Bull. Spec. Astrophys. Obs., 1996, 39, 161–163

On the problem of measurement of radial velocity

S.V. Yermakov and V.E. Panchuk

Special Astrophysical Observatory of the Russian AS, Nizhnij Arkhyz 357147, Russia

Received December 1, 1995; accepted December 7, 1995.

Abstract. Capabilities of the cross-correlation method of radial velocity measurements of cool disk and halo stars using the spectra taken with the high resolution echelle spectrometer with a CCD are analyzed.

Key words: methods: numerical – techniques: radial velocities – stars: kinematics

The wide scope of problems require radial velocity measurements of a large number of relatively faint stars. To use the classical, so called "from line to line" method (LM), of radial velocity measurements it is necessary to obtain spectra with a sufficiently high signal/noise (S/N) ratio, which would allow lines to be visually recognized and locations of their "mass centres" to be confidently measured. This restricts seriously the application of the classical radial velocity measurement method in statistical problems being solved at large and moderate size telescopes.

Fellget (1953) had proposed a method of optical cross–correlation (OCC) which was first realized by Griffin (1967). The main idea of the method is that the cross–correlation peak formed by the shift of the spectrum relative to the mask, which isolates spectral lines, is considered as generalized information about spectral lines. It contains data on the line shift in the spectrum of an object under investigation with respect to a standard object apart from the broadening parameters. It is important that less exposure time may be taken to obtain the cross–correlation peak than to record an ordinary spectrum. The optical cross–correlation method was later extended to the spectra formed in the systems with the echelle grating (Baranne et al., 1979).

The implementation of CCD allows one to realize the well known method of mathematical cross-correlation (MCC) in spectroscopic investigations and thus avoid a number of technical difficulties associated with the optical cross-correlation method. Below are presented some estimates made for CCD echelle spectra.

As original data for numerical simulation we used the spectra registered with the high resolution echelle spectrometer with a CCD (Panchuk et al., 1993). First, all the necessary procedures of an echelle frame processing were accomplished, including extraction of the spectral orders. Then for one of the spectral orders covering the interval 5550–5620Å, radial velocities were measured from individual lines. The corresponding radial velocity measurement errors $\sigma(V_r)$ (in km/s) are listed in Table 1. The atmosphere parameters for α Per (T_{eff} = 6500K, [Fe/H] = 0.0) and α CMi (T_{eff} = 6500K, [Fe/H] = −0.1) have been taken from the paper by Klochkova and Panchuk (1988) and Klochkova and Panchuk (1986), respectively, while those for HD65583 (T_{eff} = 5725K, [Fe/H] = −0.3) and HD122563 (T_{eff} = 4600K, [Fe/H] = −2.6) have been determined by the model atmosphere method. In the fifth column of Table 1 are presented the estimates of radial velocity error σ_e when measuring the lines in all simultaneously registered spectral orders (to simplify the estimation we have assumed that 25 orders are registered and the lines suitable for measuring are distributed evenly with the orders). Note that the estimates obtained in such a way are close to the accuracy of radial velocities of subdwarfs (0.1 – 0.2 km/s, (Klochkova and Panchuk, 1995)) and high luminosity stars (0.4 km/s, (Klochkova, 1995)) obtained with the same spectrometer but within a longer wavelength range, where the number of the lines being measured is smaller.

After that the orders obtained from the echelle spectrum were simulated with noise up to $S/N = 20$ and 10. In spectra obtained in this way radial velocities were measured from individual lines as well. The results of the $\sigma(V_r)$ measurements and σ_e estimates are tabulated in the last four columns of Table 1.

Then the cross–correlation method of radial velocity measurement was simulated. For this purpose the "sample spectrum" registered in the mentioned spectral order was shifted by the specified value and the gaussian noises were added randomly to the spectrum. The "spectrum of an object" obtained in this way was analyzed together with the "sample" one. The cross–correlation function was computed by convolution of the two spectra in the coordinates "in-

Table 1: *On the accuracy of radial velocity determination by measuring individual lines*

	S/N					
	>100		20		10	
	$\sigma(V_r)$	σ_e	$\sigma(V_r)$	σ_e	$\sigma(V_r)$	σ_e
αPer	0.35	0.07	0.99	0.20	1.01	0.20
αCMi	0.61	0.12	0.89	0.18	0.84	0.17
HD65583	0.58	0.12	1.51	0.30	0.66	0.13
HD122563	1.01	0.20	1.78	0.36	1.63	0.33
Mean		0.13		0.26		0.21

Table 2: *On the accuracy of radial–velocity determination by the cross–correlation method*

		S/N					
		100	50	20	10	5	3
αPer	$\sigma(V_r)$	0.07	0.18	0.43	0.84	1.88	1.67
	σ_e	0.01	0.04	0.09	0.17	0.38	0.33
αCMi	$\sigma(V_r)$	0.06	0.09	0.31	0.63	1.33	2.20
	σ_e	0.01	0.02	0.06	0.13	0.27	0.44
HD65583	$\sigma(V_r)$	0.06	0.09	0.18	0.45	0.63	2.58
	σ_e	0.01	0.02	0.04	0.09	0.13	0.52
HD122563	$\sigma(V_r)$	0.12	0.14	0.46	0.89	1.44	5.62
	σ_e	0.02	0.03	0.09	0.18	0.29	1.12
Mean	σ_e	0.02	0.03	0.07	0.14	0.26	0.60

Table 3: *On the accuracy of radial velocity measurement by the cross-correlation and classical methods with the echelle spectrometer LYNX. The slit width is 1 arcsec, seeing is 2 arcsec. Data for the optical cross-correlation method are also presented*

t, *min*	$\sigma_e, km/s$							Method
15	0.02	0.03	0.05	0.14	0.29	0.71		MCC
60			0.02	0.03	0.08	0.20	0.49	MCC
15	0.12	0.15	0.19	0.26				LM
60		0.11	0.13	0.16	0.23			LM
15-20					0.83	1.22		OCC
m_V	9	10	11	12	13	14	15	

tensity — lnλ". A more detailed method of cross–correlation radial velocity determination is described by Tonry and Davis (1979), but the measurement error $\sigma(V_r)$ we determined in other way, namely, by comparison of the results over the 20 independent simulations of the "spectrum of the object". The results are presented in Table 2. Here σ_e is the error of cross-correlation radial velocity measurement made over the 25 spectral orders of the model. It follows from the table that the relations between σ_e and S/N are sensitive to both the differences in macroturbulent broadening of the disk stars' lines (αPer and αCMi) and the differences in metallicity (HD122563 and HD65583).

Consider the estimation of the limiting magnitude of the method. In order to simplify this we use the values of σ_e averaged over four stars. Given the magnitudes m_v as a function of S/N for the fixed exposure time determined by Klochkova (1995a), transform it into the m_v as a function of the $\sigma(V_r)$ for the two values of the exposure time t using the averaged dependence of σ_e on S/N (see Table 2). The results are given in Table 3. The results of estimation of the limiting magnitude of the classical radial velocity measurement method, which were obtaned with the data from Table 1, are presented in Table 3 as well.

The capabilities of the optical cross-correlation method are also presented in Table 3. A statistical analysis of the data from Table 2 (see Gunn and Griffin, 1979) shows that given the 15–20 min exposures at the coude focus of the 5-m telescope, the mean error of radial velocity measurements was 0.83 and 1.22 km/s for the stars of 13 and 14 magnitude, respectively.

One can see that with equal requirements to the radial velocity measurement accuracy the difference between the methods of optical and mathematical cross–correlation at the weak side of the limiting magnitude curve is more than one magnitude in favour of the latter.

Considering bright side of the curve one should remember that the accuracies given in Table 3 characterize the mathematical part of the method, while the final accuracies may not be provided by the calibration accuracy of the radial velocity of a standard star. For example, the final accuracy of the optical cross–correlation method used by Gunn and Griffin (1979) cannot be better than 0.25 km/s – the accuracy of the radial velocity measurement of the standard star HD126778 ($m_v = 8.2$).

In the present paper the random errors of the radial velocity measurement, which are associated with S/N ratio, were investigated. It should be noted that there is a number of other sources of errors, both random and systematic, which are not considered here. In particular, when measuring radial velocities from individual lines, one should take into account the errors in the original effective wavelengths of stellar lines.

The conclusions of this paper are valid for the case when the widths of spectral lines are close to that of the instrumental function peak of the spectrometer. Other cases and the problems of the accuracy improvement of the calibration with velocity standards as well as possible systematic errors and account of them will be considered in the next paper.

Acknowledgements.
The authors thank V.G.Klochkova and E.L.Chentsov for the helpful discussion of the results. The work has been

supported by the Russian Foundation of Fundamental Research (project RFFR N95-07-19306).

References

Baranne A., Mayor M., Poncet J.L.: 1979, Vistas in Astronomy, **23**, 279.
Felget P.: 1953, Optica Acta, **2**, 9.
Griffin R.F.: 1967, Astrophys. J., **148**, 465.
Gunn J.E., Griffin R.F.: 1979, Astron. J., **84**, No.10, 752.
Klochkova V.G.: 1995, Mon. Not. R. Astron. Soc., **272**, 710.
Klochkova V.G.: 1995a, SAO technical report No.243, 39.
Klochkova V.G., Panchuk V.E.: 1986, Pis'ma Astron. Zh., **12**, 446.
Klochkova V.G., Panchuk V.E.: 1988, Pis'ma Astron. Zh., **14**, 77.
Klochkova V.G., Panchuk V.E.: 1995 in: The light element abundances, Proc. ESO/EIPC Workshop, ed.: P.Crane, Springer, 328.
Panchuk V.E., Klochkova V.G., Galazutdinov G.A., Ryadchenko V.P., Chentso E.L.: 1993, Pis'ma Astron. Zh., **19**, 1061.
Tonry J., Davis M.: 1979, Astron. J., **84**, 1511.