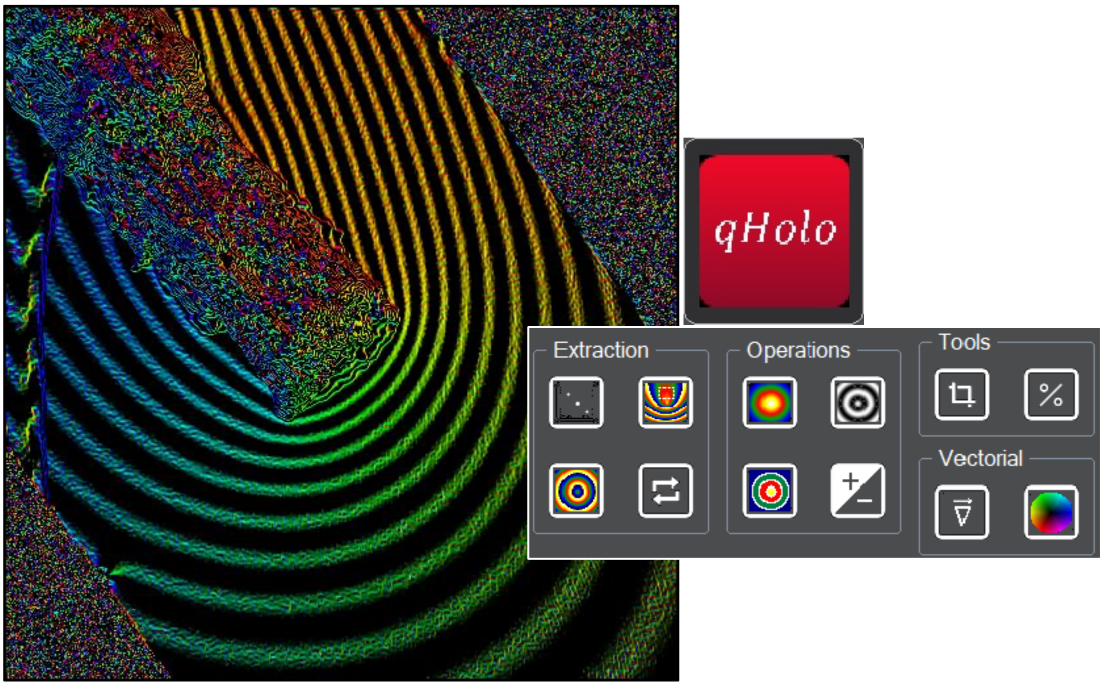
March, 2025

qHolo
for DigitalMicrograph

Quantitative analysis for
off-axis electron holography



qHolo Manual 1.1 Provisional

HREM Research Inc

Conventions

The typographic conventions used in this help are described below.

Convention	Description
Bold	Used to denote components of the user interface such as buttons, field names, menus, and menu options. For example, the **New** button.
Menu...MenuOption	Select the menu from the menu bar then select the menu option from the menu. For example, **File...Open** would mean to select the **File** menu and then the **Open** option.
CAPS	Used to denote the name of a key on the keyboard. For example, the ENTER key.
Italics	Used to denote emphasis, captions and the result of an action in a procedure.

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Introduction to qHolo

Welcome to the *qHolo* plug-in for DigitalMicrograph (Gatan Inc.). The software provides all the tools you need to carry out the quantitative analysis of off-axis electron holograms, or any other interference patterns for that matter. In particular, the software was designed for the analysis of magnetic and electric fields. This area of electron holography is known as "medium resolution" as opposed to high-resolution electron holography that aims to image atomic structure.

The software is designed for off-line analysis, for quantitative analysis and the highest precision. For at-the-microscope help with holography, please use the *HoloLive!* module dedicated to live reconstruction of the hologram phase during experiments.

Here are the main features of *qHolo*:

- Phase reconstruction using the Fourier transform method
- Automatic side-band detection
- Carrier frequency refinement via user-defined reference area
- Distortion correction via a reference hologram
- Phase unwrapping
- Phase gradients
- Quantification of magnetic and electric fields
- Vector field visualisation tools

qHolo has been developed over a number of years and the original scripts have already been used in several publications:

[1] C. Gatel, B. Warot-Fonrose, N. Bizière, L. A. Rodriguez, D. Reyes, R. Cours, M. Castiella, M.-J. Casanove, **Nature Communications** 8, 15703 (2017). *Inhomogeneous spatial distribution of the magnetic transition in an iron-rhodium thin film*. [10.1038/ncomms15703]

[2] C. Gatel, X. Fu, V. Serin, M. Eddrief, V. Etgens, B. Warot-Fonrose, **Nano Letters** 17, 2460−2466 (2017). *In Depth Spatially Inhomogeneous Phase Transition in Epitaxial MnAs Film on GaAs(001)*. 10.1021/acs.nanolett.7b00144

[3] C. Gatel, J. Dupuy, F. Houdellier, M.J. Hÿtch, **Appl. Phys. Lett.** 113, 133102 (2018). *Unlimited acquisition time in electron holography by automated feedback control of transmission electron microscope*. 10.1063/1.5050906

[4] M. Brodovoi, K. Gruel, A. Masseboeuf, L. Chapuis, M. Hÿtch, F. Lorut, and C. Gatel, **Appl. Phys. Lett.** 120, 233501 (2022). *Mapping electric fields in real nanodevices by operando electron holography*. 10.1063/5.0092019, hal-03752638

[5] C. Gatel, R. Serra, K. Gruel, A. Masseboeuf, L. Chapuis, R. Cours, L. Zhang, B. Warot-Fonrose, and M. J. Hÿtch, **Phys. Rev. Lett.** 129, 137701 (2022). *Extended charge layers in metal-oxide-semiconductor nanocapacitors revealed by operando electron holography*. 10.1103/PhysRevLett.129.137701, hal-03787333

[6] L. Zhang, F. Lorut, K. Gruel, M.J. Hÿtch, and C. Gatel, **Nano Letters** 24, 5913-5919 (2024). *Measuring electrical resistivity at the nanoscale in phase-change materials*. 10.1021/acs.nanolett.4c01462

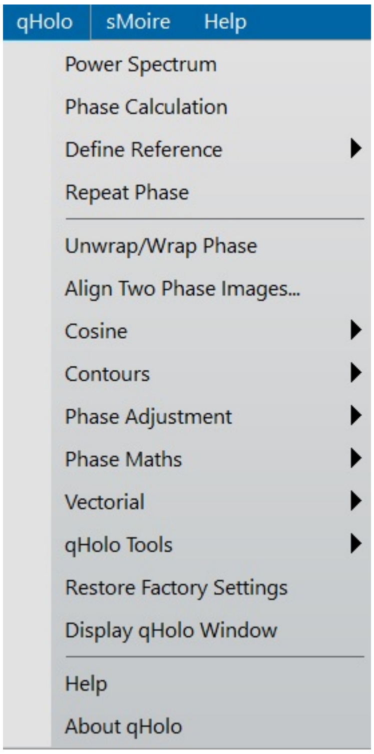
This manual is more of a tutorial: we will go through the main functions of *qHolo* step by step with a prepared example. For details of all the commands you can use the Quick Reference Guide.

Glossary of abbreviations and technical terms

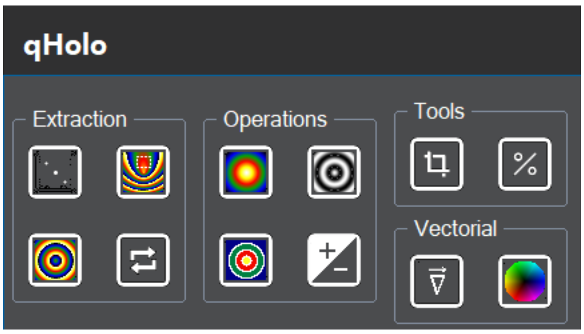
DM	Digital Micrograph (Gatan Inc.)
q	Carrier frequency vector
ROI	Region of interest

But before starting, there are a few important points to remember:

1. *qHolo is a plug-in for DigitalMicrograph (Gatan Inc.)*. This means that results are fully compatible with the other functions present in DM. For example, profiles drawn across the live phase images using the **DM line profile tool** will be automatically updated. Similarly, any calibration of the images within DM will be transferred to the phase images.
2. *The complete list of commands related to qHolo* are located in the menu:



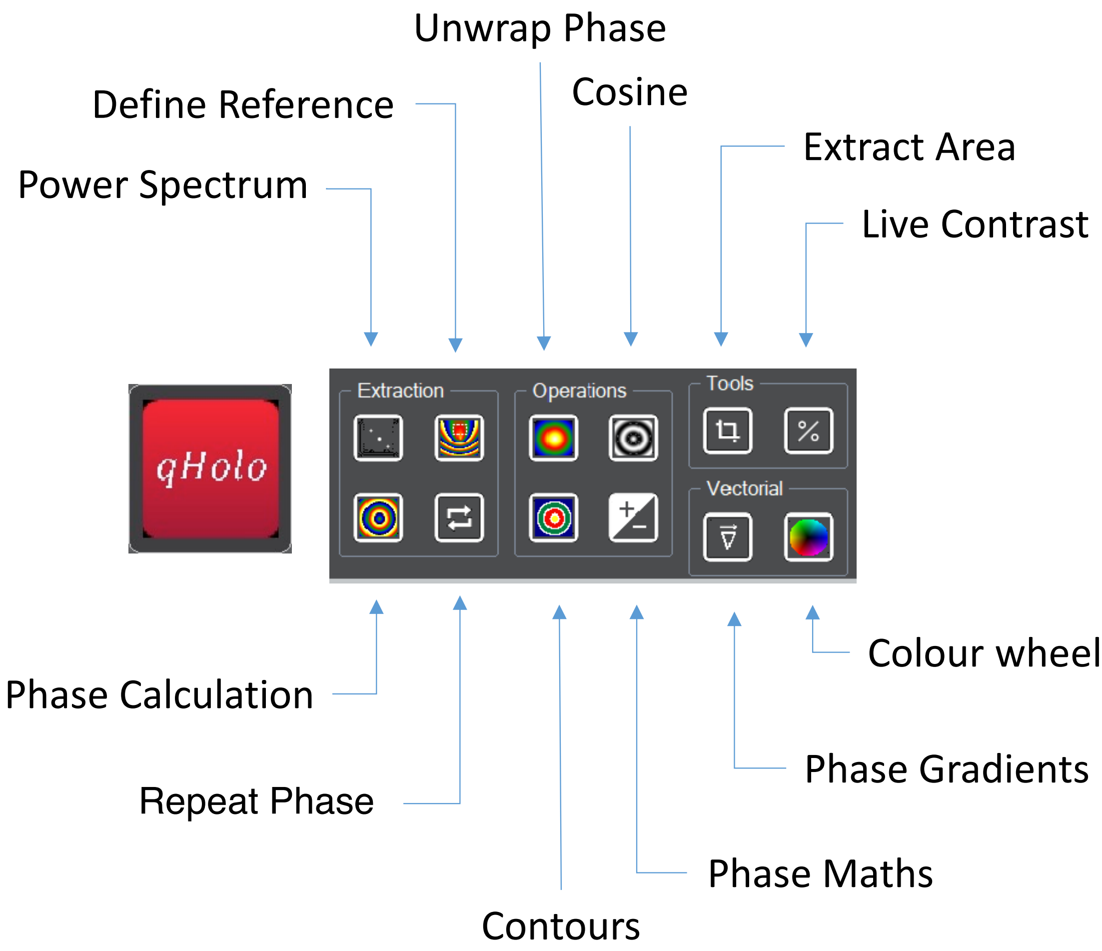
3. *However, it is more fun to access command using the* ***qHolo Control window*** below. You have direct access via the Technique Manager (**DM Window>Floating windows>Technique Manager**).



Technical note: For GMS 2.x, the window can be opened from the last menu item of the qHolo menu: Display qHolo Window.

In the following, we will assume use of the **qHolo** control window but everything can be accessed via **qHolo** menu, along with all the others.

A summary of the features can be seen below:

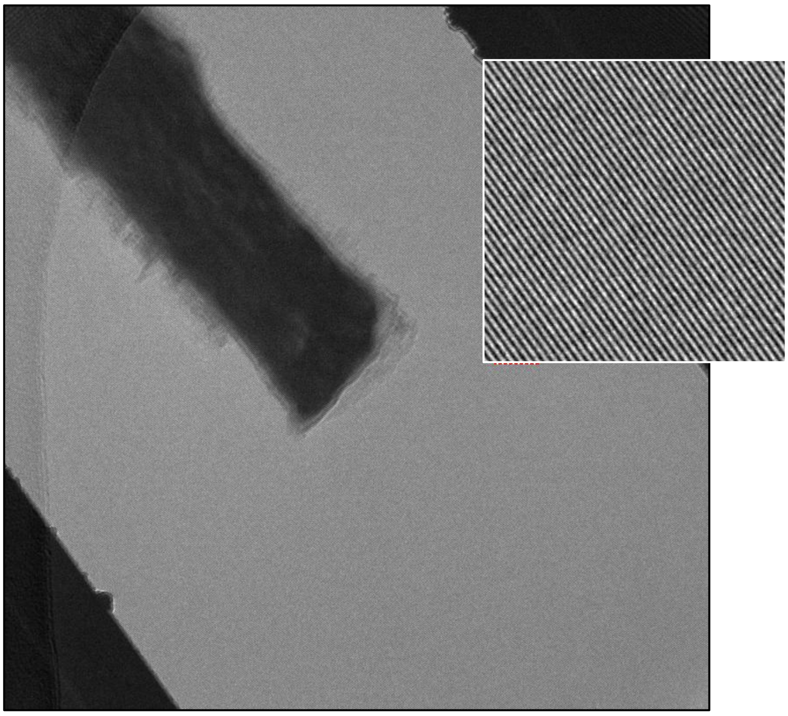


Note: Clicking on a button with **CTRL** key down will reveal the Settings (if available).

qHolo Tutorial

Getting Started

Open the image “qHolo Obj” using the DM command **File…Open** from the qHolo Manual folder:



Technical note: this hologram was acquired on the I2TEM microscope in Toulouse (Hitachi HF 3300-C) using a 4K OneView camera (Gatan Inc.)

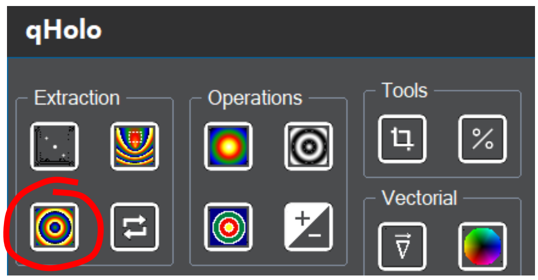
Hint: right-click on the image to make the DM image tools to appear

The hologram is of a metallic nanowire supported by a holey carbon grid which you can just see on the top left. We call this the Object Hologram, hence the “Obj” in the title, which indicates the hologram contains the region of interest of the specimen. Later, we will encounter the Reference Hologram, taken in a field-free region of vacuum.

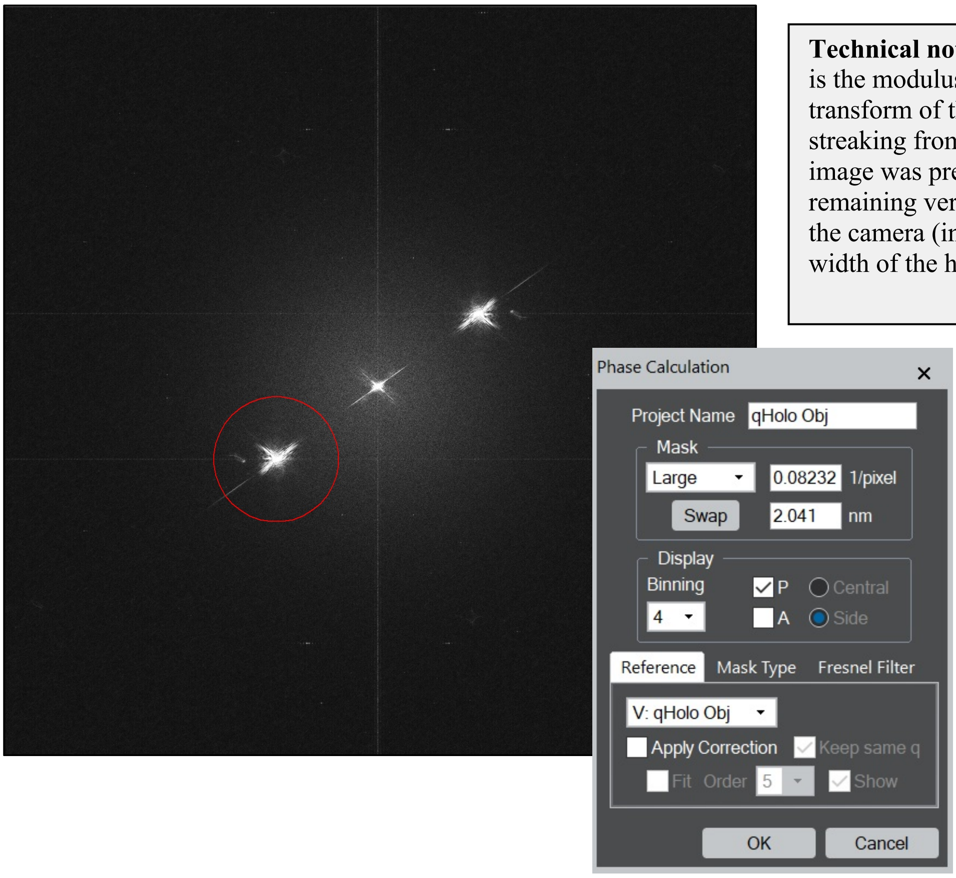
Use the **DM magnifying glass tool**  to zoom in to see the narrow holographic fringes. The fringes do not fill the full field of view, hence the dark regions in the top-right and bottom-left corners. The fringes are only formed in the overlap region in the centre. We also used the ingenious two biprism method so that no Fresnel fringes are present in the hologram[1].

qHolo…Phase Calculation

Now let us calculate the phase by clicking on the **Phase Calculation** button or selecting Phase Calculation from the qHolo menu. The Power Spectrum will appear along with a floating menu.



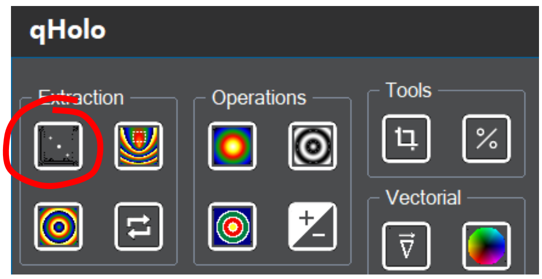
[1] K. Harada, A. Tonomura, Y. Togawa, T. Akashi, T. Matsuda, Appl. Phys. Lett. 84, 3229 (2004). *Double-biprism electron interferometry*. 10.1063/1.1715155



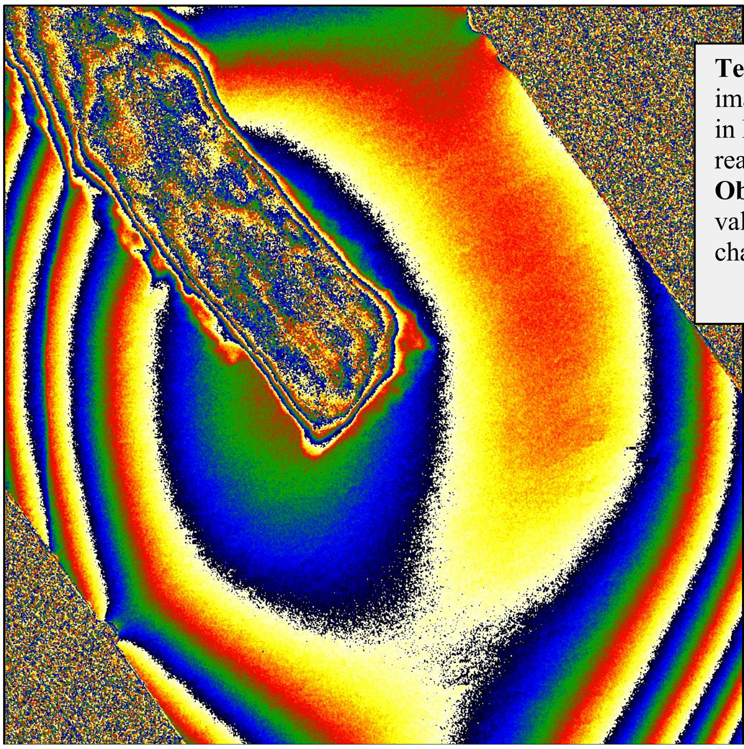
Technical note: the power spectrum is the modulus squared of the Fourier transform of the image. To avoid streaking from edge effects, the image was prefiltered. Any remaining vertical streaking is due to the camera (in this case) or the finite width of the hologram.

Notice that the side band (at carrier frequency **q**) has been automatically detected. The red circle indicates the cut-off radius of mask. If for some inexplicable reason (this is a worked example!) there is no circle, or the circle is in the wrong place, press **Cancel**. The Phase Calculation Window will disappear allowing you place a **DM Rectangular ROI tool**  around the side band. Press again on **Phase Calculation** to find the side band position within the ROI. Just make sure the ROI encloses the sideband spot.

Indeed, if you prefer starting this way, you can do so by using the **Power Spectrum** button or command. The Power Spectrum will appear and you can choose the sideband by placing a Rectangular ROI. Clicking on **Phase Calculation** will display the floating menu with the chosen sideband. In practice, most people prefer using the **Phase Calculation** command directly with automatic sideband selection.



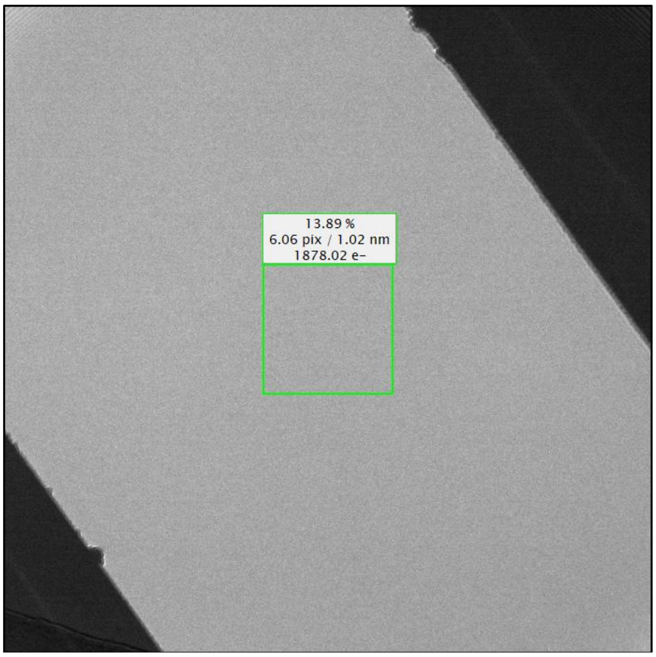
We will look at the other features later, but for now just click on **OK** for the phase calculation, and you should see your first phase image, called “qHolo Obj P”:

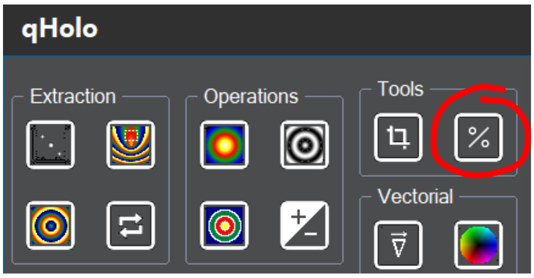


Technical note: we like displaying phase images using the “Temperature” colour scale in DM but you can use grey scales if you really want, just use the DM menu **Object…Image Display…Color**. The actual values in the phase image will not be changed, only its appearance.

This is what we call a raw object hologram: it has not been corrected for any distortions. For example, the phase changes rapidly at the edges of the field of view. This is caused by the projector lenses of our microscope. On a finer scale, you may be able see that there is a hexagonal contrast from the fibre optics of the camera. We can eliminate these features using a Reference hologram.

Open the image “qHolo Ref” and use the **qHolo…Live Contrast** button to examine the quality of the fringes:

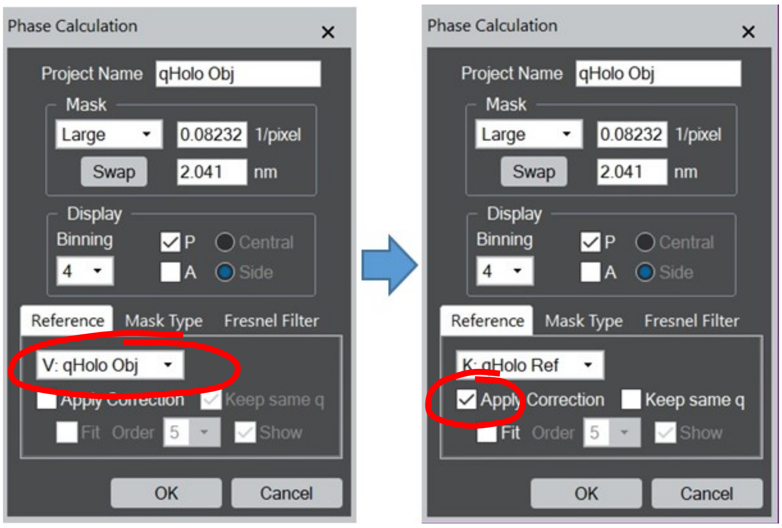




Technical note: the Live Contrast ROI can be moved and is updated automatically. The percentage at the top gives the fringe contrast, below is given the fringe spacing in pixels and physical units if the hologram image is calibrated, and on the bottom the mean intensity.

The nanowire has been moved away before taking this hologram so that in principle only the artefacts from the projector lenses and camera are present. You might notice that there are some dust particles on the biprism, visible at the edges of the overlap region. They are usually charged and can create their own electric field. It is important that they are in the same place for the object and reference holograms, as here. That is why we recommend taking a reference hologram shortly after the object holograms and to move the specimen away with the stage controls rather than the image shifts.

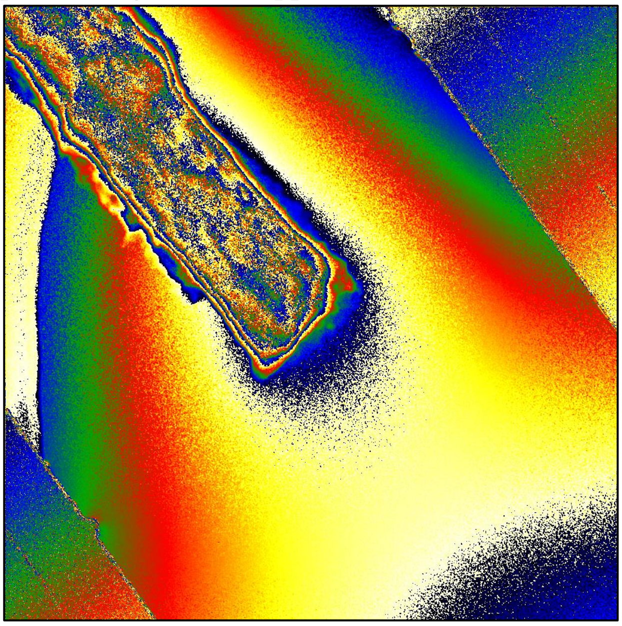
With the reference hologram available, click again on the object hologram and launch the phase calculation as before.



Hint: scrolling menus mimic the order of images on the display, the frontmost image appearing first.

Before lauching Phase Calculation click first on the Reference hologram and then the Object hologram. They will be the first in the list.

Choose the Reference hologram from the scrolling menu and click on the Apply Correction option to tell **qHolo** to use the reference hologram to correct the phase. On **OK**, the corrected phase image should appear:



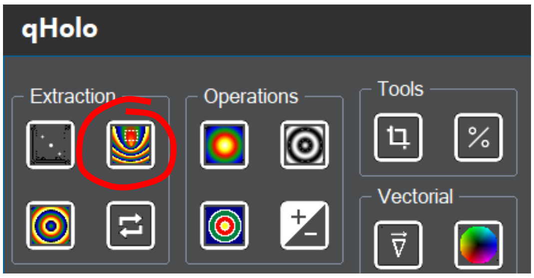
Technical note: in qHolo, every image has a “type”, used in the titles and in the image tags. For example, a phase image is type P.

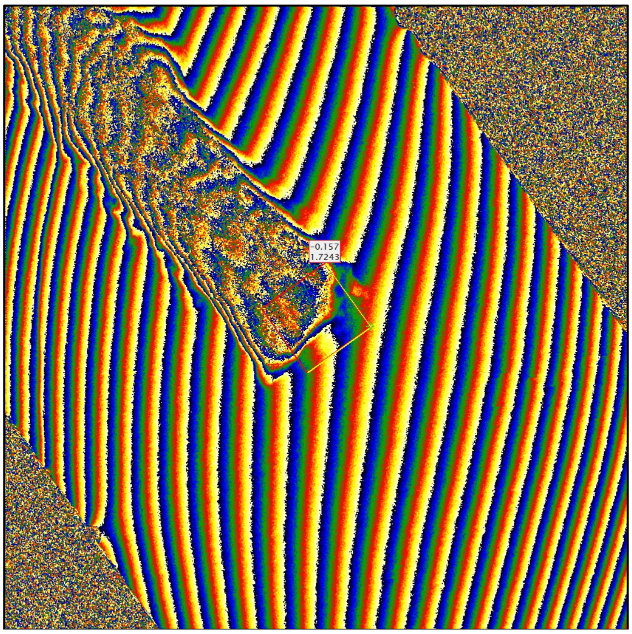
The phase image is smoother and the phase variation around the nanowire is clearer. Within the nanowire, the phase varies rapidly due to the mean-inner potential.

qHolo…Reference Area

The initial value for the carrier frequency **q** came from the analysis of the power spectrum of the hologram. It therefore corresponds to the average position of the fringes, irrespective of the presence of a specimen. It is therefore customary to define a reference area, typically where we expect the hologram fringes to be uniform and undisturbed.

Once a reference area is defined, **qHolo** will determine the average phase gradient in the reference area and subtract the corresponding phase ramp from the whole image. This is equivalent to ensuring that the carrier frequency **q** corresponds exactly to that of the chosen reference area of the hologram. Click on the **Reference Area** button to see what happens:

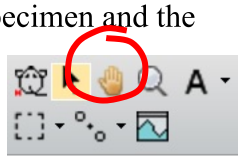


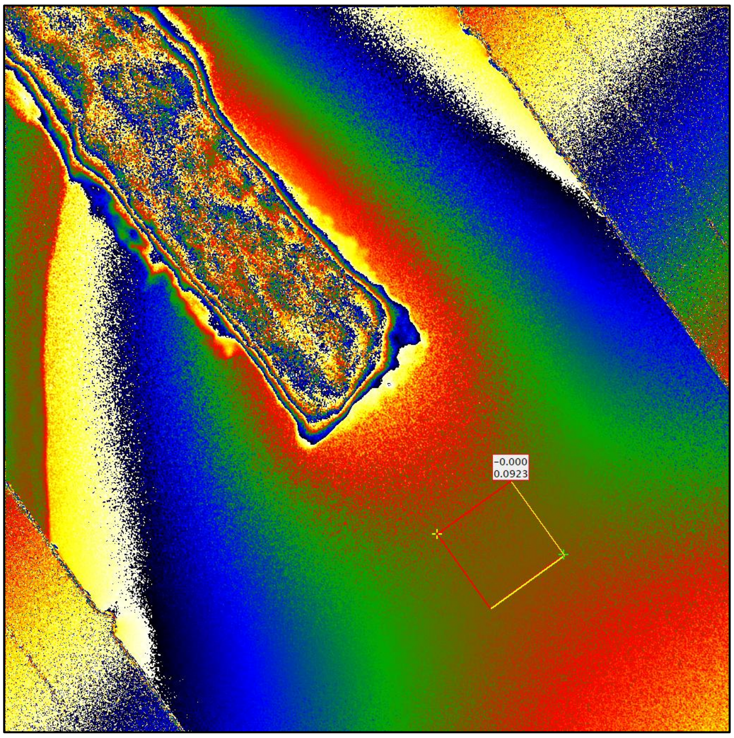


Technical note: the default settings is a reference area at the centre of the image, rotated parallel to the hologram fringes.

These settings can be modified in the **Reference Area** dialog that will be accessed via the **Settings->Reference Area...** menu or by pressing **CTRL** while clicking on the **Reference Area**

We might not consider the resulting phase image as an improvement. However, this is because the default setting for **qHolo** is to define a reference area in the centre of the image. In this case, the centre coincides with a region of the nanowire overlapping the vacuum. The carrier frequency will therefore be set to an average of the fringes in the specimen and the vacuum, which does not make much sense. Take hold of the reference region ROI with the **DM Selection Tool** set to the **Arrow** and slide the reference area towards the vacuum. The result should look something like this:

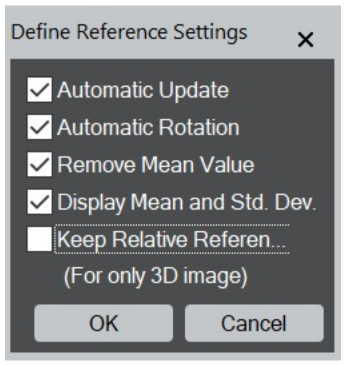




Technical note: the Reference Area ROI is active, in the sense that it reacts when it is moved. It is also an object in a programming sense. If you delete a part of it, it will no longer work. Click on the **Reference Area** button and it will reappear at its last position.

Similarly, if you want to delete it, just select the whole object by clicking with the **DM Arrow** (four green squares should appear) and press the Delete button on the keyboard. Again, clicking on the **Reference Area** button will make it reappear.

The mean phase and standard deviation of the phase in the reference area are displayed on the top left of the reference ROI. Feel free to move the ROI around and you will see the phase image automatically updated (if not, check that the Automatic Update box is ticked in the **Reference Area** dialog. Remember that **Settings->Reference Area...** menu or **CTRL** plus clicking on the **Reference Area** button will display the settings.) You can also change the size, shape and orientation of the ROI by gripping and dragging the different corners.



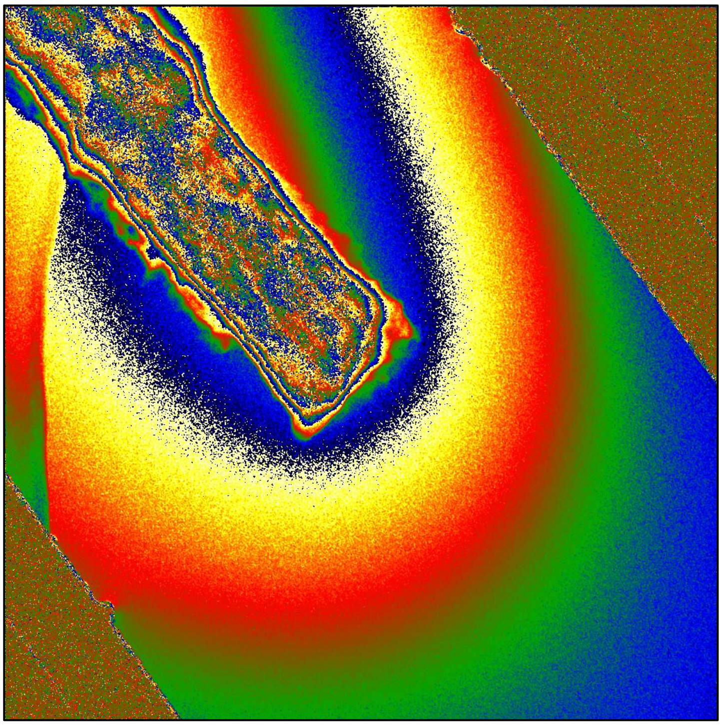
In the default setting, the mean value of the phase in the reference area is set to zero. Unclick this option to see what happens when you move the reference area around. This can be useful to keep a track of the difference in phase between difference parts of the image, for example from one to the other side of the nanowire.

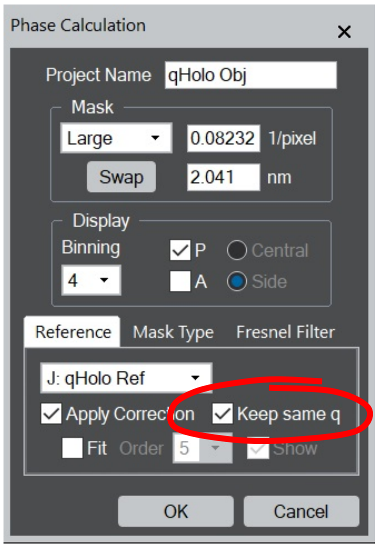
qHolo…Phase Calculation: Keep same q

The reason why there is a net phase change from one side of the nanowire to the other is because there is an electric field present. The nanowire is charged, creating an electric field around the tip. The phase is directly related to the electric potential, integrated along the path of the fast electron, in the viewing direction. The phase in the vacuum therefore varies from place to place: it is not constant. We might legitimately question where the correct reference area should be? This is where an Option in **qHolo…Phase Calculation** comes in handy for quantitative analysis.

You may or may not have noticed this intriguing option when calculating the phase.

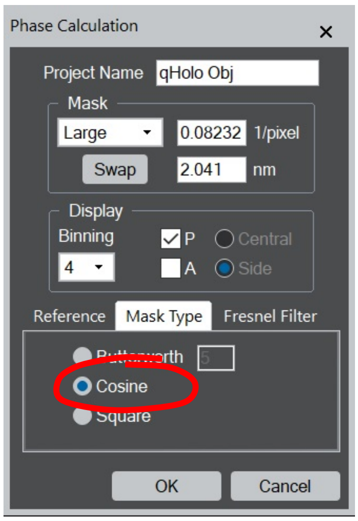
Click on the original hologram image and recalculate the phase but this time with the option **Reference…Keep same q**. You should see the following result.





We can now see the electric potential emanating from the nanowire, as it should do. What has happened? With **Keep same q**, **qHolo** has applied exactly the same carrier frequency for the calculation of the phase of the Object and Reference holograms. Subtracting the two phase images means that we directly see the phase due to the electric field.

It works because in the actual experiment, the Reference hologram was recorded just after the Object hologram, after having moved the sample away with the stage controls. The optical conditions have remained the same and the biprism voltage, position and orientation are the same. This means that the only difference between the two holograms is the electric field. We can therefore assume that the carrier frequency of the Reference hologram is the undisturbed carrier frequency for the Object hologram.



qHolo…Phase Calculation: Mask tab

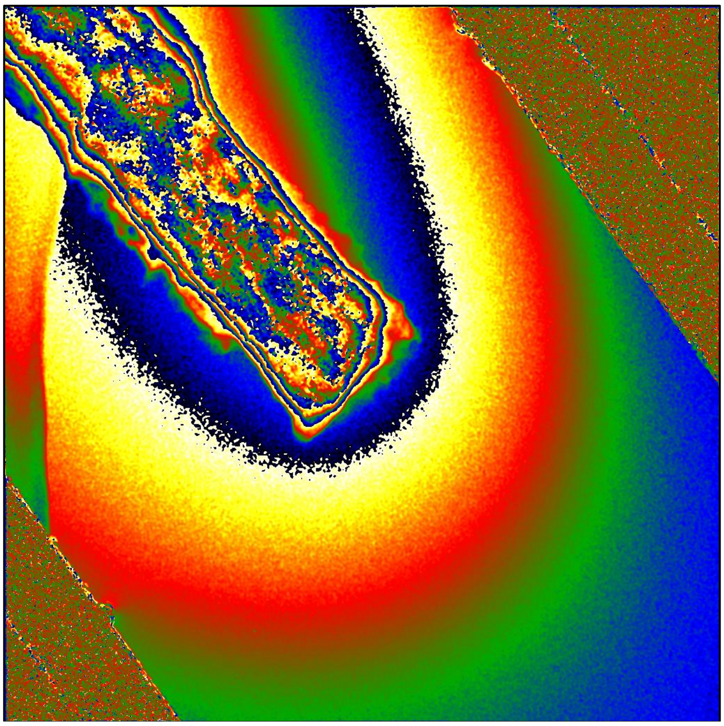
The phase calculation also depends on the mask used to collect the information associated with a given side-band. Have a look at the size options of the **Mask tab**. The shape of the mask depends on both the **Mask Type** and the size.

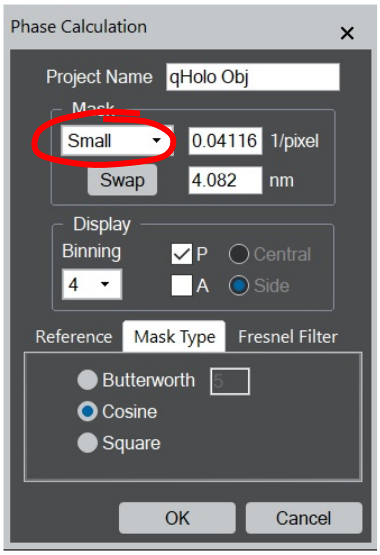
By default, the Mask type is **Cosine**. Its value is the cosine of the distance from the carrier frequency, **q**, normalised in such a way that the mask falls to zero at the chosen cut-off radius, given by the Mask size. The **Butterworth** mask is a standard mask used in image processing and is flatter up to and till the cut-off radius and then drops off rapidly as a function of the power law defined in the box. The **Square** mask is the most basic: it is unity inside a square region defined by the cut-off region and zero beyond. We have included it for completeness.

Feel free to look at the effect the Mask type has on the resulting phase images. The **Butterworth** and **Cosine** give very similar results whereas the **Square** mask can introduce fringing effects at the edges of the phase image. For the rest of the results, we will assume that the **Cosine** mask is in use.

The Mask size, or cut-off radius, is the more important feature. By default, the value is set to **Large**, equivalent to q/2. The actual radius in pixel^{-1} (remember, we are in Fourier space) is indicated in the box. In our case, the cut-off corresponds to 0.08232 pixel^{-1} equivalent to 1/0.08232 = 12.15 pixels in real space. If the original hologram was calibrated, as for this example, the equivalent will be given in real-space units, or 2.041 nm in our case. The phase image will therefore have a spatial resolution of almost exactly 2 nm.

Change the Mask size to **Small** and the result should look something like this:



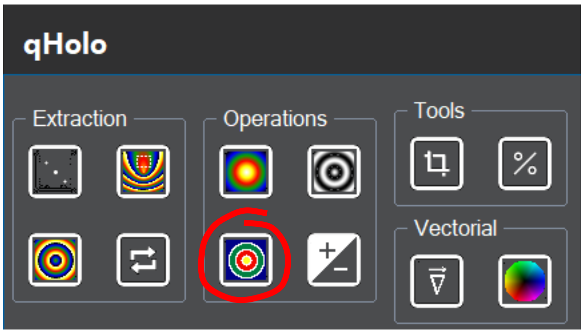


Hopefully, you can see that the phase image appears smoother and less noisy. Indeed, you can measure the effect using **Define Reference**. The standard deviation of the phase in the reference area is now only 0.045 radians, compared with 0.088 radians for the **Large** mask. Indeed, for random variations the standard deviation of the phase is proportional to the reciprocal mask size. The *Small* mask has a radius of q/4, half the **Large** mask. The noise is therefore reduced by a factor of 2.

There was a price to pay of course: the spatial resolution. For the **Small** mask, the spatial resolution is only 4 nm, compared with 2 nm for the **Large** mask. As always, there is a compromise to be made between precision and spatial resolution.

The **Medium** mask completes the standard choices, with a mask size of q/3. For some, this is the maximum size that should be used as the effect of the centre-band is excluded (though see later). **qHolo** does not take sides and we allow any size of mask to be used. Just change the value directly in the boxes, either pixel^{-1} or spatial resolution. The Mask size will then be indicated as **Custom**.

qHolo…Contours

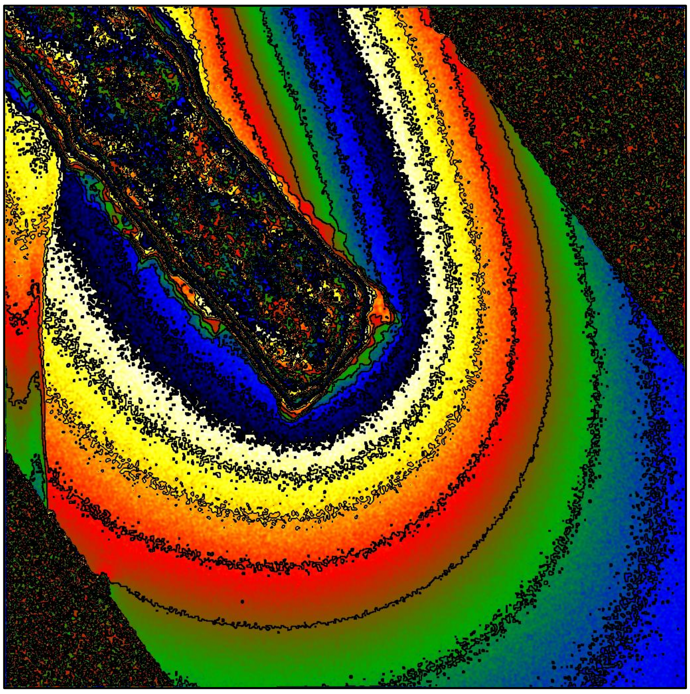


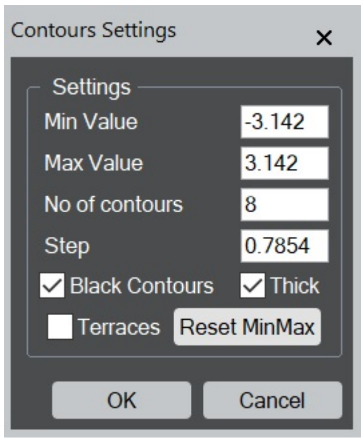
It is sometimes useful to add contours to phase images, either to better understand the results or for presentations and papers.

As usual with **qHolo**, you can access the command using the button on the control window or from the menu.

Click first on the phase image created using a **Small** mask and then on the **qHolo…Contour** button.

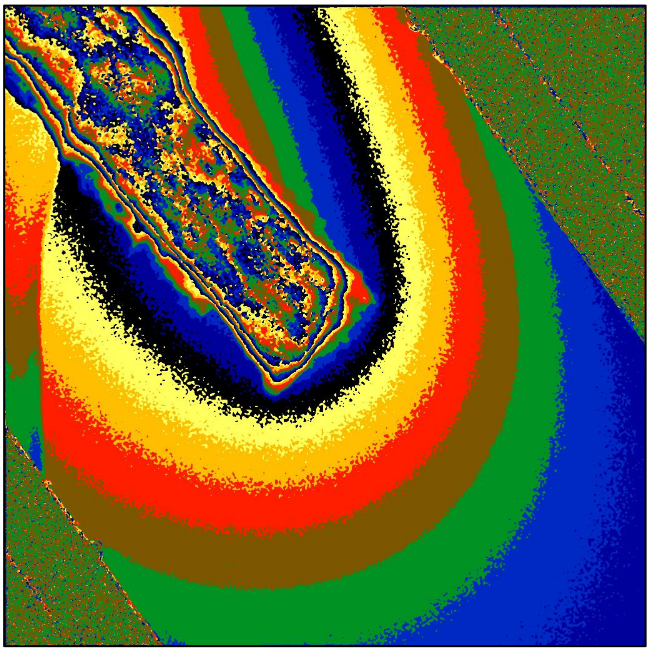
A window will appear with a set of options and settings. The settings include the minimum and maximum value for the contours. By default, qHolo uses the minimum and maximum value of the image, but you can choose what you want by directly changing the values in the boxes. For a phase image, the range of values is usually between $-\pi$ and π, as here. The number of contours, N, defines the Step between the contours. For ordinary images, this will actually mean N+1 contours being presented. We chose this definition to avoid mental gymnastics for determining the Step size, which is the more important parameter. In our case, 8 means that the Step will be the range of values, 2π, divided by 8 giving $\pi/4$ for the separation between contours.

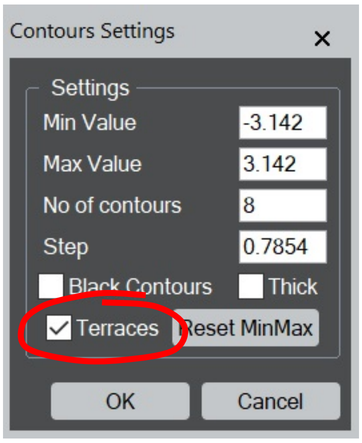




Hint: Contours are very sensitive to noise, so if your contours look much wavier than this example, check your Mask size is set to *Small*.

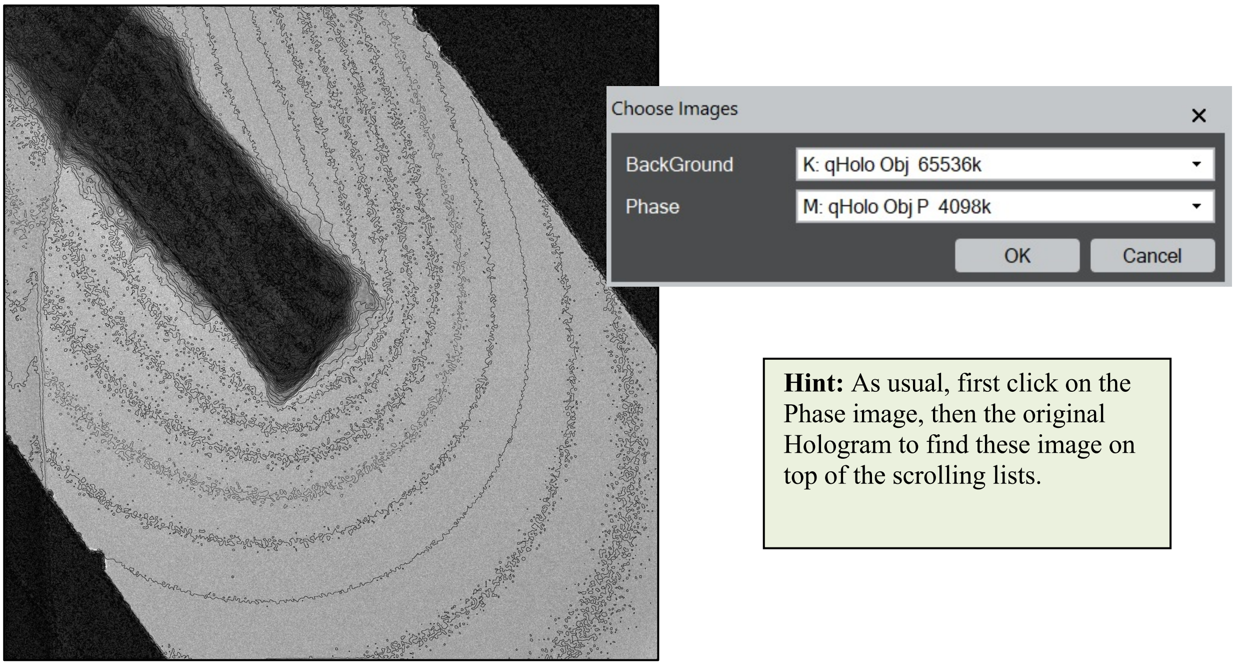
Sometimes, the **Terraces** option can be an attractive alternative. Click on this option to see the result:





qHolo…Contours: Coupled Contours

Sometimes it is useful to display the contours on a different image, for example the original hologram. Examples are given in recent publications.[2,3]



Hint: As usual, first click on the Phase image, then the original Hologram to find these image on top of the scrolling lists.

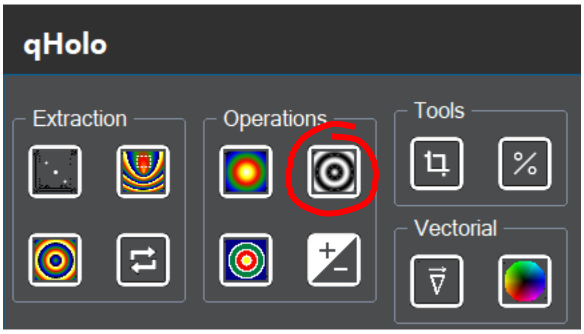
[2] M. Brodovoi, K. Gruel, A. Masseboeuf, L. Chapuis, M. Hÿtch, F. Lorut, and C. Gatel, Appl. Phys. Lett. 120, 233501 (2022). Mapping electric fields in real nanodevices by operando electron holography. 3/5.0092019" 10.1063/5.0092019

[3] L. Zhang, F. Lorut, K. Gruel, M.J. Hÿtch, and C. Gatel, Nano Letters 24, 5913-5919 (2024). Measuring electrical resistivity at the nanoscale in phase-change materials. 10.1021/acs.nanolett.4c01462

Note that this function takes into account a difference in pixel size between the "BackGround" and "Phase" images. Since we have been using Binning 4 for the phase images, the phase image is actually four times smaller in pixel dimensions than the original hologram image.

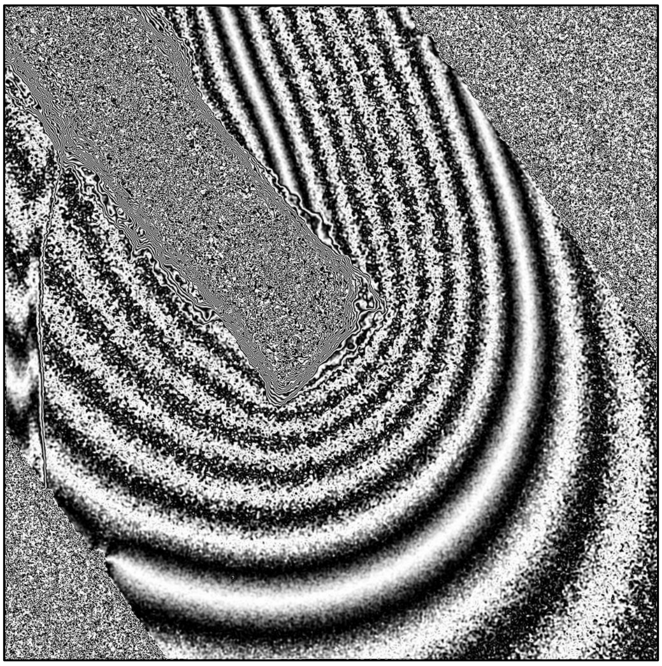
As a final remark, **qHolo…Contours** is not limited to phase images!

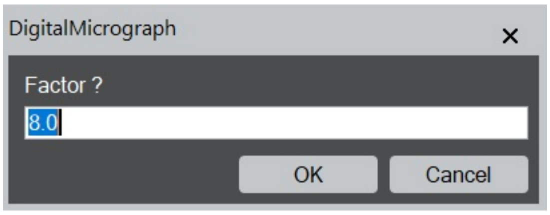
qHolo…Cosine



Another traditional way of representing the phase maps in holography is to display the cosine of the phase, which can be accessed using the **qHolo control window** or through the menu **qHolo…Cosine…Cosine**.

A Dialog will appear asking for the Factor. qHolo will calculate the cosine of the phase multiplied by the factor, a kind of amplification for the phase variations. With a factor of 8 the following image will be obtained:

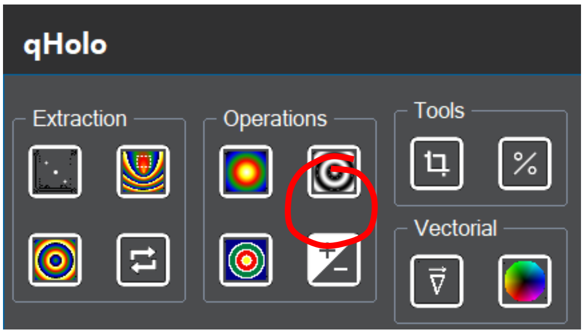




The factor can be changed by clicking on the UP and DOWN ARROWS of the keyboard. The result will be updated live. The various options can be assigned via the Settings. Coupled Cosines can be obtained, similarly but not identically, to the Contours.

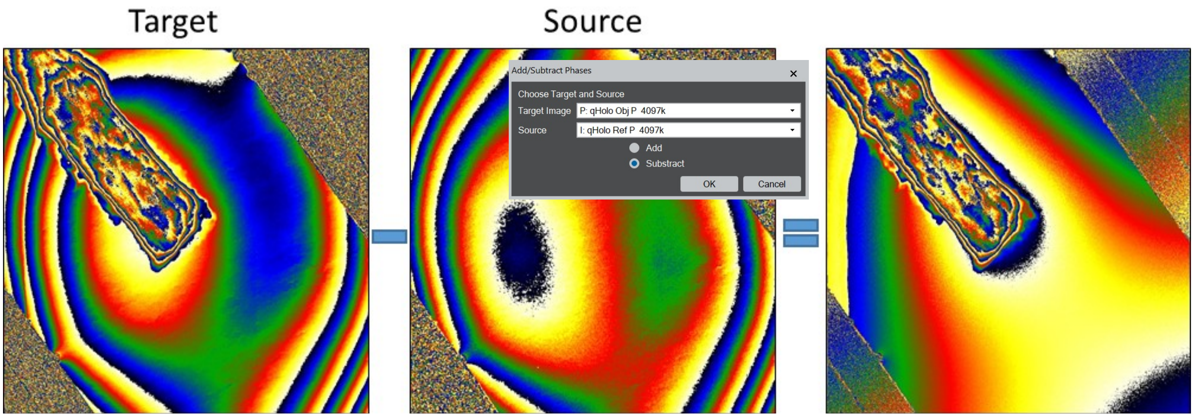
qHolo…Phase Maths

Digital Micrograph provides many ways to add and subtract images, multiply and divide and other operations (see for example **DM…Process…Simple Math…**). However, phase images require some delicacy, notably concerning the normalisation and the preservation of the processing information carried with the image.



The most common operation is the adding and subtracting of two phase images, which can be accessed directly via the qHolo Control Window button, or via the menu **qHolo…Phase Maths…Add/Subtract Phase Images**. As a simple example, let us carry out the reference hologram correction manually.

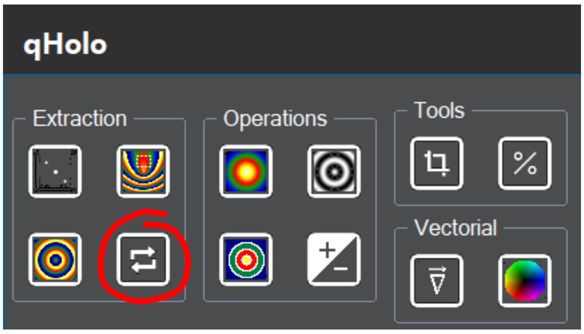
First calculate the phase of the Object hologram, *without applying a reference*. Now calculate the phase of the Reference hologram. Click on the **qHolo…Add/Subtract Phase** button and enter the two images to be subtracted.



You should find the same result as for the **qHolo…Phase Calculation** with the Reference hologram applied.

qHolo…Repeat Phase

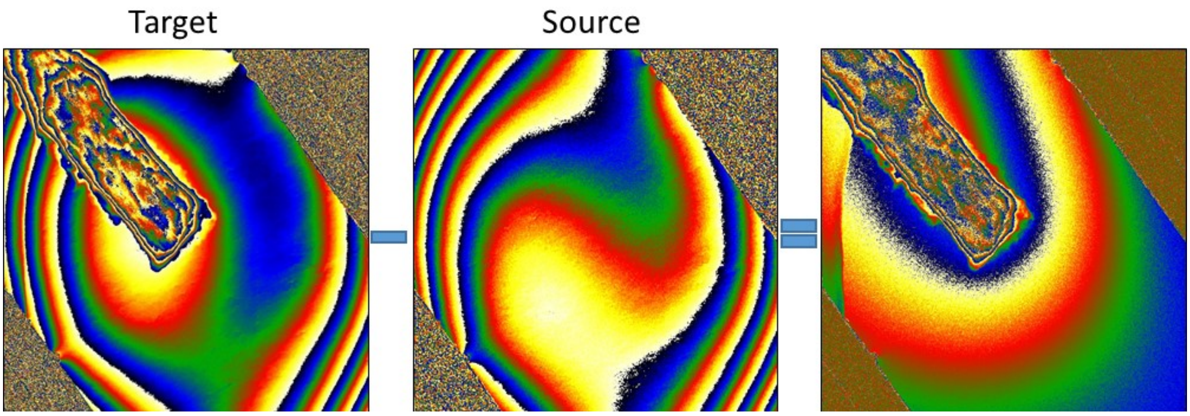
To illustrate one of the subtleties of phase calculations we will use the **qHolo…Repeat Phase** button. This allows phase images to be calculated using identical parameters to the previous case.



To begin, calculate the phase of the Object hologram without using a Reference hologram, as previously. Now, click on the Reference hologram, to make it the frontmost image, and then press on the **qHolo…Repeat Phase** button. You will see the usual dialog window for phase calculations. All of the options and parameters are exactly like the previous phase calculation. For the moment, do not change any of the options, and press OK.

The phase image of the Reference hologram looks slightly different to that calculated previously. What has changed? To understand, subtract the phase image of the Reference hologram from that of the Object hologram using **qHolo…Phase Maths…Add/Subtract Phase images**. The resulting phase is identical to the phase of the Object hologram calculated using the Reference hologram and choosing the option "Keep same q".

Indeed, **qHolo…Repeat Phase** does exactly that. The carrier frequency, **q**, from the previous calculation is applied directly. This means that the phase of the Reference hologram is calculated using exactly the same **q** as the Object hologram. On subtraction we find the previous result. More generally, if you want to compare the effect of a particular parameter, say the Mask size or shape, it is best to use this command. You will be sure that none of the other parameters have been modified between times.



The command is also saves time when many images are to be processed.

qHolo Tags

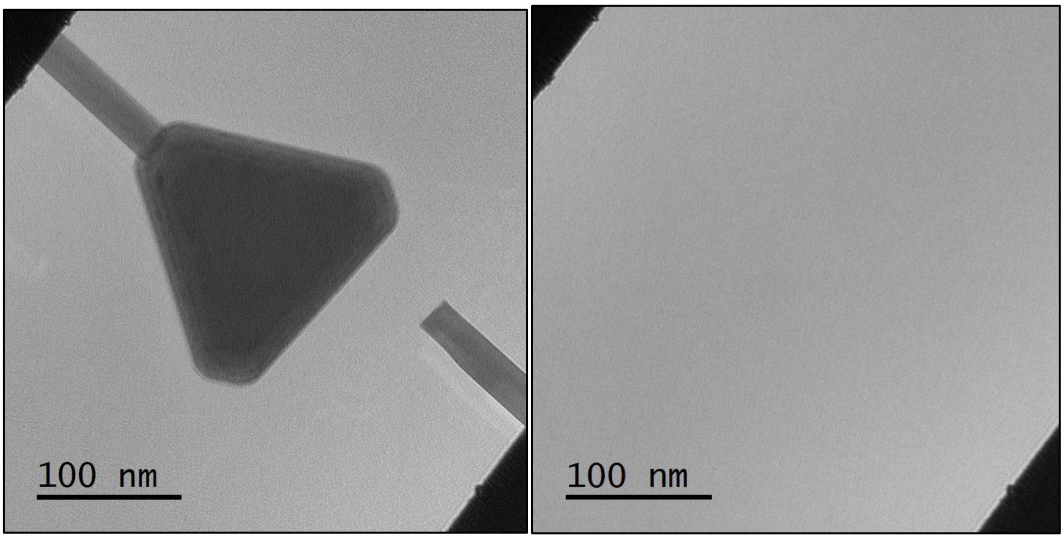
At this point, you may have been wondering how *qHolo* keeps a track of all the parameters and options. In fact, we make ample use of wonderful DM facility of tags. Tags can be global, see **DM…File…Global info…**, or attached to an image, see **DM…Display…Image info…** All the tags related to *qHolo* are in folders called qHolo. If you delete or edit them, expect *qHolo* to behave strangely. They are extremely important as they provide the history of the processing. In principle, it is possible to recreate a phase calculation and processing route just from the information in the tags.

One of the most important tags is the information on the carrier frequency, **q**, stored as the x and y reciprocal pixel vector coordinates. For example, many different phase images can be created from the Object or Reference holograms, as we have seen. Only through the tags can the differences be identified. For example, if you look at the tags of the previous two phase images calculated from the Object and Reference holograms, you will see that the carrier frequencies used were indeed identical.

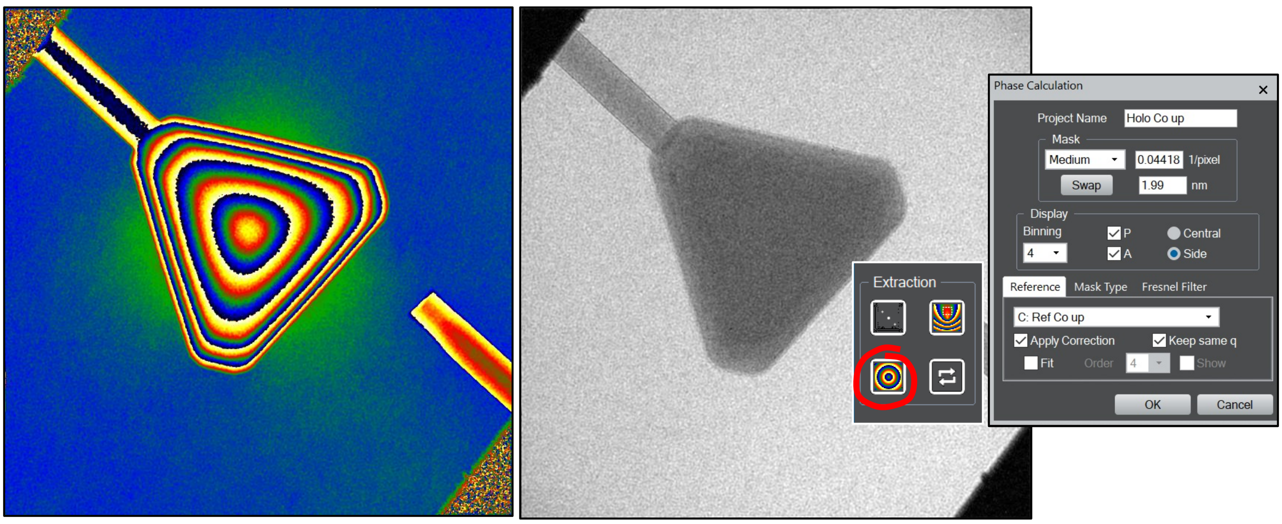
Here ends the first part of the qHolo Manual meant as a rapid overview of the main functions. The next two sections are a tutorial on the quantification of magnetic and electric fields. As always, you can find descriptions of all the functions in the qHolo Quick Reference Guide.

Quantitative Analysis: Magnetic Phase

As a first example of quantitative analysis, let us consider the determination of the phase shift caused by a magnetic field. It will be the opportunity to see some of the features of **qHolo** already described and some new ones as we go along. Open the hologram image intriguingly named “Holo Co up” and its corresponding reference hologram “Ref Co up”:



The object is a long prismatic rod ending in a triangular shape, all made of Cobalt[4]. It was first placed in the strong magnetic field of the objective lens to magnetise the sample in the out-of-plane direction, hence the mention of “up” in the title. The sample was then removed and placed in the Lorentz stage of our Hitachi HF-3300 double-stage microscope where the sample is free from any magnetic field. In other configurations or microscopes, it is also possible to switch off the objective lens and use Lorentz mode to have the field-free imaging and wide field of view. Go on and calculate the phase and amplitude (this will be useful for the alignment later) of the hologram.



[4] W. Huang, C. Gatel, Z.-A. Li, G. Richter, Materials & Design 208, 109914 (2021). *Synthesis of magnetic Fe and Co nano-whiskers and platelets via physical vapor deposition*. [10.1016/j.matdes.2021.109914](https://doi.org/10.1016/j.matdes.2021.109914)

You can see that there is a large phase change within the particle but also a smaller phase change in the vacuum. This is because the phase has two contributions, one from the mean-inner potential (MIP) of the material and the other from the magnetic field:

$$\phi = \phi^{MIP} + \phi^{\mathrm{mag}}$$

All materials have a mean-inner potential that is the result of the average field from the protons of the atomic nuclei and the surrounding electrons. Assuming neutrality, this potential is always positive: the positive charges are more localised than the negative electrons. The phase change of the fast electron is then given by:

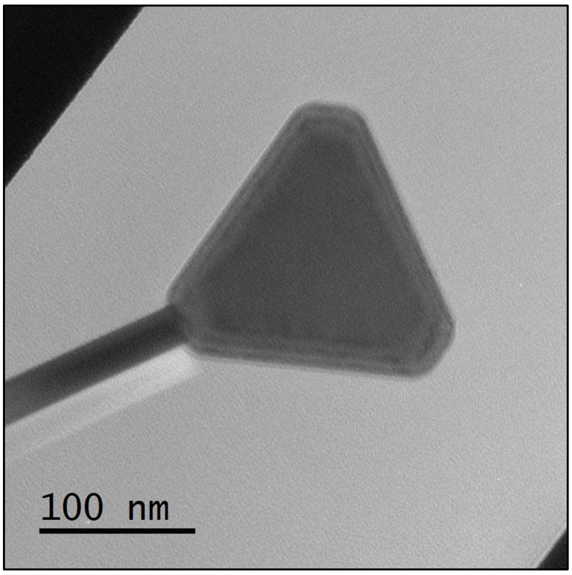
$$\phi^{MIP} = c_E \int V^{MIP} dz$$

where c_E is a constant for a given accelerating voltage. To have the actual value, use **qHolo…qHolo Tools…Calculate Lamda and CE**. The phase change depends on the mean-inner potential of the material in question and the thickness of the sample. You can verify that you have used the correct side-band by seeing that the phase increases within the particle with respect to the vacuum. But this is not the only contribution to the phase. The magnetic field also produces a phase change:

$$\phi^{\mathrm{mag}} = \frac{e}{\hbar} \int A_z dz$$

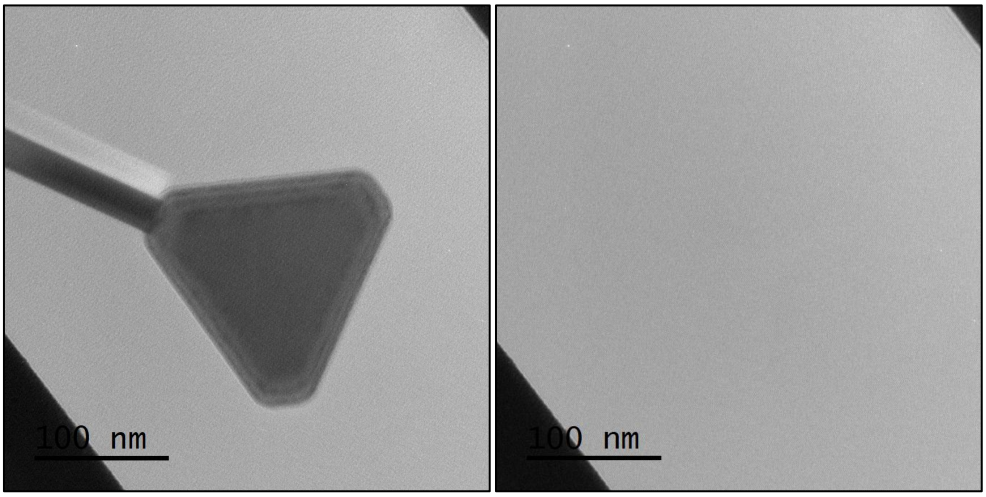
where A_z is the z-component of the magnetic vector potential, **A**. The magnetic phase is always much smaller than the electrostatic contribution but is clearly visible in the vacuum next to the triangle where there is no contribution from the MIP.

The accepted method to eliminate the contribution from the MIP is to invert the magnetic field. This can be achieved by magnetising the sample in the exact opposite condition or, as in our case, flipping over the sample stage and taking another hologram "Holo Co down" under the exact same imaging conditions:

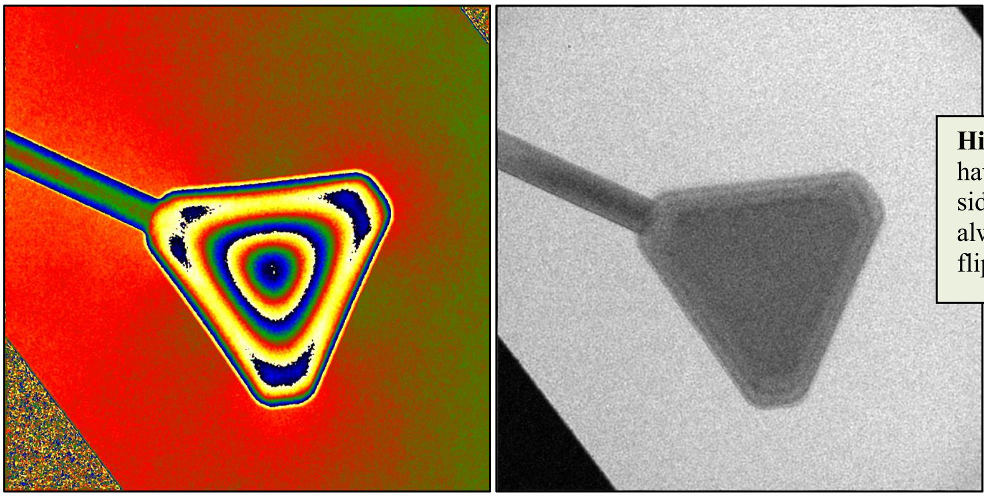


For this hologram the electrostatic contribution will be the same but the magnetic contribution will have changed sign. Subtracting the two phase images will produce the magnetic phase, and adding the two phase image will produce the mean-inner potential phase. This sounds simple but requires a few processing steps as we will see.

First of all, the flipping of the stage means we need to flip the image as well. Use **DM…Process…Flip vertical**, and do not forget to flip the reference hologram too.



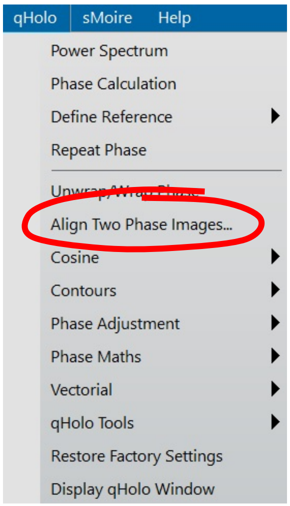
We could also flip all the amplitude and phase images but this method is cleaner. Now calculate the phase and aplitude images using the previous settings:

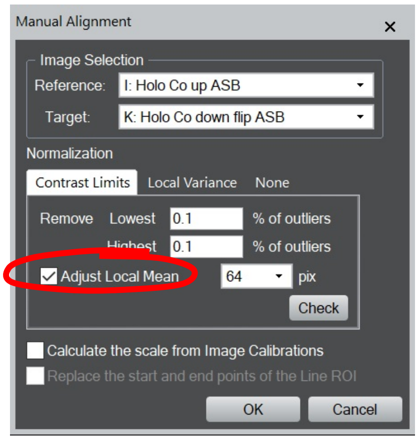


Hint: Check that you have used the correct side-band, which is not always obvious when flipping and rotating.

Align Two Phase Images…

Before adding and subtracting the phases, we need to align the images. Click on the two amplitude images in succession to make them frontmost and launch the command **qHolo…Align Two Phase Images** from the qHolo menu.

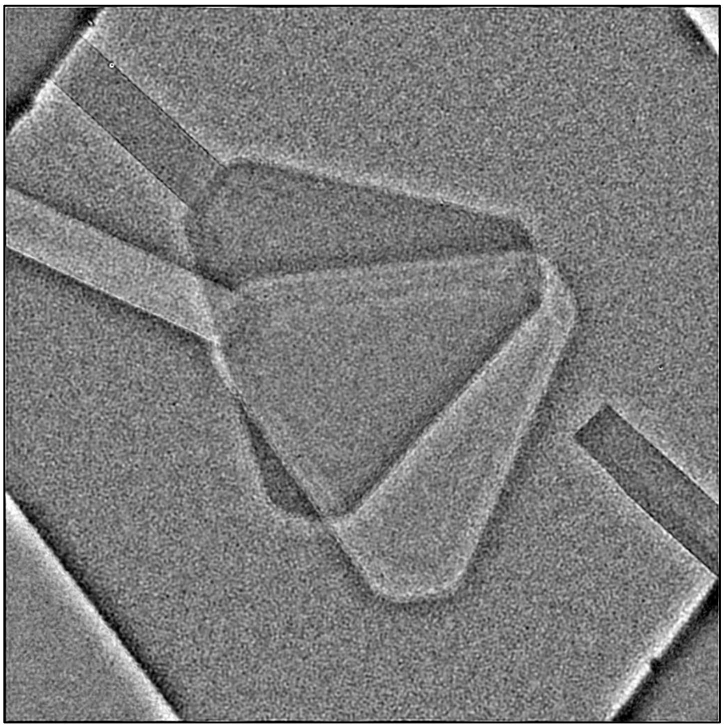


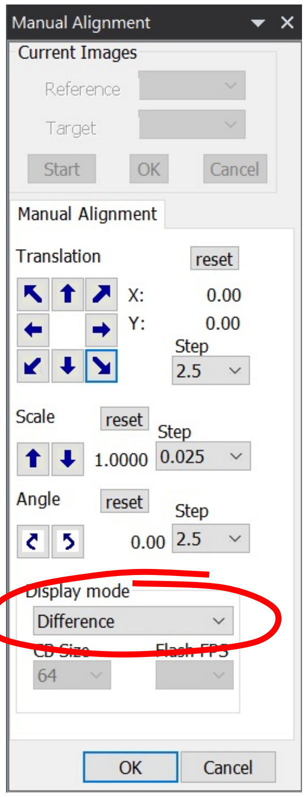


Technical note: the displacement of the **Target** image is measured with respect to the **Reference** image.

In other words, aligning will adjust the Target image so that it is positioned and oriented exactly the same as the Reference image.

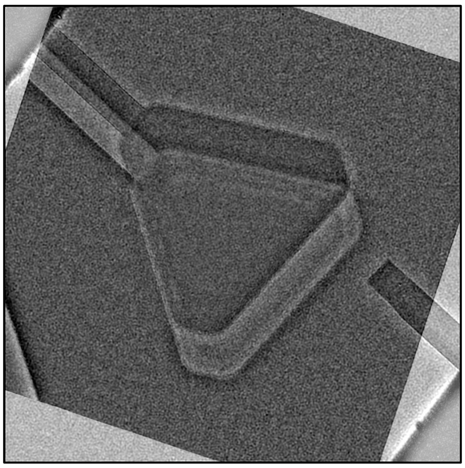
There are different options on this panel. The most important is of course the choice of the two images to align. The result of the alignment will always be applied to the phase images, so you are free to choose the amplitude images to carry out the alignment process, as here. We have also chosen to use the option **Adjust Local Mean**. This option removes large scale intensity variations, thus highlighting the edges of objects. It can be useful for alignment, particularly when the intensity scales of the two images are dissimilar. Press on OK to launch the procedure. You should see two windows appear :

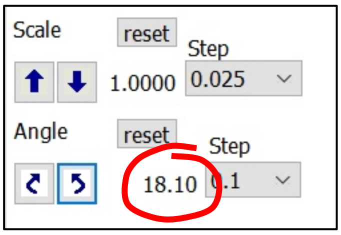




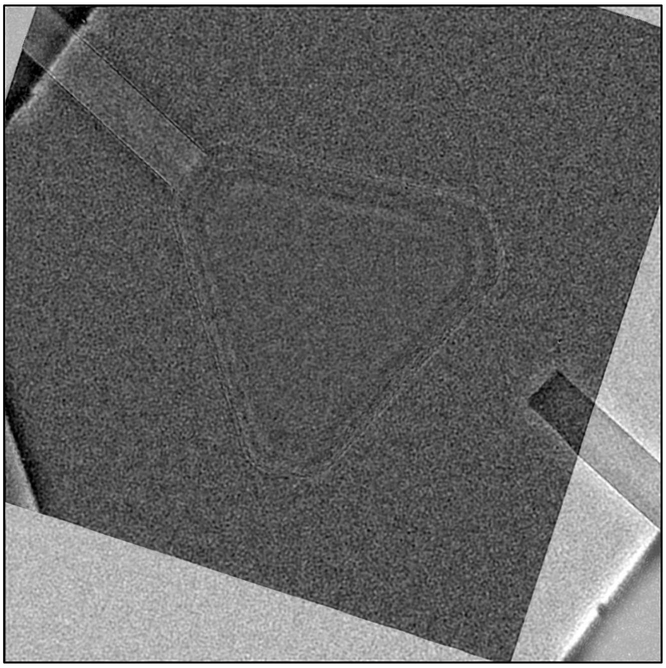
On the left is an image called "Manual Alignment" and on the right, a floating command window ***Manual Alignment***. The image superimposes the Target and Refence images to help visualise the alignment. Check out the different **Display modes** available to find which one works best for you. There is a slight delay when changes from one mode to another.

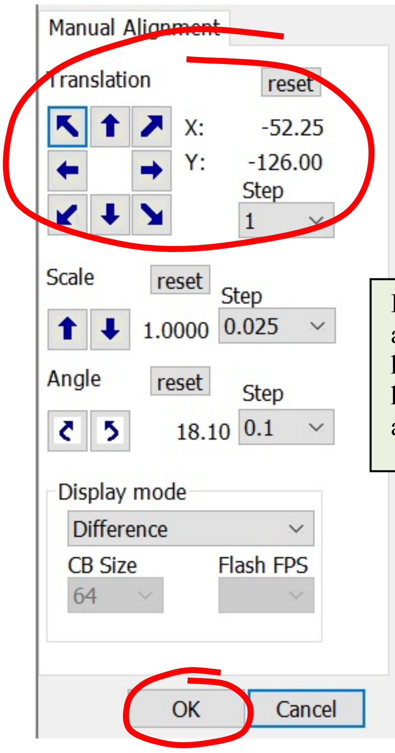
As you can see the images are rotated and shifted with respect to each other. Start with the rotation, by clicking on the toggles beneath **Angle**. The **Step** is initially set to 2.5° but as you refine, you can reduce this to 1° and even 0.1°. A tally of the total applied rotation is shown on the menu, in case 18.10°. At any point you can press on **Reset** to go back to zero.





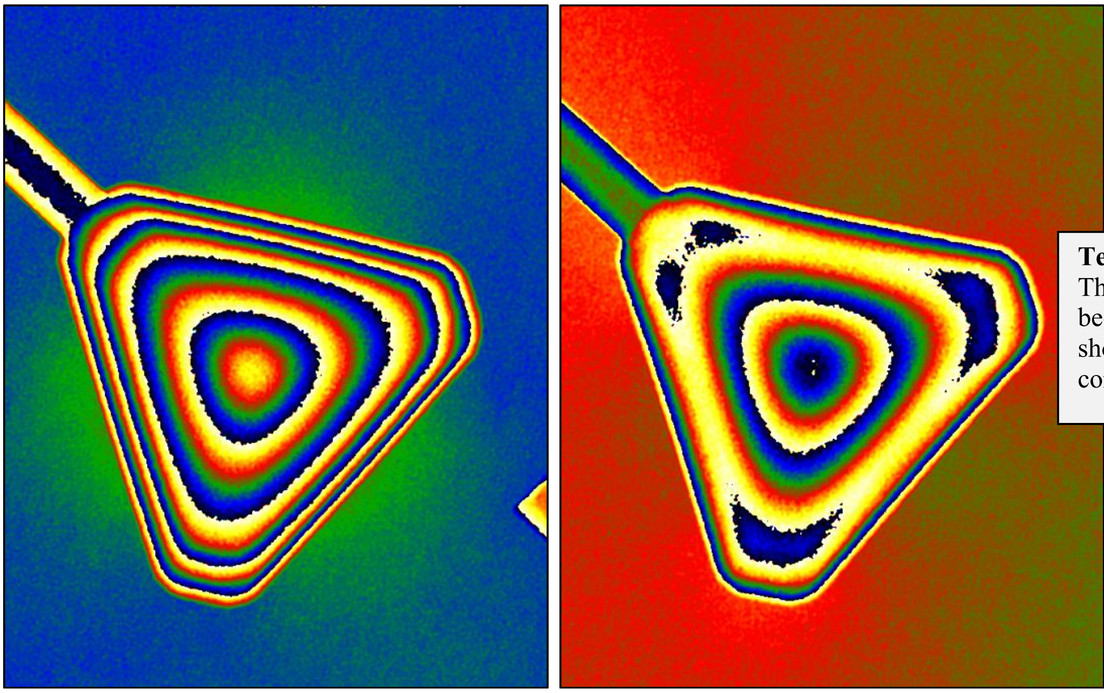
The next step is to deal with the shift between images by clicking on the **Translation** toggles. The Step size starts at 2.5 pixels (in pixels of the binned image) and you can refine all the way down to 0.25 pixels. Once you are happy press OK.





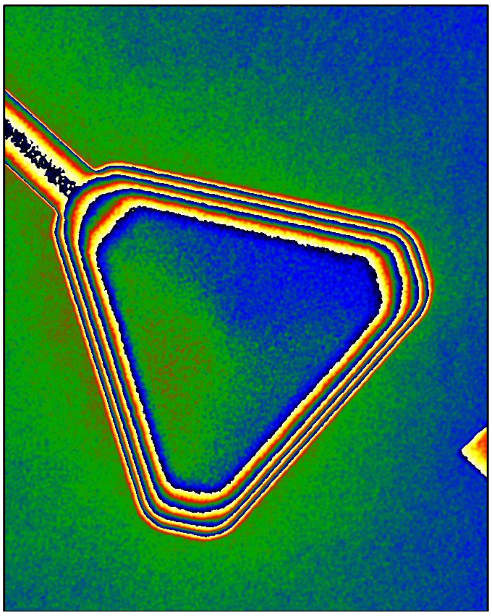
Hint: You can also use the arrow keys of the keyboard for rapid alignment.

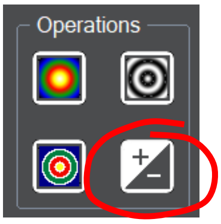
The alignments will be applied to the amplitude and phase images producing a mosaic of aligned images. We show just phase images below :



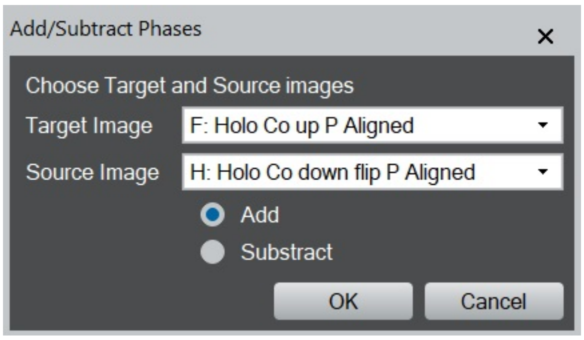
Technical note: The images have been cropped to show only the part common to both.

We are now in a position to separate the MIP and magnetic contributions to the phase. Use **qHolo…Phase Maths…Add/Subtract Phase images**, or the corresponding button on the ***qHolo control window*** to first add the two phase images :

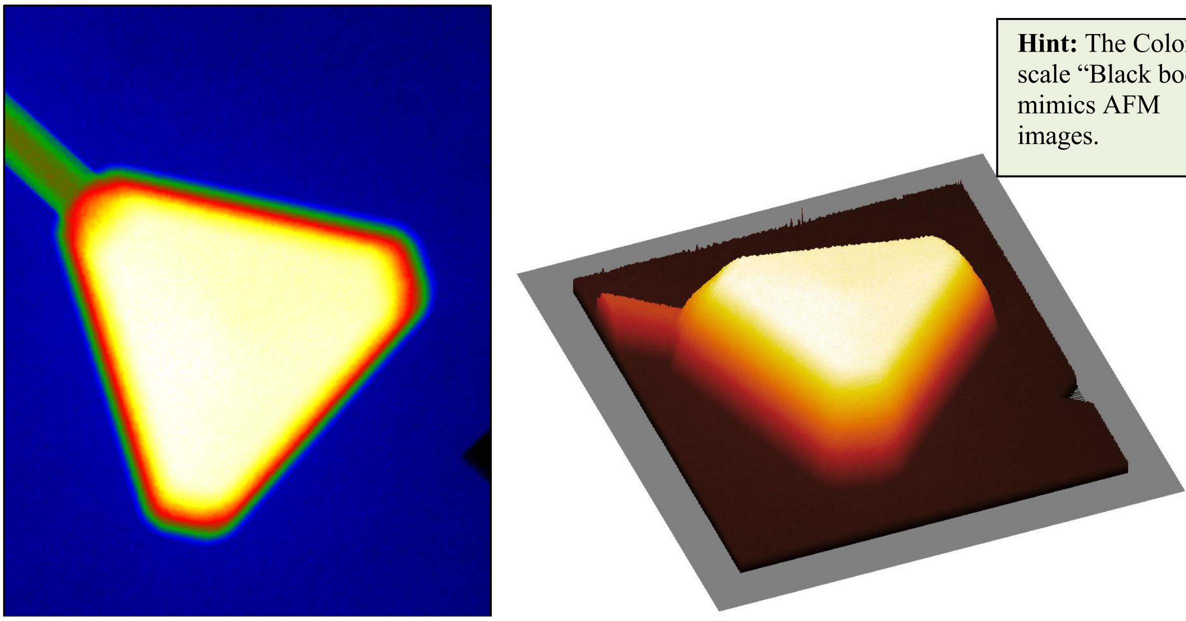




Hint: The two frontmost images are chosen by default as Target and Source, so click on the images you want before applying the command.



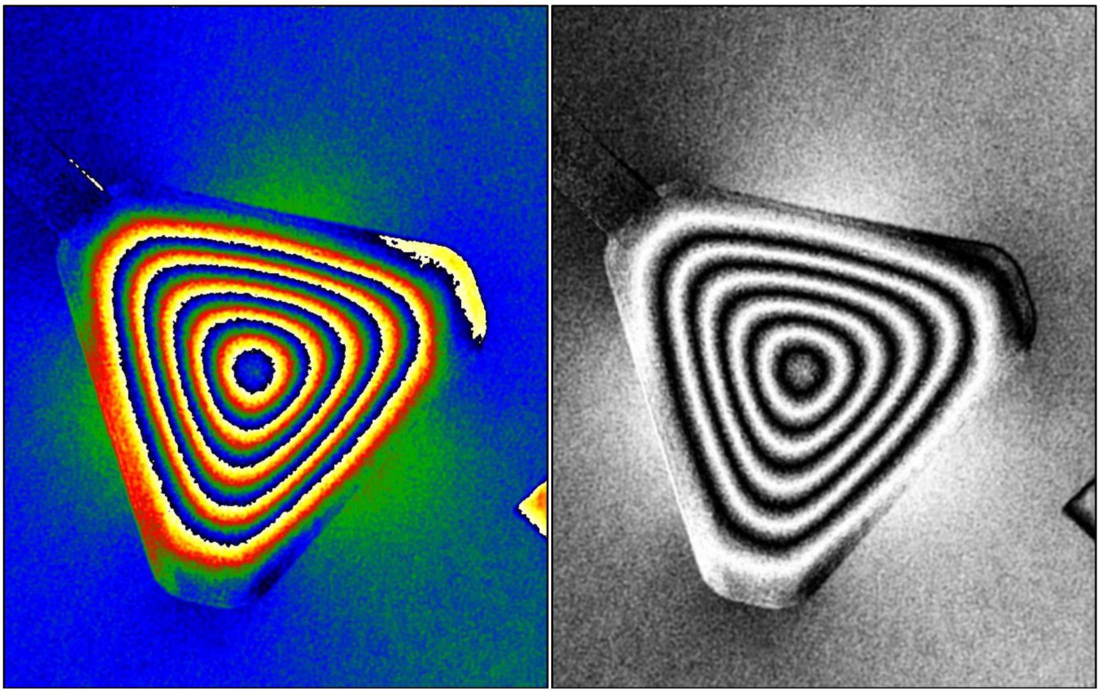
This is the phase from the MIP times two. The material is in principle all the same so the phase corresponds to a thickness map. You can even see the facetting on the rod and the triangles surface. Unwrapping will give an even better view, and you can even play with the **DM…Display…Display Type… Surface Plot** for fun :



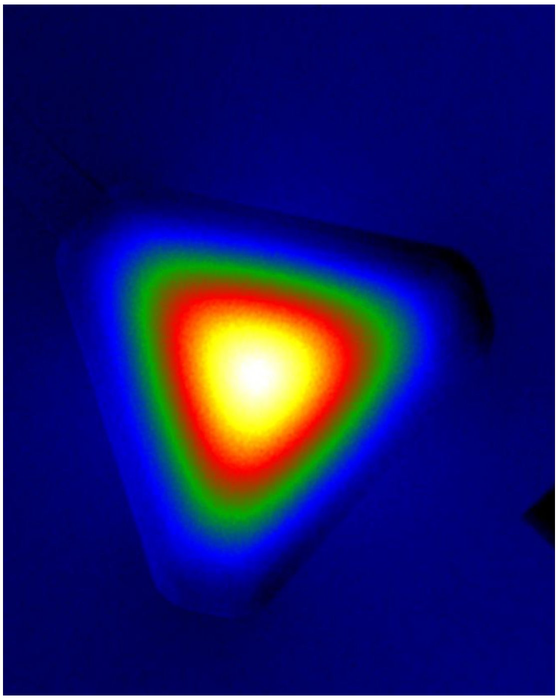
Hint: The Color scale “Black body” mimics AFM images.

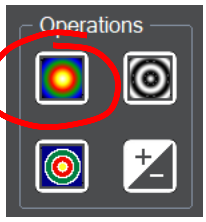
If the mean-inner potential of the material is known, the phase image could be converted into a quantitative thickness map.

Moving on to the magnetic phase, use **qHolo…Phase Maths…Add/Subtract Phase images** to subtract the two phase images.



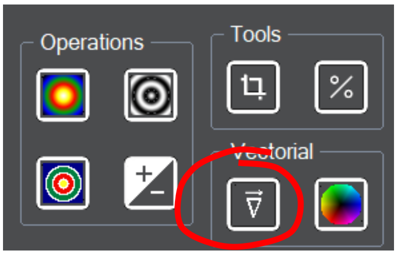
The result of the subtraction is the magnetic phase of the structure. The edges of the triangle and the rod have almost disappeared. You can use **qHolo…Cosine** to create more familiar picture of the magnetic configuration : a triangular vortex ! The three lobes of flux closure are also visible in the vaccuum. Unwrapping provides another view of the magnetic phase :

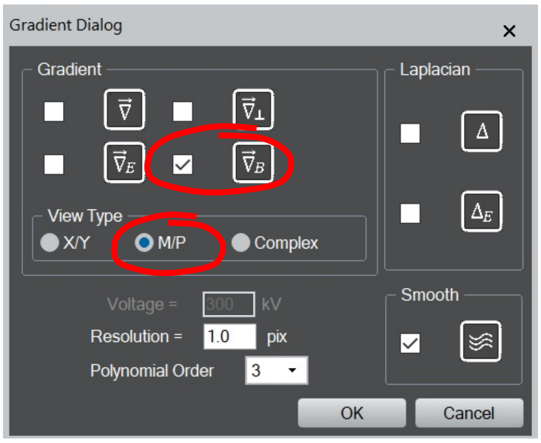




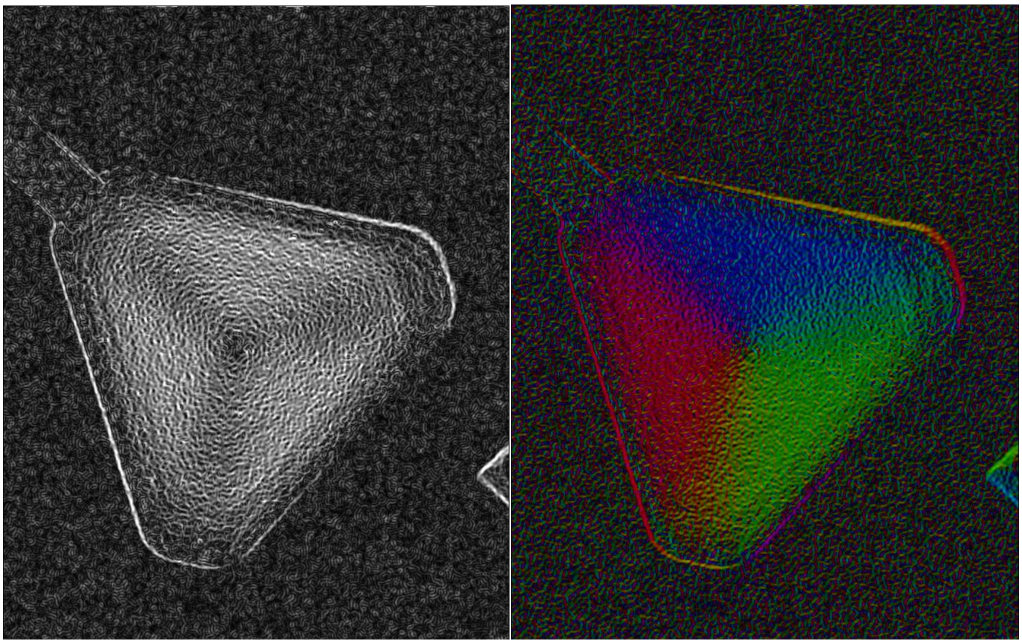
The vectical component of the magnetic vector potential is indeed pointing upwards and increases steadily to the centre of the triangle.

To visualise the field, we can calculate the gradient of the magnetic phase using **qHolo…Vectorial…Gradient**, or directly the button on the ***qHolo Control Window*** :

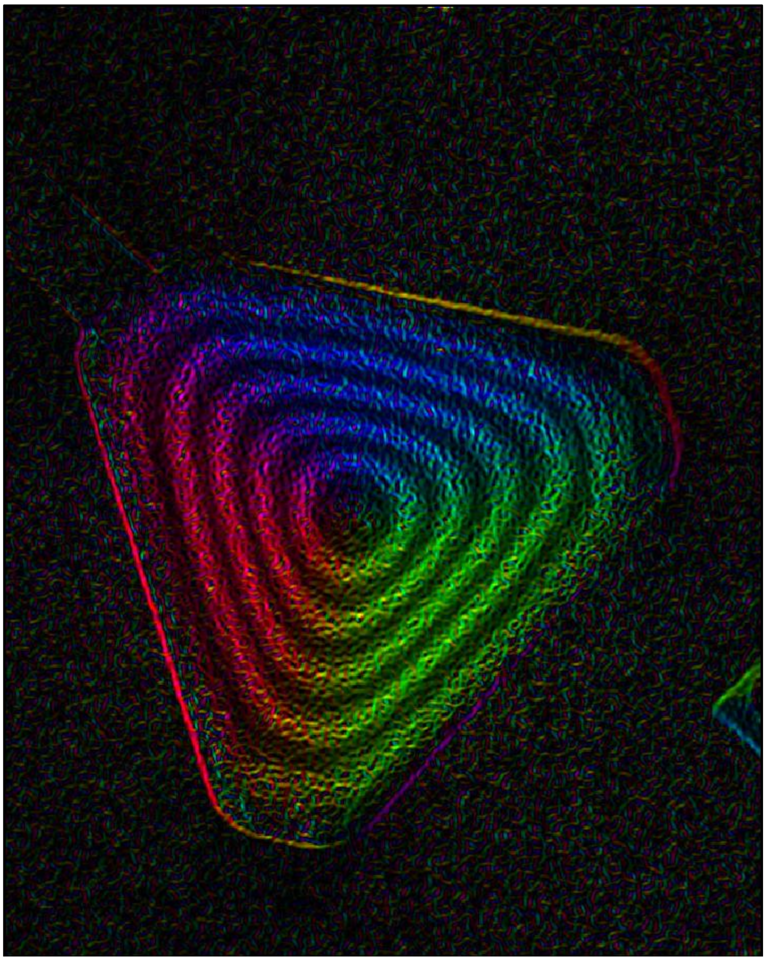




For magnetic fields, it is the perpendicular gradient which is important. The result being a vector can be displayed in different ways. We have chosen to show the magnitude and the direction (in-plane phase) of the vector using the option **M/P**.



Again the result is rather beautiful, almost ready for publication. As a final excercise, use the **qHolo…Cosine…Coupled Cosine** command to produce the following image :



Quantitative Analysis: Electrostatic Phase from Biasing

Let us now consider the determination of electrostatic phase using in-situ biasing holography with the help of a worked example. It will be the opportunity to see some of the features of **qHolo** already described and some new ones as we go along.

For in-situ biasing holography, electrodes are connected to the sample and different biases applied to the sample. The sample can be a p-n junction, capacitor or a transistor, for example. The aim is to determine the electrostatic potential change caused by biasing the sample. In the simplest cases, the electrostatic potential can be written as follows:

$$V = V_{MIP} + V_{Bias}$$

where V_{MIP} is the mean-inner potential of the material and V_{Bias} the change in the electrostatic potential when a bias is applied. Now, the phase is proportional the electrostatic potential integrated along the path of the fast electron:

$$\phi = c_E \int V dz$$

where c_E is a constant for a given accelerating voltage.

The accepted methodology is therefore to record a hologram at zero bias, with both electrodes grounded, and a hologram applying bias. The phase of the zero bias hologram contains all the unwanted information from the mean-inner potential (MIP) of the materials in question or eventual static charging. Therefore, by subtracting then the phase of the zero-bias hologram from the phase of the biased hologram, the phase due only to applied bias can be obtained.

Simple as it sounds, this procedure requires careful alignment of the two phase images as the sample may have moved between acquisitions. We will see this with the following example.

Nanocapacitor

Open the holograms “MOS 0V”, “MOS 1V” and “MOS Ref”. These holograms correspond to an experiment on a nanocapacitor of a thin layer of silicon oxide grown on a highly doped substrate of silicon (bottom electrode) and topped with a titanium layer (top electrode) [5]. As you can see, however, this structure is not very visible in the holograms, like the 0V hologram below:

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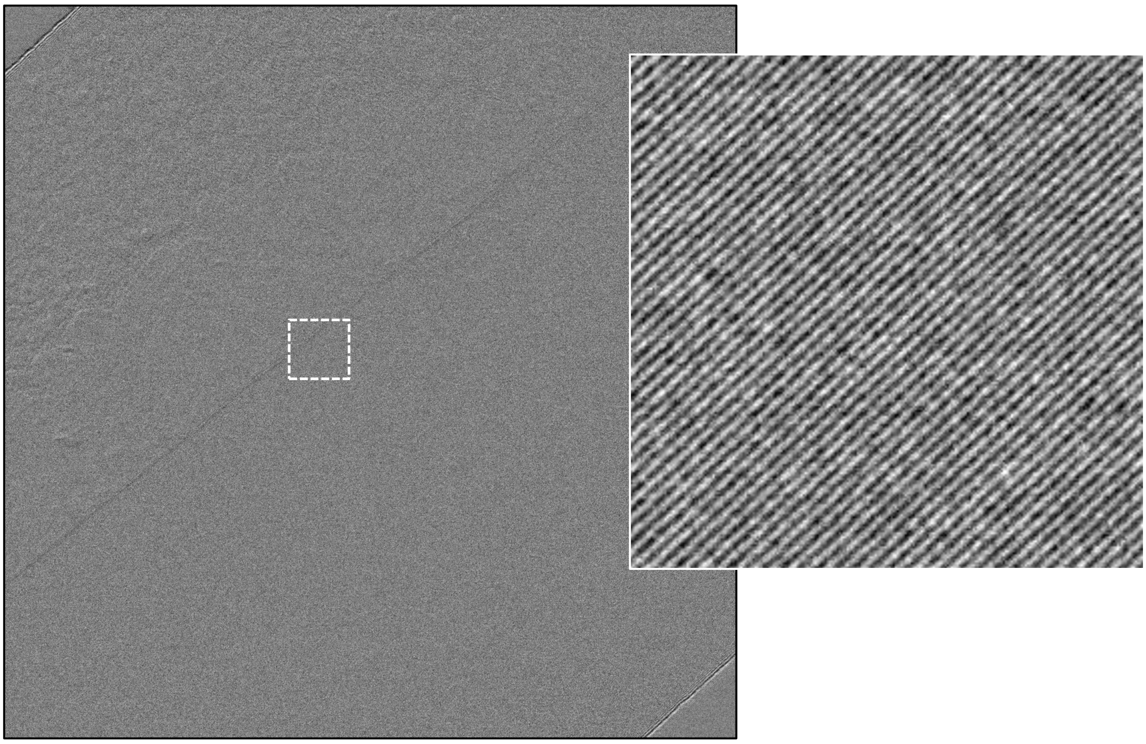
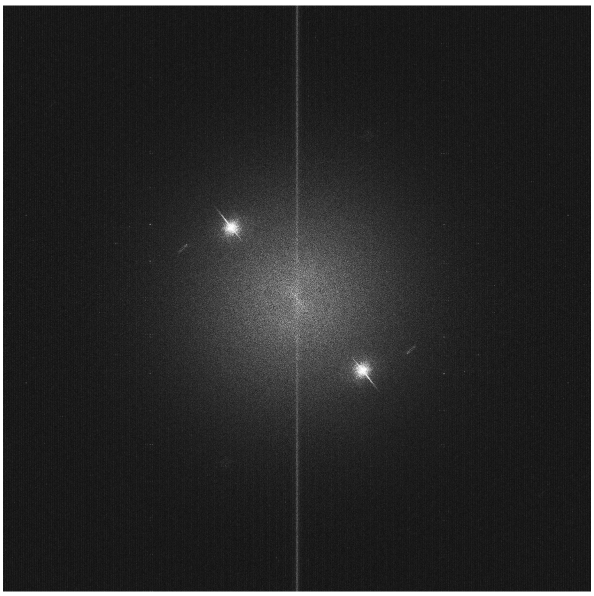
[5] C. Gatel, R. Serra, K. Gruel, A. Masseboeuf, L. Chapuis, R. Cours, L. Zhang, B. Warot-Fonrose, and M. J. Hÿtch, Phys. Rev. Lett. 129, 137701 (2022). *Extended charge layers in metal-oxide-semiconductor nanocapacitors revealed by operando electron holography.* 10.1103/PhysRevLett.129.137701



The reason is that this hologram is what we call a *pi-shifted* hologram. They are obtained by recording two holograms shifted in phase by exactly π and then subtracting them. The method was developed to remove the centre-band from the hologram[6]. In the past, such holograms were difficult to obtain, but with automation and control of hologram fringes, are now routine[7]. To see the effect, look at the **Power Spectrum** of the MOS 0V hologram:



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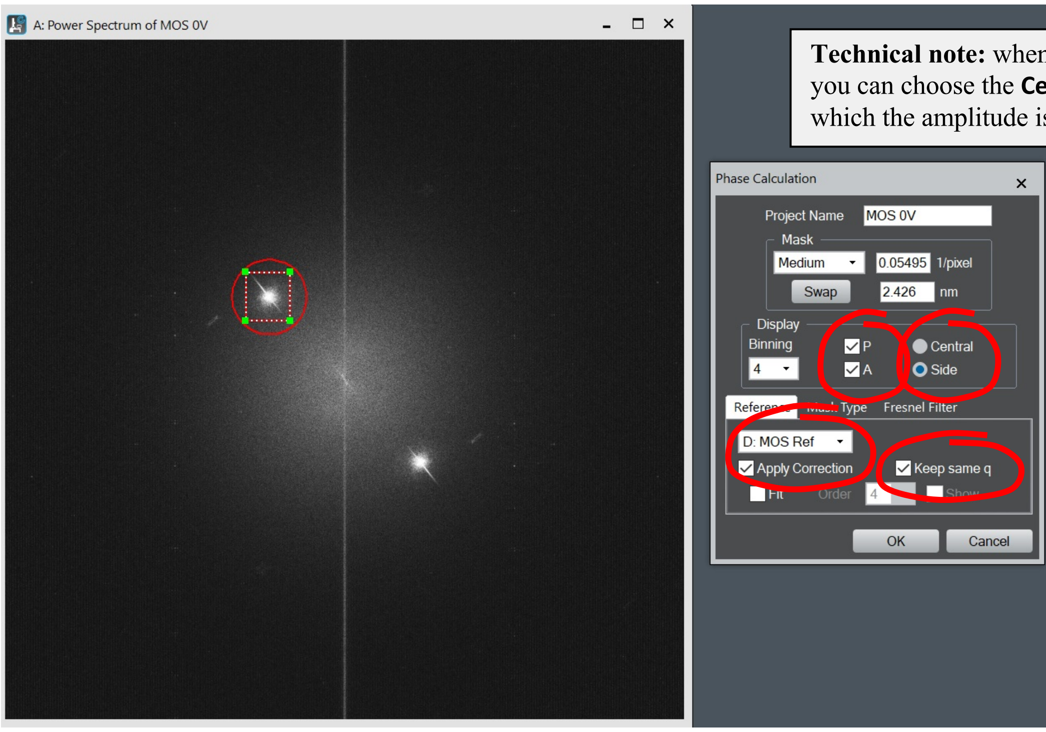
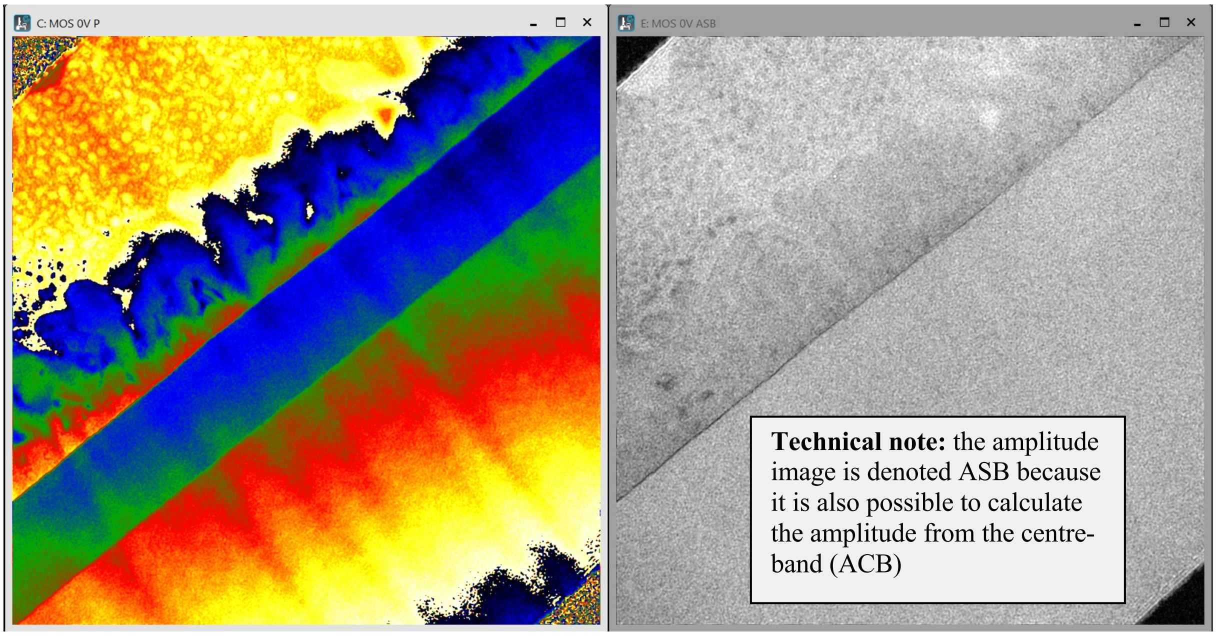
[6] V. V. Volkov, M. G. Han, Y. Zhu, Ultramicroscopy 134, 175–184 (2013). *Double resolution electron holography with simple Fourier transform of fringe-shifted holograms*. [10.1016/j.ultramic.2013.06.018](https://doi.org/10.1016/j.ultramic.2013.06.018)
[7] C. Gatel, J. Dupuy, F. Houdellier, M.J. Hÿtch, Appl. Phys. Lett. 113, 133102 (2018). *Unlimited acquisition time in electron holography by automated feedback control of transmission electron microscope*. [10.1063/1.5050906](https://doi.org/10.1063/1.5050906)

The power spectrum is dominated by the two side-bands and the centre band has almost completely disappeared. Now select the top-left side-band using the **DM rectangular ROI** and calculate the phase *and amplitude* images choosing the right options and reference hologram:



Technical note: when you tick Amplitude (A), you can choose the **Central** or **Side** band from which the amplitude is calculated.

You can also calculate directly from the hologram image using **Phase Calculation** of course. The resulting images should look something like the following for the phase (P) and amplitude (ASB) of the hologram at 0V:



Technical note: the amplitude image is denoted ASB because it is also possible to calculate the amplitude from the centre-band (ACB)

The structure goes from bottom-right to top-left: substrate, dielectric layer, top electrode. The reference wave passed through the vacuum top-left, explaining why the side-band in that direction was chosen. The correct choice can be verified by noting that this hologram, at zero applied bias, corresponds to the effect of the mean-inner potential (MIP) in grand majority. For example, the phase increases with increasing thickness to the bottom-right, as it should do. Equally, the MIP of the dielectric (silicon oxide) is smaller than that of doped silicon (substrate); we can see the phase is smaller in the dielectric than the silicon. Indeed, the dielectric layer is much more visible in the phase image than the amplitude image.

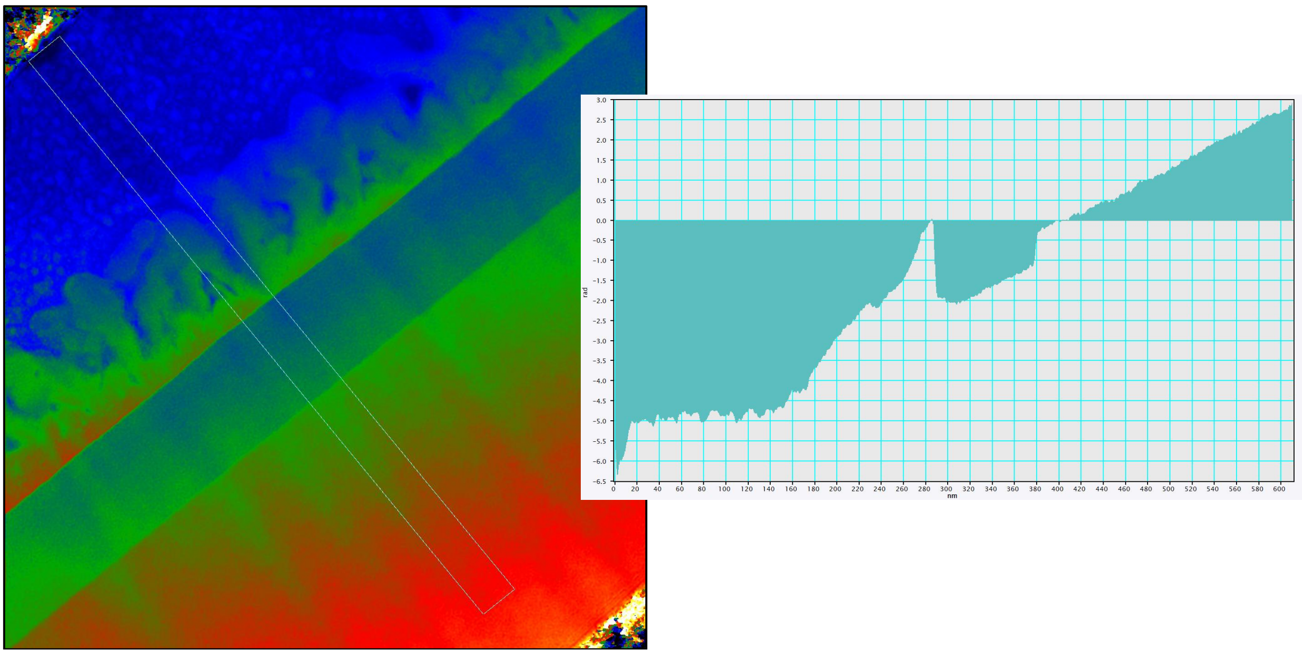
This is an example where we do not want to use **Define Reference** because we do not have an area where the phase should be uniform. The vacuum region would have been ideal but we can only see a very small part at the top left. This can be a problem when carrying out quantitative analysis. Oftentimes, we cannot enlarge the width of the hologram sufficiently to include the vacuum and the region of interest. The reason is that the visibility of the hologram fringes decreases with increasing width of the overlap: the object and reference wave become further and further apart. Likewise, reducing the magnification between object and biprism may increase the fringe spacing beyond the desired spatial resolution.

This is why we included the option **Keep same q**, as we saw for a previous example. This ensures that the same carrier frequency is used for the object and reference holograms when calculating the phase.

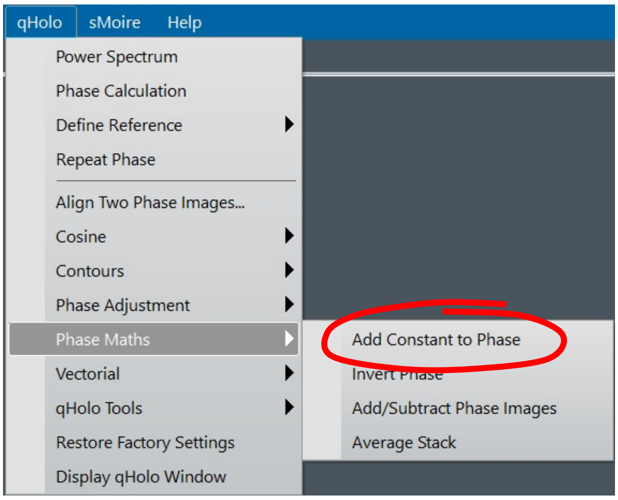
Indeed, let us obtain an estimation of the thickness of the sample with this example. Since the mean-inner potential creates no stray field, the MIP phase is given by:

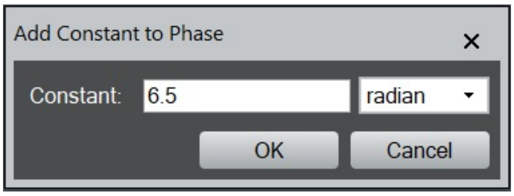
$$\phi_{MIP} = c_E \int V_{MIP} dz = c_E V_{MIP} t$$

where t is the thickness of the thin lamella. This of course assumes that the material is uniform over the thickness of the foil. To interpret the phase in terms of the thickness we need to unwrap it first, using **qHolo…Unwrap/Wrap Phase**:



For our example, we need though to adjust the phase so that it is zero at the vacuum. We can use **qHolo…Phase Maths…Add Constant To Phase**. Add 6.5 radians.





Hint: You can also choose fraction of pi using the scroll.

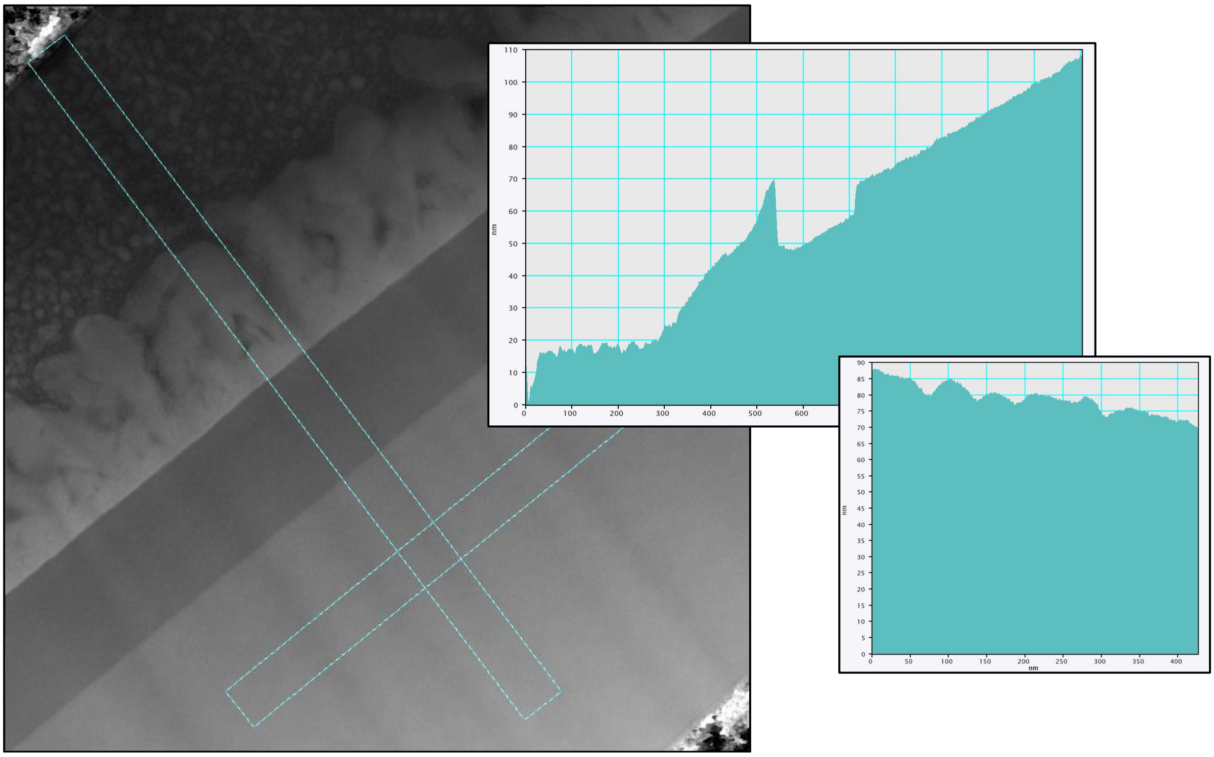
Technical note: if the image is unwrapped, no phase renormalisation is applied. **qHolo** is clever.

The phase profile is automatically updated (a nice feature of **DM**) and the phase begins at zero and works up to about 10 rad within the silicon substrate. To estimate the specimen thickness, within the substrate, we can invert the formula. The value of the constant cE can be obtained in the DM Output Window using **qHolo…qHolo Tools…Calculate Lamda and CE**. For 300 kV, for our example, the value is CE = 6.5262e+06 1/(V.m).

You can create an estimate of the specimen thickness using your own scripting or the following example:

```
// Script to estimate the specimen thickness from
// a phase image due to the mean-inner potential
// MJH 15/01/2025

image ima_p := GetFrontImage()
image ima_t = ImageClone( ima_p )
ImageCopyCalibrationFrom( ima_t, ima_p )

number c_E = 6.5262e+06 // C_E @ 300 kV
number V_MIP = 14 // 14 V for silicon

ima_t = ima_t/C_E/V_MIP/1e-09  // result in nm

ImageSetIntensityUnitString( ima_t , "nm" )
SetName( ima_t, "Thickness Estimate" )

ShowImage( ima_t )
```

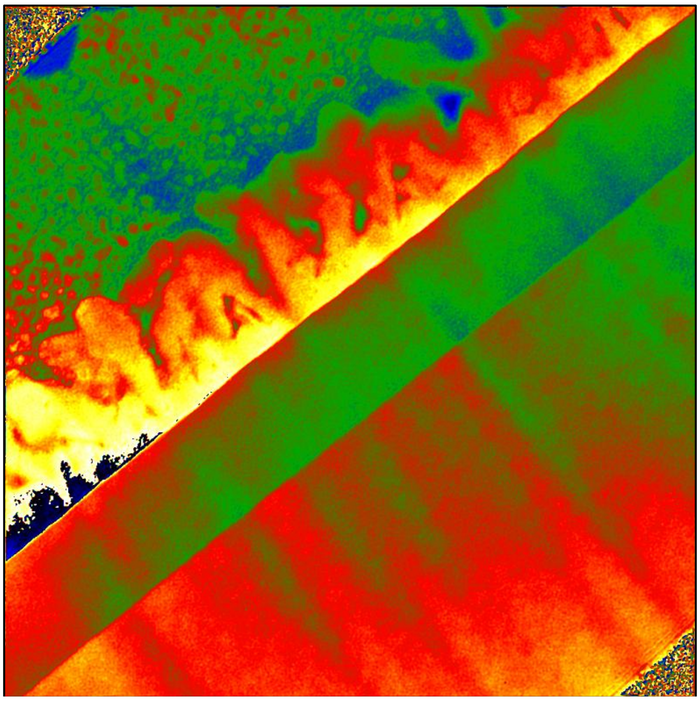
The result is the following:



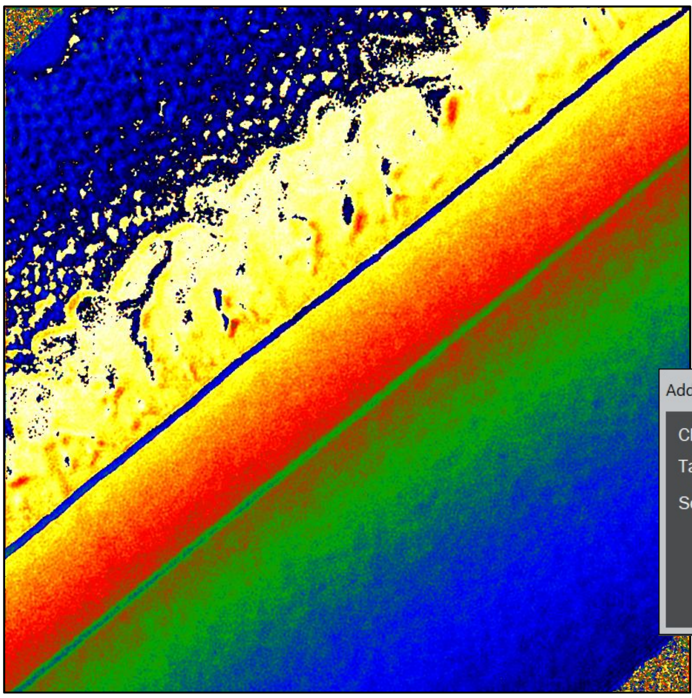
The lamella at the interface between the silicon dioxide and the silicon substrate has a thickness of about 70 nm. It then increases steadily to 110 nm in a 10° slope. This sample was not the best produced by FIB but the difficulty is to prepare a sample where the area of interest is close to the sample surface (allowing a reference wave for the hologram). The values for the thickness should not be interpreted elsewhere than in the silicon substrate since we used the MIP of silicon for the estimation. The MIP of silicon dioxide, for example, is smaller. We can however note that the signal varies considerably in the Ti layer.

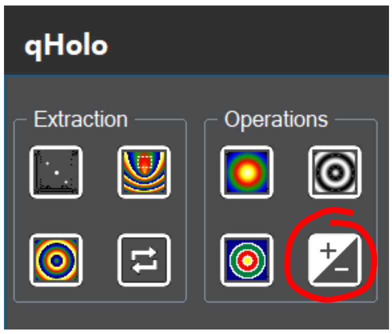
Another interesting feature is the longitudinal undulations in the substrate notably (see the other thickness profile parallel to the interfaces). This is the well-known curtaining effect in FIB milling. These will actually be useful for the image alignment later on.

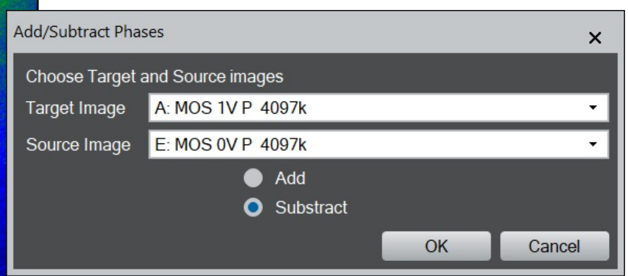
Now calculate the phase image with 1V of bias applied to the top electrode (MOS 1V) using **qHolo…Repeat Phase** to ensure identical carrier frequencies to the 0V hologram:



The phase image at a bias of 1V does not look very different form that at 0V. This is generally the case, as the MIP contribution usually dominates. We can eliminate it though by subtraction using **qHolo…Phase Maths…Add/Subtract Phase Images:**



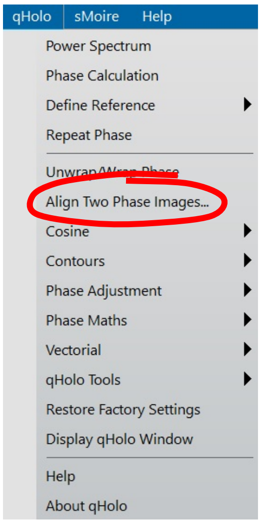


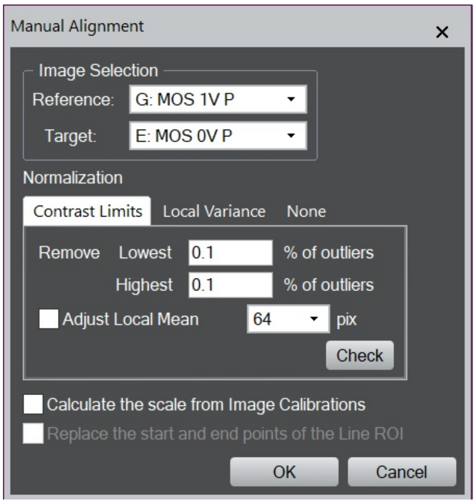


The result is at first hand disappointing. Indeed, it could have been obtained simply by calculating the phase of MOS 1V with a reference hologram of MOS 0V. The reason is that the specimen has moved slightly between the recording of the two holograms. The blue and green lines indicate, notably, that the interfaces are not well aligned. We therefore need to align the two phase images before subtraction.

Align Two Phase Images…

In the previous example for magnetic phase, we used the amplitude images to align the images, but we can also use the phase. Place the two phase images next to each other and choose the **qHolo…Align Two Phase Images…** command from the main menu:

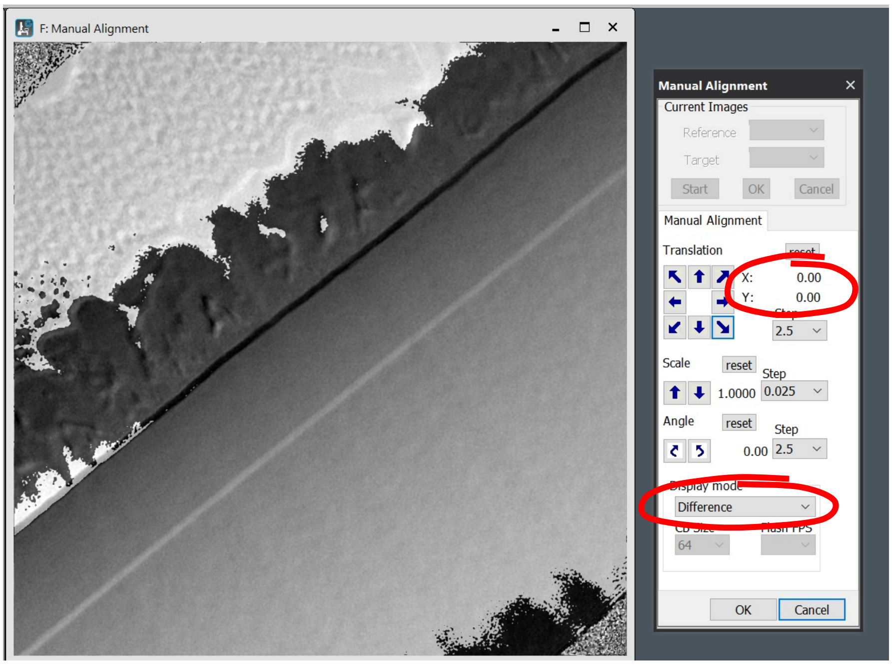




Technical note: the displacement of the **Target** image is measured with respect to the **Reference** image.

It is logical to choose the 0V image as the **Reference** as it will used to align all the other biased phase images.

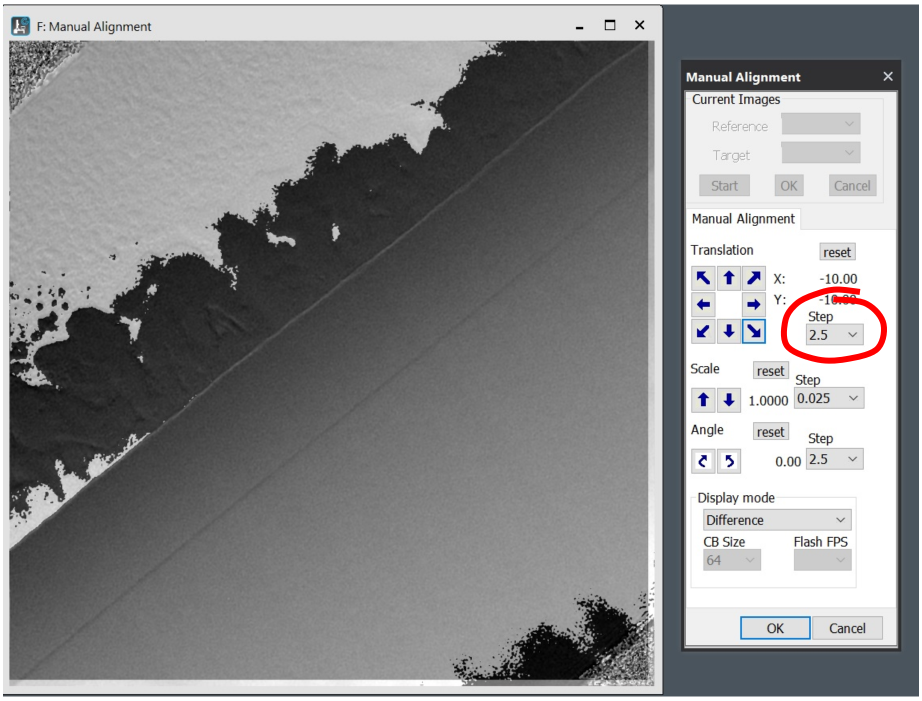
Once you have clicked on OK, two things will happen. An image along with a floating window will open called "Manual Alignment":



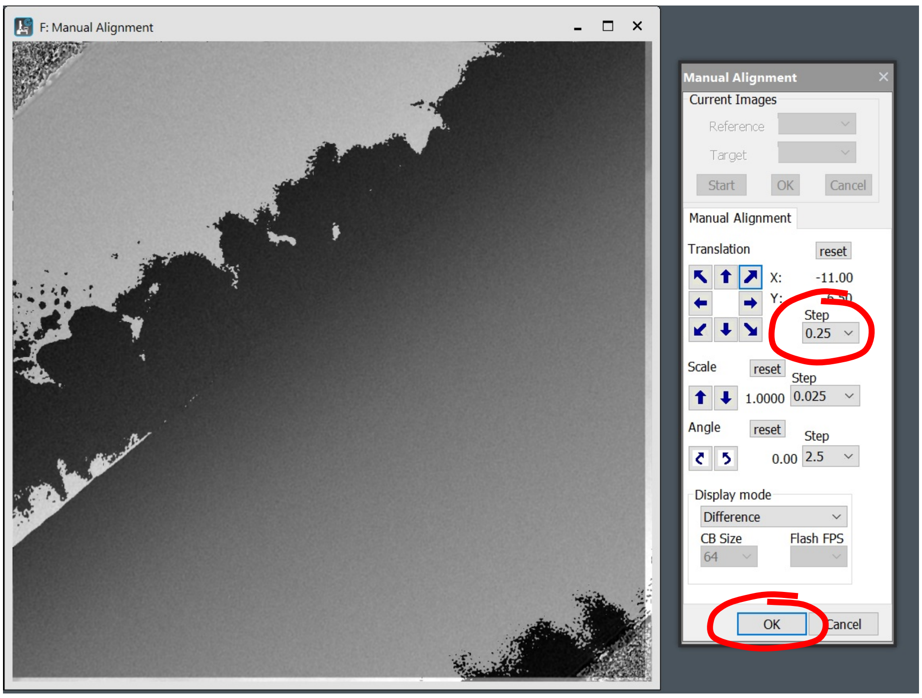
Technical note: the displacements are measured in pixel units of the phase image, which can be binned with respect to the original hologram.

Different ways are proposed in **qHolo** to display the two images superposed but this example works the best with **Display Mode: Difference**. As its name implies, the Manual Alignment image shows the difference between the two source images for a given displacement. The displacement in pixels is always displayed in X and Y.

Now click on the **Translation** arrow pointing to the bottom left. You should see the interface getting wider and wider. Now press on the arrow pointing in the opposite direction until the interfaces look as narrow as possible. This should occur for an (X, Y) displacement of around (-10, -10):

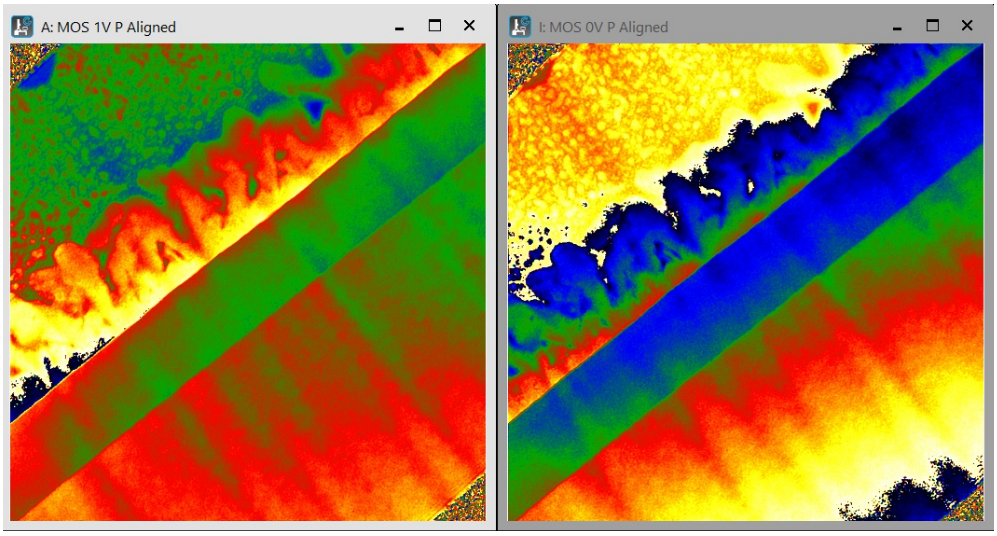


Now that we are close, reduce the **Step** size from 2.5 to 1 pixel and continue. The best result we found for the smallest Step size of 0.25:

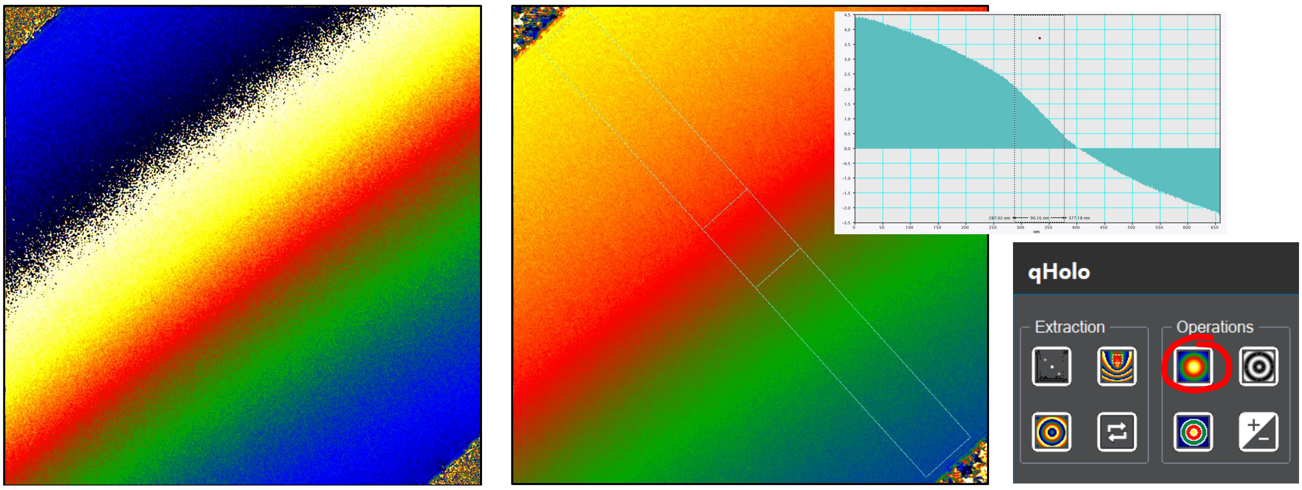


As you can see, we have managed to eliminate the contrast in the Ti layer as well by making slight adjustments in other direction. See if you can do as well.

When you are ready, press OK. The displacement will be applied and the two Aligned images will be displayed:



You can now subtract these two to produce the bias phase image which we recommend to unwrap:



The phase image is now smooth and free from artefacts; the variations in thickness have disappeared. All we see now is the phase from the applied bias.

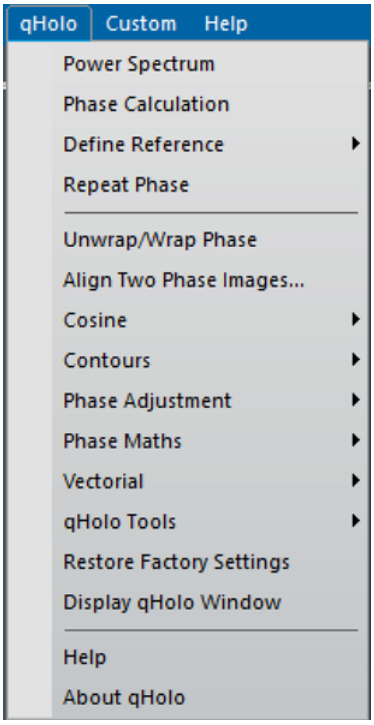
But since nothing is simple, the biasing of the sample has created a large stray field. The phase from the bias is the sum of the electric potentials inside and outside the thin lamella. For example, this explains why the phase is not uniform inside the top and bottom electrode where the electric potential is indeed uniform. Only by careful finite-element method (FEM) modelling can the experimental results be explained (see References [4-6] cited at the beginning of the manual). However, following this procedure of hologram processing, the experimental results are now directly comparable to modelling.

Here ends the second part of the qHolo Manual. Please continue to explore the different options and commands!

Quick Reference Guide

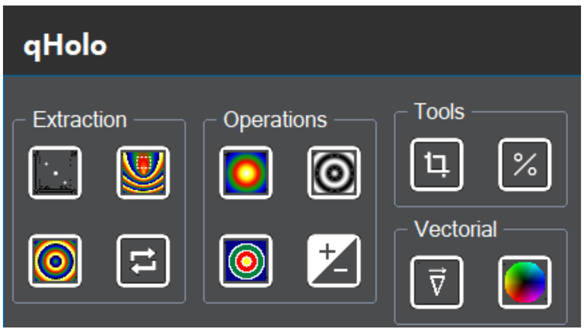
The qHolo Menu and Windows

The qHolo Menu



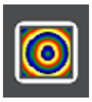
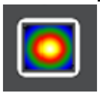
The qHolo Window

The qHolo menu is not the only way to access the commands in qHolo. Open the qHolo Window with **Window…Floating Windows…Technique Manager** (GMS 3.x). The window can also be accessed through **qHolo…Display qHolo Window** (Before GMS 3.x).



Commands can be activated by clicking on the buttons. In fact, this is the way we usually use qHolo.

The commands in the qHolo menu are described below.

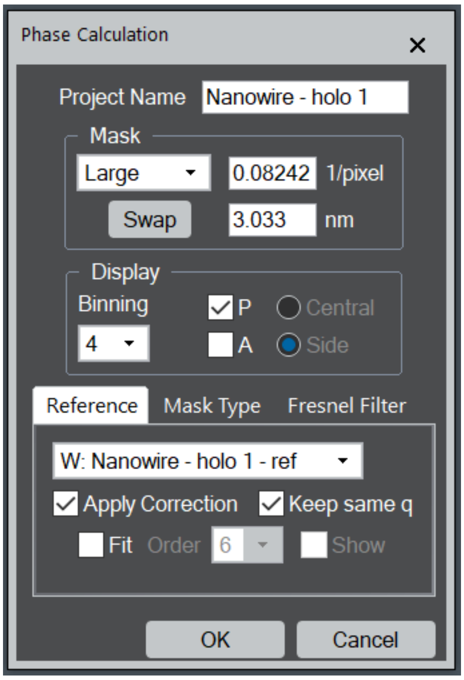
Command	**Description**
Power Spectrum 	Calculates and displays the Fourier transform of the front most hologram (or stack of holograms). The side-band is then selected in the image of the Fourier transform (called Power Spectrum) using the DM rectangular ROI tool. **Button** is identical to selecting the menu.
Phase calculation ... 	Calculates phase from front most hologram (or stack of holograms). The Power Spectrum is displayed with an automatically selected side-band circled in red. A dialog appears with the choice of options (see Phase calculation dialog below). When a Power Spectrum was front most, Phase Calculation will continue using the Power Spectrum. **Button** is identical to selecting the menu.
Define Reference  (see sub menus)	Define Reference submenu of this command defines the area to be used as reference in the hologram phase image (see other sub-menus below). **Button** is identical to selecting the Define Reference submenu.
Repeat Phase 	Repeats phase calculation on the front most hologram using the previously defined options. Nevertheless, the Phase Calculation dialog will appear, allowing options to be changed. **Button** is identical to selecting the menu.
Unwrap/Wrap Phase 	Unwraps the phase using the Goldstein algorithm, or wraps the phase between –Pi and +Pi. Unwrap or wrap will be automatically selected according the current phase value. **Button** is identical to selecting the menu.
Align Two Phase Images...	Allows two phase images from different Holograms to be aligned. Corresponding amplitude images will be used to find alignment conditions.
Cosine (see sub menus)	Menu for creating a cosine image of the phase amplified by a specified factor.
Contours (see sub menus)	Menu to add contours to the phase image.
Phase Adjustment (see sub menus)	Menu to make adjustments to the calculated phase image, for example to use the same q-vector as another phase image, or to rotate the phase image.

Vectorial (see sub menus)	Menu to calculate derivatives of phase images (Gradient and Laplacian) including smoothing options.
qHolo Tools (see sub menus)	Menu of useful operations, like extracting image areas, not necessarily restricted to phase images.
Restore Factory Settings	Resets all defaults and options to the initial values for qHolo.
Display qHolo Window	Makes the floating qHolo Window appear (before GMS 3.x).

Phase Extraction

Phase Calculation Command

Phase Calculation Dialog

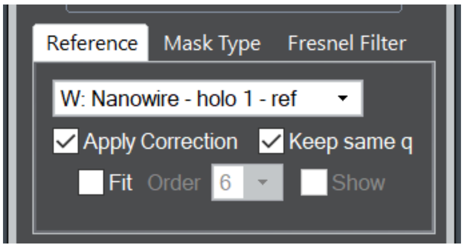


The components of the dialog are described below.

Component	Description
Project Name	Name given to the group of images and results. By default, this is the same as the front most hologram.
Mask Box	
Size selection	Large (q/2), Medium (q/3), Small (q/4) and Custom. Mask size in 1/pixel in Fourier space and nm in real-space (if calibrated).
Swap	allows the opposite side-band to be chosen. The q-vector should point towards the reference wave.

Display Box	
Binning	Binning means the phase image will be smaller (in pixels) than the original hologram, the number of rows and columns being divided by the binning factor. This speeds up the calculation and saves space without loss of information. The binning factor can be selected from 1,2,3,4,5,6,7,8. Default is 4.
P and A	When checked, Phase (P) and/or Amplitude (A) will be displayed.
Mask selection	Radio buttons to select Central or Side band.
Reference Tab	For information about the components of the Reference tab, see Display Tab below.
Mask Type Tab	For information about the components of the Mask Type tab, see Mask Type Tab below.
Fresnel Filter Tab	For information about the components of the Fresnel Filter tab, see Fresnel Filter Tab below.
OK	Closes the dialog and starts the image calculation according to the specified parameters.
Cancel	Closes the dialog without executing the command.

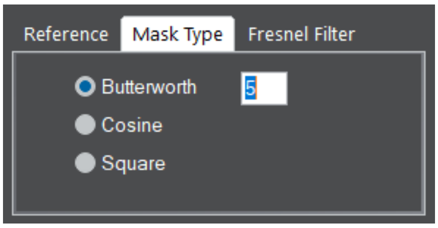
Reference Tab



Component	**Description**
Reference hologram selection	Pulldown menu to choose a *reference* hologram from the list of opened images.
Apply Correction	When checked, the hologram phase will be corrected using a selected reference hologram image.
Keep same q	When checked, the q-vector will be made identical for the object and reference holograms.
Fit	When checked, the phase of the reference hologram is smoothed by performing a polynomial fit before subtraction. Only the low-frequency artefacts in the phase, from dust on the biprism for example, are removed without adding the high-frequency noise present in the reference hologram. Unfortunately, the camera may have fixed pattern high-frequency components that will no longer be removed.
Order	Order of polynomial.

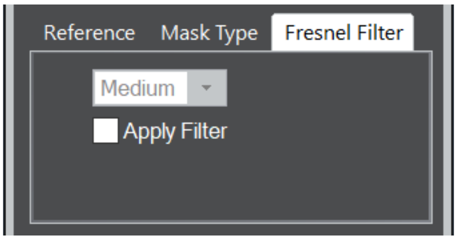
Show	When checked, polynomial fit image will be displayed in a separate window.

Mask Type Tab



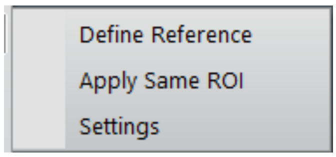
Component	Description
Butterworth	Butterworth shape for the mask.
Order	Order of Butterworth filter
Cosine	Half-cosine mask with hard-cut off given by Mask Size.
Square	Square mask with hard edges. The edge of square is two times of the Mask Size.

Fresnel Filter Tab



Component	Description
Fresnel Filter Strength	Strength of Fresnel filter: Weak, Medium, Strong.
Apply Filter	When checked, Fresnel filter is applied

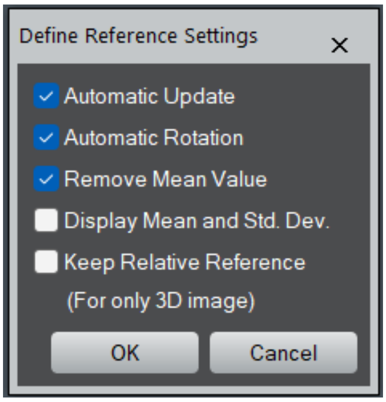
Define Reference Submenu



Command	Description
Define Reference 	If a DM rectangular ROI is present in the phase image, the command defines this region as the internal reference area for the hologram fringes. The corresponding carrier frequency **q** is recalculated and the phase image adjusted accordingly (see Settings).

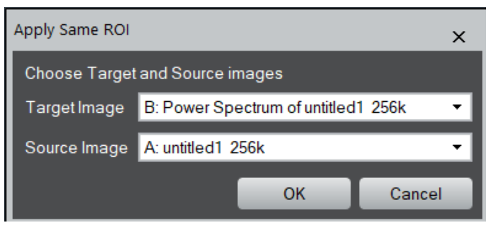
	If no ROI is present, a rectangular ROI is created by default at the center of the phase image. You may have to move the ROI, and change its size. **Button** is identical to selecting the menu.
Apply Same ROI	The ROI in the Source Image is copied to the Target Image, and then Define Reference is applied on the Target Phase Image using the new ROI. See Apply ROI dialog (see below).
Settings	Opens Settings dialog (see Setting dialog below).

Settings Dialog



Component	Description
Automatic Update	Moving the reference area updates the phase images automatically. If the Mean and Std. Dev. values have been displayed, they are also automatically updated.
Automatic Rotation	The ROI is rotated automatically parallel to the hologram fringes.
Remove Mean Value	The average phase in the reference area is subtracted from the whole phase image.
Display Mean and Std. Dev.	The Mean and Standard Deviation of the phase in the reference area is displayed above the ROI.
Keep Relative Reference	This option is relevant only for a stack of holograms. When checked, Slice 0 is used for the calculation for all slices. Otherwise, the reference is calculated and corrected for each slice independently.

Apply Same ROI Dialog

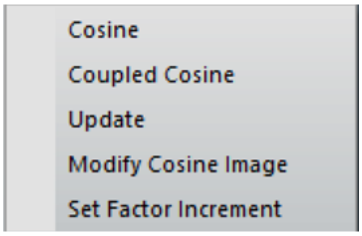


Component	Description
Target Image	Phase image to be adjusted using the same ROI.

Source Image	Phase image with ROI.
OK	The ROI in the Source Image is copied to the Target Image. If there is a ROI in the Target Phase Image, the ROI in the Source Image will replace it. Then, Define Reference is applied on the Target Phase Image using the new ROI.
Cancel	Operation is abandoned.

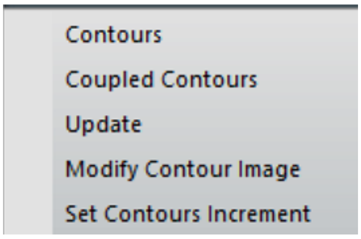
Phase Operations

Cosine submenu



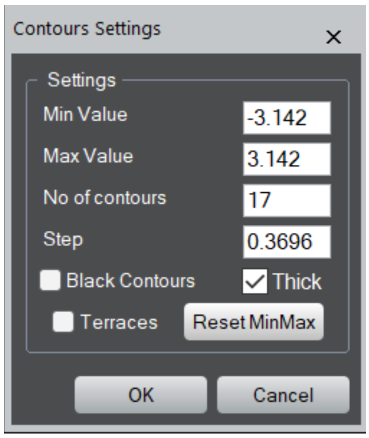
Component	Description
Cosine 	Creates an image that is equal to the cosine of the frontmost *phase image* multiplied by a user-definable Factor. If a Cosine image of the frontmost *phase image* is already present, the existing Cosine image will be updated. **Button** is identical to selecting the menu.
Coupled Cosine	Creates a cosine image that is superimposed on a "Background" image selected via a dialog. In the same dialog, you can define whether Background image is Multiplied or Replaced by the Cosine Image. **NOTE**: It does not matter if the phase image has a different size to the Background image. **NOTE**: Replacement option is useful, when the original hologram is chosen as Background image, but the phase image has a different size to the original hologram owing to binning.
Update	Ensures that the Cosine Image is updated using the current Cosine Factor.
Modify Cosine Image	Allows the user to change the Cosine factor, when the cosine image is frontmost.
Set Factor Increment	Defines an increment of the Factor for Cosine image changed by the Arrow keys. **NOTE**: When the Cosine image is frontmost, by using the keyboard Arrow keys, the Cosine image is automatically updated by increasing/decreasing the Cosine Factor with this increment.

Contours submenu



Command	Description
Contours 	Creates an image that has contours superimposed according to the Settings (see Contours Settings below). **Button** is identical to selecting the menu.
Coupled Contours	Creates a Contours image that is superimposed on a “Background” image selected by the user.
Update	Ensures that the Contours Image is updated using the current Step size.
Modify Contour Image	Allows the user to change the Contours Settings, when the contours image is frontmost. (see Set Contours Settings dialog below).
Set Contours Increment	Defines an increment of the number of contours changed by the Arrow keys. **NOTE**: When the Contour image is front most, by using the keyboard Arrow keys, the Contour image is automatically updated by increasing/decreasing the number of contours with this increment.

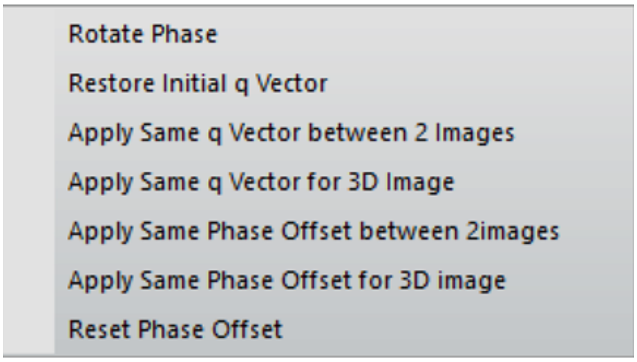
Contours Settings Dialog



Component	Description
Min Value	Minimum contour value. The minimum value of the target image is shown as a default. If the frontmost is the phase image, this will be -Pi.
Max Value	Maximum contour value. The maximum value of the target image is shown as a default. If the

	frontmost is the phase image, this will be +Pi.
No of contours	Number of contours to be created (excluding maximum contour). Automatically adjusts the Step accordingly if modified.
Step	Step between contours. Automatically adjusts the number of contours to nearest integer value.
Black Contours	By default, the contours are white. When checked, the contours are shown in black.
Thick	When checked, the width of the contour lines is made thicker to be more visible.
Terraces	When checked, the resulting image has the values flattened between each contour, creating a terraced image. Note that on terraced images, no contours are superimposed.
Reset MinMax	Resets the minimum and maximum values to the default setting.
OK	Creates the Contour image.
Cancel	Abandons the operation.

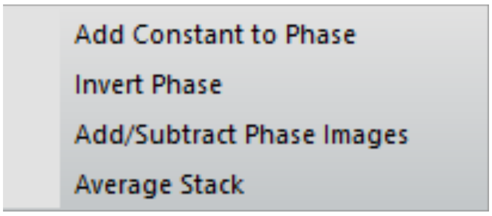
Phase Adjustment submenu



Command	**Description**
Rotate Phase	Rotates the phase image whilst correctly dealing with phase jumps.
Restore Initial q Vector	Resets the current q-vector equal to the initial q-vector obtained with Phase Calculation command. Phase image is automatically updated.
Apply Same q Vector between 2 Images	The q-vector of the Source phase image will be applied to a Target phase image. The Target phase image is automatically adjusted and renormalized. The target image can be 2D or 3D. When both the Target and Source images are 3D, the q-vector of the Source image will be applied to a Target image slice by slice.

Apply Same q Vector for 3D Image	For phase image stacks, the q-vector of the slice specified via a dialog is applied to all the images in the stack.
Apply Same Phase Offset between 2 images	The mean phase of the Target image is set to that of the Source image. When there is a ROI on the Source image, the mean phase within the same area of the Target image is set to that within the ROI on the Source image. The target image can be 2D or 3D. When both the Target and Source images are 3D, the mean phase of the Target image is set to that of the Source image slice by slice.
Apply Same Phase Offset for 3D Image.	For phase image stacks, the mean phase of the whole stack is set to that of the slice specified via a dialog. When there is a rectangular ROI on the Source image, the mean phase within the same area of other slices is set to that within the ROI.
Reset Phase Offset	The mean of the whole phase image is set to zero. When there is a ROI on the phase image, the mean phase within the rectangular ROI is set to zero. This command works for both 2D and 3D images.

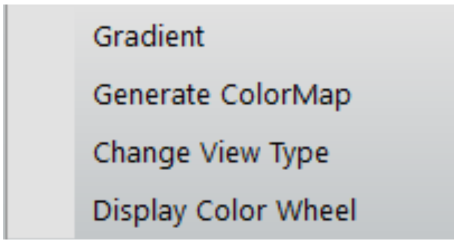
Phase Maths submenu



Command	**Description**
Add Constant to Phase	Adds a constant phase specified via a dialog in radian or in Pi to the whole phase image. As might be expected, a negative value results in subtracting a phase.
Invert Phase	Calculates the negative of the phase (and simultaneously inverts the q-vector).
Add/Subtract Phases 	Adds/Subtracts two phase images chosen via a dialog. Add or Subtract can be chosen with the radio buttons in the dialog. The new phase image is rewrapped automatically. **Button** do the same thing with the menu.
Average Stack	Averages the phase images in a stack, correctly dealing with the phase jumps.

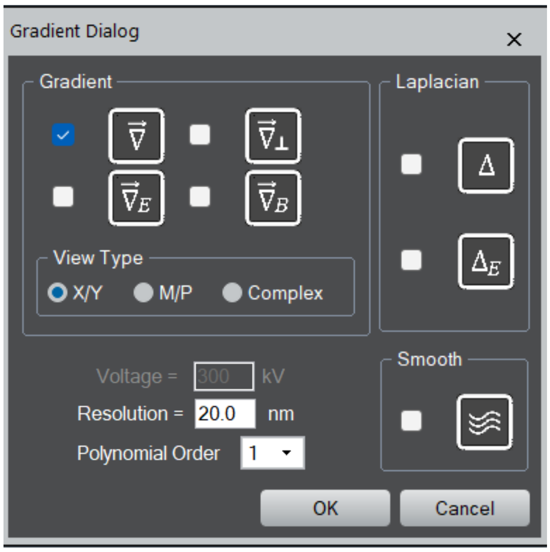
Tools and Vectors

Vectorial submenu



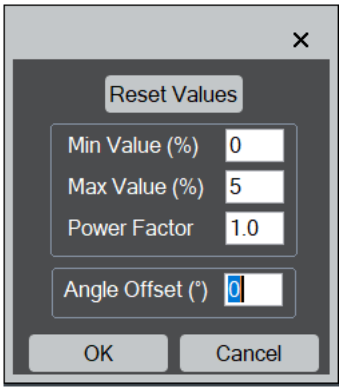
Command	**Description**
Gradient 	Opens a dialog to calculate different image gradients (see Gradient Dialog below). The x/y components will be displayed in different two windows. **Button** is identical to selecting the menu.
Generate ColorMap 	Generates a color map to display the gradient in a single image: the modulus and direction of the gradient are given by the intensity and by the color, respectively. Options can be defined by dialog window (see Generate ColorMap Dialog below). **Button** is identical to selecting the menu.
Change View Type	Changes display type of gradients among x/y components, Modulus/Phase and Complex selected via a dialog.
Display Color Wheel	Creates an image of the Color wheel, useful as figure legend to go with the ColorMap. The size of color wheel can be specified.

Gradient Dialog



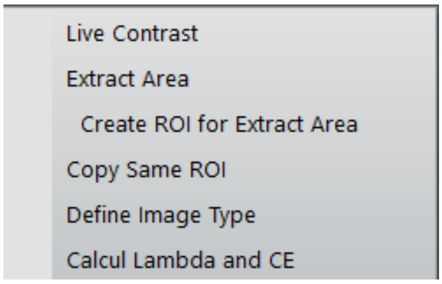
Component	Description
$\vec{\nabla}$	Calculates the gradient in x (horizontal) and y (vertical) directions $\vec{\nabla} = \vec{\nabla}_{xy} = (\nabla_x, \nabla_y)$ at the requested spatial resolution (see Resolution below) and displays them as separate images.
$\vec{\nabla}_E$	Calculates the gradient in x and y directions in units of electric potential, assuming that the phase is purely electrical in origin (i.e., no magnetic contribution). $$\phi^E = c_E \int V\,dz$$ $$\vec{\nabla}_E = \frac{1}{c_E}\vec{\nabla}\phi^E = \int \vec{\nabla}V dz = -\int \vec{\mathrm{E}}_{xy} dz$$
$\vec{\nabla}_\perp$	Calculates the vector perpendicular to the gradient $\vec{\nabla}_{xy}$, i.e., $\vec{\nabla}_\perp = \hat{\boldsymbol{z}} \wedge \vec{\nabla}_{xy} = (-\nabla_y, \nabla_x)$
$\vec{\nabla}_B$	Calculates the perpendicular gradient in x and y directions in units of magnetic potential, assuming that the phase is purely magnetic in origin: $$\phi^M = \frac{e}{\hbar}\int A_z\,dz$$ Now: $$\mathbf{B} = \boldsymbol{\nabla} \wedge \mathbf{A}$$ Therefore: $$\vec{\nabla}_B = \int \mathbf{B}_{xy}\,dz = \frac{e}{\hbar}\left(\hat{\boldsymbol{z}} \wedge \vec{\nabla}_{xy}\phi^M\right)$$ The result is the integrated in-plane magnetic field in units of T.nm.
Voltage	Accelerating voltage, necessary for the calculation of the in-plane electric field. Greyed out if not necessary.
Resolution	Spatial resolution for the calculation of the gradient. It is usually necessary to choose a lower spatial resolution than that of the phase image, because taking gradients amplifies noise.
Polynomial Order	The gradient is calculated using the Savitzky–Golay algorithm in 2-dimensions by locally fitting a polynomial to the phase image (in a square region of dimensions given by the resolution). The maximum order of the polynomial is 4. The gradient is given by the first order of the resulting polynomial function in the x and y directions.
Smooth	This option shows the phase image smoothed by the spatial resolution chosen for the gradient calculation.

Generate ColorMap Dialog



Component	**Description**
Reset Values	Resets all the values back to the default values, namely 0 and 100 %.
Min Value (%)	Outliers below this percentage of the maximum gradient present in the image will be removed.
Max Value (%)	Outliers above this percentage of the maximum gradient present in the image will be removed.
Power Factor	Allows a stretching of the intensity values in the ColorMap (non-linear LUT for the grey scale). By default, the value is 1 and no stretching is applied. A value of 0.5 (square root) means the variations are damped, and a value of 2.0 (square) means the variations are accentuated.
Angle Offset (°)	Sets the zero angle for the color wheel (blue color direction).
OK	Calculates and displays the ColorMap from the Gradient X and Gradient Y images.
Cancel	Cancels the operation.

qHolo Tools submenu



Command	Description
Live Contrast 	Displays the fringe contrast, the fringe spacing (in pixels and calibrated units) and mean intensity above a rectangular ROI in the hologram image. These values are updated as the ROI is moved. If no ROI is present, a rectangular ROI will be automatically created. Then, you may have to move the ROI, and change its size. **Button** is identical to selecting the menu.
Extract Area 	Creates a new image corresponding to a *rotatable* ROI on front most image. **Button** is identical to selecting the menu.
Create ROI for Extract Area	Creates a *rotatable* ROI on front most image from a Rectangular ROI placed in advance.
Copy Same ROI	Copies an ROI from the "Source" image to a "Target" image selected via a dialog.
Define Image Type	Allows the image type to be changed, changing the tag of the image "Type". Useful for images calculated outside qHolo.
Calculate Lambda and CE	Calculates the value of the electron wavelength λ and the hologram constant c_E from a given accelerating voltage, and outputs their values in the DM Output window. NOTE: $c_E = \frac{\pi}{\lambda E}$ where *E* is the total energy of the fast electron.