HST as a reliable astrometric tool for pulsar astronomy: the cases of the Vela and Geminga pulsars.

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Abstract
The quest for the distance of the Vela and Geminga pulsars yielded, so far, a set of four WFPC2 images for each object. The availability of couples of images taken at the same period of the year, thus affected by the same parallactic displacement, prompted us to use Vela and Geminga as test cases to assess the reliability of HST astrometry.

1 Introduction.
Optical astrometry becomes important when peculiar characteristics of the pulsar emission prevent the use of radio techniques, such as timing or interferometry, to measure accurate pulsar positions. This is the case for the Vela pulsar (PSR B0833-45), whose signal shows irregularities that affect the accuracy of the radio positioning, as well as for Geminga, whose radio signal appears erratic, if at all present (Kassim & Lazio 1999 [3] and references therein).

Thus, accurate positioning of these objects has to rely on the astrometry of their faints optical counterparts. Over the years, the WFPC2 on HST has been repeatedly used to image both pulsars with the aim to measure their distances through their parallactic displacements. In order to do so, for each target a sequence of at least three observations were to be performed at the times of maximum parallactic elongation, 6 months apart, at the same date, with identical instrument set-ups. Unfortunately, obtaining three time critical observations is not always an easy task. While for the V=25.5 Geminga, it was possible, during cycles 4 and 5, to collect the triplet of observations used by Caraveo et al. (1996)[1] to infer the object’s distance, for the V=23.6 Vela, the cycle 6 observing programme yielded only two images (collected in june 1997 and january 1998).

The whole program has been repeated in cycle 8 with two images available so far (June 1999 and January 2000) and a third one scheduled for July 2000. The availability of two couples of WFPC2 observations of Vela, both obtained at the same period of the year, i.e. with the same parallactic factor, and both spanning a same time interval of 2 years (see Table 1), prompted us to use them to check the consistency of the procedure we have developed to superimpose WFPC2 images to measure proper motions and, eventually, parallaxes of isolated neutron stars. Indeed, two similar couples of WFPC2 observations, covering a time span of 1 year each, are also available for the fainter Geminga (see Tab.1), for which a fourth (unpublished) observation can be added to the triplet used by Caraveo et al. (1996)[1]. For both Vela and Geminga we can thus obtain two pure, totally independent, measurements of the proper motion, which can be used both to confirm the reproducibility and consistency of WFPC2 astrometry and to assess the weights of the known systematic errors possibly related to the target’s brightness, the number of reference objects in the field, the instrument jitter, etc.

2 Data Analysis.
After performing the standard data reduction (OTF recalibration, exposures association and cosmic ray cleaning), we worked on the accurate frame superposition through a grid of “good” reference stars (see Fig.1 for an outline of the astrometric procedure). The reference stars coordinates were computed by 2-D gaussian fitting of their intensity profiles,yielding a positioning accurate to within 0.01-0.07 pixels.

Using the same procedure, we computed the coordinates of Vela and Geminga with an average accuracy of 0.04 and 0.08 pixels, respectively. In all cases, the overall centering accuracy depends upon several factors: the objects S/N, the local background conditions, the shape of the PSF, the size of the centering area and
Table 1: Summary of the HST/WFPC2 observations used in the present work. In all cases the observations were taken through filter F555W and the target was centered in the PC chip (45 mas/px). The columns give the pulsar name, the observation ID, the observing epoch, the total number of repeated exposures for each observation and the time per exposure in seconds. For each target, observations 1-3 and 2-4 define couples ♯ 1 and ♯ 2, respectively.

| Pulsar | Obs. ID | Date           | N.of exp | Exposure(s) |
|--------|---------|----------------|----------|-------------|
| Vela   | 1       | 1997 June 30   | 2        | 1300        |
|        | 2       | 1998 January 2 | 2        | 1000        |
|        | 3       | 1999 June 30   | 2        | 1000        |
|        | 4       | 2000 January 15| 2        | 1300        |
| Geminga| 1       | 1994 March 19  | 2        | 700         |
|        | 2       | 1994 September 23| 4       | 700         |
|        | 3       | 1995 March 18  | 4        | 700         |
|        | 4       | 1995 September 20| 4       | 700         |

Figure 1: Schematic overview of the procedure required to compute relative astrometry measurement between sets of images taken at different epochs.

| PSR     | Couple | Telescope Jitter (pixel) | References Centroids Accuracy (pixel) | Target Centroid Accuracy (pixel) | ♯ stars | Frame Superposition Accuracy (pixel) | Total Accuracy (pixel) |
|---------|--------|--------------------------|---------------------------------------|----------------------------------|---------|--------------------------------------|------------------------|
| Vela    | ♯1     | 0.03                     | 0.01-0.06                             | 0.02-0.03                        | 26      | 0.04                                | 0.07                   |
|         | ♯2     | 0.02                     | 0.01-0.07                             | 0.02-0.04                        | 25      | 0.05                                | 0.07                   |
| Geminga | ♯1     | 0.02                     | 0.01-0.04                             | 0.06-0.08                        | 5       | 0.03                                | 0.09                   |
|         | ♯2     | 0.06                     | 0.01-0.04                             | 0.06-0.09                        | 9       | 0.08                                | 0.14                   |

Table 2: Summary of the errors (in PC pixels) affecting the relative astrometry of the Vela pulsar and Geminga. The first column lists the objects names and the second the couples of observations compared (see caption of Table 1). The third column lists the telescope jitter, the fourth and the fifth the errors on the centroids of the reference stars and of the target, respectively. The sixth reports the number of reference stars used for each couple and the seventh the error on the frame superposition. The overall error on the object displacement is reported in the last column.
the telescope jitter. We then corrected the measured coordinates for the effects of the instrument geometrical distortion (Gilmozzi et al. 1995 [2]) applying the task STSDAS/METRIC. Next step was thus the registration of the reference frames. While for Vela the large number of reference stars (25) in the field (Fig. 2, left) allowed us to follow the traditional astrometric approach (fitting a linear transformation with 2 independent translation factors, 2 scale factors for X and Y and a rotation angle), for Geminga no more than 10 stars were available (Fig. 2, right) and we reduced the number of free parameters by using the HST roll angle to align the frames. The fits on the frame superposition turns out to be very accurate, with a rms of 0.04 and 0.08 pixels for the Vela and Geminga fields, respectively.

In both cases the accuracy of the superposition is determined primarily by the number of reference stars and by their relative distribution, while the algorithm used for the coordinate transformation and the correction for the CCD distortions play a less important role. Table 2 summarizes the overall uncertainty on the target relative position resulting both from the combination of the errors due to the centering procedure and on the frame registration.

### 3 Results.

The Vela and Geminga displacements measured from each couple of images are reported in Table 3. The quoted uncertainties are conservative and result from a standard propagation of the errors affecting objects centroids and frame superpositions. In the case of Geminga, the higher uncertainties are due mainly to the paucity of reference stars, to the faintness of the pulsar optical counterpart and to the higher jitter value of the fourth image. Last but not least, the Geminga errors are diluted over a shorter time span (1 year vs. 2 years for Vela). All this may contribute to the small difference (5 mas/yr) between values of \( \mu_\delta \), measured for the two couples

| PSR | Couple | PM(RA) mas/yr | PM(DEC) mas/yr | PM mas/yr | PA degrees |
|-----|--------|---------------|---------------|-----------|-------------|
| Vela | 1     | -45.2 ± 2     | 26.2 ± 2      | 52.2 ± 3  |             |
|     | 2     | -45.6 ± 2     | 26.3 ± 2      | 52.6 ± 3  |             |
|     | average | -45.4 ± 1.5  | 26.2 ± 1.5    | 52.4 ± 2  | 300 ± 2     |
| Geminga | 1    | 141.3 ± 4     | 94.0 ± 4      | 169.7 ± 6 |             |
|       | 2     | 140.9 ± 6     | 99.1 ± 6      | 172.3 ± 8 |             |
|       | average | 141.1 ± 4     | 96.5 ± 4      | 171.0 ± 6 | 56 ± 2      |

Table 3: Results. For both Vela and Geminga the proper motions values (in mas/yr) are computed independently using the couples of observations 1 and 2 i.e. the ones obtained in the same period of the year (see caption to table 1). The average results with the corresponding proper motion position angles (P.A.) in degrees are also reported.

Figure 2: Planetary Camera observations of the fields around the Vela and Geminga pulsars (left to right) taken with the filter 555W. The arrows marks the proper motion directions.
of images. In any case, the reproducibility of the results, always well within the quoted errors, gives a further demonstration of the reliability of the WFPC2 as an outstanding astrometric tool for faint targets.

We can thus confidently compute a standard average for each couple of measurements. The final results, also reported in Table 3, are bound to become the reference values for the proper motions of these two nearby isolated neutron stars.

References

[1] Caraveo, P.A., Bignami G.F., Mignani, R.P. and Taff, L.G., 1996, ApJ 461, L91
[2] Gilmozzi R., Ewald S. and Kinney E., 1995, WFPC2 Instrument Science Report 95-02
[3] Kassim, N.E., Lazio T. and Joseph W., 1999, ApJ 527, L101