1. Introduction

Determining the structure of the Universe and the nature of its expansion are key questions in modern science, let alone astronomy. Here we highlight how LOFAR can play a major role in measuring the cosmological parameters, including dark energy properties and tests for alternative gravity models. Important constraints on cosmology will be gained from LOFAR alone, and combination with other surveys allows measurements which improve on current constraints by a factor of at least two.

LOFAR Surveys can play a vital role in developing our understanding of the Universe at large. The unique redshift distribution of radio sources, coupled with the ability to survey large swaths of sky make radio continuum surveys an attractive tool to study the evolution of large-scale structure in the Universe, how the Dark Energy and Dark Matter components may evolve with cosmic time and also to determine whether there is evidence of departures from General Relativity. Our initial simulations are very encouraging and are presented in Raccanelli et al. (2012). Here we outline the key experiments that we will carry out within the LOFAR Survey KSP.

1.1 Large-scale clustering of radio sources and the evolution of bias

The clustering properties of radio sources can be used to provide important constraints on galaxy formation and evolution, and how this is related to the underlying dark matter distribution. Previous studies of the clustering of radio sources have found that the angular-two-point correlation function can be described by two power-law components (e.g. Blake & Wall 2002; Overzier et al. 2003), one which is dominant on small scales (< 6 arcmin) due to the size distribution of classical double radio sources and the other which describes the true cosmological clustering of the radio source population. Overzier et al. (2003) conducted the most in-depth study of the large-scale clustering of radio sources to date, using the NVSS and FIRST radio surveys, and find that the more luminous, FRII-type sources are more strongly clustered than their lower luminosity counterparts. They explain this with the hypothesis that the more luminous FRII sources trace the some of the most massive structures in the Universe, i.e. (proto-)clusters. With the combination of depth and area covered by the proposed LOFAR Survey KSP we will be able to take such studies to the next level. The Tier-1 survey will be used to determine the large-scale clustering of the radio source population, and in combination with optical and near-infrared surveys such as SDSS, PanSTARRS, UKIDSS-LAS and WISE, be able to determine photometric redshifts for all powerful AGN at \( z < 0.5 \) and possibly up to \( z < 1 \) in the future. This will be combined with the deeper Tiers-2 and 3 to measure the evolution in the clustering of sources up to \( z > 4 \) as a function of luminosity, spectral index and possibly morphology in the future. This will place powerful constraints on the evolution of the underlying dark matter distribution traced by radio sources of luminosities spanning FRII-type AGN down to starburst galaxies.

Furthermore we will be able to infer the bias of radio sources from the real space two-point correlation function over sub-areas of the Tier-1 survey where there is spectroscopy, e.g. from the GAMA survey.
Driver et al. (2009). This will allow us to make the first direct measurement of the evolution of bias from $z \sim 0 \rightarrow 0.5$.

1.2 The Integrated Sachs-Wolfe Effect

An important feature of General Relativity is that gravitational fields can alter the energies of photons and cause spectra of light to be redshifted or blueshifted, just like a relative velocity between source and observer. Gravitational redshifting / blueshifting introduces anisotropies into the Cosmic Microwave Background, since some of the photons at the surface of last scattering would traverse gravitational potential wells caused by matter over-densities, while others would not.

The Integrated Sachs-Wolfe (ISW) Effect comes from the fact that, due to structure in the Universe, there are potential wells all over the sky that the CMB photons will have fallen into and climbed out of on their way to us. In a matter dominated Universe there would be no net gain or loss of energy for the photon, since any blueshift caused by falling into the over-densities will be cancelled by the redshift from climbing out.

Since the change in the photon energy is proportional to the rate of change in the gravitational potential, the key factor which would result in a net loss or gain of energy, is if the depth of the potential well changes while the photon is crossing. In a Dark Energy dominated Universe this is possible. As a photon from the CMB propagates through the Universe and down a potential well, if the Dark Energy density of the Universe at that cosmic epoch is significant then the potential well is reducing its amplitude, and the photon will require less energy to escape than the amount it gained on entering the well. Thus there is a net blueshift of the CMB photon which correlates with overdense regions, in a universe where Dark Energy is present.

Detecting the ISW effect is a challenging problem; this is principally because the anisotropies are small in comparison with the anisotropies arising at higher redshifts. Furthermore, the anisotropies are expected to be seen on large scales, where the cosmic variance severely hampers obtaining significant quantitative results.

Therefore, studies so far have concentrated on cross-correlating tracers of the density field in the relatively nearby Universe with the temperature maps from the CMB. As the primordial anisotropies should be uncorrelated with the nearby density field then it is possible to measure the relatively weak anisotropies caused by the ISW effect. Recent work in this field has used most of the large datasets in observational astronomy across all wavebands as a tracer of the nearby density field. For example Fosalba, Gaztañaga & Castander (2003) used the SDSS galaxy catalogue and measured the ISW effect at the $3\sigma$ level, Padmanabhan et al. (2005) used only the Luminous Red Galaxies from the SDSS and again found a marginally significant detection of the ISW effect between $0.2 < z < 0.6$. Several groups have already attempted to use large area radio surveys to measure the ISW effect at a higher median redshift. Boughn & Crittenden (2004a, 2004b) were the first to use the distribution of NVSS sources, which covers around $\sim 80$ per cent of the sky and found a $2.5\sigma$ correlation with the first-year WMAP data. Subsequently Nolta et al. (2004) and Vielva, Martínez-González & Tucci (2006) confirmed this result using different techniques. With the release of the WMAP 3rd year data came further analyses with the NVSS catalogue (Pietrobon, Balbi & Marinucci 2006; Ho et al. 2008; Giannantonio et al. 2008; McEwan et al. 2008; Raccanelli et al. 2008).

With LOFAR we can push such studies to similarly wide areas, with more sources at all redshifts. The LOFAR Surveys “Tier-1” survey will provide deep radio maps over the whole northern hemisphere with which to measure the ISW effect and thus constrain cosmological models (Raccanelli et al. 2012; see also Figure 1).

1.3 Cosmic Magnification

It is possible to pioneer weak gravitational lensing at radio wavelengths with LOFAR. Rather than
measuring shapes of galaxies we plan to measure cosmic magnification by cross-correlating LOFAR surveys with optical surveys such as SDSS-II, WISE and/or PanSTARRS.

The cosmic magnification signal is due to two competing effects, both due to the lensing of light rays by gravitational potentials along the path from object to detector, as described by General Relativity. The first effect is that the patch of sky seen behind a mass concentration is expanded in appearance; therefore the number density of objects in that patch is rarified. The second effect is that images of galaxies are themselves magnified, leading to a net increase in flux from each galaxy; therefore objects which were too faint to be detected before are now detected, increasing the number density of objects in the patch. Which of these two effects is dominant depends on the local slope of the luminosity function of galaxies. Either way, one can correlate the number density of sources with those of foreground objects which act as lenses, and constrain a combination of bias, matter power and geometry.

We propose to carry out this correlation technique, with LOFAR Tier 1 objects as the background sources, with a median redshift of approximately $z \sim 1.1$, and the SDSS-II main galaxy catalogue with a median redshift of $\sim 0.2$. We have calculated the expected signal for LOFAR/SDSS-II; this depends on the luminosity function for LOFAR surveys which we estimate from the SKADS $S^3$ catalogue at 150MHz (Wilman et al 2008; 2010). Figure 2 shows our predictions for cosmic magnification measurements. We see that the signal is measured at high significance; this amounts to a measurement of the combination of cosmological parameters $b^2 \Omega_m \sigma_8$ to within 5%. This is competitive with current constraints, and is complementary by being a totally distinct method for constraining these parameters.

An important issue for cosmic magnification is that the background and foreground samples should be distinguished in redshift, to minimize the physically close pair correlation. We will therefore carefully select suitable background sources in LOFAR surveys, by means of brightness cuts and matching with SDSS-II. The remaining overlap will be carefully quantified so that the theoretical models of the correlation will include both physical and lensing correlations; the former will be marginalised over. In practice initial cosmic magnification correlation measurements with LOFAR may show significant systematics in flux calibration on all scales from tens of arcseconds to tens of degrees. The correlation may therefore act as a powerful systematic test for LOFAR calibration before it reaches cosmological accuracy.

In the longer term, LOFAR also offers opportunities for extending the study of weak gravitational shear into radio frequencies to a much greater degree, building on the work of Patel, Bacon et al. (2010) showing that the shear dispersion for radio emission from typical galaxies at $\sim 40 \mu$Jy is comparable to that in the optical. A large shear survey, providing dark matter maps across the sky, can be attempted with LOFAR once all international baselines are functioning; resolution of $\sim 1''$ is required. However, this requires a careful understanding of all LOFAR systematics affecting the shape of objects at the resolution limit. This is an ambitious venture which we will explore with Tier 2, but more likely Tier 3 high-resolution data, on which we will carry out ellipticity measurements, shear correlation functions and mass map reconstruction over $\sim 1$ square degree patches within the deep fields where we are able to include all international baselines.

### 1.4 Detection of the Cosmic Dipole Anisotropy

The motion of our Galaxy through the cosmos produces a systematic shift in the temperature map of the Cosmic Microwave Background due to the Doppler effect. This temperature shift is apparent at the $\sim 0.1$ per cent level, i.e. the temperature of the CMB is 0.1 per cent higher in the direction of motion of our Galaxy. In the other direction the CMB is $\sim 0.1$ per cent cooler. This is known as the dipole anisotropy. In the standard cosmology the dipole anisotropy should also be reflected in the surface density of discrete sources within the Hubble flow, i.e. distant radio sources. Such an effect has been detected at optical (Lahav 1987), infrared (Rowan-Robinson et al. 2000) and radio wavelengths (Blake & Wall 2002); now LOFAR will be able to improve on these detections by greatly increasing directional
accuracy (Crawford 2008) and examining the signal at $z = 1.1$. If a difference in dipole direction between LOFAR and the CMB is detected, this will indicate either an intrinsic dipole in the CMB or a substantial inhomogeneity in the local Universe, and could thus be of ground-breaking importance.

2. Spectroscopic follow-up

Although the tests discussed in Section 1 do not rely on redshift information for individual sources, it would obviously be beneficial to obtain accurate redshift information for as many radio sources as possible to produce tighter constraints on the cosmological models. However, the LOFAR continuum surveys may provide a unique niche in Baryon Acoustic Oscillations (BAO) measurements at high redshift. We have a broad interest and strong scientific leadership in the study of BAO. It is also involved in the development of the required instrumentation to pursue these studies at $z \gtrsim 1$, namely the next generation of multi-object spectrographs (MOS), such as WEAVE on the WHT (Balcells et al. 2010).

The LOFAR-deep survey will provide an ideal dataset from which to select targets for BAO surveys with MOS facilities, for a number of reasons. LOFAR-deep delivers above the critical density $dn/dz$ of objects ($\gtrsim 2000 \text{ deg}^{-2}$) that is needed for power-spectrum measurements at $z \approx 1.5$ to be cosmic-variance (rather than shot-noise) limited. In addition, the objects identified are those that, through their radio emission, are known to be either starbursts or AGN, and therefore likely to have narrow emission line; this means that redshifts can be obtained in relatively short spectroscopic observations. Furthermore, the few hundred square degree coverage proposed for the LOFAR-tier-2 survey is approximately the size needed to produce the required $\sim 2\%$ accuracy in the BAO length-scale measurement. Another case for the future use of LOFAR Surveys is that the source density at $z > 1.8$ is also sufficient to measure the BAO signal at these high redshifts if suitable blue-optimized wide-field multi-object spectrographs are available on 4-m and/or 8-m class telescopes (e.g. WEAVE). The LOFAR Tier-2 survey can thus be an extremely valuable resource for future BAO surveys.

3. MSSS

Some of the science issues raised above can be investigated to some degree by MSSS. We therefore plan to use MSSS as an initial phase of understanding the LOFAR data and its noise properties prior to investigating the cosmological parameters and large-scale structure. First of all we will aim to recover the cosmic dipole and thus help perform accurate absolute and relative flux-calibration across the MSSS with a view to help the full survey to be calibrated accurately. Once this has been done we will then aim to perform the first measurement of the ISW-effect (section 1.1) and Cosmic Magnification (Section 1.2) which will both be high-impact results from just LOFAR commissioning data.

4. Link to Tiers 2 and 3

The predictions presented in Raccanelli et al. (2012) rely on knowledge of the redshift distributions (not individual redshifts) and the evolution of bias. We therefore emphasise the close synergy between the proposed Tiers 2 and 3 over the deep fields with the cosmology that will be carried out over the Tier 1 area, with Tiers 1 and 2 allowing us to measure the redshift distributions of radio sources and their clustering in redshift bins very accurately. Therefore, much of our initial work will be to use these deeper data to obtain these measurements working closely with the projects led by Best and Lehnert.

5. International Baselines

As mentioned in Section 1.2, one of the long-term aims of our case is to measure directly the weak-lensing signal over $\sim 5$ square degree fields. This will be possible when the international baselines with the high-band antennae are fully integrated into the LOFAR surveys. This also has direct relevance to the other deep-field science cases proposed by Best, Lehnert and Miley as part of the Survey KSP umbrella proposal. Our initial plan will be to correlate the international baseline over $\sim$arcmin scales.
around bright sources to assess issues and develop algorithms using the plan of the long baseline team (PI Wucknitz) and then in the central parts (∼ 1 square degree) of the Tier 3 fields as these are where we will attempt to push LOFAR to its maximum depth and where the best ancillary data are. In the longer term our aim would be to correlated the longer baselines over larger fields of view.

6. Management

We have defined various working groups to deal with the technical, theoretical and scientific exploitation of LOFAR surveys for Cosmology. Obviously only a limited amount of technical work can be done until we are able to full calibrate LOFAR survey data. However, our team has already been developing simulated images for other SKA precursor telescopes (e.g. Heywood et al. 2011), producing optimal cross-matching algorithms (Smith et al. 2011; McAlpine et al. 2012) as well as being central in producing the SKADS simulated skies (Wilman et al. 2008; 2010). Our team have also already performed predictions for the “ideal” LOFAR Surveys in terms of their ability to detect the ISW and cosmic magnification signals as well as the predicted measurement of the auto-correlation function (Raccanelli et al. 2012). These studies are currently being enhanced by including envisaged redshift information (Camera et al. in prep.) and also realistic noise statistics. We are therefore well positioned to fully exploit initial and full LOFAR Survey data when available for use in cosmology and large-scale structure.

Technical Working Group (Coordinators: Matt Jarvis & Kris Zarb-Adami)

- Verify source finding algorithms, determine noise properties as function of scale, develop cosmology quality catalogues
  (Chair: Kris Zarb-Adami ; Team: Jon Zwart, Dominik Schwarz)
- Cross-matching of LOFAR data to shorter wavelengths, particular for photometric redshifts and follow-up spectroscopy
  (Chair: Dan Smith ; Team: Kim McAlpine, Dave Bonfield, Mattia Vaccari, Jon Zwart)
- Generate realistic LOFAR mock catalogs and data using SKADS and simulated LOFAR beam.
  (Chair: Ian Heywood ; Team: Kim McAlpine, Kris Zarb-Adami)

Science Exploitation Working Group (Coordinators: David Bacon & Matt Jarvis)

- Source auto-correlation function and large-scale clustering
  (Chair: Will Percival; Team: Matt Jarvis, Sam Lindsay, Mattia Vaccari, Daniele Bertacca, Russell Johnston, Dominik Scwarz, Alvise Raccanelli, Huub Röttgering)
- Cross-correlations: ISW and cosmic magnification
  (Chair: David Bacon; Team: Daniele Bertacca, Matt Jarvis, Russell Johnston, Kim McAlpine, Bob Nichol, Alvise Raccanelli)
- Dipole Measurement
  (Chair: Dominik Schwarz; Team: Matthias Rubart, David Bacon, Huub Röttgering)
- Shape correlation code (i.e. pushing towards measuring resolved shear)
  (Chair: Filipe Abdalla; Team David Bacon, Prina Patel, Andreas Faltenbacher)

Theoretical Working Group (Coordinators: David Bacon & Dominik Schwarz)

- Include better estimates of noise, and inclusion of some redshift information in the predictions and figure of merit calculations
Figure 1. Power spectra of the combined source populations (black solid lines) for the LOFAR Tier 1 survey, with 1- errors (grey shaded regions). Figure taken from Raccanelli et al. (2012).

Figure 2. Cosmic magnification predictions for correlating MSSS with SDSS-II galaxies. The horizontal axis gives the angular scale on which number densities of galaxies are correlated; solid lines give expected signal for $\Omega_m = 0.25, \sigma_8 = 0.7, 0.8, 0.9$ and 1.

Figure 3. Forecast of constraints for dark energy (left) and modified gravity (right) parameters, for the LOFAR Tier 1 survey. Ellipses show constraints for different combinations of probes (MAG = cosmic magnification; ACF = autocorrelation function; ISW= Integrated Sachs-Wolfe). Figure taken from Raccanelli et al. (2012).
7. References

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