Space All-Sky Imaging with a High Angular Resolution

Dollet, C., Bijaoui, A. & Mignard, F.
Cassiopeia CNRS - Observatoire de la Côte d'Azur Laboratory
B.P. 4229 – 06304 Nice Cedex 4 – France
dollet@obs-nice.fr

Objectives:

- Past or current sky surveys differ in their astrophysical aims, resolution, wavelength, sky coverage and on whether they rely on ground or space observations…

-This work looks at the possibility of **combining a high angular resolution and a full sky coverage**. However a **resolution of about 0.1 arcsec** generates a huge data flow implying specific data management:

- A **lossly** compression should be performed: it consists of taking off the known information followed by the statistical selection of the residual and relevant information.

- A payload design adapted for large field imaging and high speed acquisition chain.

- A specific operation mode: the scanning mode allows to have several observations at the end of the mission of the full sky with different orientations.

Here the ESA space mission Gaia is used as a testbed

Compression of astronomical fields:

-The transmission of all the pixels of the Astrometric Sky Mapper (ASM) = 100 Mbits/s
But 4 Mbits/s allowed for the three instruments of Gaia
- A compression of several hundreds is then necessary to obtain a telemetry rate of some hundreds of kbits/s. That is achievable only with **lossly** compression !!

- The **wavelet transform** is an efficient way to represent astronomical fields over a very limited number of components.

A possible algorithm:

The compression is performed in the wavelet space in four successive steps :
- (i) A **generalized Anscombe transform** stabilizes the variance noise. The pixel noise results from a combination of a Poisson process due to the photons and a Gaussian from the read-out.
-(ii) A **wavelet transform** to project the signal on a basis generated from the dilation and the translation of a single function.
- (iii) A statistical selection of the information corresponding to a **signal trimming at kσ** of the wavelet coefficients. Below this value, the coefficients are considered as non-significant and are set to zero.
- (iv) A 4-bits **coding** with a fast and reversible algorithm.. Each of the N bits necessary for the value coding provides a binary image. Each one is separately coded by an asymmetric quadtree.

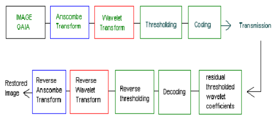


Fig 4: Schematic chart showing the successive steps used for the compression and the decompression of astronomical observations.

On ground, these different steps have to be applied in reverse order: decoding of the thresholded wavelet coefficients, application of the reverse thresholding and that of the reverse wavelet transform. A reverse generalized Anscombe transform terminates the processing.

The threshold of some wavelet coefficients may **generates artefacts** in the restored image. This depends on the choice of the wavelet transform. A Haar wavelet produces block effects whereas the bi-orthogonal 9/7 filter leads to display faint structures without astronomical significance.

Tab 2: Compression rate obtained for a simulated field without subtraction of known information about the contents of the fields. The field sizes 0.015 deg². A density of 1.6 millions of stars per deg² up to the magnitude 26 and 15 galaxies are generated by the SKYMAKER software adapted to the Gaia technical features.(Bertin &Arnouts, 1996)

1.5σ	2σ	2.5 σ	3σ
36	76	186	480

Subtraction of known information:

With this algorithm, the information selection in the wavelet space appears not sufficient to lead to a compression rate of several hundreds. In order to increase this factor, it is possible to **subtract** the **stellar information up to the on-board limiting magnitude of the instrument which is separately transmitted**.

In the Gaia case, the magnitude 20 is the limiting G one. **The stars up to G=20** are already detected by the ASM and transmitted. Their position and magnitude are available. On-board an image with only these detected point sources can be generated (called here **a map**) and then be **removed** from the observed field (the so-called **image**). Above a limiting magnitude like 20, the remaining information is limited. So high compression rates can be obtained. The kept information on faintest stars and large structured objects can be resolved at the end of the mission when all the observations will be combined.

After the map **subtraction on board**, the adding of the same information has to be done once on ground. From the star catalogue, the map is build. A generalised Anscombe transform, following by the wavelet transform is carried out so as to complete the residual transmitted thresholded wavelet coefficients. At this moment, only the reverse wavelet transform and the reverse Anscombe transform remain to do.

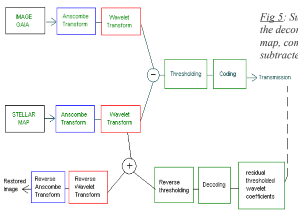


Fig 5: Successive steps used for the compression and the decompression of astronomical image when a map, composed of the already known information, is subtracted on board and added on ground.

threshold	1.5σ	2σ	2.5 σ	3σ
with map	37	80	209	670

Tab 3: Compression rate obtained when the stars brighter than the magnitude 20 are subtracted to the observed field. The used field is the same as the previous one in Table 1 .

Correlation with a mean point spread function of the instrument:

This new step can be added because it allows the **increase of the signal to noise ratio** and **the detection of faintest objects.** The additional information leads to a **less efficient compression for a identical thresholding**. Nevertheless a threshold at 4.5 σ provides an interesting compression rate. Even if this correlation seems to have no advantage in term of telemetry rate, **a gain of magnitude in the restoration of extended objects** becomes visible in the final restored images.

Tab 4: Compression rate obtained when the stars brighter than the magnitude 20 are subtracted to the observed field. The field is correlated with a mean point spread function of the instrument. The used field is the same as the previous one in Table 1 . The indicated telemetry rate corresponds to the one necessary for the transmission of all the pixels of the Astro Sky Mapper.

	3σ	4σ	4.5σ
rate	116	290	450
kbits/s	1672	669	431

Optical design

The payload of Gaia is composed of:

2 identical astrometric telescopes
+
1 spectrometric telescope

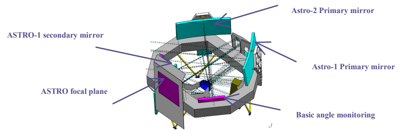


Fig1: Gaia payload

Features of the astrometric telescope:
- a **rectangular mirror**: 0.4 x 1.4 m² amounting to 0.65 x 0.80 deg²
That will facilitate its transport and its orbit installation. The resolution in the worst direction can be restored by a combination of many observations.

- **scanning mode**: a Lissajous orbit around the Sun-Earth Lagrange point L2 during five years
  - about **one hundred observations** available at the end of the mission
  - distribution of the angles of view depending on the galactic latitude and longitude

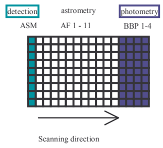


Fig 2: Focal plane for the Gaia astrometric telescope

Focal plane:

Its assembly is adapted to the Gaia scientific aims: three parts
. 1 CCD row for the detection: Astro Sky Mapper (ASM)
. 11 CCD rows for astrometric measures
. 4 CCD rows for broad band photometry

The used **pixel** is identical for all the focal plane.
0.0442 x 0.133 arcsec²
However various binning and integration time are used according to the CCD rows.

the **ASM case = binning 2x2 and 1.9 sec** TDI time
That leads to **an on-board limiting magnitude of 20**

The spectral band G for the astrometrical measures corresponds to λ = **300 – 1050 nm**

Another assembly for the focal plane….

For a mission more dedicated for a cartography of all the sky, a different organisation of the pixels can be proposed. Particularly for a multispectral study, four identical rows can be determined.

With a scan rate of 30''/s (the Gaia one is of 60''/s) , a higher integration time (24s) and upper limiting magnitude are obtained. 21 observations will be available at the end of the mission. The necessary compression rate could be more realistic thanks to a compression of the four bands together.

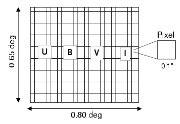


Fig 3: A schematic design of the focal plane assembly of a scanning satellite designed to map the sky in four spectral bands.

Tab 1: Limiting magnitude with a scan rate of 30''/s for different spectral bands.

	G	U	B	V	I
M_{lim}	23.9	22.3	23.4	22.7	22.1

Restoration at the end of the mission:

- About **one hundred observations** will be obtained at the end of the five years mission of Gaia. Each of them has a specific rotation and translation compared to a given reference system. That offers one the possibility to **improve the resolution** of an unique final image having the best resolution in all the direction.

- A method has been envisaged to **combine observations of the same sky area but with different orientations**. The correction of the rotation of these images is carried out in the Fourier space.

If I_k is the image I with the rotation θ_k, the invariance property of the Fourier transform (TF) gives the relation:

$$TF(I_k) = TF(rot_k(I)) = rot_k(TF(I))$$

So a **correction of the rotation** θ_k of each observation can be **done in the Fourier space** with an interpolation .

- So as to limit the artefacts in the restored image, some precautions have to be done.
  (i) Before the Fourier transform application of a M window allowing to decrease the presence of discontinuities of the edge. This window has a shape of a sinus.
  (ii) The I_k TF is multiplied by a Von Hann or Blackman window called W.

- To increase the signal to noise ratio of the final image, the sum of the Ik TF for which the orientation has been corrected is multiplied by the sum of TF of the point spread function of the instrument. Only the reverse Fourier transform is so necessary to obtain the final image. The sum of TF of the observed images can be divided by the contribution of the Von Hann or Blackman window to normalize.

$$I_{final} = TF^{-1}\left[\left(\frac{\sum_{k=1}^{N} W \times rot_{-k} TF(MI_k)}{\sum_{k=1}^{N} W} \right) \sum_{k=1}^{N} W \times rot_{-k} TF(PSF) \right]$$

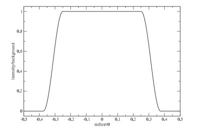
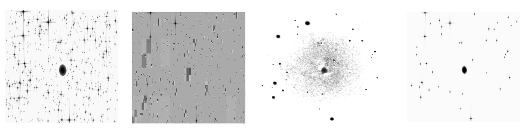


Fig 6: The M window allowing to decrease the presence of discontinuities of the edge. This window has a shape of a sinus.

Fig 7: Field with a standard density of stars (1.6 millions stars per deg² up to the magnitude 26). A galaxy has been included close to the center of the simulation. Illustration of the results obtained with a single observation or after a combination in the Fourier space of 100 observations.



Initial image without noise — Restored image from one observation — Restored image from 100 observations — Initial image without noise With only the stars up to the magnitude 22

A **gain of 2 magnitudes compared to the on-board limiting magnitude** is obtained after a combination of all the observations in the Fourier space. The best resolution is available in all the direction.

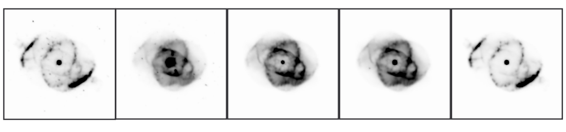


Fig 8: Results for the nebula NGC 6543 obtained after a combination in the Fourier space of 100 observations. Five HST WFPC2 images are used for the simulations. The filters are different. From left to right: F375N, F437N, F487N, F588N and F673N

Conclusion: Gaia as a test bed for a new mission…

- The Gaia mission was a good opportunity to do simulation and assessment of compression rates and restoration of astronomical fields. Some features of the payload are satisfactory for the development of a space mission dedicated to an all-sky imaging. To favour a **scanning operation** mode allows one to use a **rectangular mirror**, reducing the costs of the mission and avoiding a spreading out in space. A **rectangular pixel** can be used too because the observations during the mission will permit to **restore all the directions at the best resolution**.

- The combination of the restored images allows one the **realisation of an all-sky imaging at a resolution between 0.05 and 0.1 arcsec**. **Two magnitudes** compared to the on-board limiting magnitude are obtained so. The final result of such data leads to a **homogeneous and deep imaging** of all the sky. The payload concept can be retained for future projects of all-sky imaging with a resolution below 0.1 arcsec.

- Another possible evolution of the design is to envisage a **new assembly of the focal plane of Gaia and turn to multispectral studies**. There will be a fundamental interest for the astrophysical objects to be observed by such a survey.