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Survey of long-term variability of stars

I. Reliability of magnitudes in old star catalogues

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Abstract. The comparison of visual magnitudes of stars compiled in old catalogues is expected to yield information about their long-term magnitude variations. In seven old catalogues whose historical data have been intensively compared, 2123 sampled stars have been studied, disregarding stars that we could not identify, double stars which could be misidentified, or stars observed under poor conditions, and known variable stars with large amplitude discrepancies. The independence of stellar magnitude catalogues is demonstrated by comparing seven old studies to each other, suggesting that the magnitude estimates in each catalogue reflect the brightness at each observational period. Furthermore, by comparing them with a modern star catalogue, the magnitude differences show a Gaussian distribution. Therefore, if they are sufficiently larger than the deduced standard deviations, the magnitude variations between the catalogues can be considered real. Thus, the stellar magnitudes compiled in old studies can be used as scientific data within the average intrinsic uncertainty. These seven old catalogues can be used as data for the survey of the long-term variability of stars.

Key words. stars: general – stars: variables: general – catalogs

1. Introduction

Approximately 100 years have passed since the first systematic and accurate observations of fixed stars were catalogued. However it is still possible that there are stars with variability on longer timescales than 100 years. Our goal here is to study such long-term variable stars and find the nature of their magnitude variations through the survey of stellar magnitudes in old star catalogues.

Long-term variabilities with large amplitudes can occur through several mechanisms; an eclipsing binary is one possible example. Currently, the longest period of a known eclipsing binary is 27.1 years of ε Aur, varying between 3.37–3.91 mag. This variance can be recognized by naked-eye observations. One could assume that the duration of the minimum should be longer for a system with a longer orbital period, thus the variability of such a system can be overlooked if the observation was made within a short period. Essentially, it means that the photometric observations for some catalogues may have been performed during an eclipse where the recorded magnitudes could be at the minimum, while other observations show the magnitudes out of an eclipse.

Except within the eclipsing binaries, variabilities with timescales longer than those of Mira-type pulsating variables (~1 year) have rarely been observed. The timescale of Mira-type variables is measured in the stellar dynamic timescale, which cannot be longer than several years. On the other hand, some variabilities with timescales longer than 1 year may have been recorded. The helium flash at the core of an intermediate mass star which leads a star from the red giant branch to the horizontal branch is one possible example. Another example is a final helium shell flash and a thermal pulse stage, as in FG Sge (Herbig & Boyarchuk 1968) or V4334 Sgr="Sakurai's Object" (Duerbeck et al. 1997).

Other violent variables can be observed, such as S Dor-type variables (P Cyg, η Car) or ones with uncertain mechanisms like V838 Mon. One such variable is the widely recognized δ Sco, which brightened unexpectedly from 2.3 mag to about 1.8 mag since July 2000. Previously known as a stable normal B star, this star is now classified as an eruptive irregular variable of the γ Cas-type. This type of star is a rapidly rotating B III-IVe star with mass outflow from its equatorial zone. The formation of equatorial rings or disks is often accompanied by temporary fading. Light amplitudes may reach 1.5 mag in V. (Otero et al. 2001; Fabregat et al. 2000). The variability of δ Sco was not expected. As in this star, there may be

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many magnitude variations hitherto unknown. We expect that our survey will reveal such astronomical phenomena.

To study stellar magnitudes of earlier eras, we referred to old astronomical catalogues. The following seven catalogues have been selected as reliable:

1. *Almagest* (Ptolemy AD127–141);
2. *Kitāb Ṣuwar al-Kawākib* (al-Ṣūfī 986);
3. *Ulugh Beg's Catalogue of stars* (1437);
4. *Astronomiae Instauratae Progymnasmata* (Brahe 1602);
5. *Uranometria* (Bayer 1603);
6. *Historia Coelestis Britannica* (Flamsteed 1725);
7. *Uranometria Nova* (Argelander 1843).

Before we could use the above studies, we had to check their reliability as scientific data. We analyzed this problem on the basis of a statistical test of the distribution of magnitude differences taken from each pair of these studies. As an additional check on the reliability of the seven historical catalogues, we also compared the data compiled in them with modern data taken from the "*Sky Catalogue 2000.0*" (Hirshfeld et al. 1991).

2. Characteristics of old catalogues

"*Almagest*" was compiled by Ptolemy in the 2nd century AD. Intensive philological studies of "*Almagest*" were conducted by Kunitzsch (1986-1991) and Toomer (1998). We used the star catalogues of these two works, which contain 1022 stars of 48 constellations compiled with their ecliptic coordinates and visual magnitudes. Ptolemy's own recorded observations range from AD 127 to 141 and his catalogue epoch is about AD 137.

"*Kitāb Ṣuwar al-Kawākib*" was written in Arabic in the 10th century by al-Ṣūfī. The epoch of this star table is 964. Since the manuscript was transcribed by hand, our most serious concern was that a clerical error may have been made. We examined many manuscripts and literature relevant to this material (al-Ṣūfī 986a,b; al-Bīrūnī 1030; Schjellerup 1874; Kunitzsch 1989), and adopted relative magnitude data for all of the records. If there was a discrepancy between catalogues, we followed the studies of Kunitzsch (1989).

Knobel (1917) revised "*Ulugh Beg's Catalogue of Stars*" using all the contemporary Persian manuscripts kept in Great Britain. This catalogue also includes star coordinates and magnitudes, as observed from Samarkand (epoch 1437).

Tycho Brahe observed a supernova in Cassiopeia (Tycho's nova) in 1572 and recorded it in two books (Brahe 1573, 1602). One of them, "*Astronomiae Instauratae Progymnasmata*" was published after his death in 1602 and includes a star catalogue. The data in this catalogue are based on Tycho's own observations and are highly precise, especially in the determination of stellar positions (errors are within $1'$).

Bayer introduced a new method to name fixed stars in "*Uranometria*" (Bayer 1603). He named each star, per constellation, with Greek or Roman alphabet characters in order of magnitude. Until then, the identification of stars was usually done by numbers and means of elaborate descriptions: for example, α UMi was described as "the star on the end of the tail of the Little Bear". Bayer's identifications clarified obscure descriptions and has been used widely up to the present. In this material, Bayer added 12 southern constellations to Ptolemy's original 48. It depicts the positions and magnitudes of about 1200 stars.

Flamsteed performed positional astronomy at Royal Greenwich Observatory and made 20 000 observations of nearly 3000 stars. His observational data, compiled in "*Historia Coelestis Britannica*" (Flamsteed 1725) was published after his death. This record is spread out over three volumes of which the first two include data on planetary movement. His star catalogue, including stellar equatorial coordinates, ecliptic coordinates and magnitudes is contained in Tome (volume) III. The observation epochs are described in the catalogue; the mean epoch is 1689.

Argelander observed a few thousand stars with the naked eye. His "*Uranometria Nova*" (Argelander 1843) records 3256 stars with equatorial coordinates and magnitudes of fixed stars.

In all of the star catalogues mentioned above, stellar magnitudes were classified from 1st to 6th based on the Hipparchus system. In addition, for refinement, observers used plus or minus signs to indicate "a little brighter" or "a little dimmer", respectively. To quantify these magnitude descriptions, we subtracted or added 0.33 according to the plus or minus sign, respectively. For example, we assigned 2.67 for 3+ and 3.33 for 3−.

3. Data selection and analysis

When these catalogues were recorded, there was no concept of zero or minus magnitude. Therefore, the stars brighter than 1 mag were omitted. In addition we omitted the stars that we could not identify. For example, since Bayer recorded the six stars π^1, $\pi^2 \cdots \pi^6$ Ori all together and described them as π Ori, we could not assign them individual magnitudes. The constellation "Argo" was divided into 4 constellations (Puppis, Pyxis, Vela, Carina) in the 18th century by Lacaille. We could not identify the stars belonging to "Argo" in the old star catalogues. We omitted visual double stars and binaries (except for spectroscopic binaries) whose apparent distance exceeds $1'$ (limit of the resolving power of the naked eye) and recorded as one single object. For example, the apparent distance between α^1 Cap and α^2 Cap is $7'$ and magnitude data recorded as "α Cap" were rejected. For close stars (separated by less than $1'$), we used the compiled magnitude from the old material. For the present-day magnitudes of close multiple stars, we used the combined magnitudes of component stars taken from the "*Sky Catalogue 2000.0*". Known variables with amplitude larger than 0.5 mag (o Cet (Mira), β Per (Algol), δ Cep, etc.) were omitted.

The catalogues we used were recorded or compiled by different people at different places and times. Therefore, it might be possible that the listed magnitudes show discrepancies only because of different observational conditions. To find these discrepancies and to correct them, we compared the mean magnitude averaged over all stars listed in each study to the mean magnitude of corresponding stars listed in the "*Sky*

Table 1. Mean magnitudes and discrepancies.

ID	*epoch*	N_{total}	N	$N/N_{\text{total}}(\%)$	$\bar{m}$	$\bar{m}_{2000}$	$\bar{m}-\bar{m}_{2000}$
1	137	1022	910	89	3.98	4.06	–0.08
2	964	1025	911	89	4.16	4.07	0.09
3	1437	1018	889	87	4.16	4.06	0.10
4	1572	777	658	85	4.27	4.08	0.19
5	1603	~1200	949	~79	4.42	4.26	0.16
6	1689	~3000	1003	~33	4.61	4.36	0.25
7	1843	3256	1946	60	5.03	4.81	0.22

Catalogue 2000.0". The mean magnitudes and discrepancies thus obtained are presented in Table 1. The catalogue *ID* (listed in Sect. 1) is found in Col. 1, the observational (usually not published) epoch of each catalogue is given in Col. 2, the total number of stars in each catalogue N_{total} is shown in Col. 3, the number of selected stars N is listed in Col. 4, the ratio of selected star N/N_{total} is given in Col. 5, mean magnitude of the catalogue $\bar{m}$ is listed in Col. 6, present-day mean magnitude $\bar{m}_{2000}$ is given in Col. 7, and $\bar{m}$–$\bar{m}_{2000}$ is shown in Col. 8. Most datasets were obtained over extended periods. However, these are much shorter than the epoch differences between the catalogues. We therefore neglected errors of several years and adopted probable epochs.

According to the catalogues, the number of selected stars differed greatly. For example, from the oldest catalogue, "*Almagest*", out of 1022 stars, we use 910 (89%), however only 1946 stars out of 3256 (60%) are taken from the most recent and probably most reliable list (Argelander). We accepted only 30% from the catalogue of Flamsteed. In the case of these two catalogues there were special reasons for the high rejection percentage. In Flamsteed's catalogue, there were many stars without identification marks (Bayer names or Flamsteed's numbers) which were not selected. Flamsteed's numbers were not found in "*Historia Coelestis Britannica*" which we could consult at the Paris Observatory but in another book. As for the catalogue of Argelander, the stars identified by neither Bayer names nor Flamsteed's numbers were not sampled. We could not associate the other identification marks with currently known ones. Therefore, we used the stars marked with common identifications.

4. Results and discussion

4.1. Independence of catalogues

To investigate whether these catalogues were based on individual observations or copied from predecessors, we compared these seven catalogues to each other. If material was copied from predecessors, their magnitude data would be identical and the distribution of stellar magnitude differences would have a very small standard deviation. If the standard deviation is large, we could assume that the magnitude data was observed independently. The distribution of the differences of stellar magnitudes between each pair of studies is shown in Fig. 1.

The standard deviations σ of these distributions and the numbers of sampled stars N are given in Table 2. To clarify the value of the standard deviations, we set the mean of the magnitude difference for a pair of catalogues to zero by adding a small (up to 0.1 mag) constant for each pair.

Table 2. Standard deviations σ between two old catalogues and numbers of sampled stars N.

ID	*epoch*		137	964	1437	1572	1603	1689	1843
						σ			
1	137		– – –	0.47	0.41	0.69	0.67	0.77	0.62
2	964		901	– – –	0.29	0.72	0.72	0.78	0.60
3	1437		860	861	– – –	0.66	0.68	0.72	0.55
4	1572	N	584	585	575	– – –	0.40	0.54	0.65
5	1603		709	706	699	593	– – –	0.59	0.65
6	1689		688	688	680	602	832	– – –	0.67
7	1843		792	793	780	644	878	952	– – –

With the exception of the correlation between "*Kitāb Ṣuwar al-Kawākib*" and Ulugh Beg's catalogue, the standard deviations σ range from 0.40 to 0.78 mag for all catalogue comparisons. These values are much larger than expected for non-independent records. Therefore, the stellar magnitudes listed in these catalogues are considered to have been observed independently.

The correlation between "*Kitāb Ṣuwar al-Kawākib* (964)" and "*Ulugh Beg's Catalogue of stars* (1437)" is very close with little to no deviation. In Fig. 1, one can see the large peak in the distribution difference graph comparing these two sets.

Despite a span of over 450 years, the dispersion σ is much smaller than in the other correlations. However, if most of Ulugh Beg's catalogue was copied from "*Kitāb Ṣuwar al-Kawākib*", the dispersion should be close to 0. The standard deviation of 0.29 mag indicates that Ulugh Beg's catalogue is not a complete copy, but gives strong reasons to suspect that the two catalogues are not fully independent either.

4.2. Consistency of magnitudes

In addition to this comparison, we compared the stellar magnitudes in these old surveys with those in the "*Sky Catalogue 2000.0*" (Hirshfeld et al. 1991). The standard deviations σ of these distributions are shown in Table 3, and the number of sampled stars N are given in Table 1.

The standard deviations σ range between 0.41 and 0.70. Magnitude differences measured for any combination of old catalogue and the "*Sky Catalogue 2000.0*" show a Gaussian distribution (see Fig. 2). These facts demonstrate that their magnitude variations are considered to be real when the variation is sufficiently larger than the dispersion. Therefore, we can use these star catalogues as scientific data within an average intrinsic uncertainty of about 0.5 mag.

We show discrepancies between the mean magnitude of the catalogue $\bar{m}$ and the present-day mean magnitude $\bar{m}_{2000}$ in each catalogue as $\bar{m}$–$\bar{m}_{2000}$ in Table 1. These discrepancies are much less than 0.5, negligibly small for the discussion of dispersions. At later epochs, the value shifts toward more positive residuals and more stars were recorded. We propose that these

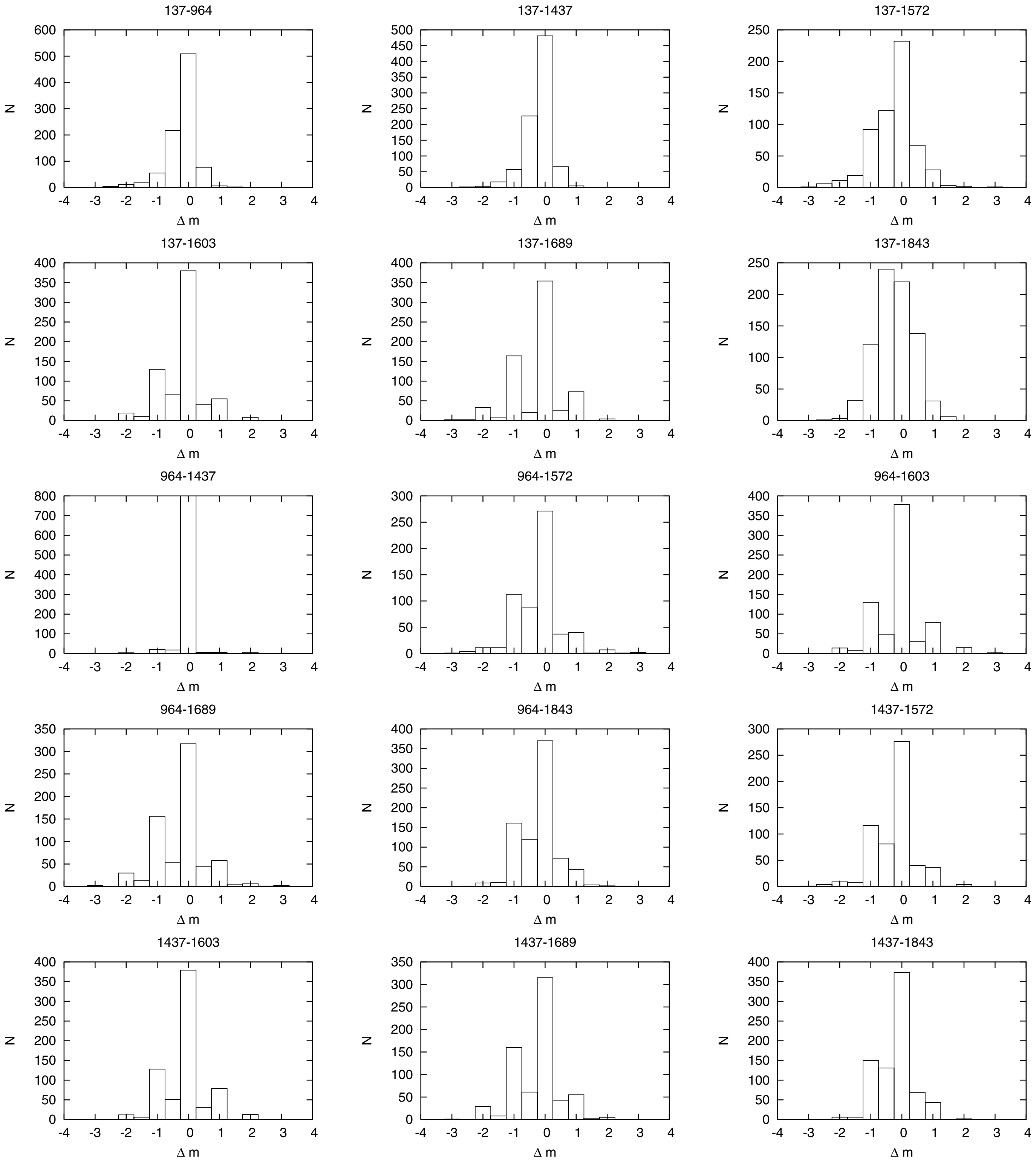

Fig. 1. Differences of stellar magnitude between two old catalogues.

discrepancies were ascribable to dimmer stars which were estimated imprecisely.

5. Conclusions

1. The comparison of stellar magnitudes recorded in seven old catalogues indicates that the magnitudes in most of these catalogues were obtained from independent observations. The only exception is "*Ulugh Beg's Catalogue of stars*", which is probably not entirely independent of the earlier "*Kitāb Ṣuwar al-Kawākib*" list and should therefore be given lower weight.

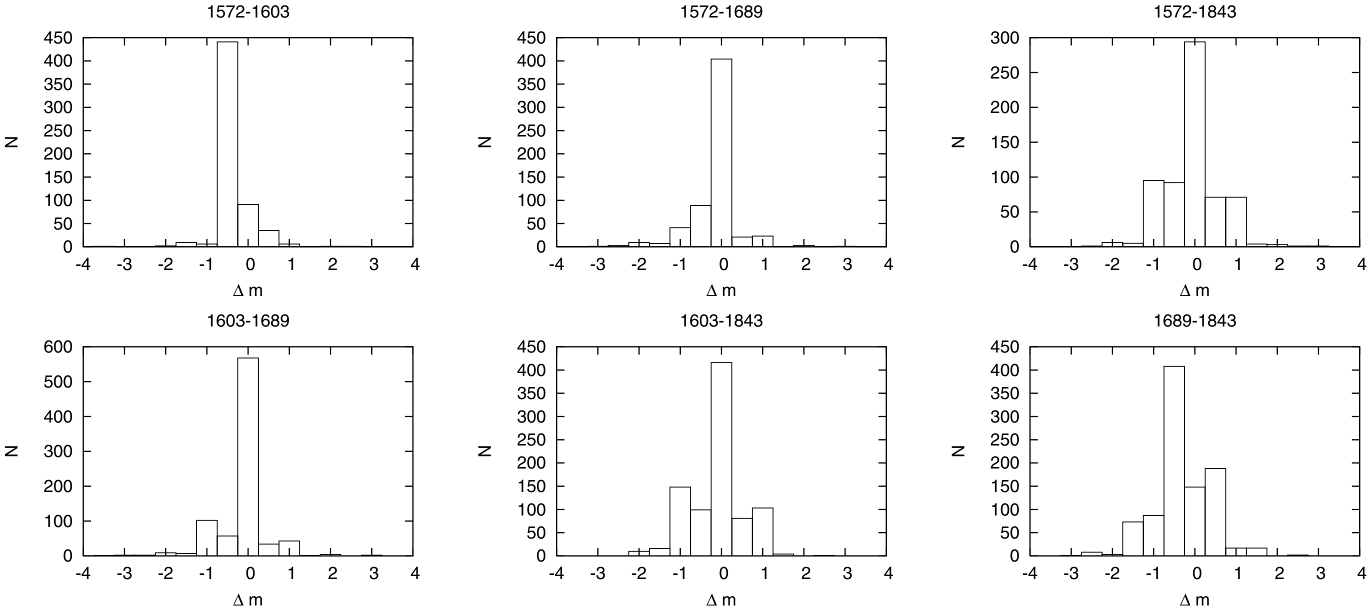

Fig. 1. continued.

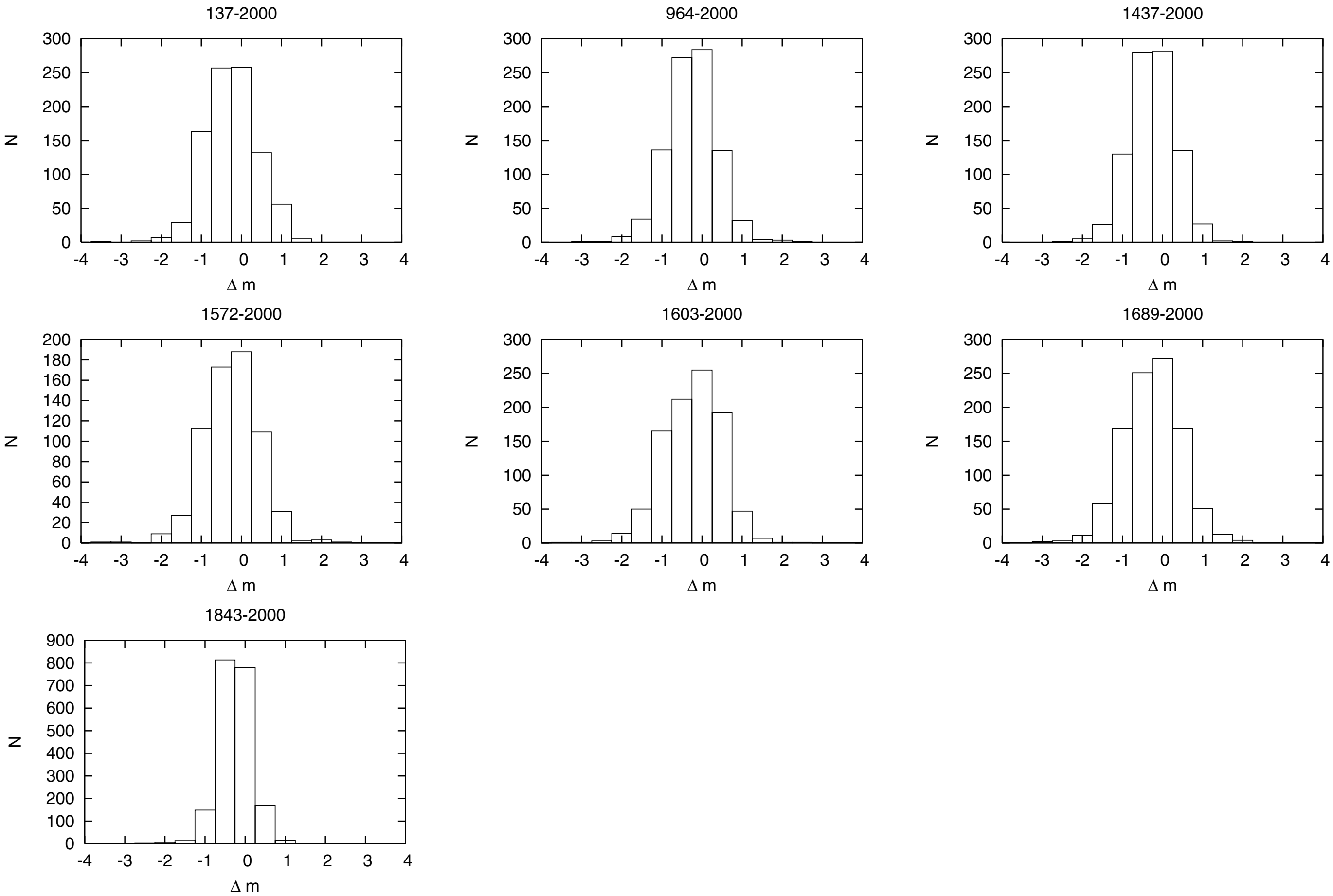

Fig. 2. Differences of stellar magnitude between old catalogues and "*Sky Catalogue 2000.0*".

2. The magnitude variations found from the comparison of stellar magnitudes recorded in seven old catalogues and one modern star catalogue can be considered to be real.
3. Magnitude differences between old catalogues and the modern star catalogue also represent Gaussian distributions, thereby supporting the above conclusions.

Essentially, the stellar magnitudes compiled in the old studies we investigated here can be used as scientific data within an average intrinsic uncertainty of about 0.5 mag.

Table 3. Standard deviations σ between old catalogues and "*Sky Catalogue 2000.0*".

ID	*epoch*	2000 σ
1	137	0.64
2	964	0.61
3	1437	0.56
4	1572	0.67
5	1603	0.70
6	1689	0.70
7	1843	0.41

Although it is beyond the scope of this paper, some of the stars we could not identify and have omitted here might be transient objects (nova, supernova or others) caught in an outburst.

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References

Argelander, W. A. 1843, Uranometria Nova (Berlin: Berlag von Simon Schropp und Comp.)

Bayer, J. 1603, Uranometria, reprinted in 1987 (England: British Library)

al-Bīrūnī 1030, Al-Qānūn al-Mas'ūdī, vol. 3, reprinted in 1956 (Hyderabad: Dāiratu'l-Ma'ārif-il-'Oṣmānia)

Brahe, T. 1573, De nova et nullius aevi memoria prius visa stella, facs.ed. in 1901 (Copenhagen)

Brahe, T. 1602, Astronomiae Instauratae Progymnasmata, reprinted in 1969 (Bruxelles: Impression Anastaltique)

Duerbeck, H. W., Benetti, S., Gautschy, A., et al. 1997, AJ, 114, 1657

Flamsteed, J. 1725, Historia Coelestis Britannica, Tome III (London)

Fabregat, J., Reig, P., & Otero, S. 2000, IAU Circular No. 7461

Gillispie, C. C. 1970, Dictionary of Scientific Biography (New York: Scribner)

Hearnshaw, J. B. 1996, The measurement of starlight (Cambridge: Cambridge U.P.)

Herbig, G. H., & Boyarchuk, A. A. 1968, ApJ, 153, 397

Hirshfeld, A., Sinnott, R. W., & Ochsenbein, F. 1991, Sky Catalogue 2000.0 vol. 1, 2nd ed. (Cambridge: Cambridge U. P. & Sky Publishing Corporation)

Knobel, E. B. 1917, Ulugh Beg's Catalogue of stars (1437) (Washington: The Carnegie Institution of Washington)

Kunitzsch, P. 1989, The Arabs and the Stars (London: Variorum Reprints)

Ptolemäus, C. 1986-1991, Der Sternkatalog des Almagest Die arabisch-mittelalterliche Tradition Teil I-III (AD 2 c.), translated into German and ed. P. Kunitzsch (Wiesbaden: Otto Herrassowitz)

Otero, S., Fraser, B., & Lloyd, C. 2001, International Bulletin on Variable Stars, 5026

Schjellerup, H. C. F. C. 1874, Description des étoiles fixes, reprinted in 1987 (Frankfurt am Main: Institut für Geschichte der Arabisch-Islamischen Wissenschaften)

al-Ṣūfī 986, Kitāb Ṣuwar al-Kawākib, edited in 1954 (Hyderabad: Dāiratu'l-Ma'ārif-il-'Oṣmānia)

al-Ṣūfī 986, Kitāb Ṣuwar al-Kawākib (986), facs. ed. in 1986 (Frankfurt am Main)

Toomer, G. J. 1998, Ptolemy's Almagest (AD 2 c.), translated into English and annotated by Toomer, G. J. (Princeton: Princeton U. P.)

Warner, D. J. 1979, The Sky Explored: Celestial Cartography 1500-1800 (New York & Amsterdam: Alan R. Liss, Inc. & Theatrum Orbis Terrarum, B. V.)

Werner, H., & Schmeidler, F. 1986, Synopsis der Nomenklatur der Fixsterne (Stuttgart: Wissenschaftliche Verlagsgesellschaft mbH)