

# Optimising the Resolution of TEM/STEM with the Electron Ronchigram

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## BIOGRAPHY

Prof John Rodenburg's early research work was on instrumentation development for various novel techniques in electron microscopy and spectroscopy. From 1988 he was a Royal Society Research Fellow based in the Cavendish Laboratory Cambridge, working on the phase problem as applied to super-resolution methods in electron microscopy. Since 1999 he has held the Chair of Materials Analysis in the Materials Research Institute of Sheffield Hallam University. His current interests include all areas of bulk and surface analysis, PVD coatings, advanced lubricious coatings, glow discharge optical emission spectroscopy, sol-gel coatings, contrast mechanisms in ESEM, as well as novel methods in conventional electron microscopy.



## ABSTRACT

We categorise alignments which affect the resolution of a TEM/STEM and describe a method for improving resolution using the electron Ronchigram. The effects of defocus and astigmatism on the Ronchigram are illustrated using a conventional tungsten source CM20 TEM, together with a ray diagram. Methods are described for optimising the condenser and objective lens pre-field alignment. Unlike most manufacturer's alignment schemes, the Ronchigram expresses all the relevant lens transfer characteristics of the whole electron column simultaneously. With practice, it represents the quickest way of obtaining optimal STEM and microanalytical resolution.

## KEYWORDS

transmission electron microscopy, STEM, resolution, Ronchigram, alignment, optics, scanning, ADF imaging

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## INTRODUCTION

The most effective way to align a scanning transmission electron microscope (STEM), or TEM/STEM, is via the electron Ronchigram. Although the method has been used for many years by a small community interested in 'dedicated' scanning transmission electron microscopy (STEM) [1, 2], its utility is generally not widely appreciated by the TEM community. Scanning units are now widespread in TEMs, especially field emission gun (FEG) TEMs. In this article we describe in simple terms what the Ronchigram is and what it looks like, how to obtain it in a TEM/STEM column (whether using an FEG or not), and then how to use it to align the pre-specimen electron optics. We hope this will enable the TEM/STEM community to obtain routinely optimal probe resolution for dark-field imaging and very high-resolution analytical work.

## THE ELECTRON RONCHIGRAM

Figure 1 shows a simplified view of STEM optics, drawn with the electron source at the top of the picture as in TEM: in the dedicated STEM literature the source is usually at the bot-

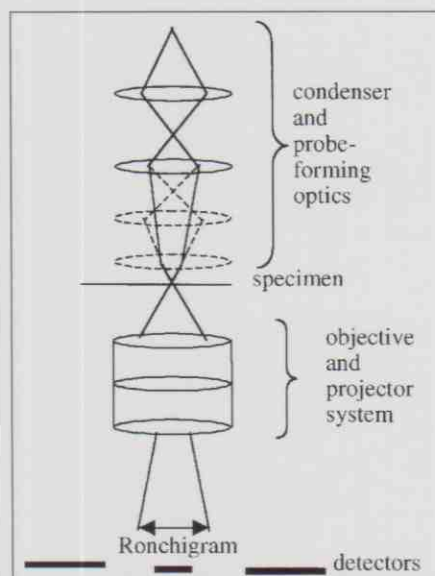


Figure 1: Main optical components of the STEM or TEM/STEM configuration. Below the condenser system, there is either a mini-condenser or a modified objective pre-field (dotted lens), depending on the make of microscope. There can also be one or more beam crossovers, depending on the strength of these lenses. The objective lens below the specimen coupled with the projectors merely serve to define the optical plane which is imaged on the detectors and the effective camera length. Ideally, the Ronchigram lies in the Fraunhofer diffraction plane, i.e. the projector lenses are set to image the back focal plane of the objective. The beam crossover at the specimen is scanned by double deflection coils (not shown).

tom of the column. The electron probe is the beam crossover focused at the specimen plane. The detectors are positioned in the microdiffraction plane at the bottom of the diagram, where we can observe the convergent beam electron diffraction (CBED) pattern. The Ronchigram (also known as the 'Gabor hologram' or 'shadow image') is simply the undiffracted disc of electrons at the centre of the pattern.

Assuming for a moment that the source of electrons is small and the trajectories of the electrons are unaffected by diffraction effects, then Fig 2 shows how a feature in the Ronchigram should reverse as a function of changes of focus in the probe-forming lens. When the probe is perfectly focused (Fig 2d), then in this simple model the Ronchigram will have entirely even intensity. Either side of focus, we see a magnified shadow image of the specimen. The magnification is largest when the probe is only slightly defocused. As the probe-forming lens is increased in strength, the image orientation starts unreversed (Fig 2a), then reverses (Fig 2c), then becomes again unreversed (Fig 2e). Some experimental examples are shown in Fig 3. These have been obtained in a Philips CM20. The source is a conventional tungsten tip, but with spot size 10 (i.e. a small probe size) selected. It is a common myth that Ronchigrams can only be obtained with a field emission source: in fact, provided the condenser has sufficient demagnification, a tungsten source can give good Ronchigrams, albeit with low counting statistics.

In Fig 2 we have assumed that the detector plane is a long way from the specimen. In practice, though, especially when a TEM is in both 'STEM' and 'image mode' (the diffraction button switched off) the detector plane can be very close to, or even at the specimen plane because the lower half of the lenses in Fig 1 can map the specimen plane directly onto the detector. In this case, when the probe appears focused on the detector (Fig 2d) the underlying image of the specimen is undistorted because it is in exactly the same plane as the probe, as is usual in normal TEM imaging. However, in general the image plane is not congruent with the specimen for optimal STEM imaging and so if we try to image the probe (Fig 2b) we see a demagnified shadow image of a region of specimen disappearing into the focused spot. Either side of focus we see a distorted, squeezed image of the specimen, a phenomenon which can confuse even the most experienced user. For what follows, we assume we are in diffraction mode, i.e. the detector plane is effectively a long way from

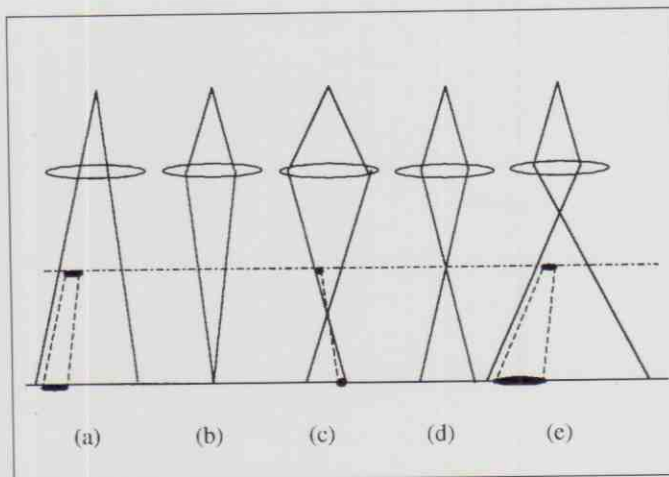
the specimen. However, note that many manufacturers' alignment procedures are performed in image mode where these distortions can occur.

The presence of aberrations in the probe-forming optics adds more complications to the Ronchigram. Spherical aberration causes high-angle rays to be brought to a premature focus higher up the column (Fig 4a). When the probe-forming lens is underfocused, the Ronchigram has two distinct areas: a central region where the shadow image is reversed, and an outer region where the shadow image is not reversed because adjacent rays in this region are crossing each other above the specimen plane (Fig 4b). The presence of any other misalignment or astigmatism in the probe-forming optics will further drastically distort the symmetry of the pattern, as we see in the experimental data in Fig 3: this is why the Ronchigram is such a good tool for lining up the STEM mode column. If it is possible to adjust the electron optics so that the Ronchigram is completely flat (the same intensity everywhere), then this implies that every electron has passed through one point in the specimen: in other words, the STEM probe is perfectly focused. Aberrations prevent us from achieving this, but if we get close to a 'flat' Ronchigram (i.e. with as little structure as possible) then the STEM performance will be very good indeed.

#### ALIGNMENT PROCEDURES USING THE RONCHIGRAM

It must be emphasised that the spatial resolution of a STEM probe is completely unaffected by anything that happens to the electron optics below the specimen, although the projector system does determine the camera length of the STEM detector arrangement. In other words, our task is to get the gun, the condenser, the condenser aperture, the condenser stigmators and the objective pre-field aligned with each other. Figure 5 illustrates some common forms of misalignment. Different manufacturers have different lens configurations, the main variable being the height of the mini-lens (either condenser or objective) between C2 (or the lowest condenser lens) and the objective pre-field, and the number of beam crossovers in this region. However, whatever the exact configuration, the only thing to remember is that in a perfectly aligned microscope, all image movement in the Ronchigram from an amorphous or non-crystalline material is concentric around a single axis (the optic axis) as a function of any lens used to form the probe.

Start by aligning according to the manufacturer's procedures for both TEM and STEM. Load an easy test specimen like gold particles evaporated on a thin carbon film. Select the largest condenser aperture in TEM mode and align it in the usual way. Obtain the Ronchigram in 'STEM' and 'diffraction mode': the Ronchigram should just appear on the phosphor screen. If it doesn't, go down in camera length until you see something. Check the probe is not scanning and that the STEM is at

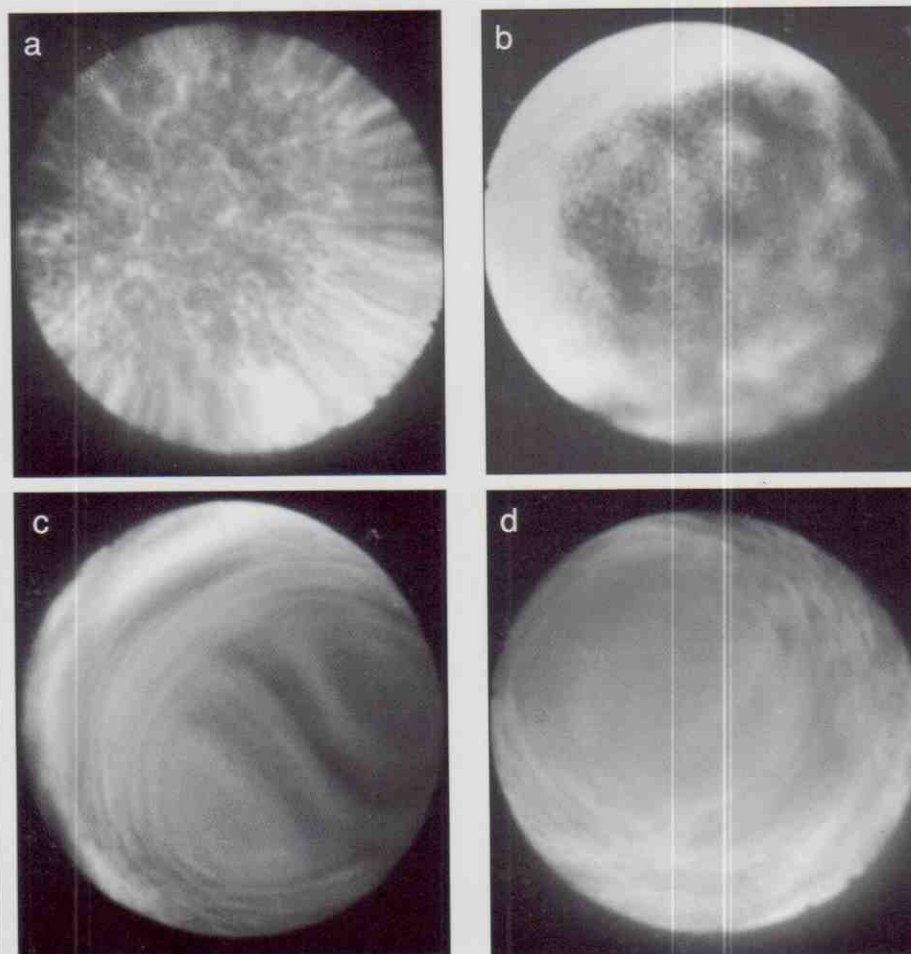


**Figure 2:** How a probe-forming lens changes what is seen in the Ronchigram. The dotted horizontal line is the plane of the specimen, the solid horizontal line the plane of the detector (ideally, an infinite distance from the specimen). The lens strength increases from left to right. A feature on the specimen casts a shadow onto the detector (the Ronchigram is sometimes called a shadow image). Note the reversal of the shadow image in (c), that the probe is imaged in (b), that (a) and (e) give similar images, and that the STEM probe is focused on the specimen in (d).

its highest magnification. Wobble the objective lens (i.e. the current rotation centre), adjusting the beam tilt until the centre of magnification is at the centre of the condenser aperture: this corrects the errors of the type shown in Fig 5a. Coarsely adjust the condenser stigmators. Astigmatism in the Ronchigram appears as streaking across the centre of the pattern (Fig 3c). Adjust the focus of the objective until it lies between the two orthogonal extremes of the streaking, and then adjust the stigmators, i.e. the condenser stigmators, to

get a smooth, flat intensity region at the centre of the Ronchigram, as much like Fig 3d as possible. Remember that in contrast to conventional imaging, this flat featureless condition is when the Ronchigram is 'in focus' in the sense that the probe is as small as possible in the specimen plane (think of Fig 2d).

Starting from this coarse in-focus Ronchigram, try altering C2. This may be fixed by the computer control software, but there is usually a way to unlock it: e.g. on the Philips CM series by going to 'μdiff' mode, on the JEOL JEM



**Figure 3:** Experimental Ronchigram obtained in a CM20 with a tungsten filament. The specimen is gold islands on thin amorphous carbon. (a) Underfocusing. The central region is reversed (see Fig 2c), the streaking in the outer region is called the ring of infinite radial magnification. (b) Overfocusing (see Fig 2e). (c) Severe astigmatism in the condenser at focus. (d) In focus (see Fig 2d): the large flat area of intensity arises because all central beams pass through the same point of the specimen.

series, press the condenser wobbler. Wobble or vary C2 slightly above and below the focused condition. The effect on the Ronchigram should be identical to wobbling the objective lens, but the likelihood is that the centre of magnification in the Ronchigram will be in a different position, and, furthermore, different above and below the condenser focus. This is because so far we have aligned the objective lens with the condenser aperture, which itself was aligned in TEM mode, typically for a much higher condenser excitation. Residual mechanical lens tilt and misalignment can lead to significant discrepancies between modes.

For optimal resolution, the trick is to make sure that any perturbation from the desired settings have a symmetric influence around the optical axis of the Ronchigram. In this particular case, we must ignore the position of the condenser aperture, and realign the objective rotation centre to make it coincident with the condenser lens axis. The process is not always easy, especially since each change may also slightly change the required setting of the stigmators. Similarly, try changing the voltage centre, and, if appropriate (and if you have control over it), the field emission extraction voltage. If these induce lateral or non-centrosymmetric movements in the Ronchigram then the gun tilts and/or shifts are misaligned. Note that a new alignment is probably necessary for every setting of C1 (spot size). If the optics have a lot of hysteresis, a mode change can throw out the alignment: perfectionists beware!

Once the lenses and gun are aligned, we can now insert an optimal condenser aperture for nanoanalysis. Focus the Ronchigram so that the central region is as flat in intensity and as wide possible (see Fig 3d). Moving the specimen back and forth slightly can help to determine whether the central region has any structure. Insert the largest condenser aperture available that has a diameter equal to or smaller than the central flat region of intensity. Roughly speaking, what we are seeing here is a representation of the transfer function of the whole probe-forming optics. We choose the largest aperture so that the STEM probe is not compromised by diffraction broadening. Of course, rays outside the flat region of the Ronchigram have missed the focus of the probe, and so we cut them out to stop them adversely blurring the outer lobes of the probe (Fig 4b). As you insert the aperture, you may be dismayed to find that the centre of Ronchigram becomes distorted. The reason is your condenser aperture is charging up in the electron beam and thereby adding its own electrostatic aberrations - try cleaning the aperture!

The great advantage of the Ronchigram is that the whole of the probe-forming optics are expressed simultaneously. If you rely on positioning the condenser aperture by minimising objective lens wobble in the STEM image, or by optimising the image of the

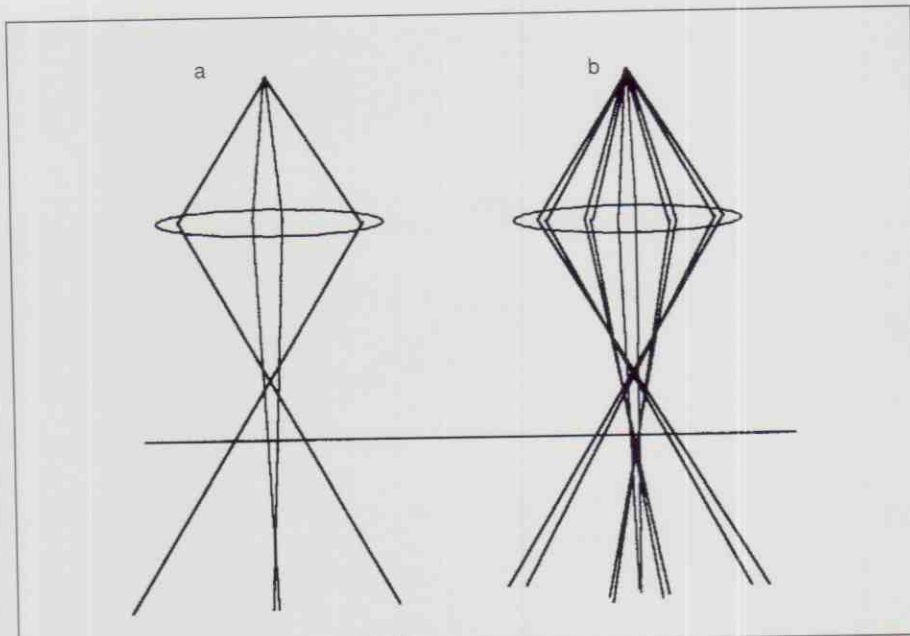


Figure 4:  
(a) When aberrations are present, different parts of the Ronchigram crossover above or below the specimen according to their angle relative to the optical axis. High-angle beams are prematurely focused.  
(b) The local magnification in the Ronchigram is determined by the point of crossover of adjacent beams. In this diagram, high angle rays crossover above the specimen, axial rays below the specimen; other beams cross at the specimen - this defines the ring of infinite magnification (see Fig 3a), although note that infinite magnification in azimuthal and radial components occur at different angles.

probe, then misalignments can easily compound each other. Iterative methods in these planes can take hours to converge, whereas with a little practice all the problems can be very quickly adjusted in the Ronchigram. When you flip to scanning mode and observe your real-space STEM image, you should find it will very well focused and stigmated. The only adjustments you may need to make will be to align the detector. If you see an image of the detector at low magnification, it could mean that your pivot points are wrongly adjusted (Fig 5b), so that the far-field beam is sweeping over the detector plane (the magnification calibration will also be wrong). To get true dark-

field contrast you must ensure that the camera length is short enough to put the annular detector at a sufficiently high angle. For bright-field STEM imaging, the camera length should be as long as possible to ensure the detector is much smaller than the Ronchigram.

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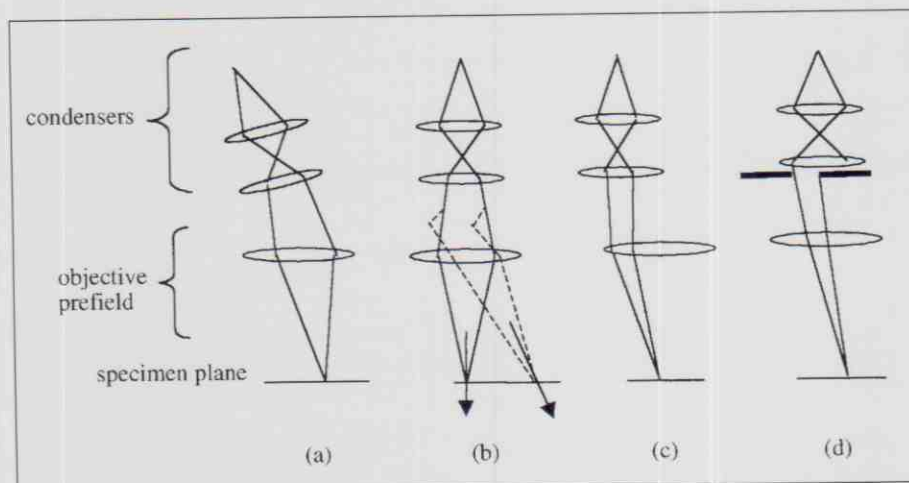


Figure 5:  
Some classes of misalignment in the probe-forming optics.  
(a) Beam tilt error: correct using the rotation centre align.  
(b) Beam tilts as a function of probe position when scanned: correct pivot points.  
(c) Condenser system shift error: realign according to manufacturers instructions, but certainly not with beam tilt.  
(d) Condenser aperture misaligned. Check all lens alignments before this one.

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