unit cost. The Gantt chart below (Fig 11) summarizes the plan.

From 2012 onwards the LOFAR-UK array would be complete in terms of hardware installation and commissioning, constituting a powerful new radio astronomy facility in the UK, as well as part of a wider European facility. Operational costs would then be requested via Telescope Operations and/or European funding.

5.3 Proposed schedule of management meetings, formal reviews and proposed communications routes

Currently the LOFAR-UK Management committee (MC) has a meeting monthly, either at a face-to-face meeting (approximately tri-monthly) or otherwise via a telecon. The meetings are minuted by one of the three Technical Coordinators.

We anticipate that the management structure will evolve following the appointment of a Project Manager at the 50% level (see Work Package D1), and that the procedure for reporting to and coordinating with STFC will be decided bilaterally.

We anticipate that LOFAR-UK will have a formal review following the installation and commissioning of the first station (2008Q4) and the second set of stations (2009Q4), as well as at the end of the funded period (2011Q4).

5.4 Management structure

LOFAR-UK came into existence in 2004, and since then has evolved a formal structure based around a Memorandum of Understanding (MoU). This management structure for is outlined Fig5.4.

Currently Fender and Rawlings, as PI and co-PI, take overall responsibility for the project, chair meetings and telecons, and conduct negotiations with ASTRON and the other E-LOFAR partners.

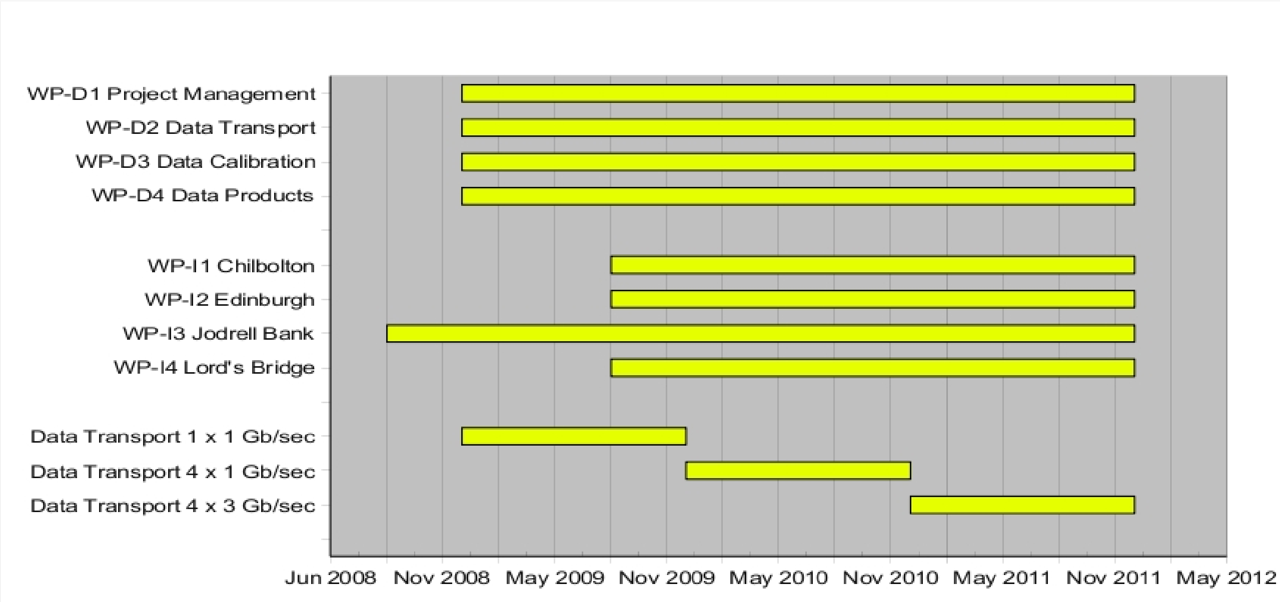

Figure 11: Gantt chart for LOFAR-UK. Note that the selection of Jodrell Bank as the first LOFAR-UK station is only given as an example, and final site selection has yet to be made. This initial station purchase will be funded by existing LOFAR-UK resources, and the STFC-funded part of this proposal runs fropm Jan 2009 to Dec 2011.

5.5 Key Personnel, consortium members, responsibilities

The LOFAR-UK consortium consists of the Universities of Cambridge, Cardiff, Durham, Edinburgh, Glasgow, Hertfordshire, Kent, Manchester, Oxford, Portsmouth, QMU, Southampton, Sussex as well as Liverpool John Moores University, The Open University and The University of Wales at Aberystwyth. Each of these Universities has a member on the LOFAR-UK Management Council (MC), the decision-making body.

A successful SEPNET bid to HEFCE will result in the Universities of Sussex, Kent, and Queen Mary (London) joining the consortium.

The MC has representatives from STFC at RAL and ATC, and key members responsible for:

- **Science coordination:** Philip Best (Edinburgh)
- **Technical coordination:** Rob Beswick (Manchester)
- **e-Science coordination:** Bob Nichol (Portsmouth)
- **Finances:** Elias Brinks (Hertfordshire)

In addition, local site managers (not indicated in the organogram) are:

- **Chilbolton:** Davies
- **Edinburgh:** Best
- **Jodrell Bank:** Garrington
- **Lord's Bridge:** Alexander

UK scientific efforts within LOFAR will be coordinated by those members we propose to join at board level the existing Key Science Projects (KSPs).

The structure is summarized in the organogram (Fig 12).

5.5.1 Key Roles

The STFC-defined Key Roles within LOFAR-UK are as follows:

- **Principal Investigator:** Rob Fender (University of Southampton)

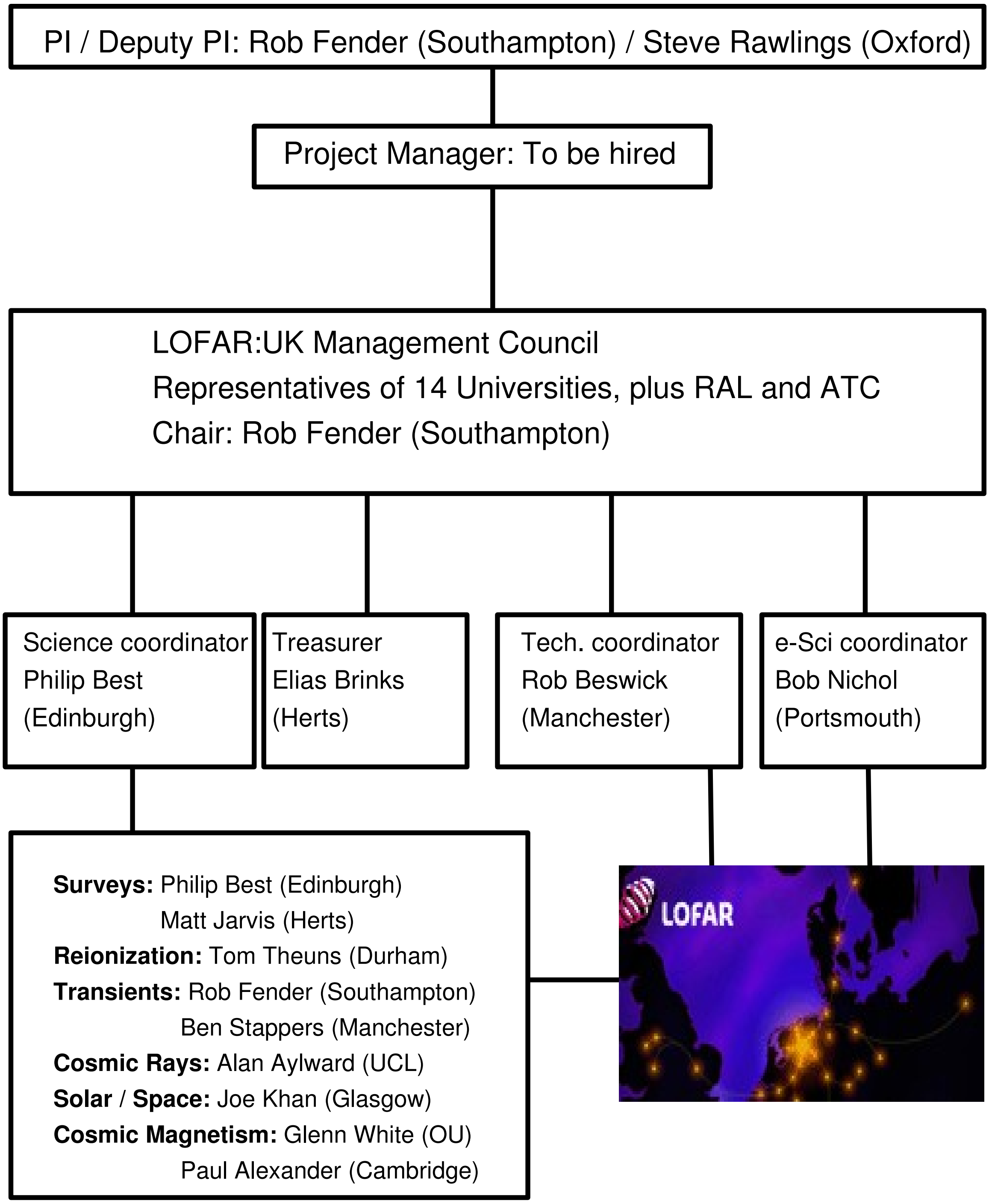

Figure 12: Organogram for LOFAR-UK

- **Deputy Principal Investigator:** Steve Rawlings (University of Oxford)
- **Project Manager:** A Project Manager (PM) will be hired to work on LOFAR-UK at the 50% level (this is in our budget). This post will be based at Oxford.
- **Project Sponsor:** Colin Vincent / Simon Berry at STFC (TBD by STFC)

5.6 Change control procedure

(TBD, with STFC)

5.7 Oversight arrangements

(TBD, with STFC)

5.8 Technology and Industry Plan

The LOFAR-UK arrays will be purchased in collaboration with the main LOFAR project. Therefore, the technology has already been developed and is now being procured through a major European effort. We will join this procurement and simply purchase the same technology. Therefore, there is no "upfront" technological development in this project but there are two key areas of potential industrial involvement in LOFAR-UK. These are outlined below:

- The LOFAR collaboration will only provide the necessary hardware to build an array. They will help supervise the installation of that array but it is the responsibility of the LOFAR-UK consortium to oversee the construction of these arrays in the UK and thus prepare the sites prior to their delivery. Therefore, LOFAR-UK will be employing local companies in the construction of these sites especially to perform the tasks of levelling the ground (to a few centimeters), building the support infrastructure (fencing and concrete plinth) and installing the complex cabling required for each station. Furthermore, LOFAR will make demands on the local internet connections at each site and we will work closely with these IT providers (mostly in industry) to ensure that we get the best connectivity across the UK. In this way, much of the construction costs of the LOFAR-UK sites will aid local companies and beyond.
- Beyond the construction of the stations, the most direct collaboration between LOFAR-UK and industry will be via the large data volumes produced by the LOFAR stations. The potential storage, analysis and transport of this data can be used as a testbed for industrial systems that would benefit from access to such copious amounts of streaming data. We have already held initial discussions with EADS Astrium in Portsmouth to explore development of novel signal processing techniques to handle such data. Astrium is interested in such technology for future satellite missions as well as the opportunity for recruiting excellent scientists into their organisation (via CASE studentships). We will further develop such plans with various industrial partners across the country.

  In addition to industry, the LOFAR data-streams pose a challenge to the emerging e-Science community and again can provide an interesting test case for such technology. For example, we will explore synergies with existing and planned grid-computing projects including GridPP. We will also engage with the e-Science centres around the country and have already held discussions with such centers at RAL and Edinburgh. We have also discussed possible LOFAR-UK storage and analysis using the National Grid Service (at RAL) and their Petabyte Storage Group. Such work has indirect spin-offs to industry and will produce high-tech expertise within the UK academic community. We will continue to cooperate with the UK High Performance Computing (HPC) community as well as computer scientists around the country (e.g. Mark Baker at the University of Reading).

  The LOFAR-UK consortium will also develop strong connections with the STFC Knowledge Transfer scheme and ensure all members of the collaboration are aware of their funding opportunities (Discipline Hoppers, Follow on Funding, and Partnership schemes). We will invite members of this scheme at STFC to visit researchers and staff across the country to explain the programme as well as arrange at least one workshop on the subject of knowledge transfer for our collaboration. We will also encourage researchers to engage with their local university initiatives in knowledge transfer.

5.9 Outreach

LOFAR and LOFAR-UK provide significant new opportunities for public outreach across the UK and in Europe. In the UK, we will develop a coherent outreach plan based around the LOFAR-UK array sites as well as liaison with our european colleagues in the main LOFAR project. We will also liaise with the various SKA initiatives around the world to help increase the profile of radio astronomy both at home and abroad.

Within the LOFAR-UK consortium, our outreach plan will contain several key components with clear goals. They include:

- Recruitment of a "Publicity Officer" (PO) from the inception of the project, who will be responsible for coordinating all public relations activity across the collaboration (this is part of WP-D1). The PO is proposed to be Dr Alastair Gunn (Manchester) who has a proven record of interacting with the media and public in general. We request 5% FEC for the PO from the start of the project to allow our project to first develop a coherent plan (within the first year) and then execute this plan over the course of the project. We also believe the construction and commissioning of the LOFAR-UK arrays has huge potential for public engagement (see below) and feel we should hit the ground running from the start. Finally, the PO will also act as a "clearing house" for all requests for popular talks by astronomical societies, etc.

- We will foster our existing connections with Science Centers around the country to develop exciting exhibits and shows that can be used to promote the science of LOFAR to the general public. For example, we are already in discussions with the South East England Development Agency (SEEDA) and the Intech Science Centre near Winchester to build an interactive display of the LOFAR-UK data, potentially streamed directly from the close-by Chilbolton array. This collaboration builds upon our successful collaboration with Intech in developing an exhibit of the Sloan Digital Sky Survey (funded via the PPARC Science Centre Awards scheme). The advantage with working with such science centers is they have direct contact with local teachers and educators, thus allowing us to tailor the material towards the national curriculum. We will consider further requests for funding via the STFC Large Awards and Science Center schemes, and our goal is to provide at least one exhibit over the course of this project.

- We aim to develop a multi-media website for the LOFAR-UK project, the initial set-up and maintenance of which will be a task of the 'Data Archiving' PDRAs (see WP-D4-T2). We have already begun discussions with the Department of Creative Technologies at the University of Portsmouth about the development of a website along these lines. The goal of this would be provide the public (including educators) with an interactive webpage hosting informative material in several formats. We have already discussed the creation of video podcasts tracking the construction, commissioning and first operations of the LOFAR array sites. This could include interviews with the scientists and engineers, thus providing the public with a "real-time" view of this project as it progresses . We would also provide blogs and forums for both the public and scientists to interact and exchange details of the science and technical progress. From the start, we would also plan to provide animations and sophisticated graphics explaining many aspects of the science and advanced technology used by LOFAR. Our goal is to make the LOFAR website a dynamic site with a community of interested participants. We will draw upon our recent experience with GalaxyZoo (www.galaxyzoo.org) in the design and operation of a successful public science site. We are also in discussions with SEEDA to help partially fund this work.

- We will liaise with the STFC Press Office to help promote any LOFAR-UK (and LOFAR) discoveries and major events. Via the PO above, we will work together on developing joint press releases and work with the STFC staff to circulate to the appropriate media. The PO will also work with the scientists to help them promote their science especially at major conferences both in the UK and abroad e.g., the US AAS meetings, NAM, etc. Together, the PO and STFC press office will ensure LOFAR has a high profile in the international media.

5.10 Exploitation and Data acquistion, distribution and analysis

Scientific exploitation of LOFAR / LOFAR-UK by the UK community will follow two paths:

5.10.1 E-LOFAR

The primary use of the LOFAR-UK stations will be in forming part of a high resolution low-frequency array in which the measurements from the stations are correlated with those from stations in the Netherlands and the rest of Europe (see Scientific and Technical cases).

The predominant exploitation of the LOFAR data by UK scientists will then take place via direct involvement in the LOFAR Key Science Projects (KSPs). The UK will be involved in all KSPs, providing the community with access to LOFAR data across all areas of science. It is notable that the UK expects to have board-level (i.e. strategic decision making) membership of all six KSPs, demonstrating leadership in all areas. The current plan for KSP observing time is that it will slowly ramp down as a fraction of the total observing time over a five year period, after which point all time will be open internationally. Year one of this phase is unclear but will probably be 2009/10. We fully expect that LOFAR projects will be driven and published by British staff, post-docs and PhD students from $\sim$ 2009 onwards. Even beyond the 5-year proposed lifetime of the KSPs, the UK will have gained so much experience with LOFAR data that it will continue to hold an advantageous position.

Furthermore, the UK's investment in stations means that some fraction (yet to be negociated) of all LOFAR time will be available specifically to UK scientists for specialist projects that are not part of the existing KSPs. We propose that this LOFAR time be made available to the entire UK community, through a competitive proposal process. Note that even just 1% of all LOFAR time, with 8 beams, is equivalent to 30 full days per year.

5.10.2 Stand-alone use

There may be times when one or more beams from the LOFAR-UK stations are not correlated with other E-LOFAR stations, particularly in the early phases of the project when the existing computing facilities in Groningen are stretched. During these phases the UK stations can be used as stand-alone telescopes, effectively acting as single dishes with a very wide field of view. Projects in this mode are likely to be focussed on variable and transient phenomena, e.g. The Sun, flare stars, pulsars. Stand-alone mode observations will be allocated through competitive proposals, which will be open to the whole of the UK community. The data will go directly to the parts of the UK community actively involved in these areas.

6 Costings

All costs in this section are in £k.

6.1 Costs to STFC including contingency and Working Allowances

Annex A provides a breakdown of the total project cost per workpackage (and for WP-D3 and WP-D3, per task). These costs are given at 100% (PPRP guidelines on FECs were not totally clear).

Annex B provides the *costs to STFC* broken down by institute and by financial year, for the three years of the project. These costings have been makde using the 80% FEC rule for non-RAL staff. However, the majority of project costs are equipment and exceptionals (which include station electricity and data transport) and so the difference is not great.

6.1.1 Base Cost

Based on the costs in Annex B, and following the PPRP guidelines, we first identify a Base Cost. This base cost can be considered to be the sum of the components as calculated, minus the contributions from LOFAR-UK (already in hand) and HEFCE/SEPNET (bid to be submitted in Jan 2008) – see below for more details of costs to be noted. This is summarised in the table below.

Total costs at 80% FEC	4901.42
LOFAR-UK (550.0)	-550.0
HEFCE/SEPNET (298.0)	-298.0
Base Cost	4053.42

We should be clear about the roles of the matching contributions, which are discussed in more detail below.

- The LOFAR-UK funds (550.0) will be used, in 2008, to purchase the first LOFAR-UK station, albeit at a slightly reduced specification (e.g. only 48 High Band Antennae initially). These costs can be directly subtracted from the STFC costs, as we have done above.
- Of the HEFCE/SEPNET funds, 148.0 is earmarked for Chilbolton, and an additional 150.0 is flexible (will go into central LOFAR-UK 'pot').
- The SUPA2 bid has 500.0 earmarked for Edinburgh, which is included in the costings for the Edinburgh station in Annex B1. If the SUPA2 bid fails then a station at Edinburgh will not be pursued.

Clearly if one or both of the SUPA2/HEFCE bids fails the costings willneed re-evaluation. Equally costs to STFC may be reduced if bids to SEEDA or other regional agencies are successful. More details of this are given in *Costs to be noted*, below.

6.1.2 Working Allowance

The working allowance has been calculated in Annex C, and has a total value of 417.3. *This sum has not currently been included on any of the JeS forms, following advice from STFC SPO.*

6.1.3 Contingency

Contingency for the entire project is very hard to calculate, so we estimate an initial figure of 10%, rounded to 450.0.

6.1.4 Approved Cost

The Approved Cost is defined as the sum of the Base Cost, Working Allowance, and Contingency:

Base Cost	4071.0
Working Allowance	417.3
Contingency (10%)	450.0
Approved Cost	4920.72

6.2 Costs to be noted

LOFAR-UK has attracted a lot of financial contributions from non-STFC sources, details of which are given below.

6.2.1 Funds in hand

LOFAR-UK has raised £600k by means of a"joining fee" of £50k from 12 of the member institutions.

This money will be used to purchase and install the first UK LOFAR station. In the funding details provided in Chapter 3, and in the Annexes, the example is given of this money being used to purchase and install the station at Jodrell Bank (probably minus the Transient Buffer Boards, see Annex A). However, the final decision on the location of the first LOFAR-UK site will depend upon the exact state of funding as of April 2008. This is the latest we can delay the site decision before ground works need to begin, and is the stage by which we should know the outcome of the additional funding bids listed below. £550k of these funds can be directly subtracted from the STFC costs, as indicated above. £50k is reserved for preliminary operations (one station at 1 Gb/sec) in 2009.

6.2.2 Additional funding

In addition to the LOFAR-UK central funds listed above, we have several additional bids for funding support. The consequences for the STFC bid of the success or failure of these bids is explicitly listed.

- **HEFCE/SEPNET:** In January 2008 a bid will be submitted to HEFCE for funding to support Physics in south eastern England; known as the "South East Physics Network" or SEPNET. This bid has an large astronomy component which is focused on the support of radio astronomy across the region, especially LOFAR-UK research. The total value of the bid to astronomy is £2148k, of which £148k is earmarked as a contribution to hardware at Chilbolton (LOFAR station and/or upgraded fibre connection). Furthermore, the bid includes significant new academic and technical staff across the South (Southampton, Portsmouth, Kent, QMU, Oxford, Sussex) as well as up to £200k for new LOFAR–related computer hardware. The bid includes LOFAR-UK joining fees for Kent, QMU and Sussex (£150k). In WP-D3-T2, Oxford will use two years of funding from the SEPNET bid in support of their ionospheric software development work, while Portsmouth will use 1.5 years of SEPNET funding to match the same amount from STFC for data archiving in WP-D4-T2. If the SEPNET bid fails, this will lead to a reduction in the scope of this work package as well as lower research capacity in these universities.
- **SUPA2:** In October 2007, the Scottish Universities Physics Alliance, part 2 (SUPA-2) funding bid was submitted to the Scottish Funding Council, part of which was for the support of a Scottish LOFAR station, likely to be sited at Edinburgh University Science Park. The bid requests £500k towards the purchase and installation of the LOFAR station. The consequence of this bid failing is we will no longer pursue the station in Edinburgh (WP-I2), thus reducing the STFC bid by £469.4k. There would also be no matched funding available for work package tasks WP-D3-T1 and WP-D4-T3 in Glasgow, nor WP-D4-T1 at the ATC and WP-D4-T2 in Edinburgh. Work packages WP-D4-T3 and WP-D4-T1 would be withdrawn, and the STFC bid refocussed on maintaining full support for WP-D3-T1 and WP-D4-T2 (at essentially no change in cost).
- **SEEDA:** A bid is being prepared to the South East England Development Agency (SEEDA) for £180k, of which £160k would contribute towards hardware costs at Chilbolton, and £20k towards LOFAR public outreach based at the INTECH Science Centre near Winchester. If this bid was successful, it would result in a reduction of £160k of the STFC bid. There are no additional consequences if the bid fails.

6.3 Costs: Conclusion

This proposal has outlined a technical bid to purchase, install, commission and perform initial operation, of a four-station LOFAR-UK array. This would confirm our status as a major partner in the LOFAR project, the only fully-funded low-frequency SKA pathfinder, and the only SKA pathfinder of any type under construction in Europe. It would allow us to maintain our very strong influence on, in many areas leadership of, the project, and would match the ambitious deployment currently already funded in Germany.

In the event that the matching bids from SUPA2 and HEFCE/SEPNET are successful, this goal could be realised for a base cost of $\sim \pounds 4$M.

Work Package details

A Annex A: Work Package Details

In this section we provide detailed task breakdown and costings for the LOFAR-UK work packages. Recall that at level 1 the WBS breaks down into two clear major subsystems.

- **Management / Development / Commissioning Personnel.** This system provides the essential infrastructure for the successful operation and exploitation of the LOFAR-UK stations.
- **Installation / Comissioning of LOFAR stations.** The installation of the hardware which constitutes the four-station LOFAR-UK array.

Each of these subsystems has four workpackages. For all of these we list tasks and detailed costings. However note that only for WP-D3 (Data Calibration) and WP-D4 (Data Products) does it make sense to strictly separate these tasks, since they will be performed by different teams (for the other work packages the same team will perform all tasks). This is reflected in the WBS diagram, repeated below.

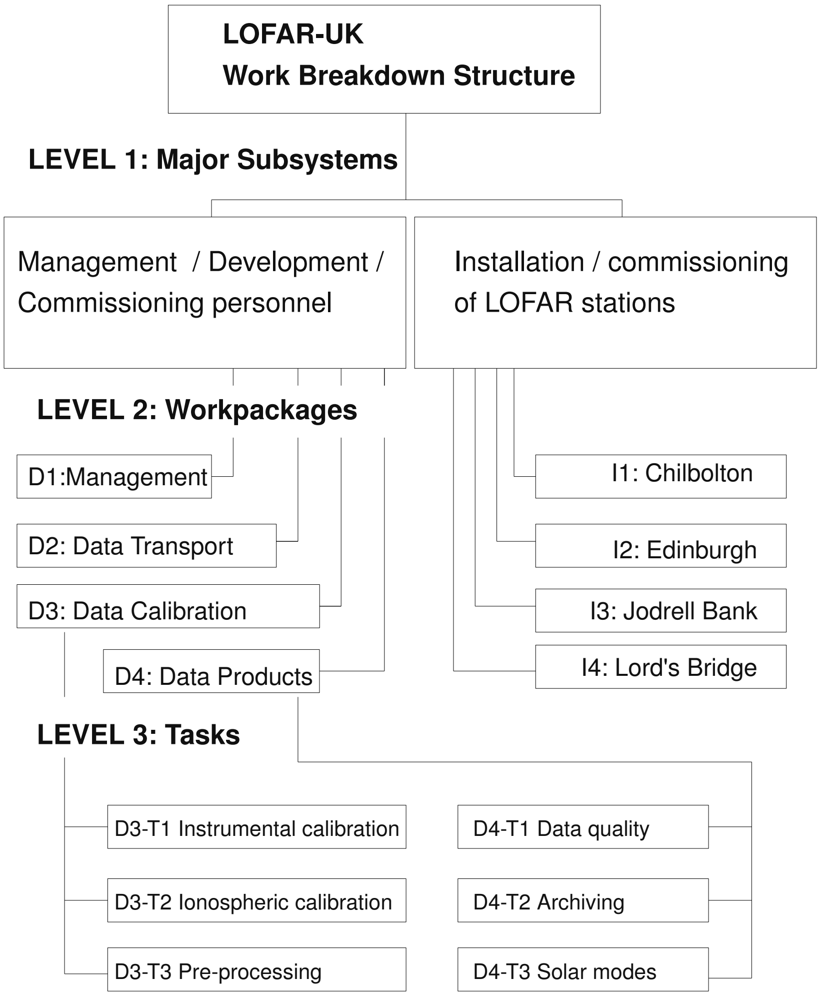

Figure 13: Work Breakdown Structure (WBS) for LOFAR-UK.

Note that as the FEC guidelines were not clear to us, we have presented 100% costs in this Annex, but costs to STFC (i.e. 80% of these, except for RAL and Exceptionals) are presented in Annex B and in the Costs to STFC section in the main text (section 6).

The 100% costs for the work packages are summarised below:

Work Packages D1-D4

Work Package	Total Cost
WP1 Project Management	£333.687k
WP2 Data Transport	£249.328k
WP3 Data Calibration	£480.307k
WP4 Data Products	£494.721k
TOTAL	**1558.043**

Work Packages I1-I4

Installation, including operating costs up to the end of 2011

Site	Total Cost
I1 Chilbolton	£1270k
I2 Edinburgh	£969.4k
I3 Jodrell Bank	£860.6k
I4 Lord's Bridge	£893.82k
SUBTOTAL	£3993.82k
LOFAR-UK contribution	- £550000
SUPA-2 contribution (→ I2)	- £500000
HEFCE/SEPNET contribution (→ I1)	-£298000
TOTAL	£**2 645.820k**

→ **Total Project Cost:** £**4203.86 k**
(at 100% costs but before working allowances and contingency)

LOFAR-UK-WP-D1 Project Management

Responsible Institutes: Southampton (PI), Oxford (Deputy-PI and Project Manager), Manchester (Jodrell Bank site management and Public Outreach), Cambridge (Lord's Bridge site management), RAL (Chilbolton site management), Edinburgh (Edinburgh site management).

Background

This workpackage encompasses all management aspects of LOFAR-UK.

In summary we request some FECs for the PI, co-PI, station site managers and Public Outreach officer. We also request FEC costs for 50% of a Project Manager.

The Project Manager of LOFAR-UK will be based in Oxford allowing easy access to all four proposed UK LOFAR stations, to the sites of LOFAR-UK technical activity and to Holland and the rest of Europe via Heathrow. LOFAR-UK activities will have a wide geographical distribution so centralised and efficient management is essential. The project manager will spend 50% of his time on LOFAR-UK management, with the rest of her or his time devoted to projects in related areas like PrepSKA, MeerKAT or other projects in radio astronomy.

The Work Packages are distributed amongst the LOFAR-UK consortium to make best use of existing expertise, and to ensure that additional UK expertise spreads beyond the traditional centres of UK excellence as will be required if the UK is to retain scientific leadership in radio astronomy into the SKA era. As one of the three UK contributors to PrepSKA, but not one of the two (Manchester and Cambridge) with many decades of radio astronomy heritage, Oxford provides the ideal environment for tieing together the twin aims of utilising and growing UK radio astronomy expertise.

There is considerable interdependence between the LOFAR-UK work packages, so to mitigate the associated risk, a formal but flexible managment structure will be implemented (based on PRINCE2 principles). This work package provides that management. The project manager will report to the PI (in Southampton), the deputy-PI (in Oxford) and a Management Board which will subsume the responsibilities of the existing LOFAR-UK Management Committee. The Project Manager will set up a new Project Managemement Committee to provide project oversight and control. The manager will also work in close coordination with the LOFAR Project Management Team in ASTRON and the management teams delivering E-LOFAR throughout Europe. The Project Manager will ensure that all UK-led work packages are delivered on time and on budget to the specification set by LOFAR-UK, and ultimately by the LOFAR project itself.

Input

Work Package	Description
All LOFAR-UK Work Packages	Overall Management

Tasks

- To prepare and maintain the overall LOFAR-UK project plan and timeline; to manage change procedures.
- To report on project progress to the LOFAR-UK Management Board by distilling regular reports from work-package leaders and putting processes in place to ensure the delivery of project deliverables.
- To set-up and chair a Project Managemement Committee that, via regular telecons, steers the programme and pinpoints any changes required.
- To monitor the timeline of the delivery, comissioning and first operation of the LOFAR-UK stations.
- To monitor and coordinate milestones and deliverables of the project.
- To monitor the financial status of the overall project.
- To organise and present the major design reviews, including ensuring all documentation is prepared and circulated.
- To provide and manage the link and interface with the overall (Dutch) LOFAR and (European) E-LOFAR projects.
- To prepare and present reports to the LOFAR-UK Management Board and the management boards of LOFAR and E-LOFAR.

Output

Description	Work Package	Date Delivered
Project Schedule For LOFAR-UK	All LOFAR-UK work packages	Mar 2009
Final Report on LOFAR-UK operation	All LOFAR-UK work packages	Dec 2012

Justification

Staff Effort. The management position is obviously required over the full length of the programme, and an experienced project manager is needed. Provided the manager's portfolio of projects is relatively small, and provided the portfolio includes projects with similar techical and administrative challenges (such as Prep-SKA, MeerKAT etc at Oxford), a 50% position is adequate to manage the LOFAR-UK project.

The PI of the project is Fender (Southampton) and the deputy-PI is Rawlings (Oxford). These two are responsible for the overall success of the project. The PI requests significant (20%) FECs, the deputy-PI a smaller amount. A comparable amount of FECs to the deputy-PI are also requested for the managers at the four station sites.

We also request FECs at the level of 5% for a Public Outreach (PO) officer. We propose Dr Alastair Gunn at JBO/University of Manchester for this role. Dr Gunn has acted as the outreach officer for RadioNet, an EC-funded initiative, pulling together all the major European radio astronomy observatories (24 partners from 10 countries), since 2003. He plays a significant role in outreach activities at JBO, including most recently a spectacular sound and light show projected on the Lovell Telescope, to celebrate its 50th anniversary.

Computer Equipment/Consumables. For computer equipment and consumables we calculate rates via contribution to the standard Oxford computing environment (desktop plus laptop plus secure backup system) whose rates are £2.4k and £0.84k per man-year respectively. For the 50% Project Manager position over three years, this totals £4.9k.

Exceptionals. Management meetings will be via telecon wherever possible. Bi-weekly telecons lasting ~ 1 hour, involving ~ 3 sites costing $\sim$ £0.25 per minute gives a three-year total of £3.5k.

Travel and Subsistence. The manager will need to travel within the UK on average once every two weeks, and within Europe (chiefly to ASTRON, Holland), on average once every two months. We adopt a UK travel cost of £100 per trip and a European travel cost of £250. For subsistence we assume each trip involves on average one overnight stay per trip, meaning a subsistence cost per trip of £125. The total T&S budget over 3 years is therefore £24.3k. The PI is expected to make half of this amount of travel, therefore £12.15k over three years. No travel expenses are requested for the deputy-PI or local station managers.

100% FeC Costs of STFC Proposal

Category	Items	FEC Cost
Investigators	Fender (Soton)	£43.868k
Estates	Soton	£9.673k
Indirects	Soton	£23.622k
Travel and Subsistence	Fender	£12.150k
Investigators	Rawlings (Oxford)	£5.523k
Staff	Project Manager (PM, Oxford)	£80.514k
Estates	Oxford	£24.609k
Indirects	Oxford	59.493k
Equipment	PM – Desktop/laptop system	£3.6k
Consumables	PM – Computer consumables	£1.3k
Travel and Subsistence	PM – UK+Europe travel	£24.3k
Exceptional	PM – Telecons	£3.5k
Investigators	Best (Edinburgh)	£3.813k
Estates	Edinburgh	£0.972k
Indirects	Edinburgh	£2.491 k
Investigators	Alexander (Cambridge)	£4.602k
Estates	Cambridge	£0.966k
Indirects	Cambridge	£2.499k
Investigators	Garrington (Manchester)	£5.479k
Investigators	Gunn (Manchester)	£7.614k
Estates	Manchester	£3.533k
Indirects	Manchester	£9.564k
		£333.685k

LOFAR-UK-WP-D2 Data Transport

Responsible Institutes: University of Manchester

Background

The data transmission network is a key part of the LOFAR project, both within the Netherlands and for the international partners. Each LOFAR station (outside the core) has a maximimum observing bandwidth of 32 MHz in each of two polarisations and which can be divided into a maximum of 8 simultaneous beams. The analogue signals are sampled with 16 bits so that the total raw data rate from a LOFAR station is 2 Gb/s. Allowing for overheads and additional monitor and control signals, the required bandwidth is approximately 2.5 Gb/s. The network connections must be capable of sustaining this data rate for long periods and with low error rates.

In the Netherlands, much of the data network is being installed as part of the LOFAR project, requiring a significant amount of new cable installation. At Effelsberg, the location of the first German international station, approximately 40km of new fibre has been laid for the LOFAR connection.

In the UK, we plan to use the new lightpath facility on the SuperJanet 5 network, offered by UKERNA for connections from the nearest SJ5 point of prescence (PoP) to an interconnection with the Geant network operated by Dante, which provides a peering connection to SURFnet in the Netherlands. The LOFAR project have offered to provide the data connections from Amsterdam to the Central Processor in Groningen.

Each LOFAR-UK station will need a connection to a SJ5 10 Gb/s PoP, with a capacity of at least 1 Gb/s initially and 3 Gb/s eventually.

Sustaining data rates of this order for real-time transmission to a central processor is challenging. The European VLBI Network began a proof-of-concept project to carry out real-time VLBI observations in 2003, with several radio telescopes in Europe streaming data in real time to the EVN data processor at JIVE in the Netherlands. The first real-time VLBI image was produced on 28 April 2004, using telescopes at Jodrell Bank, Onsala (Sweden) and the Netherlands and a data rate of 32 Mb/s. The development of e-VLBI is now also funded by ExpreS, via the EC FP6, and continual progress of the last three years had made e-VLBI observations at a data rate of 512 Mb/s with six telescopes almost routine. The most recent experiments achieved a payload data rate of just below 1 Gb/s.

In the UK, staff at Jodrell Bank Observatory and the University of Manchester have played a key role in e-VLBI and developed strong collaborations with the high energy physics community who have similar requirements for LHC data transport. Particular contributions include: first demonstration of > 500 Mb/s e-VLBI traffic UK-NL, development of UDP transmission protocols for e-VLBI, diagnosis of bottlenecks in system hosts and the networks.

These achievements require detailed understanding of the hardware used for data transmission and all the elements of the networks which are used. The use of dedicated light-paths is essential. The most recent development which allows the data rate to be adapted to the available capacity (rather than the VLBI standards of 256, 512, 1024 Mb/s etc) is also relevent to LOFAR.

Much of this work occurred as part of the ESLEA (Exploitation of Switched Lightpaths for E-science Applications. Lightpaths were provided through SuperJanet 5 by UKLight, and the ESLEA project was set up to make use of the lightpaths. As well as eVLBI, projects in medical science, high performance imaging and particle physics were included. The eVLBI project was very successful, achieving all its original aims. It became clear early in the project that congestion on conventional packet switched links would disallow the use of the bandwidths required in radio astronomy, and so fixed point to point circuits were more appropriate.

We plan to capitalise on this e-VLBI experience and use the expertise of staff involved in e-VLBI.

Input

Work Package	Description
LOFAR-NL	Detailed data transport requirements

Tasks

- Gain familiarity with tranmission requirements and protocols for LOFAR.
- Liaise with LOFAR-UK sites, UKERNA (SJ5), Dante (Geant) and LOFAR to establish lightpath connections from each LOFAR-UK site to Amsterdam.
- Carry out tests to check capacity of these links; investigate throughput, rates of packet loss, duplication and re-ordering.
- Liaise with other international LOFAR partners on data transmission best practices.

- Take responsibility for continued operational monitoring of these links.
- Investigate techniques to reduce bandwidth requirements for LOFAR-UK stations (reduced RF bandwidth, reduced number of bits) for initial tests and to reduce total costs.

Output

Description	Work Package	Date Delivered
Data transport requirements definition	WP-D2	Mar 2009
Commissioning first LOFAR-UK lightpath	WP-D2	Sep 2009
Commissioning other LOFAR-UK lightpaths	WP-D2	Sep 2010

Justification

Staff Effort.

Co-ordination will be by a senior staff member at University of Manchester (Dr R Spencer): 0.1 FTE/yr for 3 years. We request a PDRA at 0.67 FTE/yr for establishing, testing & monitoring links, plus bandwidth reduction techniques. It is planned that this position can be shared with other e-VLBI and LOFAR activities in Europe.

Computer Equipment/Consumables.

Two Supermicro PCs with Intel NICs for link testing £5200 +VAT. Personal computing provision at 2.5k/FTE/yr for PDRA: £5000.

Travel and Subsistence.

Travel between LOFAR-UK sites, typically once per month at £100/trip: £3.6k. Travel to the Netherlands and other European sites, typically three times per year at £375/trip including subsistence: £3.375k.

100% FeC Costs of STFC Proposal

Category	Items	Cost
Staff		£97.392k
Estates		£36.078k
Indirect staff costs		£97.773k
Equipment	PCs for link tests	£6.11k
Consumables	Computer consumables	£5k
Travel and Subsistence	UK+Europe travel	£6.975k
Exceptional		
		£249.328k

LOFAR-UK-WP-D3 Data Calibration

Responsible Institutes: Glasgow (Instrumental Calibration), UCL (Ionospheric Calibration), Hertfordshire (Pre-processing Algorithms)

Overview and Additional Effort

This work package breaks into three tasks: instrumental calibration (WP-D3-T1) led by Glasgow; ionospheric calibration (WP-D3-T2) led by UCL; and pre-processing (WP-D3-T3) led by Herts. We note that the four man years of PDRA effort required for WP-D3-T2 and WP-D3-T3 is requested entirely from STFC, and is focussed on employing software developers (i.e. expert C++, Python, HPC programmers). These will deliver UK-led software packages as part of the integrated LOFAR Common Software (LCS). The request to STFC for WP-D3-T1 of one man-year of effort is predicated on the assumption that the SUPA-2 bid is successful: if it is not, a second STFC-supported man-year of effort will be transferred to WP-D3-T1 from WP-D4-T3. Given the intimate way in which these calibration tasks must inter-relate, the UK team will work closely together.

If the LOFAR-related HEFCE/SEPNET bid is successful, the core ionospheric 'software developer' work (WP-D3-T2) will be supplemented by two years of dedicated LOFAR-project work (Jan 2010 - Jan 2012) of the 'Roberts Fellow' to be jointly appointed between Oxford and RAL as part of the HEFCE initiative; the Oxford component funded directly from HEFCE, with the RAL element presumably incorporated into the STFC Service Level Agreement if the HEFCE/SEPNET bid is successful. This person is likely to work at the interface between radio astronomy and ionospheric physics, and would develop advanced algorithms that give the best hope of near-continuous operation at the lowest LOFAR frequencies. These algorithms will expand on those core schemes to be implemented in task WP-D3-T2 below, and she or he would obviously work closely with the PDRA at UCL. Existing ionospheric propagation models will be extended to implement radio ray-tracing through a realistic model ionosphere (approximating to the LOFAR Minimum Ionospheric Model) in a real-time and self-consistent manner. This will be tied to implementation of diagnostics to measure both large-scale (gross morphology and Travelling Ionospheric Disturbance [TID] detection) and small-scale (metal-ion layers and turbulent structures) for a variety of frequencies under varying diurnal, seasonal solar cycle and geomagnetic activity conditions, leading to optimum dynamic scheduling of the LOFAR long baselines.

This additional 'in-kind' contributions to WP-D3 will, if realised, be used as part of the total UK contribution to LOFAR, maximising the science return from the LOFAR-UK programme.

Input

Work Package	Description
WP-D1	Management
WP-I1	Deployment of LOFAR-UK Station 1
WP-D2	Transport of Data from LOFAR-UK Station 1 to Correlator

Common Justification

Computer Equipment/Consumables. For computer equipment and consumables we calculate rates via contribution to the standard computing environment at each institute (desktop plus laptop plus secure tape and RAID backup system, high-end server services, commercial compilers, libraries and printers) whose rates are £2.4k plus £0.8k per man-year respectively.

Travel and Subsistence. Each PDRA will spend a significant amount of time working with the LOFAR project developers at ASTRON in the Netherlands. We adopt a travel cost of £0.8k per year for European travel and £0.4k per year for travel within the UK. Assuming that the PDRA will spend approximately one-third of their time at ASTRON we calculate the subsistence as $\sim$ £80 per day for a total period of 120 days per year. This equates to £9.6k per year. The total T&S budget is therefore £10.8k per PDRA per year.

WP-D3-T1: Instrumental Calibration

Background. The new UK baselines will be considerably longer than those achievable by the Dutch stations alone and, as a consequence, will require specialised analysis methods. The curvature of the Earth introduces a fundamental challenge to the instrumental calibration. LOFAR antennas are not steered mechanically – they point permanently at the local zenith. Although the antennas are co-planar at any particular station, widely-spaced stations will necessarily point in different directions in the sky and will therefore see the sky slightly differently. For example, a station at Jodrell Bank would have to be tilted by about 12 m to be co-planar with one at the core in the Netherlands. This misalignment means that UK stations see the sky slightly differently to those in the core, and this difference needs to be accounted for correctly via instrumental calibration if the UK baselines are to be properly exploited.

Instrument calibration is a basic component of the global LOFAR calibration, and it is widely recognised that dealing with the effects of polarization are likely to be the most challenging in over-coming dynamic range limitations post calibration. The ultimate LOFAR survey science requirement is a dynamic range of close to 70 dB. Both LOFAR arrays contain linearly-polarized antennas, one for $x-$ and one for $y-$polarization, and the sky is full of highly linearly-polarized sources, and this complicated 'vector field' continuously rotates with respect to the xy plane. An extra level of analog beam forming in the high-band antennas complicates things further. For these reasons, accurate calibration of the complex gains of each antenna gets intrinsically mixed up with variations in the projected (onto the xy plane) polarisation angles of each source in a sky full of sources. In addition, station sidelobes (determined by the distribution of antennas within each station) present much more serious issues for a phased array than for more conventional dish antennas. Although some of this work is necessary for the most basic imaging requirements of LOFAR, the non-coplanar UK stations present a special challenge, and the LOFAR calibration team have invited the UK to lead this work package.

Some of these technical challenges are common to the (higher frequency) phased array elements of the Square Kilometre Array, and the proposed work on LOFAR would follow directly on from SKADS work currently in progress at Glasgow. We seek PDRA resource for this task whose key elements include the following.

- Use extrapolations from the flux and polarization information in the WENSS source catalogue, and early data from LOFAR, to compile a grid of potential polarization calibrators, integrated with the 'Global Sky Model'. Perform an initial study of the impact of curvature on the polarimetric calibration of long LOFAR baselines.
- Finalise choice of instrumental calibration algorithm, and implement minimum long-baseline calibration scheme as LOFAR Common Software (LCS).
- Commission the calibration scheme on a UK-to-Dutch-core baseline making maps of bright polarized sources, using the phase and amplitude corrections determined locally at each station, using correlated visibility data for each of the (up to) eight beams.
- Ensure reliable pipeline for previous step, evolving a strategy (develop LCS) to implement a fully time- and station-dependent polarimetric gain correction.
- Implement a more sophisticated long-baseline polarisation calibration scheme as LCS. The initial algorithm to be used for commissioning is liable to be a variant on the 'peeling' algorithm which calibrates in a sequential fashion from the brightest sources available down. More sophisticated, and potentially more efficient, 'parallel' calibration schemes will be developed.

Output

Description	Work Package	Date Delivered
Initial study of polarization calibrators	WP-D3-T1	Feb 2009
Simple Long-baseline LCS	WP-D3-T1	May 2009
Commissioning	WP-D3-T1	June 2009
Develop and test LCS	WP-D3-T1	Dec 2009
Sophisticated Long-baseline LCS	WP-D3-T1	Dec 2010

Task Justification

Staff Effort. Instrumental calibration is fundamental to any working LOFAR-UK station and this requires software development by a hardware-competent PDRA. The named post-doc for this position is Dr Tobia Carozzi who will transfer from SKADS funding to LOFAR-UK funding in Jan 2009. Staff effort is requested at the level of 5% of Graham Woan to supervise this work.

100% FeC Costs of STFC Proposal

Category	Items	Cost
Staff	PDRA	£38.409k
Investigators	Woan	£3.002k
Estates	PDRA + Woan	£13.524k
Indirects	PDRA + Woan	£37.850k
Equipment	Desktop/laptop system	£2.4k
Consumables	Computer consumables	£0.8k
Travel and Subsistence	UK+Europe travel	£10.8k
		£106.785k

WP-D3-T2: Ionospheric Calibration

Background. The low operating frequencies of LOFAR are highly susceptible to disturbances in the ionosphere, particularly given the long baselines involved, e.g. from the Dutch core to the UK. UCL has experience in both traditional and specifically-low-frequency methods of correcting phase and amplitudes and has a world-leading group in ionospheric research. UCL is developing algorithms for calibration of e-MERLIN data and the UCL Co-I has access to the UCL Legion super-computer. This resource (3000 cores, 192 Tbytes of disk space, 12 Tbytes of RAM) can be used to develop and test the algorithms required by the proposed calibration procedures. The testing of these algorithms will require the use of up to half of Legion for several days at a time. This resource will be provided by UCL.

It is of vital importance that an accurate model of the ionosphere above each LOFAR station is developed, and for the longest baselines (e.g. to the UK) this is a severe challenge because each station sees an ionosphere that's essentially independent of the ionosphere above the LOFAR core, and the size of the isoplanatic patch can become smaller than the size of each 'station beam', requiring a set of calibration sources per beam, and recalling that there are up to eight independent beams. Each station must be calibrated independently of every other. A perfect model of the behaviour of the ionosphere would provide a movie (at arbitrary time resolution) of the column density of free electrons above arbitrary locations on the earth's surface (coordinates xyz) and in arbitrary directions (coordinates lm) from those points. An imperfect model will result in residual errors in the phase and amplitude response of objects in the field, and consequent image artifacts, and such problems are bound to get much worse at lower frequencies and longer baselines.

Published schemes, such as those used for the Cambridge Low-Frequency Synthesis Telescope (CLFST) or the VLA at 74 MHz are very simplistic and clearly inadequate for LOFAR. UK researchers have already been invited to join the LIONS (LOFAR IONosphere Simulations) team which is the ASTRON/Leiden team working on a 'Minimum Ionospheric Model' (MIM) description of a thin, plane-parallel atmosphere which may be adequate for the LOFAR core. At the recent inaugural LIONS meeting, the UK has been asked to lead the implementation of the more complex algorithms needed to account for effects like curvature and multi-layer ionospheres which are essential for the longest baselines. These algorithms will constrain the time-varying parameters of a generalized ionospheric screen using a combination of LOFAR data and data from GPS receivers placed around each LOFAR station. We seek PDRA resource for this task whose key elements include the following.

- Use existing catalogues – e.g. Cambridge Low Frequency (38/151 MHz) surveys, and early data from LOFAR to compile a grid of potential phase and amplitude calibration sources, integrated with the 'Global Sky Model'. Perform an initial study of the availability of astronomical and GPS calibrators for pointing directions from LOFAR-UK stations.

- Finalise choice of ionospheric calibration algorithm, and implement minimum long-baseline calibration scheme as LOFAR Common Software (LCS).

- Commission the calibration scheme on a UK-to-Dutch-core baseline making maps of bright sources, using the phase and amplitude corrections determined locally at each station, using correlated visibility data for each of the (up to) eight beams.

- Ensure reliable pipeline for previous step, evolving a strategy (develop LCS) to fully sample the field-of-view of each station beam as a function of time without increasing errors in phase/amplitude corrections

- Implement a more sophisticated long-baseline calibration scheme as LCS. An existing UCL/Bath model uses GPS sources to provide 5-minute time-resolution and includes some vertical information. LOFAR data will be used to fine-tune this model in a feed-back loop designed to produce a continually updating model of the ionosphere over the entire field-of-view of each station beam.

Output

Description	Work Package	Date Delivered
Initial study of calibrators	WP-D3-T2	Feb 2009
Simple Long-baseline LCS	WP-D3-T2	May 2009
Commissioning	WP-D3-T2	June 2009
Develop and test LCS	WP-D3-T2	Dec 2009
Sophisticated Long-baseline LCS	WP-D3-T2	Dec 2010

Task Justification

Staff Effort. Ionospheric calibration is fundamental to any working LOFAR-UK station and this requires software development by an experienced (C++, Python) developer. We will recruit such a PDRA at UCL. He will be locally managed by Yates (5% FEC).

100% FeC Costs of STFC Proposal

Category	Items	Cost
Staff	PDRA	£75.160k
Investigators	Yates	£4.840k
Estates	PDRA + Yates	£10.775k
Indirects	PDRA + Yates	£83.950k
Equipment	Desktop/laptop system	£4.8k
Consumables	Computer consumables	£1.6k
Travel and Subsistence	UK+Europe travel	£21.6k
		£202.725k

WP-D3-T3: Pre-processing

Background. The number of visibilities that need to be measured for a LOFAR with long baselines is huge. The visibilities must be sampled at high time (< 1s) and frequency (< 1 kHz) resolution to avoid the pernicious effects of time-averaging and bandwidth smearing on the longest baselines. A few-hour observation for a long-baseline-capable LOFAR will generate 100s of Tbytes of data, and even if such huge datasets could be piped into current software packages, the current generation of algorithms would require too much computing power to efficiently remove bright sources from wide fields via conventional techniques like 'CLEAN'. Moreover, these visibilities must be mapped into ∼100 separate facets per pointing to ensure phase coherency across each facet, and to minimise the effects of non-coplanar baselines.

LOFAR must use new algorithms based on 'real-time' manipulation of the visibility data streams and these are under development at ASTRON. The UK has been asked to lead a work-package aimed at implementing the most challenging algorithms, i.e those capable of pre-processing visibility datasets including the longest baselines. In essence, the pre-processing must accomplish three things: (i) apply phase shifts to the raw visibilities so that the fringe-tracking centre is shifted to the centre of ~ 100 separate sub-fields; (ii) solve for ionospheric parameters (see WP-D3-T2); (iii) subtract the strongest sources (present in the Global Sky Model). Images subsequently made from the pre-processed data will then have sufficiently small dynamic range that given adequate instrumental calibration (see WP-D3-T1), no CLEAN-like processing is necessary. Current back-of-the-envelope estimates of the computing resources required for long-baseline mapping of whole station beams yield estimates that the BlueGene would need to process the data-stream for a week or more to analyse the data from a single day's observation. Implementing efficient algorithms to address such issues is thus clearly crucial if we are going to avoid dynamic range limitations, and thus carry out deep wide-field surveys, i.e. the Key Science Project of LOFAR in which the UK has the largest interest.

This work will be concentrated on algorithm development and implementation for efficient long-baseline pre-processing, which will be crucial for the LOFAR-UK stations to be fully incorporated in the LOFAR project. This is a particularly important area for the UK to establish a leading role in because the E-LOFAR project will rely on such developments. It will also promote the forging of close links with other E-LOFAR partners, such as GLOW, FLOW and SLOW. We seek PDRA resource for this task whose key elements include the following.

- A comprehensive review of algorithms being investigated for the LOFAR core and for other existing and planned radio astronomy instruments, particularly those with long baselines.

- Benchmarking of possible algorithms for deployment on the BlueGene or satellite computing clusters.
- Implementation of final algorithm of choice within the LCS.
- Commissioning of a full pre-processing software system within LCS for use with LOFAR long baselines.

Output

Description	Work Package	Date Delivered
Review of algorithm capabilities	WP-D3-T3	June 2009
First implementation of pre-processing algorithms in LCS	WP-D3-T3	Jan 2010
Final implementation in LCS	WP-D3-T3	Dec 2010

Task Justification

Staff Effort. The LOFAR project is currently concentrating their effort on the shorter baseline calibration which is needed for the initial phase of a working LOFAR. With E-LOFAR, the problems highlighted above will need to be overcome, and the LOFAR-UK community are well placed to take a leading role in this crucial aspect of E-LOFAR. This requires software to be written by an experienced HPC developer. We will recruit such a PDRA at Hertfordshire where there is on-site HPC expertise and hardware (for software testing), and a strong radio astronomy group (e.g. Brinks, Hardcastle, Jarvis). The local manager will be Jarvis (5% FEC). The PDRA's main task will be to implement pipelines capable of efficiently preprocessing LOFAR long-baseline data, and she or he will benefit from research work on algorithms undertaken under the auspices of the FP7 RadioNet ALBUS (Advanced Long Baseline User Software) programme in Cambridge and Oxford.

100% FeC Costs of STFC Proposal

Category	Items	Cost
Staff	PDRA	£66.407k
Investigators	Jarvis	£4.918k
Estates	PDRA + Jarvis	£44.119k
s Indirects	PDRA + Jarvis	£27.353k
Equipment	Desktop/laptop system	£4.8k
Consumables	Computer consumables	£1.6k
Travel and Subsistence	UK+Europe travel	£21.6k
		£170.797k

LOFAR-UK-WP-D4: Data Products

Responsible Institutes: ATC (Automated Catalogue Construction), Edinburgh and Portsmouth (Data Archiving), Glasgow (Solar Algorithms)

Overview and Additional Effort: The UK has a long tradition in the pipelining, analysis and archiving of astronomical data. Through this Work Package, we propose to actively engage in these tasks to ensure that UK (and international) scientists have easy and straightforward access to the science data products they require, and to maximise the scientific return from the LOFAR-UK stations when they are used in a stand-alone mode. It is also clear that, especially after their recent rescope, the Dutch LOFAR project on their own can not deliver all the functionality we require; we must help them. The UK's contribution in these areas will be treated as an 'in-kind' contribution by the UK to LOFAR, thus also maximising the scientific return on our investment in LOFAR.

This work package breaks down into three tasks: automated catalogue construction led by the ATC (WP-D4-T1); data archiving led by Edinburgh and Portsmouth (WP-D4-T2); and solar algorithms led by Glasgow (WP-D4-T3). The PDRAs involved will work closely with the the relevant Dutch and International Partners, making frequent extended trips to the Netherlands (and in the case of solar algorithms, also to Potsdam in Germany where the Solar Key Science Project is being led).

We note that for all three of these tasks, the PDRA support requested from STFC for this work is proposed to be matched by in-kind contributions from the SUPA-2 and HEFCE/SEPNET funding bids. In the event of failure of one or both of these bids, then the work in this Work Package will have to be de-scoped. If the SUPA-2 bid fails then, as discussed in WP-D3, the 1 STFC-funded man-year of PDRA effort requested for WP-D4-T3 will be diverted to complete the funding of WP-D3-T1, and WP-D4-T3 will be withdrawn, with a clear cost to the scientific return, especially from LOFAR-UK stations in stand-alone mode. Failure of the SUPA-2 bid will also result in the 1-year of STFC PDRA-funding for WP-D4-T1 being diverted to support WP-D4-T2; the 'quality-control flagging' aspect of this task would be transferred to WP-D4-T2 as this is essential for the catalogue archives, while the remainder of the WP-D4-T1 would fall back on the over-worked Dutch consortium. Finally, in the event of the HEFCE/SEPNET bid being unsuccessful then there would be a reduced level of man-power available for WP-D4-T2, leading to a reduction in the list of achievable tasks. The priorities would then be the development of the catalogue archive for UK scientists and a minimal archive for stand-alone LOFAR-UK data, and only any residual resource would be put into the LOFAR virtual observatory development.

Input

Work Package	Description
WP-D1	Management
WP-I1 to WP-I4	Deployment of LOFAR-UK stations

Common Justification

Computer Equipment/Consumables. For computer equipment and consumables we calculate rates via contribution to the standard computing environment at each institute (desktop plus laptop plus secure tape and RAID backup system, high-end server services, commercial compilers, libraries and printers) whose rates are $\pounds 2.4$k plus $\pounds 0.8$k per man-year respectively.

Travel and Subsistence. Each PDRA will spend a significant amount of time working with the Dutch and International Partners in the Netherlands and Potsdam. We adopt a travel cost of $\pounds 0.8$k per year for European travel and $\pounds 0.4$k per year for travel within the UK. Assuming that the PDRA will spend approximately 2 months per year of their time abroad, we calculate the subsistence as $\sim \pounds 80$ per day for a total period of 60 days per year. This equates to $\pounds 4.8$k per year. The total T&S budget for one PDRA per year is therefore $\pounds 6.0$k.

WP-D4-T1: Optimisation and quality control of catalogue construction

Background: Once the long-baseline calibration issues have been solved (see WP-D3), and high dynamic range radio maps can be constructed, the issue then becomes one of reliably extracting sources from the maps and producing source catalogues with suitable quality control flags. This is of fundamental importance to the Surveys Key Science Project, but is also of relevance to other KSPs, such as Transients.

The Dutch Surveys team have been working on a number of aspects related to the construction of reliable source lists, but a significant number of outstanding issues remain. The UK have been asked to lead a work-package to address a particular set of these, as discussed below. UK ATC has considerable expertise in many of these areas (in particular, that of Nuria Lorente, a software developer with extensive knowledge of radio astronomy, available in 2009), having been responsible for several well-known data pipelines as well as the heuristics for ALMA and EVLA. We seek 1 year of PDRA funding (to be matched by a year of funding from SUPA-2) for this task, whose key elements include:

- A comprehensive review of the suitability of existing extraction and clump-finding algorithms (e.g. SAD, SExtractor, etc), and both the existing work and future plans of the Dutch Surveys KSP team in this area.
- Modelling and studying the variations of the LOFAR point-spread function across the field of view, due to ionospheric variations. In liaison with the KSPs, developing source extraction methods which reliably deal with this.
- Optimising source extraction algorithms to deal with extended diffuse radio sources (such as powerful large radio-AGN, or cluster halo sources) in the source extraction, and the separation of these from the underlying point source population.
- Coding the source extraction algorithms in automated form for the post-processing computer cluster. Rigorous testing of source extraction techniques and pipelines based on early LOFAR imaging and mock images.
- Development and implementation of quality-control flagging for the catalogues produced.

Output

Description	Work Package	Date Delivered
Review of existing algorithms	WP-D4-T1	March 2009
Development of optimised source extraction methods	WP-D4-T1	May 2010
Automated algorithms and quality control	WP-D4-T1	Dec 2010

Justification
Staff Effort. A software developer with experience of radio astronomy techniques and source extraction, as well as scientific software development, is required for this workpackage. The named person for this position is Nuria Lorente, a radio astronomer and software engineer, who has developed the Specsim software package, a tool which models the operation of the *JWST*/MIRI, VLT/KMOS and E-ELT/EAGLE IFU spectrometers, generating synthetic data frames which are then used to illustrate and inform instrument design, calibration and data reduction activities. Nuria also developed clump-finding software specifically designed for radio data, and has been involved in data pipeline projects, most recently working on the ESO Common Pipeline Library project. Staff effort is requested at the level of 5% pro-rata of Prof. Rob Ivison to supervise the work.
100% FeC Costs of STFC Proposal

Category	Items	Cost
Staff	Lorente	£45.15k
Indirect staff costs	Ivison	£3.379k
Estates	Lorente + Ivison	£17.057k
Indirect Costs	Lorente + Ivison	£29.505k
Equipment	Desktop/laptop system	£2.4k
Consumables	Computer Consumables	£0.8k
Travel and Subsistence	UK+Europe travel	£6k
		£104.291k

WP-D4-T2: Data Archives

Background: This is the most substantial of the three sub-packages and exploits UK leadership in the development and operation of world-leading astronomical data archives. This work builds upon our expertise in publishing large data sources like SDSS, UKIDSS and VISTA to the UK scientific community and beyond.

Although the first LOFAR station is already producing data, it is fair to say that there is no co-ordinated plan from the Dutch community for developing a global LOFAR data archive. Each of the Key Science Projects is currently investigating different systems, according to their different scientific requirements. Distribution of the Surveys KSP data, for example, is proposed to be via the Astro-WISE system; this offers a good basic functionality, but the user interface (or portal) is crude and lacks the user-friendliness of optical catalogues like the UKIDSS and SDSS catalogues. Furthermore, the Dutch archive plans take no account of the new International Key Science Projects (e.g. solar observations), and nor do they offer the opportunity for data taken by UK stations in stand-alone mode to be stored. These are all areas in which UK effort would provide considerable tangible benefits for UK (and other) scientists.

We seek PDRA resource in support of the development of UK LOFAR archives. The main elements of this work will be:

- *Development of a catalogue archive for UK scientists.* Working with the KSPs, we will: (i) Develop a catalogue-based relational database with a user-friendly web-based portal thus enhancing the productivity of both UK and international LOFAR scientists (like the present UKIDSS and SDSS portals). This would include the development of database schemers, and the design of interfaces both to ingest the data from Astro-WISE and to provide public access. We would further help with continually upgrading for new data releases and enhanced functionality in the database. Furthermore, we would implement cross-matching (band-merging) and SQL scripting to allow simultaneous searching of multiple LOFAR frequencies, as well as across other source catalogues like SDSS, PanSTARRS and UKIDSS. This work will be done in collaboration with the main LOFAR consortium and would greatly enhance their present plans to simply serve data through rudimentary Astro-WISE interfaces.

- *Design and construction of an archive for stand-alone LOFAR-UK data.* As outlined in the Science case, there are several science motivations for stand-alone operations of LOFAR-UK stations. Moreover, there is a clear legacy value in ensuring that data obtained by our stations is preserved for the collaboration and wider community to enable time-domain studies and source monitoring. In consultation with UK scientists, we will design a data archive for UK stand-alone science. We will explore collaborations with the e-Science community, especially the National Grid Servise (NGS) and petabyte storage facility at RAL, to share resources and expertise. Therefore, we request no hardware costs in this proposal for this package as we strive to use existing (or planned) national facilities supplemented with new hardware available via Portsmouth (SRIF investment) and the HEFCE/SEPNET proposal (totalling up to a £230k investment). Such collaborations have successfully been used to store the SDSS data (see tinyurl.com/23x43h).

- *Design and development of a general LOFAR archive.* We will participate in the construction of a "global" LOFAR archive in collaboration with the Dutch and other international partners. The planning for this general archive (which will include all processed data – catalogues and images – from both the core Dutch stations and the international stations) has just begun with the recent creation of the LOFAR Archive Working Group and initial meetings with industrial partners. We believe it is important for the UK to take a lead in this activity because of our expertise, our long-term science goals, and our future needs for the SKA. It is also clear that the Dutch can not totally support this endeavour themselves and are eager to develop such an archive in collaboration. Specifically, we would: (i) help design general access to the array of databases being developed across the KSPs and countries, using distributed database technology as well as standards and tools (e.g. database access control) developed as part of the Virtual Observatory (AstroGrid in particular); (ii) develop a user-friendly interface to the system, thus ensuring that the LOFAR data becomes one of the premier data sources in astronomy; (iii) carry out an initial deployment of the system over a restricted set of databases e.g. the different databases within the UK discussed above.

These archivers, with their substantial web-skills, would also be responsible for creating a multi-media website for the LOFAR-UK project. As discussed in the 'outreach' section, this website would be aimed at a wide variety of interested readers, from the general public (including those involved in teaching) to the specialised scientist. The website would include explanations of many aspects of the science and advanced technology used by LOFAR, together with an up-to-date view of the progress of the project in the UK, tracking the construction, commisioning and early operations of the LOFAR-UK sites.

Output

Description	Work Package	Date Delivered
Minimal UK stand-alone archive facilities	WP-D4-T2	June 2009
Multi-media LOFAR-UK website	WP-D4-T2	Dec 2009
Basic UK catalogue archive web-portal	WP-D4-T2	Dec 2009
Cross-matched survey catalogues	WP-D4-T2	June 2010
Fully-functional UK stand-alone archive	WP-D4-T2	June 2010
Fully-functional UK catalogue archive	WP-D4-T2	Dec 2010
Maintenance of UK archives & LOFAR-UK web site	WP-D4-T2	Dec 2011
First deployment of LOFAR Virtual Observatory	WP-D4-T2	Dec 2011

Justification

Staff Effort. We request PDRA funding at both IfA Edinburgh and ICG Portsmouth in support of this work. In both cases, this funding will be equally matched by funds from the SUPA-2 and HEFCE/SEPNET bids (if successful). We therefore deliberately do not distinguish which deliverables will be associated with which institute at this time, as the precise division of tasks will depend upon the success of these bids and hence the relative levels of funding available. At the IfA Edinburgh, we request support for 50% funding of an archivist in the years 2009 and 2010, matched by SUPA-2 money. This person will be supervised by Best (5% FEC pro-rata). At the ICG Portsmouth, we request support for 50% funding of an archivist (matched by HEFCE/SEPNET) through all 3 years. This person will be supervised by Nichol (5% FEC pro-rata). We also request funding for a 3-yr PhD computer science student at Portsmouth (plus standard £1k/year T&S), who will concentrate on the development of the stand-alone LOFAR-UK database. This student will work closely with the Distributed Systems Group (DSG) in the School of Computing, and explore previously successful collaborations on the design and construction of astronomical databases.

100% FeC Costs of STFC Proposal

Category	Items	Cost
Staff	Edinburgh + Portsmouth	£34.878k + £50.489k
Staff	Portsmouth PhD	£47.520k
Investigators	Best + Nichol	£2.566k + £6.096k
Indirect staff costs	Edinburgh + Portsmouth	£34.878k + £57.696k
Estates	Edinburgh + Portsmouth	£13.604k + £11.606k
Equipment	Desktop/laptop system	£6.0k
Consumables	Computer consumables	£2.0k
Travel and Subsistence		£18.0k
		£285.333k

WP-D4-T3: Algorithms for LOFAR Solar Data

Background: Solar Physics with LOFAR is an International Key Science Project, and as such there has not been Dutch investment of effort in any aspect of the technical issues that must be addressed to enable efficient LOFAR solar observations. The German leaders of the Solar Physics KSP have welcomed the UK's involvement in technical preparations, and our activity will be coordinated closely with theirs to make maximal use of our complementary expertise for the benefit of international solar observations. However, the stand-alone LOFAR-UK stations also present opportunities for solar observations independently of the international stations. In particular, solar radio spectrograms are an obvious use during daylight hours, but automated algorithms need to be developed in order to maximise the science coming out of these observations. In addition, automated algorithms and services operating on the archived solar data would greatly increase the ability of scientists to access the scientific data products that they require, and increase the scientific return. The UK has considerable expertise in these areas, and this element of the workpackage requests PDRA resource for these tasks. The PDRA will work closely with the Potsdam group heading the LOFAR "Solar" Key Science Project. The key elements of the proposed work are to:

- Develop algorithms for real-time processing of solar spectrographic data from the UK stand-alone stations, to detect solar radio bursts and issue alerts for start and end times.

- Develop and provide the infrastructure for a target-of-opportunity style of operations relating to solar radio bursts, which is the most effective use of limited LOFAR time for solar imaging observations.
- In the archived data, develop algorithms to identify and characterise bursts, and create a solar radio burst catalogue. These algorithms, essentially feature recognition software for flexible, on-demand cataloguing would be useful for the solar scientist as a necessary first step in solar radio research to identify the type of radio burst.
- Develop selected solar-specific virtual observatory interfaces in close consultation with the Potsdam group. The tasks will include, but not be limited to, quicklook images and spectra. Due to the range of solar physics timescales and spatial scales it is not possible to provide a single solar radio imaging data product that could answer all the relevant science questions. Consequently, we will develop services to provide basic imaging at a few selected frequencies, and at appropriate cadences and accumulation times during determined solar radio bursts.

We note that both the catalogues and the alerts will also be directed at non-solar scientists, who will be concerned to know whether their non-solar observations might be affected (e.g. via side-lobe emission).

Output

Description	Work Package	Date Delivered
Real-time burst detection	WP-D4-T3	Dec 2009
Characterise bursts in archive data	WP-D4-T3	Jun 2010
Services for quick-look images	WP-D4-T3	Dec 2010

Justification

Staff Effort. A PDRA with experience of scientific software development, and ideally also of solar radio astronomy, is required for this workpackage. 1 man-year of STFC effort will be matched in-kind from SUPA-2 funding. Staff effort is requested at the level of 5% FEC (pro-rata) of Dr Lyndsay Fletcher to supervise the work.

100% FeC Costs of STFC Proposal

Category	Items	Cost
Staff	PDRA	£43.65k
Investigators	Fletcher	£3.02k
Estates	PDRA + Fletcher	£13.52k
Indirect Costs	PDRA + Fletcher	£37.85k
Equipment	Desktop/laptop system	£2.4k
Consumables	Computer consumables	£0.8k
Travel and Subsistence	UK+Europe travel	£6.0k
		£107.240k

LOFAR-UK-WP-I1 Chilbolton

Responsible Institute: Space Science and Technology Department, STFC

Overview:

This work package details the installation of a LOFAR station. The installation site of the LOFAR station will be at the Chilbolton Observatory. The Chilbolton Observatory is a facility owned by STFC and managed by the Space Science and Technology Department. It is located in the county of Hampshire, approximately 40 miles from the Rutherford Appleton Laboratory. The main activity of the site is currently the ground based remote sensing of the atmosphere. Some of the instrumentation required to support this work is installed on the 25 m dish, which is the main asset of the site. In the last 3 years, a new area of work has developed in the area of signal inspection of navigational satellites. This work has supported the In-Orbit Testing (IOT) of the GIOVE-A satellite, the first of the Galileo navigational satellite constellation.

The Chilbolton Observatory site encompasses an area of 600 x 1400 m. It is located on a plateau on the south side of the Test Valley. The site is located on part of a former airfield, which was first developed during World War II and later saw the testing of the early jet fighters. The airfield was decommissioned in the early 1960's, with the majority of the land reverting to agricultural use with an area reserved for the construction of the 25 m dish, which was competed by 1967. The present day activities on the site are concentrated within a fenced compound, approximately 150 by 100 m in size, on the western edge of the site. Some activities take place outside the compound, the largest of these being the 500 m radiowave propagation range, which extends from the compound to the north of the site. The remainder of the site is leased to a local farmer, which he predominantly uses to grow barley. The terms of the lease allow for the claw back of land at short notice.

Representatives from ASTRON visited the Chilbolton Observatory in June 2007 to present a briefing on the requirements for a LOFAR station. They viewed the site and were happy that it offered an excellent location for the installation of a LOFAR station. They organised for the site to be RFI tested to ensure that it was suitable. This was performed in July 2007 and the results issued in September 2007. This showed that the site was suitable from an RFI perspective and was better than many of the sites in Holland that were being considered for LOFAR stations. This was of no great surprise since the Chilbolton Observatory is located in a predominantly rural environment and is away from major transports links (road or rail) and overhead power lines. In addition the current activities of the site benefit from being in a benign RFI environment and efforts are made to ensure this.

Input

Work Package	Description
WP-D1	Management
WP-D2	Data Transport
WP-D3-T1	Instrument Calibration
WP-D3-T2	Ionospheric Calibration
WP-D3-T3	Pre-processing

Tasks

An area for the LOFAR station, approximately 80 x 160m in size, within the overall Chilbolton Observatory site has been chosen. This site is in the middle of the southern section of the site and offers the LOFAR station an excellent view to the horizon and minimises any undetected RFI interference, since it is away from the main activity of the site. In addition, the southern section is furthest from Chilbolton village, which is located to the north of the site.

The location of the LOFAR station within the southern section has been constrained by the requirement for the station to be constructed upon an area of which is flat. This is to allow the elements of the arrays that comprise a LOFAR station to be installed to an accuracy of +/- 2 cm in height with respect to each other. The land at the Chilbolton Observatory is predominantly flat, with a 16 m height variation across the whole site. Data obtained from an aerial lidar survey has allowed the height variation to be characterised to better than 0.5 m accuracy. Flattening represents one of the main costs of the installation and this most cost effective way to achieve this is to level the area of land required. It is fortunate that the area in the middle of the southern section lends itself to be being levelled, since there is only a 2.5 m height variation across it.

At present information for the planning application for the LOFAR station is being compiled. As soon as this is completed the application will be submitted to the local planning authority. After this stage has been completed contractors will be selected and installation will commence once the funds have been obtained.

Installation can be divided in to four main areas:

Site Preparation

As mentioned before, the elements within a LOFAR array must be installed with a high tolerance in position. This will be achieved by preparing a set of level pads for the array elements. The first stage of preparation will involve stripping the existing surface of vegetation and levelling the area for the pads. The location and orientation of the elements will be marked out by GPS survey. The pad for each element will be built to the required height using gravel. The equipment cabin for the LOFAR station will sit on a concrete base and a series of channels will be cut from the cabin to the elements of the array. Efforts will be made to suppress the growth of weeds by using weed suppressant fabric beneath the pads and the area between the pads will be in filled with gravel. The perimeter of the LOFAR station will be surrounded with a wooden fence, integrated into this fence will be a plastic mesh to minimise rodent intrusion.

A new power cable will be buried from the closest connection point to the equipment cabin along with ducting for a new fibre cable fibre. The fibre cable will extend back to the main building within the compound.

Array Construction

The LOFAR station will arrive at the Chilbolton Observatory in kit form. The kit will be constructed using staff and students from the nearby LOFAR-UK Universities under the direction of staff from the Chilbolton Observatory.

UPS Installation

The LOFAR station is designed to operate on a near continuous basis with high reliability. Some routine maintenance will be required but it is expected that this will be minimal. In order to achieve this a UPS will be installed on the power feed to the LOFAR site. This will ensure that the site has a near continuous power availability during it's operational lifetime.

Data Link

The LOFAR station requires a lightpath circuit back to Astron in Holland. JANET(UK) will provide this service across the SJ5 backbone. The 1 Gbps lightpath circuit will be installed using the SJ5 access point is at Southampton. This will be reached in two stages. The first stage will be by a BT Openreach ethernet extension service to Winchester, which is the access point for the nearest regional JANET(UK) network (LEarning Network South East, LENSE). Chilbolton Observatory already has services operating over BT Openreach fibre along this route. The second stage will be a circuit from Winchester to the SJ5 connection at Southampton.

The same route can be used for the 3 Gbps lightpath circuit, however this will most likely be made using a dark fibre connection to the SJ5 access point in Reading. This solution is considered to be more cost effective.

The Building Projects Group at RAL has provided costing for the installation of the LOFAR station. They are involved with most constructional projects on the RAL site and have also constructed other antenna arrays similar in nature to LOFAR. They estimate that the build time for the LOFAR station will be 12 weeks.

Output

Description	Work Package	Date Delivered
Site Preparation	WP-I1	
LOFAR LBA Installation and commissioning (stand-alone)	WP-I1	TBD
Interferometric tests with other LOFAR stations	WP-I1	TBD
LOFAR HBA installation and commissioning	WP-I1	TBD

	Items	Cost
Staff	Commissioning Technicican	99.0
Equipment	Full station hardware	610.0
Exceptional	Site preparation and installation, 1 Gb/sec connection, UPS	262.0
Exceptional	Installation of 3/10 Gb/sec connection	175.0
Exceptional	10 Gb/sec connection (1 year)	124
Total		**1270k**

LOFAR-UK-WP-I2 Edinburgh

Responsible Institute: University of Edinburgh

Overview:

This work-package is concerned with the purchase, installation, commissioning, and initial operations of the proposed Edinburgh LOFAR station. The funding for this station is largely proposed to be sourced from the SUPA-2 bid; however, due to significant increases in both the purchase and installation cost estimates for a LOFAR station since the SUPA-2 bid was submitted, additional funding is required for this. Funding is also requested for the running costs of the station during the shake-down period. It should be stressed that if the SUPA-2 bid is unsuccessful, then the request for an Edinburgh station (and hence this entire work package) will be removed.

A LOFAR station in Scotland would have the clear benefit of providing both the longest possible UK baselines, and also a different subtended angle relative to the main LOFAR core, providing improved coverage of the *u-v* plane. The currently favoured site for this station is about 10 km south of Edinburgh, on land owned by the University of Edinburgh between Woodhouselee and Roslin (see Figure ??). The advantage of this site is that a 10 Gb/s fibre connection is already available to the Edinburgh Technopole Science Park and the Veternary School, so that only the last 1-2 km of fibre connection need by laid. The precise location of the station will only be finalised if and when the SUPA-2 bid is successful; RFI testing for site suitability would be carried out as soon as possible thereafter. The nearby location of the UK Astronomy Technology Centre would be very beneficial in terms of long-term technical support for this station.

Input

Work Package	Description
WP-I1	Deployment of the first LOFAR-UK station
WP-D1	Management
WP-D2	Data Transport
WP-D3-T1	Instrument Calibration
WP-D3-T2	Ionospheric Calibration
WP-D3-T3	Pre-processing

Tasks

Once the outcome of the SUPA-2 bid is known, then (if successful) the next step will be to finalise the location for the station site, and to test the suitability of this. This will involve RFI testing by the ASTRON team, seeking planning permission for the installation of the station, and obtaining a full and detailed costing for the station. This costing will include levelling the site, preparing the land, laying the antennae fibres and electrics, installing fencing and security, and connecting the station to the 10Gb/s fibres at Technopole or the Vet School. Subject to a satisfactory outcome of these investigations, the LOFAR station will then be procured, as will contracted labour for preparing the site, and site preparation will ensue, along the lines of the more detailed description in WP-I1. On delivery of the station hardware, this will be installed in collaboration with the ASTRON team, and the installed station will be fully commissioned, operated and maintained.

Output

Description	Work Package	Date Delivered
Select site and test suitability (RFI; planning permission, costings)	WP-I2	December 2008
Procure hardware and contracted labour	WP-I2	December 2008
Prepare land (levelling, fibres, electrics, etc)	WP-I2	October 2009
Install station	WP-I2	December 2009
Commission station for basic operation	WP-I2	June 2010
Fully commissioned and opertational station	WP-I2	December 2011

Justification

All of these tasks are required to install and commission the station. Cost estimates for these tasks have been made by using locally-obtained numbers where possible. Where these are not available (due to the site location uncertainty) the costs have been estimated based upon the quotes received for the Jodrell, Lords' Bridge and

Chilbolton sites. Staff costs indicated in the table below are for a commissioning technician. Local project management costs will be covered as part of the SUPA-2 contribution, and have been subsumed into the general 'installation' costing.

Running costs are estimated to be £45k for the first year of operations at 1Gb/s. This is based on ≈£25k data transport costs, ≈£10k electricity costs and ≈£10k technical support. For the second year of operations at 3Gb/s, the data transport costs are estimated to rise to ≈£75k giving an overall running cost of £95k.

	Items	Cost
Staff	Commissioning Technician	27.0
Indirect Staff costs		12.4
Equipment	Full station hardware	610.0
Consumables		
Travel and Subsistence		
Exceptional	Site preparation, contracted labour, local project management	180.0
Exceptional	Running Costs (2010, 2011)	140.0
Total		**969.4**

NB The SUPA-2 bid, if successful, will bring £500k directly to this cost, reducing it to **£469.4k**. If the SUPA-2 is unsuccessful, this work package will be withdrawn.

LOFAR-UK-WP-I3 Jodrell Bank LOFAR Station Installation

Responsible Institutes: University of Manchester

Overview:

This workpackage covers the costs of purchasing a full LOFAR station, installing and commissioning it at Jodrell Bank Observatory (including all ground works for the site preparation) and operating costs for three years.

Two potential sites for the LOFAR installation have been identified at JBO: one within the current Observatory boundary and one in an adjacent field owned by the University of Manchester and currently leased for agricultural use. Both sites are quite flat and have ready access for power and data connections. The Observatory has been tested for radio-frequency interference and an initial site assesment was undertaken by ASTRON. Results from this detailed survey found the radio-frequency interference and proposed site at the observatory to be satisfactory for the hosting LOFAR station.

Input

Work Package	Description
LOFAR-NL	LOFAR Station installation information
LOFAR-UK-WP1	Project Management and Co-ordination
LOFAR-UK-WP2	Information and assistance with data connection

Tasks

- Liase with LOFAR-UK project manager and LOFAR-NL and purchase LOFAR station hardware
- Install LOFAR station equipment at JBO using contractors for groundworks and University of Manchester staff effort for some installation and commissioning tasks
- Commission and test LOFAR station in stand-alone mode with assistance from LOFAR-NL
- Establish operational data connection between LOFAR-JBO station and LOFAR Central Processor with assistance from WP2
- Commission LOFAR-JBO correlation with other LOFAR stations
- Operations and maintenance of LOFAR-JBO, including grounds maintenance, regular inspection of antennas and processing equipment, diagnosis and repair of system faults

Output

Description	Work Package	Date Delivered
Site Preparation	WP-I3	TBD
LOFAR LBA Installation and commissioning (stand-alone)	WP-I3	TBD
Interferometric tests with other LOFAR stations	WP-I3	TBD
LOFAR HBA installation and commissioning	WP-I3	TBD

Justification

We propose that all of the ground works are done by an external contractor and have obtained budgetary quotes for this work from three local and national civil engineering companies. As part of this process a detailed survey of one of the sites was carried out. For the costings given below, we have used the middle of the three quotes an allowance of 15% for various fees, such as local authority planning approval, CDM compliance and project management by the University Estates Dept.

Additional material costs (mainly the steel ground planes) have been estimated from quotations received from UK suppliers. Technician effort to assemble the antennas and test the cable connections to each one have also been included (1310 hrs).

Jodrell Bank Observatory already has a 70km 'dark fibre' connection to the University campus, which was installed for real-time e-VLBI experiments and observations. This was funded by a PPARC grant, and made use of the dark fibre network installed for e-MERLIN (largely funded by the North West Development Agency). This link is currently being upgraded to a total capacity of 12 Gb/s, which will be sufficient for LOFAR and e-VLBI.

Currently, e-VLBI uses two 1 Gb/s lightpaths from JBO to Dwingeloo in the Netherlands for e-VLBI. JANET are planning to install extra 10Gb/s capacity from Manchester to interconnect with Geant, which would be ideal for LOFAR.

Once installed and commissioned, the LOFAR station should be relatively low-maintenance. However, it is a large installation, with a large number of individual active electronic components and connectors, and so it will require a programme of regular inspections as well as the capability to respond to faults shown up by the monitoring system and analysis of the station performance data. The total effort, ranging from grounds maintenance to diagnosis of RF/electronic faults has been estimated at 0.5 FTE/yr. This is includes a 'friend-of-LOFAR', who like the 'friend-of-VLBI' at all European VLBI Network telescopes acts as the point of contact between the observatory and the LOFAR central operations for all operational matters.

The range of staff on-site at JBO are well placed to provide all these services.

Travel and Subsistence.

Travel between LOFAR-UK sites for meetings, typically 6 times per year at £100/trip: £1800. Travel to the Netherlands or other European sites, typically twice per year at £375/trip including subsistence: £2250.

Category	Items	Cost k£
Staff	Commission Technicican	27.7
Indirect staff costs		
Estates		
Equipment	Full station hardware	610
Equipment	Additional materials (UK)	9.4
Consumables		
Travel and Subsistence		2.25
Exceptional	Site preparation (contracted)	89.6
Exceptional	Fees & local project managment	10.9
Exceptional	Operational manpower (3 yrs)	48.5
Exceptional	Electricity (3 yrs)	27.0
Exceptional	Data transport JANET 10GB/s Mcr-London (1 yr)	35.25
		860.6k

LOFAR-UK-WP-I4 Cambridge

Responsible Institute: University of Cambridge

Overview:

This work-package is concerned with the purchase, installation, commissioning, and initial operations of the proposed LOFAR station at the Mullard Radio Astronomy Observatory, which is operated by the University of Cambridge. Funding for the costs of installation and operation of this station are sought in this application.

The Mullard Radio Astronomy Observatory is an established radio astronomy observatory. It is located at Lords Bridge, approximately 5km South West of Cambridge. The observatory has been used extensively in the past for low-frequency radio-astronomy experiments. Locating a LOFAR station at this site provides the shortest baseline between the UK and the Netherlands. Site evaluation and RFI testing of the site by ASTRON personnel show that this, along with the other proposed sites, is an excellent potential site. Staff of the observatory have considerable experience and expertise in low-frequency radio astronomy and the technologies employed in a LOFAR station. A specific area within the observatory has been identified for the LOFAR station which meets all the requirements specified by ASTRON; the area is already part of the observatory and therefore only planning consent is required for the use of this site.

Installation and operation would be performed by staff of the observatory: funding for this work is the subject of this proposal. The availability of skilled technical effort means that the long-term maintenance of the station will not only be possible, but also efficient. The cost of providing a dedicated data connection initially at 1GB/s (upgraded to 3 GB/s) is required for the Lords Bridge site.

Input

Work Package	Description
WP-I1	Deployment of the first LOFAR-UK station
WP-D1	Management
WP-D2	Data Transport
WP-D3-T1	Instrument Calibration
WP-D3-T2	Ionospheric Calibration
WP-D3-T3	Pre-processing

Tasks

Planning permission for an ASTRON station on the designated site is being actively persued. Tasks needed for site preparation include provision of an improved access road (to be provided as an in-kind contribution by the observatory) preparing the land, digging and backfilling trenches for power, fibre and control cables, preparing base for electronic cabinet, laying the antennae fibre and cables, installing fencing etc. Procurement of the station hardware and installation of the antennas etc. will then follow. Finally commissioning for basic and full operation. Ground works, installation and comission will be undertaken by observatory staff; other tasks will be done by external contractors.

Output

Description	Work Package	Date Delivered
Procure hardware	WP-I4	December 2008
Prepare land (as above)	WP-I4	October 2009
Install station	WP-I4	December 2009
Commission station for basic operation	WP-I4	June 2010
Fully commissioned and opertational station	WP-I4	December 2011

Justification

All of these tasks are required to install and commission the station. Cost estimates are based on firm quotes or estimates of man power required after extensive discussion with ASTRON. Local project management costs are also included.

Running costs are estimated to be £60.4k for the first year of operations at 1Gb/s. This is based on $\approx$£29.375k data transport costs, $\approx$£9k electricity costs and $\approx$£22k technical support. For the second year of operations at 3Gb/s, the data transport costs are estimated to rise to $\approx$£88.1k giving an overall running cost of £119.1k.

	Items	Cost
Pool Staff	Commissioning Technicican	22.0
Staff	Local project management	9.34
Indirect Staff costs		7.56
Estates		2.69
Equipment	Full station hardware	610.0
Consumables		
Travel and Subsistence		
Other costs	Site preparation	62.73
Exceptional	Running Costs (2010)	60.4
Exceptional	Running Costs (2011)	119.1
Total		**893.82**

Justification of resources

A Annex B

A.1 Annex B1: Staff effort overview per institute

NB we have based this part on a modified table template which was previously sent to Simon Garrington. This is a slightly different format to that given in the PPRP guidelines.

All sums in Annex B are in £k.

Portsmouth	FY1	FY2	FY3	Total
Staff	27.288	27.890	27.890	83.068
Travel	3.2	3.2	3.2	9.6
Other costs	4.536	4.536	4.536	13.608
Indirect & Estate costs	18.082	18.680	18.680	55.442
Overall by year	53.106	54.306	54.306	**161.718**

Glasgow	FY1	FY2	FY3	Total
Staff	0	70.455	0	70.455
Travel	0	13.440	0	13.440
Other costs	0	5.120	0	5.120
Indirect & Estate costs	0	82.197	0	82.197
Overall by year	0	171.212	0	**171.212**

Hertfordshire	FY1	FY2	FY3	Total
Staff	28.102	28.958		57.060
Travel	8.64	8.64		17.28
Other costs	2.56	2.56		5.12
Indirect & Estate costs	28.626	28.6256		57.2512
Overall by year	67.928	68.784	136.7112	

Cambridge	FY1	FY2	FY3	Total
Staff	32.2	22.0	22.0	75.4
Other costs	672.7	38.4	169.9	881.0
Indirect & Estate costs	8.4			7.8
Overall by year	713.3	60.4	182.9	964.2

Oxford	FY1	FY2	FY3	Total
Staff	22.626	23.101	23.101	68.829
Equipment	0.960	0.960	0.960	2.880
Travel	6.480	6.480	6.480	19.4400
Other costs	1.170	1.170	1.170	3.51
Indirect & Estate costs	22.427	22.427	22.427	67.281
Overall by year	53.663	54.138	54.1388	**161.9412**

Southampton	FY1	FY2	FY3	Total
Staff	14.623	14.623	14.623	43.868
Travel	4.05	4.05	4.05	12.150
Indirect & Estate costs	11.098	11.098	11.098	33.295
Overall by year	29.771	29.771	29.771	**89.313**

UCL	FY1	FY2	FY3	Total
Staff	29.312	30.816	–	60.128
Travel	8.64	8.64	–	17.28
Other costs	5.136	5.136	–	10.272
Indirect & Estate costs	37.89	37.89	–	75.78
Overall by year	80.938	82.482	–	**163.46**

Manchester	FY1	FY2	FY3	Total
Staff	34.5	35.2	36.1	105.80
Travel	3.4	3.4	3.4	10.2
Other costs	779.7	26.7	62	868.4
Indirect & Estate costs	49.2	49.2	49.2	147.60
Overall by year	866.8	114.5	150.7	**1132.0**

RAL	FY1	FY2	FY3	Total
Staff	45	27	27	99
Travel	0	0	0	0
Other costs	821	226	124	1171
Overall by year	866	253	151	**1270.0**

UK ATC	FY1	FY2	FY3	Total
Staff	18.88	19.94	0.00	38.82
Travel	2.40	2.40	0.00	4.80
Other costs	2.24	0.32	0.00	2.56
Indirect & Estate costs	17.33	19.92	0.00	37.25
Overall by year	40.85	42.58	0.00	**83.43**

Edinburgh	FY1	FY2	FY3	Total
Staff	15.442	16.287	0.998	32.727
Other costs	473.080	3.680		476.760
Indirect & Estate costs	20.316	20.316	0.924	41.556
Overall by year	508.838	40.283	1.922	551.043

A.2 Annex B2: Overview of costs to STFC – Total funding per financial year of the project

This table is also slightly modified, but fulfills the goal of clearly summarizing costs to STFC per financial year of the project (based upon the format adopted in Annex B1).

	FY1 (2009)	FY2 (2010)	FY3 (2011)	TOTAL
Staff Effort				
Portsmouth	27.288	27.890	27.890	83.068
Glasgow	0.0	70.455	0.0	70.455
Hertfordshire	28.102	28.958	0	57.060
Cambridge	32.2	22.0	22.0	75.4
Oxford	22.626	23.101	23.101	68.829
Southampton	14.623	14.623	14.623	43.868
UCL	36.64	38.5	0	60.128
Edinburgh	15.442	16.287	0.998	32.727
ATC	18.88	19.94	0	
Manchester	34.5	35.2	36.1	105.80
RAL	45	27	27	99
Travel				
Portsmouth	3.2	3.2	3.2	9.6
Glasgow	0	13.440	0	13.440
Hertfordshire	8.64	8.64	0	17.28
Cambridge	0	0	0	
Oxford	6.48	6.48	6.48	19.44
Southampton	4.05	4.05	4.05	12.150
UCL	8.64	8.64	0	17.28
Edinburgh	0	0	0	0
ATC	2.4	2.4	0	4.8
Manchester	3.4	3.4	3.4	10.2
RAL	0	0	0	0
Other costs				
Portsmouth	4.536	4.536	4.536	13.608
Glasgow	0	5.120	0	5.120
Hertfordshire	2.56	2.56	0	5.12
Cambridge	672.7	38.4	169.9	881.0
Oxford	2.13	2.13	2.13	6.39
Southampton	0	0	0	0
UCL	5.136	5.136	0	10.272
Edinburgh	473.080	3.68	0	476.760
ATC	2.24	0.32	0	2.56
Manchester	779.7	26.7	62	868.4
RAL	821.0	226	124	1171
Indirect & Estates				
Portsmouth	18.082	18.680	18.680	55.442
Glasgow	0	82.197	0	82.197
Hertfordshire	28.626	28.626	0	57.251
Cambridge	8.4	0	0	8.4
Oxford	22.427	22.427	22.427	67.281
Southampton	11.098	11.098	11.098	
UCL	37.89	37.89	0	75.78
Edinburgh	20.316	20.316	0.924	41.556
ATC	17.33	19.92	0	37.23
Manchester	49.2	49.2	49.2	147.6
Overall Project Cost	3290.56	979.61	631.25	4901.42

NOTE THAT THE BASE COST ONCE LOFAR-UK AND HEFCE MATCHING IS SUBTRACTED IS 4071K – see section 6 of main text.

Risk register

A Annex C: Risk register and risk management

Risk Management

The desired outcome of the LOFAR-UK project is four LOFAR-UK stations working as part of the E-LOFAR array for the largest possible fraction of time at the largest possible efficiency. The results of a preliminary risk identification, analysis and assessment is shown in the Table. The project manager, and ultimately the PI and Management Board, will 'own' any required risk management action. The work objectives and timescales have been designed such that the risk likelihood is always 'possible', and the impact 'moderate'. The mitigation strategy incorporates our estimate of the working allowance (WA) needed to avoid any possibility of 'major' risk. The key for the risk levels is as follows.

1. Solution available, just requires implementation.
2. Straightforward application of available technology, but some development required
3. Significant R&D needed but high confidence in success.
4. Significant R&D needed but chance technology will not succeed.
5. No solution yet apparent.

The risks associated with uncertainties associated with other funding streams (e.g. HEFCE/SEPNET, SUPA2, SEEDA) are clearly identified in the proposal, and eliminated by clearly explained de-scope options. Although named specialist staff are to be funded through this proposal, there is enough UK expertise in relevant areas to replace these particular people should the need arise. The LOFAR funding in the Netherlands is sufficient to deliver the project, with any cost over-runs being translated into project de-scopes rather than time slippages due to the strict time limits placed on the spending of the Dutch funding. The level of German GLOW funding impacts the LOFAR-UK programme as follows: if current GLOW financial plans turn out to be optimistic then a less-capable LOFAR instrument will result, but one in which the UK is clearly the most influential international partner to the Netherlands.

Note that in estimatin the working allowance for the LOFAR station hardware,

- Since we have a fixed price for the Low Band Antennae (LBAs) we are only considering a WA for the High Band Antennae (HBA) component of the station hardware costs (in Euros)
- The WA includes a small component for fluctuations in the Sterling–Euro exchange rate, although of course this is extremely hard to estimate

WP	Risk	Risk Factor	Effect of Risk	Mitigation (and working allowance)
WP-D1	insufficient resources to cover all requirements	1	schedule delay or impaired results	10% WA staff effort
WP-D2	unacceptable cost of lightpaths	2	lower achievable data rates	accept lower data rates while working on technical solution (use of lower bit-rate sampling) at cost of 10% WA staff effort
WP-D3-T1	Over-run on development of instrumental calibration	3	poor dynamic range images	accept lower dynamic range while working on technical solution at cost of degraded performance; 5% WA staff effort
WP-D3-T2	Over-run on development of ionospheric calibration	3	poor low-frequency performance	focus on exploiting high-frequency LOFAR while working on technical solution at cost of degraded low-frequency performance; 5% WA staff effort
WP-D3-T3	Over-run on development of pre-processing	3	restricted field of view (FOV) on long baselines	focus on exploiting restricted FOV science while working on technical solutions at cost of degraded mapping speed; 5% WA staff effort
WP-D4-T1	Over-run on development of cataloguing	2	degraded catalogue completeness or depth	work on technical solutions at cost of poorer data products; 5% WA staff effort
WP-D4-T2	Over-run on development of archiving	2	degraded archive capability	work on technical solutions at cost of poorer data products; 5% WA staff effort
WP-D4-T3	Over-run on development of solar software	2	degraded solar-science capability	work on technical solutions at cost of poorer data products; 5% WA staff effort
WP-I1	Delays in deployment of Chilbolton station / increase in station installation costs	1	unacceptable slippage of project	5% WA staff effort, 15% WA equipment/installation costs
WP-I2	Delays in deployment of Edinburgh station / increase in station installation costs	1	unacceptable slippage of project	5% WA staff effort, 15% WA equipment/installation costs
WP-I3	Delays in deployment of Jodrell Bank station / increase in station installation costs	1	unacceptable slippage of project	5% WA staff effort, 15% WA equipment/installation costs
WP-I4	Delays in deployment of Lord's Bridge station / increase in station installation costs	1	unacceptable slippage of project	5% WA staff effort, 15% WA equipment/installation costs

Working allowance summary

Work Package	Working Allowance	cost (k£)
WP-D1	10%	33.4
WP-D2	10%	24.9
WP-D3-T1	5%	5.4
WP-D3-T2	5%	10.1
WP-D3-T3	5%	8.6
WP-D4-T1	5%	5.2
WP-D4-T2	5%	14.2
WP-D4-T3	5%	5.4
WP-I1	5% staff, 15% equipment/installation	95.8
WP-I2	5% staff, 15% equipment/installation	89.9
WP-I3	5% staff, 15% equipment/installation	70.1
WP-I4	5% staff, 15% equipment/installation	54.3
		£417.3k

The Working Allowance will be held – at least initially before a Project Manager has been hired – at the PI institute (Southampton).

Contingency

We estimate a 10% overall contingency for the project. This is evaluated in Section 6 ('Costs to STFC') in the main text.