Estimating Visual Magnitudes for Wide Double Stars

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Abstract: The WDS catalog data error contamination rate is especially high for the visual magnitudes of fainter secondaries rather often given as rough estimations instead of precise measurements. This report presents a formula for calculating a rather precise Vmag estimation from GAIA DR1 Gmag and 2MASS J/H/K-mag data.

1. Introduction

A possible substitute for missing measured Vmags (for example from AAVSO APASS) is a well-founded estimation for example by using the procedure for estimating Vmags from J- and K-band magnitudes (Caldwell et al. 1993) based on the formula

$$V(J,K) = \sum J + 0.1496 + 3.5143(J-K) + 2.325(J-K)^2 + 1.4688(J-K)^3$$

with the caveat that objects with J-K outside the range -0.1 to 1 are not suited for estimating Vmag. This formula works based on our own experiences rather well even with the mentioned J-K range slightly extended and the number of objects with J- and K-mags given is with ~471,000,000 2MASS objects quite large and covers most wide double stars with a separation >2-3 arcseconds. With the availability of GAIA DR1 we have now for all these objects also Gmag data available. Gmag is a photometry value over the full visual band including B and I and has (depending mostly on the I-band value) a good correlation with visual magnitude values (according to Jordi et al 2010) with Gmag by definition generally a bit brighter than Vmag so of good use as upper threshold. So it should be possible to develop an even better formula for estimating Vmags by using not only J- and K-mags but also Gmags.

2. Sources for Objects with Reliable Vmags

As data base for such an approach a good number of objects with reliable Vmag data is indispensable. Yet the number of catalogs with such data is limited, so we did some research and came up with the following options:

2.1 Landolt objects

The Landolt catalog (VizieR II/183A, Landolt 1992) contains 526 stars with precise V-filter photometry data perfectly suited for this project with the caveat of rather unreliable positions – a cross match between the Landolt and the 2MASS catalog with a 5 arcsec search radius using the CDS X-Match service yields only 234 objects. This problem was already handled by Guillaume Blanc in August 2001 providing USNO A2.0 based J2000 positions for all Landolt objects (http://web.pd.astro.it/blanc/landolt/landolt.html). Using CDS X-Match with these positions yields 512 objects but to be on the safe side without the effort of checking each single object for being a hit indeed we decided to cross match this list with URAT1 to get not only the J- and K-mags for the matched Landolt objects but also the Vmags provided here for most objects based usually on AAVSO APASS as well as recent precise positions at the price of "losing" all Landolt objects in the southern sky. This step resulted in 468 remaining objects after eliminating those without URAT1 Vmag and J/Kmag data. The Vmags from Landolt and

URAT1 (based mostly on AAVSO APASS) were then compared and found to be close enough for all but two eliminated objects to consider them valid matches. In the next step we cross matched then the accordingly reduced list with GAIA DR1 to get the Gmag value and the precise J2000 epoch 2015 position for each of the 420 remaining objects after eliminating multiple matches and obviously odd matches with Landolt Vmags fainter than GAIA Gmags.

2.2 UBVRI standard stars around the celestial equator objects

The "UBVRI standard stars around the celestial equator" catalog (VizieR J/AJ/146/88, Clem and Landolt 2013) extends the scope of the Landolt catalog from 526 to over 43,000 objects with precise measured Vmags based on images taken with V-filter. All or at least most of the Landolt objects are also included in this catalog. A sequence of cross matches with 2MASS and GAIA DR1 yielded 15,492 objects with J/H/K/G-mags.

2.3 Faint UBVRI standard star fields at +50deg declination

The "Faint UBVRI standard star fields at +50deg declination" catalog (VizieR J/AJ/152/91, Clem and Landolt 2016) provides another ~2,000 objects with precise Vmags according to the Landolt standard. Cross-matching with 2MASS and GAIA DR1 reduced this number to 1,090 objects.

2.4 LSPM and STT objects

Our JDSO reports on LSPM and STT objects contain several hundred objects with Vmags based on differential photometry from our images taken with V-filter using mostly URAT1 reference stars for plate solving with an average error of about 0.1Vmag. Selecting manually the most promising objects we ended up with 345 objects after cross-matching with 2MASS and GAIA DR1.

2.5 Re-reductions of own images

Plate solving with Astrometrica gives a list of used reference stars with Vmags and Vmag error (compared to the used reference catalog URAT1). Selecting a few images with quite good average plate solving errors we re-reduced these images to gain hundreds of objects with an average Vmag error of 0.1 per image resulting in a total of 1,966 such objects after cross-matching with 2MASS and GAIA DR1.

2.6 AAVSO APASS

APASS is a long ongoing AAVSO effort to determine Vmags for as many faint stars as possible (Henden et al. 2016) containing over 60,000,000 objects. This effort is to some degree marred by a large number of technical issues so we had to look for an approach to select objects from this catalog without risking a bias. The number of caveats due to different technical issues mentioned in the catalog description is large so we decided it would be better not to use APASS directly for our project because we were unable to come to grips with how to select objects from this catalog without risking a bias. But as APASS is the Vmag source for most faint URAT1 stars used for plate solving of our own images APASS is at least indirectly used.

2.7 Hipparcos

The Hipparcos main catalog contains 118,218 objects brighter than about 9mag with reliable photometry results but not using the standard UBVRI filters. There is a good relationship between Hipparcos V_T-mags to standard Vmags (Bessell 2000) but as Vmags for such bright stars are anyway not topic of this report no attempts in this regard are used in this project.

2.8 Tycho-2

The Tycho 2 catalog contains about 2,500,000 objects brighter than about 11.5mag. While the given V_T-mags are claimed to be very precise up to a value of at least 12 (Hog et al. 2000) and the VizieR standard description of this catalog gives an approximate relation Vmag = V_T -0.090*(B_T-V_T) this is still not a good base for our project so we decided against the use of Tycho-2 data.

2.9 Other catalogs

One additional UBVRI catalog containing Vmags for about 34,000 faint objects (Skiff 2007) is compiled from different sources so the use of this catalog would mean an overlap with the other sources so we decided against using it. VizieR lists also more than 20 small catalogs with UBVRI photometry of mostly open clusters. We opted against the use of these catalogs to avoid problems potentially combined with the restriction of such small areas of the sky. Several other catalogs offer V-filter based photometry for double stars but the usual presentation of double stars with coordinates given only for the primary with angular separation and position angle for the secondary poses an additional obstacle for cross matching with 2MASS and GAIA DR1 so we decided to not use such catalogs.

3. Final selection of objects

So the decision was to use the UBVRI standard 1992 and 2013 catalogs from Landolt and Clem and our own photometry results as discussed above but keep the UBVRI catalog from 2016 as sample for quality control.

The combined final data set for statistical analysis was then checked in detail for mis-matches and doubled objects caused by different reasons (overlaps between

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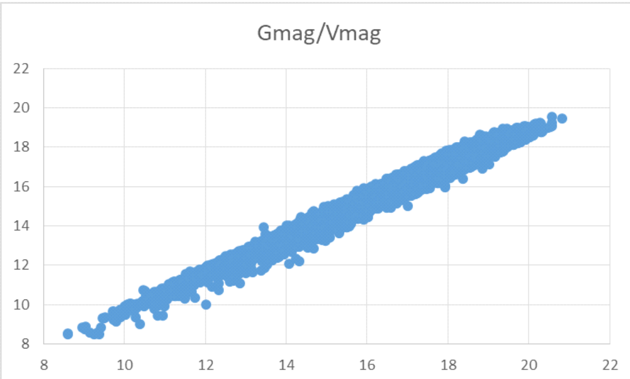

Figure 1. Comparison Gmag and Vmag in the used data sample

the different sources, objects too close for conclusive matches etc.). This was done by sorting the objects by their coordinates and checking then for identical G/J/H/K-values indicating the very same 2MASS or GAIA DR1 object. As expected, most Landolt objects were also included in the "Faint UBVRI …" catalogs. As tribute to the pioneer work of Landolt "his" objects were kept in all cases with acceptable similar Vmags (which means in most cases a difference of less than 0.05Vmag). In several cases some LSPM objects with very close companions were matched with the same 2MASS object – in such cases we tried to select the correct match and when in doubt we deleted both objects. In a next step we then looked with different statistical tools for obvious outliers indicated by suspect V/G/J/H/Kmag values detecting for example a correctly matched object with a so far overlooked missing Kmag value. In a last selection step we eliminated all objects with Vmags brighter than 8.5 as this Vmag range is well covered by Hipparcos.

The final data set for statistical analysis contained then 16,209 objects in the Vmag range between 8.60 and 20.82.

3. Statistical analysis and results

On average Vmag is about 0.5 fainter than Gmag (see Figure 1), which means that the Gmag value plus 0.5 is already a reasonable good estimation for Vmag with a standard deviation of 0.281.

The next steps of statistical analysis were made with the XLSTAT tool allowing for nonlinear regression to determine parameter values for a given model minimizing standard deviation of residues (differences between Vmags and estimations). To determine the model is a mixture of experience and trial and error and knowledge or attempts done before – in our case the Caldwell et al. 1993 formula given in the introduction served as starting point.

Step by step we modified the formula with the intention to increase correlation and reduce standard deviation. After a few attempts we got with

$$V_{mag} = 1.49862180368262*G_{mag} - 0.963151863557621*J_{mag} + 0.408663420738689*K_{mag} + 0.0364530908380005*H_{mag} + 0.373973178473384*(J_{mag} - K_{mag}) + 0.175229950887202*(J_{mag} - K_{mag})^{2} - 0.0652237092480494*(J_{mag} - K_{mag})^{3}$$

not only a nearly perfect correlation coefficient of 0.997 but also a modest standard deviation of 0.103 for the residuals. This model then allowed even for the detection of outliers remaining hidden in the preparation of

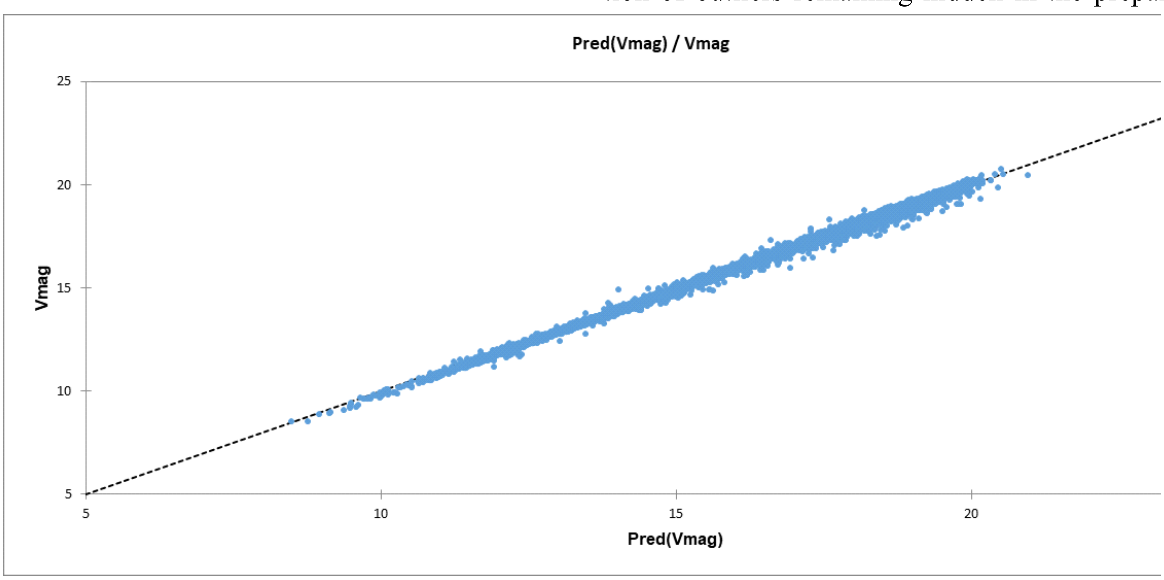

Image 2: Comparison Vmag with model "prediction" for the used data sample

the data set with overly large residuals like for example BU 997 B with a very suspect Jmag value in 2MASS (indicated by a rather curious Jmag error value of 9.998) which simply confirms that even the best formula depends on the quality of the input data. Other outliers detected this way were objects with a questionable Vmag value due to overlapping star disks or other reasons indicated by Vmag brighter than Gmag which is simply impossible. This led in consequence to the elimination of all such objects with this difference larger than an acceptable measurement error. This reduced the number of objects in the sample to 16,187 objects assumed to be correct but a few errors might still exist yet without having much influence on the statistical analysis. Re-running the same model yielded then again a correlation coefficient of 9.997 with a standard deviation of now 0.099 with the following parameters:

$$V_{mag} = 1.50326776322482*G_{mag} - 0.58954519968568*J_{mag} + 0.0314622406908976*K_{mag} + 0.0351929061060541*H_{mag} - 0.00651215643426878*(J_{mag}-K_{mag}) + 0.168254721054116*(J_{mag}-K_{mag})^{2} - 0.061069721467548*(J_{mag}-K_{mag})^{3}.$$

See Figure 2.

That said, we do not assume that we have found the best possible Vmag estimation model but we think that the presented model is very well suited for getting Vmags about as good as possible given the current state of CCD based photometry utilizing very good equipment like the iT24 telescope we used or even better. The data sample used for statistical analysis is available for download from the JDSO web site as “Vmag_sample”.

5. Summary

To counter-check this opinion we used the UBVRI Clem and Landolt 2016 catalog for comparison with the result of a correlation coefficient of 0.997, a mean residue value of 0.091 and a standard deviation of 0.129. Looking again at objects with unusual large residues we found again objects with suspect 2MASS data like for example 01513503+4659274 with blanks for Jmag and Kmag error so the presented model is probably better than the given values suggest.

Sorting the objects by Vmags (Figure 3) indicates then a weakness of the model for stars fainter than 20mag with an average residual of 0.220 compared to 0.083 for the objects brighter than 20mag – this is probably a side effect from the rather small number of such faint objects in the sample.

The data sample used for this counter-check is available for download from the JDSO web site as “UVBRI_counter-check”.

To compare the validity of our model also with APASS and URAT1 we cross-matched the data set used for counter-check with APASS and URAT1 and got the following results:

- APASS covers only 156 objects (out of 1,078) with a correlation coefficient of 0.995 and a standard deviation of 0.116 compared with 0.998 and 0.077 for our model and it is interesting to note that the faintest object in this sample is given with 16.797mag.
- URAT1 covers after eliminating all objects without Vmag data only 179 objects (out of 1,078) with a correlation coefficient of 0.997 and a standard deviation of 0.093 compared with 0.998 and 0.071 for our model and it is again most interesting to note that the faintest object given here is URAT1 ID 617 -001347 with 17.155mag.

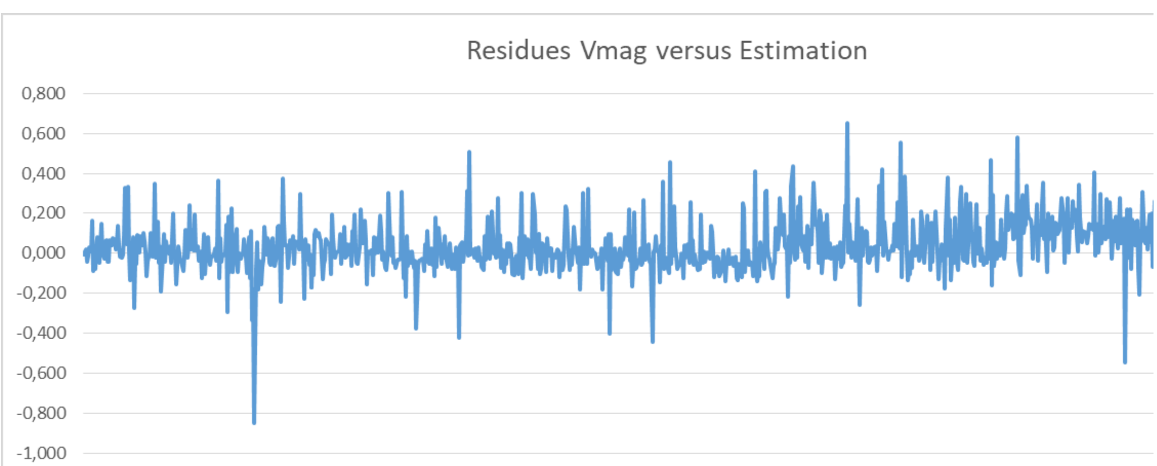

Figure 3. Difference Vmag versus model "prediction" sorted by coordinates

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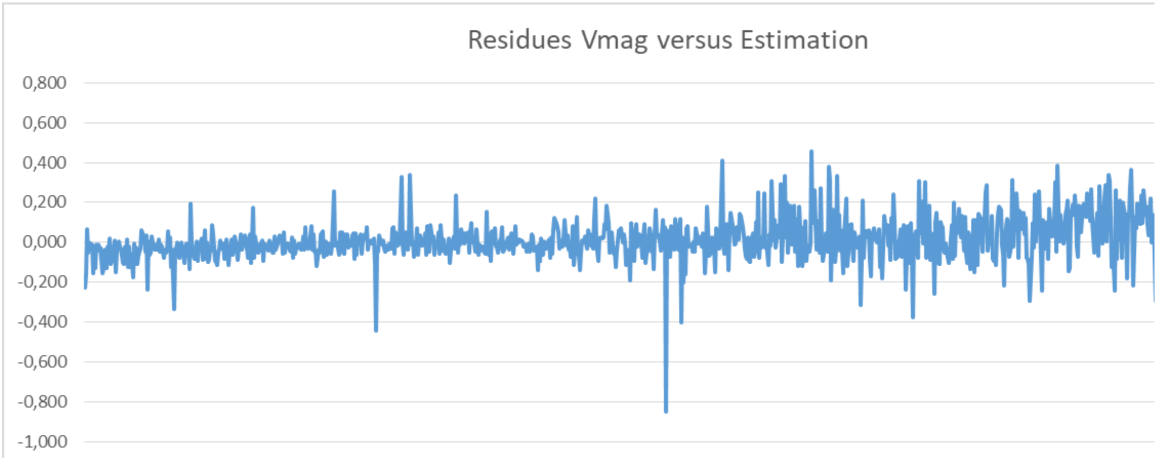

Figure 4. Difference Vmag versus model "prediction" sorted by Gmag

This allows for two conclusions:

- Both APASS and URAT1 do a good job in delivering Vmags as reliable as possible with priority for APASS as URAT1 uses APASS as Vmag source for faint stars
- Our model does a comparable or even slightly better job in this regard and has what is most important - no problem with coverage as most faint stars have G/J/H/K-mags available
- Both catalogs are of little help when it comes to the really faint stars beyond 17mag putting a question mark to plate solving results in this range.

We finally had then another look at the obvious bias in the results for the very faint stars around 20mag. Already the basic statistics offer some surprising insights:

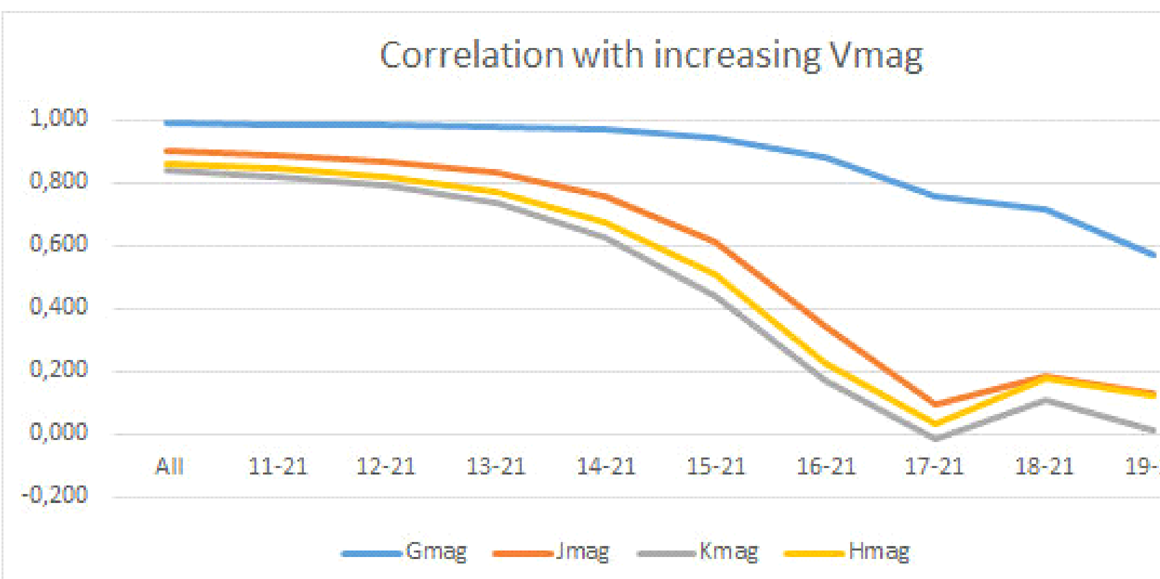

Image 5: Correlation G/J/H/K-mag to Vmag with increasing lower Vmag threshold. All means full data set, 11-21 means Vmag 11 up to 21, 12-21 means Vmag 12 up to 21

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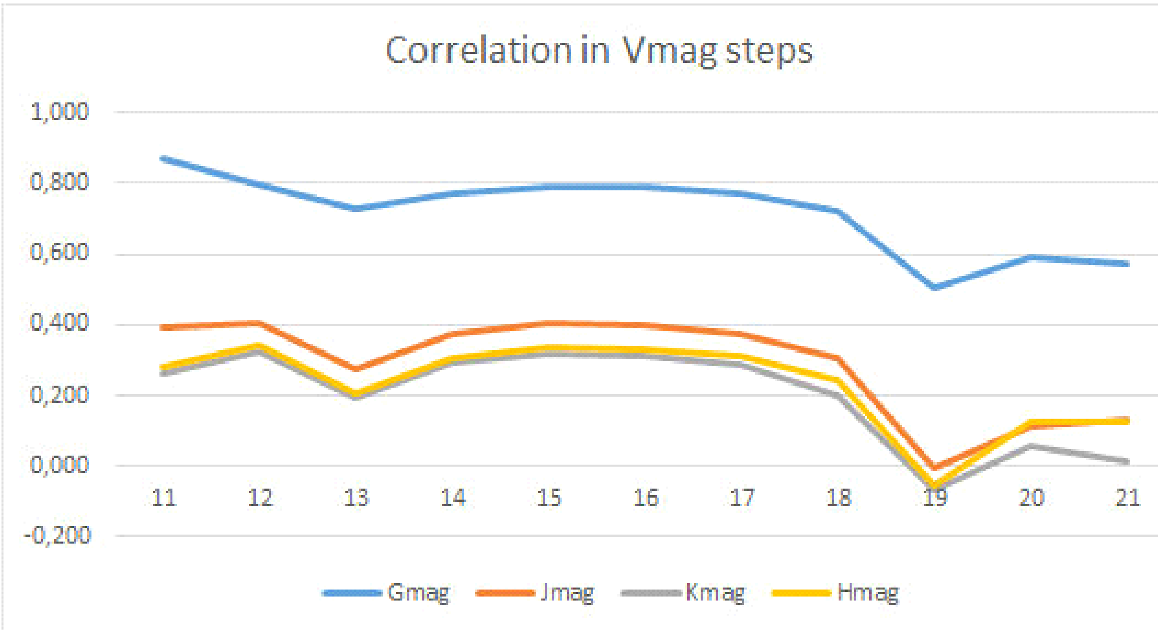

Image 6: Correlation G/J/H/K-mag to Vmag in steps. 11 means Vmag up to 11, 12 means Vmag 11 to 12, …

This means that the parameters we are using lose significant correlation with increasing magnitudes down to nearly zero for J/H/K-mags and even for Gmag the correlation goes down from 0.989 to below 0.6 suggesting an increasing magnitude data quality problem with increasing faintness regardless band getting significant between Vmag 18 to 19. For this reason we hesitate to follow through with our idea to increase the reliability of our model by splitting into different magnitude ranges even if this allows for significantly better results from the statistical point of view. So if the Vmag estimation using the given model formula results in a value above 18.5mag it might be worthwhile to apply different parameter values as follows:

$$V_{mag>18.5} = 1.63666432527439*G_{mag} - 0.321344836409207*J_{mag} - 0.192838139785561*K_{mag} - 0.164232310269182*H_{mag} - 0.110262544792707*(J_{mag}-K_{mag}) + 0.0421204840435933*(J_{mag}-K_{mag})^{2} - 0.0378226153139809*(J_{mag}-K_{mag})^{3}.$$

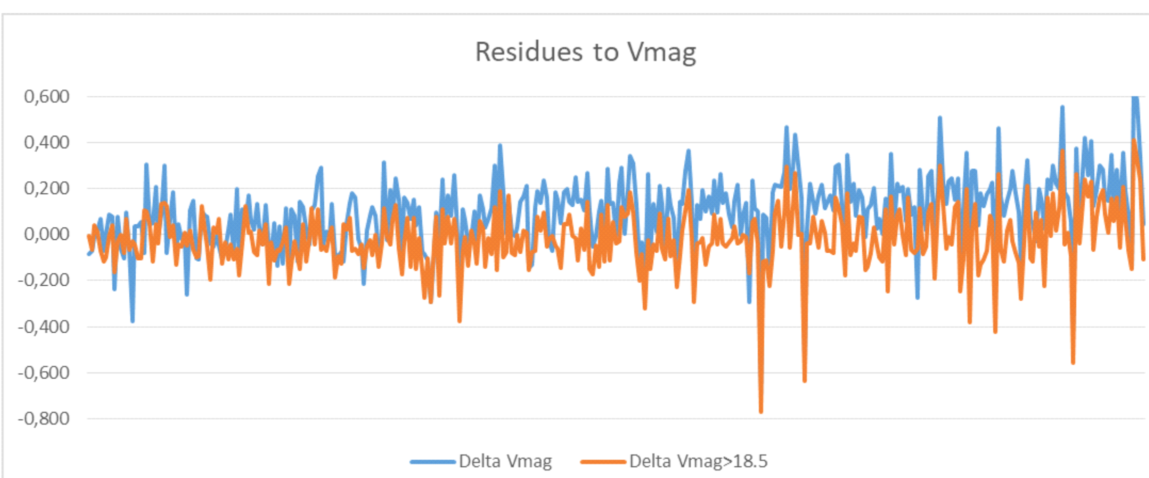

Figure 7. Comparison of residues

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The correlation coefficient for this data subset is 0.920 with a standard deviation of 0.128.

Applying this $V_{mag>18.5}$ model on the counter-check data set gives a correlation coefficient of 0.976 with a standard deviation of 0.132 which is slightly better than the overall model with corresponding values of 0.965 and 0.161 for this Vmag range. The comparison of the residues shows that the modified formula provides with the exception of a few outliers a somewhat better behavior for keeping the residues around zero. The spreadsheet for calculating the estimated Vmag is available for download from the JDSO website as "Estimating_Vmag_from_G_J_K_H-mags".

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