On the feasibility of gravitational lens surveys with an extended-baseline LOFAR array

Summary

In principle, surveys with LOFAR are capable of detecting $\sim 10^6$ sources in shallow surveys at high frequency, and assuming that these sources are at high ($z > 1$) redshift about 10^3 lenses will be detected. The major practical problem is that of false positives, because no other pre-2010 radio instrument is capable of following up $> 10^4$ sources.

The survey speed can be calculated assuming an rms of $\sim$70μJy/beam in 1 hour at 200MHz or 240MHz. To survey sources of 2mJy or more with signal-to-noise of 30:1, about one hour per pointing is needed. Each pointing will map an area of approximately 2 square degrees.

The major problems which will decrease the lensing detection rate or cause false positives to enter the survey are:

1. Resolution. An extended LOFAR array will have a resolution of about 550mas, assuming a 550-km maximum baseline. This is just sufficient to detect lenses of 500mas or larger separation, although the details depend on the available followup time and on the source population. The distribution of separations of CLASS lenses (a survey sensitive to separations >300mas) is shown in figure 1, so in principle about 90% of CLASS lenses could be detected using LOFAR.
2. Field of view. This together with the sensitivity is obviously critical for the survey speed.
3. Nature of the source population. There are two main effects. First, the slope of the source counts affects the magnification bias and hence the number of lenses, and also affects tradeoffs between shallow and deep surveys. Second, whether the sources are point or resolved sources strongly affects the detectability of lensing effects.

I argue here that a wide, shallow survey is most efficient, and that 200 beam-days at 240MHz followed by 10 days of EVLA time is capable of multiplying the known number of gravitational lenses by about three. 400 beam-days would cover most of the northern sky and yield 6 times the known number of lenses. In addition, there are many other projects in extragalactic astronomy which could benefit from a 2π-sr survey at half-arcsecond resolution.

1. Nature of the source population and survey strategy.

Surveys at LOFAR depths after about one hour of integration will be sensitive to lens systems whose total flux density is about 2mJy at 240MHz. This corresponds to the point at which AGN are likely to give way to the starburst population, although the exact details are unknown at this frequency; equivalent deep surveys have been done at 1.4GHz (e.g. the Phoenix survey, Hopkins et al. 1998, 2003).

Probably the best guess is provided by the evolution models produced by Carole Jackson and Jasper Wall (Jackson & Wall 1999, Jackson 2003) which predict source numbers per degree at low frequencies given in Table 1.

In a shallow survey with LOFAR (1 hour per pointing at 240MHz) the parent population for lens detection would therefore be about 40 starbursts, 40 FR1 and 20 FR2 sources per square

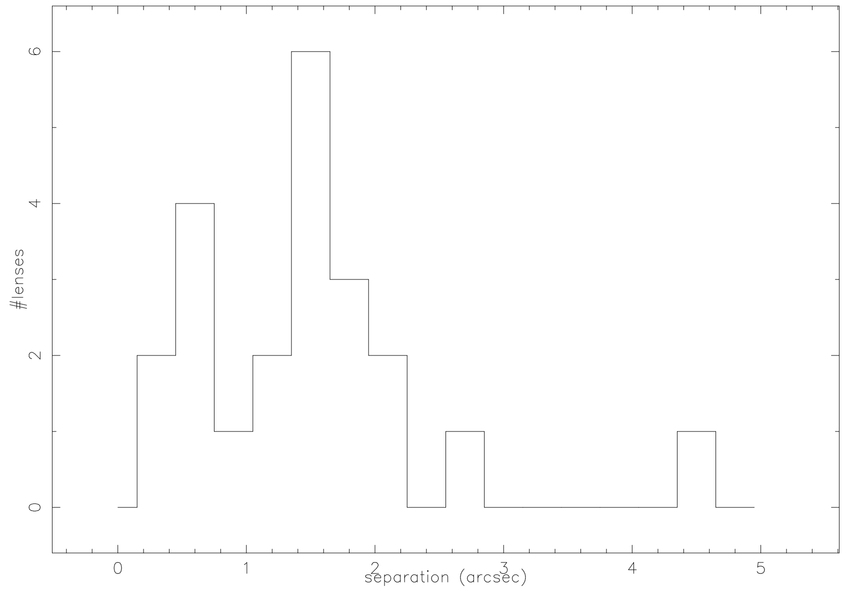

Figure 1: Histogram of separation distribution of CLASS gravitational lenses.

degree, as systems of total flux >2mJy would be studied. The lensing rate is approximately 1 in 600 for sources at redshifts >1, and decreases as $(1+z)^{-4}$ below redshift 1, assuming a standard magnification bias (integral source count going as the inverse of the flux density). Correcting for the approximate mean redshift, a shallow LOFAR survey would pick up about 0.008 lensed starburst galaxies (average redshift 0.5), 0.03 lensed FR1s and 0.03 lensed FR2s per square degree. However, there is a very strong inverse magnification bias caused by the FR2 counts cutting off below 2mJy, and almost no lenses would be found in the 2-10mJy range if the cutoff is sharp; this reduces the FR2 lensing rate to about 0.005 per square degree. For the FR1s, a flatter than -1 slope in the integral source count probably reduces the lens yield by a smaller factor to about 0.02. We therefore expect about 0.03 lenses per square degree.

Assuming one beam to be available for 200 days, one could cover approximately 10000 square degrees leading to 300 lenses and 10000 false positives (section 2); this number would in principle be easy to follow up with the EVLA, although it would take about 10 days of EVLA time. Again in principle, this number of lenses would make a major contribution to the subject, exceeding the number of known lenses by a factor of 3. Obviously if more beams or time were available, the survey could be extended by a factor of 2 to the whole of the northern sky.

An alternative strategy would be to conduct a deep survey, spending about 1 day per pointing to get to an RMS of 16μJy and detect lens systems of total flux >0.5mJy. For lensed starburst galaxies, this would have two advantages; because of the steep RLF more would be detected (about 200 per square degree) and the slightly higher mean redshift of the fainter sources would mean an improved detection rate, probably yielding about 0.06 lenses per square degree.

Limiting flux density	#Starbursts	#FR1	#FR2
2mJy, 151MHz	65 (z=0-1)	50 (z=0-1.5)	20 (z>1)
1mJy, 151MHz	120 (z=0-1)	60 (z=0-2)	25 (z>1)
2mJy, 325MHz	25 (z=0-0.5)	30 (z=0-1.5)	20 (z>1)

Table 1: Numbers of sources from evolutionary models by Jackson & Wall 1999, per square degree.

However, because of the shape of the luminosity function of FR2s almost no further sources would be detected by going deeper, and the extra yield in FR1s would be marginal. Hence the lensing rate per square degree would only double by going four times deeper, and the slower survey speed would mean that a factor of 10 fewer lenses would therefore be found.

2. Detection of lenses

Having found that a few hundred lenses could be detected, we now consider whether they could be recognised as such in a reasonable amount of followup time.

Point sources. The CLASS survey has detected 22 lenses by observing 16503 flat-spectrum radio sources >30mJy, the overwhelming majority of which are point sources. The original CLASS survey searched for lenses of separation 300mas ($\sim 1.36\lambda/d$). A further investigation using blind mapping of CLASS database sources together with simulated visibility datasets has shown that lenses of 180mas ($\sim 0.8\lambda/d$) can be recovered at the 80% level (i.e. a false negative rate of 20%).

The false-positive rate in CLASS was about 3%, or 20 false-positives per lens. This is clearly unsustainable for a survey which aims to find about a thousand lenses, as it would imply followup of the order of 30000 candidates with the EVLA/EMerlin. The false-positive rate in the small-separation investigation, however, is about 1%. The reason for the difference is that the CLASS survey was very concerned about 100% survey completeness, and many marginal or dubious candidates were followed up. In general, for point sources the irreducible false-positive rate, mainly due to extended structures in the background source, is probably around 1%.

The signal-to-noise requirement for point source lenses is set by the need to detect the faintest typical secondary image (about one-tenth of the primary) at 3:1 signal-to-noise.

Extended sources. Detection of lenses from extended radio sources depends on the extent of the radio source and the Einstein radius of the lens as a function of the resolution, as well as the signal-to-noise. Some success has already been achieved by a collaboration led by Lehar, and a number of lensed radio lobes have been detected including the ring lens MG1131. Since the detection of a lens involves separating such systems from the extended background population, both the false-positive and false-negative functions are rather complicated.

Figure 2 shows some simulations of a ring lens for various different assumed source sizes, resolutions and signal-to-noise.

3. Followup issues from a LOFAR 240-MHz survey.

False positive rate. From manual inspection of large samples of radio maps such as those in Fig. 2, it is possible to recognise typical lens configurations and distinguish them from intrinsic structure such as jets. For point sources, 99% of the sample can be rejected as a possible (separation$> 0.8\lambda/d$) lens in the process. Automatic recognition algorithms developed so far for CLASS, based on examinations of visibility functions by modelfitting, have not been as efficient, rejecting only 97% of objects. For extended objects, the same false positive rate could be maintained provided one did not consider the smaller ($0.8\lambda/d < S < 1.2\lambda/d$) lenses which would be likely to produce at least twice this number of false positives[1]. This has the unfortunate effect of excluding about one-third of the lens sample which would be likely to have

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[1] These opinions are rules of thumb based on experience of examining radio maps for gravitational lenses. Unfortunately, the detailed simulations required to test these more accurately probably require better knowledge of the source population than we currently have

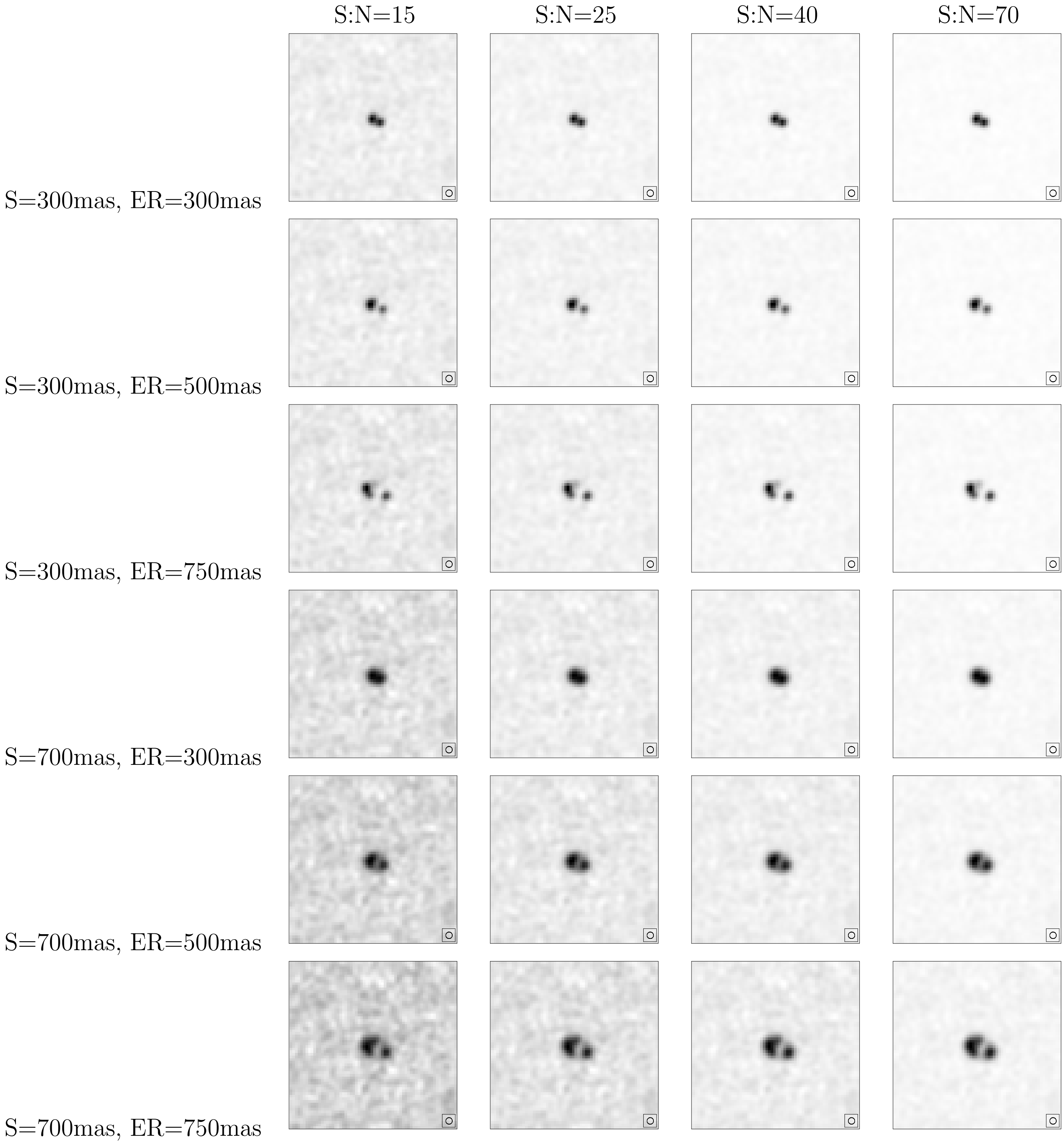

Figure 2: Simulated lenses with different S:N, source size (S) and lens Einstein radius (ER). The resolution is fixed at 550mas throughout. The splitting is approximately twice the Einstein radius.

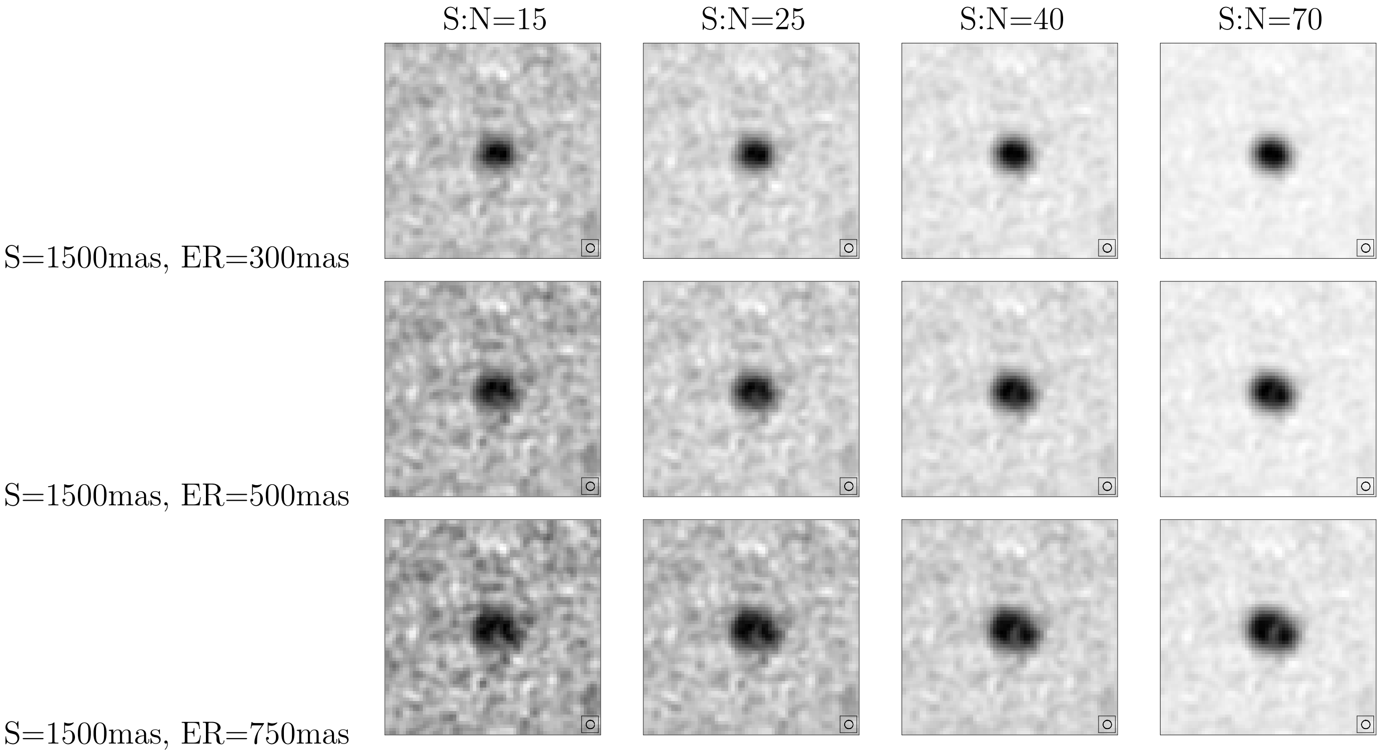

Figure 2: Continued.

smaller separation than $1.2\lambda/d$, and this false-negative problem would become considerably worse if one did the survey at 200MHz.

It takes a human approximately 1 minute to examine visibility data and maps a single object. Assuming a sample of 10^6 sources and a 3% false-positive rate from an initial pass through an automatic algorithm, the human would require about 500 hours to reduce this to the required 1% to begin further followup of 10000 sources with the EVLA. However, we have found that such automatic algorithms become unreliable, in the sense of producing false negatives, when the sources become extended or when the lens system is only marginally resolved. Both are true for a LOFAR survey with a substantial starburst source component and modest resolution. Hence some development of neural networks would be needed, using simulations such as Fig. 2 together with maps of unlensed extended starburst galaxies as a training set.

False negative rate. Assuming a parent population of about 300 lenses, one would expect to lose about 20% given the LOFAR resolution (Fig. 1) and possibly a few further objects with large source size and in which the Einstein ring is marginally resolved; even here, however, inspection of the map and visibility function together can often leave genuine lens systems within the sample. In the case of large sources in which the source is within the radio lobe, the most important criterion is signal-to-noise (see e.g. the last row of Fig. 2) and it is likely that lenses produced from >5-arcsec radio lobes may be lost from all but the strongest sources or most massive lenses.

Followup would require snapshots with the EVLA at 8.4 GHz, with a significant (10 days) but not major expenditure of time, and would be likely to reject essentially all of the remaining candidates which were not lenses, because of the factor ∼ 50 difference in surface brightness sensitivities. For the lenses, the EVLA and e-Merlin would then need to be used in order to obtain detailed information and mass models for the individual lenses. This last phase would require a major investment of time - about 50–60 days between the two instruments – and would need to be done as a Key Project which would directly produce mass models and astrophysically significant conclusions.