Nonlinear Force-free Coronal Magnetic Stereoscopy

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Abstract

Insights into the 3D structure of the solar coronal magnetic field have been obtained in the past by two completely different approaches. The first approach are nonlinear force-free field (NLFFF) extrapolations, which use photospheric vector magnetograms as boundary condition. The second approach uses stereoscopy of coronal magnetic loops observed in EUV coronal images from different vantage points. Both approaches have their strengths and weaknesses. Extrapolation methods are sensitive to noise and inconsistencies in the boundary data, and the accuracy of stereoscopy is affected by the ability of identifying the same structure in different images and by the separation angle between the view directions. As a consequence, for the same observational data, the 3D coronal magnetic fields computed with the two methods do not necessarily coincide. In an earlier work (Paper I) we extended our NLFFF optimization code by including stereoscopic constrains. The method was successfully tested with synthetic data, and within this work, we apply the newly developed code to a combined data set from SDO/HMI, SDO/AIA, and the two STEREO spacecraft. The extended method (called S-NLFFF) contains an additional term that monitors and minimizes the angle between the local magnetic field direction and the orientation of the 3D coronal loops reconstructed by stereoscopy. We find that when we prescribe the shape of the 3D stereoscopically reconstructed loops, the S-NLFFF method leads to a much better agreement between the modeled field and the stereoscopically reconstructed loops. We also find an appreciable decrease by a factor of two in the angle between the current and the magnetic field. This indicates the improved quality of the force-free solution obtained by S-NLFFF.

Key words: methods: numerical – Sun: corona – Sun: magnetic fields

1. Introduction

Knowledge of the 3D structure of the solar coronal magnetic field is essential to understand basically all physical processes in the corona. The reason is that the magnetic field clearly dominates and structures the corona, because the plasma β (ratio of plasma and magnetic pressure) is very small. Unfortunately, direct measurements of the coronal magnetic field are not routinely available, and two distinct methods have been developed to reconstruct the coronal magnetic field: (1) extrapolations of photospheric vector fields into the corona under the force-free assumption (see Wiegelmann & Sakurai 2012, for a review) and (2) stereoscopy of coronal images (see Aschwanden 2011, for a review). Neither method is perfect when applied to observational data. Photospheric vector magnetograms contain noise and are not necessarily force-free consistent because of the mixed plasma β in the lower solar atmosphere (Gary 1990). For a stereoscopic reconstruction from different vantage points, we first have to extract loop-like structures from EUV images, identify the same loop in both images (association problem), and finally perform the 3D stereoscopy (large error at the loop top for east-west loops). Consequently, the output of NLFFF and stereoscopy can be different (see De Rosa et al. 2009, for a comparison of NLFFF models and stereoscopy).

It is therefore natural to combine photospheric measures and stereoscopy to obtain coronal magnetic field measurements that comply with both data sets. Several such attempts have been made, but the methods developed so far use the photospheric line-of-sight (LOS) field, rather than the full vector field, as boundary condition. First attempts have been made about one and a half decade ago by Wiegelmann & Neukirch (2002) using linear force-free fields with SOHO/MDI magnetograms as boundary conditions. In this approach, the linear force-free parameter α was computed by comparing the resulting fields with 3D loops from dynamic stereoscopy (see Aschwanden et al. 1999). At that time, well before the launch of STEREO, images from different vantage points were observed using the rotation of the Sun, and it was therefore necessary to limit the method to almost stationary structures. The method was later extended by Carcedo et al. (2003) to compute the linear force-free α also directly from coronal images from one viewpoint alone. In subsequent works, still within the limitations of linear force-free models, projections of the magnetic field loops were used to solve the stereoscopic association and ambiguity problem. The method was dubbed magnetic stereoscopy (see Wiegelmann & Inhester 2006; Feng et al. 2007, for details).

Linear force-free fields have their limitation (see, e.g., Wiegelmann 2008), and in particular, the best-fit values of α for different loops within one active region are different, and α can even change its sign. Aschwanden et al. (2012) incorporated a forward-fitting method that uses analytic expressions and different values of α along different loops, thereby approximating a nonlinear force-free field (NLFFF). The method was refined in Aschwanden (2013a, 2013b), and subsequent code versions allow using 2D loop projections rather than 3D stereo-loops. The method was intensively tested, compared with extrapolations from vector magnetograms, and further refined in a number of subsequent papers (e.g., Aschwanden 2013c; Aschwanden & Malanushenko 2013; Aschwanden et al. 2014; Aschwanden 2016). It was dubbed the vertical-current approximation nonlinear force-free field (VCA-NLFFF) code.
While VCA-NLFFF avoids several problems of magnetic field extrapolations from photospheric vector magnetograms, e.g., the assumption that the boundary data are force-free consistent is not necessary, the method uses only the LOS photospheric magnetic field and not the full vector field.

Malanushenko et al. (2012, 2014) proposed an NLFF field extrapolation method, called quasi-Grad-Rubin, which uses the LOS component of the surface magnetic field and the 2D shapes of the coronal loops from a single image as constraints for their extrapolation. They tested the method with a semianalytic solution and also applied it on observational data.

Within this work, we propose a new method that we call stereoscopic nonlinear force-free field code (S-NLFFF). The method uses both photospheric vector magnetograms (here from SDO/HMI) and stereoscopic reconstructed 3D loops as input. Necessarily providing all these conditions overimposes the boundary condition, and no solution can be found that strictly fulfills constraints that probably contradict each other. The advantage of our new method is that the different constraints (force-freeness, photospheric magnetic field vector, 3D stereo-loops) are all considered as terms of one functional, each weighted with certain Lagrangian multipliers. These free parameters allow us to specify measurement errors (in the photospheric field as well as in the prescribed 3D loops), and the code iterates for an optimal solution in the sense that deviation from the boundary conditions are allowed in regions with a substantial measurement error (photospheric field vector) and reconstruction error (stereo-loops). The method was described and tested with synthetic data in Chifu et al. (2015, Paper I).

The paper is outlined as follows: in Section 2 we briefly describe the methods used for the reconstruction of the 3D coronal loops and of the 3D magnetic field, in Section 3 we present the data used for the reconstructions, in Section 4 we show the 3D reconstruction, in Section 5 we present the results, and in Section 6 we discuss the results.

2. Methods

2.1. Multiview B-spline Stereoscopic Reconstruction (MBSR)

The 3D shape of solar loop-like structures (e.g., coronal loops, prominences, the leading edge of coronal mass ejections) can be obtained using stereoscopic reconstruction. Two-view directions are sufficient for a 3D reconstruction from an ideal data set. The use of more views brings more accuracy to the reconstruction if the data are noisy. The main steps in the stereoscopic reconstruction are the identification of the object to be reconstructed in all of the available views, matching the object by tie-pointing, and the reconstruction (Inhester 2006). As a final step, the stereoscopically reconstructed points from the loop-like structure often need to be smoothed by fitting a polynomial or a spline curve (Chifu 2016).

The main idea of the MBSR method is the reconstruction in one step of an entire loop-like structure. Instead of calculating pairwise reconstructions from multiple views, which in the end needs to be averaged, our code is able to directly reconstruct tie-pointed curves from two or more views. The tie-points do not have to be related by a common epipolar coordinate and can therefore be used directly in more than 2 views. It is designed to yield a unique 3D B-spline as approximation to the reconstructed loop curve, the projections of which optimally match all tie-points in all images. The local error only depends on the projected distances of the tie-point positions to the final spline curve (Chifu 2016).

2.2. Stereoscopic Nonlinear Force-free Field Extrapolation (S-NLFFF)

The modeling of the magnetic field in the solar corona is possible under certain assumptions. The plasma β model by Gary (2001) shows that in the corona the magnetic pressure dominates the plasma pressure and gravity effects, and the kinematic ram pressure of plasma flows are also small (Wiegelmann & Sakurai 2012). In this approach, called the force-free field assumption, the Lorentz force vanishes and has to fulfill the nonlinear equation \( (\mathbf{j} \times \mathbf{B} = 0) \) together with the solenoidal condition \((\nabla \cdot \mathbf{B} = 0)\).

To model the coronal magnetic field using nonlinear force-free field extrapolations, we need surface observations of all three components of the magnetic field as boundary condition. We solve the force-free equations with the help of an optimization approach, which has originally been proposed by Wheatland et al. (2000) and was extended by Wiegelmann (2004) and Wiegelmann & Inhester (2010). Recently, the NLFFF optimization method was extended by constraining the magnetic field to be aligned to the 3D coronal loops that are stereoscopically reconstructed from EUVI images (Chifu et al. 2015).

The essential approach of the extended S-NLFFF method is to minimize a scalar cost function \(L_{\text{tot}}\), which consists of a number of terms that quantify the constraints that the final solution should satisfy. The terms of the functional are

\[
L_1 = \int_V w_i \frac{|(\nabla \times \mathbf{B}) \times \mathbf{B}|^2}{B^2} d^3r, \\
L_2 = \int_V w_i |\nabla \cdot \mathbf{B}|^2 dr^3, \\
L_3 = \int_S (\mathbf{B} - \mathbf{B}_{\text{obs}}) \cdot \text{diag}(\sigma_n^{-2}) \cdot (\mathbf{B} - \mathbf{B}_{\text{obs}}) d^2r, \\
L_4 = \sum_i \int_{c_i} \frac{1}{\sigma_c^2} |\mathbf{B} \times \mathbf{t}_i|^2 ds,
\]

where \(t_i = \frac{dc_i}{ds}\).

The function to be minimized is

\[
L_{\text{tot}} = \sum_n \xi_n L_n,
\]

where \(\xi_n\) are regularization weights. Our experience from Chifu et al. (2015) suggests \(\xi = 1\) as an acceptable choice for the weights.

The computational box has an inner physical domain surrounded by a buffer zone on the top and lateral boundaries. The force-free and divergence-free conditions are satisfied if the first two terms (Equations (1) and (2)) are minimized to zero. \(w_i\) is a boundary weight function that is set to unity in the physical domain, and it decreases monotonically to zero toward the outer buffer zone (see Wiegelmann 2004, for more details).

The third term (Equation (3)) minimizes the differences between the observed and modeled magnetic field at the bottom boundary, while the fourth term (Equation (4)) minimizes the angles between the modeled magnetic field and the tangents of the stereoscopically reconstructed loops. In Equation (3), \(\sigma_n(r)\) are estimated measurement errors for the
three field components $q = x, y, z$ on $S$ (see Tadesse et al. 2011, for more details). In Equation (4), $\sigma_i(s)$ is a relative measure of the estimated error of the tangent direction $t_i(s)$ along the loop $i$. A detailed description of the NLFFF optimization method (the $L_1$, $L_2$, and $L_3$ terms) can be found in Wheatland et al. (2000), Wiegelmann (2004), and Wiegelmann & Inhester (2010), and the S-NLFFF method (the $L_4$ term) is described in Chifu et al. (2015).

3. Observational Data

One of the criteria for selecting the data set was the separation angle between the two STEREO spacecraft. The stereoscopic reconstruction requires a separation angle between the view points larger than zero degrees and smaller than 180°. For the selected event, the separation angle with respect to the center of the Sun between the two STEREO spacecraft was approximately 147°, between STEREO A and SDO 77°, between STEREO B and SDO 70° (Figure 1).

Another selection criterion was the position of the active region on the solar surface as seen from the SDO spacecraft. As the accuracy of the photospheric field measurements become strongly reduced toward the limb, we choose ARs close to the disk center as seen from SDO (Figure 1, middle panel). A data set that fulfills these criteria is the active region AR 11087, which was observed on 2010 July 15. We performed the 3D stereoscopic reconstruction using simultaneously extreme ultraviolet ($\lambda = 171$ Å) images recorded by the EUVI telescope on board STEREO A and B and by the AIA telescope on board SDO. The EUVI telescope has a FOV of up to 1.7 $R_S$ ($\approx$1182.7 Mm) and a spatial sampling of 1.6 arcsec pixel$^{-1}$ (Wuelser et al. 2004). AIA on board SDO takes EUV images with a FOV of 1.5 $R_S$ and 0.6 arcsec pixel$^{-1}$ spatial sampling at each 12 s (Lemen et al. 2012). For the extrapolation of the NLFFF we used vector magnetograms provided by HMI/SDO (Figure 2).

4. Data Reconstruction

4.1. Two- and Three-view Stereoscopic Reconstruction

One of the very important steps in 3D stereoscopic reconstruction is the correct identification and matching of the objects for reconstruction (e.g., coronal loops). In an ideal case, the objects for reconstruction have to be clearly visible and therefore easily identifiable.

In many of the solar EUV observations the objects for reconstruction are not traceable in a straightforward manner. According to Stenborg et al. (2008), the main reasons for poor visualization of the data are the low contrast between the coronal structures and the background and the multiscale nature of the coronal features. Another reason is that in the EUV images we see the LOS integration of the radiation emitted by all the loops in a particular wavelength band. A variety of data

![Figure 1. Images of the Sun with the active region AR 11087 from three different views observed on 2010 July 15 at 08:14 UT in 171 Å wavelength. The red rectangle marks the active region. In the left panel we display the EUVI/STEREO B image, in the middle panel we show the AIA/SDO image, and in the right panel we provide the EUVI/STEREO A image.](image1.png)

![Figure 2. HMI/SDO vector magnetogram observed on 2010 July 15 at 08:14 UT.](image2.png)
processing procedures exists to enhance the visibility of the loop structures (Stenborg et al. 2008). The best method for our data processing we found to be the noise-adaptive fuzzy equalization method developed by Druckmüller (2013). The method is based on histogram equalization and unsharp masking. We have applied this method for all of the three EUV images used in our 3D reconstructions.

While some of the visualization problems can be resolved with image processing techniques, other problems such as saturated pixels cannot be resolved. In the data from STEREO A and B patches of saturated pixels restrained our identification and the matching possibilities required by the reconstruction.

The configuration of the three spacecraft does not provide images with a visibility of the entire AR from all three vantage points simultaneously. Even though the data captured by the spacecraft fulfill our selection criteria, the position of the three telescopes limits the number of loops that we can identify, trace, and reconstruct. While the SDO satellite (see Figure 1, middle panel) has a full view of the AR, the STEREO A (see Figure 1, right panel) and B (see Figure 1, left panel) spacecraft were viewing a limited common area. In spite of all these above difficulties, we were able to identify 10 loops. Three loops were traced in all of the three images, 3 more loops in STEREO A and SDO, and 4 loops in STEREO B and SDO.

In Figure 3 we show the projection of the 3D stereoscopically reconstructed loops together with their tie-points (the black crosses) in each of the EUV images. In Figure 4 we present the 3D configuration of the Sun, represented as a gray sphere, and the direction of the three spacecraft together with the 3D reconstructed loops. The red loops are reconstructed using all three spacecraft simultaneously, the blue loops are reconstructed using the data from STEREO A and SDO, and the green loops are based on the data from STEREO B and SDO.

### 4.2. S-NLFFF Reconstruction

The S-NLFFF reconstruction uses as input the photospheric vector magnetograms provided by SDO/HMI and the 3D reconstructed loops described above. The HMI vector-magnetograms are mapped from the Helioprojective Cartesian to the Carrington Heliographic—Cylindrical Equal Area (CRLT/ CRLN-CEA) coordinate system (Bobra et al. 2014) in which we compute the 3D field reconstruction. The stereoscopically reconstructed loops were first calculated in Heliospheric Earth Equatorial coordinates and then mapped to the Carrington Heliographic coordinate system.

The computational box is $480 \times 272 \times 240$ (pixels)$^3$, which is the equivalent of $350 \times 198 \times 175$ (Mm)$^3$. In Figure 5 we show a 3D plot of the radial component of the magnetic field,
color-coded at the bottom surface, along with the 3D stereoscopically reconstructed loops above.

The NLFF field reconstructions are calculated iteratively from an initial magnetic field until the field has relaxed to a force-free state. In order to clarify how the final solution depends on the initial field and also to determine the impact of the loop data, we present alternative solution strategies.

Typically, the initial field for the iteration is the potential field $B_{pot}$ determined in the entire box from the normal component of the surface field. As an alternative, we iterate $B_{pot}$ first on a coarse $240 \times 136 \times 120$ grid and map the force-free field thus obtained from the coarse to the final $480 \times 272 \times 240$ grid (so-called multiscale approach). This interpolated force-free field is then used as initial field for the final iteration. For the coarse-grid iteration, the boundary data are resampled accordingly from the original vector magnetogram data. To show the effect of the loop data, we switch the loop constraint on, at different stages of the iteration.

We present here the result from five different setups.

**Setup 1:** Starting from $B_{pot}$, we iterate the force-free solution using the NLFFF on the final $480 \times 272 \times 240$ grid without loop data. This is the conventional approach.

**Setup 2:** Starting from $B_{pot}$, we use S-NLFFF on the final grid, i.e., we include the loop data from the beginning of the iterations.

**Setup 3:** We use the solution from Setup 1 as initial field for an iteration with S-NLFFF.

**Setup 4:** We start from $B_{pot}$ on the coarse grid and interpolate the coarse-grid force-free solution as initial field ($B_{coarse}^{NLFFF}$) for NLFFF on the final grid. No loop data are used.

**Setup 5:** We use the interpolated coarse-grid field from Setup 4 as initial field ($B_{coarse NLFFF}^{NLFFF}$) for S-NLFFF.

The natural approach would be to apply the S-NLFFF method on the fine grid (Setup 2) and to evaluate the $L_1$, $L_4$ (Equations (1)–(4)) and the angles between the magnetic field and the tangents of the 3D loops. We apply the S-NLFFF method to Setups 2, 3, and 5 to determine which setup provides the best solution. We run the Setup 3 to see whether the force-freeness is maintained, and at the same time, the angles are minimized. Metcalf et al. (2008) claimed that the solution of the multiscale version of the NLFFF converges to a lower $L$ (Equation (6)) value when compared with the single-grid solution. For this reason, we considered the multiscale approach for the NLFFF and S-NLFFF method.

### 5. Results

We calculated the angles ($\theta_{B_{ij}}$) between the magnetic field ($B_{NLFFF}$) obtained with the NLFFF optimization method and the tangents ($t_{ij}$, $j = 1...10$, $i = 1...100$) of the 3D stereoscopically reconstructed loops (see Figures 6, 7). The angles are calculated for each position $i$ along the $j$th loop. Different colors represent different loops. The misalignment angles between $B_{NLFFF}$ and $t_{ij}$ are on average $20^\circ$ and reach a maximum of approximately $60^\circ$ (see Figure 6). The angles from Figure 6 are obtained using $B_{NLFFF}$ as a result of Setup 1, but the same profile is obtained using $B_{S NLFFF}$ from Setup 4.

By applying the S-NLFFF method, the angles $\theta_{B_{ij}}$ between $B_{S NLFFF}$ and $t_{ij}$ were reduced by a factor of more than 20, as shown in Figure 7. For the calculation of the final angles $\theta_{B_{ij}}$ from Figure 7, we used $B_{S NLFFF}$ as a result of Setup 5. Nevertheless, Figure 7 is also representative for the angles between the 3D loop tangents and the $B_{S NLFFF}$ obtained as a result of Setup 2 and 3.

With the S-NLFFF method we could recover a magnetic field that is closer to the force-free condition. In Table 1 we present the values for the terms of the functional (see the detailed description of the terms in Wiegelmann 2004; Wiegelmann & Inhester 2010; Chifu et al. 2015), namely the force-free ($L_1$), term, the divergence of the magnetic field ($L_2$) term, the closeness with the bottom boundary observation ($L_3$) term, and the closeness with coronal observable ($L_4$) term. The residual values of the functional terms when applying the S-NLFFF method are lower than those obtained with the NLFFF method for Setup 2 and 3, but they are slightly higher for Setup 5.

We evaluated the angles ($\phi_{B_{i}}$) between the magnetic field and the current for each loop along the loop. We derived the $\phi_{B}$ angles between the NLFFF, the S-NLFFF field, and the current. To compare the two cases, we calculated the root mean square (rms) of the angles $\phi_{B_{i}}$ for each loop. This is a critical test because the current $J$ is derived by differentiation from the magnetic field $B$, which amplifies the noise, especially where the field strength is low. In Figure 8 we show the rms of $\phi_{B_{i}}$ for each loop. Here we present the angles derived using the $B_{NLFFF}$ obtained as a solution of Setup 1 and the $B_{S NLFFF}$ obtained as a solution of Setup 5. The evolution of the $\phi_{B}$ from Figure 8 is also representative for angles derived using the NLFFF solution of Setup 4 and the S-NLFFF solution of Setups 2, 3, and 5. The
current is more aligned with the magnetic field after using the reconstructed 3D loops as constraint for the S-NLFFF method.

6. Discussions

De Rosa et al. (2009) compared different coronal NLFFF models with EUV coronal loops observations. The conclusion of the study was that the misalignment angles between the extrapolated NLFFF field and the 3D stereoscopically reconstructed loops reaches a maximum of approximately 45°. In agreement with the results of De Rosa et al. (2009), we derived similar angles between the magnetic field ($B_{NLFFF}$) obtained with NLFFF optimization method (for Setup 1 and 4) and the tangents $t_{ij}$ of the 3D stereoscopically reconstructed loops (see Figure 6).

In a previous paper (Chifu et al. 2015), we presented and tested the S-NLFFF method with semianalytic data. The results of the tests predict that the S-NLFFF method is capable of reducing the values of the $\theta_{B_{ij}}$ angles to below 2°. In all of the cases studied in this paper, the S-NLFFF method was capable to reduce the angles even further (see Figure 7).

In an ideal case, the residual values of the functional terms $L_1$–$L_4$ (Equations (1)–(4)) would be zero. Since the observational data contain errors and the magnetic field model is based on certain assumptions, the residual values cannot be exactly minimized to zero. The lower the residual value $L_1$ (Equation (1)), the closer the field to the force-free condition. For Setups 2 and 3, S-NLFFF was able to bring the magnetic field closer to a force-free solution than the reference field (Setup 1).

From evaluating the rms angles ($\theta_{B_{ij}}$) between the current and the magnetic field, we were able to obtain an improvement in the average alignment for all of the three setups. The high values in the angle between the force-free magnetic field and the current are probably due to the large uncertainties in the horizontal vector field component, in particular in the weak regions of the magnetic field. Even for Setup 5, for which the residual values for the force-free terms did not improve when applying S-NLFFF, the average angle along the loop between the field and the current became smaller. Overall, the new method that includes the constraints from the corona improves not only the agreement between modeling and observations, but also improves the force-freeness of the obtained magnetic field.

For most of the 3D stereoscopically reconstructed loops used as constraint for the magnetic field, the S-NLFFF method is able to reduce the angles between the magnetic field and the 3D loop tangents to below 2°. Nevertheless, there are a few loops for which the angles between $B_{NLFFF}$ and $t_i$ remain large after S-NLFFF treatment. These loops have a deviation of $\geq 65°$ when compared with the NLFFF model field (Setups 1 and 4). When this field was used as initial condition for S-NLFFF (Setup 3), the average angle was reduced by a factor of 2–10, but not to below 5°.

In this paper we presented the performance of the S-NLFFF method using 10 3D coronal loops as a constraint for modeling the coronal magnetic field. For these 10 loops we showed that the S-NLFFF method can obtain a good agreement between the modeled coronal magnetic field and the coronal loops observations. The S-NLFFF method can also obtain a much better alignment between the current and the magnetic field, which is an indication that we obtain a better field in terms of force-freeness. The residual value of force-free integral value (Equation (1)) decreases only little. The reason is probably that the few loops we included improve the field in their local environment, but have limited impact on metrics, which average over a much larger volume. We believe that more loops that occupy a larger part of the computational box will also improve the quality measures over the entire box.

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### Table 1

The Residual Values of Each of the Functional Terms

| Configuration | No. Grids | Initialization | Methods       | $L_1$ | $L_2$ | $L_3$ | $L_4$ |
|---------------|----------|----------------|---------------|-------|-------|-------|-------|
| Setup 1       | one      | $B_{Rot}$      | NLFFF         | 5.2   | 3.2   | 12.9  | ...   |
| Setup 2       | one      | $B_{Rot}$      | S-NLFFF       | 4.6   | 2.7   | 12.2  | 0.0011|
| Setup 3       | one      | $B_{NLFFF}$    | S-NLFFF       | 4.9   | 3.0   | 11.5  | 0.0041|
| Setup 4       | two      | $B_{Rot}$      | NLFFF         | 3.7   | 2.2   | 12.2  | ...   |
| Setup 5       | two      | $B_{NLFFF}$    | S-NLFFF       | 4.0   | 2.3   | 11.9  | 0.0007|

![Figure 8. Root mean square of the angles between the current and the extrapolated NLFFF (green squares), and the extrapolated S-NLFFF (orange triangles) for each of the 3D loops.](image-url)

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