Constraining the Radio-Submillimetre Redshift Indicator using data from the SCUBA Local Universe Galaxy Survey.

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ABSTRACT
Many of the faint submm sources uncovered by deep SCUBA surveys still remain unidentified at most, if not all other wavelengths. The most successful method so far of obtaining accurate positions and hence allowing more secure identifications has been to use centimetre wavelength imaging with the VLA. This has led to a tempting approach for obtaining redshift estimates for this population (Carilli & Yun 1999, 2000), which relies on the tight FIR–radio relationship and takes advantage of the steep spectral slope in the submm. In this paper we use the submm data from the SCUBA Local Universe Galaxy Survey (SLUGS) to estimate the usefulness of, and the uncertainties in, the radio–submm redshift estimator. If the submm–radio spectral index were correlated with either dust temperature or 850 µm luminosity, this method could produce biased redshift estimates for 850 µm selected galaxies. We find, however, that within SLUGS, these correlations are not significant. The ratio of 850 µm/1.4 GHz flux was found to decrease with increasing radio and FIR luminosity, and we propose that this is due to a component of the dust not associated with recent star formation, but which is instead heated to 15–20 K by the general interstellar radiation field.

Key words: galaxies; high-redshift – galaxies; submm – galaxies; radio – galaxies; primeval

1 INTRODUCTION
Ever since the discovery of Ultra-luminous Infrared Galaxies (ULIRGs) (Joseph et al. 1985; Sanders et al. 1988) which emit up to 99 per cent of their bolometric luminosity in the far-IR, there have been suspicions that our optical/UV view of the early universe might be biased by large amounts of dust obscuration. These were supported by the discovery of the Cosmic infrared Background (CIB) (Puget et al. 1996;Fixsen et al. 1998), which contains up to twice the luminosity of the integrated optical/UV background. It thus seems likely that much of the star formation activity in the early universe takes place in obscured environments. Many deep surveys have been conducted with the SCUBA bolometer array on the James Clerk Maxwell Telescope (JCMT)* in order to uncover the sources responsible for this background. Significant numbers of sources, far in excess of no evolution

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models have been found at both submm (Smail, Ivison & Blain 1997; Barger et al. 1998; Hughes et al. 1998; Eales et al. 1999) and far-IR (Puget et al. 1999; Kawara et al. 1998) wavelengths.

The next step after finding these sources is identifying them and determining their redshifts, thus allowing the true star formation history of the universe to be traced. This has proved to be a difficult task, due to the large SCUBA beam size at 850 µm (15 arcsec) and the several arcsec positional uncertainty inherent in all of the SCUBA maps (Ivison et al. 1998, 2000; Downes et al. 2000; Barger, Cowie & Richards 2000; Eales et al. 2000). The SCUBA sources can sometimes be identified with several plausible optical candidates, or in other cases they remain optical blank fields, even to the magnitudes probed by HST and Keck. A possible solution to the problem of poor positional accuracy lies in the tight correlation between thermal FIR emission and synchrotron radio emission seen in the local universe (Helou et al. 1985; Condon 1992). The mechanism for this relationship is believed to be the massive stars from recent star-formation, which both heat the dust to produce the FIR flux and, when they explode as supernovae, provide relativistic electrons which
constitute the synchrotron radio emission. This means that radio observations with the VLA are also sensitive probes of star formation, albeit not as sensitive as the submm at higher redshifts given the unfavourable K-correction at radio wavelengths. For example, Barger, Cowie & Richards (2000) have recently targeted 1.4 GHz sources in the deep VLA images (Richards 1999) of the Hubble Flanking Fields (HFF) with SCUBA and found that the majority of bright (> 6 mJy) submm sources have radio counterparts. By observing the submm sources from the deep surveys at radio frequencies (particularly 1.4 GHz), more accurate positions can be obtained, allowing more secure identifications of the submm sources with optical or near IR counterparts. However, even with the accurate VLA positions, many SCUBA sources still have no detectable optical/IR counterparts, or they are too faint for spectroscopy. This creates a great problem in determining the redshifts for the sources, necessary to trace their evolution.

One possible route for obtaining redshift estimates for these objects has been suggested by Carilli & Yun (1999). This is based on the FIR-radio correlation plus the break in the spectral slope at around 3 mm, where the thermal dust emission takes over from the declining synchrotron tail. This puts the radio on one side of the spectral break and the FIR (or submm in this case) on the other, creating a redshift sensitive ratio. Carilli & Yun (1999) used the submm-radio spectral index, defined as:

\[ \alpha_{850}^{1.4} = 0.42 \times \log \left( \frac{S_{850}}{S_{1.4}} \right) \]

where \( S_{850} \) and \( S_{1.4} \) are the fluxes at 850µm and 1.4 GHz.

The exact dependence of \( \alpha_{850}^{1.4} \) on redshift is sensitive to a few parameters:

(i) The slope of the thermal Rayleigh-Jeans tail in the FIR and submm. This depends on frequency as \( \nu^{2+\beta} \) where the dust emissivity index (\( \beta \)) is thought to lie between 1 and 2 (Hildebrand 1983). It is the steepness of this slope which potentially makes the indicator sensitive to redshift

(ii) The slope of the radio synchrotron emission. For star forming regions this is assumed to be \( \alpha_{850}^{1.4} = 0.7 \Rightarrow -0.8 \) (Condon 1992). At higher frequencies this will flatten due to radio free-free emission but this is not simple to model. Free-free absorption at lower frequencies can also lead to a flattening of the radio spectra, the likely effect of this on \( \alpha_{850}^{1.4} \) is discussed in Carilli & Yun (2000) and they conclude that it is unlikely to be a dominant cause of scatter in the relationship. In any case the slope at radio frequencies is much shallower than in the submm and any uncertainties in it have less effect.

(iii) The temperature of the dust. This determines the redshift at which the thermal spectrum turns over. When this happens the ratio only depends weakly on redshift, and so becomes useless as a redshift indicator. Accurate dust temperatures are notoriously difficult to estimate and require measurements at many different wavelengths throughout the submm and FIR.

(iv) Contribution by AGN. Galaxies containing a radio-loud AGN will have higher radio emission than a purely star-forming galaxy and so lower values of \( \alpha_{850}^{1.4} \). This could lead to ambiguity between high redshift objects with AGN and lower redshift starbursts.

(v) The FIR-radio correlation and its variability with redshift. In using this technique to estimate redshifts, an inherent assumption is made that the FIR-radio correlation does not vary with redshift. Possible causes of such a change could be a variation in magnetic field strengths in galaxies in the past, or changes in the dust mass opacity coefficient which relates the FIR/submm emission to the mass of dust. The latter would depend on the dust composition and grain sizes so there is scope for it to have been different at the epoch of galaxy formation, when metallicities would have been lower.

(vi) Linked to (v) is the possibility that the FIR-radio, or more importantly, the submm-radio relationship itself depends on some other galaxy property such as dust temperature, luminosity etc.

The possible impact of points i–vi above will be discussed later.

Several authors have already used this technique to determine redshift estimates or limits for sources discovered in deep submm surveys with SCUBA (Hughes et al. 1998; Lilly et al. 1999; Smail et al. 1999; Barger et al. 2000; Eales et al. 2000). This paper uses data from the SCUBA Local Universe Galaxy Survey (SLUGS) to examine the usefulness of the submm-radio ratio as a redshift indicator, to try to normalise it with respect to the local universe and to estimate the uncertainties in it.

We will use \( H_0 = 75 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \) and \( q_0 = 0.5 \) throughout.

2 CONSTRAINING THE REDSHIFT INDICATOR

The low redshift data is taken from the SLUGS survey (Dunne et al. 2000) which is a complete sample of 104 galaxies selected from the IRAS Bright Galaxy Sample. The sample includes mainly infra-red bright objects (\( L_{\text{IR}} = 7 \times 10^{10} - 2 \times 10^{12} \, L_{\odot} \)), some ULIRGS as well as many ‘more normal’ galaxies. The objects were mapped at 850µm with SCUBA and so should provide reliable submillimetre fluxes.

We fitted a single-temperature dust spectral energy distribution (SED) to the measured fluxes for each galaxy, allowing the dust emissivity index (\( \beta \)) as well as the temperature to vary to find the best fit. While the assumption of a single temperature is probably wrong, and indeed the low values of \( \beta \) we derive suggest that there is a cold dust component, the SEDs are still a good empirical fit to the data, which is all that we require for the present analysis.

The original Carilli-Yun models for the behaviour of the radio-submm spectral index with redshift were simple two power-law models, along with some empirical SED data for 2 local galaxies. They have since modified their original estimator by using data from nearby galaxies (17 objects) to try to provide a normalisation and to estimate the scatter in the submm-radio ratio with redshift (Carilli & Yun 2000). We have independently undertaken a similar analysis but using the full SLUGS data set (104 objects), thereby providing a more statistically valid measure of the relationship and its scatter.

We have taken the real spectral energy distributions of the 104 SLUGS galaxies as determined from the IRAS 60 and 100µm fluxes and the SCUBA 850µm data, and the 1.4 GHz radio flux (Condon et al. 1990). The measured radio spectral indices were used where available (for about
Table 1. 1σ uncertainties on $Z_{\text{med}}$

| $Z_{\text{med}}$ | $\pm \sigma_z$ |
|-----------------|----------------|
| 1.0             | 0.28           |
| 2.0             | 0.44           |
| 3.0             | 0.63           |
| 4.0             | 0.94           |
| 5.0             | 1.25           |
| 6.0             | +3.13          |
|                 | −1.44          |

Uncertainties based on scatter in low redshift data only, there will be additional uncertain when the flux errors of the high-z sources are accounted for.

half of the sample) and the median $\alpha_{\text{radio}}$ was found to be $-0.7$. This was used in the SEDs of those galaxies with no measured $\alpha_{\text{radio}}$. If the change in each of these SEDs with redshift is plotted, we get 104 separate curves from which the median can be selected. The uncertainty in this method (at any given redshift) can be estimated from the spread in the 104 curves. In Figure 1, the thick solid line shows the median curve with the upper and lower solid curves being those ranked 16 per cent from the top and bottom respectively, to give the $\pm 1\sigma$ errors (defined as the range of $\alpha_{850}^{\text{med}}$ in which 68 per cent of the lines lie). So at any given redshift, the horizontal distance between the thin lines provides an estimate of the $\pm 1\sigma$ uncertainty on the redshift provided by the median curve. The rms scatter in $\alpha_{1.4}^{\text{med}}$ is almost constant with redshift, decreasing very slightly from 0.097 at $z = 0$ to 0.080 at $z = 6$. A rough guide to the redshift uncertainties at various redshifts are given in Table 1. The median curve can be approximated by the expression

$$z = 0.551 - 6.652\alpha + 25.57a^2 - 30.56a^3 + 13.75a^4$$

Our estimator starts to loose its effectiveness at redshifts greater than about 4–5, where it starts to turn over due to the peak in the thermal dust spectrum. This can be seen from the increase in $\sigma_z$ with redshift (Table 1). Also, as mentioned in Carilli & Yun (1999) at $z > 6$ the radio emission begins to become quenched by inverse Compton losses off the microwave background. The dashed line in Fig. 1 shows the new Carilli-Yun estimator (with $\pm 1\sigma$ uncertainties) using the data from 17 local galaxies (Carilli & Yun 2000). It can be seen that their mean estimator lies outside the $1\sigma$ uncertainties from our analysis, however the upper $1\sigma$ curve from theirs is consistent with our lower $1\sigma$ limit, with agreement being better at lower redshifts ($<2$). The differences in redshift estimates from the two indicators are listed in Table 2 for various values of $\alpha_{1.4}^{\text{med}}$.

There are two main differences between the present results and those in Carilli & Yun (2000). The first is in the zero redshift normalisation in the two samples. The mean value of $\alpha_{1.4}^{\text{med}}$ at $z = 0$ in Carilli & Yun (2000) is $\approx 0$ with an rms scatter of 0.14, while for our sample the mean $\alpha_{1.4}^{\text{med}} = 0.18$ at $z = 0$, with a lower rms scatter of 0.097. The shape of the Carilli-Yun estimator is also different due to the SED shapes of the galaxies in their sample (which in general had higher values of $\beta$ than ours). These differences are partly due to our much larger sample size, but there are also discrepancies in the submillimetre fluxes of the individual galaxies which are present in both the samples used by ourselves and Carilli & Yun (2000). Most of their submm data comes from a sample of 19 bright IRAS galaxies (Lisenfeld, Isaak & Hills 2000). Seven of the galaxies in this sample were also observed by us, and in several cases the fluxes we derived were as much as a factor of two higher. This was attributed to Lisenfeld et al. missing flux from extended objects (Lisenfeld, private communication), and has been corrected in the revised version of the Lisenfeld et al. paper. The consequences of using under-estimated submm fluxes would be to i) lower the mean $\alpha_{1.4}^{\text{med}}$ and ii) increase the value of $\beta$ determined in single temperature fits to the 60, 100 and 850μm fluxes, which explains the different shape of the Carilli-Yun estimator. We also note a possible error in the 1.4 GHz fluxes used for Zw049.057 and NGC 5936 by Carilli & Yun (2000). An erratum has since been published to accompany Carilli & Yun (2000) and this is discussed further in Section 5.

If we now place the handful of SCUBA sources from the deep surveys which have both spectroscopic redshifts and radio fluxes (Smail et al. 1999 and references therein; Eales et al. 1999; Lilly et al. 1999; Barger et al. 2000; Eales et al. 2000; Ivison et al. 2000) on the redshift estimator we have created from our observed SEDs (Fig. 2), we see that the agreement is satisfactory given the uncertainties. The object at $z = 2.8$ is SMM02399-0136 from Ivison et al. (1998) and is known to harbour an AGN, which explains why it
lies below the predicted lines. Given that sources may have AGN activity but cannot be confirmed as such, this redshift estimator can give only reliable lower limits. Additionally, if taken with another redshift estimation, such as photometric redshift, it could help to identify the presence of AGN (a point first noted by Carilli & Yun 1999).

3 THE FIR AND SUBMM VS. RADIO PROPERTIES

The SLUGS sample provides an ideal test for the variation of the FIR-radio and submm-radio relationships with galaxy properties, such as dust temperatures, luminosities etc. which may affect the reliability of $\alpha_{1.4}^{850}$ as a redshift indicator, and which is also interesting in its own right. Figure 3 shows the FIR-radio correlation for the SLUGS galaxies along with the 850µm–1.4 GHz relationship. Both are highly significant (Table 3 lists all the correlation coefficients in this discussion) but the scatter in the FIR-radio correlation is smaller (0.06 (15%) than that which exists for the submm-radio (0.097 (25%). This suggests that it is actually the FIR which is physically related to the radio rather than the submm. There is also a difference in slope between the two, which we will return to later. The FIR-radio correlation in the local universe does not depend on galaxy luminosity (except at very low $L_{500}$) or dust temperature, something which is confirmed by this sample. However if the submm-radio relationship is tested in this way by plotting $\alpha_{1.4}^{850}$ against $L_{500}$, $L_{1.4}$ and $L_{850}$ (Figure 4) then it is clear that there is a strong dependence of $\alpha_{1.4}^{850}$ on both $L_{500}$ and $L_{1.4}$ but not on $L_{850}$. The link with $L_{850}$ was noted by Carilli & Yun (2000) but the trend is even more evident with radio luminosity. The most likely explanation for these correlations is that both $L_{500}$ and $L_{1.4}$ are very sensitive to recent star formation in a galaxy but $L_{850}$ is not as sensitive, as a significant fraction of the 850µm flux may be produced by colder dust heated by the general interstellar radiation field (ISRF). Therefore $L_{850}$ will not change by as great a fraction as $L_{500}$ with increasing star formation. This explains the larger scatter and steeper slope in the 850µm–1.4 GHz correlation.

One of the two crucial relations for determining whether $\alpha_{1.4}^{850}$ is a biased redshift indicator is that between $\alpha_{1.4}^{850}$ and $L_{850}$. Since SLUGS was selected at 60µm, it is quite possible that the 850µm luminosities of SCUBA-selected galaxies are distinctly different from those in SLUGS. If there were also a significant relationship between $\alpha_{1.4}^{850}$ and $L_{850}$, the calibration of the Carilli-Yun method using SLUGS galaxies would lead to biased redshift estimates. Fig. 4(c) shows, however, that there is no significant correlation. To examine this, the dot-dash line on Fig. 4(c) shows the lower end of the rest-frame 850µm luminosity range for a galaxy with $S_{850} = 4$ mJy at redshifts of $> 2$ ($\beta = 2$ and $T_d = 50$ K, lower $\beta$ and $T_d$ give slightly higher rest-frame $L_{850}$ for the same flux and redshift). If we look at the values of $\alpha_{1.4}^{850}$ for the SLUGS galaxies, which correspond to the luminosities of the high redshift objects (i.e. the crosses to the right of the dot-dash line in Fig. 4(c)), they do not display a lower mean value than that for the whole sample. Given how little we know about the properties of the high-z SCUBA galaxies, and whether they are related to galaxies of the same
luminosity at low redshift (density evolution) or to galaxies of lower luminosity (luminosity evolution), we do not feel that there is a need for a luminosity dependent indicator. This is further supported by Fig. 2, showing a relatively good agreement of the indicator with the high-z data, and in particular, there is no systematic bias from the line in one direction, which may be indicative of changes in $\alpha_{1.4}$ with redshift/luminosity.

The second important relationship is that between $\alpha_{850}$ and dust temperature, since an 850$m\mu$m selected sample may well have a different mean dust temperature than one selected at 60$m\mu$m. It has also been suggested by Blain (1999) that there should be a dependence of $\alpha_{850}$ on dust temperature, and that this produces a degeneracy in the redshift indicator whereby a hot galaxy at high redshift may be indistinguishable from a colder galaxy at lower redshift. We have tested for a temperature dependence by plotting $\alpha_{850}$ against dust temperature, and we find no significant correlation (Figure 5(a)). The slight correlation seen between $\alpha_{1.4}$ and dust emissivity index $\beta$ (Figure 5(b)) is probably linked to the relationship of $\alpha_{850}$ with $L_{1.4}$ and $L_{60\mu}$3. Despite the significant correlation given by the statistic to this relationship, it appears to only hold for the lower values of $\beta$ (0.9–1.4). This could be because a low $\beta$ (when produced by fits to 60,100 and 850$m\mu$m points only) is another possible indicator of the fraction of 850$m\mu$m emission produced by the ISRF, rather than directly by star forming regions. Evidence for this comes from observations of a sample of optically selected galaxies presently under way with SCUBA and also from studies of NGC 891 and the Milky Way (Alton et al. 1998; Masi et al. 1995), where the SEDs using only 60, 100 and 850$m\mu$m fluxes give a very low $\beta$ of $\sim 0.7$. These galaxies are known to have large fractions of cold dust at $T < 20$ K, however this does not lead to a dependence of $\alpha_{1.4}$ on the fitted dust temperature because that is determined by the FIR fluxes which are dominated by the warmer dust.

![Figure 3. The FIR–radio relation and the 850$m\mu$m–radio relation for the SLUGS galaxies. The FIR–radio correlation is the tighter one implying that this is where the physical connection lies.](image)

**Table 3.** Correlation coefficients.

| $y$ | $x$ | $r_s$ | significance | S.D. |
|-----|-----|------|--------------|------|
| $L_{1.4}$ | $L_{\text{fir}}$ | 0.92 | $1.5 \times 10^{-20}$ | 9$\sigma$ |
| $L_{1.4}$ | $L_{850}$ | 0.89 | $1.1 \times 10^{-19}$ | 9$\sigma$ |
| $\alpha_{850}$ | $L_{\text{fir}}$ | -0.43 | $1.3 \times 10^{-5}$ | 4$\sigma$ |
| $\alpha_{850}$ | $L_{1.4}$ | -0.61 | $5.4 \times 10^{-10}$ | 6$\sigma$ |
| $\alpha_{850}$ | $L_{850}$ | -0.22 | 0.03 | 2$\sigma$ |
| $\alpha_{1.4}$ | $T_{\text{dust}}$ | -0.22 | 0.03 | 2$\sigma$ |
| $\alpha_{850}$ | $\beta$ | -0.42 | $2 \times 10^{-5}$ | 4$\sigma$ |

**Notes:** Column (3)-Spearman rank correlation coefficient; Column (4)-probability that $x$ and $y$ are unrelated (i.e. of accepting the null hypothesis); Column (5)-standard deviation at which the null hypothesis is rejected.

4 DISCUSSION

The submm-radio spectral index appears to provide a moderately satisfactory redshift indicator out to redshifts of $\sim 4 - 5$ where it ceases to be as sensitive to redshift. The uncertainties in the estimated redshifts are obtainable using the spread of the local SEDs, and range from $< \pm 0.3$ at $z < 1$ to $\pm 1$ at $z > 4$. Sources which harbour radio loud AGN will not follow this pattern as they will lie below the indicators, leading to AGN sources which are not recognised as such being given misleadingly low redshifts.

Let us now return to the assumptions and limitations discussed in section 1, and apply them to our data sets.

(i) The submillimetre emissivity index has a mean value of 1.3 for the SLUGS sample, as determined by single temperature fits to the 60, 100 and 850$m\mu$m fluxes. As discussed at length in Dunne et al. (2000), if a colder dust component is present this may not represent the true value of $\beta$, the
(a) Dependence of $\alpha_{850}^{1.4}$ on $L_{850}$, first noted by Carilli & Yun (2000).

(b) A stronger correlation is seen with $L_{1.4}$

(c) $\alpha_{850}^{1.4}$ shows no significant correlation with $L_{850}$

Figure 4. Relationships between $\alpha_{850}^{1.4}$ and luminosities for the SLUGS galaxies. The strongest connection is with radio luminosity while there is no strong dependence on $L_{850}$. The dot-dash line in (c) shows a rough lower limit to the rest-frame 850$\mu$m luminosity of a deep SCUBA source with $S_{850} = 4$ mJy, $z > 2$, $\beta = 2$ and $T_d = 50$ K. Lower $\beta$ or $T_d$ will produce slightly higher luminosities. The flat flux density-redshift behaviour at 850$\mu$m means that sources brighter than 4 mJy will have $L_{850}$ higher than the line, and vice-versa for fainter ones.

Table 4. Parameters used in ‘grey’ cold component models.

| Model                  | $T_w$ (K) | $T_c$ (K) | $N_c/N_w$ | $\beta$ |
|------------------------|-----------|-----------|-----------|---------|
| 1 (thick dashed)       | 40        | 20        | 5         | 2       |
| 2 (thin dashed)        | 40        | 20        | 10        | 2       |
| 3 (thin dotted)        | 40        | 20        | 40        | 2       |
| 4 (thick dotted)       | 30        | 15        | 10        | 2       |

Column(1)-Refers to model in Fig 6; Column(2)-Temperature of warm dust component; Column(3)-Temperature of cold dust component; Column(4)-Ratio of cold dust mass to warm; Column(5)-Value of emissivity index assumed

true value being higher than that determined using a single component model. If the true value of $\beta$ were nearer to 2 this would increase the rate of change of the ratio with redshift as the submm flux in the Rayleigh-Jeans tail $\propto \nu^{2+\beta}$ (see (iii)).

(ii) The radio spectral index is also somewhat uncertain, but being flatter it has much less impact than the submm slope. However, if high-redshift dust sources have systematically different spectral indices than those at low redshift, this would lead to a bias. The range of measured indices for the SLUGS sample is $\sim -0.2$ to $-1.0$. The situation at high redshifts is harder to determine as the value of $\alpha_{radio}$ for $\mu$Jy sources may depend on the selection frequency, with sources selected at $\nu > 5$ GHz likely to have flatter radio spectra than those selected at 1.4 GHz (Richards 1999). For example, the sources from the Canada-UK SCUBA survey have 5 GHz radio fluxes from Fomalont (1991) and an average $\alpha_{radio} = -0.38$, while SCUBA observations of 1.4 GHz sources in the Hubble Flanking Fields were associated with radio sources with steeper spectra, $\alpha_{rad} \sim -0.7$ (Barger et
(a) No significant correlation is found between $\alpha_{850}$ and the fitted dust temperature.

(b) Possible slight dependency of $\alpha_{850}$ on emissivity index $\beta$, see text for discussion.

Figure 5. Variation of $\alpha_{850}$ with fitted dust temperature and emissivity index.

Figure 6. Median and 1σ estimators (solid lines) along with models for two-component dust SEDs. Parameters are detailed in Table 4: $T_w = 40$ K, $T_c = 20$ K, $N_c/N_w = 5$ (thick dashed); $T_w = 40$ K, $T_c = 20$ K, $N_c/N_w = 10$ (thin dashed); $T_w = 40$ K, $T_c = 20$ K, $N_c/N_w = 40$ (thin dash-dotted); $T_w = 30$ K, $T_c = 15$ K, $N_c/N_w = 10$ (thick dash-dotted).

This is most probably only a selection effect, as only relatively flat spectrum sources would be detected at 5 GHz. In general, it is preferable to survey at 1.4 GHz as this gives the best sensitivity to high redshift objects.

The mean dust temperature in the local galaxies could be over-estimated. If a colder component is present then it will produce a flattening of the thermal dust spectrum at longer wavelengths when compared to warm dust, thus lowering the redshift at which the estimator loses its sensitivity to redshift. We can model the implications of points (i) and (iii) as they are inter-related. If there is a cold dust component in the local galaxies, the true value of $\beta$ is likely to be nearer 2 and the mean dust temperature lower. If we make assumptions about the temperatures of the two components and the relative masses in each (and that $\beta = 2$), we can then produce a new indicator. Figure 6 shows these ‘grey’ indicators for a few values of the various parameters which reflect current observational evidence (Frayer et al. 1999; Alton et al. 1998; Calzetti et al. 2000). The parameters used are given in Table 4, and all ‘grey’ models were normalised at zero redshift to have the mean value for the sample (0.18). There is generally no great difference until $z \sim 2$, and at this point the different parameters assumed start to make a larger impact. In general, we might expect that the galaxies detected by both SCUBA and the VLA would have $T_w > 30$ K, since it is the recent star formation which the VLA is sensitive to (and which also produces higher dust temperatures). This makes the upper ($T_w = 40$ K) curves more plausible although their shape is still sensitive to the mass fraction and temperature of the cold dust (colder dust or more cold dust will cause the indicator to turn over earlier and flatten more), and is also dependent on the value of $\beta$. If in reality, $\beta$ lies somewhere between 1.3 – 2, then this will make the ‘grey’ models more like the median one at low redshifts. Figure 6 suggests that the uncertainties in whether there is actually a single dust temperature, or in the true value of $\beta$, do not add much to the uncertainty we have derived from the single-temperature fits. Currently, it is not possible to be more specific about the nature of any cold dust components as there are only a handful of local galaxies with enough FIR and submm fluxes to make a decomposition of the SED feasible. Our knowledge of dust properties in local galaxies should improve in the near future (Dunne et al. 2000).

Contributions to the radio flux by AGN will produce...
misleading redshift estimates if the object is not recognised as such. Since the fraction of deep SCUBA sources harbouring radio-loud AGN is still not well determined, the estimator must be treated as a statistical tool rather than a redshift indicator for individual objects. The redshifts given by the upper 1σ curve should be treated as a robust lower limit.

(4) A variation in the FIR-radio correlation with redshift is quite possible if either magnetic fields or dust properties were different in the past, although currently this is difficult to test. Condon (1992) does however point out that the FIR-radio relation in the local universe holds over a large range of magnetic field strengths. The tendency of the galaxies observed so far in both the radio and submillimetre at high redshifts, to lie in agreement with the estimator (Fig. 2) suggests that there has been no dramatic evolution in the underlying FIR-radio relation, although more data is needed to fully investigate this.

5 CONCLUSIONS
We have used the submm data from a large, complete sample of local IRAS galaxies, along with complementary radio data, to define a median redshift estimator using the change in spectral slope between the submm and the radio at ∼5mm. The scatter in the data has been used to provide 1σ uncertainties on the relationship. The limited number of submm sources from the deep surveys with both radio fluxes and spectroscopic redshifts generally agree with the estimator (within the uncertainties), except for one object which is known to be an AGN (Fig 2). The estimator is useful in a statistical sense rather than for predicting the redshifts of individual objects as there are many uncertainties, especially the possible contribution to the radio flux by AGN which would lower the data relative to the models thus leading to an under-estimated redshift. Our redshift indicator differs from the recent one of Carilli & Yun (2000) in terms of shape and normalisation. The difference is significant, particularly at redshifts > 2 (Fig 1). The discrepancy can be attributed primarily to the larger sample size used in this work and also, in part, to the under-estimation of submm fluxes used in CY 2000. An erratum to CY 2000 has since been published which produces a revised redshift estimator using the corrected Lisenfeld et al. (2000) submm fluxes. This removes ∼30 per cent of the discrepancy between the estimators, and we postulate that the remaining difference is a result of sample selection (the Lisenfeld sample is not a complete sample and contains a higher proportion of radio bright objects compared to SLUGS), and the smaller sample size (17 objects compared to 104 in SLUGS).

The submm-radio spectral index decreases as radio and FIR luminosity increase, but shows no strong trend with 850µm luminosity (Fig. 4). The correlations are believed to be due to the sensitivity of the nonthermal radio and thermal FIR emission to recent star formation, while a significant fraction of the 850µm flux may be due to colder dust, and not linked to the star formation rate. The absence of a correlation between α1.4 and 850µm luminosity means that any differences in F850 between SLUGS and the SCUBA-selected galaxies will not lead to biased redshift estimates. Importantly, we also find no significant evidence for a systematic variation of α1.4 with dust temperature (Fig. 5(a)) implying that the redshift-temperature degeneracy hypothesised by Blain (1999) does not play a dominant part in the scatter of the α1.4 − redshift relation.

We have investigated the impact of neglecting a possible colder dust component in the SEDs of the local galaxies (Fig 6). While sensitive to the parameters assumed, in general the differences are not very significant for most plausible models and the agreement is still within the 1σ uncertainties at lower redshifts (< 2). If cold components are present but unaccounted for, using the median line in Fig 1 to estimate redshifts will most likely lead to an over-estimate of z.

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