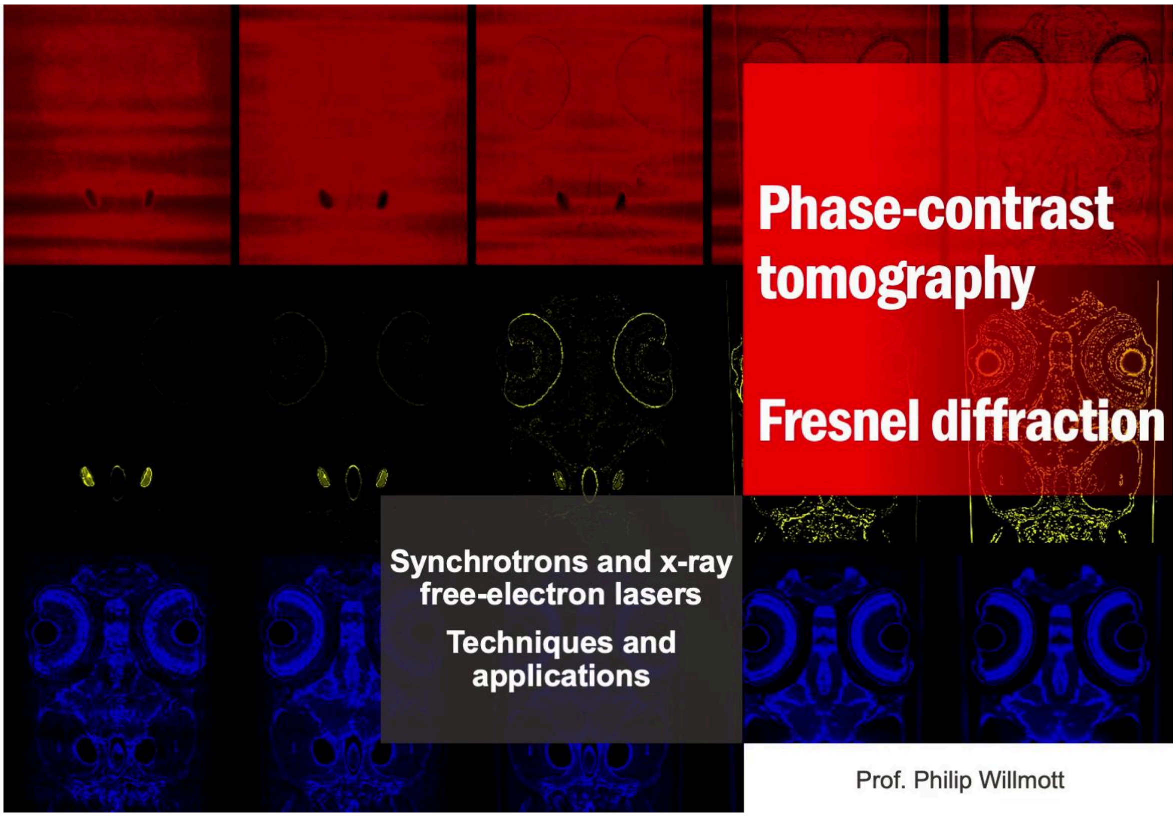
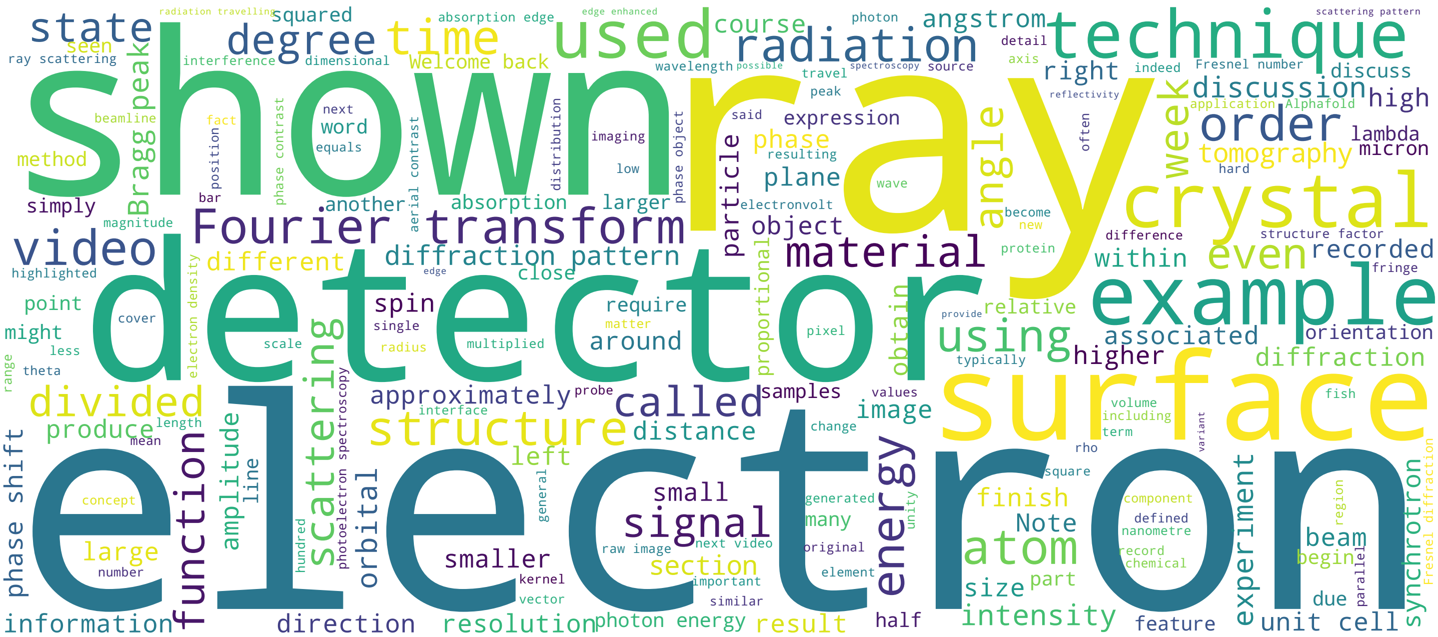
EPFL



Prof. Philip Willmott

École polytechnique fédérale de Lausanne



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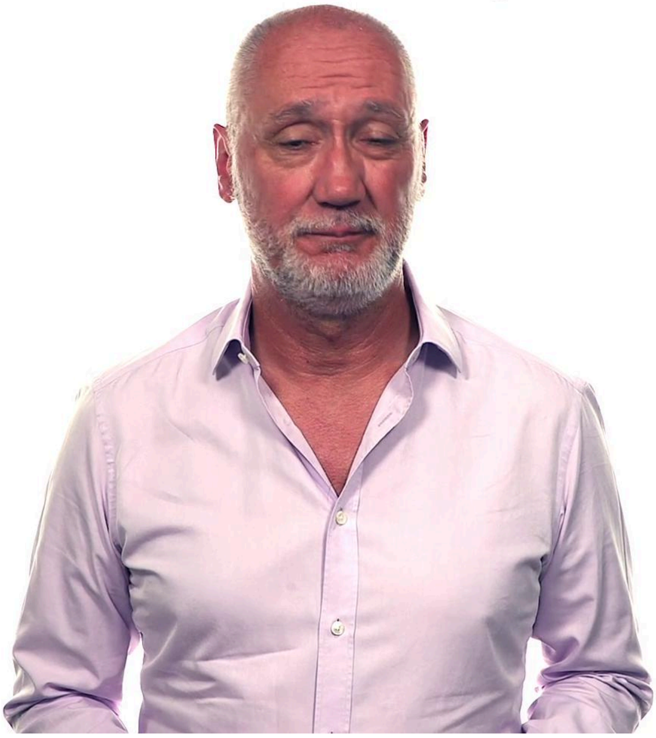
EPFL

Contents and objectives of this video



- Phase advance in transmitting objects
- The Fresnel condition v Fraunhofer condition
- Phase objects
- Example of phase-contrast images
- From fringes to contrast

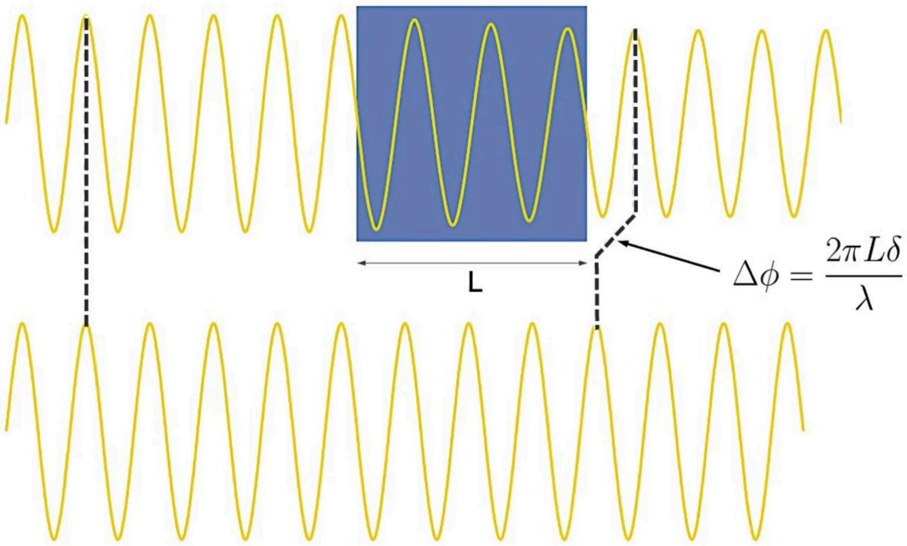
Welcome back to this introductory course on synchrotron and XFEL radiation. In this second video of the second section of the fifth week, we continue our discussion of phase contrast as exploited in tomography and differentiate between far-field Fraunhofer, and near-field Fresnel diffraction. We also introduce the concept of phase objects. We will finish by demonstrating how one converts the line-like raw images produced by fringes to ones exhibiting real aerial contrast.

Notes

Summary

0m 05s

Phase gives you the edge



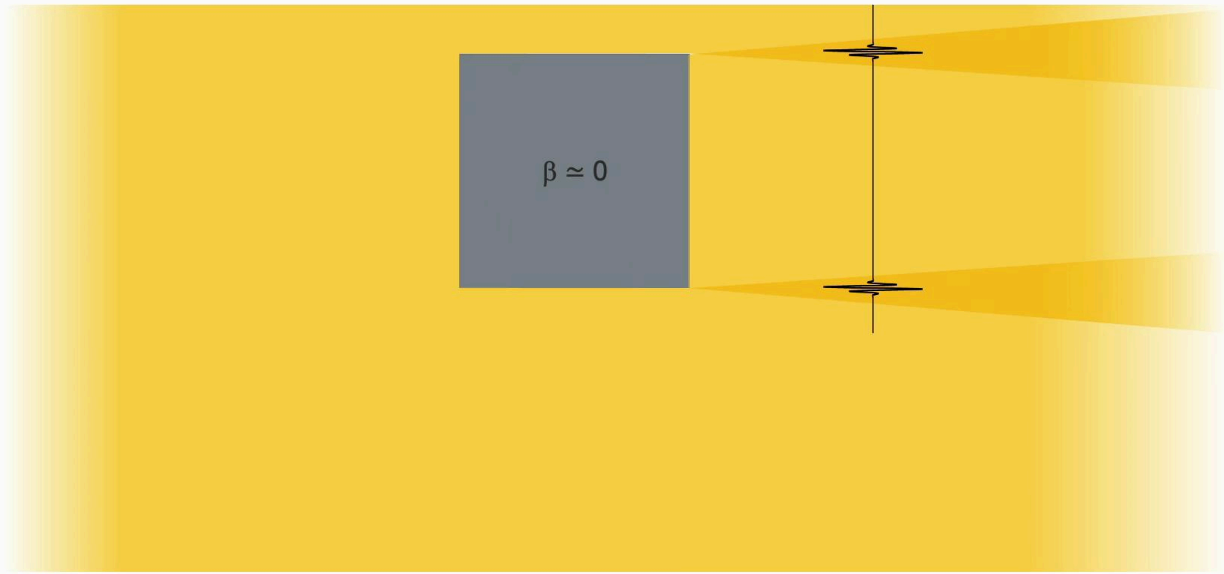
Okay. Let's remind ourselves about what happens to X-radiation as it travels through condensed matter. First, the radiation is attenuated during its travel through that matter. But as we've said, in many cases, this can be a very weak phenomenon with essentially undetectable contrast with radiation compared to radiation travelling outside the sample. However, there will also be a phase shift with the phase velocity of radiation travelling through the matter exceeding the speed of light. The phase shift of radiation of wavelength lambda after travelling through a piece of matter of thickness L with a refractive index decrement delta is, in radians, two times pi times L times delta divided by lambda. Even for a sample of 0.1 millimetre thickness and a very small delta of 2 times 10 to the -7, half angstrom radiation will experience a phase shift of 4 pi divided by 5, or 144 degrees.

Notes

Summary

0m 37s

Phase gives you the edge



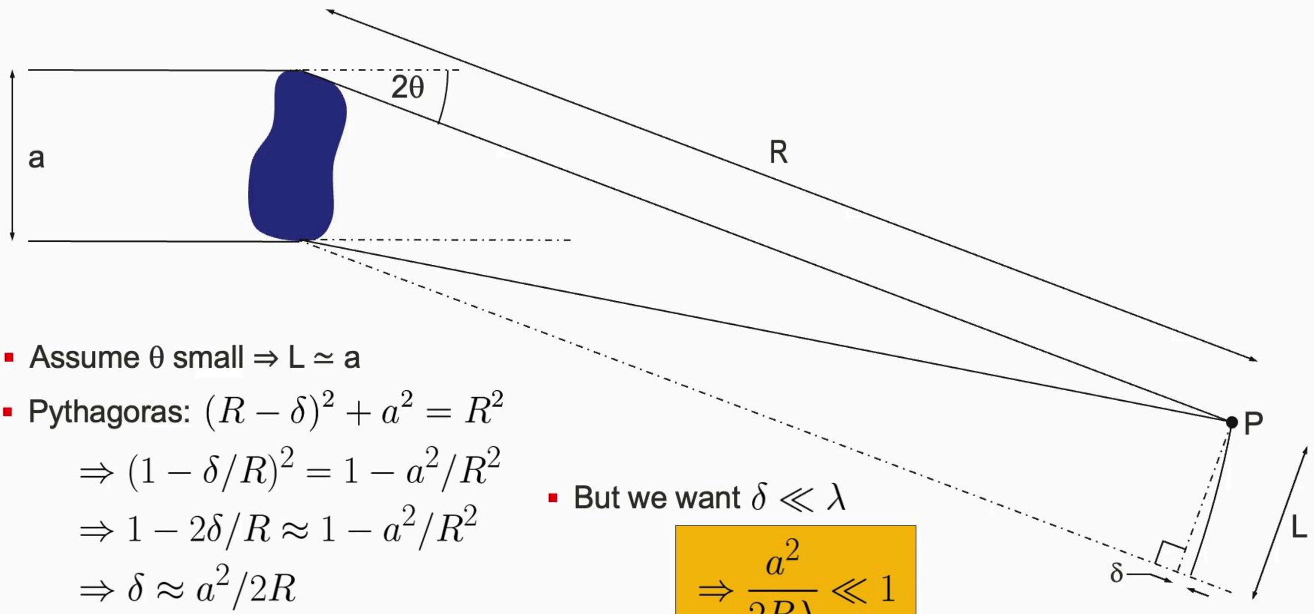
What is now needed is for radiation that travels through the sample to mix with the radiation that hasn't travelled through the sample, or even radiation that has travelled through material with a different refractive index. Now, even for samples in which the interfaces are precisely at right angles to the propagation of the X-rays, as I'm showing here, we have seen in the video that the radiation doesn't simply move forward, but does spread sideways due to diffraction, as explained by the Huygens' construction. Hence, even a completely transparent phase object with flat perpendicular faces will induce an overlap between the phase advanced part of the radiation travelling through it, and the remainder of the beam outside the sample. This overlap produces fringes in this overlap region that will become more spread out with propagation distance.

Notes

Summary

1m 50s

From SAXS discussion - the Fraunhofer condition



- Assume θ small ⇒ L ≃ a
- Pythagoras: $(R-\delta)^2 + a^2 = R^2$

$$\Rightarrow (1-\delta/R)^2 = 1 - a^2/R^2$$
$$\Rightarrow 1 - 2\delta/R \approx 1 - a^2/R^2$$
$$\Rightarrow \delta \approx a^2/2R$$

- But we want $\delta \ll \lambda$

$$\boxed{\Rightarrow \frac{a^2}{2R\lambda} \ll 1}$$

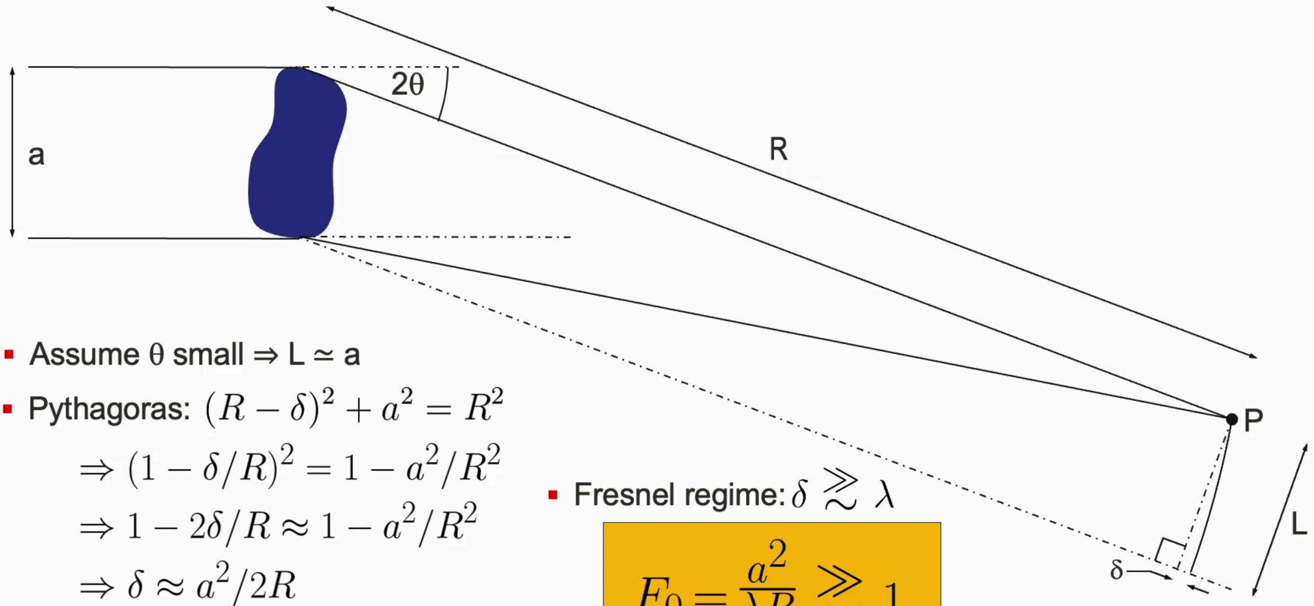
From our discussion about small-angle X-ray scattering, we saw that for the Fraunhofer regime, we want a² divided by 2R lambda to be much less than unity, which also holds also for a² upon R lambda as well. I skip through this derivation extremely swiftly, so please go back to video W2S4V1 in week two for a step-by-step derivation.

Notes

Summary

2m 50s

Fresnel condition opposite to the Fraunhofer condition



- Assume θ small ⇒ L ≃ a
- Pythagoras: $(R-\delta)^2 + a^2 = R^2$

$$\Rightarrow (1-\delta/R)^2 = 1 - a^2/R^2$$
$$\Rightarrow 1 - 2\delta/R \approx 1 - a^2/R^2$$
$$\Rightarrow \delta \approx a^2/2R$$

- Fresnel regime: $\delta \gtrsim \lambda$

$$\boxed{F_0 = \frac{a^2}{\lambda R} \gtrsim 1}$$

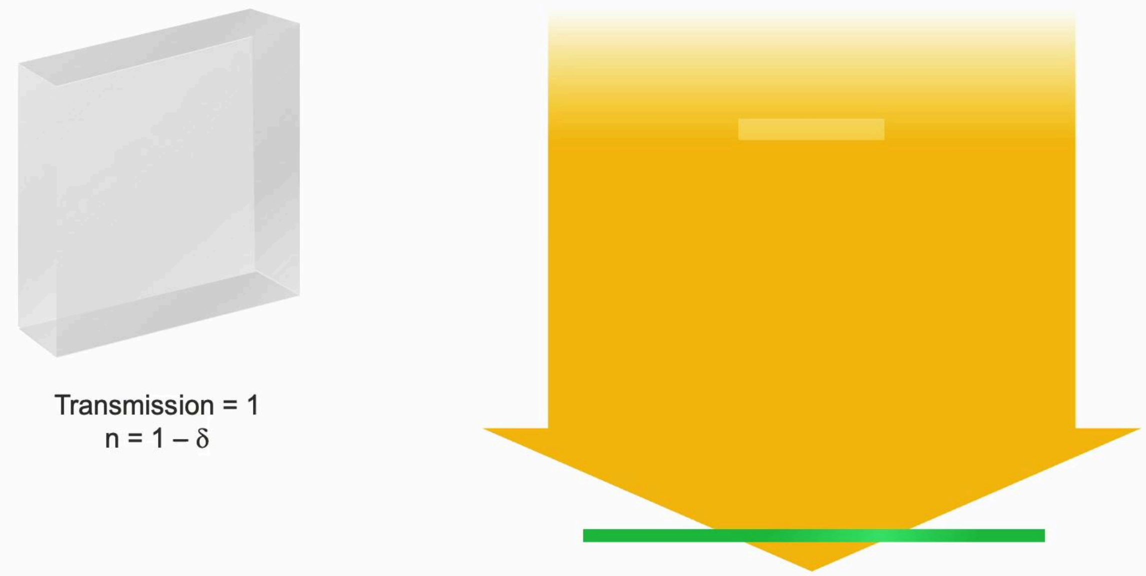
Fraunhofer diffraction satisfies the condition that the scattering pattern is detected sufficiently far away from the scatterer itself that it accurately represents the Fourier transform of the scatterer, or more accurately, the absolute square of the Fourier transform. However, at shorter distances before the Fraunhofer condition is met, interference is still happening, and it doesn't just turn on instantaneously. As a result, we get something of a halfway house in so-called Fresnel diffraction. Here, the so-called Fresnel number, F0, is equal to a² divided by lambda R, should be approximately equal to, or preferably a lot greater than unity. Hence, for example, for a micron-sized object, irradiated with one angstrom X-rays, the detector should be a good deal less than a centimetre from the sample to record the Fresnel diffraction image.

Notes

Summary

3m 23s

Phase objects



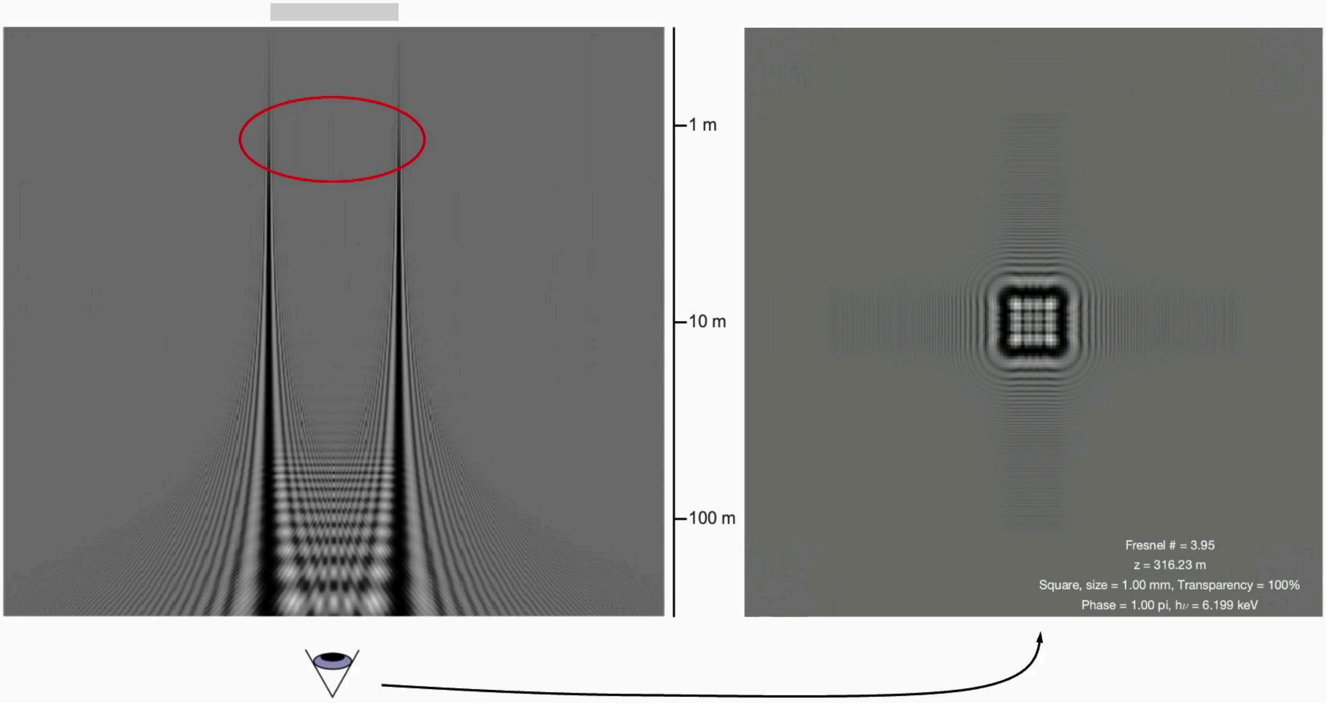
Let's now look at this in a simulation in which we take a model block of wholly transparent material and move the detector screen away from being very close to the sample to large distances.

Notes

Summary

4m 23s

Phase objects



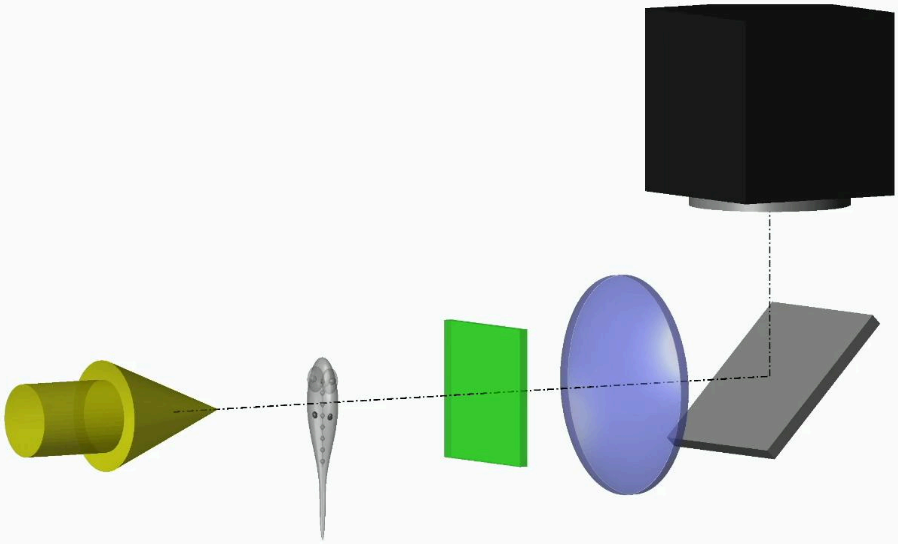
We take a material that induces exactly pi phase shift in the two-angstrom or 6.2 keV radiation. On the left, the cross-section through the wavefront is plotted as a function of Z, the detector position downstream of the sample, whereby Z has been plotted logarithmically. On the right, is what is seen on the detector by an observer. Let's start. We see how the Fresnel number begins at a value of several thousand, thus easily fulfilling our criterion. However, the strength of the interference increases swiftly producing a sharp fringe boundary at a distance of about a metre. As the detector is moved further and further away, F0 gets smaller and smaller until at approximately 200 metres, the F number, Fresnel number, is only marginally above unity, and the fringe pattern is extremely spread out. We are approaching the Fraunhofer regime, where we could expect to see the classical diffraction pattern of a square aperture, which is, in fact, a so-called sinc-squared function. An ideal propagation distance is highlighted here at around 1 metre, for which the Fresnel number is somewhere between a few hundred and a thousand. Here, the fringe contrast is high while still remaining tight and defining the boundary of the phase object accurately.

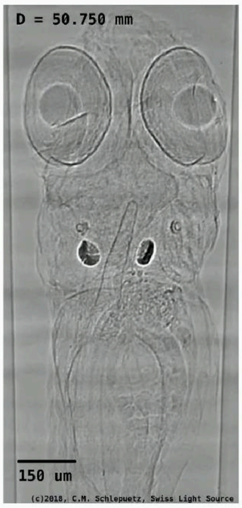
Notes

Summary

4m 37s

Example I – zebrafish embryo





In this cartoon of an experiment which was performed on a zebrafish embryo at the TOMCAT beamline of the Swiss Light Source, so using real data, we see how the embryo is essentially undetectable at the beginning, where the detector or scintillator is at a position of around 5 millimetres from the sample. We do see two dark features called otoliths made of denser calcium carbonate used by the fish to detect gravity and acceleration. As the scintillator is moved downstream relative to the fish, the outline of the fish and its internal features become increasingly obvious. As an aside, note the shimmering background signal caused by extremely small vibrations of the X-ray optics. This can only be partially removed in post-processing by a flat field if these changes are too rapid. Like we have said before, the best optics are no optics.

Notes

Summary

6m 09s

Example II – cretaceous insects in amber

1000 mm sample-detector distance, 30 keV

Courtesy: P. Tafforeau. Recorded @ ID19, ESRF, 5 μm pixel size on detector

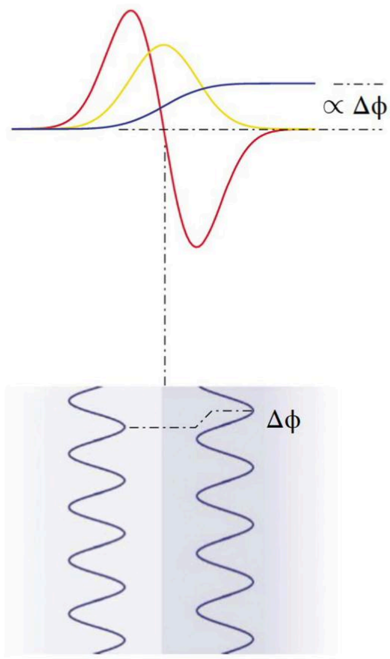
The second example comes from the ID19 beamline at the ESRF, in which cretaceous insects entombed in amber can be seen very clearly, but only if the detector is moved from 50 to 1,000 millimetres downstream when using 30 keV radiation.

Notes

Summary

7m 12s

From fringes to contrast



$$d^2y/dx^2 = x\exp(-x^2/2\sigma^2)$$

$$dy/dx = A\exp(-x^2/2\sigma^2)$$

$$y = 2A\sqrt{\pi}\sigma$$

By positioning the detector scintillator system at a judicious distance downstream from a sample, its features can be recognised by tight fringes that produce something akin to a line drawing. But what we would really like is an aerial rather than edge contrast, which we can achieve through a mathematical trick as follows. From our discussion of edge diffraction in the last video, you might remember that it is the first peak and fringe minimum that really dominate. We thus approximate the first fringe of a feature in a raw phase contrast image as being equal to a Gaussian multiplied by X, as shown here by the red curve. Now, the integral of this shown in gold and ignoring integration constants, is simply a Gaussian with the same width as that used in the red curve. Integrating once more produces the blue curve, which has an amplitude that is proportional to the phase shift Delta 5.

Notes

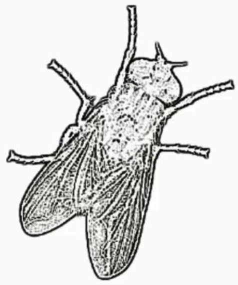
Summary

7m 32s

From fringes to contrast

5x5 Laplace
edge detector kernel

–1	–1	–1	–1	–1
–1	–1	–1	–1	–1
–1	–1	24	–1	–1
–1	–1	–1	–1	–1
–1	–1	–1	–1	–1



$$O \otimes L = E$$

$$E = L \otimes O \qquad \mathcal{F}(E) = \mathcal{F}(O) \times \mathcal{F}(L) \quad \Rightarrow O = \mathcal{F}^{-1}\left\{\frac{\mathcal{F}(E)}{\mathcal{F}(L)}\right\}$$

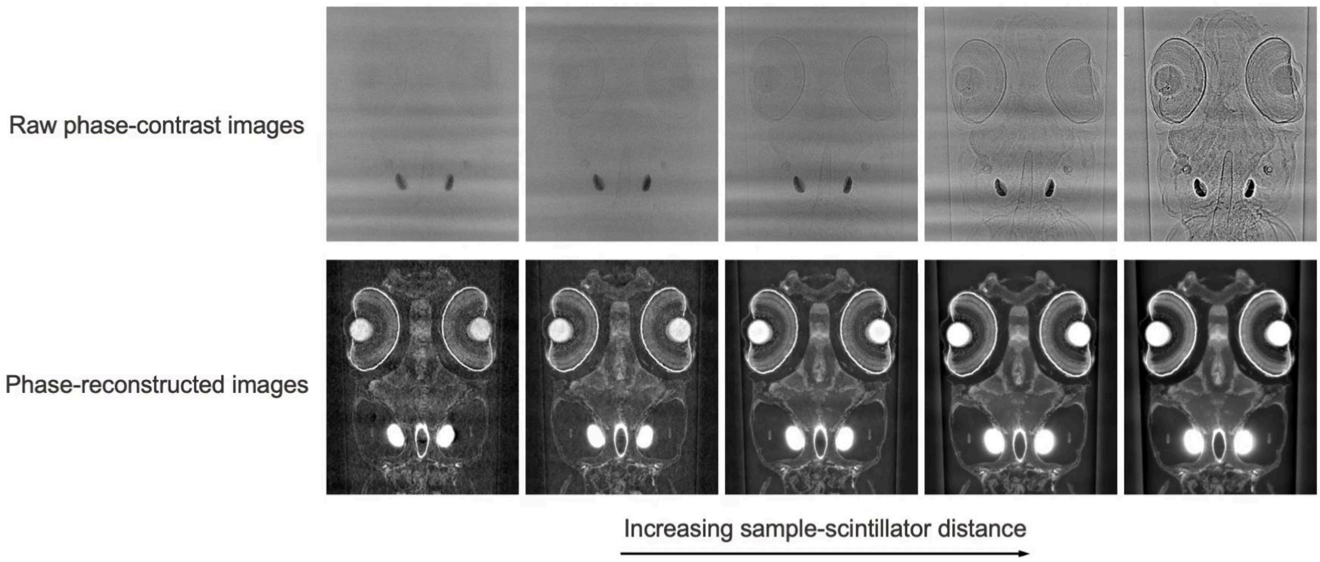
Now, in image processing, edge enhancement of an image can be generated by several means. Now, here, the original image, O, of a fly, is convoluted with the shown five-by-five kernel, which we label L. For any pixel in the original, the central strongly positive, plus 24-weighting element of the kernel is exactly cancelled out by the other 24 singly negative elements, assuming the surrounding pixels in the original have the same or very similar value. However, where the intensity in the original changes rapidly, the convolution with the kernel will produce a non-zero value resulting in edges being highlighted and shown here in the edge-enhanced image E. Expressed mathematically, E is equal to L convoluted with O. Once again, we now resort to the convolution theorem, which states that the Fourier transform of the convolution of two functions is equal to the Fourier transform of one multiplied by the Fourier transform of the other. Hence, the original, or in our case, an aerial contrast version of the edge-enhanced raw image, can be generated by taking the Fourier transform of that raw image, represented here by E, dividing it by the Fourier transform of the kernel L, and then inverse Fourier transforming the whole again to produce O.

Notes

Summary

8m 38s

From fringes to contrast



Importantly, it doesn't require much amplitude in the fringes to extract an aerial contrast image, as we can see here. Even the barely-visible edge-enhanced image at top left is enough to get all but the most subtle details in the aerial reconstruction.

Notes

Summary

10m 15s

In the next video...

We finish our discussion of tomography through direct imaging in the next and final video of this section with a discussion of fast tomography, a technique which is now capable of recording entire tomograms at hundreds of Hertz, especially since the advent of high-brightness, fourth-generation DLSR synchrotrons.

Notes

Summary

10m 32s