USING HIPPARCOS TRANSIT DATA FOR APERTURE SYNTHESIS IMAGING

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ABSTRACT

The ESA Hipparcos astrometry satellite did not contain an imaging detector (such as a CCD) but used a modulating grid of alternating transparent and opaque bands to modulate the light from a given object. The Fourier coefficients of the modulated detector signal were the basis for the astrometric and photometric processing leading to the Hipparcos Catalogue. These coefficients are included (for a subset of the stars) in the CD-ROM version of the Hipparcos Catalogue as the 'Hipparcos Transit Data'.

The modulation components are equivalent to the interference fringes from an interferometer with baselines of 0, $\simeq 10$ and $\simeq 20$ cm (at 550 nm wavelength) oriented along the scan direction of the satellite. Each scan, therefore, gives a few points on the complex uv plane, which is the Fourier transform of the image. All points collected through the mission lifetime fall onto two concentric circles corresponding to the two modulated components and a central point corresponding to the total flux of the scan. In a similar fashion to radio astronomy, it is possible to use these complex visibilities (including both amplitude and phase information) calculated from the Transit Data to create an aperture synthesis image of an object. Applications of the method are shown using a standard radio astronomy software package (Difmap, CLEAN) to deconvolve several images including: a new double star discovered by Hipparcos, a set of images showing annual parallax, and orbital motion in a binary.

Key words: Hipparcos; aperture synthesis; Transit Data; image processing; CLEAN; double stars.

1. INTRODUCTION

One does not usually think of images or image processing in connection with the Hipparcos satellite. Nevertheless, it was realized early in the Hipparcos concept stage (Lindegren 1982) that it would be possible to produce images using the Hipparcos modulated detector signal and aperture synthesis software.

Instead of a CCD camera in the focal plane of the special split-mirror telescope, there was a modulation grid consisting of opaque and transparent bands.

Behind the modulation grid was the image dissector tube which collected the photons from the program stars as they traversed the satellite's field of view.

This convolution between the star's diffraction image and the modulation grid looks very similar to the response that one could obtain from an interferometer, where the interference pattern between the telescopes would correspond to the modulation grid. A single scan looks like sinusoidal corrugations projected onto the sky-plane. The orientation of the corrugations on the sky-plane is perpendicular to the scan direction, giving, in essence, positional information only in the scan direction. An image is created by superimposing all of the sinusoidal corrugations from the mission lifetime for a given object. The best images are for objects scanned in many different directions.

The modulated signal for a single-star point source can be well modeled using just a few harmonics in a Fourier expansion of the convolved signal. The response to a multiple star is a superposition of single star models with varying intensities and phases. For any arbitrarily complex object, the signal is therefore equally well fitted with a small number of Fourier coefficients. These coefficients and spatial frequencies are contained in the Hipparcos Transit Data.

Once the raw images (dirty maps) have been created using standard radio astronomy software packages, they can be enhanced using a deconvolution algorithm. In this work, we are using the Caltech Difmap package (Shepherd et al. 1995) and the CLEAN deconvolving algorithm (Högbom 1974). Both Difmap and CLEAN are publicly available.

Presented here are some examples of the types of objects that one could examine using this aperture synthesis method. These objects include a first image of a double star discovered by Hipparcos, images demonstrating annual parallax and images showing orbital motion in a binary.

2. THE HIPPARCOS TRANSIT DATA

The Hipparcos Transit Data were derived from the Case History Files which in turn were from an intermediate step in the Northern Data Analysis Consortium (NDAC) data reduction (Lindegren et al. 1992; Söderhjelm et al. 1992). A detailed description of the Transit Data can be found in Volume 1, Section 2.9

of the Hipparcos Catalogue (ESA 1997). What follows is an overview of these data as pertaining to this project.

The Hipparcos split-mirror telescope focused the images of stars onto a modulation grid. As the satellite spun, the images traversed the modulation grid perpendicular to the slits. The convolution of the diffraction image (basically the Airy pattern) with the grid resulted in a periodic intensity modulation at the detector, an image dissector tube with a steerable sensitive spot having a diameter of about 35 arcsec. The grid band dimensions were carefully chosen such that the Airy pattern convolved with grid gave two distinct modulation frequencies in addition to the mean intensity (zero frequency).

The Transit Data have been, in as much as possible, corrected for instrumental and time varying effects of the satellite. This was accomplished by determining the instrumental response to point sources as a function of time, position in the field, etc. All data were then 'rectified' in such a way that the response from a point source with magnitude Hp at a designated point on the sky was:

$$I_k = 6200 \times 10^{-0.4Hp}[1 + \bar{M}_1 \cos p_k + \bar{M}_2 \cos 2p_k] \quad (1)$$

where I_k is the modulated intensity, p_k and $2p_k$ are the phases relative to the reference point for successive samples ($k = 1, 2, \ldots$) and $\bar{M}_1$ and $\bar{M}_2$ are constants chosen to be 0.7100 and 0.2485, respectively. The reference points were the positions given for each object in the Hipparcos Input Catalogue (HIC). A single star not located at the reference point, when scanned, would have an additional phase term proportional to the error of the input catalogue.

Of course, a large percentage of the objects in the Hipparcos Catalogue are non-single. The response to an object that had more than one star in the 35 arcsec sensitive spot was a superposition of the modulated signals coming from each star. Each star's response had the form of Equation 1, however, each with its own amplitude and phase relative to the HIC reference position.

Figure 1 shows 'rectified' scans for a single star (Frame A) and a double star (Frame B). The modulated signal from a single star has a shape that is symmetric about the maxima while the double star's modulated signal (again, a superposition of two single star light modulation curves, each with its own amplitude and phase with respect to the HIC position) has an asymmetric shape. Three distinct spatial frequencies are easily seen in Frame A. These include a dc component giving a vertical offset and two oscillation frequencies.

From Equation 1, it can be seen that the modulated light curve of an object of arbitrary complexity can be well represented by just a few harmonics in a Fourier series expansion, namely:

$$I_k = b_1 + b_2 \cos p_k + b_3 \sin p_k$$
$$+ b_4 \cos 2p_k + b_5 \sin 2p_k \quad (2)$$

where $b_1 \ldots b_5$ are the Fourier coefficients and p_k and $2p_k$ are the phases of the two spatial frequencies. These coefficients and the spatial frequencies, along

with the HIC values for position, proper motion and parallax for the epoch 1991.25, are contained in the Transit Data of the Hipparcos Catalogue (CD-ROM #6). Also included on CD-ROM #6 is an index file, which allows the Transit Data to be accessed as a 'direct access' file.
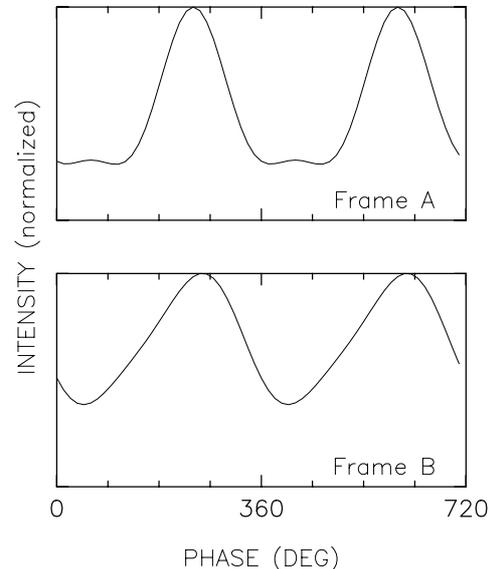

Figure 1. Two sample scans from the the Transit Data. Frame A is from a single star and it shows a typical single star scan profile. Positional information is obtained from the phase of the scan. Frame B is from a double star. The shape of the scan contains the multiplicity information.

All scans in the Transit Data are referenced to one epoch (1991.25) and the ICRS system. It should also be noted that the astrometric parameters of the reference point in the Transit Data *do not* correspond to those in the Hipparcos Catalogue. For the most part, they are values taken from the HIC.

The Transit Data contain a wealth of information. All of the positional, proper motion, parallax and multiplicity information is contained in these data. The aperture synthesis method is only one of the many possible exploitations of these data. The Transit Data could also be used, for example, to solve for curved motion in a double system (the standard data reduction only took into account proper motion). These results could then be used to determine mass ratios (Söderhjelm et al. 1997).

3. UV COVERAGE

In aperture synthesis, one inevitably ends up talking about *uv* coverage. Below, we discuss how this applies to the Hipparcos Transit Data. For more information on the general principle of aperture synthesis, see e.g. Thompson et al. (1994).

In optical telescopes, a single mirror collects the light from each star (or whatever object being looked at) and then focuses the light onto the focal plane. In modern astronomy, there is usually a CCD camera located at the focal plane to collect the photons. A 'real' image of the object is taken.
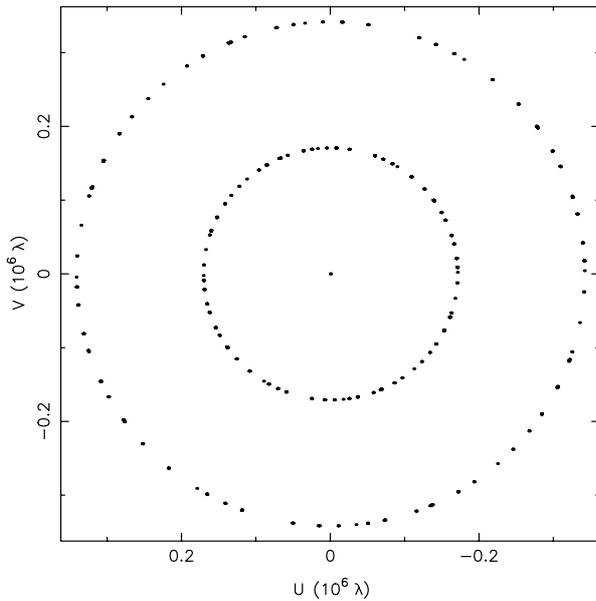
Figure 2. An example of uv coverage for a Hipparcos object. This object (HIP 15719) was scanned from virtually all angles. Objects near the ecliptic plane were not so well sampled. The middle point gives the total flux from all the scans while the two circles represent the two spatial frequencies that the Hipparcos satellite scanned each object.

Now imagine cutting up the mirror into infinitely small segments and then taking any two of pieces from the mirror. With just these two pieces, we no longer get an image of the star in the focal plane, but we get an interference pattern. A single interference pattern is a sampling of the sky at one spatial frequency for a given wavelength and only unidirectional information is obtained. If we could then combine the interference pattern from every combination of mirror pieces, we would restore the focused image from the whole mirror. Combining the various mirror segments (or telescopes in the case of radio astronomy) to get an image of the object is the process of aperture synthesis.

Each scan of the Hipparcos satellite gave three unique points on the *uv* plane; one for each spatial frequency. In radio astronomy, a point on the *uv* plane is a projection of the telescope baseline (measured in wavelengths) onto the sky-plane. The *u* direction is the east-west component of the baseline and the *v* direction is the north-south component. The longer the baseline, the further a point is from the center of the *uv* plane for a given wavelength. The three spatial frequencies from the Hipparcos satellite are equivalent to an interferometer with three baselines. If we take a wavelength of light at 550 nm, the Hipparcos satellite would be equivalent to baselines of approximately 0, 10 and 20 cm. The Fourier transform of a single point on the *uv* plane is a sinusoidal corrugation, which is how the sky looks to an interferometer or the image dissector tube of the Hipparcos satellite.

The center point on the *uv* plane is equivalent to a

zero baseline, which gives the flux of the observed object. Points that are off center give the orientation of the telescopes and their separation.

The Hipparcos satellite scanned each object at the three spatial frequencies of approximately 0, 1073400 and 2146800 rad/rad. These values were fairly constant over the mission lifetime. Therefore, the distances from the center point to the two non-zero spatial frequencies were nearly constant. The orientation of these points on the *uv* plot show the scan angle of the satellite (as opposed to baseline orientations in radio astronomy).

Figure 2 gives an example of a well scanned star (HIP 15719). The *uv* points from all the scans form the central point and two concentric circles. For stars near the ecliptic plane, large sections of these two circles are not filled in. This is to be expected as a natural consequence of the scanning law and the 43 degree Sun aspect angle. Having large gaps in these circles could make the visual quality or sharpness of the deconvolved images rather poor.

The points on the *uv* plane contain all the relevant scan information. The location on the *uv* plane shows the scan angle and spatial frequency while the complex visibility $V(u, v)$ stored at that position contains the amplitude and phase information for that particular scan. The three complex equations needed to reproduce one Hipparcos scan (three spatial frequencies) are:

$$V(0,0) = b_1$$
$$V(f_x, f_y) = \frac{b_2 - ib_3}{\bar{M}_1}$$
$$V(2f_x, 2f_y) = \frac{b_4 - ib_5}{\bar{M}_2} \tag{3}$$

where f_x and f_y are equivalent to the u and v baseline projections from radio astronomy, respectively, and where $\sqrt{f_x^2 + f_y^2} \approx 1073400$ rad/rad. It can also be shown that the complex conjugate of the visibilities are:

$$V(0,0) = V^*(0,0)$$
$$V(-f_x, -f_y) = V^*(f_x, f_y)$$
$$V(-2f_x, -2f_y) = V^*(2f_x, 2f_y) \tag{4}$$

In terms of these *uv* plots, this means that each spatial frequency's *uv* point can be plotted twice, symmetrically about the origin. Each Hipparcos scan is represented by five points in Figure 2, though as previously mentioned, only three of the points are non-redundant.

Because the information from an interferometer can be expressed by a few terms (two spatial frequencies, two Fourier coefficients, and time) an efficient and memory saving way of storing these data was needed. The standard FITS files were not capable of handling this type of data. The radio astronomy community developed an extension to the FITS files called
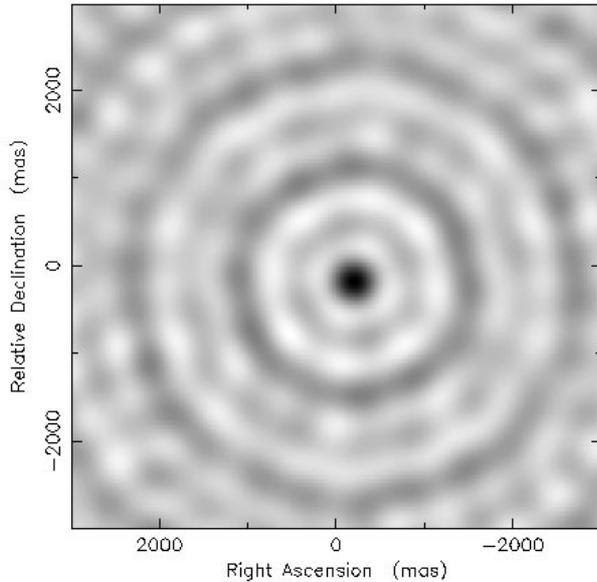
Figure 3. The raw image (dirty map) of Hipparcos object 15719. This dirty map is the Fourier transform of the uv plane in Figure 2.
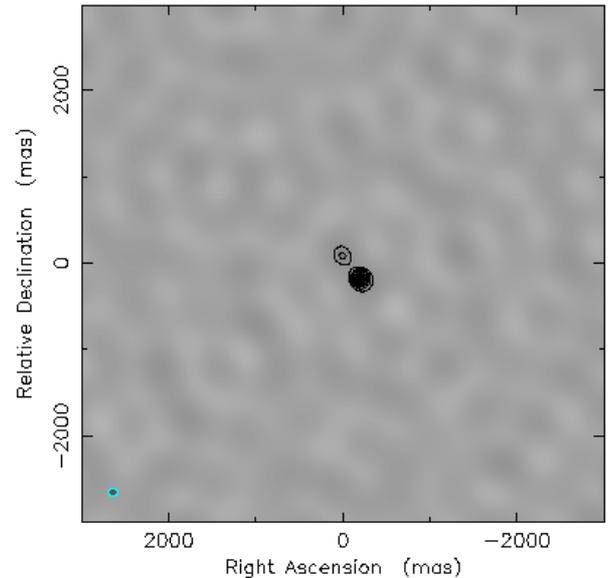

Figure 4. An image of a binary discovered by the Hipparcos satellite. These two objects (HIP 15719) have a separation of 0.32 arcsec on the sky and a difference in magnitude of 2.8. The restoring beam is shown in the lower left hand corner.

Random Groups or, more commonly, UV FITS files (Greisen & Harten 1981). This is the file data structure that radio astronomy software packages prefer or require. The Hipparcos Transit Data can be stored in this type of data file (Quist & Lindegren 1998).

4. IMAGE RECONSTRUCTION

An image of the Hipparcos satellite is obtained by taking the Fourier transform of the *uv* plane along with the phase and amplitude information. This image is a superposition of the sinusoidal corrugations, each with their corresponding amplitude and phase. This process produces what is called in radio astronomy a dirty map, see Figure 3. In a dirty map, it is not always easy to 'see' a single star, let alone a multiple star system or extended object and, therefore, a little image processing is usually necessary.

In this work, we are using the CLEAN algorithm contained in the Caltech Difmap package. The main idea behind the CLEAN algorithm is simple. A model of a point source (dirty beam) is created using the scan information. (This model is created from a normalized superposition of uniform sinusoidal corrugations centered on the reference position.) If it can be assumed that the dirty map is from any number of point sources, the model is placed over the dirty map maximum. A percentage of the total intensity multiplied by the point-source model is then subtracted from the dirty map. The process is then repeated at each subsequent maxima until the residual map represents the background noise. Each point where the model was placed over the map for subtraction is then assumed to be from a point source. These points are finally convolved with a Gaussian point spread function (restoring beam) and set upon the residual map to form the final images, as shown below.

As previously mentioned, the phase information contained in the Transit Data is with respect to the reference point. Positional errors in the Input Catalogue manifest themselves as a phase shift of the modulated signal. Input Catalogue errors for the proper motion and parallax manifest themselves as motion of the real star, over the mission lifetime, with respect to the reference point. In producing aperture synthesis images, the positional errors would be seen as offsets of the objects from the image center while proper motion and parallax errors would be seen as a blurring of the objects.

5. EXAMPLE IMAGES

The Transit Data contain the scan information for 38 535 objects. Of these stars, approximately 5000 are bona fide single, which can be used for calibration or comparison purposes.

The remaining objects are known, newly discovered, or suspected double or multiple stars, or they were problematic objects (objects with questionable solutions in the Hipparcos Catalogue). A good example of a double star discovered by the Hipparcos satellite is shown is Figure 4. This is probably the first ever resolved image of this object (HIP 15719). The difference in magnitude between the primary and secondary star is approximately 2.8 and the separation is 0.32 arcsec on the sky. The restoring beam (with a FWHM of 0.1 arcsec) is shown in the lower left hand corner of the figure.

Figure 4 was produced by combining all of the scans during the mission lifetime. One is not forced to do this for all types of images. By dividing all of the
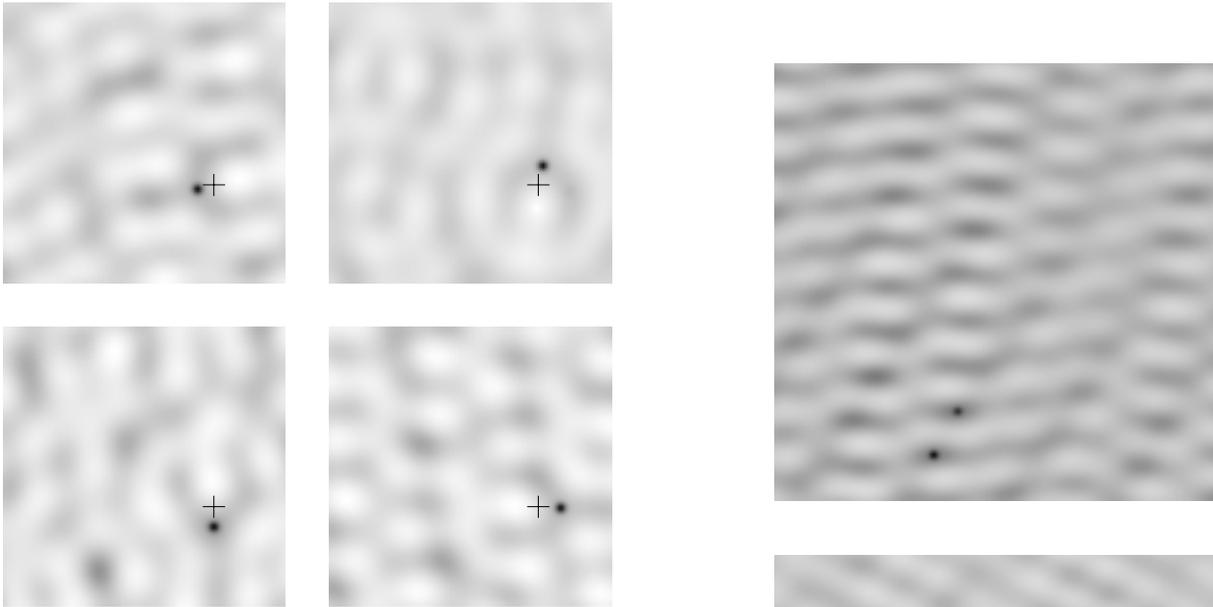
Figure 5. The scans from the mission lifetime are divided up into four 'seasons' and then deconvolved to show annual parallax. These four seasons (clockwise from the upper left hand image) are approximately Feb–April, May–July, Aug–Oct and Nov–Jan. This object (HIP 86162) has an ecliptic latitude of around 88 degrees and, therefore, has nearly circular annual parallax motion. The four images all have 3.0 arcsec per side and the same RA and Dec orientation as in Figure 4.

scans into four periods (seasons) of three month each, independent of the year of the scan, one could search for annual parallax motion. An object near the ecliptic poles would show its annual parallax as circular motion on the sky. Figure 5 shows the annual parallax motion for HIP 86162, which has an ecliptic latitude of around 88 degrees.

The last three images (Figure 6) demonstrate another way in which one can divide up the scans. By taking a well resolved binary system with a fairly short orbital period, the absolute orbital motions of each component can be seen. In this example (HIP 46706), the orbital period is around 18.3 years. The mass ratio is 0.97 (Söderhjelm et al. 1997) and the separation on the sky is 0.65 arcsec. The two stars have nearly equal magnitudes of 10.7 and 10.9. The time periods for the three images were 1989.8–1990.5, 1990.5–1992.0 and 1991.5–1992.9. Note how the last two images have overlapping times. This was necessary in order to have enough scans in different directions to get sufficiently good *uv* coverage for the last third of the mission. In the Hipparcos Catalogue, this system was solved as a 'fixed' binary having a position angle of 313 degrees. This is an example of where the Transit Data allow us to extract more information on a system than what is contained in the printed catalogue.
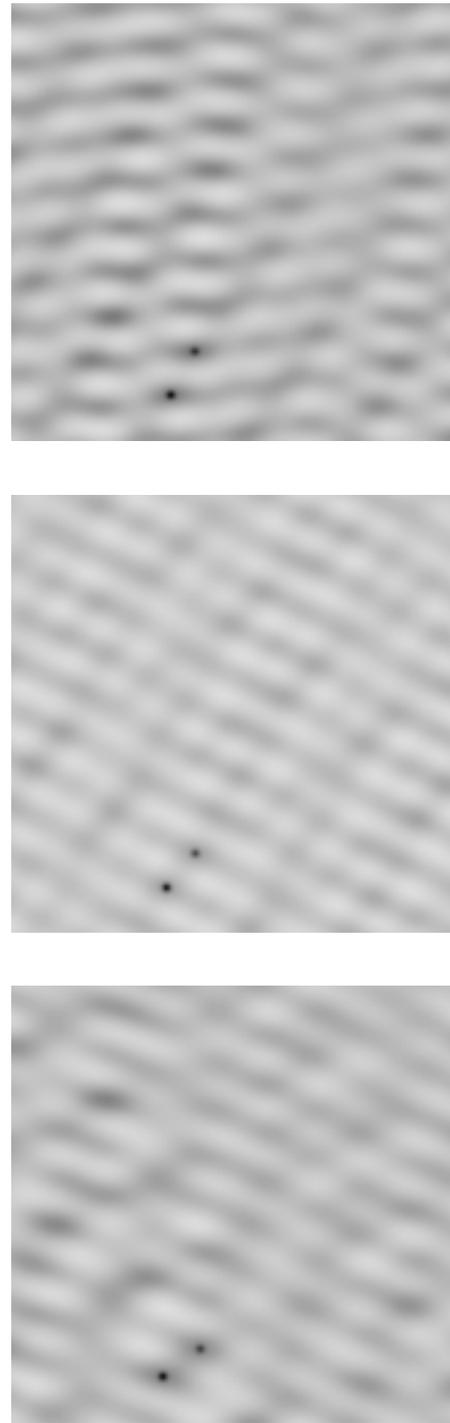

Figure 6. Three images showing orbital motion for HIP 46706. Scans from the entire mission are divided up into three times periods. They are, from top to bottom, 1989.8–1990.5, 1990.5–1992.0 and 1991.5–1992.9. This binary system has an orbital period of 18.3 years, a mass ratio of 0.97 and magnitudes of 10.7 and 10.9. The RA and Dec orientations are the same as in Figure 4 and each image has 6.0 arcsec per side.

6. CONCLUSIONS

While the Hipparcos satellite was not designed for imaging, the production of aperture synthesis images emerges as a natural by-product of the scanning law and the modulation grid. The Transit Data, included in the Hipparcos Catalogue, give the opportunity to apply this method to about a third of the total stars in the catalogue. One advantage of this method is that no models are assumed in producing an image. When the two consortia were reducing these data, often these data were assumed to be from, for example, a double star. The fit of the data was not always optimal. This aperture synthesis method needs no special treatment of the data for multiple star systems as compared to single stars and can, therefore, be used to check the solutions of some problematic objects in the final Hipparcos Catalogue.

There are some 1000–2000 solutions in the final catalogue where the two consortia could not come to an agreement as to the best values for the positions, proper motions and parallaxes for these objects. The aperture synthesis method could be systematically applied to these objects in order to help resolve any discrepancies. Confirmation of such work could then be done with the aid of optical and speckle interferometry. A paper (Quist & Lindegren 1998) is in preparation which will give a more detailed description of the aperture synthesis properties of the Transit Data and a description of the various functions incorporated into the software developed at Lund Observatory which makes the above types of images possible.

ACKNOWLEDGMENTS

REFERENCES

ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP–1200

Greisen E.W., Harten R.H., 1981, A&AS, 44, 371

Högbom J.A., 1974, A&AS, 15, 417

Lindegren L., 1982, ESA SP–177, 147

Lindegren L., Høg E., van Leeuwen F., et al., 1992, A&AS, 258, 18

Quist C.F., Lindegren L., 1998, A&AS, in preparation

Shepherd M.C., Pearson T.J., Taylor G.B., 1995, BAAS, 27, 903.

Söderhjelm S., Evans D.W., van Leeuwen F., Lindegren L., 1992, A&AS, 258, 157

Söderhjelm S., Lindegren L., Perryman M.A.C., 1997, ESA SP–402, this volume

Thompson A.R., Moran J.M., Swenson Jr. G.W., 1994, Interferometry and Synthesis in Radio Astronomy, Krieger Publishing Company