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The ISOPHOT Far-Infrared Serendipity Sky Survey

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ABSTRACT

The ISOPHOT Serendipity Survey utilizes 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. Since the structure of the obtained data is almost unique, the development of dedicated software to extract astrophysically interesting parameters for the crossed sources is mandatory. Data analysis is currently in its early stages and concentrates on 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 % for sources with $f_{100\mu m} > 2$ Jy, dropping below $\approx 50\%$ for $f_{100\mu m} < 1.5$ 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.

Keywords: Far Infrared Surveys, Observatory Operations

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1. INTRODUCTION

The Infrared Space Observatory (ISO[1]) is a liquid helium cooled 60 cm telescope with four instruments covering the middle and far infrared (FIR) wavelength range up to 200 μm. In contrast to the IRAS survey mission, pointed observations of selected celestial targets with a single instrument is ISO's primary observing mode. The sequence of scheduled observations requires the slewing of the telescope between individual measurements, which can be quite long and thereby cross a significant part of the sky. To maximize the scientific return of the mission, the ISOPHOT team[2] proposed that the otherwise unused slewing time should also be utilized for scientific purposes.

Since the sum of all ISO slews represents an almost unbiased but incomplete survey of the sky, it is highly desirable to observe a wavelength region which will extend the currently available FIR data, particularly those from the IRAS survey mission restricted to 100 μm. It was therefore decided that the ISOPHOT C200 array,[3] which is sensitive up to 200 μm, would be 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 not only for cold point or marginally extended sources but also for extended cold FIR emitting material distributed on large scales in the Galaxy.

During the Performance Verification Phase of ISO, the implementation of this so-called ISOPHOT Serendipity Survey was successfully tested. Since then, the survey is running smoothly and delivers data streams.[4] The crossed sky regions cannot be accurately predicted, which will result in a random pattern of slew paths. Only sources observed repeatedly for either calibration purposes or scientific reasons will lie in sky regions more densely covered with slews. After the end of the ISO mission, the Serendipity Survey will be an unprecedented 170 μm all-sky survey with incomplete sky coverage, providing FIR measurements for a large number of different sources.

The source types expected to appear on the slews divide naturally into two almost distinct groups, namely unresolved point or marginally extended sources as well as resolved or large scale emission from galactic cirrus regions, molecular clouds and the diffuse galactic FIR background. At the long wavelength observed, the former mostly consist of galaxies, a small fraction of galactic sources, and most likely solar system objects such as planets and asteroids. An additional 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 will not necessarily 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 will be sampled on all spatial scales, allowing for the first time its detailed study over large areas of the the sky at a wavelength beyond the IRAS 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 this early stage of the project, emphasis is put on the detection and completeness of point-like sources in comparison with previously known IRAS sources. Large scale structures from the Galaxy are the subject of a parallel investigation, which will be described in detail elsewhere. For a few small regions of the sky, an almost full sky coverage is expected by the end of the mission, which will be used to create maps at 170 μm.

2. OPERATIONAL ASPECTS

After each pointed observation with ISOPHOT, the instrument is reconfigured for the Serendipity mode. For starting the Serendipity mode, the instrument has only to be switched on and the necessary telemetry to be established. The decision whether a Serendipity Mode observation can be performed during a slew is taken by the ISO Mission Planning Software. After the scheduling of the sequence of pointed observations, a post-processor identifies slew time spans longer than $\approx$ 30 s and adds the corresponding commands for the execution of a Serendipity Mode observation. If the slew is longer than $\approx$ 75 s, an illumination by the internal Fine Calibration Source (FCS) is included in the command sequence to provide an independent photometric calibration. The illumination level of this internal reference measurement is always kept constant.

The mission planning policy for a particular revolution tries to collect the celestial targets within $10° \times 10°$ sky bins, so that a large number of slews is carried out within this sky bin. Only if all targets in one sky bin have been observed or the sky bin has been lost due to visibility constraints, several larger slews per revolution are necessary and slew lengths longer than 100° will occur.

ISO's orbital period is about 24^h, 16.5^h of which can be used for observations. The total slewing time of ISO is about 5% of the useful ISO time.[5] With an expected ISO life time of ≈ 900 revolutions, the total integration time of the Serendipity Survey will be $\approx 550^h$.

3. OBSERVATIONAL DATA AND STANDARD REDUCTION

The ISOPHOT C200 detector is a 2×2 pixel array of stressed Ge:Ga with a pixel size of $89''\!.4$, which is 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 slew speed of the telescope (max. $\approx 8' s^{-1}$), the fastest read-out rate of the C200 camera of 1/8 sec was chosen, during which 4 detector readouts take place.

For each detector pixel, the raw data consist of detector voltages as a function of readout time, where the integration time is given by the detector reset interval. Signals are derived by fitting a straight line to these four point integration ramps. The signals are converted to surface brightnesses [MJy/sr] using either the default detector responsivities for short slews or with 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*.

A slew consists of three parts, an acceleration phase at the beginning, a phase of constant angular velocity, and a deceleration phase at the end, when the next target is approached. Only for long slews, a constant angular velocity is reached after the acceleration phase at the beginning. The initial phase of increasing angular velocity, however, is not seen in the data streams because the FCS measurement is carried out at that time. For short slews without a calibration measurement the deceleration phase follows directly the acceleration phase.

The reset interval of 1/8 sec together with the highest slewing speed of $\approx 8' s^{-1}$ determines the maximum distance of $\approx 1'$ between two detector positions on the sky. Even at the highest slewing speed, there is considerable overlap between successive sky measurements. The acceleration and deceleration phases lead to an even smaller distance between the sky positions. Because of this highly variable angular distance between successive sky positions, even point sources will have variable widths as measured in number of signals, depending on the slew length and slew phase.

During the slewing phase, the sky positions as a function of time are 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. Therefore, the slew positions contained in the Serendipity Survey data are still preliminary, and will be improved over time by using algorithms to correct for the gyro drifts. The accuracy of the slew positions is not as accurate as ISO's pointed measurements, but the error is expected not to exceed $\approx 2'$ even for the longest slews with a length of $\approx 150°$.

4. EXTRACTION OF POINT SOURCES

The ISOPHOT Serendipity slew data are an almost one-dimensional cut across the sky, lacking, to first approximation, practically any redundancy. Only if a particular source is crossed several times during different slews, independent information can be obtained. The derivation of parameters of crossed sources, the most important of which are the positions and total fluxes, can therefore not rely on data analysis algorithms available for other astronomical data utilizing larger two-dimensional detectors. In particular, fluxes can not be derived from the one-dimensional data stream alone, as was done for the IRAS Point Source Catalog, because sources will be crossed with an arbitrary impact parameter where the detector not necessarily samples the central peak of a source. Data analysis will have to make use at least in parts of a two-dimensional reconstruction and analysis of the source profiles. Dedicated software is thus being developed to deal with the specialties of the slew data.

The first step to extract the astrophysically relevant information for point sources lying on the slews (Fig. 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

*The ISOPHOT Interactive Analysis (PIA) is a joint development by the ESA Astrophysics Division and the ISOPHOT consortium led by the Max–Planck–Institut für Astronomie, Heidelberg. Contributing ISOPHOT Consortium institutes are DIAS, RAL, AIP, MPIK, and MPIA.

brightnesses ranging from a few to several hundred MJy/sr. Moreover, a slew may also contain parts, where the detector was saturated.

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 wavelet filter,[6] a morphological rolling ball algorithm[7] is applied to remove all peaks up to a width somewhat larger than that of point sources. 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. To avoid sharp edges in the background, the result of the morphological filtering is eventually slightly smoothed to some extend by using a Savitzky-Golay filter[8] (Fig. 1b).

While the current background estimator is adequate for almost unresolved point sources, circular symmetric but resolved sources such as nearby galactic planetary nebulae, supernovae remnants and galaxies of very low redshift will have their broad extended wings removed by this background subtraction. Moreover, extended cirrus structures such as ridges or bright elongated knots may or may not be automatically removed by the background subtraction. Narrow ridges can appear as unresolved, if the slew path crosses the ridge almost perpendicular to the major axis. However, it will be removed if the slew has a position angle similar to that of the ridges' major axis because of the slowly varying surface brightnesses having a scale length much larger than that of point sources. Bright cirrus regions with a relatively broad baseline widths can have a very narrow central peak reminiscent of point sources. These central parts will therefore appear in the background subtracted data streams. Once identified, these case will need a special treatment to derive total fluxes.

Cosmic ray hits (glitches) are removed from the individual background subtracted data streams (Fig. 1c) of the four pixels by using a noise peak elimination filter,[9] 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 high one signal wide peaks 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 deglitched and background subtracted signals (Fig. 1d) of the four pixels are averaged and the resulting mean is wavelet filtered,[6] from which regions of source candidates are selected by setting a cut on the filtered mean surface brightness. This cut is usually rather low, 2 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.

For each source candidate region, a non-linear least-squares fit of a two-dimensional gaussian together with a tilted plane is applied to the data from the four background subtracted data streams. This results in source widths, peak fluxes, source positions, 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 fit residuals for the brightest sources exceed by far the local noise levels and fits occasionally converge to unacceptable values for the parameters, mostly in such a way that a very bright source is positioned far off the slew to accommodate the observed brightness profiles.

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.

An improvement to be implemented for the brightest sources will replace the two-dimensional gaussian by a two-dimensional analytical source profile with an asymmetric brightness distribution in one and a symmetric in the other direction. It will be used in conjunction with a transformation of the detector pixel positions from sky positions (Right Ascension, Declination) to a coordinate system where one axis is aligned with the vector of the slew velocity. Furthermore, the ratio of the four peak fluxes to the highest flux among the four pixels together with the position

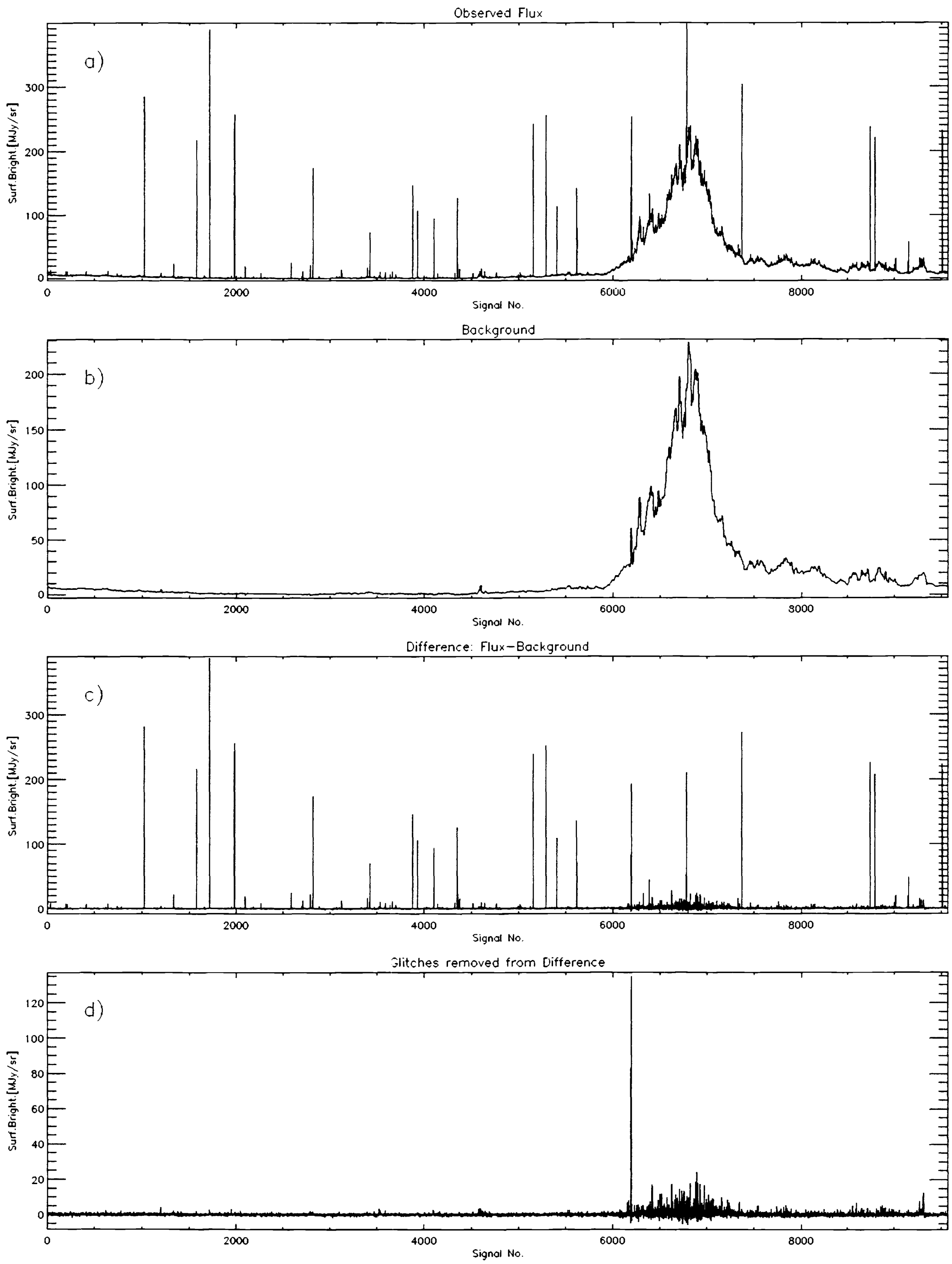

Figure 1. (a) Data stream of one detector pixel for a long (> 130°) Serendipity slew crossing the galactic plane. (b) Estimated Background (see text). (c) Background subtracted slew data showing strong glitches and increased noise near the Galactic Plane. (d) Glitches removed from the difference. The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

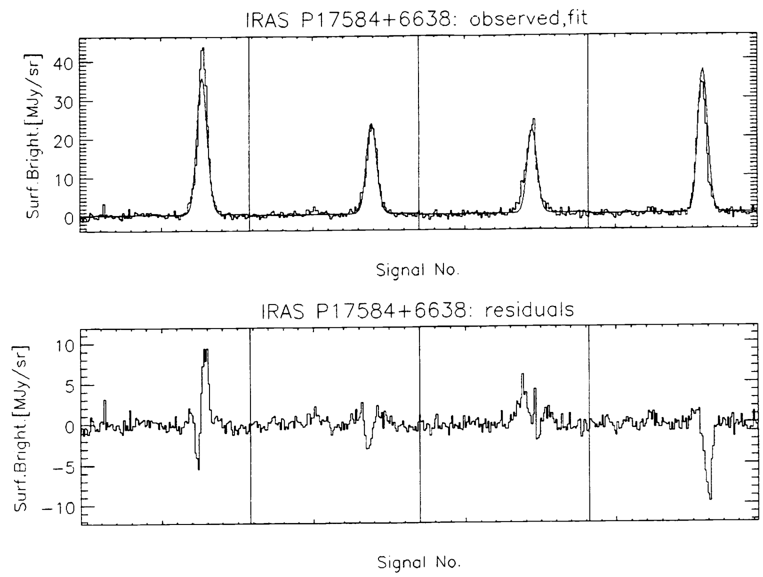

Figure 2. Serendipity Slew data for NGC 6543. Each panel shows for all four detector pixels the region used for the two-dimensional fit side-by-side. For each source the upper panel shows the background subtracted data (histogram) together with the fit results (continuous line), while the lower panel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

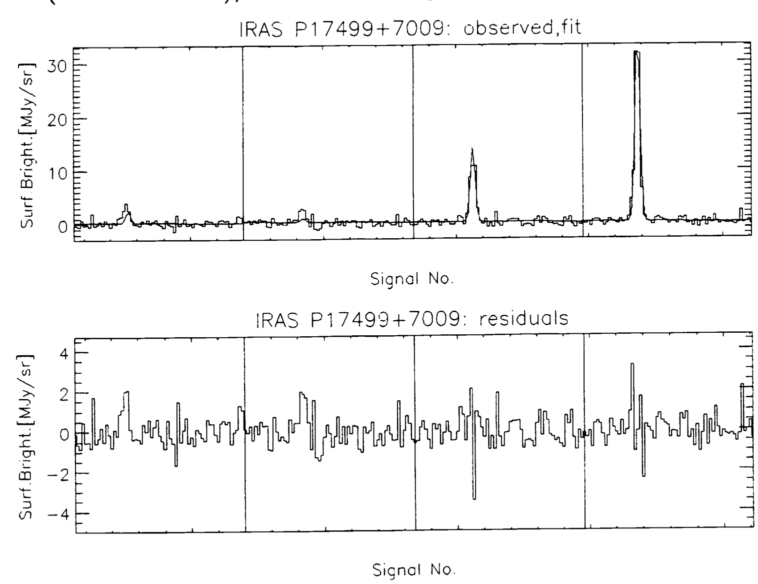

Figure 3. Same as Fig. 2 for NGC 6503.

angle of the detector (rollangle) and the position angle of the slew velocity can be used to determine the minimal distance of a crossed source perpendicular to the slew. This will decouple the derivation of the source position from the determination of its total flux, which in turn prevents that the two-dimensional fit converges to undoubtedly incorrect values for both the flux and the position.

The slew processing is illustrated with the fit results to sources covering a wide range in fluxes. Two of the brightest Serendipity Sources are the planetary nebula NGC 6543 (IRAS 17584+6638, Fig. 2) having an IRAS 100

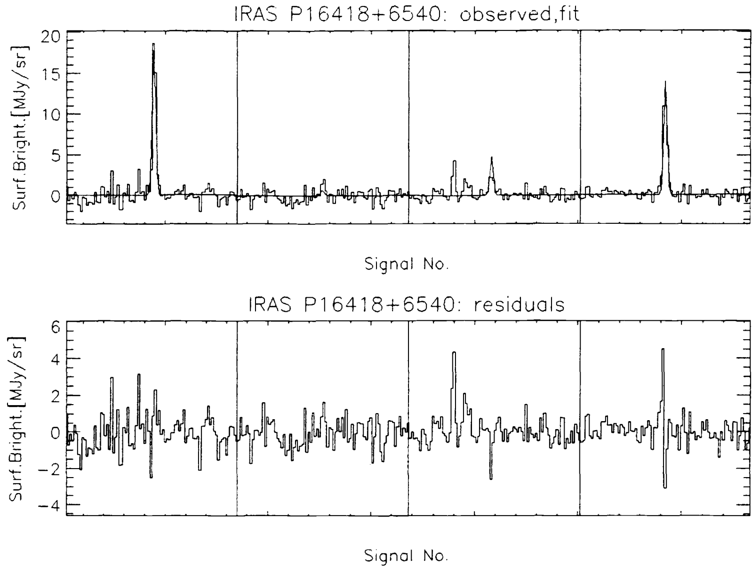

Figure 4. Same as Fig. 2 for IC 1228.

μm flux of $\approx$ 63 Jy and the galaxy NGC 6503 (IRAS P17499+7009, Fig. 3) having an IRAS 100 μm flux of $\approx$ 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 resolved nature of this source or because of detector drifts. The derived Serendipity 170 μm fluxes for both NGC 6503 and NGC 6543 is $\approx$ 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, Fig. 4) with $f_{100\mu m} \approx 7.4$ 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 10% and yielding $f_{170\mu m} \approx 7.1$ Jy. UGC 11099 (IRAS P18012+6725, Fig. 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, Fig. 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 not completely removed glitches become important, as can be seen in the residuals of detector pixel no. four (rightmost) for UGC 11099 (Fig. 5).

5. FIRST RESULTS : THE NORTH ECLIPTIC POLE MINISURVEY

Early results using a few selected slews have shown, that the Serendipity Survey data can be used to investigate astrophysically relevant questions.[4] In order to test the software under development, and to gain experience with the bulk data processing, the Consortium on the ISOPHOT Serendipity Survey (CISS) has selected a 100$\square^\circ$ 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. As of August 14, 1997, the Minisurvey field has been crossed by 336 slews of various individual lengths, totaling 1263 degrees inside the Minisurvey field, corresponding to 4.2 hours of observing time.

The investigation of this field emphasized the detection and completeness of point sources in comparison with previously known IRAS sources. In view of the early stage of the data analysis, the derived fluxes as well as the

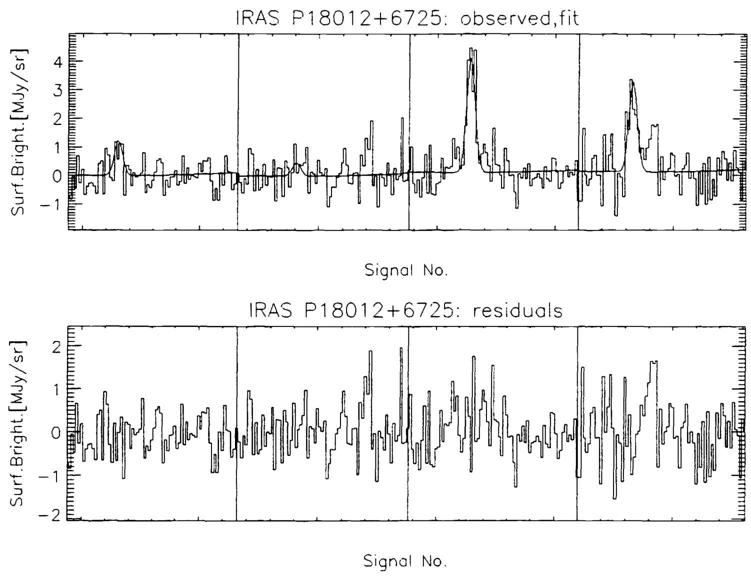

Figure 5. Same as Fig. 2 for UGC 11099.

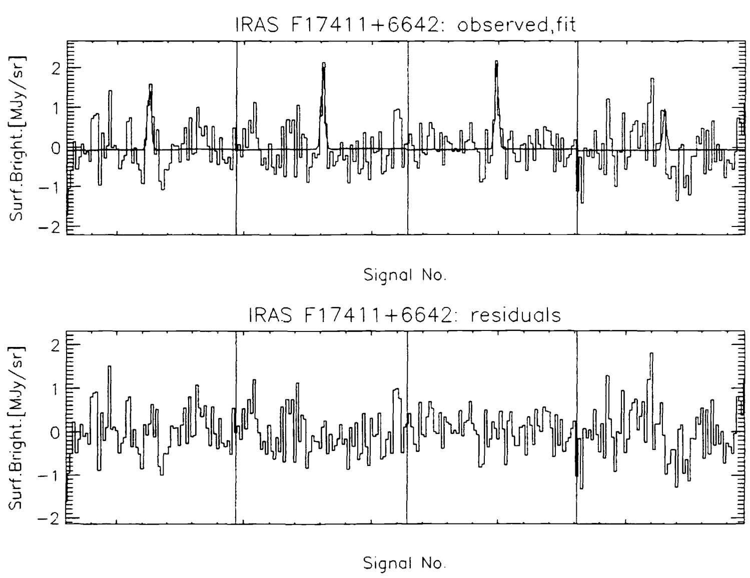

Figure 6. Same as Fig. 2 for UGC 10953.

Table 1. Cumulative statistics of the source detection completeness in the Minisurvey field for IRAS sources nominally closer than 2′ 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%

reliability of sources found on the slews were used to assess necessary improvement in the processing of the slews.

5.1. Completeness

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

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 to 50%, 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′ 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.

5.2. Fluxes

The two aspects of importance concerning source fluxes are the internal accuracy, 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. As noted above, the internal flux accuracy of the brighter sources appears to be limited by the inaccuracy of the two-dimensional gaussian to represent accurately the source profile. Moreover, a trend is seen for repeatedly crossed sources that only crossings where the source lies closer than $\approx 1'$ to the slew will result in trustable fluxes, whereas larger distances give a much larger scatter in the derived fluxes. Tieing the fluxes derived from the Serendipity Slews to an absolute photometric level requires dedicated calibration measurements of repeatedly crossed sources with varying impact parameters covering a wide flux range. For ten such Serendipity sources covering the whole observed flux range dedicated photometric calibration measurements using small raster maps have been obtained. These measurements will eventually be used to check if a common rescaling will be sufficient or if brightness dependent corrections have to be applied to the Serendipity fluxes.

5.3. Reliability

In a first attempt to assess the reliability of the source detections, i.e. the nature of sources which do not necessarily have an IRAS counterpart, all sources were selected having a detection with a signal-to-noise ratio of more than 3 in at least 3 detector pixels and a fitted width in right ascension and declination of $0.5' < \sigma < 2'$. About 2/3 of these are associated with IRAS point sources, while all others are either contained in the IRAS faint source catalog or are identified on ISSA maps as narrow, highly elongated cirrus ridges, which have accidentally been crossed along the short axis. While selecting sources according to their widths will definitely eliminate cosmic ray hits and very broad cirrus regions, further improvement of the software is required to separate narrow cirrus ridges from point sources and also to find point sources on top of broad cirrus regions.

6. CONCLUDING REMARKS

The assessment of the Serendipity Minisurvey field yielded a frequency of source detections of $\approx 0.025/°$ or one detected source along a slew length of 40°, which is equivalent to a surface density of $0.5/\square°$. The IRAS database of cataloged galaxies and quasars gives an extragalactic source density of $0.5/\square°$ for the Minisurvey field which exactly coincides with the measured source density along Serendipity slews. Taking these values one can estimate that more than 3000 galaxies have been seen so far on Serendipity slews, which is in agreement with previous estimations.[10] As of January 1998, about 450^{h} of slew measurements with a total length of $\approx 140000°$ have been obtained. By the end of the ISO mission, it is expected that a total of $\approx 150000°$ of strip maps will have been gathered, containing the crossing of ≈ 4000 galaxies. The anticipated total sky coverage will be $\approx 17\%$. However, as noted above, 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 useful flux values. This would bring the effective sky coverage down to $\approx$ 10%, 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% can eventually be expected. This will provide a large database of 170 μm fluxes mostly for galaxies. The investigation of the Minisurvey field is the starting point for a catalog of well detected sources with distances of less than 45″ to the slews and a signal-to-noise ratio of at least 3 in at least 3 detector pixels.

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