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Image Enhancement using the IRAS Survey Data

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Grant No. AFOSR-86-0140

Final Scientific Report
March '86 to March '89

P.R. Wesselius, Principal Investigator

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SRG Note 89-01

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On the cover:
On the front cover, one of the regions is shown that has been studied with the high resolution techniques developed in this project. The false-color photograph represents N11, an HII region in the Large Magellanic Cloud.

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1 Summary

The goals of this project have been defined in 1985 as follows: "An improved global calibration will be derived and image enhancement techniques developed to increase the image quality, sensitivity, and spatial resolution of maps from the Infrared Astronomy Satellite (IRAS) survey data. Enhanced maps of selected regions of the sky will be used to improve and validate the AFGL infrared celestial background model". These goals were achieved by augmenting and extending the work started in 1984 on IRAS data Processing in Groningen. The total project, operational from 1984 to probably 1992, is called "GEISHA" (Groningen Exportable IRAS High-resolution Analysis) system. All goals of the AFOSR part of GEISHA were achieved by March '89. Therefore, it was necessary to make a few more products than anticipated.

A completely new calibration scheme using the zodiacal light emission as a standard candle has been designed and implemented. The standard IRAS data products presently available, that were produced at the IRAS Processing and Analysis Center (~~IPAC at Caltech,~~ Pasadena, U.S.A.), were all calibrated using the point-source-like response of the calibration "flashes". Our calibration is better suited for smaller spatial frequencies. Comparison of the zodiacal light calibration and that of IPAC, for point sources, gives very satisfactory results (< 10 %) at the wavelengths 12, 25, and 60 μm, but a 50 % error at 100 μm. Also scans making an angle larger than 5° 6 with the plane perpendicular to the line Sun-IRAS cannot be calibrated properly; there are only few of such scans.

An iterative least squares (ILSQ) routine has been prepared that makes it possible to enhance the resolution of an IRAS image to slightly better than 2 arc minutes, for most regions of sky. The output of this routine is directly traceable to the input and the method is rather straightforward and, because of that, a lot faster than other non-linear methods developed to restore IRAS images: e.g. FIER ~~by Kennealy~~ et al. (1987). FIER produces higher-resolution images than ILSQ, but the method needs verification. Our ILSQ program is ideal for creating large spatial resolution enhanced images, and for checking e.g. FIER results.

While preparing these two main products it became evident that a number of other — originally unforeseen — products were also needed.

It was not as simple as expected to combine the detector data and the pointing restoration. The IPAC-produced Boresight Pointing History File (BPHF) needed to be reduced by a factor five, and to be cut in pieces that corresponded to the 363 sky regions defined in an earlier stage of the GEISHA project (stored on 363 "plate" tapes).

The "sample" file was defined, a combination in one Fits-like file of the calibrated detector data and the pointing information.

Before being able to run the ILSQ program it is essential to correct the input image for responses not caused by actual sky sources (deglitching) and for the baseline differences between scans (destriping). A deglitching/destriping/imaging program was made, and is so succesful that the IPAC-produced Super Sky Flux product uses that routine.

A spline-smoothed "plate" system was created as well, consisting of 40 instead of 363 tapes. Images with a resolution of 8 arc minutes can be made using this data base, and because of the low spatial resolution it is feasible to make images of very large sky regions.

Resolution-enhanced images of quite a number of sky regions have been produced already, and are being produced at present. The recent arrival of an Alliant computer will make it possible to handle really large regions of sky.

An overview of the GEISHA system has been published in 1988 (see Appendix 1). It now runs on a Cyber 170/760 (NOS), a VAX8600 (VMS), a SUN 3-280 (UNIX), an Alliant (UNIX), and a Convex (UNIX). This proves that the package is exportable, although it is advisable — at present — to use sample files, created in Groningen, as input for further processing.

2 Data Bases

The following data bases have been created **and** will be maintained in the coming years.

2.1 complete scans in FITS format

We originally started the job with 1000 magnetic tapes imported to Groningen from the IRAS ground station at Chilton, U.K. in 1984. As the first data processing step an index of the contents of these tapes was made and they were converted to the astronomical standard for data exchange, FITS (Flexible Image Transport Standard). That led to 6 sets of 30 tapes for the up and down scans of the three HCON's, 2 sets of 5 tapes for the Minisurvey, 60 tapes for the AO data, and a few tapes for calibration and administration (these have the labels RID<id><nn>; id = A, B, C, D, E, F for the survey scans; id = G, H for the minisurvey; id = I for AO's; id = J for calibration and administration).

2.2 Plate Tapes

These complete scans were subsequently cut into pieces of about 15° long and sorted to sky regions. The goal of the sorting operation was to put **all** IRAS data pertaining to a certain region of sky (of order $15^\circ \times 15^\circ$) on **one** magnetic tape. Another requirement was to be able to make a map of any $1^\circ \times 1^\circ$ region of sky just accessing one tape. In order to achieve this we had to divide the sky in 363 regions, and consequently the data base consists of 363 magnetic tapes (density 6250 bpi).

If a sky region needs to be studied that is larger than $1^\circ \times 1^\circ$ it may be needed to access more than one tape. For convenience in transporting the data of such regions there exist *cutting* and *glueing* programs to create a new tape (or set of tapes) that contain all data of the desired sky region.

The actual sorting to *plate tapes* was done in two stages, because it was more efficient and to have another intermediate data base as a backup (tapes are definitely not the best way to store data permanently). In the first stage the scans were cut into scan *snips* suitable to incorporate in the plate tapes, but only ordered to *families*, i.e. rather large sky regions. That led to tapes RIF<Fam.><nn> (Fam. = A ...S).

Subsequently each large sky region was sorted to plates, the tapes RIP001 ...RIP363.

2.3 BPHF

The boresight pointing history file (BPHF), giving information about the pointing direction of IRAS for every second of its life (about 26 million seconds) has been obtained from IPAC, 103 magnetic tapes (BPH01 ...BPH103). By omitting redundant numbers and recording movement rather than absolute position, it was possible to reduce this data base to 21 tapes in FITS format (RIBH01 ...RIBH21, at 1600 bpi), without loss of accuracy.

The BPHF was cut into snips and sorted such that all BPHF data relevant to a certain plate were combined. It is the eventual aim to put these data on the plate tapes themselves, but at present they are stored on separate tapes (RIP401 ...RIP408).

Many sky maps have already been made by combining detector data and BPHF data, and usually that is quite succesful. We have verified that the match is normally OK. However, about one scan per region of $3^o \times 3^o$ lies of the order of 15^o away from the region. We have been unable until now to discover where the error is introduced. In the near future we will obtain SUPERBORESIGHT from IPAC. Then we will snip and order those data anew, and hopefully the problem will disappear.

2.4 Miscellaneous

Some other data bases, relevant for IRAS data processing, are stored as well.

The response functions of all detectors as derived by Moshir from IPAC are on tape RRB001.

All raw detector data were smoothed using cubic splines to a resolution of about 8 arc minutes. Then all IRAS data can be put on just 25 tapes, RIDS<Hcon><n>.

Finally, the data pertaining to all stimulator flashes, that were done at the begin and the end of each scan, were put aside and compressed, by using an appropriate template, to just one value and its uncertainty per flash. This led to two tapes (RIFZC0, RIFZC1).

3 Sample files

In order to make the raw IRAS data in a computer-independent way available to the astronomical community a new intermediate data product has been designed: sample files. For a given region of the sky, a sample file contains all information present for one of the IRAS wavelength bands. Each **flux calibrated** detector readout and its position are present, leading to a long table of brightnesses and coordinates, and their respective uncertainties. Even the orientation on the sky of a particular detector is given for each sample.

This table can be processed further for several applications. The main one is a destriping/imaging program, followed by the iterative least squares image enhancement program.

It is also possible to study individual scans by plotting intensity versus time, and to coadd the data of all scans running through a particular point on the sky.

4 Destriping and Imaging

The IRAS satellite made scans of order 180^o long and 0.5^o wide. The first set of maps were made at IPAC, the *Sky Flux* maps. These have been widely used. They were made by dividing the sky in bins of 2×2 arc minutes; when a sample overlapped a bin its value was stored in the bin. Averaging all values in a bin resulted in a sky map. Maps created in this way have a resolution corresponding to the detector size or poorer, if scans at different angles are combined. Other methods to co-add the scans lead to similar resolutions.

Imaging methods like those creating Sky Flux leave responses due to *stripes*, *spikes*, and *space debris* in the map. Stripes are caused **both** by local imperfections in the flux calibration which show as straight-lined structure in the scan direction of the satellite and by differences in the zodiacal light level at the time of observation.

Spikes are the results of particle hits on the detectors. They can be mistaken for genuine point sources (a point source is only seen in two to three samples). Not too close-by space debris and asteroids are indistinguishable from point sources in a single scan. The IRAS Point Source Catalog had a confirmation strategy that eliminated all such undesired point sources, but for images other methods have to be used.

A program has been developed to produce images from sample files and to correct these images in an interactive way for striping and unconfirmed point sources. It is possible to read in an existing map (in FITS format) or the program can create a new map first. Either just a map or an iteratively destriped map can be made. Images are produced by a coadd of sample file data into a map either with a circular beam or with the 'true' detector size as a beam. Some scans can be excluded from the process, if they are deemed bad or are unwanted otherwise.

Stripes are removed as follows. Each individual detector scan is modelled as a straight line. The line, determined using linear regression, is subtracted from the detector scan and the result is coadded into a new map. This process is done for all scans. A new map ensues which contains less stripes. Typically, the whole procedure is iterated five times. Usually the resulting maps have no visible stripes any more. Occasionally the map is still bad in a small region. That is often due to calibration problems with the snip of an originally short scan (not running from ecliptic pole to pole). A simple remedy is removing that scan snip.

Spikes, asteroids and space debris are eliminated from the final map by applying a median filter in the coadd algorithm. The unwanted responses appear only in some of the overlapping scans, while the majority of the scans has proper information on that position. A median filter puts heavy emphasis on the response of the majority of the scans, and eliminates largely deviating points.

With this program it is possible to make sky maps retaining the resolution of a simple coadd. The maps are free from artefacts which plagued the Sky Flux maps such as stripes, spikes, space debris, and asteroids. Moreover, all three HCONs can be combined into one map which increases the signal-to-noise ratio by at least a factor 2. Finally, the output from this program is the ideal input to the ILSQ program described below.

5 Calibrating IRAS using Zodiacal Emission

Inspired by the work of Dr. Price during a visit of half a year to Groningen a new calibration has been developed employing the zodiacal emission, that is clearly present in each long scan (at least at 12, 25 , and 60 μm). Such a calibration has advantages over the scheme employed by IPAC. The IPAC calibration uses the very short (few tenth of a second) stimulator flashes at the begin and end of each scan. These are ideal to calibrate the detector response to point sources, but it is known that the long-term behaviour of the detectors is different. In order to calibrate extended features using the zodiacal emission that extends over many tenths of degrees as a standard candle might produce a more consistent result. IPAC applied the point source calibration to their Sky Flux product. It is interesting to compare our eventual maps with theirs.

We have assumed, because of several IRAS studies of zodiacal emission by others, that the zodiacal emission as a whole can be approximated by the emission of a tilted oblate ellipsoid of uniform density and temperature. The socalled side bands at low ecliptic latitudes have newly been discovered by IRAS, are interesting in their own right, but are a nuisance for our calibration goal. We therefore ignore a small part of the emission near ecliptic latitude 0°.

Apart from the zodiacal emission, there is always a contribution of galactic emission, especially prominent at 60 and 100 μm. The large-scale galactic emission can, just as the zodiacal emission, be used as a standard candle. At 100 μm the large-scale galactic emission is in fact more important for calibration purposes than the zodiacal emission, which is faint and only present at low ecliptic latitudes (just a few degrees). The method is described in more detail in a conference paper that is attached as Appendix 2.

To calculate the calibration parameters we make the following assumptions. As a standard candle we take the sum of a (too be determined) Zodiacal Emission Model (ZEM) and Galactic Emission Model (GEM): $ZEM + GEM$. The baseline is allowed to change linearly over a scan. It is assumed that the slow exponential decay of the detector response that occurs will be sufficiently approximated by a straight line. Finally, an in-house developed model for the non-linear behaviour of the gain is applied.

All linearization corrections to the data have to be applied first. The actual model values for ZEM and GEM have to be derived from the linearized IRAS uncalibrated data in a kind of least-squares fashion. Many iterations through all the data of a band are needed to derive a final calibration.

To actually perform this calibration a lot of data processing had to be done, and software had to be created. The original uncalibrated IRAS data were smoothed, in a number of steps, to just a few promille of the data volume. These smoothed data were extensively studied to arrive at a suitable ZEM and GEM, and to develop a processing method.

The smoothed data base still comprises several hundred Mbytes, and running one calibration task for one band (a lot of iterative operations are done) costs a few days on a stand-alone SUN 3-280. Therefore a simplified version, only using a ZEM as the standard candle, is operational at present.

The simple calibration compares well with the Point Source Catalog calibration at 12, 25, and 60 μm (to within 10 %). It does not work well if the scans to be calibrated had an angle to the Sun-satellite direction that deviates more than ten degrees from 90°. It also does not work well at 100 μm, because the zodiacal emission is a feeble standard candle at that wavelength.

In the summer months of 1989 a much larger, Alliant computer will become available and will make it possible to run the calibration jobs in a reasonable time. We expect to have the improved $ZEM + GEM$ calibration ready and operational by October 1989.

6 ILSQ Image Enhancement Program

Reconstruction of images from a collection of scans, like obtained with IRAS, requires the developement of new techniques in the field of image restoration. Conventional image restoration methods do not work, because they start from already existing images, which are degraded to some extent. A collection of scans, however, does not form an image. A scan can be regarded as a one-dimensional cross-cut through the image. More precisely, a scan represents the brightness of a narrow strip of the sky, convolved with the response function of one of the IRAS detectors. The image has to be reconstructed from the deconvolution of the scans, together with the arrangement of the scans over the region.

It is especially important to improve the poor spatial resolution in the cross-scan direction. That is — in principle — possible, because of the confirmation IRAS survey strategy: over most positions on the sky there run six scans, and more specifically the detectors are shifted by half a detector width between two — one orbit apart — scans.

An iterative linear least squares deconvolution scheme has been devised which is insensitive to the uneven coverage of an area by scans. The method allows both to obtain a higher angular resolution than the simple co-adding technique and to provide an ensuing map on a regular mesh. In order to apply this method without introducing artefacts it is needed to use the best possible response functions of the detectors; the rectangular approximation of the co-adding ("Sky Flux" type) method is inadequate. The method makes the following assumptions.

Each sample is regarded to be the convolution of the sky with the response function of the detector that has obtained the sample. It is assumed that the zodiacal emission has already been subtracted, and that the detection process is linear, which ignores the memory effects in the detectors. The map area is divided into a number of pixels, and the brightness is regarded constant over one pixel area. The pixels are surfaces and measure typically one square arc minute.

The ILSQ method amounts to solving an equation of the type:

$$D = PB, \tag{1}$$

with D a vector of length N representing all measured values, B a vector of length M being the unknown brightnesses, and P a $N \times M$ matrix. Clearly for this equation to be solvable $N \geq M$; also all pixels must be covered at least once.

The possible angular resolution of the reconstructed image depends on the number of samples per unit area. The place and orientation of the scans running over a map with respect to each other will obviously also play a role: the sought spatial frequencies must be present.

Fortunately the matrix P is sparse, because the solid angle of the response function of one detector covers an area much smaller than the usually requested map area. The majority of pixels is not covered when a sample is overlayed on the map grid. The sparseness is determined by the surface area ratio.

Direct least squares methods, which solve overdetermined systems, tend to fill the entire matrix P, which becomes rapidly unmanageable on present computers. Iterative methods that preserve the sparseness of the matrix are therefore required. The LSQR algorithm of Paige and Saunders (1982) turns out to work well, and does even more, viz. it solves damped least squares problems. The introduction of a damping factor λ 'regularises' the problem, in the sense that the solution B has become less sensitive to outliers in the data D.

The right damping factor has to be chosen for each map anew. The pixel size should be chosen such that the system remains sufficiently overdetermined: the smaller the pixels the larger the noise. In general, the reconstruction of a map turns out to be acceptable when the number of equations N exceeds the number of pixels M by a factor 3–4.

We conclude that the iterative LSQ method to produce images of the far-infrared sky using the IRAS survey data as input works very satisfactorily. For most regions of sky, images can be made with a resolution of slightly better than 2 arc minutes, also in the **cross-scan** direction. A more extensive paper on this topic is in preparation and some preliminary figures of that paper illustrating the results have been attached to this report as Appendix 3.

Reference

Paige, C.C., Saunders, M.A. 1982, ACM Trans.Math.Softw. Vol 8, No 2, p 195–209.

Publications

Quite a number of publications have directly resulted from the work performed for this grant. The major ones are presented below.

- Bontekoe, Tj.R., Kester, D.J.M., Wesselius, P.R., Price, S.D. 1989, Creating High-Resolution IRAS Maps, in preparation (Figures added as Appendix 3)
- Kester, D.J.M. 1985, Superresolution, SRON-SRG Internal Report, GEISHA-GA 85/11/28
- Kester, D.J.M. 1986, IR Photon Detectors, SRON-SRG Internal Note GEISHA-GA 86/05/07.
- Kester, D.J.M., Bontekoe, Tj.R., de Jonge, A.R.W., Wesselius, P.R. 1989, IRAS Calibration, Proc. 3rd International Workshop on Data Analysis in Astronomy, Erice, Italy (added as Appendix 2).
- Kester, D.J.M., Wesselius, P.R., Price, S.D. 1989, Improvements in the IRAS Calibration by Separation of the Different IR Surface Brightness Components, IAU Symposium No. 139, Contributed Paper.
- Wesselius, P.R., Bontekoe, Tj.R., de Jonge, A.R.W., Kester, D.J.M. 1988, GEISHA, in Astronomy from Large Databases, ESA Conference and Workshop Proceedings No. 28, p. 85. (added as Appendix 1).

G E I S H A

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SUMMARY

The GEISHA (Groningen Exportable Infrared Survey High-resolution Analysis) system has as its two main goals to provide astronomers with direct access to the raw (uninterpreted) data and to develop high-spatial resolution algorithms. Exportability was formulated as a secondary design goal of the project.

The problem of calibration of detector read-outs in terms of surface brightness distribution over the sky involves a non-trivial, and possibly subjective, decomposition in detector physics and astrophysics. This led us to the decision to make un-interpreted detector readouts accessible, especially for attempting the highest possible resolution in imaging, but also for study of large-scale structures (tens of degrees).

GEISHA has two main output products for astronomers: sample files and sky maps. A sample file has all necessary information on detector positions and orientations, errors, and flux calibration. It can be used to make a sky map, or as input for the application of high-resolution techniques.

In order to be able to make maps, surface brightness and position calibrations are required. If (extra)galactic emission needs to be studied a zodiacal emission model (ZEM) is also needed. Such calibrations and a ZEM model are provided by GEISHA.

I IRAS DATA ACCESS

The basic material for the GEISHA project is the raw IRAS data, containing all telemetry data from the survey instrument detectors, and the pointing information. The data were originally taken in almost random scans over the sky, and presented in order of observation, distributed over 1000 tapes. To optimise the GEISHA system for detailed investigation of (not too large) sky regions both the detector data for the scans and all auxiliary data necessary for pointing and flux calibration were reorganised into a system of 363 plates. A plate is here defined as a coherent region of the sky, large enough to fill one magnetic tape in FITS format, which then forms a totally self-contained dataset.

For routine inspection of the data a set of programs is available, applying position and/or flux calibration to the raw detector outputs, with some variation in algorithm used. The end products of these programs are

- a file ("sample file") containing the sampled output of all IRAS detectors covering the region of interest during survey scans, each sample labeled with time, position and orientation of the detector, and errors in these quantities;
- an image of the region, formed by the surface brightness on an almost arbitrary pixel grid, as reconstructed from these samples.

All intermediate and end products of these programs are in FITS format to fulfill our export requirements. The subroutines used in these standard programs are available as a software library for special research projects.
Currently, we have the detector data distributed over the plate tapes, but not yet the auxiliary data. Auxiliary data and software are available for a flux calibration method based upon the zodiacal light, positional calibration according to IPAC methods, and imaging by co-adding.

II EXPORTABILITY

Exportability was formulated as a secondary design goal of the project, both for the data sets and for the access software. This would give the system better survival chances after the initial effort, enabling us to migrate to the best environment for funding/computing/access facilities.

The exportablity was achieved by:

- use of Fortran-77 as the commonest language in astronomical computing,
- isolation of computer-system dependencies into a small set of subroutines,
- use of magnetic tape in FITS-standard format for all data bases,
- use of two widely different computer systems in development, a DEC PDP-11/44 running UNIX V7 and a CDC Cyber 170 running NOS,
- a (present) transfer of the GEISHA user system to a VAX 8600 running VMS.

III CALIBRATION

III.1 Introduction

The GEISHA system will supply the astronomer with a choice of calibration routines and zodiacal emission models (ZEMs) to subtract if required.

All calibrations have a common structure: it is assumed that the raw detector data consist of a baseline (the detector bias) plus the 'true' infrared flux multiplied by a gain. Both the baseline and the gain might vary slowly due to photon and particle induced memory effects, instrumental degradation etc.

The main differences between IPAC (IRAS Processing and Analysis Centre, U.S.A.) and GEISHA are in philosophy. IPAC uses the instrumental response of the internal calibrator as their standard candle to determine the gain and the daily observation of a piece of sky near the ecliptic north pole (TFPR) as a monitor of the baseline. GEISHA has an external standard candle: the zodiacal emission. It tries to autocalibrate the IRAS database.

The first calibration schemes, both at IPAC and GEISHA, were quite simple: the changes in gain and/or baseline were slow and global. The later schemes involve some model on the behaviour of the detectors. Different instrumental models give rise to differences in calibration routines.

There exists a whole range of possible ZEMs, from a simple lower-envelope cubic spline fit to a full-fledged physical model with densities, emissivities, and temperatures as a function of position in the zodiacal dust cloud. Here again the choice is to the astronomer.

III.2 GEISHA calibration nr 1

The model for the first GEISHA calibration consists for each scan of a linearly changing baseline plus a constant gain. The zodiacal emission is the standard candle: data = baseline + gain * ZEM. A gain and a baseline is found for each detector in every scan. The ZEM itself is derived as the mean lower envelope to all scans.

As the intensity of the zodiacal emission changes also with the solar aspect angle, the ZEM can not simply be used as a standard candle. In this calibration procedure our assumption was that the ZEM could be separated into the product of two functionals, one in ecliptic latitude, $ZE90(\beta)$, and one in solar aspect angle, $f(\theta)$. The latter is temporarily married to the gain. This product will be derived from a lower envelope fit of the scan to the ZE90. Afterward divorce takes place: the θ-dependent part moves into the ZEM = $ZE90(\beta) * f(\theta)$ and the remainder is the gain.

This calibration is operational since begin 1987.

III.3 IPAC calibration nr 1

In the first IPAC calibration every scan has a constant baseline. Monitoring the TFPR (total flux prime reference field) twice a day leads for every SOP (= Satellite Operating Plan = 1/2 day) to a new set of baselines, one for each detector. In flight it was discovered that the baselines at 60 and 100 µm were affected by the bias boost. A slow decay was included with timescales of 50 minutes typically. The gain is calculated from the response on the internal calibrator source at the begin of the scan and at the end. The gain was allowed to change linearly during the scan.

All presently available standard IPAC products are based on this calibration.

Note: this calibration will NOT be implemented in the GEISHA system.

III.4 GEISHA calibration nr 2

As a result of the first GEISHA calibration a ZEM was found that was a product of two functions, one in ecliptic latitude and one in solar aspect angle. The function in ecliptic latitude could be very precisely approximated by an ellipse. This led to the conjecture that the zodiacal emission as a whole could be approximated by the emission of a tilted oblate ellipsoid of uniform density and temperature. At the IRAS conference in London (1987) our geometric model was corroborated by a paper presented by W. Reach and C. Heiles who had made a physical ZEM consisting of ellipsoidal equidensities and had the model integrated up to a 'last equidensity contour'.

An ellipsoidal model can never fit the so-called sidebands of the zodiacal emission (Hauser et al., 1984). The sidebands have been identified with 3 asteroid families (Dermott et al., 1984). From considerations of celestial mechanics it seems reasonable to model them with a number of inclined tori fanned over all nodal angles. A side band model (SBM) incorporating these ideas is still under study by us.

Apart from the ZEM there is always a contribution of galactic emission. The galactic emission is so granulated that only a map of the whole sky can function as a model. A fairly coarse map is sufficient. We took an equal area projection with pixels of 1 by 1 degree. Each pixel is the mean of all overlapping detector values.

As a standard candle we take the sum: ZEM + SBM + GEM. We allow the baseline to change linearly over a scan. We assume that the slow exponential decay as found by IPAC will be sufficiently approximated by a straight line. The non-linear behaviour of the gain will be corrected according to a model developed in the report "IR Photon Detectors" May 7, 1986 by Do Kester.

The complete model, data = baseline + gain * (ZEM + SBM + GEM), contains as free parameters: 5 for ZEM, 6 for SBM, 40000 (pixels) for GEM, 4 for each scan (2 baseline and 2 starting conditions), and 4 for each detector (2 decaytimes and 2 increments). In total about 64000 parameters have to be estimated, still a tiny fraction of the complete database of 13 Gbyte.

This calibration and the pertaining ZEM will be available by middle 1988.

III.5 IPAC calibration nr 2

In IPAC's second model the baseline is a slowly varying function, now for the two shorter wavelength bands too. Its value at the time of the so-called bias boost decays on a typical timescale of 1000 seconds. For the two longer wavelengths (60 and 100 μm) a photon induced enhancement is incorporated in the gain. When the detector response exceeds a preset threshold the gain increases proportional to the detector response. That increase decays on timescales of 500 and 1500 seconds for 50 and 100 μm resp. The maximum correction is 10 to 20 %.

This calibration is under development and will also be made available to GEISHA users by middle 1988.

A physical ZEM is under development by J. Good.

III.6 References

Dermott, S.F., Nicholson, P.D., Burns, J.A., Houck, J.R. (1984), Nature, vol. 312, p. 505.
Hauser, M.G. et al. (1984), Astroph. J. Lett. vol. 278, p. L15.

IV <u>SAMPLE FILES</u>

In order to make the raw IRAS data in a computer-independent way available to the astronomical community a new product has been made: sample files. For a given region of the sky, a sample file contains all information present for one of the IRAS frequency bands. Each detector readout is present, leading to a long

table of coordinates and brightnesses. This table has to be processed further to make maps of the region of interest. Presently, coadded maps can be made having a resolution equal to the sizes of the detectors: about 5 arcminute in the cross-scan direction, and 0.75 to 3 arcminute in the in-scan direction, depending on the frequency band. The overall accuracy of the coordinates is better than 3 arcseconds. The position of known point sources is reconstructed only to 3" in-scan and 20" cross-scan, due to the asymmetrical point spread function of the detectors.

The brightness can be calibrated against the zodiacal light emission (GEISHA calibration). Samplefiles can be used by an astronomer who wants to make his own (high-resolution) image of the sky.

V IMAGING

V.1 Linear Resolution Enhancement

In order to give an idea of the amount of data IRAS gave us: 1 square degree of the sky near the ecliptic equator has been sampled 40000 times in 12 and 25 μm (60 μm: 20000; 100 μm: 10000). Towards the ecliptic poles these numbers increase by an order of magnitude, due to the convergence of the scans.

A resampling of the 40000 detections evenly over the area, would give a linear sampling distance of 30 arcseconds. A linear least squares reconstruction technique has been devised which actually yields 30 arcsecond pixel images. However, the resolution cannot be better than the telescope quality permits, i.e. 25", 25", 60", 100" at 12, 25, 60, and 100 μm. The resolution will be worse because only some high spatial frequencies are present, but a resolution of 3 arcminutes should easily be attainable.

The method works as follows. If the area of interest is divided into small pixels, each detector readout covers a number of them, say 10. The measured brightness is then the sum of the unknown brightnesses of these 10 pixels convolved with the point spread function. This coverage can be described as one equation in many unknowns (= all pixels), for which the right-hand side is the one measured brightness. But the vast majority of these unknowns have a coefficient equal to zero, because most pixels are not seen by the detector under consideration. The next readout of the same detector now covers say 7 pixels of the previous 10, and 3 new ones as the satellite scans the sky. This new equation is partly coupled to the previous one through the 7 common unknown brightnesses (which are assumed to be constant).

The coverages of the area should interconnect all pixels, and the set of sparse equations thus formed can be solved for the unknown pixel values, in a least squares sense. A nessessary condition is that there are more equations (= readouts) than unknowns (= pixels). Therefore, in principle the number of pixels per unit area, and thus the resolution, will be higher near the ecliptic poles than at the equator.

V.2 Maximum Entropy

A further enhancement of the resolution is expected from Maximum Entropy Method (MEM) image restoration techniques. This method is still under study, but a further increase of the resolution to 30" seems possible (Skilling, private communication). The resolution, however, need not be constant over the map: areas with more coverages will be reconstructed with higher resolution than sparsely covered ones. A second map of the final resolution then has to be provided.

The advantage of MEM is that simultaneously a number of calibration problems can be solved for. Presently, when a strong source has been passed, the detector behaves as having got a new zero-point and a new sensitivity. This effect is not yet corrected for. Also slow drifts of zero-points and sensitivity, apart from the ones already accounted for in the calibration, can cause stripes over the map. The MEM permits parametrisation of these effects, and solves for the 'best' image and the 'best' determination of these parameters at the same time. The disadvantage, however, is the increase in computational cost by two orders of magnitude for the same area of sky.

VI CAPABILITIES OF GEISHA

The following tasks can at present be performed by the user/astronomer.

- Coordinate transformations between any of the following systems: Equatorial 1950, Equatorial 2000, Galactic, Ecliptic 1983.5, and Sunreferenced.
- Find the plate(s) where the data of a given region is stored. The output is one or more platenumber(s). Snip and/or glue a new plate with the desired region in its center.
- Calibrate the scans with GEISHA calibration nr 1.
- Subtract the zodiacal emission model.
- Plot a scan as a function of time or of ψ.
- Perform a one-dimensional coadd.
- Plot the run of all scans over a map.
- Coadd all scans with a circular beam into a map.
- Make a sample file, i.e. add position information.

- Coadd the sample file with detector sized/oriented beam into a map.
- Make a contour plot of a map.

Whenever a map or a projection is mentioned the astronomer can choose Stereographic, Gnomonic, Azimuthal equidistant, Azimuthal equal area, Orthographic, Cylindrical equal area, Mercator, Sinusiodal equal area, Hammer-Aitoff equal area or Cylindrical equidistant.

The GEISHA system can be used for a nominal fee. Call 31-50-634074 and ask for Wesselius, Kester or Arendz to arrange a visit.

Acknowledgements:

We thank P.C. Arendz, P.D. Duyst, W. v. Oosterom, and J.E. v. Weerden for their continuous efforts in creating software and running it.

APPENDIX 2

Erice conference contribution

IRAS CALIBRATION

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1 Introduction

The Groningen Exportable Infrared Survey High-resolution Analysis (GEISHA) system consists of a collection of software tools which allow an astronomer to create infrared sky maps from raw IRAS data. The Infra Red Astronomical Satellite (IRAS) observed about 95% of the sky by a semi-overlapping scan technique. There are 62 detectors in the focal plane in 4 wavelength bands at 12, 25, 60 and 100 μm. (See IRAS Explanatory Supplement, 1985, IRAS-ES hereafter)

The database of IRAS has been left unaltered apart from a re-sort. The underlying idea is that in the process of interpreting a certain astronomical object new questions may arise, which require a different processing of the data. Starting from the raw data has already proved to be a fruitful strategy.

One of the central items in the project is the calibration. The procedure for the IRAS raw data calibration consists of flatfielding. For each detector scan a set of calibration constants is extracted by fitting the lower envelopes of the detectors of all scans to each other.

2 IRAS Data Access

The basic material for the GEISHA project is the raw IRAS data, containing all preprocessed telemetry data from the survey instrument detectors, and the pointing information. The database of IRAS contains about 6000 scans running from one ecliptic pole to the other at a constant angle to the sun, the solar aspect angle. They were taken at an angular speed of 3.75′/sec and at a rate of 16, 16, 8 and 4 times per second, for the band at 12, 25, 60 and 100 μm, respectively. The scan strategy was organized in such a way that all sources were seen at least 8 times by a detector, yielding a data volume of more than 1000 tapes. To optimise the GEISHA

system for detailed investigation of (not too large) sky regions both the detector data for the scans and all auxiliary data necessary for pointing and flux calibration were reorganised into a system of 363 plates, which cover the whole sky. A plate is here defined as a coherent region of the sky, large enough to fill one magnetic tape in FITS format (Wells et al., 1981), which then forms a totally self-contained dataset.

Currently, we have the detector data distributed over the plate tapes, but not yet the auxiliary data. Auxiliary data and software are available for a flux calibration method based upon the zodiacal light, positional calibration and imaging by co-addition. The positional calibration was developed at the IRAS Processing and Analysis Center (IPAC) of Caltech, Pasadena, USA. (See IRAS-ES)

3 Calibration

An unavoidable part of the brightness which falls on the detectors is the zodiacal emission. It originates from dust inside the solar system and provides a broad background (or better foreground) feature with a FWHM of $\approx 50^{\circ}$. It is dominant at 12, 25, and 60 μm, and somewhat less at 100 μm. Although it is a nuisance for most astronomers, it can be used as a standard candle for calibration purposes. In the same process a zodiacal emission model (ZEM) can be established.

The GEISHA system will supply the astronomer with a choice of calibration routines and zodiacal emission models (ZEMs) to subtract if desired. All calibrations have a common structure: it is assumed that the raw detector data consist of a detector bias, plus the 'true' infrared brightness multiplied by a gain factor g. Both the bias and the gain might vary slowly due to photon and particle induced memory effects, instrumental degradation etc. A whole range of possible ZEMs can be developed, from a simple lower-envelope cubic spline fit to a full-fledged physical model with densities, emissivities, and temperatures as a function of position in the zodiacal dust cloud. Here again the choice is to the astronomer.

The total IRAS database is clearly too large to handle in one program. The first step in the reduction of the database was a cubic spline fit, which brought the sample rate down to one datapoint per second (or 3.75 arcmin). The splines are part of the GEISHA system; they can be used for the study of large scale structures. In total it is still 1 Gbyte.

The second step which was only taken for calibration purposes, involved a lower envelope fit over one degree to the splines. The lower envelope fit entailed that all single point sources dropped out; we are mainly interested in the large scale structure of the zodiacal emission. This last database contains 70 Mbyte or 18 Mbyte in each of the 4 bands.

4 Linear Model

In the first GEISHA calibration a linearly changing bias plus a constant gain was assumed for each detector scan.

$$O = a + b\,t + g\,(\mathrm{ZEM} + \mathrm{SKY}), \tag{1}$$

where O is the detector output, $a + b\,t$ is the linearly changing bias (the baseline), g is the gain factor, ZEM is the zodiacal emission and SKY is the astronomical sky. As the astronomical sky is quite empty in the infrared, the SKY term will be ignored in the linear model. The zodiacal emission is a function of the position of the earth, and the pointing direction of the satellite, given by the solar aspect angle θ, and the angle along the scan direction, ψ. The angle θ is constant during a scan. In a first approximation the annual motion of the earth through the somewhat tilted dustcloud (Hauser et al., 1984) can be corrected with a small shift in ψ.

For all positions on a scan the brightness of the zodiacal emission increases with decreasing solar aspect angle: closer to the sun the zodiacal emission becomes brighter. It is assumed that the ZEM can be written as the product of two functions:

$$\mathrm{ZEM} = f(\theta)\,\mathrm{ZEM}_{90}(\psi), \tag{2}$$

where $\mathrm{ZEM}_{90}(\psi)$ is the zodiacal emission model at a solar aspect angle $\theta = 90°$, and $f(\theta)$ is a scaling function. Both functions are as yet unknown and will be estimated from the data by an iterative procedure.

Knowing the n-th iterate of the function $\mathrm{ZEM}_{90}(\psi)_n$ we observe that for each individual detector scan the output can be written as a linear equation in the 3 parameters which have to be estimated: a_{n+1}, b_{n+1} and the combination of $(g\,f(\theta))_{n+1}$.

$$O = a_{n+1} + b_{n+1}\,t + (g\,f(\theta))_{n+1}\,\mathrm{ZEM}_{90}(\psi)_n. \tag{3}$$

All thus calibrated detector scans are averaged into the next iterate of $\mathrm{ZEM}_{90}(\psi)_{n+1}$.

$$\mathrm{ZEM}_{90}(\psi)_{n+1} = \frac{O - a_{n+1} - b_{n+1}\,t}{(g\,f(\theta))_{n+1}}. \tag{4}$$

In both fitting procedures we are only interested in the common lower envelope. All datapoints which stray from this lower envelope we consider as spurious. They are eliminated with an object function which is more robust than the normal least squared method. We took a one-sided biweight function of Tukey (Goodal, 1983).

When it is sufficiently converged, typically after about 10 iterations, the factor $g\,f(\theta)$ is separated for each detector into a part $f(\theta)$ which comprises the common functional behaviour with θ, and a remaining part. The former is multiplied with ZEM_{90} and represents the ZEM; the latter is the gain for each detector scan.

This calibration is operational since begin 1987.

5 Detector Behaviour

IR photon detectors of the kind IRAS was supplied with are known to show particle and photon induced memory effects (Kester, 1986). A full physical model of these effects still eludes all efforts (Westervelt and Teitsworth, 1985). The model here presented only concerns photon induced memory effects on the gain factor. The

particle induced effects due to the passage through the South Atlantic Anomaly seem to influence the bias mainly (See IRAS-ES). We already allow for a linearly changing bias and hope that that will suffice.

The non-linear behaviour of the gain will be corrected according to a two energy level model for IR photon detectors. The model can be described as two coupled first order differential equations.

$$\sigma \frac{dh}{dt} + h = A\,F + h_{min}, \tag{5}$$

and

$$\tau \frac{dg}{dt} + g = B\,F + g_{min}. \tag{6}$$

The equations are coupled by

$$\tau = \frac{\tau_0}{h}. \tag{7}$$

Here, $g(t)$ is a time dependent gain which couples the detector output O to the total incident radiation F according to equation (1). Further, $h(t)$ is a function which is inversely proportional to the decay time $\tau(t)$ of the gain. It acts as a saturation on the gain at large input fluxes. The decay time of the saturation function, $h(t)$, itself is σ. The constants σ, τ_0, A, B, h_{min} and g_{min} are parameters to be estimated: one of them can be chosen freely. We take $h_{min} = 1$. The fact that h is always greater than or equal to 1 entails that g changes on time scales equal or smaller than τ_0.

To estimate the parameters of the gain model the two differential equations must be rewritten as difference equations. (Ljung, 1987).

$$h_k = (1-p)(AF_{k-1} + 1) + p\,h_{k-1}, \tag{8}$$

$$g_k = (1-q)(BF_{k-1} + g_{min}) + q\,g_{k-1}, \tag{9}$$

where

$$p = \exp(-T/\sigma), \tag{10}$$

$$q = \exp(-Th_{k-1}/\tau_0). \tag{11}$$

T is the sample time interval. From these equations an estimator of the momentary gain, g_k, is found in terms of the previous h_{k-1} and g_{k-1}, and in terms of the previous input fluxes F_{k-1} and F_{k-2}. Via equation (1) an estimator of O_k is found which can be compared with the actual detector scan values. The difference is to be minimized under a robust objective function.

6 Non-linear Model

For most of the scans the linear scheme proved to be reasonably successful. But there are broken scans, running only part of a semicircle, for which the baseline and the gain can not be separated any more. This sometimes results in negative gains or other kinds of bad fits, particularly when the short scan covers some remaining galactic emission. Moreover for scans taken at extreme solar aspect angles (θ less than 75° or more than 105°), the assumption of separability of ZEM, as stated in equation (2), does not hold.

Still a zodiacal emission model was found of which the $\text{ZEM}_{90}(\psi)$ part could be very precisely approximated by an ellipse. This led to the conjecture that the zodiacal emission as a whole could be approximated by the emission of a tilted oblate ellipsoidal dust cloud of uniform density and temperature. The ZEM is a function of solar aspect angle θ, the longitude of the sun-referenced coordinate system ψ, and the position of the earth represented by the solar elongation $\lambda_{\odot}$. This idea is supported by Reach and Heiles (1987).

An ellipsoidal model can never fit the so-called sidebands of the zodiacal emission (Hauser et al., 1984). The sidebands have been identified with 3 asteroid families (Dermott et al., 1984). From considerations of celestial mechanics (Hirayama, 1918 and Brouwer, 1951) it seems reasonable to model them with a number of inclined tori, fanned over all nodal angles. A side band model (SBM) incorporating these ideas is still under study.

Apart from the zodiacal emission there is always a contribution of astronomical background (SKY); most of it is galactic emission. The astronomical background is so granulated that only a map of the whole sky can function as a model. A fairly coarse map in an equal area projection with pixels of 1° by 1° will suffice. Each pixel is the mean of all overlapping detector values. As a standard candle the sum of ZEM, SBM and SKY can be taken, while $g(t)$ follows the detector model expounded in the section 5.

The complete model,

$$O = a + b\,t + g(t)(\text{ZEM}(\psi, \theta, \lambda_{\odot}) + \text{SBM}(\psi, \theta, \lambda_{\odot}) + \text{SKY}(\lambda, \beta)), \tag{12}$$

contains as free parameters: 5 for ZEM, 6 for SBM, 40000 pixels for SKY, 5 for each scan (2 baseline and 3 starting conditions), and 5 for each detector (2 decaytimes, 2 increments and a minimum gain). In total about 70000 parameters have to be estimated, still a tiny fraction of the complete database of 13 Gbyte.

The non-linear model asks for a more complicated iterative scheme. Each iteration requires three passes over the data: one to determine SKY, one for ZEM + SBM and one for the baseline and the gain. In each pass the items which are not fitted, attain the values derived in the previous iteration. SKY is found by coadding the detector scans, properly scaled with baseline and gain and stripped of the contribution of ZEM + SBM, into an equal area map of the whole sky. ZEM and SBM are non-linear functions of solar elongation, sun-referenced longitude and latitude. An elegant way to fit non-linear functions is the Levenberg-Marquardt method (e.g. Press et al. 1986).

The derivation of the calibration parameters falls into two parts. For each detector the values of the gain model have to be estimated in the way that was outlined in the section 5. And for each detector scan the baseline has to be estimated plus the fictitious values h_0, g_0 and F_0, which represent the state of the system at the beginning of the detector scan.

Most of the steps outlined above need iterations in themselves. E.g. a non-linear regression model can only be solved in an iterative way. Nontheless it is hoped that one grand iteration loop, in which each set of parameters is estimated only once during an iteration loop will eventually converge. The choice of starting values for the parameters may be quite important.

This calibration and the pertaining ZEM will be available by middle 1988.

7 Further Tools

For routine inspection of the data a set of programs is available, applying position and/or flux calibration to the raw detector outputs, with some variation in algorithm used. The end products of these programs are

- a file ("sample file") containing the sampled output of all IRAS detectors covering the region of interest during survey scans, each sample labeled with time, position and orientation of the detector, and errors in these quantities;
- moderate resolution images, formed by averaging of the overlapping samples on an almost arbitrary pixel grid;
- high resolution images obtained by a linear least squares reconstruction technique exploiting the overlap between the samples, and the redundancy in the coverage of the sky.

All intermediate and end products of these programs are in FITS format to fulfill our export requirements. The subroutines used in these standard programs are available as a software library for special research projects.

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Image Reconstruction from IRAS scans

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P.R. Wesselius

June 14, 1989

Captions

- *Caption Figure 1:* IRAS focal plane. Of the 62 infrared detectors the 3 filled-in detectors were inoperative.

- *Caption Figure 2:* Point spread function of detector 15 (60 μm). The contour levels are at 99, 98, 95, 90 – 10 (10), 5, 2, and 1 percent of the maximum. The nominal size is represented by the rectangle, which corresponds to the rectangle in Figure 1.

- *Caption Figure 3:* Detector outputs of one scan covering M51 (60 μm). The scan direction is from right to left, and the scan has a length of one degree. The detector outputs are displaced vertically corresponding to their cross-scan position in the focal plane. The figure is corrected for the relative positions of the detectors in the in-scan direction and can be regarded as a ruled surface plot. The brightnesses have been scaled relative to the maximum (set at 100) in this piece of the scan.

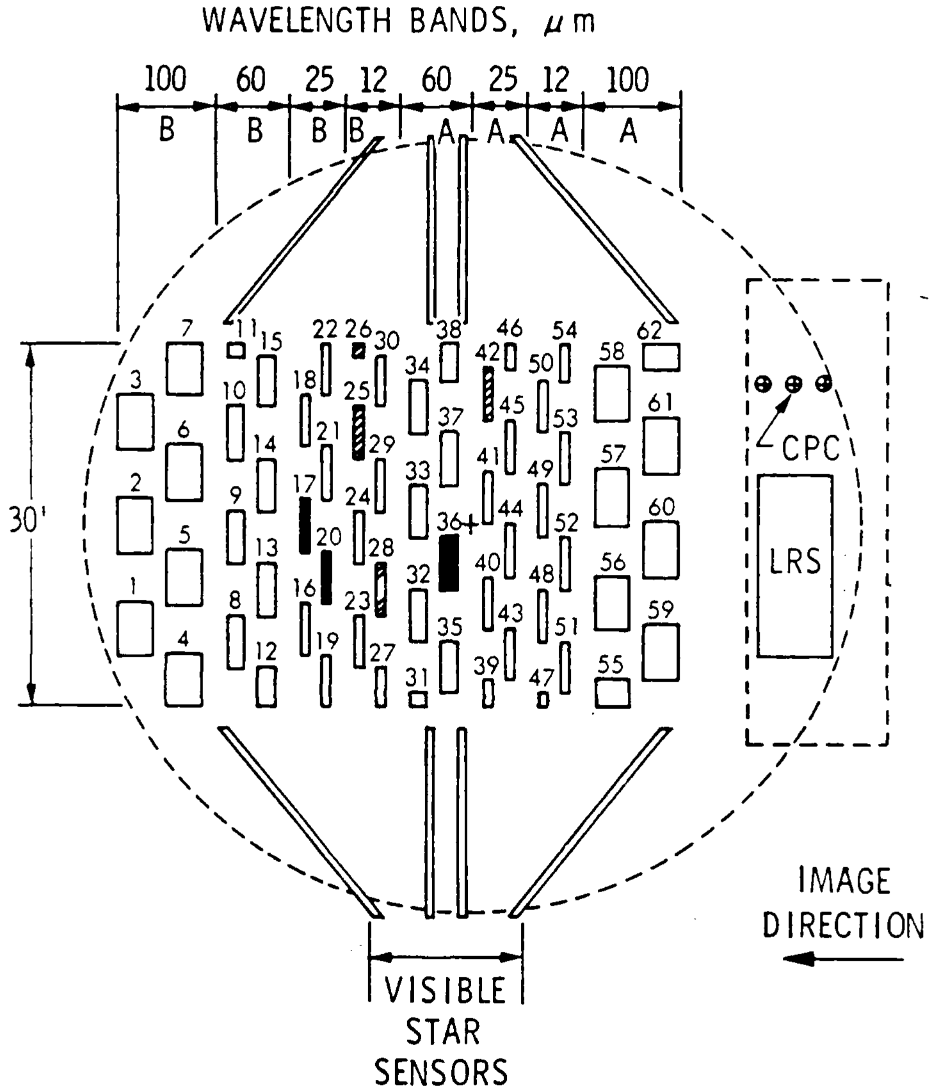
- *Caption Figure 4:* Positions of the samples in the area of M51 (60 μm). The circles represent the two smallest detectors in the band, viz. detectors 11 and 31 (see Fig. 1). The scans roughly run from top-left to bottom-right. The area is covered by about 700 samples, and the nominal size of one detector is outlined. A grid with a one arcminute spacing, suitable for image reconstruction, is superimposed. The positions are projected on a plane tangent to the map centre.

- *Caption Figure 5:* A 'co-added' map of M51, i.e. using the (5×1 arc minutes) detector size at 60 μm as the beam. The size of the map is 15 by 15 arc minutes.

- *Caption Figures 6:* Maps of M51 (60 μm) using the linear least-squares reconstruction method with two different damping factors.

- *Caption Figure 7:* A CPC image of M51 (50 μm). The resolution of this map is 1.5×1.5 arc minutes.

- *Caption Figure 8:* A 'FIER' reconstruction of an M 51 AO observation (IRAS, 60 μm).



IRAS FOCAL PLANE

FIGURE 1

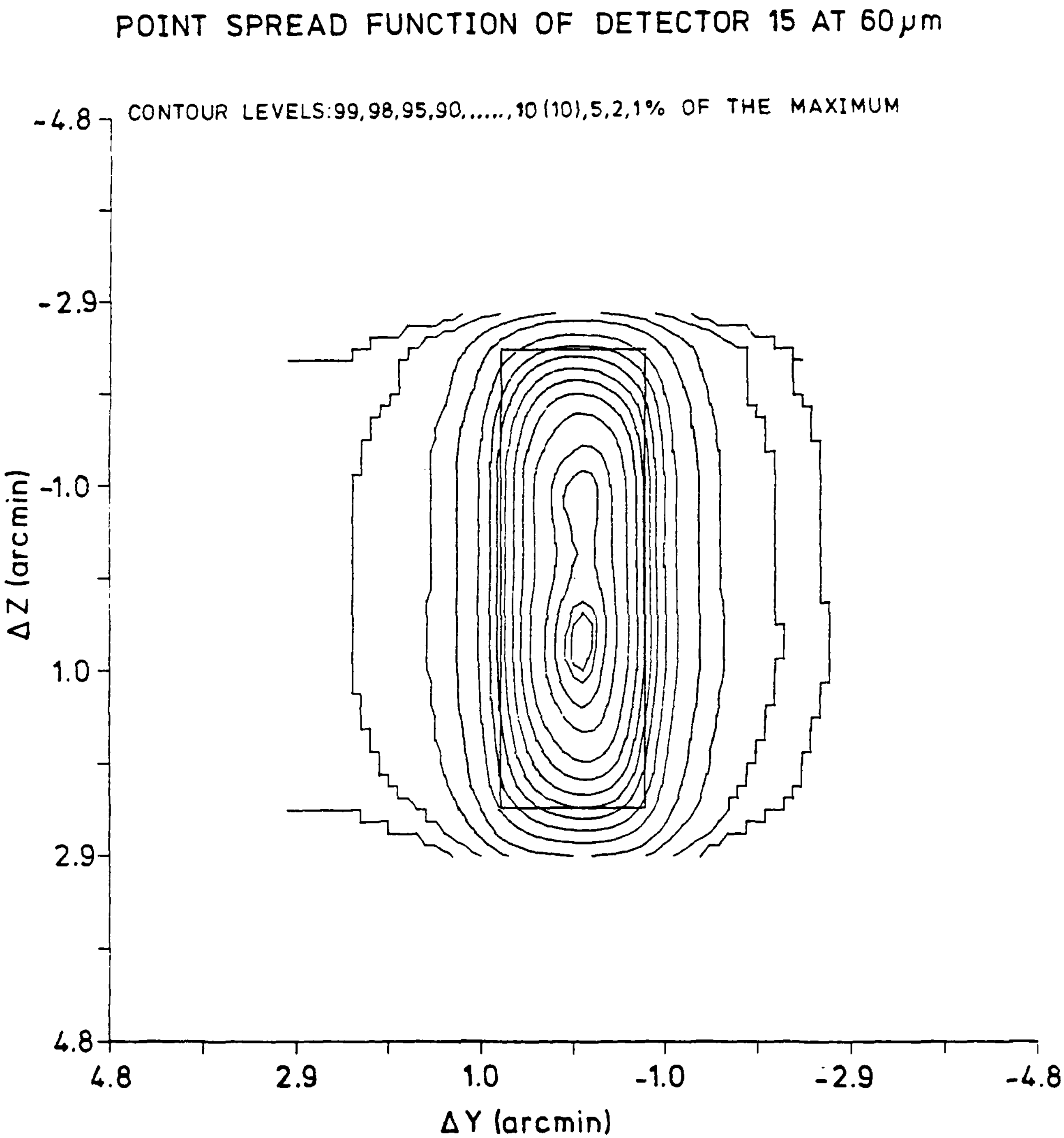
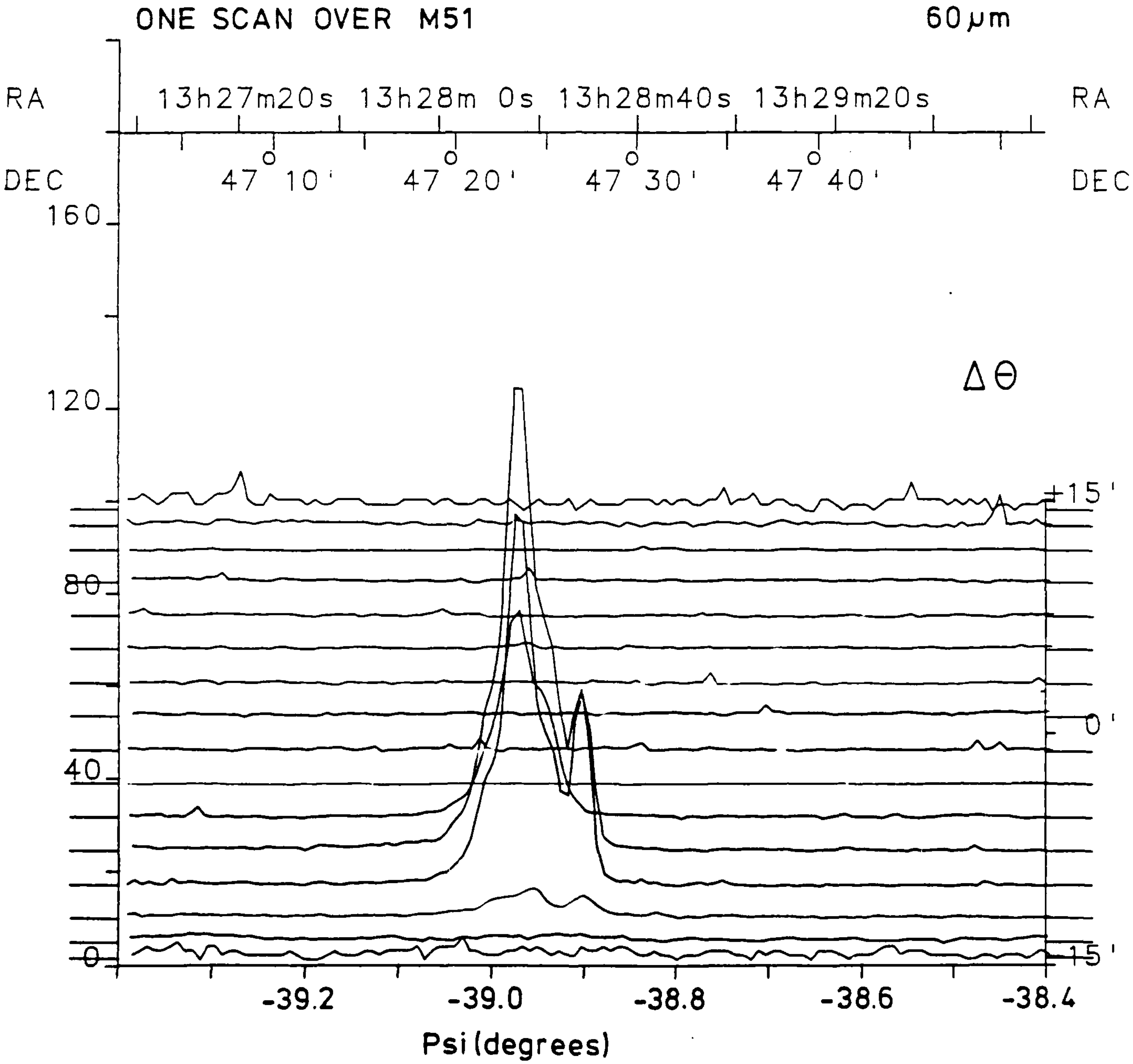

POINT SPREAD FUNCTION OF DETECTOR 15 AT 60μm
CONTOUR LEVELS:99,98,95,90,......,10 (10),5,2,1% OF THE MAXIMUM
-4.8
-2.9
-1.0
1.0
2.9
4.8
ΔZ (arcmin)
4.8
2.9
1.0
-1.0
-2.9
-4.8
ΔY (arcmin)

FIGURE 2

FIGURE 3



ONE SCAN OVER M51
60μm
RA
13h27m20s 13h28m 0s 13h28m40s 13h29m20s
RA
DEC
47°10' 47°20' 47°30' 47°40'
DEC
160
120
80
40
0
ΔΘ
+15'
0'
-15'
-39.2
-39.0
-38.8
-38.6
-38.4
Psi (degrees)

SAMPLE POSITIONS

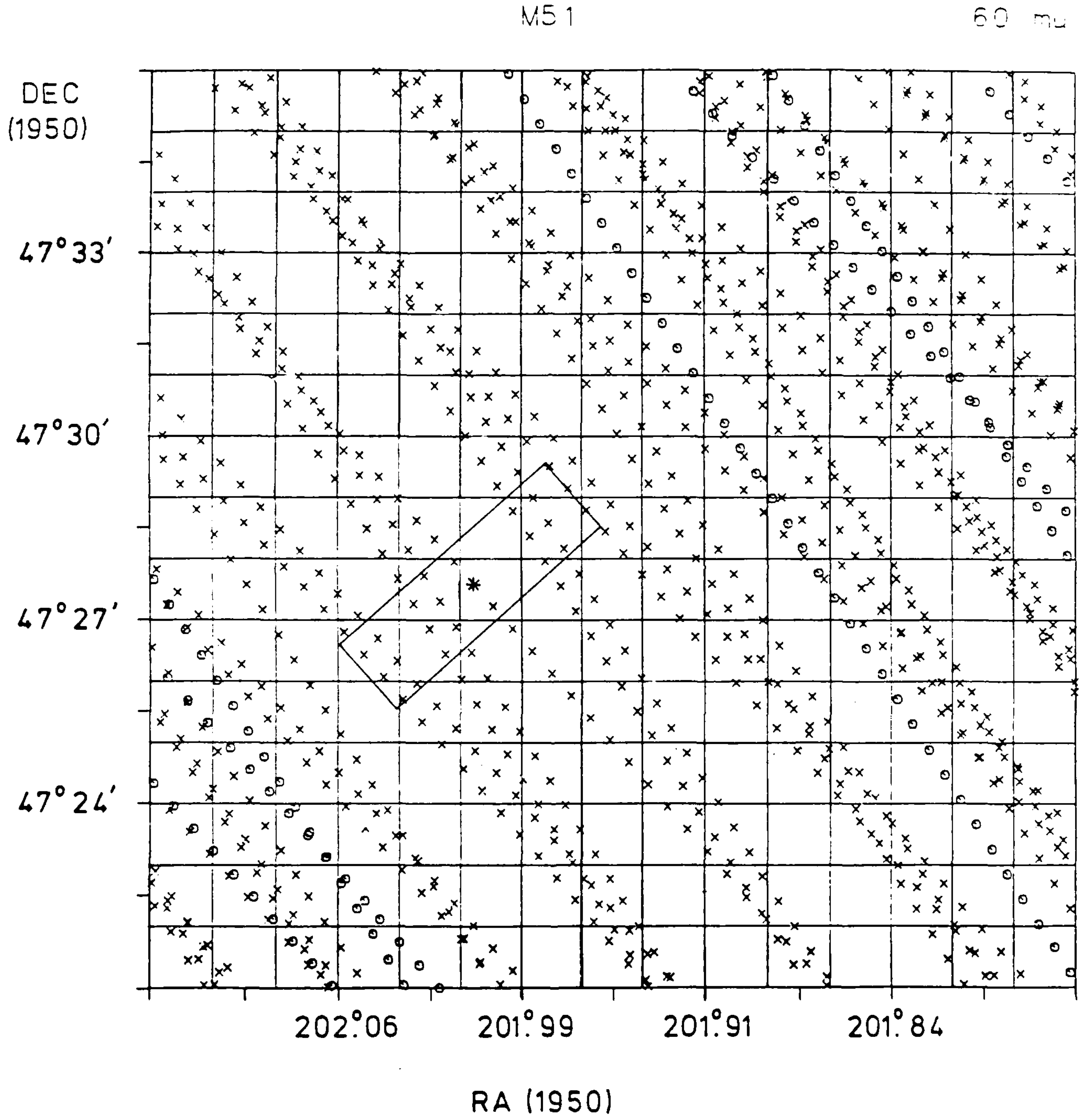


FIGURE 4

"CO-ADDED" MAP OF M51 AT 60μm

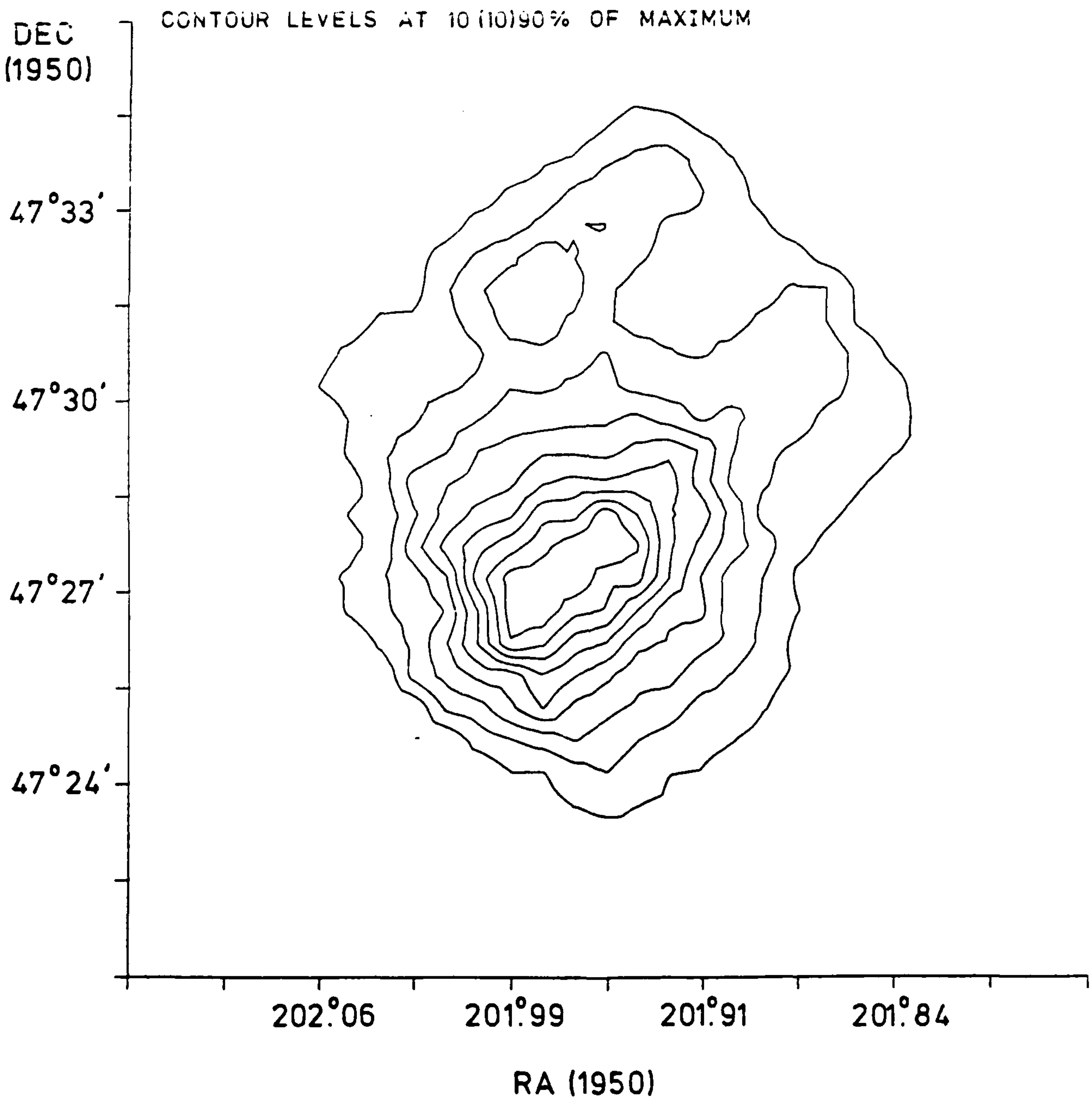


FIGURE 5

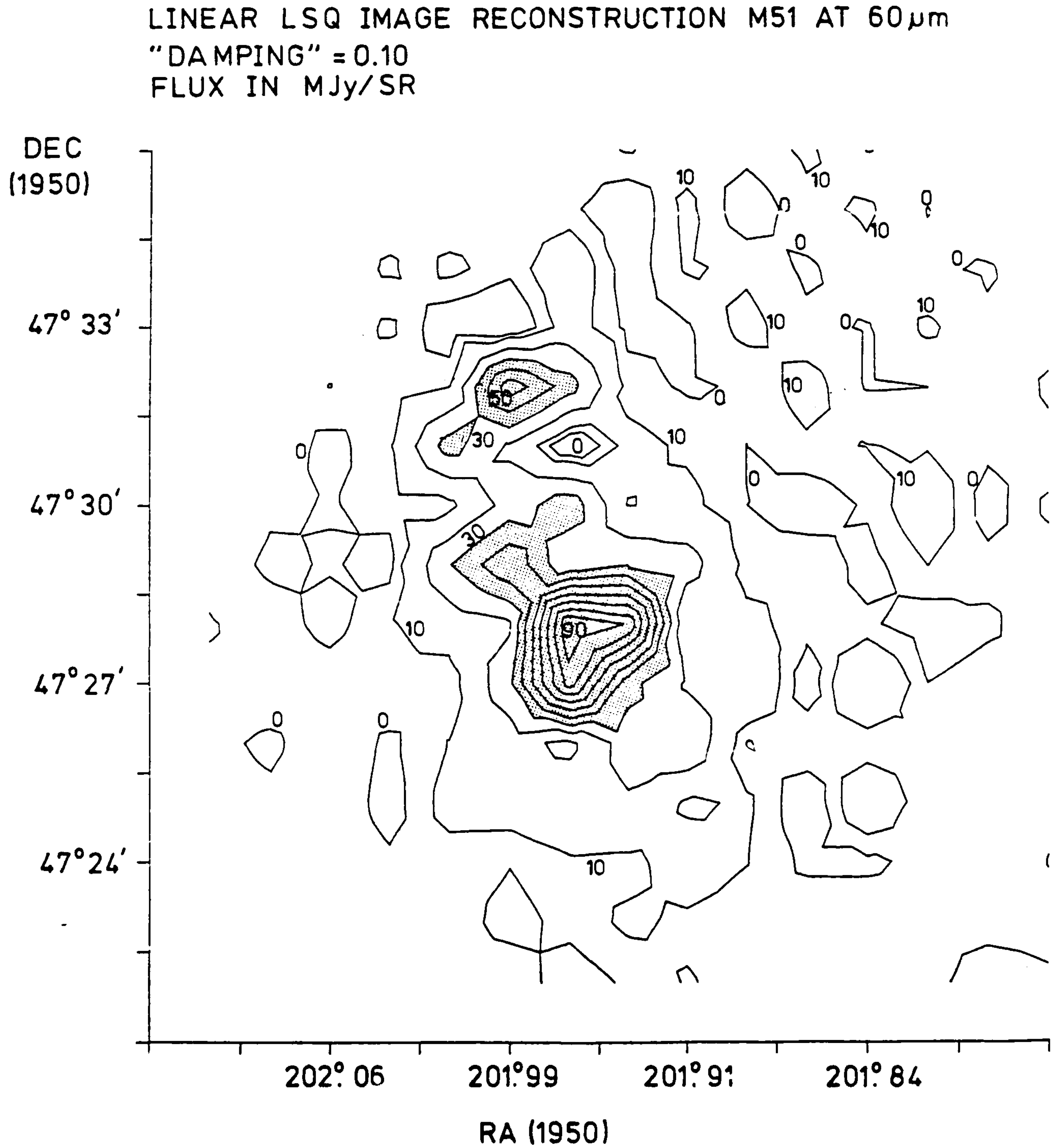
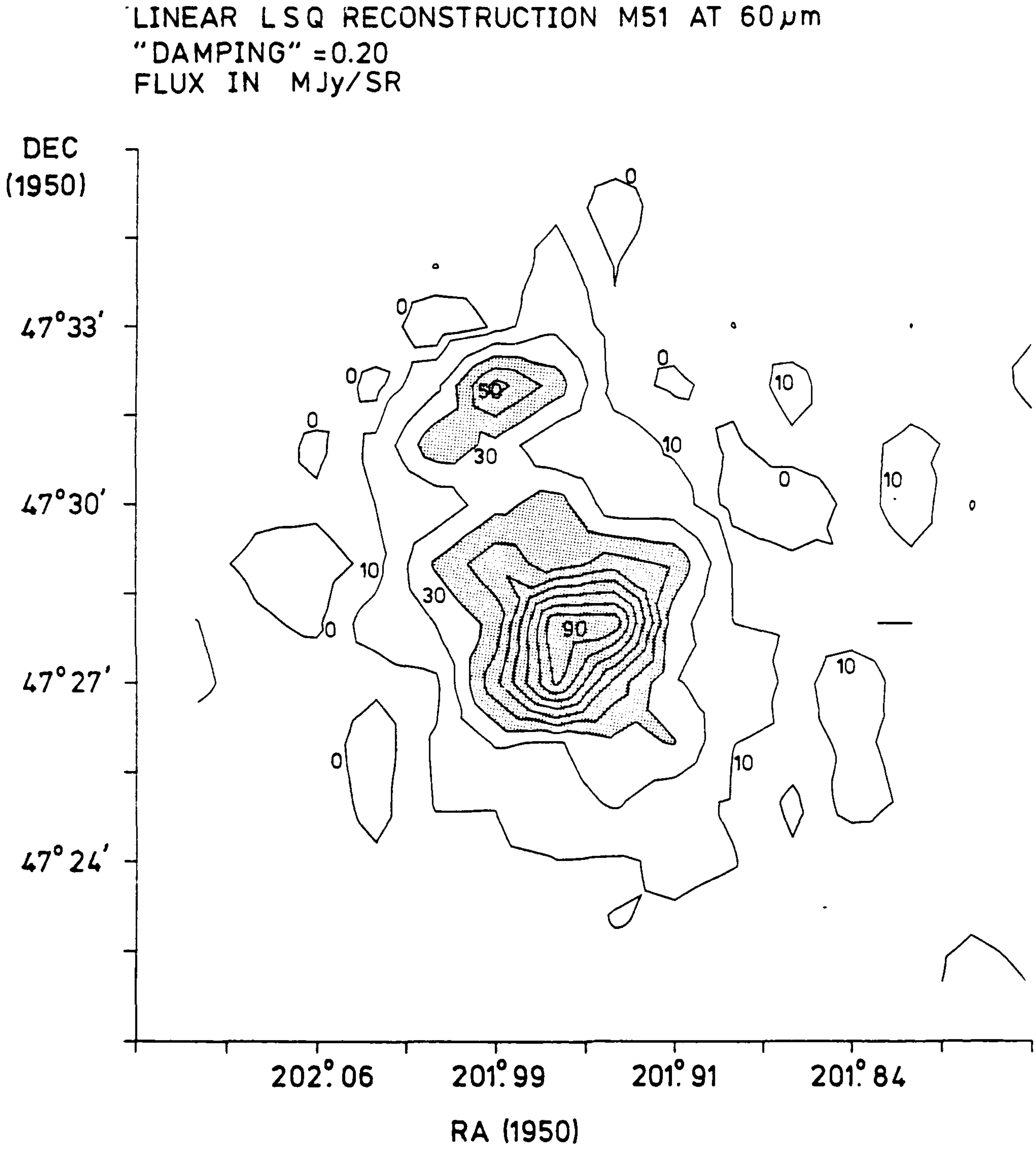

LINEAR LSQ IMAGE RECONSTRUCTION M51 AT 60µm
"DAMPING" = 0.10
FLUX IN MJy/SR
DEC (1950)
47° 33'
47° 30'
47° 27'
47° 24'
202°.06
201°.99
201°.91
201°.84
RA (1950)

FIGURE 6A



LINEAR LSQ RECONSTRUCTION M51 AT 60μm
"DAMPING" =0.20
FLUX IN MJy/SR
DEC
(1950)
47°33'
47°30'
47°27'
47°24'
0
0
0
0
0
0
0
0
0
10
10
10
10
10
10
30
30
50
90
202°.06
201°.99
201°.91
201°.84
RA (1950)

FIGURE 6B

IRAS CPC IMAGE OF M51 AT 50μm
FLUX IN MJy/SR

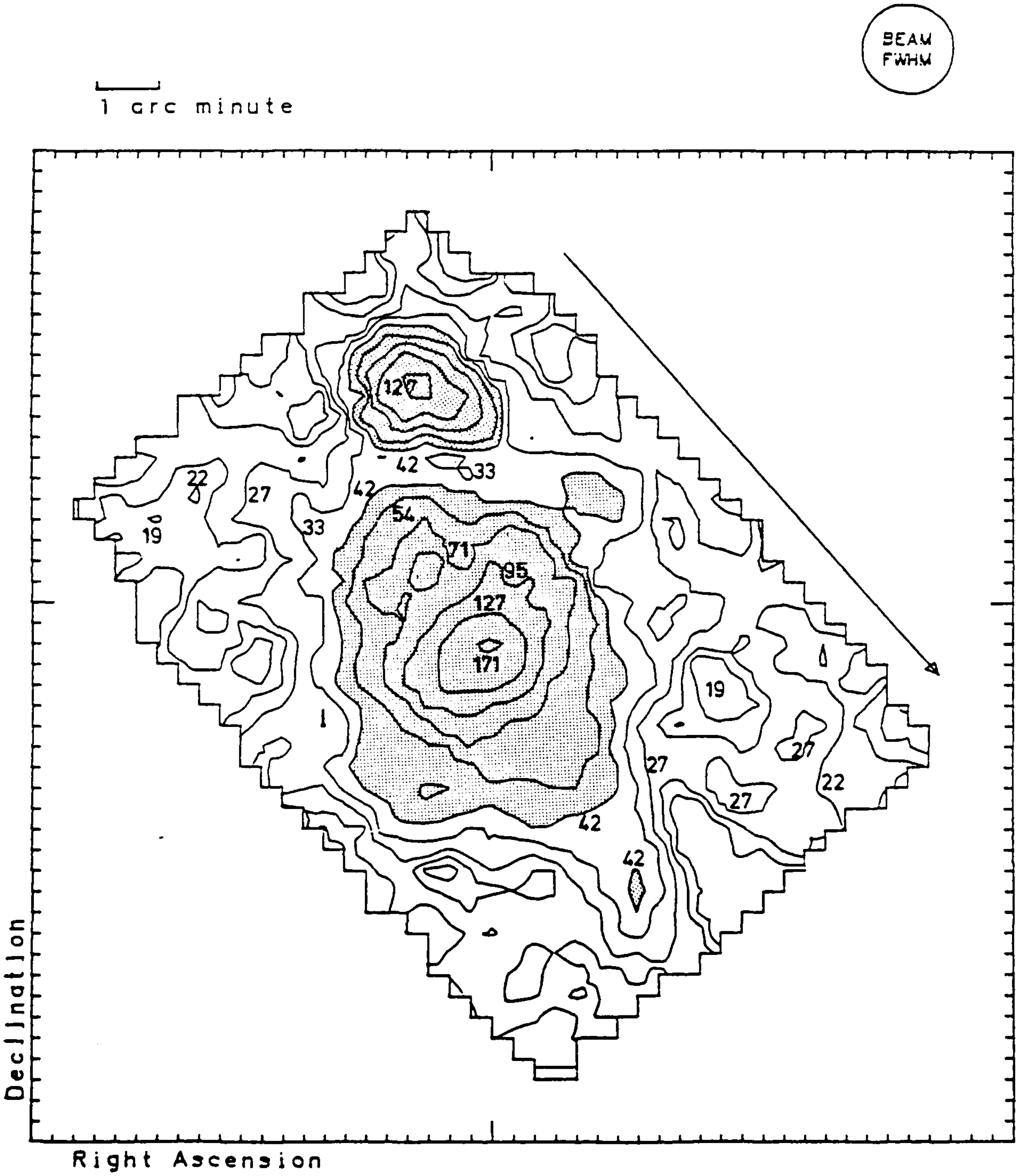


FIGURE 7

A maximum entropy "FIER" restoration of the 60 μm IRAS AO data of M51, done by MRC/TUFTS.

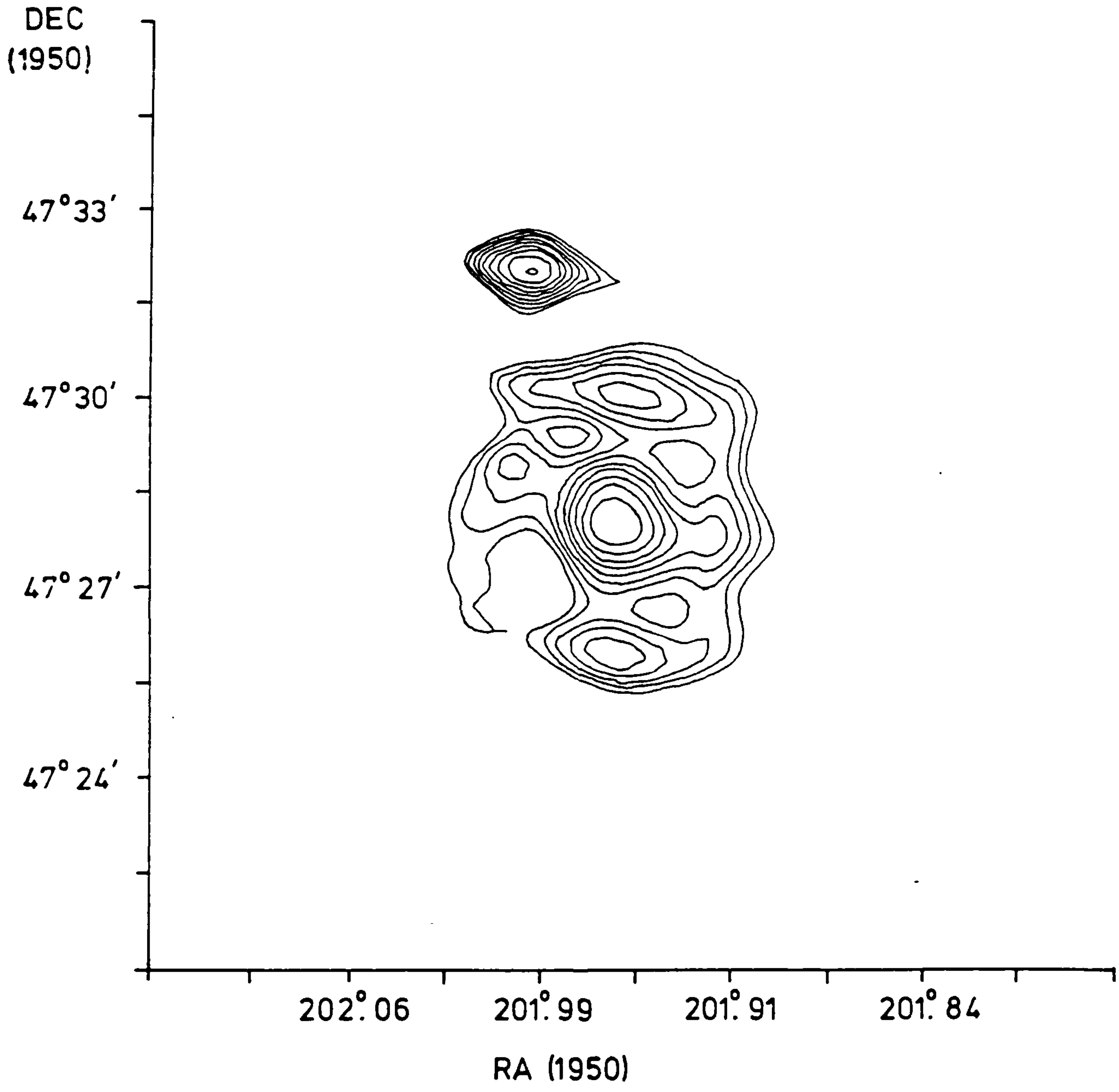


FIGURE 8