RECOVERING THE FINE STRUCTURES IN SOLAR IMAGES

M. Karovska1, S.R. Habbal1, L. Golub1, E. DeLuca1 and H. Hudson2
1 Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138
   (617) 495 7847, (617) 495 7049
2 University of Hawaii, 2680 Woodlawn, Honolulu, HI 96822

ABSTRACT
With the advent of powerful image restoration techniques capable of improving the resolution of space- and ground-based solar observations, new opportunities arise for exploration of the small-scale structures in the solar atmosphere. We present here several examples of the unique capability of the Blind Iterative Deconvolution technique to recover the real point spread function when limited a priori information is available about its characteristics, and therefore to substantially increase the yield from the space observations by improving the resolution in the images.

Keywords: corona, high-resolution imaging, coronal heating.

1. INTRODUCTION
The continuing strong interest in the study of the small-scale structure of the solar magnetic field stems from the belief that small-scale closed magnetic field structures may carry signatures of the coronal heating processes.

In general, heating mechanisms have to account for a temperature profile of the solar atmosphere that varies from 10^5K in the chromosphere to 10^6K in the corona. They also have to account for the observed properties of the outflowing plasma of the solar wind. Examples of such mechanisms include heating by acoustic waves, by slow and fast MHD waves, by body and surface Alfvén waves, by current or magnetic field dissipation, by microflares, and by heating due to bulk flows and magnetic flux emergence (e.g. Wentzel 1981, Hollweg 1985, Parker 1988).

Empirical results, such as the characteristic spatial and time scales of variability of the plasma confined in the small magnetic structure, have significant implications for the viability of some of the proposed heating mechanisms and may open new avenues for theoretical explorations.

The characteristics and distribution of the smallest spatial scale structures cannot be easily extracted directly from space observations, either because of limited resolution and noise in the images, or because of the high dynamic range between small- and large-scale structures. Recently developed image restoration and enhancement techniques now offer a unique opportunity to tap information on the small-scale structure stored in the space observations. These techniques include a deconvolution algorithm - Blind Iterative Deconvolution (BID) (e.g. Karovska and Habbal 1991), that allows both a high resolution image and the degrading point spread function (PSF) to be recovered from a single high signal-to-noise image.

To demonstrate the potential of image post-processing for probing the fine scale and temporal variability of the solar atmosphere, we highlight several results of the application of BID techniques to different samples of Solar observations from space, including Skylab, Yohkoh, and NIXT observations.

2. BID Technique
The BID technique was originally proposed for correction of the effects of atmospheric turbulence on optical images (Ayers and Dainty 1988). When applied to high signal-to-noise images degraded by an unknown function, this algorithm finds a pair of functions corresponding to the degrading function and the undegraded image, which when convolved reproduce the input image within given physical constraints. A necessary condition is that the degrading function is invariant over the image field (stationarity) and the degradation is a linear operation.

We performed a number of numerical and experimental tests of this algorithm, and found that it converges rapidly (after a few iterations) to a stable solution, independently of the starting PSF (including a random gaussian). In order to converge, BID requires input data with high signal-to-noise ratios. Solar images are ideal for this technique because of the high flux levels, even in the short exposures required to freeze the evolutionary stage of a flare or a bright point. Details on BID technique can be found in (Nisenson et al 1991, and Karovska and Habbal 1991).

This technique has been applied successfully to a number of space- and ground-based solar observations. We present here several recent results from BID processing of solar images from space observations.

3. Application of BID to Space Observations
Two decades ago the Skylab mission initiated a new era in observational solar physics by providing new vistas of the Sun at UV and X-ray wavelengths. These observations revealed the highly structured aspect of the solar upper atmosphere. The Skylab database covers a wide variety of structures on the Sun, in active and quiet regions, and in coronal holes. At coronal temperatures, the images show million degree plasmas confined within arch-like magnetic field structures forming active region loops, which are the sites of such explosive events as flares and coronal mass ejections. They coexist with the nebulous regions defining the quiet sun, and with the coronal holes - tenuous
regions with depleted emission carried along open magnetic field lines, extending from the solar surface out into interplanetary space. In addition to these distinct large-scale magnetic structures, the solar atmosphere seen in X-rays is dotted everywhere with compact bright regions, the coronal bright points.

Application of the \( BID \) technique to a number of Skylab observations recovered the point spread function, and produced images with substantially improved spatial resolution. To illustrate the potential of this technique we show several examples of improved resolution in observations of bright points and active regions.

Bright points are characterized by enhanced coronal emission observed at X-ray, EUV and radio wavelengths. They tend to cluster at the interfaces of network cells. One of the most distinctive properties of coronal bright points is the prominent spatial and temporal variability of their emission over the course of their lifetime of a few hours (e.g. Habal and Grace 1990). Figure 1 (upper panel) shows a coronal hole region on the disk containing several bright points recorded in C II 1336 Å (3 x 10^4K) using the Harvard EUV spectroheliometer on board Skylab (Reeves et al 1977).

The data were recorded simultaneously in six wavelengths through the same instrumental slit thus removing any ambiguity regarding spatial correspondence between the different wavelengths.

The starting guess for the \( PSF \) used to perform the first cycle of \( BID \) was a Gaussian with random noise, and half power width radius of about 5". Substantial sharpening of the structures in the images occurred after about 100 iterations, and the iterative process was stopped when the reconstructed image remained effectively unchanged in further cycles of \( BID \). An example of the starting \( PSF \) and the final \( PSF \) in C III 977 Å (7 x 10^4K) is shown in Figure 2. The reconstructed \( PSF \)s in all six wavelengths of observation were very similar.

![Figure 1](image1.png)

Figure 1. Intensity contour plots of \emph{Skylab/EUV} spectroheliogram of a coronal hole region (1' x 1') containing several coronal bright points, before and after \emph{BID}.

![Figure 2](image2.png)

Figure 2. (a) The starting \emph{PSF} (random gaussian), and (b) the reconstructed \emph{PSF} for \emph{Skylab} spectroheliogram of the coronal hole region in C III. The first contour is at the noise level, at 10% of the maximum.

The comparison between the sources 1, 2, and 3 in Figure 1, before and after the processing, shows striking improvement in the separation of extended sources into
distinct features. The processed images reveal details in
the structure of the bright points that could not easily
be detected in the original images. We emphasize the
fact that no spurious sources were introduced, while the
structures were resolved to the limit of the spatial reso-
lution of the instrument. The reconstructed images show
some sources that are distinctly separated on a scale of
less than 5″ (see, for example, the sources labeled 1 and
2). Source 1 reflects a distinct loop-like structures about
10″ in size. The morphology and distribution of these
sources change from height to height in the atmosphere
(Karovska Habbal 1991).

This improved resolution is extremely important in stud-
ies of the time variability of bright points. The tempo-
ral evolution of the fine-scale structure within the bright
points shows substantial brightness variations, and a dra-
matic change in the morphology of the loop-like exten-
sions and separation of the structures over a few min-
utes. However, at an angular resolution limit of 5″ and
a temporal resolution of 5.5 min, this variability appears
as chaotic in nature, with no obvious systematic pattern
(Karovska and Habbal 1991).

Application of the BID technique to simultaneous mul-
tiwavelength Skylab observations of active regions also
shows the presence of basic structure of distinct bright-
enings of 5″-10″ in size. In addition, the diffuse emis-
sion surrounding bright loops was resolved into distinct
loops. These loops are not cospatial at different tempera-
tures but coexist within the same active region complex,
a characteristic also found in the miniature loops forming
coronal bright points.

Similar results, i.e., the lack of cospatiality, and the dis-
crete nature of the loops, were obtained using the BID
technique on active region images recorded with Yohkoh
Soft X-ray Telescope (SXT) (Tsuneta et al 1991) and
with NIXT (Golub et al 1990) rocket-borne experiment
during coordinated observations carried out on April 12
1993 (in collaboration with Dr. K. Strong). Figure 3
displays NIXT and Yohkoh/SXT images before and after
processing with BID. The NIXT images were rebinned
in order to match the scale of the Yohkoh images. The
improvement of the resolution in the processed images is
particularly evident in the better definition as seen
in Figure 3b and 3d. As a result, one can compare in
these spatially resolved observations the changing aspect
of loops at different temperatures, and gain new insights
into their spatial distribution.

The BID technique also recovered the PSFs, with ran-
dom gaussians as starting guess. The recovered NIXT
PSF is about two times narrower than the Yohkoh/SXT
PSF (with FWHM about 3″). The Yohkoh/SXT PSF
shows a core/halo structure and is asymmetric. This re-
result confirms the evidence for ellipticity of PSF found
when BID was applied to other SXT images (Karovska
and Hudson 1994), and is in agreement with the results
from the pre-launch measurements (Martens et al 1994).

Figure 3. NIXT images of an active region: (a) before
processing, and (b) after processing with BID.
Yohkoh/SXT images of the same region: (c) before and
(d) after processing.

Our next example is a flare event recorded with the
Yohkoh/SXT on June 27 1993. We selected a segment
of 20 images from an extended time series. Each image
containing 64 x 64 pixels (2.46″/pixel) was processed us-
ging the BID technique. Random gaussians with 10 pixels
FWHM were used as starting PSFs in the BID restora-
tions. The individual PSFs recovered from this series of
images are very similar, and consistently show an asym-
metry.

The reconstructed images provide a sharper view of the
fine structures in the flaring region. Figure 4 shows 4 im-
ages, selected from the time series of 20 processed images
at about 20 second intervals, before and after deconvolu-
tion. Because of the high dynamic range in the images,
it is difficult to show in the contour plots the faint and
the bright structures simultaneously. Therefore, we se-
lected the brightness levels in the contour plot so as to
single out the brightest loop in the images, and show the
substructure within it.

The BID images easily resolve the bright structures at the
footpoints of the loop (Figures 4a and 4d), while Figures
4b and 4c clearly show the brightening at the top of the
loop.
4. CONCLUSION

Examples presented in the previous section show that BID technique is a powerful tool for probing the fine scale structures and their temporal variability in space observations. The processed images provide a more detailed view of the spatial structure of the solar atmosphere at different heights in regions with different large-scale magnetic field structures: coronal holes, quiet regions, and active regions. The image processing therefore presents a very promising avenue for enhancing the scientific yield of the existing and future solar observations from space.

Experience in recovering the PSF will be invaluable for investigating the PSFs of several imaging instruments on board SOHO Improved resolution in the reconstructed multiwavelength images combined with the high cadence could yield important information on the spatial and temporal characteristics of the small-scale structures in the transition region and the lower corona, crucial for better understanding of their role in the heating of the corona and the acceleration of the solar wind.

ACKNOWLEDGMENTS

Support for M. Karovska S. R. Habbal was provided by NASA grant NAGW-249 and Air Force grant AFOSR-91-0244.

REFERENCES


