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Calibration of TRACE Lyman-α images using SOHO/SUMER observations *(Research Note)*

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ABSTRACT

1216 Å channel images from the *Transition Region and Coronal Explorer* (TRACE) contain not only the desired HI Lyman-α (Lα) line emission from the Sun, but also some UV continuum around 1600 Å. By comparing TRACE data with Lα images from the *Very High Angular Resolution Ultraviolet Telescope*, Handy et al. proposed a simple procedure to remove the contamination: a linear combination of 1216 Å and 1600 Å channel images from the TRACE. In order to check the reliability of this procedure, here we compare TRACE data with Lα raster scan images from the SUMER instrument onboard the *Solar and Heliospheric Observatory* (SOHO). We obtain a linear combination coefficient very similar to that of Handy et al., and also find that the apparent spatial resolution of the Lα raster scan images from SOHO/SUMER is at least $4'' \times 4''$, which is more than 2–4 times lower than that of its single spectrum.

Key words. Sun: UV radiation – Sun: chromosphere – Sun: transition region

1. Introduction

The *Transition Region and Coronal Explorer* (TRACE; Handy et al. 1999a), launched in April 1998, has collected a vast number of HI Lyman-α (Lα) images of the Sun with a high spatial (1 arcsec) and a temporal (few seconds) resolution. HI Lα at 1216 Å is one of the brightest emission lines formed in the chromosphere and the transition region, thus it is a natural tracer of solar activity in those regions. Lα images from TRACE can be used to study the morphology and evolution of active regions on the Sun as well as the variability of solar irradiance.

The 1216 Å images obtained with TRACE, however, contain not only the desired line emission, but also some UV continuum near 1600 Å and at longer wavelengths. This contamination, known prior to launch, is due to a rather broad double peak in spectral response of the Lα channel with one peak located at ~1216 Å and a second peak at ~1550 Å (see Fig. 1 of Handy et al. 1999b). This unusual spectral response of the 1216 Å channel is a result of a narrowband UV coating on the primary mirror at 1500 Å combined with a filter centered at 1216 Å.

Handy et al. (1999b, H99b hereafter) have provided a simple method to remove this contamination by using a large number of solar irradiance data samples from the *Solar-Stellar Irradiance Comparison Experiment* (SOLSTICE; Rottman et al. 1993), and by comparing TRACE 1216 Å images with a Lα image from the *Very High Angular Resolution Ultraviolet Telescope* (VAULT; Korendyke et al. 2001) sounding rocket flight of May 7, 1998. H99b assumed that a pure Lα intensity can be obtained by a linear combination of TRACE 1216 Å and 1600 Å channels:

$$I_{\mathrm{L}\alpha} = A \times I_{1216} + B \times I_{1600}. \tag{1}$$

Here, $I_{\mathrm{L}\alpha}$ is the intensity of the pure Lα emission line, I_{1216} and I_{1600} are the intensities as observed with TRACE 1216 Å and 1600 Å channels, respectively, and A and B are the fitting parameters. Coefficient A is expected to be near unity, while coefficient B is expected to be negative because I_{1216} is contaminated by the UV continuum, which can be well represented by I_{1600}.

To obtain an initial guess for A and B, H99b first used the SOLSTICE database of solar spectra covering a wide range of solar activity. They convolved a large set of SOLSTICE spectra with TRACE 1216 Å and 1600 Å channel response functions to obtain synthetic I_{1216} and I_{1600} values, and integrated the same set of spectra along the Lα emission line profile to obtain $I_{\mathrm{L}\alpha}$ values. A least-squares regression was then applied to these intensities to find best-fit coefficients of $A = 0.97$ and $B = -0.14$.

To further improve the coefficients, they then compared TRACE observations with a VAULT Lα image. For I_{1216} and I_{1600} values in equation (1), they used the pixel intensities of TRACE 1216 Å and 1600 Å images, while for $I_{\mathrm{L}\alpha}$ values, they used the pixel intensities of a VAULT Lα image assuming that the VAULT Lα image is not contaminated by non-Lα emission (the Lα filter of the VAULT has a bandpass of 150 Å). Fixing the coefficient A to be the value obtained from the SOLSTICE spectra, 0.97, they found that $B = -0.105$ results in the highest

Spearman's rank correlation (r_s, Press et al. 1992) between both sides of Eq. (1).

As noted by H99b, it is desirable to confirm the reliability of this correction method by comparing TRACE images with other observations. In the present work, we extend the work of H99b by cross-calibrating TRACE Lα images with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER; Wilhelm et al. 1995) instrument onboard *Solar and Heliospheric Observatory* (SOHO).

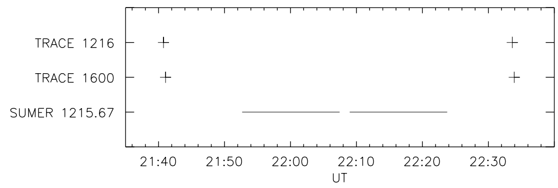

Fig. 1. Epochs and durations of the images analyzed in the present study. The integration times of the TRACE observations are too short to be shown in the plot, and those observations are denoted with crosses.

2. The data

We have searched the SUMER data archive for Lα raster scan images that were observed within a few tens of minutes from the epoch of any TRACE 1216 Å images with an observed region overlapped, and found only two cases: images SUM_990603_215302 and SUM_990603_220846.

SUM_990603_215302[1] was acquired from 21:52:40.5 to 22:07:27.3 UT of June 3rd, 1999, and is centered at (X = +480.3″, Y = −180.0″) with an image size of 31.92″ × 120.00″. SUM_990603_220846 was acquired from 22:08:46.1 to 22:23:59.0 UT of June 3rd, 1999, and is centered at (X = +481.8″, Y = −180.0″) with the same image size as SUM_990603_220846.

These SUMER images have 43 × 120 pixels, making the pixel size on the sky ~0.742″ × 1″. They are raster scan images made from the spectra that are obtained with a slit whose size is 0.278″×119.6″, and have four wavelength layers with the first layer centered at 1215.67 Å with a width of 2.1 Å. Their X- and Y-axis spatial resolutions are 1″ and 2″, respectively, and the integration time for each slit observation is 20.0 s.

The TRACE 1216 Å image that was taken at the closest epoch from SUM_990603_215302 is tri19990603.2100_0003 and its accompanying 1600 Å image is tri19990603.2100_0005. These images were acquired at 21:40:43.0 UT and 21:41:03.0 UT with exposure times of 3.44 and 1.22 sec, respectively. The TRACE 1216 Å image that was taken at the closest epoch from SUM_990603_220846 is tri19990603.2200_0205 and its accompanying 1600 Å image is tri19990603.2200_0207. These images were acquired at 22:33:36.0 UT and 22:33:55.0 UT with exposure times of 3.444 and 1.216 sec, respectively. All of these TRACE images are centered at (X = +496.677″, Y = −190.335″) with an image size of 512″ × 512″, and have 1024 × 1024 pixels with a pixel size of 0.5″ × 0.5″ (a spatial resolution of 1″ × 1″).

Although the above images are the best matches between the TRACE and SUMER data sets, the times between the closest TRACE and SUMER images are still rather long: ~17 to 19 min (see Fig. 1 for the relative epochs of these images). We find that a better correlation can be obtained between the two data sets when the images from the same instrument are combined, compared to when each match is analyzed separately. Thus for our analyses in the present study, we average SUM_990603_215302 and SUM_990603_220846 for the SUMER 1215.67 Å image, tri19990603.2100_0003 and tri19990603.2200_0205 for the TRACE 1216 Å image, and tri19990603.2100_0005 and tri19990603.2200_0207 for the TRACE 1600 Å image. When calculating the average, we appropriately weighted each two images such that the average is centered at 22:00:00.0 UT.

Calibration of SUMER data was performed with the SUMER IDL software included in the SolarSoft package[2]. The data are first flatfielded with the procedure sumer_flatfield and destreched with the procedure sumer_destretch. Calibration is then performed with the procedure sumer_calib. The photons that go through SUMER's slit do not reach the top and/or bottom few rows of CCD pixels for calibration purposes. In case of the SUMER image we consider here, we find that the top 7–8 rows and the bottom 6 rows of the CCD pixels are not illuminated and have intensities lower than 50 counts per pixel. We thus exclude these pixels from our comparison analyses below. Calibration of TRACE data was performed with the procedure trace_prep, which is included in the TRACE branch of the SolarSoft package. TRACE pixels with data numbers larger than 4000 are saturated and are excluded from our analyses.

3. Comparison to SUMER

Since the TRACE images cover a larger area than the SUMER image, for the analyses below, we crop the TRACE images to match the observed area of the SUMER image. While matching the images, we realized that either or both of the SUMER and TRACE coordinate information is inaccurate and the two images do not exactly coincide. We thus estimate the amount of pixels to be shifted for the TRACE images to match the SUMER image ($X_{\rm shift}$, $Y_{\rm shift}$) by maximizing the r_s value between the TRACE Lα image and the SUMER 1215.67 Å image.

We estimate the best-fit B value from the SUMER data by maximizing r_s between the TRACE Lα image and the SUMER 1215.67 Å image as well, thus finding the best-fit B value and ($X_{\rm shift}$, $Y_{\rm shift}$) values is performed simultaneously. However, three-dimensional maximization is a difficult numerical problem and may often give incorrect results. For this reason, we maximize r_s hierarchically: we find ($X_{\rm shift}$, $Y_{\rm shift}$) values that maximize $r_s(X_{\rm shift}, Y_{\rm shift})$, where each $r_s(X_{\rm shift}, Y_{\rm shift})$ value is the maximum r_s as a function of B for a given ($X_{\rm shift}$, $Y_{\rm shift}$) pair. In this way, the best-fit values for all three parameters, B, $X_{\rm shift}$, and $Y_{\rm shift}$, are reliably obtained.

When finding the best-fit B, $X_{\rm shift}$, and $Y_{\rm shift}$ values, we fix A to be 0.97 as H99b did when calculating their best-fit B value. This is because we are not analyzing absolute-calibrated images and thus what we actually obtain from our image comparison is the ratio between A and B, rather than absolute A and B values.

Since the pixel sizes of TRACE and SUMER images are not identical, we need to resample the images for our comparison. We first analyze the images for a sampling size of 1″ × 2″, which is the larger of the spatial resolutions between

[1] The raw fits file for this observation provided by the NASA's SOHO Archive website does not contain its first slit data. Thus here we analyze the raw IDL restore files provided by the SUMER Image Database at the Max Planck Institute for Solar System Research (`http://www.mps.mpg.de`) for both observations.

[2] `http://www.lmsal.com/solarsoft/sswdoc/index_menu.html`

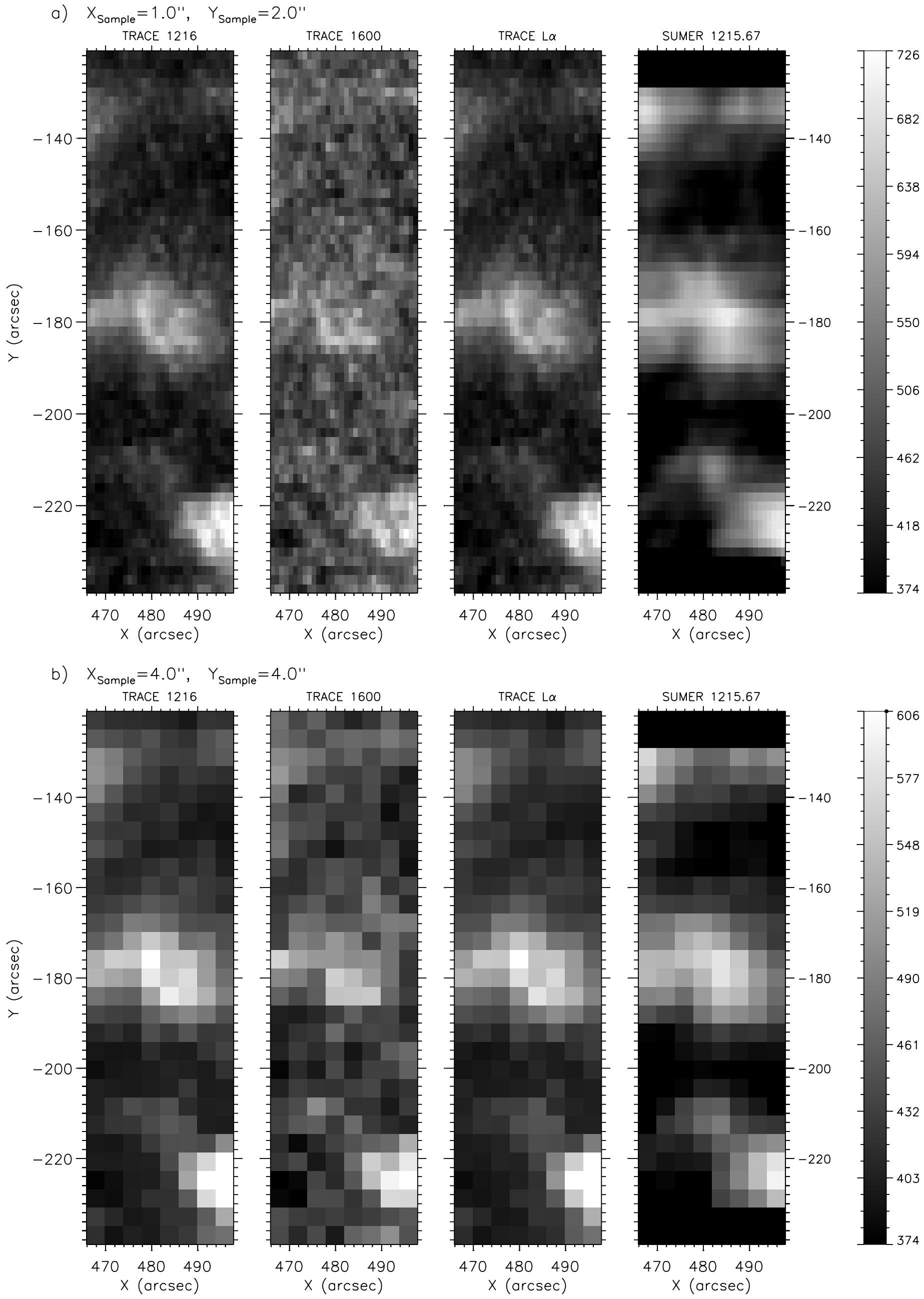

Fig. 2. TRACE and SUMER images with a sampling size of **a)** 1″ × 2″ and **b)** 4″ × 4″. TRACE Lα image is obtained by using Eq. (1) with the best-fit B value of **a)** −0.036 and **b)** −0.120. The bars indicate the intensities of the greyscale in units of count per second for TRACE 1216 images. The greyscale for other images are appropriately scaled for ease of comparison.

the TRACE and SUMER images, and obtain the best-fit parameters listed in the first row of Table 1. Figure 2a shows the TRACE and SUMER images for this sampling size, as well as the TRACE Lα image obtained by using equation (1) with the best-fit B value of −0.036. The r_s value between TRACE Lα and SUMER 1215.67 ($r_{s,L\alpha}$), 0.8374, is only slightly larger than that between TRACE 1216 and SUMER 1215.67 ($r_{s,1216}$), 0.8367, i.e., there is almost no gain in correlation from combining TRACE 1216 and 1600. This is probably because of the significant difference in *apparent* spatial resolution between the TRACE and SUMER images: the spatial resolution of the SUMER image appears to be much worse than it is supposed to be. One possible reason would be the fact that the SUMER image is a raster scan image that took ∼15 min to complete and the features in the image could have moved during the scan.

We then resampled the images with various, larger sampling sizes (see Table 1). Our eye inspection finds that a sampling size of 4″ × 4″ is the smallest size that results in similar apparent resolutions for the TRACE and SUMER images. Figure 2b shows the TRACE and SUMER images for this sampling size, as well as the TRACE Lα image created with the best-fit B value, −0.120 (see the fourth row of Table 1 for best-fit parameters). This B value increases the correlation from $r_{s,1216} = 0.9025$ to $r_{s,L\alpha} = 0.9089$, which is a much larger increase than for a sampling size of 1″ × 2″. This increase is less than the increase obtained by H99b (from 0.809 to 0.825), but the correlation value itself is larger.

Table 1. Best-fit parameters.

Sampling size	$X_{\rm shift}$	$Y_{\rm shift}$	B	$r_{\rm s,1216}$	$r_{\rm s,H99b}$	$r_{\rm s,L\alpha}$
$1'' \times 2''$	1.3 ″	−2.5″	−0.036	0.8367	0.8326	0.8374
$2'' \times 2''$	1.7 ″	−2.7″	−0.042	0.8608	0.8601	0.8625
$3'' \times 3''$	1.2 ″	−2.5″	−0.127	0.8773	0.8844	0.8858
$4'' \times 4''$	2.0 ″	−2.6″	−0.120	0.9025	0.9078	0.9089
$5'' \times 5''$	1.5 ″	−2.7″	−0.148	0.9200	0.9232	0.9248
$6'' \times 6''$	1.2 ″	−2.6″	−0.158	0.9106	0.9205	0.9256
$7'' \times 7''$	1.5 ″	−2.5″	−0.181	0.9031	0.9135	0.9215
$8'' \times 8''$	1.3 ″	−2.5″	−0.227	0.9176	0.9307	0.9472

Note– $r_{\rm s,1216}$ is the Spearman's rank correlation between TRACE 1216 and SUMER 1215.67 images. $r_{\rm s,H99b}$ is the Spearman's rank correlation between TRACE Lα and SUMER 1215.67 images with the B value obtained by H99b, −0.105, and $r_{\rm s,L\alpha}$ is that between TRACE Lα and SUMER 1215.67 images with the B value obtained by maximizing the correlation.

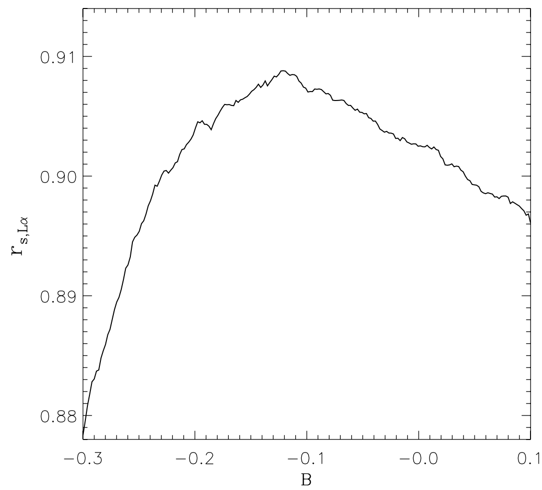

Fig. 3. $r_{\rm s,L\alpha}$ values as a function of B for a sampling size of $4'' \times 4''$ and $X_{\rm shift} = 2.0''$ and $Y_{\rm shift} = -2.6''$. These $X_{\rm shift}$ and $Y_{\rm shift}$ values maximize $r_{\rm s,L\alpha}$ as described in the text.

This best-fit B value, −0.120, is similar to the value that H99b obtained from their comparison with the VAULT observation, −0.105. When applying $B = -0.105$ to images with a sampling size of $4'' \times 4''$, we obtain $r_{\rm s,H99b} = 0.9078$, which is only slightly less than our value. This is because, as shown in Fig. 3, $r_{\rm s,L\alpha}(B)$ for a given ($X_{\rm shift}$, $Y_{\rm shift}$) has a rather broad peak around the maximum. This implies that our comparison of TRACE data with SUMER data is consistent with the result of H99b.

4. Summary

We have found one set of matches between the SUMER 1215.67 Å raster scan images and the TRACE 1216 Å images that were taken for the same area on the Sun within a few tens of minutes. The relatively long exposure time necessary for raster scan images makes their apparent spatial resolution worse than the predicted value, and we found that the apparent quality of the SUMER and TRACE images become similar when compared at a resolution of $4'' \times 4''$. We have compared the TRACE and SUMER images at this sampling size, and by maximizing $r_{\rm s,L\alpha}$, we obtained the best-fit B of −0.120 and $r_{\rm s,L\alpha}$ of 0.9089. This B value is very close to that of H99b, −0.105, and the obtained $r_{\rm s,L\alpha}$ was about 10% better than that of H99b. Thus our comparison between the TRACE and SUMER images confirms the reliability of the calibration method suggested by H99b for TRACE 1216 Å images.

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