Gamma-ray burst afterglows and the nature of their host galaxies.
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8 The Faint Sky Variability Survey I: Outline, Goals and Data reduction process


Abstract. The Faint Sky Variability Survey is aimed at finding photometric and astrometric variable objects in the brightness range between 16th and 24th magnitude on timescales between tens of minutes and years with photometric precisions ranging from 3 millimagnitudes for the brightest to 0.2 magnitudes for the faintest objects. An area of ~23 square degrees, located at mid and high Galactic latitudes, has been covered using the Wide Field Camera on the 2.5-m Isaac Newton Telescope on La Palma. Here we describe the main goals of the Faint Sky Variability Survey and the data reduction process.

8.1 Introduction

The advance of large format (>2k×2k) CCDs with high quantum efficiency has opened up a new area in Galactic and extragalactic astrophysics: the systematic study of astrophysical objects fainter than 20th magnitude. The importance of this brightness regime is nicely illustrated by the current, fast development in the field of Gamma-Ray Bursts (GRBs; for recent reviews see Katz et al. 1998; Piran 1999; Van Paradijs et al. 2000), where the localization of faint variable optical counterparts has led to a large increase in our understanding of GRBs.
In the following sections we will outline the main goals of the Faint Sky Variability Survey (FSVS\(^1\)) (§8.2), the INT Wide Field Camera (§8.3), the observing strategy (§8.4) and field selection (§8.5). After a short comparison with other, running surveys (§8.6), we will discuss the data reduction (§8.7), final data products (§8.8), availability of the data (§8.9), and conclude (§8.10). The survey started in November 1998.

### 8.2 Goals of the FSVS

Understanding the variability of stars has often been crucial in the development of astrophysics, with applications ranging from the evolution of stars, to the structure of our Galaxy and the distance scale of the Universe. Current variability studies are mainly restricted to either bright regimes (brighter than 20\(^\text{th}\) magnitude) or smaller areas (high-z supernovae and GRB searches). In the Galactic realm, a deep variability study will not only reveal the characteristics of specific groups of stellar objects, but will also shed light on the outer parts of our Solar System, the direct Solar Neighbourhood, the structure of our Galaxy, and the extent of the Galactic halo. The FSVS has observed \(\sim 23\) square degrees down to 24\(^\text{th}\) magnitude. The main targets can be divided into two broad areas of interest: photometrically and astrometrically variable objects.

#### 8.2.1 Photometrically variable objects

Among the various classes of variables stars our main targets are:
- **Close Binaries**: Current detections of low-mass close-binary systems (Cataclysmic Variables, Low-Mass X-Ray Binaries (including Soft X-Ray Transients) and AM CVn stars) are strongly biased to small subsets of their populations. Of these systems the Cataclysmic Variables (CVs) form the main subgroup we expect to find. We refer to Warner (1995) for an extensive review of CV properties. Currently, most CVs are either found as by-products of extragalactic studies like blue-excess, quasar surveys (e.g. the Palomar-Green survey: Green et al. (1986); the Hamburg Quasar Survey: Engels et al. (1994); Wisotzki et al. (1996); and the Edinborough-Cape Survey: Stobie et al. (1987)), or by their outbursts in which the system suddenly brightens 3-10 magnitudes due to an instability in the accretion disk. However, theoretical calculations show that the majority of the CV population should have evolved down to mass-transfer rates that are lower than \(\sim 10^{-11} M_\odot \text{yr}^{-1}\) (see e.g. Kolb 1993; Howell et al. 1997, 2001). At these very low-mass transfer rates, CVs are expected to be faint (typically V>20), have no UV excess, show no (frequent) outbursts, and will therefore not show up in conventional searches. However, all CVs show intrinsic variability of the order of tenths of magnitudes or

\(^1\)http://www.astro.uva.nl/~fsvs
more. This variability is either caused by ‘flickering’ (mass-transfer instabilities), orbital modulations (hot-spots or eclipses) or long-term mass-transfer fluctuations. Searching for faint variable stars is therefore a very good way to disclose the characteristics of the majority of the CV population. The same search technique will also make the survey sensitive to other classes of close binaries, such as LMXBs, SXTs in quiescence and AM CVn stars. Based on population synthesis models we expect to find 20 new CVs per square degree (Howell et al. 1997).

- **RR Lyrae stars**: Due to their standard candle properties and easy recognition by colour and variability, RR Lyrae stars can be used as excellent tracers of the structure of the Galactic halo. A few of these stars have been found at large galactocentric distances (Hawkins 1984; Ciardullo et al. 1989), but number statistics are still poor. Finding more of these stars will help to constrain the total enveloped mass in the Galaxy at different radii. A highly uncertain number of 0.2 RR Lyrae stars per square degree that are beyond 30 kpc can be deduced from the very small number of known systems.

- **Optical Transients to Gamma-Ray Bursts** The detection of optical counterparts to GRBs (e.g. Van Paradijs et al. 1997), and the subsequent classification of GRBs as cosmological (e.g. Metzger et al. 1997; Kulkarni et al. 1998b) have shown that GRBs are among the most energetic phenomena known in the Universe. The high energies implied by observations of GRB afterglows \(10^{53-54}\) erg in \(\gamma\)-rays if isotropy is assumed, Kulkarni et al. 1998b, 1999), raises the question whether GRBs are emitting their energy isotropically or in the form of jets. In the latter case the energies involved will be much lower, depending on the amount of beaming. Even if the \(\gamma\)-rays are beamed the optical afterglow is expected to radiate more isotropically, and thus one expects to observe faint afterglows without an accompanying burst in \(\gamma\)-rays. The detection rate of such transient events will constrain the beaming angle. A discussion and analysis of such results is presented in Vreeswijk et al. (2002).

### 8.2.2 Astrometrically variable objects

The observing schedule that we have adopted for the FSVS (see § 8.4) also allows for the detection of astrometrically variable objects. Our interests fall into two main categories:

- **Kuiper Belt Objects**: Kuiper Belt Objects (KBOs) are icy bodies revolving around the Sun in orbits that lie outside the orbit of Neptune (which has led to the alternative name of Trans Neptunian Objects; TNOs). Since their discovery in 1993 (Jewitt & Luu 1993), more than 100 of these objects have been found. Studying their properties will give important insight into the formation of the Solar system and planetary systems in general. One question that is particularly well suited to be answered is the inclination distribution of KBOs. Most KBOs have been found within 5° from the ecliptic, but this may constitute an observational bias, since most searches have been (and are being) performed close to the ecliptic. Since the FSVS is mostly pointing away from the ecliptic,
we will be able to set limits on the inclination distribution of KBOs.

- **Solar Neighbourhood Objects:** The planned re-observations after one year will allow for the detection of high proper-motion objects in the Solar neighbourhood. These will be extremely important to constrain the low-mass end of the IMF in the solar neighbourhood, to estimate the relative contribution of the disk and halo population of stars in the solar neighbourhood and trace the star formation history of the Galactic halo by finding old, high proper motion, white dwarfs.

### 8.3 The INT Wide Field Camera

The *Wide Field Camera*\(^2\) (WFC) is mounted at the prime focus of the 2.5-m *Isaac Newton Telescope* (INT) on the island of La Palma. The WFC consists of 4 EEV42 CCDs, each containing 2048×4100 pixels. They are fitted in an L-shaped pattern, which makes the Camera 6k×6k, minus a 2k×2k corner (see Fig. 8.1). The CCDs consist of 13.5μ pixels (0'33 per pixel on the sky), which gives a sky coverage per CCD of 22'8×11'4. A total of 0.28 square degree is covered by the combined four CCDs. With a typical seeing of 1'0-1'3 on the INT, point objects are well-sampled, which allows for accurate photometry. The Camera is equipped with Harris and Sloan filters, of which we use the Harris B, V and I filters.

### 8.4 Observing strategy

The typical timescales of variability covered by the objects listed above vary from hours (CVs, KBOs, RR Lyrae stars) to days (optical transients to GRBs) to years (high proper motion stars). To cover all possible timescales of variation we have devised an observing strategy that optimises both the coverage per field as well as the total sky coverage. The variability search is done with 10 min. V-band observations. This is a compromise between the expected colours of our sources (blue as well as red), sensitivity of the WFC (peaks in B and V) and a coverage of the optical band using the B, V and I-bands. For the photometric variability we find that at least 15-20 pointings are needed to firmly state that an object is variable and also get an indication of the timescale of its variability (or ideally its period). For the first two runs of the FSVS this number was limited to ~10, but has been raised to 15-20 in subsequent runs.

The FSVS has been observing in one-week time slots, separated by roughly half-year intervals. The main data set for each field has been obtained within the one week observing run, with observations of a particular field spread over the full week. In the

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\(^2\)see: http://www.ast.cam.ac.uk/~wfcsur for an extensive description of the WFC
8.4 Observing strategy

Figure 8.1: Graphical lay-out of the WFC 4 EEV 4k×2k CCDs. In the orientation used by the FSVS, North is up and East is to the left. The WFC rotates around its Rotator Center (RC).

Observing sequences we have tried to avoid a regular spacing of the observations since this will introduce strong aliases in any period search. On photometric nights (which were always present in each of the runs) the fields were observed in B (10 min) and I (15 min) together with Landolt fields. For the Landolt fields, observations were taken centered on each of the four chips to obtain a sufficient number of photometric standards per chip (see §8.7.9). Using this observing strategy an average of 4 square degrees per one-week run were observed. Single V-band re-observations of each field are being obtained on a yearly basis.
8.5 Field selection

The field selection was governed by the following four criteria (in order of importance) to ensure maximum quality of the data:

- Fields are located at Galactic latitudes $b > 20^\circ$: to probe the Galactic halo as well as the Galactic disk to considerable depths we target most of our fields at mid-Galactic latitudes (see Table 8.1). This also prevents problems with field crowding and interstellar extinction that will be present at lower Galactic latitudes. The effect of interstellar extinction would be to limit the distance to which we are able to observe into the halo.

- Fields are observed within a zenith distance, $z < 30^\circ$: this criterion has been set to ensure that the effect of differential extinction coefficients has no impact on the accuracy with which the differential photometry can be done.

- If possible, the fields are chosen close to the ecliptic, to increase the chances of finding KBOs. However, as explained in §8.2.2, even if we are not pointing at the ecliptic, our results may help to constrain the inclination distribution of KBOs.

- Bright stars are avoided: stars brighter than $\sim 10^{th}$ magnitude will cause large charge overflows and diffraction patterns that limit the area on a CCD that can be used for accurate photometry, depending on the placement and brightness of the star. To prevent this from happening the fields are selected to be as devoid as possible of bright stars. We checked for the presence of bright stars using the Digital Sky Survey in the selection of the fields.

It is clear that not all four criteria can be met at all times of the year. For the Northern Hemisphere all four criteria are only satisfied in late November-early December. Table 8.1 shows the center points of the FSVS fields, together with the Galactic coordinates and period of first observations.

8.6 Comparison with other surveys

The FSVS is unique in its search for variability on short timescales (tens of minutes to days), depth and precision of its differential photometry, although having a rather moderate sky-coverage. The Sloan Digital Sky Survey (SDSS; York et al. 2000) covers a much larger area of the sky (10,000 square degrees), but at brighter magnitudes ($14 < g' < 22.5$), and provides almost no variability information. The microlensing studies (e.g. MACHO and EROS; Alcock et al. 1997; Beaulieu et al. 1995) do obtain variability
Table 8.1: Field centers and period of observations of the FSVS fields. All coordinates are in J2000 units.

<table>
<thead>
<tr>
<th>Field No.</th>
<th>RA</th>
<th>Dec</th>
<th>U</th>
<th>B</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-6</td>
<td>23h44m</td>
<td>+27°15'</td>
<td>105</td>
<td>-33</td>
<td>Nov 98</td>
</tr>
<tr>
<td>7-12</td>
<td>02h32m</td>
<td>+15°00'</td>
<td>156</td>
<td>-40</td>
<td>Nov 98</td>
</tr>
<tr>
<td>13-18</td>
<td>07h52m</td>
<td>+20°40'</td>
<td>200</td>
<td>+22</td>
<td>Nov 98</td>
</tr>
<tr>
<td>19-22</td>
<td>12h53m</td>
<td>+27°01'</td>
<td>220-21</td>
<td>+90</td>
<td>May 99</td>
</tr>
<tr>
<td>23-26</td>
<td>12h51m</td>
<td>+26°20'</td>
<td>268-360</td>
<td>+89</td>
<td>May 99</td>
</tr>
<tr>
<td>27-30</td>
<td>16h25m</td>
<td>+26°33'</td>
<td>45</td>
<td>+43</td>
<td>May 99</td>
</tr>
<tr>
<td>31-34</td>
<td>17h20m</td>
<td>+27°00'</td>
<td>49</td>
<td>+31</td>
<td>May 99/00</td>
</tr>
<tr>
<td>35-40</td>
<td>03h02m</td>
<td>+18°38'</td>
<td>161</td>
<td>-33</td>
<td>Jan 00/01</td>
</tr>
<tr>
<td>41-46,59</td>
<td>07h15m</td>
<td>+21°00'</td>
<td>196</td>
<td>+15</td>
<td>Jan 00/01</td>
</tr>
<tr>
<td>47-52,60</td>
<td>10h00m</td>
<td>+21°30'</td>
<td>211</td>
<td>+50</td>
<td>Jan 00/01</td>
</tr>
<tr>
<td>52-56</td>
<td>16h23m</td>
<td>+27°03'</td>
<td>45</td>
<td>+42</td>
<td>May 00</td>
</tr>
<tr>
<td>57-58</td>
<td>16h32m</td>
<td>+21°16'</td>
<td>39</td>
<td>+39</td>
<td>May 00</td>
</tr>
<tr>
<td>61-62</td>
<td>10h37m</td>
<td>+04°00'</td>
<td>242</td>
<td>+50</td>
<td>Jan 01</td>
</tr>
<tr>
<td>63-66</td>
<td>17h25m</td>
<td>+27°30'</td>
<td>50</td>
<td>+30</td>
<td>Jul 01</td>
</tr>
<tr>
<td>68-71</td>
<td>22h02m</td>
<td>+27°30'</td>
<td>83</td>
<td>-21</td>
<td>Jul 01</td>
</tr>
<tr>
<td>72-75</td>
<td>18h32m</td>
<td>+36°00'</td>
<td>64</td>
<td>+19</td>
<td>Aug 01</td>
</tr>
<tr>
<td>76-79</td>
<td>23h47m</td>
<td>+28°10'</td>
<td>106</td>
<td>-32</td>
<td>Aug 01</td>
</tr>
</tbody>
</table>

information, but are targeted at different stellar populations (the Galactic Bulge, the LMC, or M31) and have a limit of V~21 with a photometric precision of 0.5 mag at the faint end, caused by limited signal-to-noise (S/N) and crowding in their necessarily high density star fields. High-z supernova searches reach as deep as the FSVS, but have a lower time-resolution and cover a smaller area. In Fig. 8.2 we show schematically how the FSVS compares with other deep ongoing surveys.

8.7 Reduction and analysis methods

To obtain variability information on all the objects detected in our observations we use the technique of differential aperture and point-spread-function (PSF) photometry. We have written a pipe-line reduction package, consisting of IRAF tasks, Fortran programs and at its core the SExtractor program by Bertin & Arnouts (1996). Every object in every observation is analysed and the results are stored in a master-table that lists the essential information (described in detail below) for each object. Below we outline the data flow through our pipe-line reduction, starting with the raw data as it comes from
Figure 8.2: A comparison in area and depth between major current surveys and the FSVS. Adapted from the NOAO Deep Survey Web-pages (see http://www.noao.edu/noao/noaodeep/; SDSS=Sloan Digital Sky Survey, York et al. (2000); EIS(deep) = ESO Imaging Survey (Deep), Nonino et al. (1999); Deeprange, Postman et al. (1998); INT-WAS: INT Wide Angle Survey; McMahon et al. (2001); HDF= Hubble Deep Field, Williams et al. (1996); NOAO= NOAO Survey, Jannuzi & Dey (1999); CFRS = Canada France Redshift Survey, Lilly et al. (1995); CADIS = Calar Alto Deep Imaging Survey, Hippelein et al. (1998); CFDF = Canadian French Deep Fields; Brodwin et al. (1999); LDSS Survey, Glazebrook et al. (1995)). Note that most of these surveys have no or very limited variability information, with the notable exception of OGLE. The range in depth for the FSVS is reached by using each individual image (as in the variability study) or the sum images.

8.7.1 Bias subtraction

The mean of the counts in the overscan region of each observation is used to subtract the overall bias level. After this the 2-D bias pattern, determined from bias observations taken at the start of the night, is subtracted.
8.7.2 Linearization of the data

A non-linearity in the read-out electronics causes all data taken with the INT WFC to be non-linear up to a level of ~5%. The magnitude of this non-linearity as a function of exposure level is determined by the Cambridge WFS group\(^2\) and is posted in tabular and analytic form. These corrections are applied after bias-subtraction.

8.7.3 Flatfielding

From twilight skyflats taken during a complete observing run a master flatfield is made, which is used for all the observations taken in that-band during the observing run. For the I-band observations, which suffer from fringing at the 3.5% level, we have made fringe maps from the night-time observations, which allows the fringe pattern to be removed down to the 0.6% continuum sky level (see Fig. 8.3).

Figure 8.3: Defringing of the I-band observations, using a fringe map made from the night-time observations themselves. Left: Before defringing, middle: fringe map, right: after defringing

8.7.4 Source detection

The bias-subtracted, linearized and flat-fielded data are fed to the SExtractor program. This program detects sources and measures their instrumental magnitude in a number of different ways, as set by the user. Source detection is done by requiring that three neighbouring pixels are more than two sigma above the sky-background. Visual inspection shows that this threshold value is capable of detecting virtually all objects that can be identified by eye. Some contamination from extended cosmic rays is present, but

\(^2\)see: http://www.ast.cam.ac.uk/~wfsur for an extensive description of the WFC
these are effectively removed in the subsequent steps. Apart from finding the sources and determining their instrumental magnitudes, for each source the SExtractor program determines various characteristic parameters such as the position, size, extent, ellipticity and orientation angle. Due to vignetting, a corner of CCD3 (the NE corner in Fig. 8.1) has very low count rates. We discard any object detected in a square box 200 pixels wide from this corner of CCD3.

8.7.5 **Instrumental magnitudes: aperture photometry vs. PSF fitting.**

For each object instrumental magnitudes are extracted in four different ways: fixed aperture photometry, seeing matched aperture photometry, variable PSF fitting photometry and isophotal magnitudes. The isophotal magnitudes and fixed 6 pixel (radius) aperture photometry have been included as a check on the others and for extragalactic work in case of the isophotal magnitudes. The seeing matched aperture photometry uses an aperture that scales with the seeing of the observations. This seeing is determined using bright unsaturated stars in the inner 1k x 1k region of each chip. The aperture radius for the observation is set to twice the FWHM of the seeing estimate. This relatively large aperture works well for bright stars, but the S/N deteriorates for faint objects due to the dominant sky background. In Fig. 8.4 we show the variation of the error for an aperture.
radius that is twice the seeing FWHM and for an aperture that is equal to this FWHM. This clearly shows that for bright stars they work equally well and for faint stars small apertures work better. However, in §8.7.8 we will show that the 1×FWHM aperture is too small for variability studies. The error on the instrumental magnitudes is determined by Poisson-statistics, including the source and background brightness, read-out noise of the chip and the gain.

In the variable PSF fitting the point-spread-function of the objects, and its variation, over the chip is determined from a set of 25 isolated stars, spread equally in position over the chip. Using this variable PSF the instrumental magnitude of each object is determined with the use of the DAOPHOT package (Stetson 1987) within IRAF, in which the precision is adjusted from 1 mmag to 0.1 mmag to be able to obtain the precision needed for the brightest stars. The error in the instrumental magnitude is now a combination of the Poisson statistics (as in the aperture photometry) as well as a factor from the fitting procedure. This causes the PSF errors on the brightest objects to be higher than in the aperture photometry (see Fig. 8.4), but for the faint sources it is as good as that of the 1×FWHM aperture photometry.

Although from just Fig. 8.4 it would seem that the aperture photometry is doing much better than the PSF photometry at the brighter end, the variability study (as discussed in §8.7.8) shows this not to be the case. The errors on the aperture photometry are not a good representation of the actual error on the measurement. Other sources of errors besides counting statistics such as low-level gain and read-out noise variations, flatfield errors and a variable PSF become dominant at bright magnitudes, This shows up as a flattening of the error distribution. In §8.7.8 we will show that the small aperture photometry errors introduce apparent variability for the brightest stars and is therefore not the most suitable for the FSVS.

### 8.7.6 Field matching

Different observations of the same field are automatically matched using the OFFSET program, supplied with the DOPHOT package (Schechter et al. 1993), using the 100 brightest, non-saturated stars, that are not located near the edges of the CCDs. Matching is done by triangle pattern recognition in the two images. This matching allows for linear scaling, rotation and translation of the different images. Output is given as the elements of a rotation-translation matrix. All image source catalogues are transformed to that of a reference image (the one with the best seeing). Individual objects are matched if in the new image an object is found within 1 FWHM of the position of the object in the reference image. This same criterion is used to match stars between different filters.
8.7.7 Local reference star selection

In order to obtain differential magnitudes, an ensemble of local reference stars has to be selected. The average (ensemble) magnitude of these stars is used as a baseline to compute all instrumental magnitudes. In the selection of this ensemble it is important to use the brightest, non-variable, stars that are not saturated. Using the brightest stars is essential because the error on the differential magnitude of any object consists of the error that is obtained from counting statistics for that object, and the error on the average of the reference stars (see e.g. Howell et al. 1988). The uncertainty in the mean magnitude of the ensemble must be made significantly smaller than the uncertainty imposed by counting statistics on the magnitude of any star of interest. If this is not the case, it will cause small-amplitude variability, that should have been detected on the basis of counting statistics, to become undetectable. Per CCD, an ensemble of ten local standards is selected by requiring that their variation with respect to the average is less than 5 millimagnitudes. If this requirement is set more stringently, not enough standards are found. In the Galactic North Pole observations of May 1999 the selection criterion had to be relaxed to 10 millimagnitudes in order to find a suitable number of stars. This is, of course, due to the limited number of stars in the NGP direction. As explained above, this selection criterion naturally sets the minimum amplitude ($= \text{scatter ref. stars}/\sqrt{N_{\text{ref. stars}}}$) of variation that can be found.

8.7.8 Differential magnitudes and variability

For every object the differential magnitude is calculated against the ensemble average. The error of the instrumental magnitude is propagated to the differential magnitude, adding quadratically to the error on the ensemble average. The error on the ensemble average is determined from the scatter of the ensemble stars at that epoch around their average over all epochs. The differential magnitude is calculated for all four instrumental magnitudes as described in §8.7.5. In Fig. 8.5 we show the variation on the average magnitude for a representative field of the FSVS, both for seeing matched aperture photometry as well as for the variable PSF fitting. The rise towards fainter magnitudes is a consequence of the larger instrumental magnitude errors due to lower count rates. For the brightest sources a differential magnitude variation of $< 5\text{mmag}$, which is at the level of extrasolar planet transits, is easily obtained.

Variability is determined by calculating the $\chi^2$ value of the light curve with respect to its average value. As expected this is a constant function with magnitude (Fig. 8.6). The dashed line in Fig. 8.6 shows the $\chi^2 > 5$ variability level above which we denote our stars to be variable. In Fig. 8.6 we show the $\chi^2$ distribution for the $1\times\text{FWHM}$ aperture (bottom), and $2\times\text{FWHM}$ aperture photometry (middle) and the variable PSF fitting (top). From this we see that an aperture of $1\times\text{FWHM}$ is too small for the bright stars.
8.7 Reduction and analysis methods

Figure 8.5: The standard deviation on the light curves of point sources (stellarity >0.8) in the same field as shown in Fig. 8.4. *Top* for variable PSF fitting and *bottom* for 2×seeing FWHM aperture photometry.

and introduces spurious variability. The 2×FWHM also suffers from spurious variability, although that is not immediately clear from Fig. 8.6.

Despite the accurate photometry on a single epoch, the 2×FWHM aperture photometry suffers from the introduction of systematic variability into the light curves due to the basic assumption of aperture photometry that the PSF is the same for all objects in the field. The chips of the WFC are slightly tilted with respect to the focal plane of the camera, which introduces a variation in the PSF of ~20% over the field of a single chip. This causes spurious variability both at the bright end as well as at the fainter end of the magnitude range. At the bright end the variation is caused by the change of the PSF due to tilt of the ccds. At the fainter end the change is caused by barely resolved binaries and compact galaxies. Not including this source of error in the aperture photometry at the bright end causes the high number of spurious variables. In the PSF fitting these errors are taken into account (as can be seen from the higher level of single-epoch errors in Fig. 8.4), and the spurious variability is removed (see Fig. 8.5 and 8.6).
Figure 8.6: Variability distributions for the same field as shown in Fig. 8.4 and 8.5. 
Bottom: seeing matched aperture photometry with aperture size equal to 1× seeing FWHM. 
Middle: same as bottom but with aperture size 2×FWHM. Top: variable PSF fitting.

8.7.9 Absolute calibration

Using the USNO A2.0 catalogue an astrometric solution is obtained for each CCD and each field separately. On average, we use 20-30 USNO A2.0 stars, which is sufficient to obtain a cubic solution that is accurate to 0′′.2-0′′.4 in right ascension and declination, depending on the position of a field on the sky.

During each of our runs so far, we have had photometric nights, during which all fields and several Selected Areas of Landolt (1992) were observed. After having also found the astrometric solution for the standard stars, we can measure the standard stars automatically. We use the SExtractor aperture photometry option, with an aperture radius of twice the image FWHM. For each CCD the measured B, V and I standard star magnitudes are fit with a model that includes a zero-point offset, an airmass term and a colour term. When sufficient standards are observed at different airmasses, we fit for the airmass term. If not, we hold it constant at the following values: 0.25, 0.15 and 0.07 for the filters B, V and I, respectively\(^3\). The colour term is only included if it improves the fit significantly. These solutions are applied to all objects listed in the catalogue through the ensemble reference stars that are selected for each CCD of each field (see §8.7.7).

From the scatter in the solutions, we estimate the error in the absolute calibration to

\(^3\)see http://www.ast.cam.ac.uk/~wfcsur
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be 0.1 for the B and V filters, and 0.15 for the I-band. In Fig. 8.7, 8.8 and 8.9 we show the \((V, B-V)\), \((V, V-I)\) colour-magnitude diagrams and the \((B-V, V-I)\) colour-colour diagram for the first 17 square degrees of FSVS survey data.

**Figure 8.7:** V, B–V colour-magnitude diagram of all point sources (with stellarity >0.8) in the first 17 square degrees in the FSVS. The cut-off at B–V=0.38 is caused by the average age of the thin Galactic disk.

### 8.7.10 Limiting magnitudes

Based on the amount of flux in the ten reference stars (see §8.7.7), the level of the background sky, the photometry aperture size and the background aperture size, we calculate the flux that a 3-, 5-, and 7-\(\sigma\) object would have for each CCD, field and observation. These ten estimates of the 3-, 5- and 7-\(\sigma\) limits are then averaged to produce an average 3-, 5- and 7-\(\sigma\) limiting magnitude. In this calculation we neglect the readout noise since our observations are long and have background levels whose noise is much higher than the read-out noise. On average the 5-\(\sigma\) limiting magnitudes range between 22.5-24.5 for the B and V-band images (depending on seeing and cloud cover) and between 21.5 and 23.5 for the I-band observations.
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Figure 8.8: V, V–I colour-magnitude diagram of all point sources (with stellarity > 0.8) in the first 17 square degrees in the FSVS.

Figure 8.9: B–V, V–I colour-colour diagram for all point sources (stellarity > 0.8) detected in all three bands in the first 17 square degrees in the FSVS.

8.7.11 Star - Galaxy separation

The star-galaxy separation used in the FSVS is based on the 'stellarity' parameter, as returned from the SExtractor routines (Bertin & Arnouts 1996). This parameter has
a value between 0 (highly extended) and 1 (point source). In the FSVS the stellarity value of an object is taken as the value in the combined V-band images. Due to the increased S/N in this image, the star-galaxy separation can be done reliably almost 1 magnitude deeper than from any individual image. As can be seen in Fig. 8.10 this separation of object types works very well to classify point-sources (with a value >0.8) down to V~23.5-24. Fainter stars tend to have slightly lower stellarity values (the turn down between 23 and 24) but can still be well separated from the galaxies, although some stars at the faint end of the distribution may be mis-classified as extended.

8.7.12 Astrometric variables

The proper motion analysis is currently not included in the standard pipe-line reduction but is handled separately using either the reduced images (in the case of Kuiper Belt Objects) or the SExtractor output and astrometric solution as provided by the pipeline (in the case of the high proper motion stars). Details on both analyses will be given in subsequent papers.

8.8 Final products

The pipeline discussed above returns two sets of output files:

- The reduced images
- The data tables with the photometric and astrometric information.

The data tables are made per field, per CCD and are made for four different magnitudes: the PSF magnitude, the fixed aperture magnitude, the isophotal magnitude and seeing matched aperture magnitude.

The data tables contain, for all the detected objects, the information on the time of observation (HJD), name, position and colour for each object, followed by the magnitude, error on the magnitude, fwhm, stellarity and the error flag as returned from the SExtractor program for each object and each observation.

If an object is only detected in a subset of all the observations, it is added to the final catalogue, and dummy values are introduced when it was not detected.

The objects names are given in standard IAU format as FSVSJhhmmss.ss+ddmmss.s, all in J2000 coordinates. Each object is also given an 'internal' name whose format is F_XX_Y_ZZZZZ, with XX the field number, Y the CCD number (1-4) and ZZZZZ a five digit detection number. The position of each object is given both in RA and DEC as well as in x,y-coordinates in the reference frame of the specific field.
8.8 Stellarity

**Figure 8.10:** Top: the stellarity versus magnitude for one of our fields. A stellarity of zero indicates a highly extended source, and a stellarity of one is a point-source. Detections at $V>25$ are noise spikes. Bottom: the cumulative distribution of sources over stellarity values. Using a point source cut-off of 0.8, we have $\sim45\%$ of objects as point sources.

### 8.9 Availability of the data

All raw images are available upon request from the ING-WFS archive in Cambridge after the one year proprietary right has passed. For UK and NL astronomers the data
is immediately available. All ASCII data-tables, containing the reduced information described above, are retrievable from the FSVS-website\(^4\).

8.10 Conclusions

The FSVS offers a unique possibility of studying the behaviour of variable objects in the magnitude range of 16\(<V<24\) with photometric precisions ranging from 3 millimag (at \(V=16\)) to 0.2 mag (at \(V\approx 24\)).

Besides the study of variable objects, the FSVS offers a large dataset that can serve as the basis for many research topics (e.g. young stellar objects, gravitational lenses, galaxy counts, quasar searches, etc.). The FSVS-collaboration encourages the use of the data set for purposes other than the ones mentioned here.

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\(^{4}\)http://www.astro.uva.nl/~fsvs
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