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THE ISOPHOT SERENDIPITY FAR-INFRARED SKY SURVEY: A STATUS REPORT

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ABSTRACT

The ISOPHOT Serendipity Survey utilized the slew time between ISO's pointed observations with strip scanning measurements of the sky in the far-infrared at 170 μm. The slews contain information about two fundamentally different types of objects, namely (almost) unresolved galactic and extragalactic far-infrared sources as well as extended regions of galactic cirrus emission. Initial software development and data analysis emphasizes the detection of point sources. First results from an investigation of a high galactic latitude field near the North Galactic Pole indicate that the detection completeness with respect to previously known IRAS sources will be almost 100 per cent for sources with $f_{100\mu m} > 2$ Jy. Nevertheless, even faint sources down to a level of $f_{170\mu m} \approx$ 1 Jy can be detected. Since the majority of the detected point sources are galaxies, the Serendipity Survey will result in a large database of $\approx$ 2000 galaxies. The calibration will be based on photometric observations of 12 galaxies covering a large brightness range. Follow-up observations of three highly interesting cold galaxies were carried out with ISO.

Key words: galaxies; surveys.

1. OBSERVATIONAL CONCEPT

ISO's primary observing mode was pointed observations of selected celestial targets with a single instrument (Kessler et al. 1996). The sequence of scheduled observations required the slewing of the telescope between individual measurements, which could have been quite long and thereby cross a significant part of the sky. To maximize the scientific return of the mission, the ISOPHOT team proposed that the otherwise unused slewing time should also be utilized for scientific purposes (Lemke & Burgdorf 1992).

The ISOPHOT C200 array (Lemke et al. 1996), which is sensitive up to 200 μm, was selected as the most useful instrument for such a slewing survey. A broad band filter at a wavelength of 170 μm has the prospect of delivering data serendipitously beyond the IRAS 100 μm limit not only for cold point or marginally extended sources but also for extended cold FIR emitting material distributed on large scales in the Galaxy.

At the long wavelength observed, the mostly unresolved sources consist of galaxies, a small fraction of galactic sources, and a few solar system objects such as asteroids. A special type of point-like sources are compact knots embedded in more extended cirrus regions, and highly elongated narrow cirrus ridges, which have been crossed almost perpendicular to their major axis. The separation of the latter two sources from genuine galactic or extragalactic point sources on the basis of the Serendipity slew data alone is likely difficult since a full sky coverage will not be achieved and a second crossing of a particular source was unlikely to happen. In this case, the IRAS 100 μm maps can be used to clarify the nature of detected sources.

The galactic cirrus emission and the diffuse FIR background in the slews are sampled on all spatial scales, allowing for the first time its detailed study over large areas of the sky at a wavelength beyond the IRAS

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limit. By comparison with IRAS 60 μm and 100 μm data, cold regions or spots within the galactic cirrus can be identified and the color temperatures as a function of galactic coordinates studied.

In the following, emphasis is put on the Serendipity Slew processing with respect to the detection and extraction of point or marginally resolved sources. The analysis of extended galactic molecular cloud regions is described by Tóth et al. (these proceedings), while the search for the coldest galactic objects is described by Hotzel et al. (these proceedings).

2. OBSERVATIONAL DATA AND STANDARD REDUCTION

The ISOPHOT C200 detector (2×2 pixel array, pixel size of 89.4 arcsec) was used in conjunction with the C_160 broad band filter (central wavelength 170 μm, equivalent widths 89 μm) to obtain the Serendipity Survey slew data. To cope with the high dynamic range of brightness between the galactic planes and the galactic poles in conjunction with the varying slew speed of the telescope (max. $\approx$ 8 arcmin/sec), the fastest read-out rate of the C200 camera of 1/8 sec was chosen, during which 4 detector readouts take place.

During the slewing phase, the sky positions as a function of time were delivered by the on-board gyros alone. The gyro positions show a drift away from the correct sky positions and only at the end of a slew, after activation of the star-trackers close to the target position, the positions are again precisely known. Methods to partially correct the gyro drift are being developed and will be applied. The final slew position error is expected not to exceed $\approx$ 2 arcmin even for the longest slews with a length of $\approx 150^\circ$.

For each detector pixel, the raw data consist of detector voltages as a function of readout time. Signals are derived by fitting a straight line to these four point integration ramps. The signals are converted to surface brightnesses [MJy/sr] using for short slews the default detector responsivities or for long slews (> 75 sec) the responsivities derived from a measurement of the on-board Fine Calibration Source preceding the acquisition of slew data. This standard signal derivation makes use of the ISOPHOT Interactive Analysis[1].

3. EXTRACTION OF POINT SOURCES

The first step to extract the astrophysically relevant information for point sources lying on the slews (Figure 1a) is the determination and subtraction of the large scale background from diffuse galactic emission. Particularly during long slews crossing the galactic plane, the background estimation method has to cope with strongly varying surface brightnesses ranging from a few to several hundred MJy/sr. Moreover, a slew may also contain parts, where the detector was saturated.

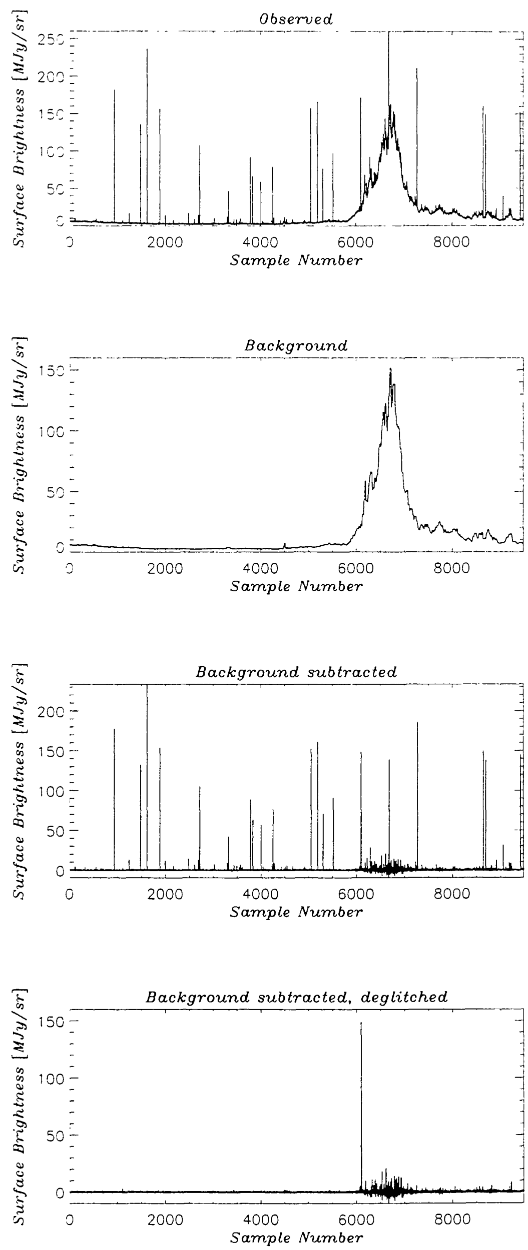

Figure 1. Top to bottom : (a) Data stream of one detector pixel for a long (> 130°) Serendipity slew crossing the galactic plane. (b) Estimated Background. (c) Background subtracted slew data showing strong glitches and increased noise near the Galactic Plane. (d) Glitches removed from (c). The remaining high peak is the nearby galaxy NGC 6946.

To avoid loss of resolution, the flux calibrated data streams of the four pixels are not rebinned, but kept as a function of signal number. After denoising with a non-linear filter (Smith & Brady 1997), a morpho-

[1]The ISOPHOT Interactive Analysis (PIA) is a joint development by the ESA Astrophysics Division and the ISOPHOT consortium. Contributing ISOPHOT Consortium institutes are DIAS, RAL, AIP, MPIK, and MPIA.

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logical rolling ball algorithm (Sternberg 1986) is applied to remove all peaks up to a width somewhat larger than that of point sources, resulting in the slew background (Figure 1b). The full width at zero intensity for point sources is taken to be five times the FWHM of the C200 170 μm beam profile. Because of the variable slew speed, the radius of the rolling ball, measured in number of signals, changes along the slew.

Cosmic ray hits (glitches) are removed from the individual background subtracted data streams of the four pixels (Figure 1c) by using a noise peak elimination filter (Imme 1991), where data points are replaced only if they are confined to one signal and exceed the local noise level by a factor of three. Very strong signals in the center of sources may erroneously be removed by this procedure, but this can be undone by copying back the signals in question once a source region has been identified. Faint glitches can hardly be recognized, because they resemble genuine noise peaks, yet may have an accompanying faint glitch in a second detector pixel. Occasionally, extremely strong glitches mimic real sources in showing several high signals in sometimes more than one detector pixel.

The background subtracted and deglitched signals (Figure 1d) of the four pixels are phase-shifted according to the rollangle of the detector and a signal-to-noise ratio weighted mean signal is derived. This resulting mean is again slightly filtered (Smith & Brady 1997), from which regions of source candidates are selected by setting a cut on the filtered mean surface brightness. This cut is usually rather low, 3 σ of the local noise level, which in turn is non-constant due to crossing of the regions with different background levels such as the galactic plane. No other criterium such as a detection with a predefined signal-to-noise ratio in several pixels is required for the definition of a source candidate region. The low threshold for the source candidate selection guarantees that even faint sources will be found. On the other hand, this obviously leads to a quite a number of false faint source candidates, mostly unremoved detector hits by cosmic rays, which, however, can easily be recognized because their widths are well below those expected for unresolved point sources.

To decouple the determination of the source position from the derivation of the source flux, the ratio of the four peak fluxes to the highest flux among the four pixels is used in comparison with the expected ratios from a gaussian source model to estimate the minimal source distance perpendicular to the slew direction. It should be noted that the slew offset is a particularly critical parameter for the total source flux, and it is foreseen to improve its derivation by including the ISOPHOT beam profile. For each source candidate region, a non-linear least-squares fit of a two-dimensional circular symmetric gaussian with fixed slew offset together with a tilted plane is then applied to the data from the four background subtracted data streams.

This results in source widths and peak fluxes, and total fluxes derived thereof. The used two-dimensional gaussian is only a first approximation to the real point source profile and ignores important effects such as detector drifts, which lead to asymmetric profiles along the slew direction. As a result, the

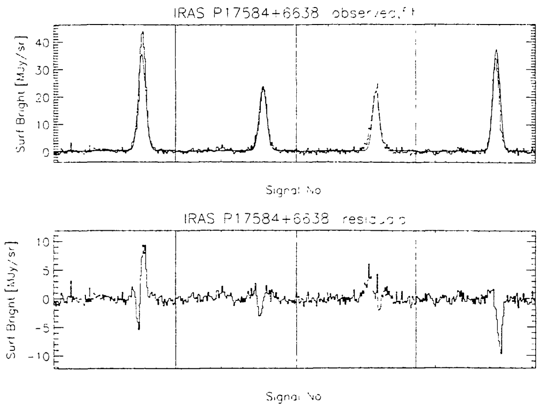

Figure 2. Serendipity Slew data for NGC 6543. Each panel shows for all four detector pixels the source region side-by-side. The upper panel shows the background subtracted data (histogram) together with the fit results (continuous line), while the lower panel shows the residuals after subtraction of the fit.

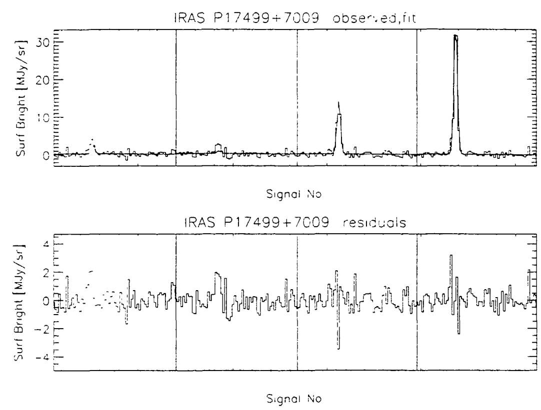

Figure 3. Same as Fig. 2 for NGC 6503.

fit residuals for the brightest sources exceed by far the local noise levels.

The derivation of source parameters will in any case be hampered and the result less accurate if only one or two pixels have a high signal-to-noise ratio, i.e. if a slew touches a sources, but do not cross it almost centrally. The information content of the brightness profiles of the four detector pixels is also significantly reduced if the detector moves parallel to its edges and not with some odd rollangle. In this case each of the two detector pixels having the same distance to a sources show an almost identified brightness profile.

Each fitted source candidate is eventually cross-checked against the IRAS Point Source and Faint Source catalogs and searched for in the NED database. Detailed results of the batch processing are written to log and plot files to allow the selection of subgroups from the source candidates found.

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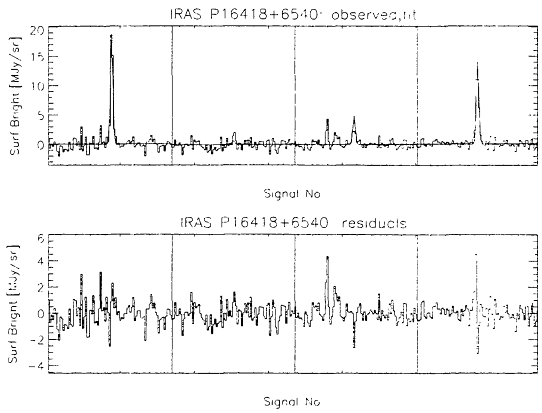

Figure 4. Same as Fig. 2 for IC 1228.

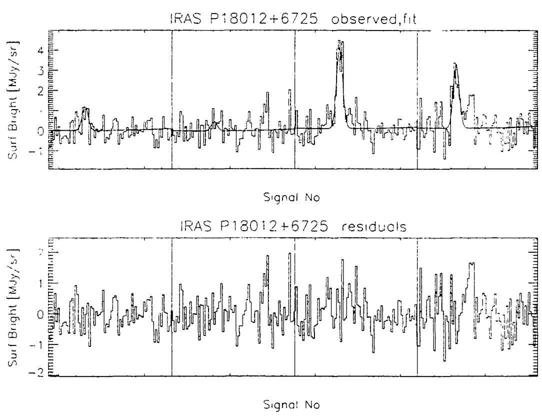

Figure 5. Same as Fig. 2 for UGC 11099.

4. CURRENT PROCESSING STATUS

During almost 800 revolutions, Serendipity data have been taken along ≈ 12500 slews. About 75 per cent have a preceding FCS calibration measurement while the rest are rather short slews calibrated with ISOPHOT default responsivities. The total on-sky integration time is ≈ 500 hours, the total slew length ≈ 150000°. The total amount of raw ERD level data is ≈ 6.5 GBytes.

The first bulk processing of the complete slew database with a initial version of the above described extraction software has been carried out in summer 1998. The resulting data amount to ≈ 20 GBytes. The results are used to get first experiences with such a large database, to improve the used processing methods and to select subsets for detailed analysis of the achievable accuracy in total flux and position, particularly for the calibration sources.

5. EXAMPLES OF PROCESSING RESULTS.

The slew processing is illustrated with the fit results to sources covering a wide range in fluxes. Two of

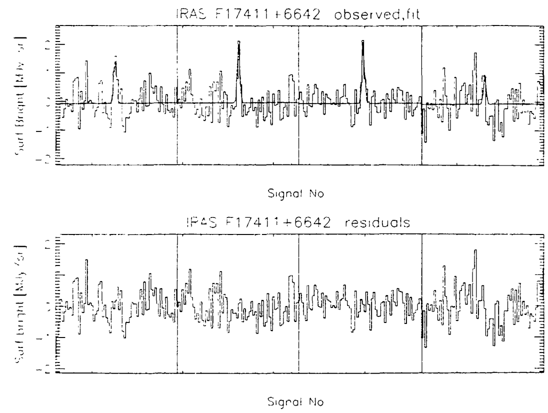

Figure 6. Same as Fig. 2 for UGC 10953.

the brightest Serendipity Sources are the planetary nebula NGC 6543 (IRAS 17584+6638, Figure 2) having an IRAS 100 μm flux of ≈ 63 Jy and the galaxy NGC 6503 (IRAS P17499+7009, Figure 3) having an IRAS 100 μm flux of ≈ 25 Jy. It should be noted that NGC 6543 appears rather wide as measured in number of signals, since it lies at the end of a slew with already decelerating slew velocity. It is moreover one of ISO's calibration sources having repeated observations. The residuals after subtraction of the fit from the background subtracted data in the case of NGC 6543 are clearly much larger than the noise in the adjacent regions and show a systematic pattern, indicating that the source profile for this bright source is not a simple gaussian. This could be due to the slightly extended nature of this source or because of detector drifts. The Serendipity fluxes derived for both NGC 6543 and NGC 6503 is ≈ 20 Jy. Both fluxes are rather uncertain, as judged from the fluxes derived from repeated crossings of both sources, and are expected to be improved once a more accurate source profile is used.

For the fainter source IC 1228 (IRAS P16418+6540, Figure 4) with $f_{100\mu m}$ = 7.4 Jy, a much better fit result is obtained, where the residuals hardly exceed the noise in the regions adjacent to the source. This is also demonstrated with the derived fluxes from three crossings, agreeing within 20 per cent and yielding $f_{170\mu m} \approx$ 7 Jy. UGC 11099 (IRAS P18012+6725, Figure 5) shows that even sources with $f_{100\mu m} \approx$ 1 Jy can not only be detected, but also a useful flux ($f_{170\mu m} \approx$ 0.9 Jy) be derived. A second example is UGC 10953 (IRAS F17411+6642, Figure 6), which does not appear in the IRAS Point Source catalog but was crossed twice yielding a consistent 170 μm flux of ≈ 1 Jy. For these faint sources, the two-dimensional gaussian is clearly adequate, since noise will play a dominant role, particularly if only two or three detector pixels show a significant signal. At such low flux levels, also distortions due to glitches not completely removed become important, as can be seen in the residuals of detector pixel four (rightmost) for UGC 11099 (Figure 5).

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6. DETECTION COMPLETENESS : THE NORTH ECLIPTIC POLE MINISURVEY

To test the software under development, and to gain experience with the bulk data processing already before the end of the ISO mission, the Consortium on the ISOPHOT Serendipity Survey (CISS) had selected a 100 square degrees large high galactic latitude field, ($16^h28^m00^s \leq \alpha_{2000} \leq 18^h12^m00^s$, $+64°00'00'' \leq \delta_{2000} \leq +75°00'00''$), close to the north ecliptic pole, the so-called Minisurvey field. It has the advantage that the foreground emission due to galactic cirrus is rather low, thereby reducing the possible confusion with compact galactic FIR sources.

The investigation of this field was carried out with 336 slews, which had crossed the Minisurvey field before August 14, 1997, totaling 1263° inside the Minisurvey field, corresponding to 4.2 hours of observing time. It emphasized the detection and completeness of point sources in comparison with previously known IRAS sources (4). In view of the early stage of the data analysis at that time, the derived fluxes as well as the reliability of sources found on the slews were used to assess necessary improvement in the processing of the slews.

As a measure for the completeness of the Serendipity processing, the number of IRAS sources expected to be seen on the Minisurvey slews was used. All IRAS point sources lying closer than 2 arcmin to one of the slews crossing the Minisurvey area were selected, but only sources with an IRAS 100 μm quality flag greater than 1 were considered to be potential serendipity sources.

Table 1. Cumulative statistics of the source detection completeness in the Minisurvey field for IRAS sources nominally closer than 2 arcmin to any Serendipity slew.

Flux range IRAS 100 μm	# expected sources	# found sources	percentage completeness
> 10 Jy	11	11	100%
5 - 10 Jy	5	5	100%
2 - 5 Jy	10	9	90%
1.5 - 2 Jy	12	6	50%
total	38	31	82%

Table 1 summarizes the cumulative statistics in several IRAS 100 μm flux bins, where each crossing of a particular source has been counted separately. Since the majority of IRAS point sources are galaxies the spectral energy distribution of which peaks in the wavelength range between 100 μm and 200 μm, their expected 170 μm flux will be close to the IRAS 100 μm flux. Most IRAS 100 μm sources therefore are expected to be detectable also at 170 μm. On the other hand, one star with $f_{100} > 2$ Jy lying in the surveyed region has been excluded because its intensity is steeply falling towards longer wavelengths and is therefore not expected to be seen at 170 μm. For sources brighter than 5 Jy, all expected sources have been found. Only one source is missing in the flux region between 2 - 5 Jy, namely IRAS 16452+6418. An inspection of the IRAS 100 μm showed that this source sits on top of an extended cirrus region, and in fact, the Serendipity processing did detect the cirrus structure but an automatic separation of the point source from the cirrus was not possible.

Below 2 Jy the percentage of detected objects drops, which is easily understood since only sources which are almost centrally crossed are expected to show up in more than 1 pixel with a sufficiently high signal-to-noise ratio. Moreover, since the pointing information of the ISO satellite is still preliminary, IRAS sources that are nominally close enough to be seen on the slews might actually be more than 2 arcmin away and hence not detected. Therefore, the completeness is expected to be improved in the near future, when better ISO slew pointing data will be available. Consequently, sources with $f_{100\mu m} < 1.5$ Jy have currently not been used for the statistical assessment.

7. FLUX CALIBRATION

The two aspects of importance concerning source fluxes are the reproducibility, i.e. the agreement of the fluxes derived from repeated crossings of a particular source, and the external accuracy, i.e. the agreement between the fluxes derived from dedicated photometric measurements and the serendipity slews. The former is mainly determined by the Serendipity data structure and quality of source crossings and can be derived from the scatter of the Serendipity fluxes for a particular source. For the latter, it is expected that due to the fast slew velocity and the finite response time of the detector only a fraction of the total source signal is seen, which requires a rescaling of all flux values derived directly from the slew data.

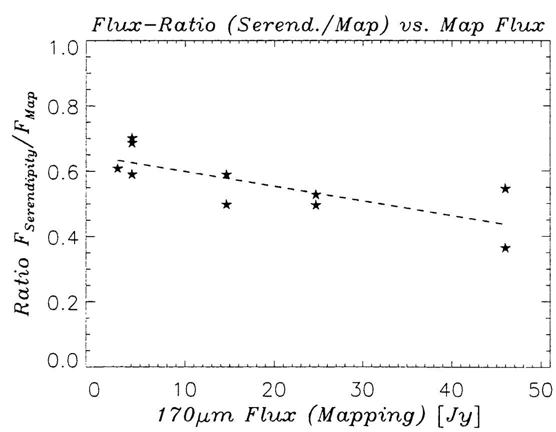

Figure 7. The ratio of derived Serendipity and photometric fluxes from dedicated calibration maps vs. the map fluxes for 5 sources with good Serendipity slew data.

To link the Serendipity fluxes to the absolute photometric flux level at 170 μm, a total of 12 repeatedly crossed galaxies have been mapped in a dedicated Serendipity Calibration programme. For 5 sources crossed almost centrally, i.e. with a signal-to-noise of a least 5 in at least three pixels, the ratio between the Serendipity and the photometric flux vs.

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the photometric flux is given in Figure 7. The ratio under standard high speed condition is ≈ 0.5 and appears to be slightly flux dependant. NGC 6543 has been crossed several times near the end of slews at lower slew velocities. These measurements indicate that a larger signal is seen by slower slews. The calibration for the conversion to absolute fluxes will be updated once a better method for the determination of the source offset position, the most critical parameter for the derivation of the total source flux, and the ISOPHOT beam profile is implemented.

8. ISOPHOT FOLLOW-UP OBSERVATIONS OF SELECTED SOURCES

Already before the end of the ISO mission, interesting candidates for follow-up observations with ISOPHOT have been selected late 1997 from a subset of gyro-drift corrected slews. Eventually, observing time was granted for 3 cold galaxies, where the combined Serendipity and IRAS data had suggested a high 170 μm / 100 μm flux ratio. Photometric mapping was carried out at 100 μm and 170 μm with ISOPHOT in Spring 1998. While for normal galaxies, this ratio is ≈ 1, the Serendipity findings of ratios > 2 could be confirmed for all sources. In fact, one galaxy showed a very high 170 μm / 100 μm ratio of 5, indicating a very low overall temperature of ≈ 14 K. Follow-up observations have been initiated to investigate this cold galaxy in more detail.

9. CONCLUDING REMARKS

The assessment of the Serendipity Minisurvey field yielded a frequency of source detections of ≈ 0.025/° or one detected source along a slew length of 40°, which is equivalent to a surface density of 0.5/square degree. The IRAS database of cataloged galaxies and quasars gives an extragalactic source density of 0.5/square degree for the Minisurvey field which exactly coincides with the measured source density along Serendipity slews. Taking these values one can estimate that with a total sky coverage of ≈ 15% ≈ 4000 galaxies have been seen on all Serendipity slews, which is in agreement with previous estimations (Bogun 1995). However, the derivation of accurate positions and fluxes will be very difficult for sources lying far off the slews. A more conservative estimate can be obtained under the assumption that a source has to lie not more than about half a detector pixel (45″) away from the detector center in order to derive reliable flux values. This would bring the effective sky coverage down to ≈ 10 per cent, and also decrease the number of galaxies for which reliable fluxes can be obtained from the Serendipity slews. For a large fraction of the sources, a photometric accuracy of about 30 per cent can eventually be expected. This will provide a large database of 170 μm fluxes mostly for galaxies.

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