

**Functional Requirements for Robust  
Astronomical Data Reduction:  
Application to Variety of Observations of  
Jupiter**

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# **Functional Requirements for Robust Astronomical**

## **Data Reduction: Application to Variety of Observations of Jupiter**

### **Abstract**

Earth-based observations, taken near the time of probe encounter, were necessary to determine the characteristics of the Galileo probe entry site(PES). This project mainly involves development and application of mosaicking and reconstruction techniques of these 5-micron data of Jupiter. A linear approach proved to be very good for interpolating over time. The interpolated image, between the 21 November 1995 and 22 January 1996, convolved with Gaussian model that closely matches the point spread function of a star image taken on 8 December 1995, is consistent with the real blurred image taken on 7 December 1996. This shows that in order to find out more about the conditions in which the Probe entered Jupiter's atmosphere, using an interpolation of the higher spatial resolution images is better than using the blurred images. Other techniques are used for making an animation of a 5-micron hot-spot motion on Jupiter ,over the period March 1995 - May 1997. These include calibration of blurred images using Goodness of fit procedure, scaling the brightness level of images, blending overlapping images and reconstruction of missing parts of images using interpolation. Along with this work, some modifications have been made to an existing data reduction manager program(DRM) in order to improve or develop the image processing methods.

### **Introduction**

My SURF project has covered a range of topics, and some of them are:

- 1.Documentation of the history and development of Probe entry Site(PES) Hot Spot motion on Jupiter over the two years period( March 1995 - May 1997)
2. Reconstruction that the image interpolated between higher spatial resolution images is a reasonable approximation to the real, blurred image
3. Improvement of the flexibility of the Data Reduction Manager(DRM). DRM is the main IDL program for data reduction that uses graphical users interfaces. I created a functional form for data preprocessing (mostly assigning information to headers and sorting the resulting files by wavelength and object) for alternative environments which do not support a screen menu.
4. Creating a procedure that will transfer cylindrical map of an image to a disk map, in order to increase signal to noise ratio of a data.

## Probe Entry Site 5-micron Hot Spot

The Galileo probe performed the first in situ measurements of the atmosphere of Jupiter on 7 December 1995. Probe entered Jupiter's atmosphere inside a thermally warm and visually dark area associated with 5-micron hot spot. Hot Spot is a region that has less cloud cover and drier conditions than more than 99 percent of the rest of the planet. Observations were made at 4.78  $\mu\text{m}$  wavelength, where Jupiter's spectrum is minimally affected by gaseous absorption (first figure). Hot spot areas have thinner clouds than other areas so that 5-micron radiation can escape from very deep levels. Outgoing radiation is dominated by thermal emission rather than reflected sunlight. Hot spot on Jupiter image at 4.78  $\mu\text{m}$  is an exceptionally bright area. Earth-based observations of PES show that the region encountered by the probe is extremely variable, both in time and spatially over latitude and longitude.

## Image reconstruction

### Importance

Due to temporary limitations of the Galileo Orbiter, the Probe Entry Site (PES) was not observed remotely by Galileo. Therefore, Earth-based observations, taken near the time of probe encounter, were necessary to determine the characteristics of the site. The poorer resolution of the December 1995 and early January 1996 dates arises from the large attenuation by the polypropylene safety screen. In order to determine the conditions in which the Probe entered the atmosphere, using an interpolation of the higher resolution images is far superior to using the blurred images. Consistency of the image interpolated between higher spatial resolution images from November 1995 and January 1996 with real Probe entry site image is proved by using different image restoration techniques. Also, in order to show the evolution of the PES hot spot, some of the reconstruction techniques were used for matching more closely the resolution of some images taken with NSFCAM camera, NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii.

### Techniques

#### *Linear interpolation over time*

This technique proved to be the best solution if image lack significant data points or it is necessary to generate new frames between data frames that are available, assuming that the motion of an atmospheric feature follows predictable patterns. Bilinear interpolation had effects only if small parts of data are missing. Images are represented as two-dimensional arrays, and each pixel contains the information of brightness at that point.

Applying linear interpolation over time means that only the corresponding array elements of images are considered ( history and future of that particular pixel in an interpolated image between), not the neighbor pixels. So, it is possible to generate new image frame applying the following equation for each pixel:

$$b = a * (1 - \frac{i}{n}) + c * \frac{i}{n} \quad (*)$$

where **a** is a corresponding pixel in the image taken before and **c** is a corresponding pixel in the image taken after the date for which we want to reconstruct the image. Time distance between real data (**a** and **c** pixels) is **n** and **i** is time distance between the real data taken before and the date that corresponds to interpolated image (**b** pixels).

### **Convolution Theorem**

The data we observe are the two-dimensional convolution of the real, unblurred image and distortion and noise from different sources( such as atmosphere, detectors,..). The problem of finding the real, unblurred image is a problem of deconvolution of data and the noise. This problem can be solved by modeling noise in a form of point spread function (psf). It is a function of a single source emission object and it can be considered as a model for the emission pattern of each single source (pixel) in the image. By using convolution theorem, we got  $fft(Data)=fft(Image)*fft(psf)$ , where  $fft$  stands for Fast Fourier Transformation and it is the fastest way for deconvolution of image data . The point spreads function for ground-based observations is usually assumed to be Gaussian in the form:

$psf = e^{-\frac{(x^2+y^2)}{\sigma^2}}$ , where the  $\sigma$  is a parameter for the width of the Gaussian at half the maximum value,  $\sigma=FWHM$ ( full width half max). On the 4.78  $\mu m$  image is blurred mostly due to atmospheric distortion and therefore the Gaussian model of psf is a good mathematical presentation. Data for star frames from dates close to the PES were available and they were used for estimation of  $\sigma$  . Using the convolution theorem:  **$fft(real\_image) = fft(psf)*fft(interpolated\_data)$** , it is possible to compare the data. When you apply interpolation and blur the image with a reasonable point-spread function(one that closely matches the function observed with stars), the result closely matches the real image.

### **Application**

#### **Animation**

My first assignment was to make an animation that will describe the motion of a 5-micron hot spot on Jupiter over the period March 1995- May 1997. This appeared near 6.5 degrees north at the J0 encounter during the time of Galileo Probe Entry (Dec 1995). I used cylindrical maps of 5-micron thermal radiation from IRTF/NSFCAM instrument to create an animation.

The list of these files is in `~jelena/movie/newgif.dat`. Assuming mean zonal speed 101.6 m/s I applied procedure `~jelena/movie/makegif.pro` in order to make the basic frames for the animation. List of useful dates is in `~jelena/movie/image.dat` and the second figure shows the data set used for the animation. Some images lack significant data points compared to the others and also there was a limited number of data available over more than two years period and I applied linear interpolation over time in both cases. Also, images were differently calibrated, so I had to scale brightness levels of data images in order to make them consistent( i.e. November 9 and 6, 1996 images), dark equatorial bands in each image are roughly the same. Some images were more blurred than others (March 2, 1996), so I had to apply image restoration techniques on them in order to increase spatial resolution of this images of Jupiter. These techniques already existed in DRM (GOF procedure) for data processing. In some images, reconstruction processes created cross-hatched patterns and that was removed by using the high-frequency digital filter.

Reconstructed images in the third figure show the evolution of a hot-spot. Time differences between dates on which images were taken, are vary from 1 day (between 9 and 10 of May, 1997) to 70 days (between March 14 and May 23, 1995). It was necessary to use different parameters for each frame I put between real images using linear interpolation over time. The animation is made of 393 frames, approximately eight interpolated frames between each two images in a row. Frames were made using the procedure(`~jelena/movie/final.pro`) and animation could be seen by using IDL function `xinteranimate` in the procedure `~jelena/movie/showpesmovie.pro`. The directory `~jelena/movie/` contains README file which describe all the functions and procedures that directory contains.

### **Consistency of data**

In order to prove that the highly attenuated & December 1995 map is completely consistent with time-interpolated versions of the 21 November 1995 and 22 January 1996 maps I applied the techniques mentioned above, first linear interpolation and then convolution theorem. From November 21 to January 22 there are 62 days and December 7 is 16th day in a row. If **a** is a two dimensional array containing information about November 22 image and **c** is a two dimensional array containing information about January 22 image, the result is also two dimensional array , **b**, that we got applying the equation for linear interpolation over time, **i=16** (\*).

The result is the image, shown at the fourth figure. It looks more like image from November than from January, because of the time difference( 16 days compared to 46 days), but the hot spot is wider and it change the shape. Real image taken on 7 December, 1995, MIRAC/IRTF camera, is blurred because of the length of the time it took to make a single image through highly attenuating polypropylene screen.

Data for the star frames were available and I used them to estimate the value of  $\sigma$  in the psf model,  $\sigma=4$ . The blurred interpolated image is the result of , first convolving the original images with psf and then interpolating over time between them:

***convolved\_interpolated\_image=fft<sup>-1</sup>(fft(psf)\*fft(interpolated\_image))***

The shape and the dimensions of the hot spot are the same on both pictures. Due to atmospheric distortion and the noise in the recording process, this psf model characterized by star observation is applicable only in the cases of very clear, free of noise, frame observations. Every impurity of data reflects in propagation of error and the result is extremely noisy. All this must be considered if we want to compare data and to have some valid results (fifth figure). The same procedure was applied on January 4 1996, MIRLIN/IRTF images and results are roughly the same. The purpose of applying image restoration techniques on Jupiter images from remote sensing observations to increase the spatial resolution. The directory **~jelena/newpes/** contains README file which describe all the functions and procedures in that directory .

## Astronomical Data Processing and Reduction

Reduction of astronomical data from planetary atmospheres requires several stages of development. Data are returned from spectroscopic or imaging experiments in a raw form which must be compared with known spectral or radiance standards. The current software for the reduction of these data is written in Interactive Data Language (IDL) in a format involving extensive use of user-friendly menu-driven options, widgets. The aim of this part of my project was to create several improvements to this software to allow for the handling of data sets from a variety of instruments and hardware platforms.

### Autopreprocessing

Preprocessing data means mostly assigning some information about the raw image to the header of that image and sorting the resulting files by wavelengths and objects. I created a functional form for data preprocessing with fixed input which does not require the full screen and runs in a 'batch' mode. The directory **~jelena/nowidgets/** contains README file which describe all the functions and procedures in that directory. I modified DRM procedures, that already existed, for preprocessing data using DRM. In the directory that contains raw data, **autopreproc** procedure will assign all necessary information to the header and sort the file by object and wavelength.

## Cylindrical Maps

Signal to noise ratio of data could be increased if we increase the signal level by coadding limb-corrected cylindrical maps of the same feature . Then they should be re-mapped back onto the disk and data should be reconstructed from that image. Re-mapping is an inverse function from procedure that already exist in DRM and that makes cylindrical map from disk. The transformations from one coordinate system to another are the same, but instead of applying interpolation like we do for making cylindrical maps, in this case we are searching for mean value of all the pixel intensities that have the same x and y coordinates on a disk map. Due to rounding the float numbers to integer (coordinates), some data are lost and it is necessary to apply the bilinear interpolation for the missing intensities. The directory `~jelena/cmap/` contains README file which describe all the functions and procedures in that directory.

## Further Possibilities

Further evolution of the Hot Spot can be followed by adding a path of new data files into `~jelena/movie/newgif.dat` and animation can be updated whenever it's necessary.

Improving the model for the point spread function considering noise and different defects, could lead to even more consistent results of images with different spatial resolution.

Correcting DRM functions for data processing by adding different kinds of digital filters could improve some image reconstruction techniques and signal to noise ratio could increase significantly.

Improving the re-mapping procedure, by finding the ways only to interpolate missing pixels inside the disk and to ignore pixels with zero intensity value near the limb of the Jupiter disk.

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