D1. Photometric comparison of surveys (75 points)

You are an astronomer working with large photometric surveys, such as the Sloan Digital Sky Survey (SDSS) and the Dark Energy Survey (DES), both of which have your host, Observatório Nacional, as a participant. SDSS used a 2.5 m telescope in Apache Point, USA, during the 2000s, and DES used a 4 m telescope in Cerro Tololo, Chile, from 2013 to 2019. Even though they mostly covered different hemispheres of the sky, they had an equatorial region in common known as Stripe 82 that you can use to compare and calibrate the photometry of different data sets, like SDSS and DES.

The following tables containing object positions and magnitudes from Stripe 82 were downloaded for analysis. However, due to a file system corruption on the computer, the file names were scrambled, and now you cannot tell which table belongs to which survey.

Tables 1 and 2 appear next to each other below, with an identification number for each source, its equatorial coordinates, and its magnitude in the g-band (m_g) with its error (err m_g).

Table 1

ID_1	RA (deg)	Dec (deg)	m_g (mag)	err m_g (mag)
1	0.047255	0.000406	21.7649	0.0120
2	0.064741	0.021568	21.1111	0.0067
3	0.064911	0.026395	21.3931	0.0084
4	0.098343	0.054871	21.3934	0.0088
5	0.022256	0.039129	21.9933	0.0157
6	0.006188	0.066928	21.5490	0.0088
7	0.083945	0.074259	21.9395	0.0126
8	0.076715	0.079496	21.4808	0.0089
9	0.057422	0.076006	21.8897	0.0127
10	0.024412	0.087688	21.8341	0.0126
11	0.044723	0.091782	21.8868	0.0172
12	0.071089	0.091053	21.4390	0.0098

Table 2

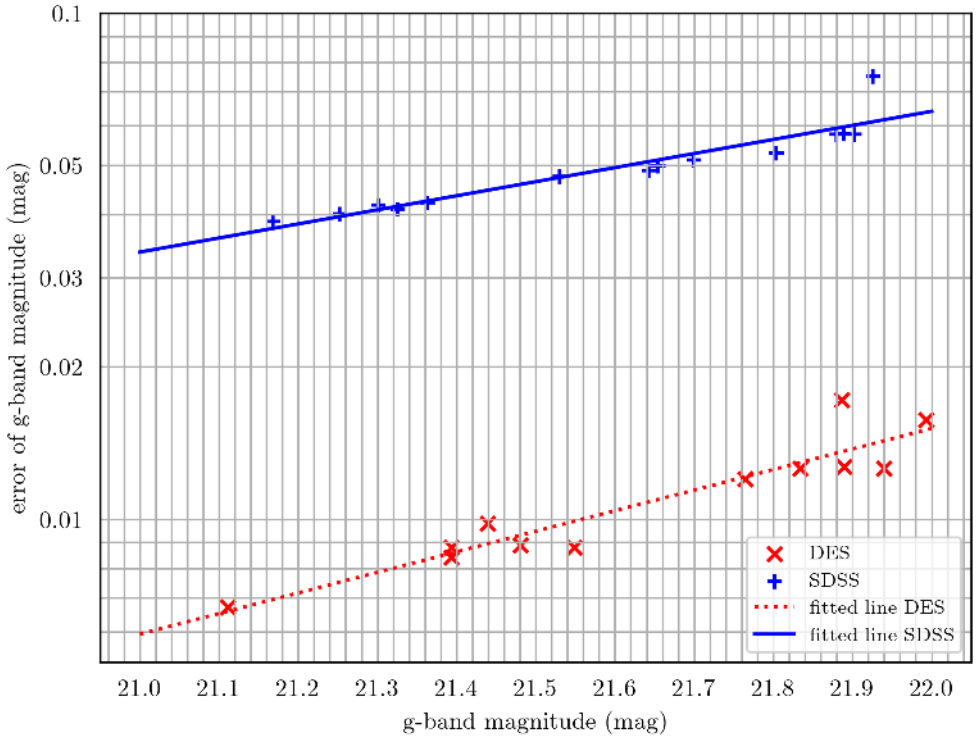
ID_2	RA (deg)	Dec (deg)	m_g (mag)	err m_g (mag)
1	0.006167	0.066874	21.9020	0.0576
2	0.018660	0.007450	21.8039	0.0529
3	0.047853	0.061487	21.3007	0.0418
4	0.050870	0.015659	21.1678	0.0388
5	0.051270	0.020812	21.2524	0.0401
6	0.057414	0.075999	21.8884	0.0578
7	0.064745	0.021583	21.3634	0.0422
8	0.064910	0.026419	21.6428	0.0488
9	0.071102	0.091058	21.9259	0.0751
10	0.074946	0.002792	21.3258	0.0410
11	0.076709	0.079474	21.5303	0.0476
12	0.092635	0.077395	21.6995	0.0513
13	0.098343	0.054854	21.6542	0.0499
14	0.099332	0.093711	21.8802	0.0577

(a) (5 points) From these tables, which survey (SDSS or DES) is Table 1 and which is Table 2? Assume that both surveys are equivalent regarding detector response, exposure times, and site characteristics.

Solution: DES is Table 1 and SDSS Table 2, since faint stars will have higher uncertainties. SDSS uses a smaller telescope (2.5 m) than DES (4 m) hence, it is typically shallower and has larger errors. Just looking at the error distribution should be enough to tell who has larger errors.

(b) (35 points) Using the data in the table, plot the magnitude (m_g) on the x-axis (linear scale) and the error in magnitude (err m_g) on the y-axis (logarithmic scale) using the semi-log paper marked as Graph 1. Estimate the angular coefficient A (slope) and linear coefficient B (y-axis intercept) for each dataset. There is no need to calculate the associated errors.

Solution: The linear regression of each curve:



The reported parameters are:

SDSS:

$$\log_{10}(err\ m_g) = A \cdot m_g + B$$

$A = 0.2780$ (acceptable from 0.2502 to 0.3058 which is within 10% range of the fit)

$B = -7.3108$(acceptable from -8.0419 to -6.5797 which is within 10% range of the fit)

DES:

$$\log_{10}(err\ m_g) = A \cdot m_g + B$$

$A = 0.4063$(acceptable from 0.3657 to 0.4470 which is within 10% range of the fit)

$B = -10.7597$(acceptable from -10.2217 to -11.2977 which is within 10% range of the fit)

(c) (5 points) The Signal to Noise ratio (S/N) is approximately the inverse of the error in the magnitude, $S/N \approx 1/(\text{err } m_g)$. Using the linear fit calculated in the previous part, what is the S/N reached for each survey at a magnitude of $m_g = 21.5$ mag?

Solution: Using that $S/N \sim 1/err\ m_g$ and above fits we can arrive at the following:
SDSS: $\log_{10}(err\ m_g) = 0.2780 \cdot 21.5 - 7.3108 \rightarrow err\ m_g = 0.0464$
DES: $\log_{10}(err\ m_g) = 0.4063 \cdot 21.5 - 10.7597 \rightarrow err\ m_g = 0.0095$
Accepted answers follow below.

	err	S/N
SDSS err at 21.5 mag	0.05	**22** (acceptable from 19.8 to 24.2 -> within 10% range of the result)
DES err at 21.5 mag	0.01	**106** (acceptable from 95.4 to 116.6 -> within 10% range of the result)

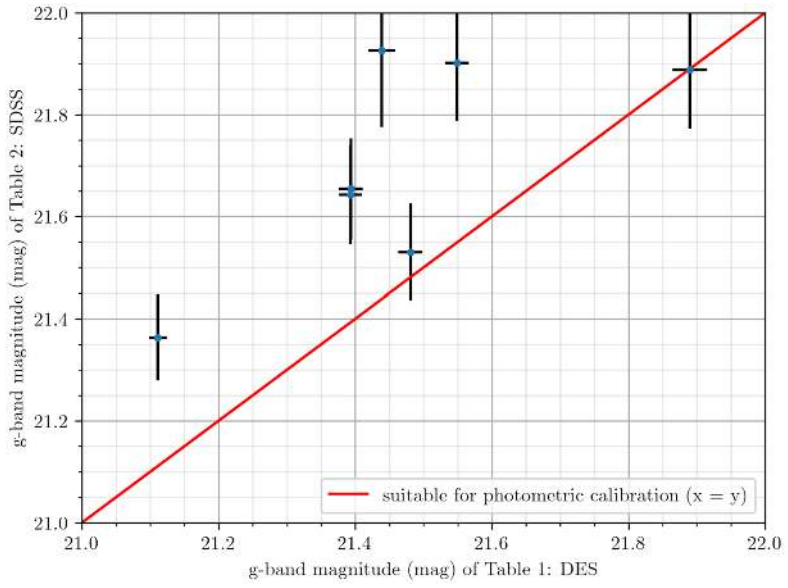
(d) (15 points) An object in Table 1 that is within 1 arcsecond of an object in Table 2 can be considered to be the same object. By looking at the RA and Dec of the objects in both tables, identify the objects in common and write down a new table with the matching IDs, ID_1 and ID_2.

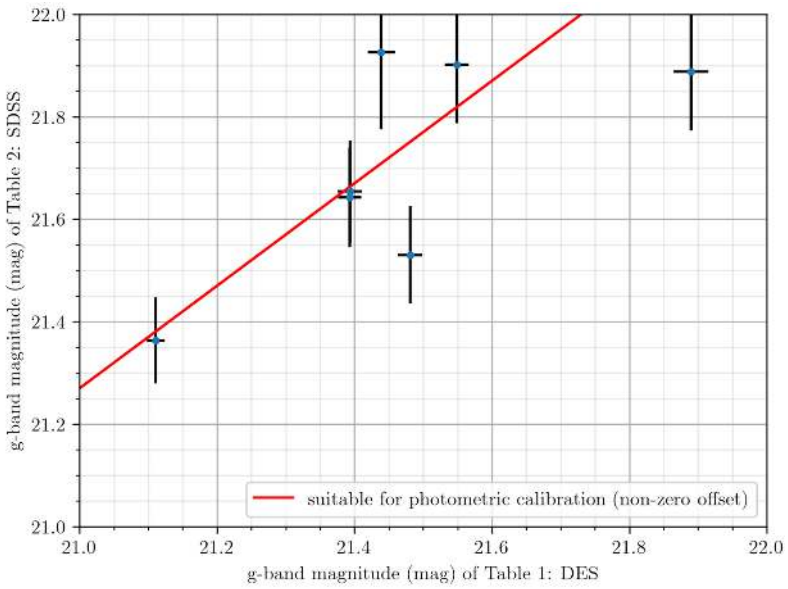
Solution: One tip for this question is that the student should realize that the SDSS RA coordinate is sorted, so it can be used as a reference for the scanning of DES coordinates to perform the match. These are the stars that can be matched between catalogs:

ID_1	RA (deg)	Dec (deg)	m_g (mag)	err m_g (mag)	ID_2	RA (deg)	Dec (deg)	m_g (mag)	err m_g (mag)	Sep (arcsec)
3	0.064911	0.026395	21.3931	0.0084	8	0.064910	0.026419	21.6428	0.0488	0.08475
9	0.057422	0.076006	21.8897	0.0127	6	0.057414	0.075999	21.8884	0.0578	0.03724
4	0.098343	0.054871	21.3934	0.0088	13	0.098343	0.054854	21.6542	0.0499	0.06186
6	0.006188	0.066928	21.5490	0.0088	1	0.006167	0.066874	21.9020	0.0576	0.2076
12	0.071089	0.091053	21.4390	0.0098	9	0.071102	0.091058	21.9259	0.0751	0.05009
2	0.064741	0.021568	21.1111	0.0067	7	0.064745	0.021583	21.3634	0.0422	0.05655
8	0.076715	0.079496	21.4808	0.0089	11	0.076709	0.079747	21.5303	0.0476	0.08276

(e) (15 points) Using the matched table from part (d), plot the g-band magnitude of each survey against the other, Table 1 on the x-axis, and Table 2 on the y-axis using the millimetre (linear) paper marked as Graph 2. Draw on error bars for each point in both horizontal and vertical directions, using values **double** err m_g (known as a 2σ uncertainty). From your graph, identify the stars that would be suitable for photometric calibration between the two surveys and write down their corresponding IDs from Table 1.

Solution: The figure of g magnitude of DES vs SDSS should look like this with the best linear fit:





The student should identify the stars that are closest to the one-to-one line (x = y) between surveys. This could be with a zero offset, or a non-zero offset. The **two** stars that would be suitable for photometric calibration with zero offset are the ones with ID's **8** and **9** of Table 1 (DES). The **four** stars that would be suitable for photometric calibration with non-zero offset are the ones with ID's **2, 3, 4 and 6** of Table 1 (DES).

D2. Shapley Hypothesis (75 points)

Globular clusters are one of the oldest components of galaxies. About a century ago, Harlow Shapley studied the distribution of globular clusters in the Milky Way in order to determine the distance from the Sun to the Galactic Centre, with the hypothesis that globular clusters were symmetrically distributed around the Galactic Centre. The table below shows the positions and distance moduli of a few known globular clusters in the Milky Way. The first three columns in the table show the cluster name, galactic longitude (l), and galactic latitude (b). The fourth column shows the distance modulus (i.e. the difference between the apparent and absolute magnitude), for which the values are extinction-corrected. Based on the data in the table: