Software for inhomogenous ensemble photometry

Michael Richmond

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Introduction

Astronomers often take a series of images of the same field of stars when studying a variable star. What is the best way to measure the change in brightness of the variable object? The simplest method is to compare the brightness of the variable to that of a single reference star. However, if that reference star turns out to be variable itself, then its changes in brightness will contaminate the measurements of the target star. It would be better to use a number of stars in the field as references; the more stars, the better. In many cases, images taken at different times are not perfectly aligned, causing some stars to fall off the edges and appear only in a subset of the entire dataset. Is there any way to include all these stars in the analysis, even those which do not appear in all images?

Yes. The technique called **inhomogeneous ensemble photometry** uses a large set of stars (the "ensemble") to create a photometric reference level. It includes as many measurements as possible, even those from stars which don't appear in all frames (hence "inhomogenous"). A very good reference for this technique is

- CCD ensemble photometry on an inhomogeneous set of exposures by R. Kent Honeycutt, which appears in *Publications of the Astronomical Society of the Pacific* vol 104, page 435 (1992)

I have written software to implement this approach to photometry of a number of stars from a number of images. There are two pieces:

- multipht which re-arranges the data into a standard format and allows the user to discard some portions
- solvepht which runs the chosen data through a least-squares analysis to find the optimal photometric solution

I will describe first some requirements on the input data, and then show how to run these two program and interpret the results.

The input dataset

The input data is assumed to come from a set of N images. There must be a single ASCII text file per image which **must** include at least four columns of data for each star:

- position in X direction (or row, or RA, etc.)
- position in Y direction (or col, or Dec, etc.)
- magnitude
- estimated uncertainty in magnitude

Common image reduction programs such as DAOPHOT or SExtractor will produce exactly this sort of data. If you don't have values for estimated uncertainty in magnitude for each measurement, you can create a column with the same positive value (say, 0.001) for each star. This will give each star the same weight in the ensemble solution.

Any comment or header lines in the input files must begin with a pound sign character (#) in column 0, like this:

```
# Photometry of image 'M57.fts'
#  taken on 2004-Oct-12 02:23:05 UT
#  exposure time 30 seconds, R-band filter
# xc     yc     mag    magerr
  50.1  201.2   12.34   0.02
 127.8   33.9   12.85   0.04
```

By default, this package will give integer index values to each image to serve as "time" values: the first image will be "time" 0, the next "time" 1, the next "time" 2, and so forth. If you wish to attach a real time value, such as JD, to each image, create a column in each file for it. the "time" values ought to be identical for all measurements in the file, like this:

```
# An example showing a column for "time" value of the image
#   ID     Julian Data    row     col    mag     magerr
#
      0 2450000.00000    13.48    16.43 10.0000  0.0500
      1 2450000.00000    18.48    36.43 10.0500  0.0500
      2 2450000.00000    23.48    56.43 10.1000  0.0500
```

Creating the ensemble with multipht

The **multipht** program takes as input a set of data files, each of which has measurements of all the objects in one image. It produces as output a single, large ASCII text file with all the measurements, re-arranged so that all measurments of a single star are grouped together.

The usage is:

```
multipht [debug] [print] x= y= mag= err= [jd=] [auto] [list= ] [outfile= ]
                 [template= ] [matchrad= ] [quiet]
                 [star_cut= ] [image_cut= ]  file.pht ...
```

where options in brackets are optional. They are

debug
: print out a great deal of diagnostic messages as the program executes

print
: print messages to the screen, stopping every 20 or so lines and prompting the user to continue

x=
: zero-indexed number of the column holding the position of each measurement in the X direction; thus, the first column in each line is number zero, the next is number 1, and so forth

y=
: zero-indexed number of the column holding the position of each measurement in the Y direction

mag=
: zero-indexed number of the column holding the magnitude values

err=
: zero-indexed number of the column holding the estimated uncertainty in magnitude values

jd=
: zero-indexed number of the column holding the "time" values. The values must be integers or floating-point numbers, not strings like "2004-Oct-18-12:54 UT". If no "jd=" argument appears, images will be assigned "time" values of 0, 1, 2, etc.

auto

if given, the program decides cutoff values for stars and images to include in the ensemble. If not given, the user chooses cutoff values interactively.

list=
: the name of an ASCII text file which in turn contains the names of other files with the input data. Those names must appear one per line, like so:

```
image23a.dat
image23b.dat
image39.dat
image43.dat
```

outfile=
: the name of a file into which to write the re-arranged data. If not given, output is written to stdout.

template=
: the name of the input file which will be used as a template for positional matches. If not given, the image with the largest number of stars is used as the template.

matchrad=
: the matching radius, in units of the input X and Y positions. If not given, the default value is given by DEF_RADIUS in "multipht.h" (currently 5.0)

quiet
: do not print out a list showing the number of stars in each field which match those in the template image

star_cut=
: require that stars appear in a certain number of images in order to be included in the ensemble. If the given value is an integer (*star_cut=12*), then that is the minimum number of image in which a star must appear. If the given value is a fraction (*star_cut=0.5*), then a star must appear in the given fraction of the total number of images. This number is used only if the **auto** option is provided. The default is given by the STAR_CUT #define in "multipht.h" (currently 0.25).

image_cut=
: require that an image contains at least a certain number of stars in order to be included in the ensemble. If the given value is an integer (*image_cut=12*), then that is the minimum number of stars which an image must contain. If the given value is a fraction (*image_cut=0.5*), then an image must contain the given fraction of the number of stars in the image with the most star; that is, if the image with the most stars has 200 stars, and *image_cut=0.5*, then any image with at least 100 stars will be included in the ensemble. This number is used only if the **auto** option is provided. The default is given by the IMAGE_CUT #define in "multipht.h" (currently 0.25).

file.pht ....
: all other arguments are taken to be the names of input data files

After reading input from each file, the program attempts to match detections of stars in different images. It assumes that all images have the same plate scale and orientation, differing only in a possible translation. First, the brightest MAXMATCH (defined in *multipht.h*) stars in each image are collected for matching purposes; all fainter stars are ignored. The matching algorithm picks one image as the "template". Stellar positions in all other images are compared to those in the template, one at a time. A brute-force algorithm considers all possible shifts which bring a star in the current image into registration with one in the template; for each possible shift, the positions of other stars are checked to see if they are within **matchrad** units of a star in the template. The shift which produces the largest number of matches between each image and the template is retained, and that shift is applied to all stars in the image. If a star matches more than one partner in the template image, it is assigned to the closest partner.

After the matching stage has finished, the program prints to stdout a list of the shifts required to bring each image into register with the template, like this:

```
lists QQ_input.000 QQ_input.001 dr =   0.96000 dc =  -1.20000    10 of   10
lists QQ_input.000 QQ_input.002 dr =   1.61000 dc =   3.40000    10 of   10
lists QQ_input.000 QQ_input.003 dr =  -0.56000 dc =   1.72000    10 of   10
lists QQ_input.000 QQ_input.004 dr =  -1.75000 dc =  -1.68000    10 of   10
```

The second column is the name of the template image ("QQ_input.000" in this example). The third column contains the name of the image being matched, the sixth and ninth columns the shifts required to bring the image into register. The final columns show how many of the stars in each image matched a partner in the template.

The next step involves choosing the stars and images to include in the ensemble. By default, the user must make decisions interactively. The program will display a histogram of the number of stars per image:

```
List of #stars,  #images with that many stars
    0    0
    1    0
    2    0
    3    0
    4    1
    5    0
    6    3
    7    5
    8    9
    9    8
   10   10
   11    3
   12    1
   13    0
   14    0
   15    0
   16    0
   17    0
   18    0
   19    0
Enter cutoff for number of stars an image must have:
```

In this example, there is one image with 4 stars, three images with 6 stars, etc., up to a single image with 12 stars. The program asks the user to choose the cutoff for the number of stars an image must contain in order to be included in the solution.

Next, the program displays a similar histogram of the number of images in which each star appears:

```
List of #images,  #stars that appear in that many images
    0    0
    1    5
    2    0
    3    2
    4    0
    5    0
    6    3
    7    4
    8    7
    9    9
   10   10
   11    5
   12    6
   13    0
   14    2
   15    0
   16    0
   17    0
   18    0
   19    0
Enter cutoff for number of images in which a star must appear:
```

In this example, there are five stars which occur in just a single image; in other words, there are give detections which cannot be matched to any other detections. Once again, the user must provide a cutoff value. Any stars which have fewer instances will be discarded from the ensemble.

If the user chooses the **auto** option, the program will pick cutoff values itself; see the STAR_CUT and IMAGE_CUT values in "multiweight.c". They are by default 25 percent of the maximum value. In other words, if the most commonly appearing star occurs in 40 images, then any stars appearing in fewer than 10 images (40*0.25) will be discarded.

Finally, if the **auto** flag has not been given, the program asks the user

```
do you wish to eliminate all saturated stars (y/n)?
```

Any measurement with an estimated uncertainty which is negative is assumed to be saturated. If the user replies "y" to this question, all such measurements are discarded from the ensemble. Otherwise, the negative sign is reversed and the measurement treated normally.

The output of the **multipht** program is a single file which contains all the measurements in the ensemble. The file has a three-part structure:

- a single line which gives the number of stars and images in the ensemble
- a section describing the images, with one line per image
- a section describing the stars, with one stanza per star; a stanza consists of one line with position information, followed by N lines, one per magnitude measurement

A very small ensemble might produce the following output. For clarity, I have added comments to delineate the sections; such comments do NOT appear in actual output.

```
# first comes the one-line header
   2 images       3 stars
# next, a section describing the images
     0                     image0.dat    1.0      0.00000      3      3
     1                     image1.dat    1.0      1.00000      3      3
# now, a section describing the stars.  Each star gets a line with
# its index value, X and Y coordinates, and number of measurements;
# then one line per measurement
     0     13.48000   16.43000     2
       0      0     13.48000     16.43000 0  10.0000   400.0
       0      1     13.48000     16.43000 0  10.1000   400.0
     1     18.48000   36.43000      2
       1      0     18.48000     36.43000 0  10.0500   400.0
       1      1     18.48000     36.43000 0  10.1897   400.0
     2     23.48000   56.43000      2
       2      0     23.48000     56.43000 0  10.1000   400.0
       2      1     23.48000     56.43000 0  10.2000   400.0
```

The columns in the "image" section give the image index number, the name of the file with data for the image, the exposure time for each image (a dummy value, always 1.0), the "time" value for the image, the number of stars in the image which will be included in the ensemble, and the number of stars which matched a detection on the template (note that only a subset of all stars are used in the matching process -- see the value of MAXMATCH in *multipht.h*). The columns in the first line of each star stanza are the star index number, X and Y coordinate on the template, and the number of instances to follow; the columns on each subsequent line are the star index number, the image index number, the X and Y coordinates after having been shifted to best match the template, a flag to mark saturation (0 = not saturated, 1 = saturated), the magnitude value, and a weight based on the estimated magnitude uncertainty. Small uncertainties produce large weights.

This single file will serve as the input to the second stage of this package, the **solvepht** program.

Finding the optimal photometric solution with solvepht

The **solvepht** program takes as input a single large datafile with information on all images and measurements in the ensemble; it finds the optimal photometric solution and creates three output files with the results.

What does "optimal photometric solution" mean? We make several assumptions:

- most of the stars are constant, with some well defined true magnitude. Let us denote the true magnitude of star *i* by the symbol **M(i)**

- each image may have some zero-point offset in its magnitude value, but there are no more complicated systematic errors. Let us use **e(j)** to stand for the zero-point offset in image *j*. If image 2 has zero-point offset 0.05, that means that all the stellar magnitude values in the image are too large by 0.05 mag.

We have a large set of actual measurements **m(i,j)** of a number of stars in a number of images. Assuming that our model of the system is accurate, the error in each measurement must be

```
        error(i,j)  =  m(i,j)  -  [ M(i) - e(j) ]
```

Our task is to find the image offsets **e(j)** and true magnitudes **M(i)** which minimize the remaining errors. The program uses standard least-squares techniques to find these parameters, then applies them to correct all measurements to the ensemble solution.

One invokes the **solvepht** program like so:

```
solvepht [debug] [infile=] [mconst=] [outfile=] [imfile=] [sigfile=]
                 [badim=] [badstar=] [varstar=] [min=] [max=]
                 [nsigma=] [niter=] [mrange[=low,high]]
```

The arguments in brackets are optional; those ending in equals signs require a value.

debug
: print diagnostic messages as the program executes

infile=
: name of a file with input data (created by **multipht**); if not provided, data is read from stdin

mconst=
: the overall zeropoint of the photometric solution is a free parameter. By default, the true stellar magnitude values are shifted so that the brightest star has true magnitude 0.0. If the user supplies a value for *mconst=*, then the brightest star will be set to that magnitude on output.

outfile=
: the name of the first output file, with corrected magnitudes for all stars on all images. The default value is *solvepht.out*.

imfile=
: the name of the second output file, with solution parameters for each image. The default value is *solvepht.img*.

sigfile=
: the name of the third output file, with true magnitudes and estimated uncertainties for all stars. The default value is *solvepht.sig*.

badim=
: signals that the image with the given index number (as listed in the **multipht** output file) is "bad", and should not be included in the solution. This option may appear multiple times in the command line, once per bad image:

```
            solvepht infile=multipht.out badim=3 badim=7 badim=23
```

badstar=
: signals that the star with the given index number (as listed in the **multipht** output file) is "bad", and should not be included in the solution. This option may appear multiple times in the command line, once per bad star:

```
            solvepht infile=multipht.out badstar=8 badstar=12
```

varstar=
: signals that the star with the given index number (as listed in the **multipht** output file) is "variable".

This means that it should not be used in finding the photometric solution, but that it SHOULD appear in the output, with image zero-point offsets applied to its values. This option may appear multiple times in the command line, once per variable star:

```
            solvepht infile=multipht.out varstar=32 varstar=1
```

min=
: ignore all input magnitudes which are less than the given value

max=
: ignore all input magnitudes which are greater than the given value

nsigma=
: stars which are at least this many times the typical scatter above the average "sigma-vs-mag" line will be marked as variable (see below). The default is given the #define SCATTER_NSIGMA value in "solvepht.h" (current value 3.0).

niter=
: number of additional times to run the ensemble solution after identifying some stars as variable and marking them so they won't affect the next round of the solution. The default is given by the #define NUM_ITERATIONS in "solvepht.h" (currently 0).

mrange[=low,high]
: by default, the output magnitude values produced by the ensemble solution start at zero, for the brightest star in the ensemble. This option shifts the output magnitudes so that they are close to the input magnitudes. If given with no values,

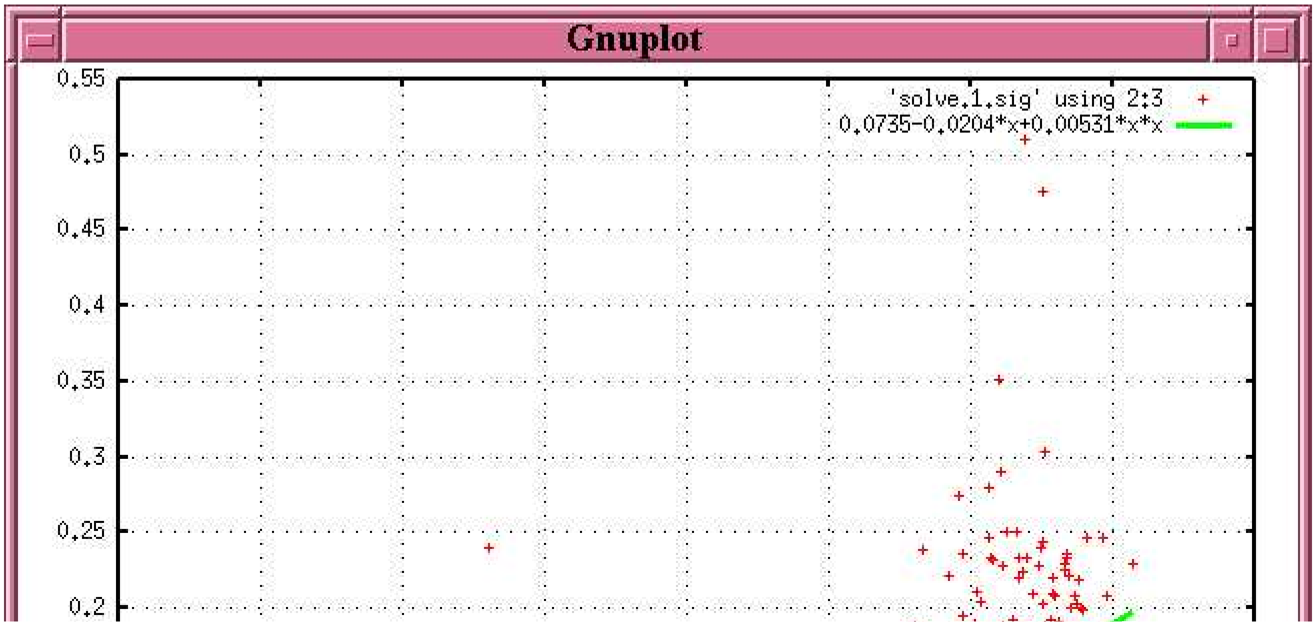
```
            mrange
```

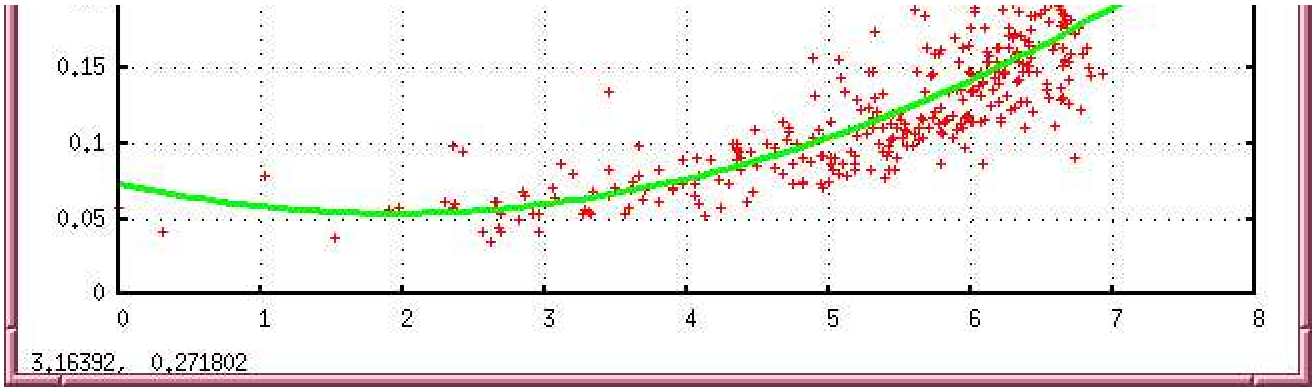
then all non-variable stars between default values given by #define MRANGE_LOW and MRANGE_HIGH in "solvepht.h" (currently 1.0 and 2.5) magnitudes below the brighest star are used to define a shift; that shift is applied to all magnitudes on output. If the user supplies values like so

```
            mrange=2.0,5.0
```

the all non-variable stars with mean ensemble solution magnitudes between these limits are used to define the shift in magnitudes.

After the ensemble solution has been found, the program calculates at the scatter of each individual star from its mean solution magnitude. In general, this scatter is small for bright stars and large for faint ones, due to photon statistics. This shows clearly in the "sigma-vs-mag" plot used as a diagnostic for photometry:





The program fits a simple parabola to the locus of points in the diagram by dividing the stars into bins by magnitude, calculating the median "sigma" value in each bin, and fitting a parabola to those median values. It also calculates the average width of this locus around the parabola; my simple tests indicate that the width does not change *greatly* from bright stars to faint stars for some datasets.

Stars which vary will appear as outliers in this "sigma-vs-mag" diagram: there is one in the example above near magnitude 2.6, with a scatter of about 0.24 magnitudes around its mean value. The program attempts to identify variable candidates by calculating the distance of each star from the parabolic fit, in units of the scatter around the fit. In the example above, the scatter around the fit is about 0.05 mag, and the outlier is about 0.24 mag above the fit; it therefore has a "variability score" of about (0.24/0.5) = 5. Any star with a score larger than given by the *nsigma*= option (default value 3.0) will be marked as variable.

If the user supplies a value of *niter*= larger than zero, then the ensemble solution will be run more than once. Between each iteration, stars with high variability scores will be marked as "variable" and excluded from the ensemble calculations. In practice, a single extra iteration appears to suffice to remove the effects of clear outliers from the calculations.

The **solvepht** program creates three output files after a successful run:

- the *solvepht.out* file contains corrected magnitudes for all stellar measurements:

```
              corrected mag  =  m(i,j)  -  e(j)
```

- the *solvepht.img* file contains information on each image in the solution (for example, its zero-point offset)
- the *solvepht.sig* file contains information on each star in the solution: its true magnitude and an estimate of the uncertainty therein

A very small sample of the *solvepht.out* file looks like this:

```
0       35.32486   7.03099   72 2452263.62176  13.193 13.312 0.163   0    0.25
0       35.32486   7.03099   75 2452263.62706  13.193 13.322 0.171   0    0.25
0       35.32486   7.03099  104 2452263.67998  13.193 13.180 0.165   0    0.25
1       35.33325   6.72861   52 2452263.58649  11.360 11.333 0.079   0   -0.26
1       35.33325   6.72861   53 2452263.58825  11.360 11.351 0.081   0   -0.26
1       35.33325   6.72861   54 2452263.59001  11.360 11.350 0.081   0   -0.26
1       35.33325   6.72861  378 2453322.71022  11.360 11.491 0.065   0   -0.26
2       35.33335   7.18730   52 2452263.58649  12.190 12.202 0.104   0   -0.75
2       35.33335   7.18730   53 2452263.58825  12.190 12.196 0.101   0   -0.75
```

The columns are:

1. star index number
2. X coordinate, shifted (*) to match template position
3. Y coordinate, shifted (*) to match template position
4. image index number
5. "time" value
6. true (or mean) magnitude of star
7. corrected magnitude in this particular image

8. estimated uncertainty in this measurement, based on the ensemble solution
9. variability flag: 0="not variable", 1="variable"
10. "variability score": how much above or below the typical amount (for stars of similar brightness) did this star vary?

(*) During the matching procedure in **multipht**, the program calculates the mean shift in the X- and Y-directions which brings star into best registration with the template image. This shift is applied to each input position in the image and appears here.

A small sample of the *solvepht.img* file looks like this:

```
0                    ./QQ_input.000    1.0  2450000.00000 10.000 0.009 0.002
1                    ./QQ_input.001    1.0  2450000.01000 10.100 0.010 0.002
```

The columns in this file are

1. image index number
2. name of file with measurements from this image
3. exposure time for image (currently a dummy value)
4. "time" value for image
5. zero-point offset value for this image
6. z1 = RMS of zero-point offset (see below)
7. z2 = ditto, divided by square root of number of stars in the image (see below)

After finding the least-squares solution for zero-point values, the program judges them by calculating weighted sums for each image: given i=1..N stars in the image, it calculates two measures the degree to which all the stars in an image can be brought to match their true magnitudes.

```
    let    z  =  corrected_mag(i,j)  -  true_mag(i)

           w  =  weight given to m(i,j) based on input mag uncertainty



                [  sum  (z*z*w)  ]
          z1  =  [  ------------  ]
                [   sum  (N*w)   ]


                        z1
          z2  =      --------------
                       sqrt (N)
```

The smaller the values of **z1** and **z2**, the more closely the (corrected) measurements on this image match the overall ensemble measurements.

A small sample of the *solvepht.sig* file looks like this:

```
     0 13.193  0.158  0    0.25     35.32486      7.03099
     1 11.360  0.073  0   -0.26     35.33325      6.72861
     2 12.190  0.078  0   -0.75     35.33335      7.18730
     3 13.695  0.137  0   -0.84     35.34351      6.66053
```

The columns in this file are

1. star index number
2. "true" magnitude in the ensemble solution
3. uncertainty in the "true" magnitude
4. variability flag: 0="not variable", 1="variable"
5. "variability score": how much above or below the typical amount (for stars of similar brightness) did this star vary?
6. X coordinate, shifted to match template position
7. Y coordinate, shifted to match template position

Recall that by default, the output magnitudes are shifted so that the "true" magnitude of the brightest star is exactly zero. In the example above, the user must have used the *mrange* or *mconst* options to re-set them to larger values, closer to the input values.

A typical example of ensemble photometry

In practice, using this package isn't all the complicated. I use it myself to analyze photometry of fields containing variable stars for the Center for Backyard Astrophysics. For example, let me explain in some detail the results for one particular night: Oct 5, 2004.

- http://spiff.rit.edu/richmond/ritobs/oct05_2004/oct05_2004.html

I took a series of 115 images of the cataclysmic variable star ASAS 002511 and its neighbors. After the usual dark subtraction and flatfielding, I extracted positions and instrumental magnitudes for every object detected in every frame; that added up to 6211 detections.

The raw instrumental magnitudes for each image were stored in a series of 115 files; here's a sample of one:

```
    1    4.28  461.12   3325  13.48   14.836  0.049  14.818  0.057    4
    2   11.53   32.51   3339  13.88   15.330  0.076  15.287  0.086    0
    3   36.66  240.87   3335  14.65   14.648  0.041  14.626  0.048    0
```

I created a file with the names of these files, one per line. I ran **multipht** with a command line like this:

```
      multipht list=asas.lst x=1 y=2 mag=6 err=7 outfile=multipht.out
```

I answered the questions to select cutoffs for the number of stars required in an image (10) and number of detections required for a star (10) to be included in the solution. The result was a big output file, *multipht.out*.

The second stage of the analysis is more complicated; it usually takes me several passes through the dataset. I ran the **solvepht** program an initial time to get a feeling for the overall properties of the images and stars. I first examined the *solvepht.img* file, plotting the zero-point value versus "time". I saw that the zeropoints of most of the images followed a gradual trend (due to the changing airmass of the field), but there were occasional outliers. Some of these were due to poor tracking (on a trailed image, all the stars look fainter than normal), others due to passing clouds. I wrote down the index numbers of the bad images so that I could remove them from the solution during the next pass.

I also looked at the *solvepht.sig* file, plotting the uncertainty in ensemble magnitude versus true magnitude. You can see a version of this graph on the web page describing this night's results. Most stars fall in a line which curves gently upward to the right: fainter stars have larger scatter in magnitude. On the first pass, a number of objects appeared far above this normal locus: one of them was a real variable star, but others were stars with bad measurements: some close to the edge of the frame, others part of close pairs, others falling near defects on the chip, etc. I noted the index numbers of these objects, dividing them into "obviously bad objects" and "possibly true variables".

I then made a second pass, running **solvepht** again with extra arguments. Here's the command line:

```
    solvepht infile=multipht.out outfile=solvepht.out imfile=solvepht.img
                sigfile=solvepht.sig varstar=13 badim=15 badstar=32
                badstar=29 badstar=38 badstar=49
```

This indicates that I removed one image and four stars from the solution, and marked one star as "variable." That star (which was the known variable ASAS 002511) was not used in deriving the ensemble solution, but it *was* retained in the output.

In most cases, I make three or four passes through the dataset, gradually placing more and more stringent requirements on the stars and images. It helps to make a small shell script with the command line for **solvepht** so that one can quickly add or subtract a few more bad stars and images.

After I was satisfied with the results, I finally looked at the *solvepht.out* file. I picked out individual stars by choosing all lines which started with a particular value, then made a graph showing each star's corrected magnitudes versus time. You can see a light curve of four objects in the field near the bottom of the web page describing this night’s results. The three non-variable stars are indeed not changing relative to each other, and the faintest in the group has the largest scatter. The fourth object, shown as green crosses, is the variable star. It is clearly varying more than one would expect for a star of its apparent brightness, just as the plot of scatter-versus-magnitude indicates.

Last modified by MWR 3/1/2005