

FINAL

IN-74-CR

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5063

p. 10

FINAL REPORT

HIGH SPATIAL RESOLUTION RESTORATION OF IRAS IMAGES

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JPL Contract No. 958005

7/17/87-5/21/90

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N96-11479

Unclas

G3/74 0068419

(NASA-CR-199506) HIGH SPATIAL
RESOLUTION RESTORATION OF IRAS
IMAGES Final Report, 17 Jul. 1987 -
21 May 1990 (Wyoming Univ.) 10 p

This report was prepared for the Jet Propulsion Laboratory,
California Institute of Technology, sponsored by the
National Aeronautics and Space Administration.

ABSTRACT

A general technique to improve the spatial resolution of the IRAS AO data was developed at The Aerospace Corporation using the Maximum Entropy algorithm of Skilling and Gull. The technique has been applied to a variety of fields and several individual AO MACROS. With this general technique, resolutions of 15 arcsec were achieved in 12 and 25 μm images and 30 arcsec in 60 and 100 μm images. Results on galactic plane fields show that both photometric and positional accuracy achieved in the general IRAS survey are also achieved in the reconstructed images.

GENERAL TECHNIQUE

To improve the spatial resolution of the IRAS data, two major problems must be solved. The most severe problem is the unevenly spaced nature of the IRAS data. Most algorithms treat this problem by interpolating the original data onto an evenly spaced grid before applying any enhancement procedure. Cosmic ray hits or detector hysteresis compromise this interpolation process. The second problem is the adequate characterization of detector response. This includes the non-linearity of the detectors over several orders of magnitude in flux, their hysteresis, and an adequate description of the point response functions (PRFs) of the individual detectors. We will address the first of these problems and demonstrate the Aerospace/Wyoming solution as applied to the AO data for the galactic plane field GS0513 and the star formation region HH 1/2.

The Aerospace/Wyoming technique is a sufficiently general one that can be applied to multi-detector data and used with a wide variety of non-linear image reconstruction algorithms. It has been successfully applied to close contact, point source galaxies, nearby extended galaxies, star formation regions, rich cirrus fields, and the galactic plane.

As an illustration of the technique we will demonstrate the procedure for one of the simplest of AO macros, DSD01A. The DSD01A macro has 18 scans at one-half the survey speed of length 28 arc min. The scans are separated by a cross-scan step of 0.5 arc min (Young et al. 1985). This IRAS macro centers the four small side detectors #47 (Band 1 = 12 microns), #39 (Band 2 = 25 microns), #31 (Band 3 = 60 microns), and #55 (Band 4 = 100 microns) on the region of interest, although all of the detectors are taking data. The placement of the detectors in the IRAS focal plane is shown in Figure 1.

The detector data positions for all four bands in image space are presented in figure 2 for the star formation region HH 1/2. The rectangular areas in each plot are the physical dimensions of each detector. At 12 and 60 microns the data are slightly under-sampled in the cross-scan direction and over-sampled in the in-scan direction. At 25 and 100 microns both dimensions are over-sampled.

For multi-detector macros, regions of interests may have areas where detector data points overlap each other. For these cases the Aerospace/Wyoming method treats each detector with its own unique point response function and does not assume an average PRF.

A new approach to the general problem of applying non-linear techniques for image reconstruction and multi-dimensional data analysis on unevenly spaced data was developed with the constraints placed upon the technique by Jaynes's Axiom (Jaynes 1985): The first thing to do with the data is to convolve it with the point response function. Let f represent the observations, which is a result of the convolution of the instrumental function, g , and reality, r , plus a noise term, n , i.e.

$$f = g * r + n$$

where $*$ is the convolution operator.

Since most non-linear and maximum likelihood schemes typically seek solutions that satisfy a least-squares criterion, Jaynes's

Axiom becomes quite obvious. Generally, solutions to the inverse problem require that the function H will be minimized, where

$$H = \sum_i (g * r - f)^i^2$$

The condition for minimization leads directly to the condition
 $= 0 = 2 (g^t * g * r - g^t * f)_i$

To apply this general solution to the IRAS data a general response matrix, R , is created which "blurs" the data with the response functions of the individual detectors and at the same time re-grids the unevenly-spaced data into an evenly-sampled image space. The general response matrix, R , is uniquely determined by the detector response functions and the detector positions. R can then be substituted for g in our general least-squares criterion which now becomes

$$(R^t * R * r - R^t * f) = 0$$

where RR^t is the transpose of the response matrix. Each data point has a unique weight, therefore no interpolation of the data is required.

If there are N_i image points on an evenly-space image grid and N_d data points on the unevenly-space data grid, then the response matrix is $N_i \times N_d$. For a 32×32 image with $N_i = 1024$, N_d may be ≈ 1000 , and the response matrix has 10^6 entries. Using this approach, images up to 200×300 pixels have been restored using the individual point response functions and individual noise figures for each of the detectors. For the HH1/2 region only one detector per band was used and a 40×80 pixel image was produced at 15 arc sec per pixel. For a typical galactic plane region all working detectors were used and a 150×250 image was produced at 15 arc sec per pixel, depending on the macro. Using a Micro-VAX II microprocessor with an array processor, real speeds of 3 megaflops/sec were achieved. Recently preliminary images on a galactic plane field took over 20 hours of CPU time to complete 20 iterations.

The Gull and Skilling (1984) maximum entropy program has been used exclusively for these data. Our novel approach will also work for the Willingale (1981) and Lucy (1974) algorithms, but we feel that the maximum entropy method provides us with the most unbiased, best estimate of reality. The final image must meet two criterion: it must satisfy a chi squared constraint, due to maximum likelihood, and a maximum entropy constraint. Convergence therefore depends only on the best estimate of the noise vector and is not a subjective decision of the operator.

To initiate the reduction of the observations we take the the AO Calibrated Raw Detector Data (CRDD) for each band and use the following procedure.

- a. Since the scans were not always parallel to the N-S or E-W equatorial axes, the data grid was rotated around the central reference position thus aligning the image grid parallel to the in-scan direction. This makes construction of the response matrix much simpler and leads to faster mathematical operations.
- b. All cosmic ray hits or other spurious data were eliminated from the data set.
- c. The two-dimensional background was set to zero. This correction also included corrections for any background

gradients; e.g. zodiacal light, diffuse cirrus. A de-striping routine is applied initially to eliminate any scan-to-scan background variation.

- d. A global estimate of the noise was determined from source-free regions in each band. This global noise is determined by the standard deviation of the differences in intensity between two adjacent points for each scan leg. Values more than three standard deviations are rejected and a new final value for the noise for each scan leg is then recalculated.

For regions with sources two terms are added in quadrature with the global noise: the first term is directly related to the gradient of the flux, to account for positional errors; and the second term is directly related to the signal, to account for the non-linearity of the detector signal.

- e. The data and noise estimates were then processed in the maximum entropy algorithm until convergence was obtained.

PUBLICATIONS

"A General Technique for Recovering High Angular Resolution Images from Unevenly-Spaced Data", J. A. Hackwell, L. M. Friesen, R. Canterna, and G. L. Grasdalen, 1988, BAAS, 20, 677.

"High Resolution Observations of the HH1 and HH2 Region with IRAS", Hackwell, J. A., Grasdalen, G., L., Canterna, R., and Friesen, L. M., 1988, Workshop on the Formation and Evolution of Planetary Systems.

"Star Counts in the Galactic Plane from High Spatial Resolution Images from IRAS". 1988, BAAS, 20, 1018

" High Spatial-Resolution Images of M 51" in The Second Wyoming Conference on The Interstellar Medium in External Galaxies, Jackson Hole, WY. by Canterna, R., Hackwell, J. A., and Grasdalen, G. L.

"Infrared Sources in the Galactic Disk from Image-Recovered IRAS data", by R. Canterna, J. Hackwell, G. Grasdalen, R. Hermann, and S. Gillam. In preparation, will be submitted to Ap. J.

" The Infrared Source Counts in the Galactic Thin Disk Population from High-Spatial resolution IRAS Images" , by A. Evans, R. Hermann, R. Canterna, and J. Hackwell. Present at January 1990 AAS meeting, Washington DC

" Infrared Studies of the Galactic Plane I: The IRAS Disk Population at $l = 30^\circ$ ", by Canterna, R. Hackwell, J.A., Hermann, R., and Grasdalen, G. L., (Submitted for publication)

"A General Technique for Recovering High Angular Resolution Images from Unevenly-Spaced Data", J. A. Hackwell, L. M. Friesen, R. Canterna, and G. L. Grasdalen, In preparation.

Star Counts in the Galactic Plane from High Spatial Resolution Images from IRAS.

R. Canterna (Wyoming Infrared Obs. [WIRO] and The Aerospace Corporation [A.C.]), John A. Hackwell (A.C.), Gary L. Grasdalen, Rob Hermann, and Steve Gillam (WIRO).

The 0.5 x 0.75 galactic plane field (IRAS identification GS0513) centered around $l = 29.3$ and $b = -0.1$ have been analyzed using several IRAS data bases. High spatial resolution images have been recovered for the same field from AO CRDD data using the general techniques for image recovery discussed by Hackwell, Friesen, Canterna, and Grasdalen (BAAS 20, p677) and the maximum entropy method described by Gull and Skilling (IEE Proc (F), 131, p646). The reconstructed images have been used to form star counts as a function of flux for bands 1 and 2 and the results are compared with the IRAS Serendipitous and Point Source Catalogs and the Regridded AO images for the same field. In addition to revealing additional point sources above the Point Source Catalog (PSC) confusion level of 2 Jy, the recovered images have also revealed more than a factor of 2 more point sources below the PSC confusion level. Monte Carlo calculations have been made to model the galactic plane structure and are compared with observations.

The InfraRed Source Counts in the Galactic Thin Disk
Population from High-Spatial Resolution IRAS Images.

Aaron Evans (U. Michigan/Wyoming Infrared Observatory [WIRO]), Rob Hermann, R. Canterna (WIRO/The Aerospace Corporation), and J.A. Hackwell (The Aerospace Corporation).

ABSTRACT

Two galactic plane fields ($l = 21.8^\circ$, $b = -3^\circ$; $l = 29.3^\circ$, $b = -0.1^\circ$) have been analyzed from high spatial-resolution images of IRAS calibrated raw detector data using the general recovery method developed by Hackwell, Friesen, Canterna, and Grasdalen and the Gull/Skilling Maximum Entropy technique. We have been able to resolve multiple sources at all flux levels, especially in the cross-scan direction. In both areas over a factor of 2.5 more sources than is recorded in the Point Source Catalog have been discovered, resulting in a complete sample, flux limited to 0.8 Jy. Flux levels down to 0.4 Jy have been measured in one area. Photometric precision similar to the IRAS PSC has been achieved at all flux levels. Source counts supports evidence for a 1.3° thin disk population with a scale height of ≤ 170 pc. The 12 and 25 μm color data show evidence of a very red population, quite different than the normal bulge and disk IRAS population.

INTRODUCTION

The true nature and description of the IRAS point source counts within the galactic plane is not well known. The confusion-limited regions for the IRAS Point Source Catalog (PSC) along the galactic plane are a result of more complicated effects than those implied by classic concepts of source confusion due to excessive source densities. The detection threshold for the PSC is raised in the galactic plane because the estimated noise is increased above the intrinsic detector noise by the large number of point sources per scan. Additional skewing is introduced by the trailing noise estimator used by the PSC algorithms. The estimator, which uses a preceding portion of the scan data to obtain a local noise estimate, underestimates the noise when entering the plane and overestimates the noise when leaving the confused region. This shadowing and memory effect add to the extreme complexities of the confusion region centered on the galactic plane. We can reduce this problem by applying new imaging techniques to IRAS fields.

HIGH SPATIAL RESOLUTION IMAGES OF IRAS GALACTIC PLANE FIELDS.

We have applied a general technique of recovering high angular resolution images to the unevenly-spaced original IRAS Additional Observation (AO) Calibrated Re-constructed Detector Data (CRDD) (Hackwell, Friesen, Canterna, and Grasdalen 1988; hereafter referred to as "The Aerospace Method"). The Aerospace method uses the maximum entropy algorithm of Gull and Skilling (1984). The final "super-resolution" images of two fields have been analyzed and compared the results from the PSC. Figure 1 shows a comparison of the IRAS survey field and a blow-up of our reconstructed field.

Our data shows an increased number of IRAS sources in the galactic plane. We have investigated the IRAS AO fields GS0513 and GS0960. GS0513 is centered at $l=29.3^\circ$ and $b = -0.1^\circ$. The area analyzed is approximately $0.3^\circ \times 0.75^\circ$. The AO macro for this field (DPS60D) was raster scanned at half the survey rate, with a scan length of 60 arc minutes, cross-scan of 0.8 arc minutes, and 4 scans per macro. GS0960 is centered at $l = 21.8^\circ$ $b = -0.3^\circ$ [area is $0.8^\circ \times 0.6^\circ$]. The AO macro was DSD01A, which was a raster scan at half the survey rate with a scan length of 28 arc minutes, cross-scan of 0.5 arc min, and 18 scans per macro.

RESULTS

In Figure 2 a plot of the logarithm the accumulative number of sources per square degree versus the logarithm of the $12 \mu\text{m}$ source flux in Jy is presented for field GS0513. The dotted line is the results from high $12 \mu\text{m}$ flux quality sources from the PSC and the solid line is from our reconstructed images. From an analysis of our high spatial resolution images

- multiple sources are clearly separated.
- a factor of 2 or more point sources have been detected.
- a completeness flux level less than 1.0 Jy is achieved.

THE NATURE OF THE INFRARED THIN DISK POPULATION

The 12 μm completeness flux level for galactic longitude 30° is approximately 1.8 Jy. In Figures 3 and 4 the natural logarithm of the number of sources per square degree with high 12 micron flux quality greater than 2.0 Jy is plotted against galactic latitude within a 1 degree band centered on $l = 30^\circ$. The results from our reconstructed image is also plotted, showing the consistency between our results and the PSC for this flux limit. A thick 3° galactic disk model can be fitted to the data with a 1.4° THIN disk component superimposed. The nature of this thin disk component is seen in Figure 4 where the relative number of sources per square degree are plotted as a function of color (ratio of 12 to 25 micron fluxes) for sources between galactic longitudes -3 to -10 degrees. A similar relation is found for galactic longitudes $+3$ to $+10$. In an overlay we plot the same relation for galactic plane field GS0960 where we have analyzed both 12 and 25 micron "super-resolution" images. One sees that the thin disk population has color temperatures that are significantly cooler than the thick disk population.