CHROMOSPHERIC AND TRANSITION REGION DYNAMICS – REASONS AND CONSEQUENCES OF THE LONG-PERIOD INSTRUMENTAL PERIODICITIES OF SUMER/SOHO

J. Rybák[1], W. Curdt[2], A. Kučera[1], U. Schühle[2], H. Wöhl[3]

[1]Astronomical Institute of the Slovak Academy of Sciences, SK-05960 Tatranská Lomnica, Slovakia
[2]Max-Planck-Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany
[3]Kiepenheuer-Institut für Sonnenphysik, D-79104 Freiburg, Germany

ABSTRACT

The instrumentally caused periodicities of the spectral line Doppler velocities, determined with the SUMER spectrometer onboard SOHO, are presented. On long-term measurements of O I, C II and O VI lines, originating in the upper solar atmosphere, it is shown that the reason of these periodicities was the slight changes of the SUMER mechanical structure. Comparison with the housekeeping heating and temperature data shows that these so-called "thermoelastic oscillations" are caused by the changes of the internal SUMER temperature within the range of ±0.15 K as it is controlled by the heaters in a closed loop.

Consequences of this instrumental effect for the SUMER measurements of the chromospheric and transition region spectral lines are discussed. A procedure how to calibrate the effect from the data post-facto is proposed and it is applied to the particular SUMER data set.

Key words: Sun: transition region – Sun : chromosphere – instrumentation: SUMER.

1. INTRODUCTION

One of the principal scientific objectives of the SOHO mission is the study of heating mechanisms of the upper solar atmosphere including the transition region and the corona. Some of the previously proposed mechanisms are based either on the wave transport of the energy from the convective layers up to the corona, where it should dissipate to heat the plasma, or by the reconnection processes of different scales taking place directly in the corona. Some of such waves/reconnections should be detected by observations when the actual properties of the particular waves 'fit' with the resolutions and sensitivity of the used instruments. Then the spatially resolved spectral line profile changes or the spatially unresolved spectral line profile broadening should be observed.

Several SUMER observations of the oscillations, especially in the chromosphere and the transition region, have been performed up to now. The first results were already published from measurements of the emission lines and continua, taken in the quiet solar atmosphere (Wikstøl et al., 1999, Muglach and Fleck, Barnejee et al., 1999 and the list of references in Rybák et al., 1999). Other studies of the quiet solar atmosphere have been focused on the average Doppler shifts of lines and/or at the unresolved mass motions manifesting in the non-thermal line broadening of the emission lines, originating in the transition region and in the corona (e.g., Chae et al., 1998a, Brekke et al., 1998, Chae et al., 1998b, Erdélyi et al., 1998, Peter, 1999, Teriaca et al., 1999).

Working with our SUMER data (emission line profiles originating in the chromosphere and the transition region), we have noticed an instrumental effect which could potentially influence the obtained results. Therefore the aim of this paper is to introduce this effect to the users of the SUMER data as well as to propose the way how to overcome the data quality degradation post-facto.

2. INSTRUMENT

The SUMER spectrometer was prepared for the SOHO mission in order to investigate processes over the temperature range from 10^4 to 2×10^6 K with the ability to measure in detail the line profiles originating in the chromosphere, the transition region and in the inner corona. High spatial, spectral and temporal resolutions of SUMER in the UV range of the solar spectrum made the instrument very suitable for the determination of the motion and broadening signatures of the spectral line profiles in the upper solar atmosphere. SUMER is a high-resolution normal-incidence spectrometer, described in detail by Wilhelm et al. (1995). Summaries of its in-flight performance were presented in papers of Wilhelm et al. (1997), Lemaire et al. (1997) and Wilhelm (1997). The high practical spectral resolution was confirmed by the in-flight measurements of the narrowest lines with the FWHM of only 86 mÅ as like as the clear separation of the H I Ly line series up to member 19 and 20 (Wilhelm et al., 1997) The spectral scale of the spectrometer is around 44 and 22 mÅ/px in the first and second diffraction order respectively. The exposure times are dictated by both, telemetry constraints, and the solar photon input. The typical exposure times of the order of 10 s are required for the for the appropriate profile determination of the most pronounced spectral lines originating in the chromosphere and the transition region.

The spectrometer was designed to work in the thermal equilibrium close to the nominal temperature of 20 °C using the additional heating of the mechanical structure to compensate the heat losses (Wilhelm et al., 1995). Due to the technical reasons it was forced after the launch of SOHO to perform several reaction changes to bring SUMER into a stable thermal configuration around 23°C. No drifts of the optical system caused by thermal effects were reported as it was possible to control the instrument compartment temperature to within ±0.05 °C (Wilhelm et al., 1997).

3. DATA

The instrumental effect was analyzed in the SUMER data set acquired on 7 Sept 1996 ($7^h53^m45^s$ – $11^h47^m45^s$). The set is a long time series of 929 spectral images around the following emission lines : O I 1027.43 Å, C II 1037.02 Å and O VI 1037.61 Å. All spectral images were taken simultaneously with the integration time of 15 s and they were telemetry limited. Data were acquired on the central part of the detector A. The entrance 1"×120" slit of the spectrometer was oriented in the NS direction. Its position in the EW direction was shifted step by step 28 times in order to follow the rotational motion of the selected target on the solar disk in the range from 4.5" to 39.88". The standard compensation scheme was used for this purpose. The quiet sun area very near the disk center was selected including two supergranular boundaries crossing the slit. More details on the data can be found in papers of Curdt et al. (1997a, 1997b).

For this paper information on action of the SUMER heaters and the SUMER thermistor records, which are used to keep the internal temperature of the spectrometer constant, were obtained from the housekeeping SUMER data. The cadence of these housekeeping data is 45 s.

4. DATA REDUCTION

The basic data reduction was performed with help of the standard SUMER reduction procedures.[1] All data have been decompressed according to the compression algorithm applied onboard. Relative sensitivity of the detector pixels was taken into account using the deep flat-field data obtained on 11 Sept 1996. Aberrations of the spectral images were corrected using the available destretching algorithm with its auxiliary data. A slight residual curvature of the spectral lines still exists after this correction, but it is stable during the run. It does not affect the results and conclusions of this paper. Data were also converted to the absolute units using the available radiometry procedure. In order to decrease the random noise the spatial binning of 2 pixels (2.02") was applied along the slit length. Due to the internal vignetting of the spectral images the spatial dimension of the final spectral images was truncated to 43 binned pixels (86.86"). Finally each spectral profile in the data sets was fitted using a simple Gaussian profile and a linear background. The CFIT algorithm of S. Haughan was used for the fitting calculations[2]. The profiles of C II and O VI lines were fitted together. Relative weightening of the data was applied in each spectral profile. Data were weighted according to the reciprocal square of their relative intensity. Few fitting results were omitted from the investigation due to very large χ^2 values.

5. SUMER THERMOELASTIC PERIODICITIES

Overcoming some initial technical problems after the lounch of SOHO the SUMER spectrometer has been brought into the a stable thermal configuration around 23°C. The spectrometer compartment temperature is being controlled to within ±0.15 K (Wilhelm et al., 1997). Nevertheless, later Curdt et al. (1997a) detected a drift of the whole spectral image in the direction of the dispersion. The drift was named *the thermoelastic oscillations (TEOs)* of the SUMER mechanical structure. This drift was later found also by Dammasch et al. (1999), Peter (1999) as well as by Muglach and Fleck (1999). In all cases there were periodic drifts with the amplitude up to pixel size (26 μm) and the period of 1–2 hours. In these papers the thermoelastic oscillations were interpreted as the manifestation of the weak time dependent mechanical deformation of the spectrometer mechanical structure due to the slight temperature variations. However no direct comparison of the image drift with the action of heaters and the thermistors records has been made up to now.

Therefore we have decided to verify the conclusions of the previous papers. We coupled the 'spectral image drift data' with the action of heaters and the thermistors records. The records of the working regimes of the three available heaters and the records of three thermistors for the period of our data set are plotted in Fig.1. Actually heater A is placed at the front of the SUMER compartment, where the entrance aperture, slit with collimator and the detectors are placed, heater B is situated in the middle of the compartment and heater C is near the rear of the instrument with the main mirror and the grating (see Fig.2 in Wilhelm et al., 1995). The heaters are realized by a pair of resistors placed symmetrically on left and right sides of the compartment (A and C heaters) and along the instrument central axis (B heater). All heaters are operated with constant power and a heater cycle has a length of 10 ticks. The full time operation of a heater (10 thicks) is given by the duty cycle value of 10. The heater "off" (0 thicks) gives the duty cycle value 0. Values in between these extremes represent the fraction of time when the heater was "on" (e.g., 5 means that the heater was in operation for 5 ticks).

[1]These can be found for example at http://www.linmpi.mpg.de/english/projekte/sumer/text/cookbook.html

[2]CFIT description is available at http://orpheus.nascom.nasa.gov/cds/home/swnotes/

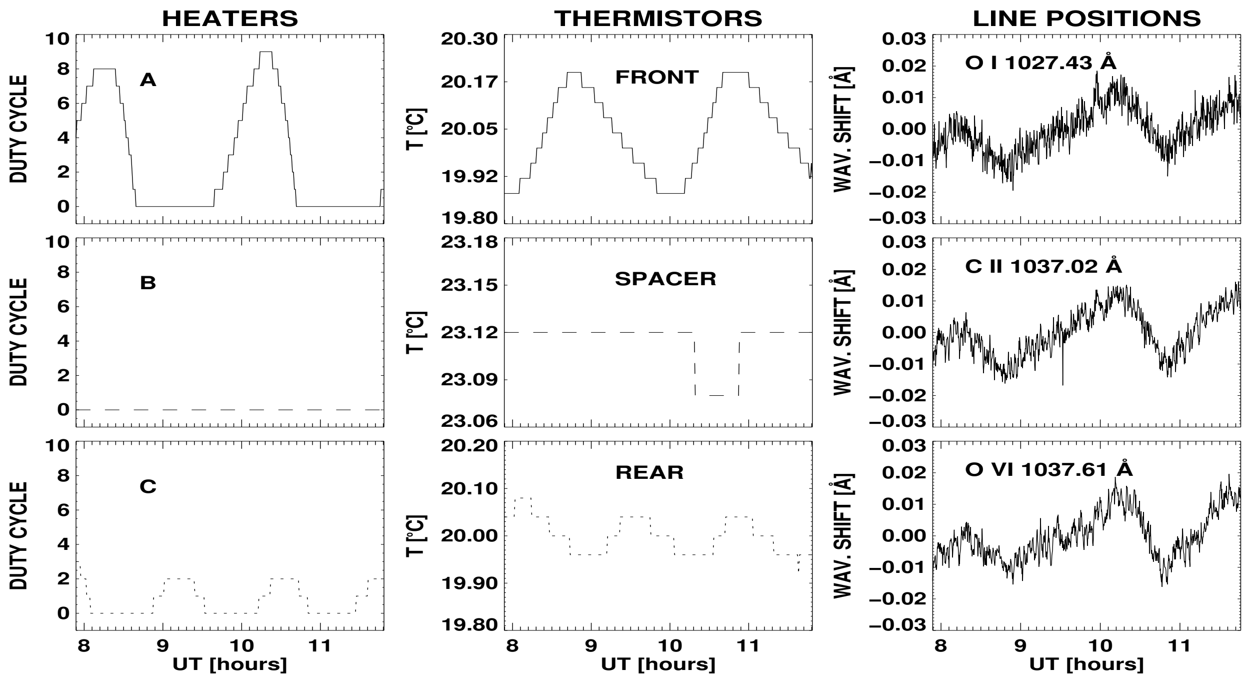

Figure 1. The plots of the heaters duty cycles (left column), the thermistors records (middle column) and the overall line drifts, determined as an average along the whole slit length. The particular heaters, thermistors and spectral lines are marked in each panel.

The front, spacer and rear thermistors are situated in areas represented by their names relatively near the heaters along the instrument central axis. The spacer heater was "off" for the whole period of our data set acqusition. Correlations of the thermistors records and the heaters duty cycles are with the delay of the temperature records for 37 minutes (front) and 21 minutes (rear). The possible coupling of the front and rear heaters action was also tested but no significant correlation was found. The overall line drifts of all three spectral lines were calculated. They were computed as the mean spectral line position averaged over all individual line positions along the slit for the whole time interval of our measurements. The temporal variations of the overall line drifts are plotted on the right side of Fig.1. The 1σ uncertainties of these mean line positions are stable during the whole run, typically of about 0.01 Å. The significant part of this uncertainty is caused by the residual curvature of lines. As the overall line drifts of all particular lines display similar behaviour, an overall spectral image drift of the whole spectral image was calculated as a mean of all three overall line drifts.

This overall spectral image drift was correlated with the duty cycle of each heater and the record of each thermistor. The periodic behaviour of these correlations, presented in Fig.2, confirm the causal relation between the thermal control of the instrument and the drift of the whole spectral image in the direction of the dispersion. The correlation coefficient would be increased up to the level of ± 0.7 if the overall spectral image drift is smoothed in order to decrease its noise contribution. In particular, the most pronounced correlation was found between the overall spectral image drift and the front (A) heater action with the image drift delayed for roughly 10 minutes. This heater is controlled by the front thermistor which outruns the image drift for 50 minutes. Less pronounced is the relation between the overall spectral image drift and the rear (C) heater with the image drift delay of 20 minutes. Here the rear thermistor record outruns the image drift for about 30 minutes. The last correlation between the image drift and the spacer thermistor, plotted in Fig.2, can not be taken into account as the change of the temperature is very small and the spacer (B) heater has not

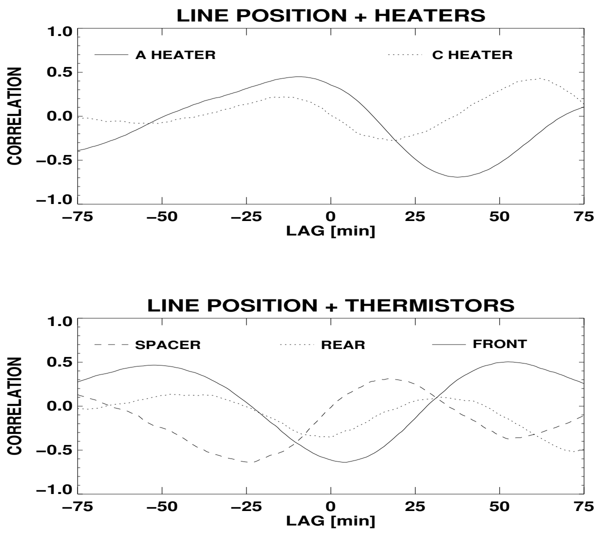

Figure 2. Correlations of the duty cycles of the particular heaters (upper panel) and the thermistors records (bottom panel) with the overall spectral image drift. Different line types correspond to those used for the particular plots of heaters duty cycles and thermistors records in Fig.1.

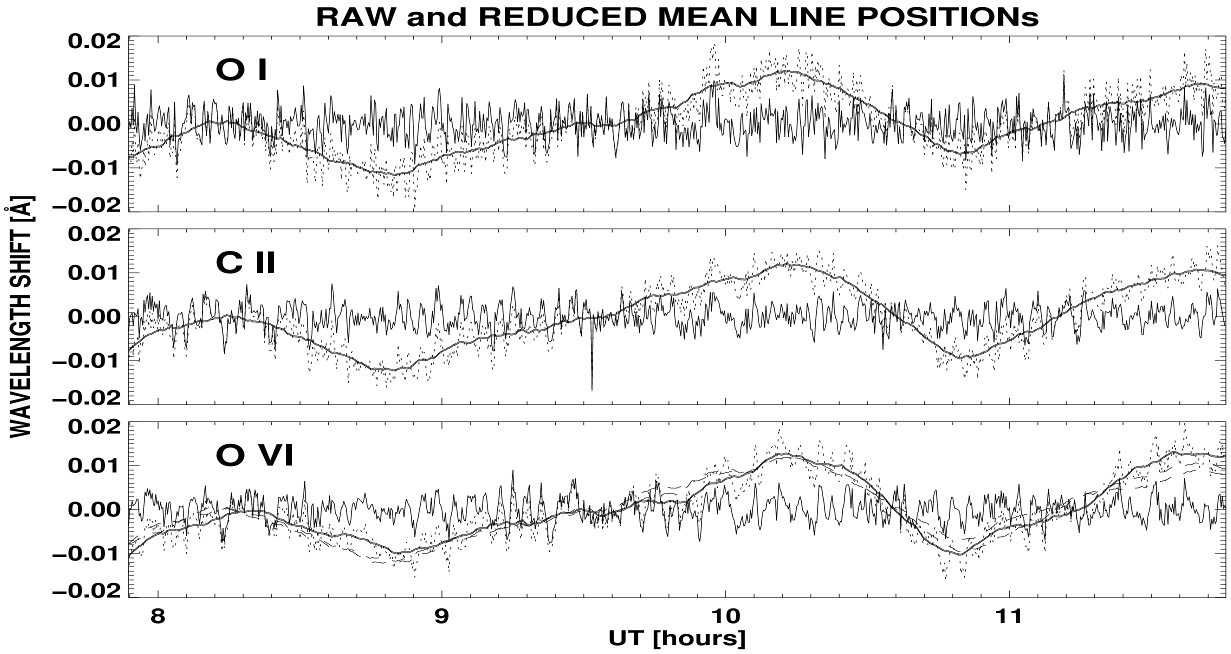

Figure 3. The plots of the raw mean line positions of O I, C II and O VI lines /the same as in the right column in the Fig.1/ are given here by the wiggly dashed lines. The plots of the smoothed line drift are displayed with the overlaying thick solid lines and the corrected mean line positions are plotted using the thin solid lines. In the bottom panel the smoothed line drifts of O I and C II lines are reploted (dashed lines) for a better comparison with the line drifts of O VI line. The vertical ranges of panels represent roughly the linear width of 1 detector pixel (26 μm), which represent the Doppler velocity shift of approximatively 13 km/s for these spectral lines.

been switched "on" with this change of the spacer temperature. The real solar line wavelength shifts, most pronounced in the 'hottest' O VI line on the supergranulation boundaries, decrease level of correlation between the parameters of the instrument thermal control and the overall spectral image drift. Nevertheless, the direct coupling of the SUMER thermoelastic oscillations and the overall spectral image drift is documented without any doubt.

6. THE CORRECTION PROCEDURE

The thermoelastic oscillations affect the long time series of the spectral images, acquired with rather short exposures, used to the oscillations studies. Additionally measurements with longer exposures (e.g., spectra of very weak lines taken above the solar limb, 2D spatial averages of many spectra on the solar disk) can be influenced as well.

In case of short exposures it is possible to subtract the overall spectral image drift from the acquired spectral images. At first the average position of each spectral line has to be calculated over the slit as long as possible. On the other hand it is reasonable to exclude from this averaging those parts of the slit, where the largest short-period variations of the line position are detected (probably the supergranular network). The positions of several lines can be added to prepare the overall spectral image drift. At this point the overall spectral image drift can be compared with the action of the instrument heaters. If their correlation is found the data have to be corrected for the overall spectral image drift. The simplest way how to do it is to smooth at first the constructed overall spectral image drift in order to smear out real short-period wavelength shifts of solar origin. Smoothing parameters should be adjusted in such a way that no significant side effects will affect the real solar velocity changes in further reduction. Finally all line shifts can be corrected for the thermoelastic oscillations subtracting the smoothed overall spectral image drift. This approach has been already applied in works of Curdt et al. (1997a), Rybák et al. (1999), Dammasch et al. (1999) and partially by Peter (1999).

The results of such procedure, applied to our data set, are displayed in Fig.3 for all three spectral lines. In this case the running mean of 60 raw data (900 s) was used for the smoothing on the time scale. Here the overall image drift drift was replaced by the separate overall spectral line drifts of each line to document possible differences which could be caused by the intrinsic solar variability of the individual spectral lines. The residual differences between the smoothed overall spectral line drifts are less than 5 mÅ (1-2 km/s) and this level can be used as the upper limit of the residual wavelength shift error of this thermoelastic ocsillations reduction. The repeated comparison of the SUMER thermal control parameters and, in this case, the overall line drifts corrected for the TEOs showed correlation coefficient lower than 0.1 for the whole lag interval ±75 minutes what is much less than the levels of correlations with the raw overall spectral image drift (Fig.2). The other way how to correct for the thermoelastic oscillations in case of long time series acquired for the oscillations studies is to filter out the false instrumental wavelength shift signal by a suppression of the amplitudes at low frequencies in the wavelength shift power spectra.

7. DISCUSSION

The thermoelastic oscillation play important role also if one adds many SUMER spectral images taken over a long time interval (e.g., to acquire a spatially averaged spectra with high S/N ratio). Here one will get the shifted line positions as well as the additionally broadened line profiles due to the effect of the TEOs. In this case the instrumentally caused line shifts can be corrected using the dispersion relation, constructed from the cooler chromospheric lines as they are affected in the same way. However the line broadening, caused by the thermoelastic oscillations, could still remain. The possible solution of this problem for the studies, which need very precise spectral line profiles taken with the long integration time, is to follow the procedure originally used by Dammasch et al. (1999). They took many short exposures, in fact taken over an 2D area, and performed the photometric reduction and the subtraction of the thermoelastic oscillations from the wavelength shifts of the individual spectral images. Only then they added the separate spectral line profiles. This approach would prevent against the additional broadening of the lines by the thermoelastic oscillations.

The influence of the thermoelastic oscillations on the line broadening can be documented on the example of our data set. The mean line profile widths (FHWM) were calculated from the line profiles averaged over the whole time interval in each of 43 positions along the slit. This was done separately for the line profiles before and after the correction of the thermoelastic oscillations effect. The comparison of these results are shown in Fig.4. The results, derived from the corrected line profiles, are systematically lower than the results coming from the raw line profiles. The absolute differences of the FWHMs are increasing from roughly 4 mÅ for the strongest O VI line through 6 mÅ for C II line up to 12 mÅ in case of the weak O I line.

Let us manifest the effect of the SUMER thermoelastic oscillations also in the term of the non-thermal line broadening. At first all measured line widths were corrected for the instrumental line broadening using Gaussian approximations of the measured lines and the instrumental broadening itself. [3] Then assuming that all the line emission is originating at the peak ionization temperature of the each ion of O I, C II and O VI, the measured line widths have been converted to the non-thermal velocity broadening of the lines following the common formula

$$\xi = \sqrt{\frac{(FWHM)^2 c^2}{4.ln2.\lambda^2} - \frac{2kT}{M}}, \qquad [km/s]$$

where ξ is the most probable nonthermal velocity and c, λ, k, T, M stem for the speed of light, the line wavelength, the Boltzman constant, the ion tempreraturе

[3]The procedure is available at http://www.linmpi.mpg.de/english/projekte/sumer/text/cookbook.html.

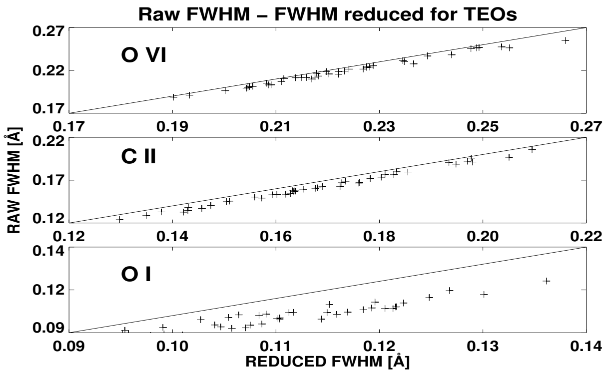

Figure 4. Comparison of the raw line widths and the corrected line widths (in term of FWHM) for the investigated O I, C II and O VI lines. These results are not corrected for the instrumental broadening of the spectral lines caused by the instrumental profile of the SUMER spectrometer.

and the ion mass (e.g., Mariska, 1992). Comparing now the calculated non-thermal velocities between the raw line widths and the widths corrected for the TEOs effect, the absolute differences were found to be 0.8, 1.5 and 5.0 km/s for O VI, C II and O I lines respectively (Fig.5). The relative differences of the raw and the corrected non-thermal velocities so start from the level of 2-3 % for O VI line, continue with 4-6 % for C II line and reach 35-75 % in case of the very narrow O I line.

These illustrations show that the non-thermal broadening of the lines, measured over the long time interval, could be determined only whith the SUMER thermoelastic oscillations taken into account. Otherwise the results could be selectively affected in the way that the more narrow lines (like our O I line) are instrumentally broadened much more than broader lines (e.g., O VI line). Of course, the significance of the effect depends on the parameters of the particular

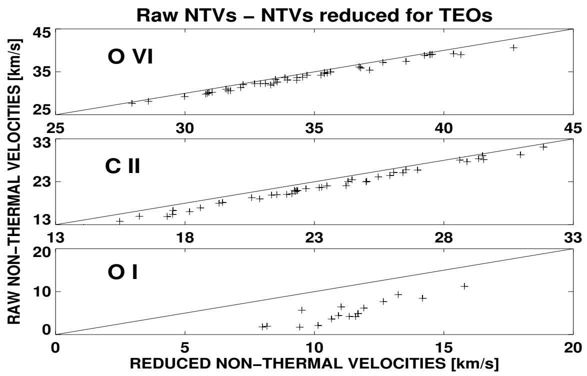

Figure 5. Comparison of the raw non-thermal line broadening and the non-thermal line broadening, corrected for TEOs effect, for the O I, C II and O VI lines. These data are already corrected for the SUMER instrumental line broadening. Some O I line results are omitted as the measured line widths were bellow the lower limit of the applied correction procedure.

measurement (e.g., the actual heating of the instrument, the line selection, the total integration time). Some studies have already reported about the correct procedure used for the elimination of the SUMER thermoelastic oscillations effect before the determination of the spectral line wavelength shifts (Dammasch et al., 1999, Peter, 1999).

8. CONCLUSIONS

The detailed investigation of the SUMER long data set have shown that any particular data of the line wavelength shifts and the line widths can be affected by the thermoelastic oscillations of the SUMER mechanics. The thermal balance control of the SUMER spectrometer was documented as the reason of this thermoelastic oscillations effect. Therefore the thermal control of the spectrometer should be checked whether the thermoelastic oscillations have drifted the spectral image in the direction of the dispersion during SUMER observations. This is not only the case of the long-term measurements of oscillations studies but also other measurements taken over the extended period of time of a couple of hours. The described correction procedure allows to calibrate the thermoelastic oscillations effect and to eliminate potential artifacts in the determined spectral line shifts and widths.

9. REMARK

The same effect was found also in other long period SUMER data set acquired on May 14, 1998. In this case the slit width has been changed to 0.3" and the bottom part of the detector B has been used. More details will be given in a paper of Curdt et al. (1999).

ACKNOWLEDGMENTS

SOHO is a project of international cooperation between ESA and NASA. The SUMER project is financially supported by DLR, CNES, NASA, ESA and PRODEX (Swiss contribution). Additional support was provided by the participating institutions. A.K. and J.R. are grateful to the GA SAV (Slovakia) for partial supporting of this work (grant No. 2/4154/99). A.K. thanks for support of the bilateral German-Slovak scientific-technical cooperation project X261.1. J.R.'s work was supported also by the DFG grant 436 SLK 17/2/98 (Germany).

REFERENCES

Banerjee, D., Doyle, J.G. and O'Shea, E.: 1999, in : *Eighth SOHO Workshop 'Plasma Dynamics and Diagnostics in the Solar Transition Region and Corona'*, ed. B.Kaldeich, ESA SP-446, in press

Brekke, P., Hassler, D.M. and Wilhelm, K.: 1997, *Solar Phys.* **175**, 375

Chae, J., Yun, H.S., and Poland, A.: 1998a, *Astrophys. J. Supp. Series* **114**, 151

Chae, J., Schühle, and Lemaire, P.: 1998b, *Astrophys.J.* **505**, 957

Curdt, W., Kučera, A., Rybák, J., Schühle, U., and Wöhl, H.: 1997a, in : *Fifth SOHO Workshop 'The Corona and the Solar Wind near Minimum Activity'*, ed. A.Wilson, ESA SP-404, 307

Curdt, W., Kučera, A., Rybák, J., Schühle, U., and Wöhl, H.: 1997b, in : *1st Advances in the Solar Physics Euroconference : 'Advances in the Physics of Sunspots'*, eds. B.Schmieder, J.C. del Toro Iniesta, M.Vázquez, ASP Conf. Ser., **118**, 322

Curdt, W., Kučera, A., Rybák, J., Schühle, U., and Wöhl, H.: 1999, in preparation for Solar Physics

Dammasch, I.E., Wilhelm, K., Curdt, W., and Hassler, D.M.: 1999, *Astron. Astrophys.* **346**, 285

Erdélyi, R., Doyle, J.G., Perez, M.E., and Wilhelm, K.: 1998, *Astron. Astrophys.* **337**, 287

Lemaire, P., Wilhelm, K., Curdt, W., Schühle, U., Marsch, E., Poland, A. I., Jordan, S. D., Thomas, R. J., Hassler, D. M., Vial, J.-C., Kühne, M., Huber, M. C. E., Siegmund, O. H. W., Gabriel, A., Timothy, J. G., and Grewing, M.: 1997, *Solar Phys.* **170**, 105

Mariska, J.T.: 1992, *The Solar Transition Region*, Cambridge University Press, Cambrigde

Muglach, K. and Fleck, B.: 1999, in : *Eighth SOHO Workshop 'Plasma Dynamics and Diagnostics in the Solar Transition Region and Corona'*, ed. B.Kaldeich, ESA SP-446, in press

Peter, H.: 1999, *Astrophys.J.* **516**, 490

Rybák, J., Curdt, W., Kučera, A., Schühle, U., and Wöhl, H.: 1999, in : *Eighth SOHO Workshop 'Plasma Dynamics and Diagnostics in the Solar Transition Region and Corona'*, ed. B.Kaldeich, ESA SP-446, in press

Teriaca, L., Banerjee, D., Doyle, J.G., Erdélyi, R.: 1999, in : *Eighth SOHO Workshop 'Plasma Dynamics and Diagnostics in the Solar Transition Region and Corona'*, ed. B.Kaldeich, ESA SP-446, in press

Wikstøl, Ø., Hansteen, V., Carlsson, Judge, P.G.: 1999, in : *Eighth SOHO Workshop 'Plasma Dynamics and Diagnostics in the Solar Transition Region and Corona'*, ed. B.Kaldeich, ESA SP-446, in press

Wilhelm, K., Curdt, W., Marsch, E., Schühle, U., Lemaire, P., Gabriel, A., Vial, J.-C., Grewing, M., Huber, M. C. E., Jordan, S. D., Poland, A. I., Thomas, R. J., Kühne, M., Timothy, J. G., Hassler, D. M., and Siegmund, O. H. W.: 1995, *Solar Phys.* **162**, 189

Wilhelm, K., Lemaire, P., Curdt, W., Schühle, U., Marsch, E., Poland, A. I., Jordan, S. D., Thomas, R. J., Hassler, D. M., Huber, M. C. E., Vial, J.-C., Kühne, M., Siegmund, O. H. W., Gabriel, A., Timothy, J. G., Grewing, M., Feldman, U., Hollandt, J., and Brekke, P.: 1997, *Solar Phys.* **170**, 75

Wilhelm, K.:, 1997, in : *Fifth SOHO Workshop 'The Corona and the Solar Wind near Minimum Activity'*, ed. A.Wilson, ESA SP-404, 17