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NEPSC2, the North Ecliptic Pole SCUBA-2 survey: 850-µm map and catalogue of 850-µm selected sources over 2 deg

Hyunjin Shim,1,⋆ Yeonsik Kim,2 Dongseob Lee,1 Hyung Mok Lee,3,4 Tomo Goto,5 Hideo Matsuhara,6 Douglas Scott,7 Stephen Serjeant,8 Yiping Ao,9,10 Laia Barrufet,11,12 Scott Chapman,13 David L. Clements,14 Christopher J. Conselice,15 Thomas R. Greve,16,17,18 Tetsuya Hashimoto,5,19 Ho Seong Hwang,3 Myungshin Im,4 Woong-Seob Jeong,3 Linhua Jiang,20 Minjin Kim,2 Seong Jin Kim,5 Woong-Seob Jeong,3 Hyunjong Seo,3 Yoshiki Toba,27,28,29 and Glenn White8

1 Department of Earth Science Education, Kyungpook National University, Daegu 41566, Republic of Korea
2 Department of Astronomy and Atmospheric Sciences, Kyungpook National University, Daegu 41566, Republic of Korea
3 Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea
4 Department of Physics and Astronomy, Seoul National University, Seoul 08826, Republic of Korea
5 Institute of Astronomy, National Tsing Hua University, 101, Section 2. Kuang-Fu Road, Hsinchu 30010, Taiwan (R.O.C.)
6 Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan
7 Department of Physics and Astronomy, University of British Columbia, Canada
8 The Open University, Milton Keynes, MK7 6AA, UK
9 Purple Mountain Observatory and Key Laboratory for Radio Astronomy, Chinese Academy of Sciences, Nanjing, China
10 School of Astronomy and Space Science, University of Science and Technology of China, Hefei, Anhui, China
11 European Space Astronomy Center, 28691 Villanueva de la Canada, Spain
12 RAL Space, STFC Rutherford Appleton Laboratory, Didcot, Oxfordshire OX11 0QX, UK
13 Department of Physics and Astronomy, Dalhousie University, Halifax, NS B3H 4J2, Canada
14 Imperial College London, Blackett Lab., Prince Consort Road, London, SW7 2AZ, UK
15 University of Nottingham, School of Physics & Astronomy, Nottingham NG7 2RD, UK
16 Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK
17 Cosmic Dawn Center
18 National Space Institute, DTU Space, Technical University of Denmark, Eletrovej 327, DK-2800 Kgs. Lyngby, Denmark
19 Centre for Informatics and Computation in Astronomy (CICA), National Tsing Hua University, 101, Section 2. Kuang-Fu Road, Hsinchu, 30013, Taiwan (R.O.C.)
20 Kavli Institute for Astronomy and Astrophysics, Peking University, No.5 Yiheyuan Road, Haidian District, Beijing 100871, P. R. China
21 Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun, Poland
22 Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, Cape Town, South Africa
23 INAF - Istituto di Radioastronomia, via Gobetti 101, 40129 Bologna, Italy
24 Astronomical Observatory Institute, Faculty of Physics, Adam Mickiewicz University, ul. Słoneczna 36, 60-286 Poznań, Poland
25 East Asian Observatory, 660 N. Aohoku Place, University Park, Hilo, Hawaii 96720, U.S.A.
26 Oxford Astrophysics, University of Oxford, Keble Rd, Oxford OX1 3RH, UK
27 Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyoku-ku, Kyoto 606-8502, Japan
28 Academia Sinica Institute of Astronomy and Astrophysics, 11F of Astronomy-Mathematics Building, AS/NTU, No.1, Section 4, Roosevelt Road, Taipei 10617, Taiwan
29 Research Center for Space and Cosmic Evolution, Ehime University, 2-5 Bunkyo-cho, Matsuyama, Ehime 790-8577, Japan

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ABSTRACT

We present an 850-µm mosaic map and extracted catalogue of submillimetre sources in the extended North Ecliptic Pole (NEP) region over about 2 deg$^2$. The 850-µm map is constructed using newly obtained observations by SCUBA-2 at the East Asian Observatory’s James Clerk Maxwell Telescope, carried out using the observatory’s large programme opportunities. The recent 850-µm survey has extended the submillimetre data coverage by almost a factor of 4 compared to previous surveys, with a depth of $σ_{\text{rms}} = 1.0 - 2.3$ mJy beam$^{-1}$. The catalogue contains 549 sources selected above a significance level of 4σ, where the false-detection rate is 10 per cent; a higher threshold of 4.5σ is required in order to achieve a false-detection rate below 3 per cent, which results in 342 sources being selected. Despite the large spatial variation of the noise, the deboosted flux density of sources is comparable to results from the SCUBA-2 Cosmology Legacy Survey (S2CLS), which covered the central 0.6 deg$^2$ of our survey area with better sensitivity. We construct the source counts at 850 µm, finding results in agreement with other 850-µm surveys in cosmological blank fields over $S_{850} = 4 - 15$ mJy. We find a slight excess of bright galaxies ($S_{850} > 15$ mJy), which can be considered to be at $z_{\text{phot}} = 2 - 4$. The 850-µm data adds valuable long-wavelength information to mid-infrared-selected sources from the AKARI NEP-deep and NEP-wide surveys, which will be helpful in preparing for future near-infrared to millimetre wavelength observations in the NEP region. Our 850-µm mosaic map and source catalogue will be made publically available.

Key words: galaxies: evolution – submillimetre: galaxies – galaxies: photometry – galaxies: starburst

1 INTRODUCTION

Dust plays a significant role during the star-formation process by enhancing the formation of molecular hydrogen and the shaping of the spectral energy distributions (SEDs) of galaxies through absorbing UV photons from stars and re-radiating the energy in the rest-frame far-infrared. To obtain a complete picture of cosmic star-formation history and to understand the physical drivers of galaxy evolution, it is necessary to investigate the properties of dust in galaxies at different cosmic epochs. The selection of dusty galaxies generally utilises observations that sample rest-frame wavelengths above 100 µm, beyond the peak of the far-IR SED. Although the number density of star-forming galaxies selected in the rest-frame far-IR (i.e. ‘dust-obscured’ galaxies) is smaller than that of optically-selected populations, such as Lyman break galaxies, the high-star-formation rates (SFRs) of IR-selected star-forming galaxies make these the most extreme star formers in the Universe (e.g., Whitaker et al. 2017; Hill et al. 2018). The contribution to the global cosmic SFR density by such obscured galaxies increases as we move to $z > 1$ (e.g., Le Floc’h et al. 2005; Magnelli et al. 2013) and the trend seems to remain out to $z \approx 3$. The selection of obscured star-forming galaxies and their characterisation also provides an opportunity to investigate the most active regions of cosmic star formation at $z > 2$ (e.g., Casey, Narayanan and Cooray 2014).

It has been more than two decades since the so-called ‘submillimetre’ galaxy population (SMGs) was discovered, and it has subsequently been widely studied (e.g., Smail et al. 1998; Blain et al. 2002; Chapman et al. 2003). Follow-up studies showed that submillimetre (hereafter ‘submm’) galaxies are heavily obscured (Geach et al. 2008; Hainline 2008; Michałowski et al. 2010), gas-rich (Greve et al. 2005; Tacconi et al. 2006; Riechers et al. 2010; Toft et al. 2014), and massive (Hainline 2008; Michałowski et al. 2010, 2014; Smolčić et al. 2015; Dudzevičiūtė et al. 2020) galaxies located at a median redshift of $(z) = 2.3$ (Chapman et al. 2005; Pope et al. 2005; Smolčić et al. 2012; Simpson et al. 2014; Koprivi et al. 2016; Brisbin et al. 2017), covering the entire redshift range of $z = 1.5 - 4$ (Dudzevičiūtė et al. 2020; Simpson et al. 2020). The large total IR luminosities of SMGs (of order $10^{13} L_\odot$) reflect SFRs as large as 100–1000 $M_\odot$ yr$^{-1}$ (Magnelli et al. 2013; Burgar et al. 2014; Toba et al. 2020), with massive SMGs constituting the upper end of the star-forming main sequence, while some less massive SMGs are located above the main sequence (Liu et al. 2019). Note, however, that the submillimetre fluxes of SMGs detected in single-dish observations could sometimes be overestimated by the blending of several sources within the large beam (e.g., Hwang et al. 2010; Hodge et al. 2013). SMGs could also be associated with active galactic nuclei (AGN; Wang et al. 2013; Banerji et al. 2015; Toba et al. 2018; Ueda et al. 2018), complicating the relationship between SFR and submm flux. Nevertheless, the properties of SMGs suggest a scenario where they are strong candidates for being the progenitors of low-redshift massive elliptical galaxies (Simpson et al. 2017; Cooray 2019); this idea is also supported by simulations (Gonzalez et al. 2011; Toft et al. 2014). Overdensities of galaxies are often found around these SMGs (Menendez-Delmestre et al. 2013; Dannerbauer et al. 2014), and thus they provide an effective tool for tracing structures in the Universe. On the other hand, there is some doubt about whether the SMGs are good tracers of galaxy overdensities at $z \lesssim 3$, contrary to the case at $z \gtrsim 3$ (Miller et al. 2015; Smolčić et al. 2017). Because of this, selection and characterisation of the SMG population opens a window for studying key aspects of galaxy evolution, in terms of enhancing and quenching star formation, the growth of black holes along with stellar mass, and the formation of large-scale structures in the Universe.
the investigation of the properties of SMGs requires well-defined multi-wavelength ancillary data sets, several wide-area submm/mm observations have been executed and these continue to be proposed and extended for several cosmological ‘blank’ fields.

Among the popular blank fields, the North Ecliptic Pole (hereafter NEP) region is a hub for existing and upcoming survey programmes using past, present, and future space telescopes, thanks to the high visibility of this region of the sky from their orbits. Multi-wavelength data over more than 4 deg² around the NEP have been accumulated, mostly based on the legacy survey of the infrared telescope AKARI (Matsuhara et al. 2006). The available data sets include observations covering UV, optical, mid- and far-IR, and radio wavelengths (e.g., Hwang et al. 2007; White et al. 2010; Kim et al. 2012; Pearson et al. 2012; Takagi et al. 2012; Oi et al. 2014; Nayyeri et al. 2018; Oi et al. 2020, submitted; Kim et al. 2020, in prep.), while there are still a number of upcoming space-based surveys that have marked this region as one of the most advantageous fields for addressing multi-wavelength galaxy evolution. The X-ray telescope eROSITA plans to carry out an all-sky survey with the goal of finding rare populations of heavily dust-obscured AGN, while having its longest total exposure in the NEP region. Euclid, a space-based mission to map the dark-matter distribution of the Universe, based on weak-lensing and precise redshift measurements (Laureijs et al. 2011), will target the NEP as one of the three ‘Euclid-deep’ fields to study numerous topics related to galaxy evolution. SPHEREx, an all-sky spectral survey mission in the near-IR, will provide a high cadence, deep survey in the NEP region. Both Euclid and SPHEREx will provide low-resolution spectra in the near-IR for most AKARI mid-IR-selected extragalactic objects. Such near-IR spectral information will be of particular use when combined with far-IR-to-submm surveys over a wide area in order to sample the dusty star-forming galaxy population out to high redshift.

With these scientific motivations in mind, we have pursued an 850-μm imaging survey in the NEP region with the Submillimetre Common User Bolometer Array-2 (SCUBA-2; Holland et al. 2013) on the James Clerk Maxwell Telescope, as part of the East Asian Observatory’s (EAO’s) large programmes. During three years of observation from 2017 to 2019, 200 hours of additional observations covered approximately 2 deg² at a shallower depth than that of the previously obtained 850-μm data over a much smaller area (0.6 deg²; Geach et al. 2017). By combining the newly obtained data with the archival data, we have now doubled the number of submm sources above S500 = 6 mJy around the NEP. These submm sources can be studied through an SED-based analysis utilising the available rich multi-wavelength photometry. The SCUBA-2 850-μm survey of the NEP will continue after 2020, providing an opportunity to better constrain far-IR dust properties and AGN contributions for mid-IR-selected star-forming galaxies at different redshifts.

In this paper, we present the observations, data reduction and 850-μm source catalogue from our JCMT SCUBA-2 large programme to map a region around the NEP, based on the data obtained up until 2019. We also combined the archival data with newly obtained data to produce an improved 850-μm map. The paper is organized as follows. In Section 2, we describe our survey programme, including how the observations were made and how the data were reduced. We describe the construction of the 850-μm source catalogue in Section 3, along with estimations of flux deboosting, completeness, positional uncertainty and false detection rate, based on statistical simulations. In Section 4 we present 850-μm number counts, a brief introduction to the multi-wavelength identification of 850-μm sources, and the SEDs of the brightest sources, those having 850-μm flux density larger than 15 mJy. Finally we summarise our paper and provide conclusions in Section 5. Throughout the paper, we have explicitly assumed a WMAP 7-year cosmology (Komatsu et al. 2011). If a Planck 2018 cosmology (Planck Collaboration 2020) were to be used instead, the luminosities would be higher by 9 per cent at z = 3.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observations

The NEPSC2 data presented in this publication were observed as part of JCMT program ID M17BL007. The data were obtained with the SCUBA-2 instrument (Holland et al. 2013) at 850 μm over the period from July 2017 to November 2019. In order to obtain 850-μm images over a wide (4 deg²) area centred on the NEP (RA= 18h00m00s, Dec= +66°33′38.5″), we used multiple 30-arcmin maps in a tiling pattern to provide even coverage, with each individual field referred to as a ‘subfield’. Each 30-arcmin map, known as a PONG1800 map (Holland et al. 2013; Thomas & Currie 2014), provides uniform sensitivity in the inner circular region of 30 arcmin (1800 arcsec) diameter. Each PONG1800 observation took 40 minutes of on-sky integration time and each subfield was observed 28 times so that the total integration time for a single subfield was 18.7 hours.

Observations were executed in Grade 3 weather conditions, with a sky opacity at 225 GHz (τ225) ranging between 0.08 and 0.12. The data quality was better when the observations were made with lower τ225 GHz combined with higher elevation. Changes in subfield observing transmission (dependent on opacity and airmass) resulted in a variation in the ‘depth’ of the data for different subfields.

As of December 2019, observations of nine subfields (NEP1 to NEP9) have been completed, with approximately 170 hours of total integration time (Table 1). The actual time spent by the programme is longer, since there are some

Table 1. Central coordinates of subfields in the NEPSC2 survey (JCMT program ID: M17BL007). The fourth column lists the 850-μm sensitivity measured in the centre of each subfield using the individual mosaic, i.e., without accounting for the overlap between subfields and with the S2CLS data.

<table>
<thead>
<tr>
<th>Subfield</th>
<th>RA</th>
<th>Dec</th>
<th>σ (depth in the centre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEP1</td>
<td>17 59 14.9</td>
<td>+66 53 58.9</td>
<td>2.2</td>
</tr>
<tr>
<td>NEP2</td>
<td>18 00 39.5</td>
<td>+66 29 36.6</td>
<td>2.3</td>
</tr>
<tr>
<td>NEP3</td>
<td>17 57 44.8</td>
<td>+66 08 56.4</td>
<td>1.9</td>
</tr>
<tr>
<td>NEP4</td>
<td>17 53 29.3</td>
<td>+66 13 25.0</td>
<td>2.0</td>
</tr>
<tr>
<td>NEP5</td>
<td>17 52 08.5</td>
<td>+66 38 34.1</td>
<td>2.1</td>
</tr>
<tr>
<td>NEP6</td>
<td>17 54 59.4</td>
<td>+65 58 27.9</td>
<td>2.1</td>
</tr>
<tr>
<td>NEP7</td>
<td>17 57 54.1</td>
<td>+67 14 42.8</td>
<td>2.2</td>
</tr>
<tr>
<td>NEP8</td>
<td>18 02 09.6</td>
<td>+67 14 13.9</td>
<td>2.2</td>
</tr>
<tr>
<td>NEP9</td>
<td>18 03 30.4</td>
<td>+69 43 30.4</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Downloaded from https://academic.oup.com/mnras/advance-article/doi/10.1093/mnras/staa2621/5898141 by Open University Library user on 07 September 2020
subfields that were observed only a few times and are not included in this work. Table 1 lists the central coordinates of the nine subfields. The effective survey area is 1.7 deg², without accounting for the previously existing S2CLS data (JCMT program ID MJLSC02), where the sensitivity level is quite different. The combined noise map (of the subfields for NEP + S2CLS) is shown in Fig. 1. In the centre of each subfield, the sensitivity ranges between 1.9 and 2.5 mJy beam⁻¹ rms (Table 1), mainly depending on the weather conditions and field elevation at the time of the observations. It can be seen that the sensitivity is better in the overlapping region between tiles. The deepest region, in the combined map of NEP and S2CLS, has a sensitivity of 1 mJy beam⁻¹. Figure 2 shows the cumulative areal coverage of the 850-μm data over the NEP that is deeper than a given sensitivity. Previously available 850-μm data in the NEP obtained as part of the S2CLS project (Geach et al. 2017) provides a uniform sensitivity of 1.2 mJy rms in the central 0.6 deg². With the new data obtained through NEPSC2, the coverage has been extended to 2 deg² (although the actual effective survey area is dependent on the sensitivity threshold) and the noise level has reached down to 1 mJy rms in the deepest region. Currently the areal coverage of the NEPSC2 survey is still smaller than that of the S2COSMOS project (Simpson et al. 2019), which provides uniform sensitivity over 2 deg². The observations are expected to be completed by 2022 through the recently approved large programme extension; we will then have approximately 4 deg² coverage with a sensitivity comparable to that of the currently existing data.

### 2.2 Data reduction

We used the ORAC-DR data reduction pipeline (Cavanagh et al. 2008), which is an automated process that follows pre-defined recipes to produce calibrated flux-density maps from the obtained data frames. The SCUBA-2 850-μm array is made up of four sub-arrays, and records a time-varying signal that is a sum of contributions from astronomical sources, background (mostly from sky emission) and noise (Holland et al. 2013). The data reduction is based on extracting the signal from astronomical sources, and producing a two-dimensional (spatial) flux-density map projected onto the celestial sphere. The SCUBA-2 data reduction pipeline is equipped with the Dynamical Iterative Map-Maker (DIMM) within the Sub-Millimetre Common User Reduction Facility (SMURF), which performs the removal of contaminating signal components and carries out the map production (see Chapin et al. 2013 for details).
The parameters we used are consistent with those proposed for ‘blank-field’ data reduction (Geach et al. 2017), which aims to detect low signal-to-noise ratio (S/N) point sources from deep-field observations. The configuration file is included in the data reduction pipeline distribution as \texttt{dimmconfig\_blank\_field.lis}.

The data reduction process uses the following set of procedures. The raw time-series data are read and resampled at a 2-arcsecond pixel scale within the pipeline, followed by a number of cleaning steps. Flat fields are applied using the associated flat scans, and a polynomial baseline fit is subtracted from each sub-array. Then the pipeline begins an iterative process that attempts to fit the data with a model comprising several components: a common-mode background signal from the atmosphere; the astronomical signal; and noise (accounting for both instrumental noise and fine-scale atmospheric noise). The iteration is performed until the maximum number of iterations is reached or if the result converges. As is suggested in the distributed configuration file (\texttt{dimmconfig\_blank\_field.lis}), we repeat the iteration four times.

For flux calibration, we apply flux-conversion factors (FCFs) to the data frames in order to convert the data from pW to units of Jy beam$^{-1}$. We explicitly used the recently released (30 January 2020) values of FCF$^{1}$ tabulated in bins of (redshift, Xairmass) for the time the observation was made. The mean value of the FCFs applied to each scan was comparable to the historical reference value (Dempsey et al. 2013), which was used in reducing S2CLS data.

After all scans were reduced and flux calibrated, the final mosaiced map was produced with the \texttt{PICARD} recipe \texttt{mosaic\_jcnt\_images}. We combined all scans in different subfields simultaneously, weighting each input image by the inverse variance per pixel. To optimize (faint) point-source detection, we applied a matched filter (\texttt{PICARD} recipe \texttt{scuba2\_matched\_filter}) to the map by convolving a Gaussian kernel that matches the instrumental point-spread function, i.e., with a 15 arcsec FWHM Gaussian. Previous work (e.g., Geach et al. 2017) on the matched-filter application to the SCUBA-2 maps suggested that a slight loss (of order of 10$^{-4}$) on the matched-filter application to the historical reference value (Dempsey et al. 2013) on the simulated flux map to quantify how many injected sources were the same. This avoids too much fragmentation that would artificially arise within the dark ring area produced by matched filtering. Even with this strategy, no sources in the final catalogue turned out to be spatially extended, and all are consistent with being point sources. Our final catalogue includes sources with S/N > 4 (i.e., 4.5$\sigma$ detection threshold). However, as we will discuss in Section 3.4, considering the false-detection rate, it would be safer to place a higher detection limit (such as 4.5$\sigma$, to give a false-detection rate lower than a few per cent) for a robust catalogue of submm sources.

3 SOURCE EXTRACTION

Essentially all submm galaxies can be considered to be unresolved sources given the SCUBA-2 resolution, except some galaxies at very low redshifts. Therefore the peak value in a beam-convolved map can be taken to be the flux density of the extracted source. We extract the sources with a simple top-down peak-finding method that has been widely adopted in other submm surveys of cosmological fields (e.g., Pope et al. 2005; Coppin et al. 2006; Geach et al. 2017; Simpson et al. 2019). We first find the most significant peak in the S/N map, then store the peak flux, noise, and position in the catalogue. Once the information has been recorded, the source is removed from both the S/N map and the flux map by subtracting a scaled version of the model point-spread function. The point-spread function (PSF) we use is constructed by coadding all > 5$\sigma$ point sources in the map. Like in previous works (Geach et al. 2017; Simpson et al. 2019), the empirical PSF shows a negative ring as a result of the matched filtering, and has a FWHM of 14.9 arcsec. The peak-finding procedure effectively ‘deblends’ in a way that is essentially the same as PSF-fitting. The source-finding steps are repeated to reach down to the specific detection-limit floor, in our case 3$\sigma$, which means the detection iteration process for exploring the lowest significance detections stops when we have reached 3 times the background rms level.

When another source is found within 7.5 arcsec of any source found in the previous run, we consider that these two sources are the same. This avoids too much fragmentation that would artificially arise within the dark ring area produced by matched filtering. Even with this strategy, no sources in the final catalogue turned out to be spatially extended, and all are consistent with being point sources. Our final catalogue includes sources with S/N > 4 (i.e., 4.5$\sigma$ detection threshold). However, as we will discuss in Section 3.4, considering the false-detection rate, it would be safer to place a higher detection limit (such as 4.5$\sigma$, to give a false-detection rate lower than a few per cent) for a robust catalogue of submm sources.

3.1 Completeness and flux boosting

Statistically speaking, flux densities of submm sources selected using a threshold tend to be ‘boosted’. The simplest form of boosting is called Eddington-type bias (Eddington 1913), which is the effect on number counts due to the statistical variation around the true flux densities of sources. Since fainter sources are more numerous than brighter ones, then at a given measured flux level it is more probable to find faint sources scattering up than bright sources scattering down. Another effect on flux boosting comes from source confusion. Objects below the detection threshold contribute to the measured flux density, increasing the observed flux density compared to the intrinsic value. Flux-boosting factors, representing a calibration of the two effects, can in general be described as a function of both signal and noise (Coppin et al. 2005; Casey et al. 2013; Geach et al. 2017), with the highest S/N sources being relatively unaffected by flux boosting. For NEPS2 850$\mu$m data, we evaluated the magnitude of the flux boosting as a function of the local noise level and the observed flux density, based on the empirical approach described in Geach et al. (2017).

We constructed a jackknife noise map for use in this analysis. The individual scans were randomly divided into two subgroups, to produce separate mosaic images for each of these two subgroups. Then we subtracted one mosaic from the other and scaled the result in terms of the square root of total integration time. In this ‘source-free’ noise map, artificial sources with known flux densities and positions were injected. The source extraction procedure was performed on the simulated flux map to quantify how many injected

\footnote{\url{https://www.eaoobservatory.org/jcmt/instrumentation/continuum/cuba-2/calibration/}}
Figure 3. Visualisation of results from simulations of the recovery of sources in the two-dimensional space of flux density and uncertainty. The left panel shows the number of artificial sources injected into the jackknife mosaic map per bin of input flux density and instrumental noise. The middle panel shows the completeness, i.e., the number of recovered sources divided by the number of injected sources, as a function of input (intrinsic) flux density and the instrumental noise. The right panel shows the average boosting factor for the output (observed) flux density and the instrumental noise. The dashed line indicates the 4σ limit applied in the source-extraction procedure.

Figure 4. Deboosted (intrinsic) flux-density distribution based on the empirical recovery method (filled distribution), compared to the observed flux-density probability distribution assuming Gaussian uncertainties (open distribution). The observed flux densities increase from left to right panels. The top row shows distributions measured when σ_{inst} = 2.2 mJy, the middle row shows results for σ_{inst} = 1.6 mJy and the bottom row shows results for σ_{inst} = 1.0 mJy. The ratio between the peaks of two (observed and intrinsic) distributions is considered to be the boosting factor.

Sources were recovered (an estimation of survey completeness) and how their flux densities compared with the intrinsic values (an estimation of flux boosting). We found that the flux distribution of sources inserted into the noise map follows the observed number counts fit from Geach et al. (2017), which has the form of a Schechter function:

$$\frac{dN}{dS} = \left( \frac{N_0}{S_0} \right) \left( \frac{S}{S_0} \right)^{-\gamma} \exp\left( -\frac{S}{S_0} \right).$$

where $N$ is the number of sources and $S$ is the flux density, with $N_0 = 7180 \text{deg}^{-2}$, $S_0 = 2.5 \text{mJy}$, and $\gamma = 1.5$. The range of flux densities of inserted sources was 1–50 mJy. Each source was placed in a random position, assuming a spatially uniform distribution (i.e., we did not consider any clustering effects). An inserted source is considered to be recovered if a point source is found above the detection threshold within $1.5 \times$FWHM of the input position. If there are multiple matches, we took the nearest one. Source extraction was
Figure 5. (Left) Average flux-boosting factor as a function of signal-to-noise ratio. The boosting is well described by a power law (dotted line, equation 2); however, in practice, we estimated boosting in the two-dimensional parameter space composed of observed flux density and instrumental noise. The average boosting factor described as a power law by Geach et al. (2017) is overplotted as a solid line. (Right) Average positional uncertainty, defined as the difference between the input and recovered positions, as a function of the signal-to-noise ratio. As in previous studies (solid line from Geach et al. 2017; dashed line from Ivison et al. 2007), and as in the case for flux boosting, the positional uncertainty is well described by a power law (dotted line, equation 3). Such positional uncertainties need to be considered in the identification process for the 850-µm sources in data at other wavelengths.

Figure 6. Comparison between the flux densities of sources measured in different images. The left panel shows a comparison between the deboosted flux densities of sources measured in the maps of individual target subfields and in the entire mosaic map, which has better sensitivity where the pointing tiles overlap. The y-axis shows the difference between the two measurements (plotted as filled circles). Open circles are sources between 4 and 4.5σ, suggesting that the apparent boundary from upper left to lower right is due to the detection limit imposed by the 4σ detection at σ_rms = 1.4 mJy. The dashed and the solid lines show linear fits that describe the flux difference as a function of flux, with varying slopes and using a fixed slope of −1, respectively. Despite the background noise fluctuations, the flux densities measured in the two maps show overall agreement within the flux density uncertainties. The right panel shows a comparison between the deboosted flux densities, measured in the previous S2CLS map (Geach et al. 2017; limited to the central 0.6 deg² region of the NEP) and in our new 850-µm mosaic map. This panel contains 222 sources that are cross-matched between the two catalogues. As in the left panel, open circles are sources between 4 and 4.5σ in the [NEPSC2+S2CLS] map. The dashed and the solid lines show the linear fits with varying and fixed slopes (of −1), respectively.

performed in exactly the same way as for constructing the source catalogue from the observed flux map, which means the extraction is a blind detection, not using the expected source position as a prior. By combining many noise maps with many artificial source catalogues, we generated 2500 sets of mock catalogues that contain matched information for 2 × 10^5 sources. Based on these results, we assessed the completeness and flux-boosting statistics.
By comparing the ‘recovered’ flux densities to the input flux densities, the amount of flux boosting can be evaluated as a function of noise and observed flux density. A source with observed flux density \( S_{\text{obs}} \) is actually drawn from the probability distribution of its true flux density, \( p(S_{\text{true}}) \). A histogram of injected source flux densities in bins of \( S_{\text{obs}} \) is considered to be an estimate of \( p(S_{\text{true}}) \). Examples of evaluating \( p(S_{\text{true}}) \) are shown in Fig. 4. The observed flux-density distribution is assumed to be a Gaussian, with a FWHM identical to that of the local instrumental noise. The mean and the variance of the intrinsic flux distribution \( p(S_{\text{true}}) \) provides the boosting factor and the uncertainty in the deboosted flux density. The boosting factor is smaller when the observed flux density is high and the noise level is low. The uncertainty on the deboosted flux density \( \sigma_{\text{deboost}} \) is quadratically added to other uncertainties (instrumental noise and confusion noise) to produce the total flux error in the source catalogue (see Table 2). In our constructed two-dimensional grid of boosting factors (Fig. 3 right panel), we derive a boosting factor for each source based on a two-dimensional spline interpolation, using the binned values as a look-up table. The average flux boosting factor \( B \) can be described as a power-law function of \( S/N \) (Fig. 5a):

\[
B = 1 + 0.3 \times \left( \frac{S/N}{5.3} \right)^{2.9}.
\]  

(2)

We also plot the equivalent relation from S2CLS survey (equation 5 of Geach et al. 2017) in Fig. 5b for comparison. While both lines have similar forms, the boosting factor is proportional to a power of \( S/N \), our recovery simulations suggest that larger boosting is expected in the NEPSC2 mosaic than in the average S2CLS map. This difference is due to the fact that the typical noise level of NEPSC2 are larger than those of S2CLS. Geach et al. (2017) showed that at a fixed \( S/N \), the average boosting factors are similar across different fields. However, in the lower \( S/N \) regime, approximately 10 per cent difference was seen between the deeper S2CLS fields (e.g., UKIDSS-UDS; \( \sigma = 0.9 \, \text{mJy beam}^{-1} \)) and the shallower S2CLS fields (e.g., COSMOS; \( \sigma = 1.8 \, \text{mJy beam}^{-1} \)). Therefore relatively large deboosting corrections are required for sources extracted from the shallow (up to \( \sigma = 2.2 \sim 2.5 \, \text{mJy beam}^{-1} \)) part of the NEPSC2 map; this can be seen from the large deviation between our results and those from Geach et al. (2017) at \( S/N \) below 4 (Fig. 5a). In Section 3.3 we will show a source-by-source flux comparison between our work and the previous S2CLS-NEP study.

### 3.2 Positional uncertainty

Simulations also allow us to estimate the differences between inserted positions and recovered positions. We measure the average offset \( \delta \theta \) between input and recovered position in bins of flux density and local instrumental noise. The quantity \( \delta \theta \) is defined as 

\[
\delta \theta = |\theta_{\text{input}} - \theta_{\text{recovered}}| \times \frac{S/N}{9}^{0.9}.
\]  

(3)

Overall, our positional uncertainty at a fixed \( S/N \) is a little larger than that from the S2CLS survey, but is comparable to the expression suggested by the earlier study of Ivison et al. (2017), when power law of the source count distribution is assumed to be \( \beta = 2.8 \) and the FWHM is 15 arcsec. Simpson et al. (2019) for S2COSMOS, also reported that positional uncertainties of 850-\( \mu \)m selected sources are similar to our results, based on source-recovery simulations. In S2COSMOS, the median positional uncertainty for 4\( \sigma \) source extraction is around 3 arcsec, while most sources are recovered with offsets less than 8.7 arcsec. Based on preliminary counterpart identification using 1.5-GHz Karl G. Jansky Very Large Array (VLA) data, we found that around 80 per cent of the 850-\( \mu \)m sources in the NEPSC2 catalogue that are identified in the 1.5-GHz image have offset smaller than 3 arcsec. Note that the typical positional offset between objects at different wavelengths may not be applicable when 850-\( \mu \)m sources are blends of multiple sources.

### 3.3 Verification of the flux deboosting

We extracted sources from the mosaic map covering the entire NEP (see Fig. 1), which is produced by combining all the existing observations including S2CLS data and the nine newly observed subfields. It is also possible to produce flux maps for each subfield separately, to obtain a circular field with uniform depth. Source extraction can be performed on each of these. In the case of sources lying in the overlap region, the observed flux densities in the former map (i.e., the mosaic map covering the entire field) and in the latter map (i.e., a map of an individual subfield) might be different due to differences in the local noise levels. Since we used a two-dimensional parameterisation to evaluate flux boosting, the deboosted flux densities should be consistent for the same

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**References:**

- Geach et al. (2017)
- Ivison et al. (2007)
source. Figure 6a shows such a comparison between the deboosted flux densities of the same sources in two distinct maps. There is an apparent boundary due to the 4σ source selection threshold, yet no trend is seen for flux differences in terms of the observed flux. Except for a small number of outliers, the deboosted flux densities of the same source are consistent, within the total flux errors. The few outliers tend to be located near the edge of the individual subfield map, thus making source extraction more challenging because of the increased noise level.

We cross-matched our catalogue with the S2CLS catalogue (Geach et al. 2017) by using a search radius of 7.5 arcseconds, and found 222 matches. The S2CLS catalogue contains 330 sources in the NEP region with a S/N threshold of 3.5σ, which is lower than our level of 4σ. In order to understand whether the failure of finding matches for 108 sources in the S2CLS catalogue is due to our S/N cut, we constructed a source catalogue from our updated mosaic map using a 3σ detection level and performed cross-matching with the S2CLS catalogue. Among the 108 sources, four are found very close (within 60 arcsec, i.e., 4 times the FWHM) to the dark ring around the bright Galactic source NGC6543 caused by the matched filtering, so it is likely that they are artefacts from the data reduction (even though these are also detected in our map). 82 sources are detected in the new mosaic map with S/N values between 3 and 4, among which 62 sources were originally detected with 3.5 < S/N < 4 in the S2CLS catalogue, while 20 sources were reported to have S/N larger than 4. The remaining 22 sources in the S2CLS catalogue are ‘not detected’ in our mosaic, even with the lower S/N cut (3σ). The S2CLS catalogue shows that most of these 22 sources have estimated S/N less than 3. The number of missed sources in the new mosaic map, 22, is comparable to the expected number of false detections for a threshold of S/N = 4 in the S2CLS catalogue (7 per cent of 330 sources; Geach et al. 2017). Interestingly, there is one fairly bright source in the S2CLS catalogue (S2CLSJ175417+664913, S850 = 21.5 mJy) that completely disappears in our 850-µm mosaic map. When we construct a mosaic map using archival data only, we find no source at the position of S2CLSJ175417+664913. The reason for this source being detected in the S2CLS map and being missed in our map needs further investigation.

The deboosted flux densities of 222 matches between the S2CLS and our catalogue show good agreement (Fig. 6b), with an average flux-density difference of less than 20 per cent.

3.4 False-detection rate

In the low S/N regime, background fluctuation may lead to ‘false detections’. To estimate the false-detection rate as a function of S/N, we compared the number of detections in the source-free jackknife noise map to the number of detections in the real flux map, using the same source-extraction method. The false-detection rate is defined as the ratio between these two numbers. Figure 7 shows that with our 4σ detection limit, the integrated false-detection rate is about 10 per cent. In the lowest S/N bin, at S/N = 4–4.2, the false-detection rate is as high as 20 per cent. If we were to adopt a higher S/N cut of 4.5σ for source detection, the integrated false-detection rate becomes approximately 3 per cent.

3.5 Source catalogue

The final source catalogue contains 549 sources detected above 4σ over the approximately 2 deg² region around the NEP. The first ten catalogue entries are presented in Table 2. We list source IDs based on the coordinates, the positions of 850-µm sources, the observed flux densities with instrumental noise, the signal-to-noise ratios and the deboosted flux densities of sources with total flux uncertainty. The total flux uncertainty is a quadrature sum of the instrumental noise, confusion noise (0.8 mJy beam⁻¹ at 850 µm), and the deboosting uncertainty, which is estimated from the intrin-
Table 2. 850-µm source catalogue from the NEPSC2 survey covering approximately 2 deg$^2$. Presented here are the first 10 rows of the catalogue, sorted in order of the observed flux density. The first source is NGC 5434, a Galactic planetary nebula. The first column indicates the IDs of each source, while the second and third columns give the (J2000) right ascension and declination, respectively. The column $S_{850}^{\text{obs}} \pm \sigma_{\text{inst}}$ is the observed flux density and instrumental noise, while $S/N$ gives the signal-to-noise ratio of the detection. The column $S_{850}^{\text{deb}} \pm \sigma_{\text{tot}}$ gives the ‘deboosted’ flux density (which is an estimate of the intrinsic flux density), and the total uncertainty. The total uncertainty is the quadrature sum of the instrumental noise, confusion noise and deboosting error. The columns $C$ and $\log_{10} F$ are the completeness and false-detection rate corresponding to each source. The completeness $C$ is estimated in the parameter space of $(\sigma_{\text{inst}}, S_{850}^{\text{deb}})$ presented in Fig. 3. The false-detection rate is estimated based on the $S/N$ (Fig. 7). The last column gives the positional uncertainty for each 850-µm source (Section 3.2); this can be used for multi-wavelength catalogue cross-matching. The full catalogue will be released in the online version of the journal.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA</th>
<th>Dec</th>
<th>$S_{850}^{\text{obs}} \pm \sigma_{\text{inst}}$ [mJy]</th>
<th>$S/N$</th>
<th>$S_{850}^{\text{deb}} \pm \sigma_{\text{tot}}$ [mJy]</th>
<th>$C$</th>
<th>$\log_{10} F$</th>
<th>$\delta \theta$ [arcsec]</th>
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<tr>
<td>NEPSC2_J175833+663758</td>
<td>17 58 33.4</td>
<td>+66 37 58.5</td>
<td>195.9 ± 1.0</td>
<td>191.2</td>
<td>195.1 ± 1.4</td>
<td>1.00</td>
<td>-664.65</td>
<td>0.99</td>
</tr>
<tr>
<td>NEPSC2_J180330+664811</td>
<td>18 03 30.7</td>
<td>+66 48 11.9</td>
<td>23.5 ± 1.7</td>
<td>13.8</td>
<td>23.2 ± 2.0</td>
<td>1.00</td>
<td>-33.75</td>
<td>0.95</td>
</tr>
<tr>
<td>NEPSC2_J175518+663359</td>
<td>17 55 18.4</td>
<td>+66 33 59.5</td>
<td>20.2 ± 2.5</td>
<td>8.1</td>
<td>16.3 ± 2.7</td>
<td>0.99</td>
<td>-13.56</td>
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<tr>
<td>NEPSC2_J180330+664811</td>
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<td>+66 48 11.9</td>
<td>18.8 ± 2.1</td>
<td>9.0</td>
<td>16.5 ± 2.3</td>
<td>1.00</td>
<td>-16.86</td>
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<tr>
<td>NEPSC2_J180000+673402</td>
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<td>+67 34 02.0</td>
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<td>6.5</td>
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<td>+66 43 55.0</td>
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<td>14.6 ± 2.7</td>
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<td>10.6 ± 4.1</td>
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<td>+65 55 04.0</td>
<td>14.1 ± 2.2</td>
<td>6.4</td>
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<tr>
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<td>+66 34 48.0</td>
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<td>11.7 ± 3.2</td>
<td>0.99</td>
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4 DISCUSSION

4.1 850-µm number counts

The surface number density of sources per flux density bin for a galaxy population is a simple measure of a specific population’s abundance and provides a powerful tool for testing galaxy formation models through the comparison of the models with observations. The estimated number counts tend to be better constrained if the survey area is larger, because large areas are relatively free of excess variance due to clustering. Simpson et al. (2019) demonstrated that by constructing number counts in the separate sub-fields of the S2CLSMOS survey (covering 1.6 deg$^2$), degree-scale fields are sufficiently wide to overcome the clustering effect for the flux range of 2–10 mJy. From the wider and shallower S2CLS survey, covering about 5 deg$^2$, the number counts from various fields generally agree to within 50 per cent in 0.5–1 degree fields, except for a marginal overdensity observed in a particularly small field (GOODS-North, 0.07 deg$^2$).

The 850-µm data in the NEP field are shallower than in some previous cosmological surveys already mentioned; this is especially true for the ‘extended’ fields where the median depth is $(\sigma_{\text{inst}}) = 2.3 \text{ mJy beam}^{-1}$. Furthermore, the coverage of the NEP SCUBA-2 survey is not the widest amongst cosmological fields that have been surveyed. As a result, our survey has limitations when it comes to improving constraints on the faint (as well as the bright) end of the 850-µm number counts. Nevertheless, the 850-µm number counts in the NEP region provide an independent test of whether the previously claimed statement is correct that degree-scale surveys are largely free of clustering effects. Wide surveys are also a way to search for rare populations of extremely bright 850-µm sources that are either lensed galaxies or highly confused sources from faint galaxy overdensities (Negrello et al. 2010; Vieira et al. 2010; Wardlow et al. 2013). Both scenarios for bright 850-µm sources are worthy of investigation in...
terms of studying galaxy cluster-scale structures at different redshifts with good supporting multi-wavelength survey data.

To construct number counts, we used 548 sources in the catalogue, excluding one known Galactic source, the planetary nebula NGC 6543. For the differential number counts, the number of sources with deboosted flux within the flux density bin was converted to surface density (in units of deg$^{-2}$ mJy$^{-1}$) using the areal coverage corresponding to the noise level where the source was detected. A completeness correction was applied to every source based on the corresponding completeness value derived from the simulations described above (Section 3.1). Each source was also corrected for the possibility of false detection (Section 3.4), by multiplying by (1−false-detection rate) before counting. The number count in a given flux density bin was calculated as follows:

$$\frac{dN}{dS} = \sum_i \left( \frac{1}{\Omega(> \sigma_i)} \right) \frac{(1 - f_i)}{C_i}$$

where $\Omega(> \sigma_i)$ indicates the areal coverage where the sensitivity is better than the observed flux uncertainty (see Fig. 2). The quantities $f$ and $C$ are the false-detection rate and completeness, respectively.

Uncertainties in the deboosted flux will contribute to uncertainties in the number counts. In order to take this effect into account, we generated 1000 catalogues of 850-µm sources by varying the intrinsic flux densities of individual sources according to the flux density distribution, i.e., the mean of 1000 cases being the deboosted flux density in the actual data catalogue (Table 2) and the standard deviation being the total flux uncertainty. Then number counts were calculated 1000 times using 1000 catalogues. Finally the mean and standard deviation of the 1000 realisations were taken as the final values for number counts and uncertainties, respectively. One of the advantages of this approach is that we obtain a continuous trend of number counts despite the small number statistics in some of the flux bins. In addition to the differential number counts, we also constructed the cumulative counts, which represent the surface number density of sources above each flux density; this provides a quantification of the total number of sources that will be selected in a flux-limited survey. The method for generating the cumulative counts is the same as the method used in calculation of differential counts. The results are summarised in Table 3 and Fig. 8. Although our source catalogue contains sources as faint as $S_{850} = 2.8$ mJy, we only present number counts for flux density bins brighter than 4 mJy where the survey becomes 50 per cent complete at least in the regions with lower noise. There are only four sources brighter than 15 mJy and thus the number counts above 15 mJy are not included in Table 3.

Figure 8 shows that the 850-µm number counts in the NEP region are in good agreement with results from previous SCUBA-2 observations of other large cosmological fields (e.g., the 2.6 deg$^2$ of S2COSMOS, Simpson et al. 2019 or the 5 deg$^2$ of S2CLS, Geach et al. 2017) over the flux density range $S_{850} = 4–15$ mJy. Previous surveys showed that the 850-µm number counts are well described by a Schechter function. The dotted line in Fig. 8 is the best-fit Schechter function presented by Geach et al. (2017), which was the flux distribution of sources used for constructing artificial source catalogues use in the source recovery simulations (Section 3.1).

Although SMGs are usually selected in low-resolution,
Figure 9. Cut-out images of the four brightest 850-μm sources, in order of appearance in the source catalogue (Table 2). All images have a size of 40 arcsec × 40 arcsec. The centre of each image, (Δarcsec, Δα) = (0, 0), indicates the position of the 850-μm source. From left to right, we show: an optical colour composite image (Subaru/HSC g, r, i for blue, green and red, respectively); the Spitzer/IRAC 3.6- and 4.5-μm image; the AKARI/IRC 15-μm (L15) image; the Herschel/SPIRE 250-, 350- and 500-μm image; and the SCUBA-2 850-μm image. The dotted lines is a circle with 15 arcsec radius, i.e., the FWHM of the 850-μm beam. The top two sources (NEPSC2 J175052+660458 and NEPSC2 J175244+660834) are associated with multiple objects at shorter wavelengths, the central object of which is very faint in the optical image. The source NEPSC2 J180330+664811 is relatively compact, and shows a faint tidal tail-like feature in the 3.6 and 4.5-μm images. The last source, NEPSC2 J175846+671948 is not spatially resolved at the resolution of IRAC, but in the HSC images the source breaks into three objects with similar colours.

In Fig. 8, we also plot the number counts from interferometric observations, in order to estimate the possible multiplicity effect of the NEP source counts over the investigated flux range. To compare counts obtained at different submm wavelengths, we applied a v^2 scaling, i.e., ALMA 870-μm number counts are assumed to be measured at 0.95x the SCUBA-2 850-μm flux density bin and SMA 860-μm counts are assumed to be measured at 0.98x the SCUBA-2 flux density bin. For sources above 10 mJy in the NEPSC2 survey, the effect of multiplicity needs to be investigated through future spatially-resolved sub/millimetre observations, since the number counts from different surveys begin to deviate in this flux density range.

As well as the possibility of multiple objects contributing to a single submm source, the number counts in the brightest flux-density bins are known to often be dominated by strongly lensed galaxies (Negrello et al. 2010; Vieira et al. 2010), even if low-redshift (z < 0.1) and Galactic sources are removed. The number density of lensed submm galaxies is relatively low if the lens candidate selection is based on a high flux density cut (e.g., S500 > 100 mJy in Wardlow et al. 2013, with a surface density of 0.14 ± 0.04 deg^-2), based on evidence from shallow surveys over 70–100 deg^2 (Vieira et al. 2010; Wardlow et al. 2013). However, Bourne et al. (2014) have suggested that lensed sources can contaminate number counts at even lower flux densities, i.e., less than 20–30 mJy in the 250–350 μm bands, suggesting that the weak lensing of Herschel/SPIRE sources by foreground structures are quite common. On the other hand, in S2COSMOS (Simpson et al. 2019), there has

wide-area single-dish surveys, recent follow-up observations using submm/mm interferometer arrays have suggested that individual single-dish submm sources often break up into multiple objects in a higher-resolution image (e.g., Karim et al. 2013; Hill et al. 2018; Stach et al. 2018; Simpson et al. 2020). The multiplicity is due to a mixture of physically associated galaxies and unrelated galaxies seen along the line of sight (Hayward et al. 2013). Therefore, the number counts in single-dish surveys will tend to be affected by the effects of multiplicity. One of the early results using ALMA (Karim et al. 2013) reported that the number counts of bright submm sources above Smm = 9 mJy had been substantially overestimated based on the 7.5 arcsec resolution imaging of 122 SFGs selected in the 19 arcsec resolution Large Apex Bolometric Camera (LABOCA) image. From the interferometric follow-up observations of the bright submm sources in the S2CLS UKIDSS/UDS field (AS2UDS; Stach et al. 2018, with Simpson et al. 2015 as a pilot study), it has been suggested that the normalization of the number counts above 5 mJy is 20 per cent lower than that of the SCUBA-2 counts, while the shape of the counts remains unchanged. The multiplicity rate is expected to increase as the flux density of sources increase (Stach et al. 2018), although the effect is found to be true only for the most luminous (~12 mJy) sources (AS2COSMOS; Simpson et al. 2020). In addition, there is debate over the strength of the effect because it depends on the precise definition of ‘multiplicity’, in terms of the separation and flux density ratios of individual peaks within each source complex (see, e.g., Hill et al. 2018).
North Ecliptic Pole SCUBA-2 survey

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Figure 10. SEDs of the four brightest 850-µm sources ($S_{850} > 15$ mJy) from optical to submm wavelengths. Squares represent the observed flux densities from Subaru/HSC grizy, CFHT/megacam ugriz, Spitzer/IRAC 3.6 and 4.5 µm, AKARI/IRC 2–24 µm, WISE 3–22 µm, Herschel/SPIRE 250, 350, and 500 µm and SCUBA-2 850 µm (if available). The IRAM/NOEMA 1.3-mm data point is also overplotted for NEPSC 175052+660458. For photometric data lying below the 5σ detection level (i.e., detections between 3σ and 5σ), we assigned flux density uncertainties to be the same as the flux densities, hence the error bar appears to be larger compared to data points in other filters. Downward arrows indicate upper limits in the given filters, which corresponds to the 3σ detection limit. Overplotted lines represent the best-fitting models, showing the results of cigale fitting: green dotted lines for the AGN component; orange dashed lines for the star-forming dust component; blue solid lines for the (unattenuated) stellar continuum component; and black solid lines for the sum of all the components.

been no evidence of such an excess at the bright end from the SCUBA-2 850-µm observations with beam size smaller than that of Herschel. The absence of such an excess in S2COSMOS is still statistically consistent with the results from S2CLS (Geach et al. 2017). In the NEP region, covering approximately 2 deg², four sources are found with $S_{850}$ brighter than 15 mJy and two among those are brighter than 20 mJy. This is again statistically similar to the results of S2CLS/S2COSMOS; nevertheless it produces an enhancement in the number counts compared to the Schechter fit (orange circles in Fig. 8). To elucidate the nature of these brightest 850-µm sources, we present their images and SEDs in the following section.

4.2 Counterpart identification of 850-µm sources

While the full multi-wavelength identification of 850-µm sources and their characterisation will follow in another paper, here we briefly describe the way to find counterparts of submm sources in other wavelength data in order to determine the properties of four of the brightest sources with $S_{850} > 15$ mJy (as described in Section 4.3). Identification of the submm galaxies selected in wide-area surveys is not straightforward, especially when the source extraction procedure is not done using prior positions (Jin et al. 2018) because of the large beam size of single-dish observations. A frequently adopted approach is to use higher-resolution radio and/or mid-IR images (e.g., Chen et al. 2016; Michałowski et al. 2017; Cowie et al. 2018). For example, Lim et al. (2020) and Chang et al. (2018) used VLA 3-GHz source positions to find counterparts of 450-µm-selected sources, and relied on the 24-µm position if the 3-GHz position was not available. A machine-learning method combined with the radio data has been reported to be highly efficient for identifying multi-wavelength counterparts of submm galaxies (An et al. 2018, 2019). When high spatial resolution radio/mid-IR images are not available, an alternative way is to find a counterpart based on the likelihood-ratio method (Sutherland & Saunders 1992) using magnitudes or colours as variables. This approach has been widely applied to far-IR/submm surveys (e.g., Huang et al. 2010; Chapin et al. 2011; Fleuren et al. 2012; Kim et al. 2012). From the fact that submm/mm galaxies tend to have red optical/near-IR colours compared to other (i.e., submm-faint) objects, a likelihood analysis using such colours is expected to identify 60–80 per cent of SCUBA-2 SMG counterparts (e.g., Pope et al. 2005; Michałowski et al. 2012; Alberts et al. 2013; Chen et al. 2016), although the actual identification rate varies along with details in the methodology selected by different authors.
The ancillary radio-imaging data in the NEP region are limited both in terms of the survey area and the sensitivity required to cross-identify 850-µm selected dusty sources that are not dominated by non-thermal radiation. The 1.5-GHz VLA imaging with $\sigma = 6 \mu\text{Jy}$ is available for 0.4 deg$^2$, but the coverage is limited to the central area inside which around 200 submm sources are located. Note that all four of the brightest sources presented here are located outside the VLA coverage. The spatial resolution of the available mid-IR imaging data (covering 2–24 µm) by the AKARI/IRC instrument (Onaka et al. 2007) is relatively poor, since the FWHM of the PSF is as large as 6 arcsec. Spitzer/MIPS 24-µm imaging data are available for central 1 deg$^2$, yet the sensitivity is also limited. Therefore we decided to mainly rely on the publicly available Spitzer/IRAC 3.6- and 4.5-µm imaging data (Nayyeri et al. 2018, PSF size approximately 1 arcsec) for the SMG counterpart identification. The [3.6–4.5] colour is used to construct a parameter distribution for SMGs. The counterparts of Herschel/SPIRE 250-, 350-, and 500-µm sources (Pearson et al. 2012) are also searched based on the [3.6–4.5] colours. If the SPIRE sources are located within one SCUBA-2 beam size from the positions of the SMGs, and if the IRAC counterpart of an SMG and that of a 250-µm-selected source (the SPIRE channel with the smallest beam size) are the same, we consider that the far-IR-to-submm (250–850 µm) emission is due to that single IRAC object. At shorter wavelengths, we use the Subaru/HSC gri$y$ combined source catalogue over the NEP-Wide field (Oi et al. 2020, submitted) to find the nearest optical source from the position of an IRAC counterpart within the HSC PSF size (i.e., 0.8 arcsec). Among the 548 sources detected at 850 µm (excluding NGC6543), IRAC counterparts are identified for 267 sources (about 50 per cent), with an estimated incorrect-counterpart rate for individual sources (based on $p$-values; Downes et al. 1986; Casey et al. 2013) of less than 5 per cent.

4.3 Properties of the brightest sources

As mentioned in Section 4.1, we found four 850-µm sources that are brighter than 15 mJy. This is slightly more than expected from the 2 deg$^2$ survey, i.e., two sources, if the source number density distribution follows the Schechter function. All four of these sources are located outside the S2CLS coverage. In the full S2CLS catalogue, over 5 deg$^2$ (Geach et al. 2019), there are five SMGs reported with $S_{850} > 15$ mJy: one in the NEP, one in the COSMOS, one in the EGS field, and the other two in the UDS field. The one in the NEP region is no longer in our updated mosaic map (see Section 3.3). The SMG in the COSMOS field is suggested to be a starburst at $z = 4.6$ from the optical spectroscopy (AzTEC/COSMOS 1, Smolčič et al. 2018). For the two SMGs in the UDS field, one is a luminous submm galaxy with the possibility of being optically dark and lensed by a foreground galaxy sharing the same line of sight (Orochi, Ikarashi et al. 2011). The other SMG comprises two counterparts in ALMA follow up (Dudzevičiūtė et al. 2020), with $z = 3.3$. In the S2COSMOS catalogue (Simpson et al. 2019), there are three SMGs with deboosted flux density larger than 15 mJy; the brightest components in ALMA follow up for these three SMGs are at $z = 3.4$, 4.3 and 2.7 (Simpson et al. 2020). All of the bright SMGs with $S_{850} > 15$ mJy are known to be located at redshifts that are higher than the median ($z \approx 2$) for 850-µm-selected SMGs. There is tentative evidence for a mild increase of redshift as a function of submm flux density (Ivison et al. 2002), and this trend is present even for the spatially resolved submm sources (Simpson et al. 2020). The four brightest SMGs found in the NEP field may be SMGs at high redshift whose number density is relatively low (if they do not suffer from the effects of source blending). In order to characterise these sources, we present multi-wavelength cut-out images in Fig. 9 and SEDs in Fig. 10.

Only one of these four sources, namely NEPSC$2_{\mathrm{J175052+660458}}$, was observed by the relatively compact morphology at optical-to-near-IR wavelengths, while the others appear to be associated with multiple galaxies seen in the optical/near-IR. For example, NEPSC$2_{\mathrm{J175244+60834}}$ has at least three possible counterparts in the optical that are not resolved in the 3.6- and 4.5-µm images. For the other two sources (NEPSC$2_{\mathrm{J175052+600458}}$ and NEPSC$2_{\mathrm{J175244+60834}}$), the resolved galaxies are aligned along a filamentary-like structure, with diffuse, low surface-brightness emission around the galaxies. The aligned structure does not seem consistent with the arc-like features typically seen in gravitational emission. Such an alignment of galaxies suggests the possibility of the bright 850-µm flux density being contributed by several star-forming galaxies that are physically associated, i.e., mergers. While more work (including interferometric follow-up observations) is needed in order to determine whether these multiple counterparts are physically associated or merely aligned by chance, the fact that most of the bright sources appear to be multiples is consistent with the previous findings. For example, two of the luminous 850-µm sources above 15 mJy in the aforementioned S2CLS-UDS field turned out to be composed of two components in ALMA images (Stach et al. 2019). The brightest source in the NEPSC2 catalogue, NEPSC$2_{\mathrm{J175052+660458}}$, was observed by the IRAM NOrthern Extended Millimetre Array (NOEMA) being selected as a candidate lensed galaxy based on the Herschel/SPIRE photometry (Burgarella et al. 2019). In the 1.3-mm continuum image, the source (designated as ‘NEP-12’ in Burgarella et al. 2019) is resolved into three components. Broadly speaking, the optical and/or radio interferometer images of NEPSC2 bright sources support the idea that the multiplicity rate is higher than or comparable to 50 per cent at flux limits brighter than 15 mJy (Stach et al. 2018; Simpson et al. 2020).

The SEDs of the four bright NEP sources are constructed using the multi-wavelength identification procedure described in Section 4.2. Optical gri$y$ magnitudes of NEPSC$2_{\mathrm{J175052+660458}}$ and NEPSC$2_{\mathrm{J175244+60834}}$ and NEPSC$2_{\mathrm{J175846+617948}}$ are taken from the optical source closest to the position measured at 4.5 µm. SED fitting is carried out using cigale$^2$ (Code Investigating GAlaxy Emission: Noll et al. 2009; Boquien et al. 2019). Cigale computes the spectral models based on an energy balance principle between the UV (mainly from direct stellar radiation) and the IR (mainly from dust-reprocessed stellar radiation), enabling one to efficiently estimate the physical properties of

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galaxies such as SFRs, attenuation, dust luminosities, stellar masses and the contributions from an AGN, by fitting the observed data to a grid of several million models. It is also possible to derive the photometric redshifts of galaxies if a grid of photometric redshifts are provided. Since we do not have spectroscopic redshifts for the four bright 850-μm sources, we run CIGALE in a photometric redshift mode (sampling z = 0.1–5, with a redshift step of Δz = 0.1) to find the possible redshift and the best-fitting SED model simultaneously.

We used a delayed star-formation history model that is flexible enough to fit the high-SFR galaxies in the early Universe (Ciesla et al. 2017), by fixing the e-folding time, but varying the age of the main stellar population. For a single stellar population, the bc03 (i.e., Bruzual & Charlot 2003) library with solar metallicity and Salpeter (1955) initial mass function was chosen, with the addition of a treatment of nebular emission. To model the dust attenuation and the dust emission, we chose to use the Charlot & Fall (2000) method with a range of A_ν, and the Draine et al. (2014) model with a range of PAH mass fraction that has also been applied to fit the SEDs for mid-IR-selected AKARI galaxies (Toba et al. 2020; Wang et al. 2020, submitted). In fitting the warm dust component from an AGN contribution that dominates the mid-IR, we parameterised the optical depth at 9.7 μm, the opening angle, the angle between the equatorial axis and the line of sight, and the AGN fraction, all based on the study described in Fritz, Franceschini, and Hatziminaoglou (2006).

All four of the sources are expected to be at z > 2, with the photometric redshift ranging over z_{phot} = 2.4–4.0. The total IR luminosities range over 0.8–2.1×10^{13} L_☉, as expected from the the clear far-IR/submm detection at a level of a few tens of mJy. Three of the four sources are dominated by star-formation, with a minor AGN contribution ranging between 2 and 5 per cent. For only one of the sources, NEPSC2-J180330+664811, does the AGN dominate (with an AGN contribution of 60%). This is in agreement with the expectation from the multi-wavelength cut-out images, i.e., the SED of the relatively isolated, compact source (NEPSC2-J180330+664811) shows a high fraction of AGN contribution, while the SEDs of others are close to that of dusty star-forming galaxies with A_ν = 3.1 mag. While the three sources with star-formation-dominated SEDs are detected in Herschel/SPIRE 250, 350 and 500 μm imaging, NEPSC2-J180330+664811 is not detected in any of the Herschel/SPIRE channels. If this source truly lies at z ≥ 4, as would be expected from its non-detection in the u-band and at 250–500 μm, this example shows that the 850-μm data provide a powerful tool to select z > 4 bright, obscured AGN that are missed by Herschel/_SPIRE. Unfortunately, the X-ray areal coverage (Krumpe et al. 2015; Miyaji et al. 2017) is limited to only the central 0.4 deg^2, therefore the confirmation of this source being an obscured AGN requires further follow-up observations.

Note that the parameters derived through the SED fitting, including far-IR luminosities, reddening, and photometric redshifts are affected by the fact that multiple sources could contribute in the 850-μm emission. For example, in case of the source NEPSC-J175052+660458, Burgarella et al. (2019) showed that each component of the source fitted to have photometric redshifts at z = 1.83 and 1.98, while using the integrated flux density points to the photometric redshift of z = 2.17. The photometric redshift can be elevated due to the source multiplicity, therefore careful counterpart identification based on the multi-wavelength imaging and spatially resolved sub/millimetre observations is needed to correctly constrain redshift and nature of bright submm sources. With the interferometric follow up observations, the submm fluxes included in the SED fitting may need to be corrected for contributions from any confused companions.

5 CONCLUSIONS
We have presented an 850-μm mosaiced map and source catalogue for the NEP region, using archival data and around 200 hours of new data from the EAO/JCMT large programme NEPSC2 taken up until 2019. The total area covered by the final map is approximately 2 deg^2 if we limit ourselves to the area with rms instrumental noise better than 2.7 mJy beam^{-1}. This area is more than 3 times larger than the previous 850-μm coverage of the NEP. In the deepest region, the rms noise of the combined map reaches 1.0 mJy beam^{-1}, i.e., close to the 850-μm confusion limit. Adopting a detection threshold at 4σ, we extract 549 submm sources, of which we estimate 10 per cent to be false detections (i.e., either not a genuine source or else a source that is substantially fainter and boosted by noise). The false-detection rate becomes less than 3 per cent if we adopt a 4.5σ detection threshold, while the number of 850-μm sources becomes 542. The 50 per cent source completeness limit occurs at flux densities between 3.9 and 8.5 mJy, depending on the source locations within the map. As part of this publication, we are releasing the 850-μm mosaic map and catalogue.

Our number counts of 850-μm sources detected in the NEP show good agreement with those from other extragalactic cosmological blank fields (Geach et al. 2017; Simpson et al. 2019) and are well described by a Schechter function. This means that our 2 deg^2 area around the NEP is neither especially overpopulated or underpopulated, which is what we expect because degree-scale fields are wide enough that the excess variance due to clustering should be small. The mild excess at the bright end is contributed by a few S_{850} > 15 mJy sources. There are possibilities that such bright sources are either high-redshift AGN or groups of star-forming galaxies that are not resolved in the single-dish FIR/submm observations; these possibilities can be distinguished using interferometric follow up observations.

An extension of the NEPSC2 to complete the 850-μm mapping over the entire 4 deg^2 has recently been approved (JCMT program ID M02AL005). Based on the number of new 850-μm sources outside the S2CLS coverage, we expect to detect about 400 new sources once the extension has been completed. The number of rare, bright SMGs should be doubled, opening the possibility of studying galaxy cluster-scale structures at different redshifts, as well as discovering 850-μm-bright obscured AGN at z > 4 that have been missed in the Herschel/SPIRE observations.
6 DATA AVAILABILITY

The data underlying this article are available in Zenodo, at https://dx.doi.org/10.5281/zenodo.3897405.

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