Photometric Properties of Network and Faculae Derived from HMI Data Compensated for Scattered Light

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Abstract

We report on the photometric properties of faculae and network, as observed in full-disk, scattered-light-corrected images from the Helioseismic Magnetic Imager. We use a Lucy–Richardson deconvolution routine that corrects an image in less than one second. Faculae are distinguished from network through proximity to active regions. This is the first report that full-disk observations, including center-to-limb variations, reproduce the photometric properties of faculae and network observed previously only in sub-arcsecond-resolution; small field-of-view studies, i.e. that network, as defined by distance from active regions, exhibit higher photometric contrasts. Specifically, for magnetic flux values larger than approximately 300 G, the network is brighter than faculae and the contrast differences increase toward the limb, where the network contrast is about twice the facular one. For lower magnetic flux values, network appear darker than faculae. Contrary to reports from previous full-disk observations, we also found that network exhibits a higher center-to-limb variation. Our results are in agreement with reports from simulations that indicate magnetic flux alone is a poor proxy of the photometric properties of magnetic features. We estimate that the contribution of faculae and network to Total Solar Irradiance variability of the current Cycle 24 is overestimated by at least 11%, due to the photometric properties of network and faculae not being recognized as different. This estimate is specific to the method employed in this study to reconstruct irradiance variations, so caution should be paid when extending it to other techniques.

Key words: radiation mechanisms: general – Sun: faculae, plages – Sun: magnetic fields – Sun: photosphere

1. Introduction

Over the past few decades, much effort has been dedicated to measuring solar irradiance variations, and to understanding and modeling the physical processes that drive them. Motivating this research is the impact that irradiance variations have on the Earth’s atmosphere and climate, especially at the 11 year solar cycle and longer timescales (e.g., Ernolli et al. 2013; Seppälä et al. 2014).

Variations of solar irradiance at temporal scales longer than one day are modulated by the area and position occupied over the disk by photospheric magnetic structures. Accordingly, various techniques have been developed to reproduce variations of both the Total Solar Irradiance (TSI, the irradiance integrated over the whole solar spectrum) and the Spectral Solar Irradiance (SSI, irradiance integrated over finite spectral bands) using direct measurements or estimates (through proxies) of varying populations of magnetic features on the solar disk (Domingo et al. 2009; Ermolli et al. 2013). While it is relatively well-understood how sunspots dominate on a daily (sunspot evolution) or monthly (solar rotation) timescale, the contribution of faculae and network, which dominate at the 11 year solar cycle and longer temporal scales, is still uncertain. This is in spite of numerous investigations of their photometric properties (e.g., Foukal & Duvall 1985; Ortiz et al. 2002; Berger et al. 2007; Ermolli et al. 2007, 2010; Narayan & Scharmer 2010; Viticchié et al. 2010; Utz et al. 2013; Yeo et al. 2013), and attempts to reconcile observed properties of faculae and network with those predicted by models (Foukal & Duvall 1985; Unruh et al. 1999; Ermolli et al. 2007, 2010). As a result, while TSI reconstructions of the last and current cycles agree up to the 96% level, SSI reconstructions, especially in the UV, and reconstructions of the past cycles obtained by different techniques, present discrepancies so large that we cannot accurately assess the effects of solar irradiance variations on the Earth atmosphere (e.g., Ermolli et al. 2013; Ball et al. 2016; Kopp 2016).

Reconstructions, in most cases, only partially take into account the variety of physical conditions that, as also inferred from numerical modeling (e.g., Spruit 1976; Pizzo et al. 1993; Steiner 2005; Criscuoli & Rast 2009; Criscuoli & Uitenbroek 2014a), determine the radiative emission of magnetic features. In particular, results obtained from the analysis of high spatial-resolution observations (Solanki & Brigljevic 1992; Ishikawa et al. 2007; Kobel et al. 2012; Romano et al. 2012; Feng et al. 2013) showed that small-size magnetic elements located in quiet regions are characterized by a higher photometric contrast in photospheric continua than magnetic elements located in active regions. Criscuoli (2013) employed three-dimensional magneto hydrodynamic (3D-MHD) simulations of the solar photosphere to show that such differences are caused by suppression of convection in active regions, which induces a decrease of the plasma temperature within and around magnetic elements.

The high spatial-resolution results characterizing network as higher-contrast features than faculae are apparently at odds with previous studies employing full-disk observations. For instance, Ortiz et al. (2002) analyzed data acquired with the Michelson Doppler Imager (MDI) aboard the Solar and Heliospheric Observatory (Scherrer et al. 1995) and concluded that the contrast of network pixels is smaller and presents a rather modest center-to-limb variation with respect to the contrast of faculae. Similar results were found by Yeo et al. (2013), who analyzed data acquired with the Helioseismic and Magnetic Imager (HMI) aboard the Solar Dynamics Observatory (SDO, Schou et al. 2012),
and by Ermolli et al. (2003) and Ermolli et al. (2007), who analyzed photospheric solar images acquired with the Precision Solar Photometric Telescope (PSPT, Coulter & Kuhn 1994). However, Ortiz et al. (2002) and Yeo et al. (2013) also noted that network elements are characterized by a higher “intrinsic” contrast, thus suggesting that the lower contrast observed for network is mostly a consequence of spatial resolution effects.

Table 1 provides a summary of photometric contrast studies published in the last 15 years. This table is incomplete, but gives the reader a comprehensive view of the findings of a variety of observational and numerical efforts at a glance, including the lead author, year of publication, whether network or faculae were found to be brighter over the majority of field strengths and disk positions, whether or not the study was full-disk or limited in its field of view, the instrument used, its pixel size, and criteria for distinguishing between faculae and network.

| Author(s) | Brighter$^a$ | Full Disk | Instr. (Pixel Size) | Criteria |
|-----------|-------------|-----------|---------------------|----------|
| Ortiz et al. (2002) | Faculae | Yes | MDI (1") | B |
| Ermolli et al. (2003) | Faculae | No | PSPT (2"), MDI (1") | CaII, B |
| Ishikawa et al. (2007) | Network | Yes | SST/SOUP (<0.02") | B |
| Ermolli et al. (2007) | Faculae | Yes | PSPT (2"), MDI (1") | CaII, B |
| Kobel et al. (2011) | Network | No | Hinode/SP (0.73") | B |
| Romano et al. (2012) | Network | No | DST/IBIS (<0.17") | AR prox. |
| Feng et al. (2013) | Network | No | DOT (0.07") | G-band I |
| Yeo et al. (2013) | Faculae | Yes | HMI (0.5") | B |
| Yeo et al. (2014a)$^b$ | Network | No | HMI (0.5") | B |
| This paper$^b$ | Network | Yes | HMI (0.5") | AR prox. |
| Criscuoli (2013) | Network | No | Stagger (24 km) | ... |
| Riethmüller & Solanki (2017) | Network | No | MURaM (10 km) | ... |

Notes. The columns correspond to authors, year of publication, whether faculae or network were found to have a higher contrast at most disk positions and field strengths, type of observation, the instrument used and its spatial pixel scale and the criteria used to discriminate between network and faculae. The bottom two rows correspond to simulation efforts. Therefore, no instrument is specified and a source code is named instead.

$^a$ Brighter indicates that the feature has a higher-intensity contrast for most field strengths and disk positions.

$^b$ These two papers represent studies in which the data are corrected for scattered-light.

Table 1: A Summary (Albeit Incomplete) of Intensity Contrast Studies from both Observations and Simulations from the Past 15 Years

SRPM (e.g., Fontenla et al. 2011, 2015), OAR (e.g., Ermolli et al. 2011), and COSI (e.g., Haberreiter et al. 2008), various types of magnetic features (which include different types of network and facular features) are classified according to their emission in chromospheric images (typically CaIIK), but the modeled network contrast is lower than the facular one, especially toward the limb (e.g., Ermolli et al. 2010). Simplifications in implementing an irradiance reconstruction that accounts for all network and facular properties arise because reported differences are dependent on the methods of feature-discrimination used, and the intensity contrasts are a function of wavelength, magnetic field strength, spatial resolution of the instrument, activity levels, and center-to-limb position (Solanki 1993).

We were inspired by Yeo et al. (2014a) who showed that the contrast-magnetic flux relation derived at disk-center, using data compensated for the instrumental Point Spread Function (PSF), presents characteristics previously observed only using sub-arcsecond spatial resolution observations and simulations. We extend the Yeo et al. (2014a) work to include full-disk analysis of HMI data compensated for the PSF for dates that sample a variety of magnetic activity on the disk.

This paper adds to the existing literature on photometric contrasts of network and faculae as pertains to irradiance modeling in the following way:

1. This is the first full-disk analysis to report on photometric contrast compensated for scattered-light of faculae and network, defined by their proximity to active regions instead of their magnetic flux only.

2. We utilize HMI data corrected for scattered light using a fast deconvolution routine already in the HMI pipeline.$^4$

$^4$ HMI data compensated for the PSF can be found within the HMI JSOC environment by searching for data series appended by “_dcon.” For example, HMI continuum intensity data obtained at a 45s cadence, normally designated as hmi.C.45s, which have been corrected, are found in the data series named hmi.C.45s_dcon. Several time periods of data are already available. The HMI team is working toward supplying data on a daily and continuous basis, but the efforts are dependent upon funding outcomes. Requests for scattered-light corrections for specific data periods and observables are welcome and should be addressed to aanorton@stanford.edu.
long-range scattering range (see Section 2). The deconvolution is fast (less than 1 s per full-disk image) and
could easily supply daily data for irradiance reconstruction purposes. Within this paper, we analyze original and
PSF corrected full-disk intensity and magnetograms from ten different days between 2013 and 2015.
3. By utilizing a pre-existing HMI data product, i.e., the
HMI Active Region Patch (HARP) data, we can
distinguish between faculae and network in one step (see
Section 2). This simple methodology could easily be
incorporated into ongoing irradiance reconstruction
efforts.

The analysis that we performed is similar to those of Ortiz
et al. (2002) and Yeo et al. (2013), who analyzed data acquired
with MDI and HMI, respectively. These previous studies did
not differentiate between pixels located near AR, except that
Yeo et al. (2013) excluded some pixels very close to active
regions using a magnetic extension analysis, although after that
exclusion there was no further distinction between, or separate
analysis of, pixels closer or further from AR. It is even noted in
the conclusions of Yeo et al. (2013) that “while the largest
effect is produced by the removal of magnetic signal adjoining
to sunspot and pores... there remains a fair representation
of active region faculae in the measured contrasts.” Instead,
network and facular regions were distinguished using the
assumption that network and facular pixels are characterized by
low/high magnetic flux values, respectively. Moreover, the
data employed by Ortiz et al. (2002) were characterized by a
different spatial resolution (about four times worse), and in
both studies, the data were affected by scattered light.
Therefore, we were inspired by Ortiz et al. (2002) and Yeo
et al. (2013) to conduct a study on full-disk data while
distinguishing faculae and network by their spatial proximity
to AR.

2. Observations and Data Analysis

We analyzed a set of 45 s Intensitygrams and Magnetograms
acquired on ten different days between 2013 and 2015 with the
HMI. The solar disk is imaged on a 4096 x 4096 pixel
detector, with a pixel/scale of 0.5 arcsec and a spatial
resolution of 1 arcsec (Wachter et al. 2012). The HMI samples
the Fe I 6173.3 nm photospheric absorption line at six
wavelength positions in two orthogonal circular polarization
states. The acquired filtergrams are then combined through an
algorithm (the MDI-like algorithm) to produce estimates of
the line-of-sight magnetic flux, Doppler velocity, Fe I
6173.34 Å nearby continuum intensity, line depth, and line
width (Couvidat et al. 2012; Cohen et al. 2015). A full
description of the HMI pipeline is provided in Couvidat et al.
(2016). Estimates of the HMI observables are known to suffer
from uncertainties resulting from various factors, which include
the assumption of a Gaussian shaped Fe I line profile, saturation
of the line in the presence of strong magnetic fields, line-shifts
induced by plasma motion, solar rotation, the orbital velocity of
the spacecraft, and the stability of the tunable filters and other
optical components (e.g., Fleck et al. 2011; Liu et al. 2012;
Cohen et al. 2015; Couvidat et al. 2016). The effects of these
uncertainties on our results are discussed in Section 4.

Scattered light is known to affect photometric studies (e.g.,
Toner et al. 1997; Mathew et al. 2007; Criscuoli &
Ermolli 2008; Yeo et al. 2014a). The PSF used for correcting
HMI data for scattered light is described in detail in Section 3.6
in Couvidat et al. (2016), so we limit our description to the
basics. The form of the PSF is an Airy function convolved with
a Lorentzian. The parameters are bound by observational
ground-based testing of the instrument conducted prior to
launch (Wachter et al. 2012), and by using post-launch, in-
flight data off the limb during the transit of Venus and during a
partial lunar eclipse. The PSF employed herein is distinctly
different from the PSF used by Yeo et al. (2014a), which takes
the form of a sum of Gaussians derived from the transit-of-
Venus data. The PSF used by Yeo et al. (2014a) does not
account for large-angle or long-distance scattering, because the
shadow of Venus is too small to effectively measure the long-
distance scattering. In addition, using the sum of simple
functions such as Gaussians does not properly describe the
diffraction-limited case, thus potentially introducing artifacts
on restored images (Wedemeyer-Böhm 2008). These can be
avoided by introducing constraints on the parameters describ-
ing the width of the PSF (Yeo et al. 2014a). For completeness,

To discriminate between pixels located in active and network
regions, we employed the HARPs available for download from
the Joint Science Operations Center (JSOC) website (http://
jsoc.stanford.edu/ajax/lookdata.html), derived from HMI
magnetograms following the procedure described in Turmon
et al. (2002). Note that the HARP mask locations do not change
between the original and data compensated for scattered light.
We discarded pixels belonging to sunspots umbrae and
penumbras by using an intensity contrast criterion. For each
image, we first estimated the average quiet-Sun limb darkening
as a function of the cosine of the heliocentric angle μ, by
computing the intensity histograms at 60 different μ values and
averaging those pixels whose intensity values are within ±3σ
the median value of the intensity distribution. We created a
contrast map to be the ratio of the intensitygram and the limb-
darkening image. We defined pixels as belonging to sunspots in
places where the contrast is lower than four times the standard
deviation of the contrast image. Projection effects were reduced
by applying a six-pixel kernel smoothing on the obtained
sunspot masks (Yeo et al. 2013).

We also discarded from our analysis those pixels where the
magnetic flux value is below three times the magnetogram
noise level. This last quantity varied quadratically with μ and
ranged from about 9 G at disk-center to about 12 G at the limb,
as described in Liu et al. (2012). Finally, due to the
uncertainties toward the limb, we restricted the analysis to
pixels located at μ > 0.2.

Examples of a contrast map, a magnetogram (showing only
pixels exceeding the noise level), the HARPs, and sunspot
masks are shown in Figure 1 for the original and restored data.
The images in Figure 1 (bottom panels) show that the method
applied to select sunspot regions also includes pores and
micropores, and a small fraction of dark intergranular lanes.
This last type of pixels typically has magnetic flux lower than
the magnetogram noise level, and would have been discarded
by the analysis anyway. Note that the difference in identifying
dark features, as shown in the bottom panels comparing the left
and right columns, arises from the standard deviation being
lower in the original data than the compensated data. This

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means that more pixels in the original data were discarded as being lower than 4 sigma level.

We refer to pixels located within HARP regions as “facular pixels,” while magnetic pixels located everywhere else on the disk will be referred to as “network pixels.” We use this notation because the first category of regions is more likely to include facular regions, whereas the second mostly includes intranetwork and quiet and active network regions. The method is also straightforward to implement, both in our efforts as well as in future irradiance reconstructions.

It is important to note that Ortiz et al. (2002) and Yeo et al. (2013) considered only pixels where the magnetic flux compensated for line-of-sight effects (|B|/μ) is lower than 800 G, the number of large magnetic flux pixels being statistically insignificant in their data. We decided instead to extend the analysis to higher magnetic flux values, as the restoration increases the number of large magnetic flux pixels (see Section 5). Yeo et al. (2013) also argued that high magnetic flux values, especially toward the limb, most likely result from horizontal fields, and that these are typically associated with sunspots and pores. Inspection of our data confirms that this statistically is the case for pixels located at the extreme limb (μ < 0.1). Those pixels are discarded from our analysis, but we do not find a clear association of “dark” pixels within locations of sunspots and big pores at other positions over the disk. Figure 2 shows, for instance, in blue and green color, pixels with magnetic flux larger than 800 G, which appear brighter and darker, respectively, with respect to the average quiet Sun intensity, belonging to a HARP Region located at μ ≈ 0.4. On the contrary, the bottom panel of Figure 2 shows that, especially on restored images, these pixels seem to be distributed everywhere over the disk, with a preference for active regions and the activity belt, but not exclusively at the disk center.

3. Results

For each pixel i over the disk, we defined the continuum intensity contrast as
\[ C = \frac{I_i}{I_q} - 1, \]
where \( I_i \) is the continuum intensity of the pixel and \( I_q \) is the average quiet Sun intensity of pixels located at similar angular distance from disk-center, estimated as described in Section 2. We investigated the dependence of the contrast on the cosine of the heliocentric angle, μ, and on the magnetic flux compensated for line of sight effects, |B|/μ. We considered 50 G bins of magnetic flux values of pixels located at 16 different radial distances from disk center, at Δμ = 0.025 intervals.

3.1. Comparison between Results Obtained on Original and Restored Data

In this section, we discuss the effects of restoration on the determination of the dependence of the intensity contrast on the magnetic flux, as well as on the cosine of the heliocentric angle. We refer the reader to Yeo et al. (2014a) for an additional description of the effects of the compensation for the instrumental PSF on the HMI observables.

Figure 3 shows how the intensity contrast depends on the magnetic flux value at eight different heliocentric angles for original and restored data. Figure 4 shows, instead, the variation of the intensity contrast with μ for eight magnetic flux ranges. In both plots, data points correspond to average intensity contrast values computed over the corresponding bins, while the error bars represent the standard deviations of values in each bin.

Figure 3 shows that toward disk center the contrast is negative for magnetic flux values smaller than 200 G, it increases to reach a maximum between 300 and 400 G, then decreases again. This “fish hook” trend has been observed in the analysis of sub-arcsecond spatial resolution observations (e.g., Kobel et al. 2011, 2012; Schnerr & Spruit 2011; Kahil et al. 2017), and was also obtained by Yeo et al. (2014a) on HMI data compensated for the instrumental PSF (a detailed comparison with the results obtained by these authors is given in Section 4). The “fish hook” trend is not seen in the original data, and is partially visible only when increasing the magnetic flux bin size (see Section 4).

Rührbein et al. (2011) employed 3D MHD simulations to interpret the physical origin of the contrast–magnetic field dependence observed at disk center. They showed that the decrease of contrast for low magnetic flux values is a consequence of the accumulation of flux within intergranular lanes, while the decrease of contrast at large magnetic flux values is an effect of reduced spatial resolution in observations, which decreases both the magnetic flux and the contrast of the bright edges of micropore structures. This also explains why the restoration (Figures 3 and 4), contrary to what is typically expected, toward disk center produces a (small) enhancement of the average contrast only at the lower magnetic flux values, while the contrast of restored pixels is up to 4–5 times smaller at higher magnetic fluxes.

Toward the limb, the restoration increases the contrast for |B|/μ > 300 G, as expected by the fact that the contrast at small values of μ is determined by the “hot wall” effect. The amount of contrast variation induced by the restoration is function of both the angular distance and the magnetic flux, generally increasing with the magnetic flux and toward the limb, where the contrast of restored pixels is up to 4–5 times larger than the original ones. On the other hand, the restoration seems to have little effect on the angular distance at which the contrast reaches the maximum, while it shifts toward disk-center the value of μ at which magnetic elements become brighter than the background. This result is explained by the fact that the restoration compensates for scattered-light effects, as previous studies indicate that the position of the maximum contrast is sensitive to the spatial resolution (e.g., Criscuoli & Rast 2009), while the angular position at which features become brighter is less so (e.g., Yeo et al. 2013).

Finally, as noted in previous studies (e.g., Criscuoli & Ermolli 2008), the standard deviation in each bin is enhanced by the restoration. In particular, as also noted in Section 1 (Figure 2), although on average the restoration causes highest magnetic flux features to appear “brighter,” there is still a considerable amount of features that instead appear “darker.”

3.2. Comparison between Network and Faculae

The differences between network and facular regions are illustrated in Figures 5 and 6 for results obtained from restored data only. Results obtained from original data show little or no difference of contrast between pixels located in different magnetic activity regions, especially at disk-center, and are shown in Appendix A. On the contrary, results obtained from restored data show that pixels located in intergranular lanes, or at low magnetic flux values (about less than 300 G), appear always darker in facular regions rather than in network ones.
Figure 1. Examples of the analyzed data acquired on 2014 December 13th. Intensitygram compensated for the limb darkening function (top), magnetogram saturated at \( \pm 100 \) G (center), and masks (bottom) obtained on original (left) and restored (right) data. The gray pixels on the magnetograms have a line-of-sight magnetic flux below the noise threshold. The mask images show the pixels belonging to faculae (derived from HARP masks, see text) in white, while black pixels on the disk belong to regions identified as sunspot umbrae, penumbras, and pores.
Pixels with higher magnetic flux are instead always brighter in network regions. We also note that the contrast differences are smaller toward the disk center, but increase toward the limb, where the network contrast at higher magnetic fluxes can be up to almost twice the facular one. Finally, inspection of Figure 6 reveals that the angular position of the maximum contrast is similar for pixels located in different regions, while the angular positions at which the contrast changes sign occur closer to disk center for network than for faculae.

These results are in qualitative agreement with results obtained by the analysis of sub-arcsecond spatial resolution observations at disk-center (Ishikawa et al. 2007; Kobel et al. 2011, 2012; Romano et al. 2012; Feng et al. 2013). As explained in Criscuoli (2013), the different contrasts obtained in active and quiet regions are a consequence of the decrease of temperature in photospheric layers induced by the suppression of convective motions within active regions. This reduces the contrast of granulation (both granules and intergranular lanes), and consequently of small-size magnetic flux concentrations whose temperature stratification is determined by the temperature of the surrounding plasma. Similarly, toward the limb, the observed higher contrast in network regions can be explained by the reduction of the “hot wall” temperature in facular regions.

Finally, a comparison of plots in Figures 4 and 5 with those in Figures 13 and 14 reveals that the effects of restoration are larger for network pixels, where, for the largest magnetic fluxes, the contrast variations can be up to twice the one obtained for faculae.

3.3. Surface Fits

Following Yeo et al. (2013), we fitted our results with cubic surface functions. The analytical form of the fit and the values of the fit coefficients are reported in Appendix B. The fits were evaluated using data binned over 16 equally spaced in \( \mu \) values and 10 G magnetic flux intervals. Bins where the number of
elements was lower than 100 were excluded from the analysis by imposing a null weight during the fit. The results are illustrated in Figures 3–6. The agreement of the fits with the observational data points is in general very good at most of the flux values and angular positions, especially at the data points employed to produce the fits. The agreement is worse at small magnetic flux values on restored data, where the fits do not reproduce the "fish hook" shape. Recently, Schnerr & Spruit (2011) modeled the contrast-magnetic field relation obtained from the analysis of SST (Scharmer et al. 2003) and HINODE (Kosugi et al. 2007) data as a sum of exponential functions, while Kahil et al. (2017), who analyzed SUNRISE data (Barthol et al. 2011), employed a logarithmic function. In this last case, however, the fit reproduced the contrast at magnetic flux values larger than approximately 90 G (i.e., the dimming at small magnetic flux values was not reproduced). We found that the contrast-magnetic flux relation obtained from restored data is reproduced best when using a 10th order polynomial in $|B|/\mu$. Figure 7 shows that this function indeed reproduces the observations at both low and high magnetic flux values at various angular positions. Results from the fit are reported in Appendix C.

4. Discussion

4.1. HMI Uncertainties

Previous investigations showed that HMI data products are affected by uncertainties stemming from the pipeline employed to estimate the data products, as well as by instrumental effects (see Section 1). Cohen et al. (2015) employed results from numerical synthesis of the FeI 617.3 nm line to show that the errors in the estimate of the continuum intensity introduced by approximations in the MDI-like algorithm are functions of the magnetic field and line of sight, and, as second-order effects, of Doppler shifts. Specifically, their Figure 3 shows that the uncertainty for a facular region with associated a magnetic field of 1000 G is lower than 2% at disk center and decreases rapidly toward the limb, while the uncertainty for quiet regions increases toward the limb up to about 1%. Therefore, uncertainties in the estimates of the contrast induced by approximations in the MDI-like algorithm are below 2% and show little dependence with $\mu$. These uncertainties are typically below the amplitude of the error bars in our plots, and we therefore conclude that they have negligible effects on our results.

Because we used the contrast to characterize the photometric properties of magnetic elements, the increase of opacity of the entrance window during the first years of operations of the SDO, also reported in Cohen et al. (2015), has no influence on our results. Uncertainties stemming from variations of the properties of the filter transmission profiles are instead more difficult to assess, as there is no direct measurement available. Criscuoli et al. (2011) estimated uncertainties lower than 10% introduced by variations of the transmission profiles for continuum measurements provided by the MDI, which, similarly to HMI, combines filtergrams acquired with a tunable filter. In the case of HMI, we expect uncertainties due to these effects to be smaller, as the filters are periodically retuned. Moreover, the data analyzed were acquired in a relatively short temporal frame (about three years), so effects introduced by variations of the positions and shapes of the filters are most likely negligible on our results.

In addition, Cohen et al. (2015) showed that HMI estimates of the FeI 617.3 nm line core intensity are affected by large uncertainties (several tens of percent). For this reason, we
refrained from using those HMI data products, although such measurements would have provided extremely valuable information about the different temperature stratification within network and facular structures.

It is also important to mention that similar studies carried out on magnetograms usually employed data averaged over a longer temporal range (Yeo et al. 2013, employed for instance HMI data averaged over 312 s) to reduce noise and p-mode oscillation effects. In our analysis, we decided to employ 45 s data. To investigate how much of a difference it might make to use 720 s data instead of 45 s data, we repeated the analysis on a subset of three 720 s images and found that the curves describing the dependence of the contrast on the magnetic flux agree within the 2% level (and are therefore not reported). Thus, we conclude that our results are not affected by the use of different types of HMI data.

Finally, the Lucy–Richardson algorithm is known to potentially enhance noise in restored data (White 1994). Inspection of the restored data (e.g., Figure 2) suggests this effect to be negligible. An analysis of the power spectra of both intensity images and magnetograms indeed reveals a small enhancement of power beyond the frequency cutoff of the telescope, but the cumulative power beyond this frequency is below 2%. To investigate the effect of this enhancement on our results, we first estimated the noise level on a subset of original and restored magnetograms employing a method similar to the one described in Liu et al. (2012) (we removed active pixels from the analysis, while Liu et al. 2012 analyzed data acquired during low magnetic activity), and found that the restoration typically doubles the noise level. We therefore repeated the analysis, increasing the noise level threshold by a factor of two, and found that the maximum relative difference between results obtained with the two noise thresholds is below 1.8%.

4.2. Features Classification and Quiet Sun Definition

It is very well known that identification methods employed to singled out features on solar images can affect the derived properties of such features (e.g., Ermolli et al. 2007; Jones et al. 2008; Ulrich et al. 2010; Yeo et al. 2013; Ashamari et al. 2015). We employ masks produced with the method suggested in Turmon et al. (2002) to distinguish between facular and network regions. As explained in Section 1, the HARP regions employed mostly include faculae and probably part of features that other methods might have classified as active network. Magnetic pixels not belonging to HARPs include intranetwork, network, and active network, and no effort was made to discriminate between these latter types of features. On the other hand, the adopted classification is sufficient for the purpose of this study, which is to investigate the effects of the level of activity of the surrounding plasma on the photometric contrast of magnetic features.

It is important to notice that, in order to further reduce the effects of noise, some authors apply a minimum size threshold (typically between 1 and 10 pixels) to the structures analyzed (e.g., Ortiz et al. 2002; Jin et al. 2011; Yeo et al. 2013; Criscuoli 2016). To investigate the effect of isolated pixels on the estimated average contrasts, we then repeated the analysis, applying an “opening” operation with a two-pixel kernel to the pixels exceeding the noise level of the magnetograms (see, e.g., Criscuoli 2016). We found that the application of such a threshold produces a modest increase of the average contrast of pixels with low magnetic flux located toward the limb, with the largest effects found on restored data. In particular, for pixels

Figure 4. Variation of the intensity contrast with the cosine of the heliocentric angle for various magnetic flux ranges derived by original (black) and restored (red) data. Continuous lines: cross-sections of the surface fits to the data (see Section 3.3); dotted lines: extrapolation of the fit.
with $|B|/\mu \leq 300$ G and $\mu \leq 0.5$, singled out on original data, the average and maximum relative increases of contrast are 0.6% and 2.6%, respectively, while for pixels singled out on restored data, they are 1.7% and 3.2%, respectively. These differences are well below the statistical uncertainties of our measurements, so that we can conclude that the application of a minimum size threshold on our data does not affect our results.

Photometric contrast is also known to be affected by the arbitrary definition of quiet Sun regions (e.g., Peck & Rast 2015). We therefore compared our results with those obtained when quiet pixels are defined as those that are below the noise level on magnetograms. The relative differences of contrast found with this method and the one described in Section 2 are below 0.6%, so we conclude that our results are not significantly affected by the criteria adopted to define quiet Sun pixels.

### 4.3. Comparison with Previous Studies

The investigation of the dependence of magnetic elements’ continuum contrast with the heliocentric angle and the magnetic flux has been the subject of several studies (see Section 1). Qualitatively in agreement with previous analysis (Foukal et al. 1990; Topka et al. 1997; Ortiz et al. 2002; Sánchez Cuberes et al. 2002; Walton et al. 2003; Ortiz et al. 2006; Yeo et al. 2013), we found that the highest magnetic flux features appear dark at disk center and bright toward the limb, the value of $\mu$ at which the contrast changes sign depending on the value of the magnetic flux considered. However, a quantitative comparison of our results with these studies is hampered by the different observing conditions, as spatial resolution, scattered-light, wavelength and methods employed to identify the magnetic features play an important role in determining the dependence of contrast on magnetic flux and line of sight (e.g., Criscuoli & Rast 2009, for a review).

The studies by Ortiz et al. (2002) and Yeo et al. (2013) were conducted with the MDI and the HMI, respectively, and are those that allow a more direct comparison with our investigation. Figure 8 shows the contrasts obtained at three angular positions from the cubic fits to our original data (Equation (1)) and those presented in Yeo et al. (2013) (their Equation (3)). For magnetic flux values smaller than 800 G, the curves present a very good agreement, having differences within the error of the measurements. On the other hand, at larger magnetic flux values, the fits presented in Yeo et al. (2013) do not seem to represent our measurements, most likely because those authors did not include high magnetic flux pixels in their analysis (see Section 2). The agreement is remarkable if we consider the difference in the type of HMI images employed (but see discussion in Section 4.1) and the different data-reduction strategies employed in the two studies. In particular, Yeo et al. (2013) employed data obtained averaging original HMI 45 s data acquired over a 315 s interval; they also employed a different method to estimate the limb darkening shape of quiet regions, and different criteria to select sunspots and pores. It is also noteworthy that Yeo et al. (2013) reported the presence of residual patterns in their intensity images compensated for the limb darkening. Following a procedure similar to the one described by those authors, we also estimated the residual intensity on our continuum contrast images, and we found an average value of about $3 \cdot 10^{-5}$, which is about two orders of magnitude smaller than the value reported by Yeo et al. (2014a), so our data were not compensated for this effect.

![Figure 5](image-url). Variation of the intensity contrast with the magnetic flux for pixels located at various radial distances from disk center in facular (red) and network (black) regions singled out on restored data. Continuous lines show cross-sections of the surface fits to the data (see Section 3.3). Dotted lines show our extrapolation of the fit.
The comparison of results obtained by Ortiz et al. (2002) using MDI data with those obtained using HMI are largely discussed in Yeo et al. (2013), and we do not repeat it here. We only note that, as shown by Liu et al. (2012), the MDI magnetic flux values are 1.3–1.4 times larger than the HMI magnetic flux values, so HMI contrasts obtained at certain magnetic flux ranges should be compared with MDI contrasts obtained at higher magnetic flux ranges. Nevertheless, as shown by a comparison of results in our Figures 3 and 4 with the ones reported in Figures 3 and 4 of Ortiz et al. (2002), this scaling factor is not sufficient to explain the different contrasts obtained with the two instruments. We therefore confirm that the different magnetic flux and angular dependencies of the continuum contrast obtained by our analysis and the one by Yeo et al. (2013) on one side, and Ortiz et al. (2002) on the other, must be ascribed to the different spatial resolution and definition of sunspot regions adopted.

In Figure 9, we compare our results with those obtained by Yeo et al. (2014a), who also compensated HMI data for scattered-light effects, but employing a different procedure (see Section 2) and restricting their analysis of photometric contrast only to disk center. The plot shows that the original data...
produce very similar results. The restoration produces, in both cases, an enhancement of the contrast at low magnetic flux values ($|B|/\mu < 200$ G), and an enhancement of the brightness at higher magnetic flux values, as expected from simulations (Röhrbein et al. 2011), but the values present some discrepancies. These differences must be attributed to the limited sample of data employed by Yeo et al. (2014a) (one day), the use of one of the filtergrams (−344 mA from line center) instead of the intensitygram data-product, the different criteria employed to define sunspots (Yeo et al. 2014a employed a −0.11 contrast threshold and a 3 pixel kernel), and finally, the different algorithms employed to derive the instrumental PSF. It is difficult to discern which of these effects plays the largest role, as, for instance, the small differences in the original data might have been amplified by the restoration. A detailed comparison of the performance of the two codes employed for the restoration goes beyond the purpose of this paper. Here, we note that the differences are, overall, within the error bars of our measurements.

To the best of our knowledge, the effects of scattered-light compensation on the center-to-limb variation of magnetic features contrast cannot be directly compared with any previous studies. Most of the studies performed on high spatial resolution data or on MHD simulations were, in fact, conducted at or close to disk center (e.g., Mathew et al. 2009; Röhrbein et al. 2011; Danilovic et al. 2013; Criscuoli & Uitenbroek 2014b), while results obtained on full-disc data mostly focused on sunspot properties (e.g., Walton & Preminger 1999; Mathew et al. 2007; Criscuoli & Ermolli 2008) or facular properties at different wavelength ranges (e.g., Ca II K Walton & Preminger 1999; Criscuoli & Ermolli 2008). Here, we note that contrast variations are, on average, larger for network pixels than for facular ones, as a result of the different effects that image degradation has on magnetic features of different sizes (e.g., Criscuoli et al. 2007; Criscuoli & Ermolli 2008; Viticchié et al. 2010).

The network and facular contrast differences estimated on restored images are small, especially at disk center, and within the error bars. On the other hand, these differences are in qualitative agreement with previous studies obtained at high spatial resolution close to disk-center (see Section 3), but a quantitative comparison is hampered by the different type of data employed. Our results are also in qualitative agreement with measurements carried out by Ortiz et al. (2002) and Yeo et al. (2013), which showed that the specific contrast of low-magnetic-flux pixels is larger than the specific contrast of high-magnetic-flux pixels. On the other hand, our results do not agree with previous observations carried out using full-disc observations, which produced a network contrast lower than the facular one and almost constant over the disk. As previously suggested by Ortiz et al. (2002), these differences are mostly caused by spatial resolution and scattered light effects. Indeed, we found that network and facular regions are characterized by different contrasts only when using restored data.

5. Implications for Solar Irradiance Studies

In this study, we employed spatial proximity criteria to discriminate between network and facular regions. Some previous studies discriminated between the two features, assuming that statistically lower magnetic flux pixels belong to network while higher magnetic flux pixels belong to faculae and active network regions. In the following, we evaluate how these different criteria affect the estimate of magnetic features contrast. Figure 10 shows the magnetic field distribution of network and facular regions derived from original and restored data. Original data show that, for $|B|/\mu < 200$ G, pixels are more likely to be located in network than in facular regions. This value is in near-agreement with the 130 G values employed by Ortiz et al. (2002) and Yeo et al. (2013) to distinguish between network and faculae. The threshold increases to about 400 G when analyzing restored data, and the difference between the two populations is up to one order of magnitude.

Results in Figure 13 and in Figure 5 show that, for $|B|/\mu < 200$ G and $|B|/\mu < 400$ G, respectively, the contrast differences between network and facular pixels are small, up to approximately 0.02 at the limb, such that the criteria employed in previous studies to separate network from faculae allow reasonable estimates of network properties. At larger magnetic flux values, instead, the contrast differences between network and faculae are larger, especially toward the limb, so we expect facular contrasts—derived using the sole magnetic flux to discriminate between the two classes of features—to be statistically affected by the network.

This is confirmed by results in Figure 11, which show, as an example, the contrasts of network and facular pixels with
magnetic fluxes of \( \approx 200 \) G (red lines) and \( \approx 600 \) G (black lines), together with the contrast derived without distinguishing between the two features, obtained from original (top) and restored (bottom) data. Both panels in Figure 11 show that the contrast derived for \( \mid B \mid / \mu \approx 200 \) G, without distinguishing between network and faculae, closely follows the results obtained for the network. For \( \mid B \mid / \mu \approx 600 \) G, however, the contrast derived without distinguishing between the two features is in between the values found for network and faculae, thus showing that the network statistically affects the estimates of facular contrast if faculae are singled out only according to the magnetic flux value. The effects are larger toward the limb and on restored images, where the network and facular contrast differences are larger.

To evaluate the effects of discriminating between network and faculae on the estimate of solar irradiance variations over the solar activity cycle, we computed the daily facular and network contribution to TSI (c.f.r. Foukal et al. 1991; Lean et al. 1998):

\[
\frac{\Delta F}{F} = \sum_k \sum_j \frac{5 \mu_j N(\mu_j, B_k) C(\mu_j, B_k) \Psi(\mu)}{2} (1)
\]

where the two sums run over the magnetic flux and the cosine of the heliocentric angle, \( N(\mu_j, B_k) \) is the area of pixels at position \( \mu_j \) and magnetic flux \( B_k \) normalized to the surface of the solar hemisphere, \( C(\mu_j, B_k) \) is the contrast as derived by the bi-cubic fits to our data, and \( \Psi(\mu) = (3\mu + 2)/5 \) is the quiet Sun limb-darkening function. It is important to note that this model is rather simple, especially if compared to modern irradiance reconstruction techniques, as it lacks detailed knowledge of the radiometric contribution of magnetic features to the disk integrated irradiance. In particular, because the bolometric contrast is known to be larger than the one measured in the red continuum (Foukal et al. 2004), our computations underestimate the bolometric facular/network contribution to TSI.

The daily facular/network coverage \( N(\mu_j, B_k) \) was estimated by employing original 45 s HMI data acquired between 2010 April and 2015 October. Coherently with the analysis presented above, network and facular regions were discriminated using the HARP masks. The facular excess was then computed using Equation (1), first employing the \( C(\mu_j, B_k) \) curves derived from the whole data set (Model A, in the following), and second using the contrast curves derived separately for network and faculae (Model B, in the following). The minimum value of the magnetic flux considered is 300 G. This value was chosen for two reasons. First, the bi-cubic fits seem to reproduce best the observations for magnetic flux values above this threshold (for smaller magnetic flux values, toward the limb, the fits overestimate the contrast up to 0.03). Second, as discussed in Schnerr & Spruit (2011), at magnetic flux values smaller than this threshold, the contrast of small, unresolved magnetic features is largely underestimated because of the brightness contribution of the dark lanes they are embedded in.

Results presented in Figure 12 show that Model A overestimates the TSI excess, mostly because, as shown in Figure 11, the facular contribution during the periods of high activity is overestimated. The variability measured between the periods of largest and lowest activity (\( \Delta F/F_{\text{Max}} - \Delta F/F_{\text{Min}} \)) is \( 1.25 \cdot 10^{-4} \) and \( 1.12 \cdot 10^{-4} \) for Models A and B, respectively, which corresponds to a difference of about 11%. This estimate must be considered a lower limit for several reasons. The most important is that, in our analysis, we discarded pixels with magnetic flux smaller than 300 G, which occupy the majority (more than 98%) of the solar magnetized surface. Indeed, Schnerr & Spruit (2011) employed high-spatial-resolution data acquired in a red continuum to show that the contribution of magnetic pixels with flux larger than 300 G to the network brightness is only \( 0.2 \cdot 10^{-4} \), compared to the excess brightness of about \( 1.1 \cdot 10^{-3} \) found when including all magnetized network pixels. We note that \( 0.2 \cdot 10^{-3} \) is in reasonable agreement with the \( 0.16 \cdot 10^{-4} \) value that we found for the network during 2010 (not shown), the period of lowest magnetic activity in our observations. Spatial resolution effects, (which reduced the estimate of contrasts, magnetic fluxes, and the contrast difference between network and faculae) and the fact that our observations did not include a period of minimum (the HMI operations started during the rising phase of cycle 24), also contribute to underestimation of both \( \Delta F/F \) and the differences between Models A and B. Finally, the use of original data instead of restored ones to derive the coverage of magnetic pixels is another source of uncertainty, as the restoration changes the distribution of magnetic pixels.
particular, Figure 10 shows that, at magnetic flux values larger than approximately 500 G, the difference between the number of facular and network pixels is smaller in restored than original data, which might have led to an overestimate of the variability difference produced by the two models.

It is also important to note that the facular/network contributions to irradiance variations were estimated using contrasts averaged in magnetic field bins. Our results show that the restoration largely increases the scatter of the contrast in each bin, thus pointing to the necessity of employing criteria to discriminate between various types of magnetic features other than the magnetic flux alone. In particular, as already noted in Section 2, some of the pixels with $|B|/\mu > 800$ G on restored images present a negative contrast at all angular positions. Although, on average, the brightness increases after restoration, the fraction of negative contrast pixels at these magnetic flux ranges is more than 50%, thus suggesting a different temperature stratification than pixels characterized by a positive contrast. If, as suggested in Foukal (2015) (see also Foukal et al. 1990; Foukal 1993), the coverage of such features increases with the activity, then available reconstruction techniques making use of facular coverage as derived by chromospheric emission (e.g., Lean 2000; Foukal 2012) overestimate the contribution of faculae to irradiance, especially during the strongest cycles. A detailed study of properties of dark faculae is under investigation.

Finally, it is important to mention that most recent irradiance reconstruction models do not make use of direct measurement of photometric contrast (if not in some cases as a proxy, e.g., Chapman et al. 2012) and that we expect the amount of uncertainty introduced by not taking into account network and faculae separately to vary for different techniques. Nonetheless, we note that the uncertainty value of $\approx 10\%$ in the contribution of network and faculae to TSI variations is smaller than, or on the same order of, uncertainties reported for some TSI and SSI reconstructions (e.g., Crouch et al. 2008; Yeo et al. 2014b; Coddington & Lean 2015).

6. Conclusions

We employed HMI data products compensated for the instrumental PSF to compare the center-to-limb variation of the contrast of network and facular regions, as determined by their proximity to active regions, in addition to continuum intensity and magnetogram threshold. Contrary to previous results obtained on full-disk observations, we found that, for magnetic flux values above 300 G, the network is brighter than faculae and present a stronger contrast center-to-limb variation. This finding for full-disk data must be attributed to the increased photometric contrast resulting from correcting for scattered-light. Note that for full-disk data must be attributed to the increased photometric contrast resulting from correcting for scattered-light. Note that the 300 G threshold is a function of the spatial-resolution of the employed data (see also discussion in Section 5). Our results are in qualitative agreement with those obtained at or close to disk-center by the analysis of sub-arcsecond observations and MHD simulations. We extend the analysis to full-disk to report the photometric contrasts of network and faculae, as determined based on proximity to active regions, as a function of magnetic flux and line-of-sight observing angle.

We employed a simple model to estimate the contribution of magnetic pixels to TSI variations ($\Delta$TSI) and found that, if the contributions of network and faculae are not taken into account separately or are only based on the magnetic flux of a pixel, $\Delta$TSI is overestimated by about 11%. This value is a lower bound for error, for the following reasons. First, the contrast measured using HMI images is still affected by limited spatial resolution. Second, in our analysis, we discarded pixels located in dark lanes, so the contribution of unresolved bright structures located in these regions is not taken into account. Third, comparison of results obtained on original and restored data shows that, for each magnetic flux bin, the restoration increases the scatter of results—even when separately accounting for faculae and network. This suggests that classification of features according to the magnetic flux value and spatial aggregation might not be enough to properly characterize the contribution of magnetic elements to irradiance variations, if irradiance reconstruction techniques just employ the above parameters as input data.

Our report on the photometric contrasts of faculae and network, defined using spatial proximity to active regions as a function of center-to-limb angles, can be used to further improve existing irradiance reconstruction techniques. A majority of irradiance reconstruction techniques either do not explicitly differentiate between features, or assume a lower contrast for the network based on previous studies. The continuity and frequency of full-disk HMI data, combined with how easily HARPS masks allow identification of active region locations, plus the availability of a fast routine for removal of scattered light, means that daily, corrected HMI images of similar quality could easily be implemented for irradiance modeling.

Finally, our results support the conclusion of Foukal et al. (2011) that the contribution of networks during the Maunder and Spörer minima might be underestimated by irradiance reconstruction models (e.g., Lean 2000; Wang et al. 2005; Tapping et al. 2007; Crouch et al. 2008) that assume a linear relation between magnetic flux and/or plage coverage and irradiance.

This work was carried out through the National Solar Observatory Research Experiences for Undergraduate (REU) site program, which is co-funded by the Department of Defense in partnership with the NSF REU Program. The National Solar Observatory is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation. S.C. is grateful to Dr. Peter Foukal for reading the paper and providing useful comments, and to Dr. Odele Coddington for interesting discussions about the NRL reconstructions.
Appendix A
Comparison of Quiet and Active Regions Derived from Original Data

Figures 13 and 14 show results obtained on original data. We note that on these data network and faculae present rather similar contrasts. Only toward the limb, for \( \mu < 0.5 \), the contrast of network shows a modest increase with respect to the facular one.

Appendix B
Polynomial Surface Fit Coefficients

The analytical formula is the following:

\[
C(\mu, \frac{B}{\mu}) = \begin{bmatrix}
-10^{-2} \left( \frac{B}{\mu} \right)^0 & 10^{-3} \left( \frac{B}{\mu} \right)^1 & 10^{-6} \left( \frac{B}{\mu} \right)^2 & 10^{-9} \left( \frac{B}{\mu} \right)^3 \\
0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0
\end{bmatrix} M
\]

Fit coefficients for original data:

\[
M = \begin{bmatrix}
-6.77 & 28 & -43 & 21 \\
0.73 & -1.46 & 2.07 & -1.18 \\
-1.22 & 4.37 & -7.99 & 4.35 \\
0.73 & -3.31 & 5.72 & -2.91
\end{bmatrix}
\]

Fit coefficients for deconvolved data:

\[
M = \begin{bmatrix}
-16.62 & 44 & -54.6 & 24 \\
0.47 & 0.71 & -1.55 & 0.56 \\
-0.25 & -1.02 & 1.05 & -0.083 \\
0.082 & 0.085 & 0.095 & -0.16
\end{bmatrix}
\]

(3)

Appendix C
The 10th Order Polynomial Fit Coefficients

The magnetic flux dependence of the contrast was fitted separately for different positions over the disk \( \mu \):

\[
C\left(\frac{B}{\mu}\right) = \sum_{k=0}^{10} a_k \left(\frac{B}{\mu}\right)^k.
\]

(6)

The coefficients of the fits are given for different \( \mu \) intervals in Table 2.
Figure 14. Variation of the intensity contrast with the cosine of the heliocentric angle in facular (red) and network (black) regions singled out on original data.

Table 2

| $\mu$     | $a_0 \times 10^{-2}$ | $a_1 \times 10^{-3}$ | $a_2 \times 10^{-5}$ | $a_3 \times 10^{-7}$ | $a_4 \times 10^{-10}$ | $a_5 \times 10^{-12}$ | $a_6 \times 10^{-14}$ | $a_7 \times 10^{-16}$ | $a_8 \times 10^{-18}$ | $a_9 \times 10^{-21}$ | $a_{10} \times 10^{-25}$ |
|-----------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 1 – 0.95  | 5.14                 | –2.86                | 3.89                 | –2.50                | 9.21                 | –2.11                | 3.12                 | –2.95                | 1.73                 | –5.76                | 8.24                 |
| 0.95 – 0.9]| 5.02                 | –2.62                | 3.47                 | –2.14                | 7.61                 | –2.17                | 1.22                 | –3.91                | 5.37                 | 8.24                 |
| 0.9 – 0.85| 7.07                 | 3.31                 | 4.39                 | –2.78                | 1.02                 | –2.33                | 3.43                 | –3.25                | 1.91                 | –6.31                | 9.00                 |
| 0.85 – 0.8| 7.10                 | 3.08                 | –3.86                | –2.29                | 7.89                 | –1.71                | 2.41                 | –2.21                | 1.26                 | –4.11                | 5.81                 |
| 0.8 – 0.75| 11.35                | 4.51                 | 5.72                 | –3.51                | 1.26                 | –2.84                | 4.15                 | –3.92                | 2.30                 | –7.68                | 11.06                |
| 0.75 – 0.7| 10.32                | –3.91                | 4.69                 | –2.68                | 8.89                 | –1.85                | 2.48                 | –2.15                | 1.16                 | –3.57                | 4.76                 |
| 0.7 – 0.65| 11.57                | –4.26                | 5.14                 | –3.00                | 1.04                 | –2.28                | 3.29                 | –3.08                | 1.82                 | –6.10                | 8.905                |
| 0.65 – 0.6| 15.28                | –5.14                | 5.94                 | –3.37                | 1.14                 | –2.45                | 3.47                 | –3.20                | 1.86                 | –6.14                | 8.82                 |
| 0.6 – 0.55| 6.46                 | –1.69                | 0.98                 | 0.21                 | –3.42                | 1.30                 | –2.58                | 2.98                 | –2.04                | 7.64                 | –12.06               |
| 0.55 – 0.5 | 9.57                 | –2.43                | 1.77                 | –0.32                | 1.11                 | 0.66                 | –1.45                | 1.76                 | –1.23                | 4.66                 | –7.41                |
| 0.5 – 0.45| 0.59                  | 0.96                 | –2.84                | 2.78                 | –12.94               | 3.44                 | –5.59                | 5.69                 | –3.53                | 12.20                | –18.05               |
| 0.45 – 0.4 | 14.60                | 5.68                 | –8.32                | 5.98                 | –23.80               | 5.75                 | –8.78                | 8.56                 | –5.15                | 17.44                | –25.43               |
| 0.4 – 0.35| 21.77                | 6.68                 | –7.96                | 4.77                 | –16.02               | 3.27                 | –4.22                | 3.44                 | –1.72                | 4.78                 | –5.60                |
| 0.35 – 0.3 | 39.17                | 10.40                | –10.84               | 5.83                 | –18.13               | 3.52                 | –4.42                | 3.60                 | –1.84                | 5.35                 | –6.80                |
| 0.3 – 0.25| 16.61                | –4.78                | 5.80                 | –3.79                | 14.56                | –3.42                | 5.07                 | –4.75                | 2.74                 | –8.89                | 12.39                |
| 0.25 – 0.2 | 151.39               | –33.19               | 30.59                | –15.60               | 48.81                | –9.84                | 13.05                | –11.30               | 6.16                 | –19.19               | 26.03                |

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