Differential photometry with Maxim DL is done by identifying the object with unknown magnitude and subsequently identifying a number of reference stars with known magnitudes on the same image. Maxim DL then calculates the object's magnitude and its uncertainty, called the error. The results can be exported to a CSV file, and to a file ready to upload to the AAVSO database, meant to be qualified for further scientific analysis. Here we take a close look at how the reported quantities are derived in a working example. We show that in the case of multiple reference stars the error reported to the AAVSO must be wrong, as it takes only the last of the reference stars into account, while ignoring all others.

The most relevant parameters in the AAVSO file contains the magnitude (MAG), which is equal to the Magnitude (Centroid) in the CSV file, and uncertainty (MAGERR), which is not contained in the CSV file, but from its provided information one should be able to reproduce these two main results. A partial description is available at http://forum.diffractionlimited.com/threads/how-does-maxim-dl-calculate-ensemble-magnitudes-and-errors.4608/, which is accessible by forum members.

We first examine a number of parameters reported in the CSV file. In addition to the identifier, time stamp, airmass and used filter, for each star several quantities are listed, among which the most relevant are: Intensity [ADU], Error, Signal-to-Noise Ratio (SNR), Instrument Magnitude (Centroid), and Magnitude (Centroid), as they are called. To study the effects of adding reference stars, we show a number of working examples with 1 to 4 reference stars (columns 1-5 and 8 extracted from the CSV file):

Identifier	ADU	SNR	Error	Vinstr	Vcatalog	Vdiff	Magnitude	MAG	MAGERR
Ref1	69764.3	296.159	0.0037	12.8909	13.735	-0.8441	13.735		
SN2019np	53323.52	208.3205	0.0052	13.1827			14.0268	14.0268	0.0064

We can verify that Error = 2.5 log10 (1+1/SNR), which is in magnitude units. The listed value is its rounded-off value with a user-specified number of digits.

We also verify that Vinstr = 25 - 2.5 log10 (ADU), the instrumental magnitude. It is calculated from the Intensity [ADU], the total number of ADUs in the aperture, already corrected for the background.

The Magnitude (= MAG) is in the case of only one reference star calculated as a simple subtraction of Vdiff = Vinstr – Vcatalog from Vinstr of the object (a recent supernova): 13.1827 – (– 0.8441) = 14.0268.

The reported value of MAGERR is SQRT(ErrorObject^2 + ErrorRef^2) (Equation 1).

With two reference stars we consider two cases, in which we changed the order. This should not make any difference. This is verified for the Magnitude, which appears to be calculated by taking a weighted average of the Vdiff values of the reference stars, with the SNR as weights. We obtain MAG = 14.02002, slightly different from the reported value 14.0201. The origin of this difference could not be traced. The value of MAGERR, however, is apparently calculated as in Eq. 1, but only taking into account the last of the two reference stars, which is easily verified to give MAGERR = 0.0064 and 0.0072, respectively:

Identifier	ADU	SNR	Error	Vinstr	Vcatalog	Vdiff	Magnitude	MAG	MAGERR
Ref1	51061.39	220.3877	0.0049	13.2298	14.058	-0.8282	14.0671		
Ref2	69764.3	296.159	0.0037	12.8909	13.735	-0.8441	13.7283		
SN2019np	53323.52	208.3205	0.0052	13.1827			14.0201	14.0201	0.0064

Identifier	ADU	SNR	Error	Vinstr	Vcatalog	Vdiff	Magnitude	MAG	MAGERR
Ref1	69764.3	296.159	0.0037	12.8909	13.735	-0.8441	13.7283		
Ref2	51061.64	220.3884	0.0049	13.2298	14.058	-0.8282	14.0671		
SN2019np	53323.52	208.3205	0.0052	13.1827			14.0201	14.0201	0.0072

We verified this odd result by adding more reference stars, which is best illustrated with 4 stars, and only changing their order while keeping everything else identical:

Identifier	ADU	SNR	Error	Vinstr	Vcatalog	Vdiff	Magnitude	MAG	MAGERR
Ref1	51061.39	220.3877	0.0049	13.2298	14.058	-0.8282	14.0768		
Ref2	38838.92	165.8224	0.0065	13.5268	14.376	-0.8492	14.3738		
Ref3	13023.73	57.1187	0.0188	14.7132	15.647	-0.9338	15.5602		
Ref4	69764.3	296.159	0.0037	12.8909	13.735	-0.8441	13.7379		
SN2019np	53323.52	208.3205	0.0052	13.1827			14.0297	14.0297	0.0064

Identifier	ADU	SNR	Error	Vinstr	Vcatalog	Vdiff	Magnitude	MAG	MAGERR
Ref1	69764.3	296.159	0.0037	12.8909	13.735	-0.8441	13.7379		
Ref2	51061.64	220.3884	0.0049	13.2298	14.058	-0.8282	14.0768		
Ref3	38838.92	165.8224	0.0065	13.5268	14.376	-0.8492	14.3738		
Ref4	13023.73	57.1187	0.0188	14.7132	15.647	-0.9338	15.5602		
SN2019np	53323.52	208.3205	0.0052	13.1827			14.0297	14.0297	0.0195

In both cases only the 4th reference star is used in Equation 1 to calculate MAGERR, resulting in 0.0064 (the same value as in the case of only one reference star) and 0.0195 (when the faintest star is the last one measured). We cannot escape from the conclusion that Maxim DL generated values reported to the AAVSO are unreliable, and hence that any scientific analysis using these errors must be in doubt.

We note that using the SNR-weighted average, as described above, gives MAG = 14.0301, again slightly different from the reported 14.0297, and again with unknown origin.

The logical question is how to calculate the proper value of MAGERR. We follow the AAVSO Guide to CCD Photometry, version 1.1, available through https://www.aavso.org, and "A Practical Guide to Lightcurve Photometry and Analysis", by B. Warner (2016). In principle, the more reference stars, the more reliable this value could be determined, and therefore the smaller the error. Both sources recommend to take a weighted average of the values of Vdiff of the reference stars to calculate the magnitude. The standard deviation of this ensemble of differences should then be the error to be quoted. This is an entirely different approach compared to Eq. 1, since adding reference stars would only increase the value of second term in Eq. 1, and hence the error, the contrary what is aimed for.

Another point is which reference stars are chosen. In the example above only stars from APASS have been carefully selected. This is on purpose, because these stars have listed uncertainties, which are in the range of 0.023 to 0.048 magnitude for this example, and which should be taken into account in the calculation of MAGERR. Intuitively this should be obvious, since two reference stars with similar magnitudes but with very different uncertainties should give different answers, but this is not mentioned in the sources above. A careful inspection of the reference stars is therefore always needed.

A last point is the choice of the dimensions of the measuring aperture radius, gap width and background annulus thickness, which have to be chosen beforehand. These values affect the outcome, including the error.

In summary: to enable a reliable estimate of the magnitude and its uncertainty with Maxim DL, our recommendations for future implementations of photometry are: (1) the option to specify the uncertainty of the reference stars, if known. (2) The exported CSV file should include (a) the catalog values of the selected reference stars, with their uncertainties if specified, and (b) the three aperture dimensions used for the measurements. (3) to document how the values of MAG and MAGERR are calculated.