

Tuning the CEOS STEM Corrector

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Tuning Prerequisites.

- Use a standard specimen – Au nanoparticles on carbon.
- Microscope **must be absolutely stable**: ie no thermal drift, lens hysteresis, stage drift, HT instability etc. Typically, this means changing the microscope voltage on a Friday and tuning on the following Monday.
- Specimen must free from contamination. Ideally, the specimen should be left in the microscope overnight. It must be beam showered.
- Instabilities will make tuning difficult and invalidate the long-term stability of the tune.



Aberrations

| Symbol | Order | Name | Target Value | How to Adjust |
|--------|-----------------|----------------------------------|--------------|--|
| A1 | 1 st | 2-fold Astigmatism | 0-5nm | Manual: Coarse stigmators |
| C1 | 1 st | Focus | 5-10nm | Manual: Focus |
| A2 | 2 nd | 3-fold Astigmatism | <50nm | Corrector |
| B2 | 2 nd | Coma | <50nm | Manual: Beam Tilt (coarse) Corrector (fine) |
| C3 | 3 rd | Spherical Aberration Coefficient | 0-3um | Corrector |
| A3 | 3 rd | 4-fold Astigmatism | <1um | Corrector |
| S3 | 3 rd | Star Aberration | <1um | Corrector |



Precision vs Accuracy

- An appropriate specimen with enough density of heavy element particles on a low background support is needed in order to measure the aberrations.
- The CEOS software measures the sharpness of the edges of the particles (in all directions). Anything which affects that sharpness (drift, contamination etc) will invalidate the measurement.
- Magnification will affect the number of particles in the field of view (accuracy) as well as the detail in them (precision).
- A balance between accuracy and precision is needed for a good measurement of aberration coefficients.
- Mag of 400K-600K, 8C probe (30pA), 20um C2 aperture.

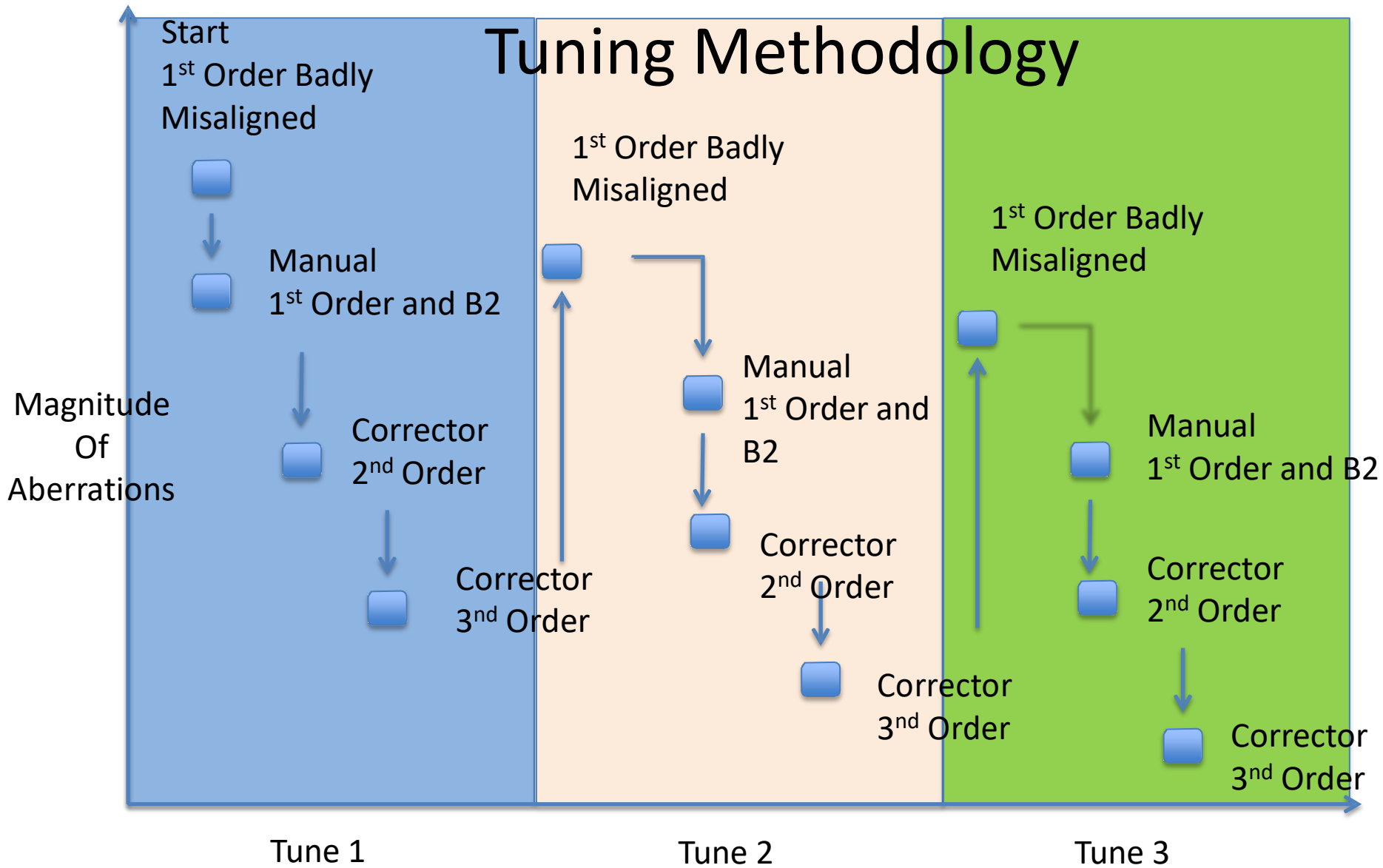


Tuning Methodology

- You must correct all first order aberrations before tuning second order aberrations.
- You must correct all second order aberrations before tuning third order aberrations.
- After a 3rd order tune – first order aberrations will need correcting.
- Repeat the above tuning cycle (1st, 2nd, 3rd, 1st, 2nd . . . etc) until all aberrations are within target range.
- The Ronchigram will grow in size and uniformity as aberrations are tuned out.

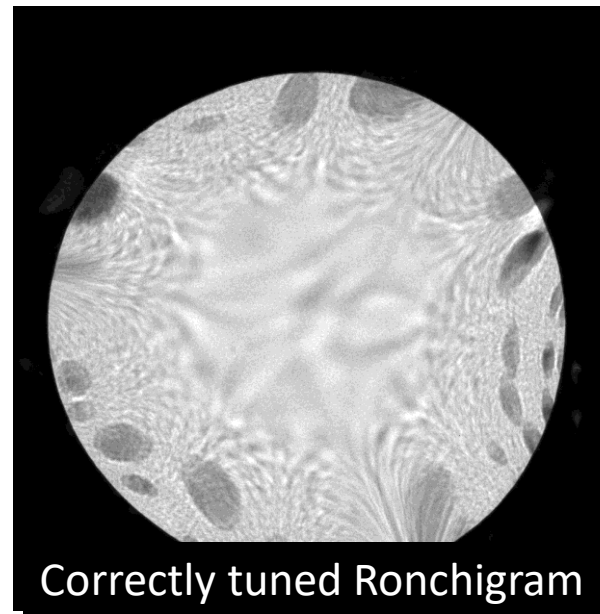
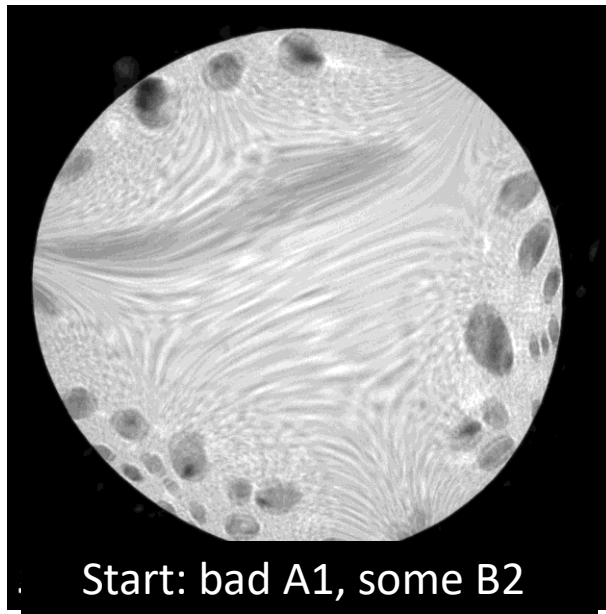


Tuning Methodology



Manually Aligning Ronchigram

- Degauss twice then correct C1 and A1 and coarse alignment of B2 (coma) using the Ronchigram. Note you can manually correct B2 to perhaps 100nm. The software will improve this to ca 20nm.



Manually Correcting 1st Order Aberrations

Ensure that the beam is centred in the HAADF detector (lower the magnification to 20kx and use projector lens shifts to centre the illumination, then return to higher mag. If off-centre, large tilts (24-27mrad) used for 3rd order correction (later), may run the beam into the HAADF detector.

Continuously monitor A1 and C1 for 30s. Ensure that there is no systematic drift (+/- a few nm is fine). If drift is present, give it more settling time.

```

C1 A1 pressed.
time: 72103s C1: -714.4pm A1: 2.129nm / +28.5deg signal mean: 2220cnts
time: 72111s C1: 5.548nm A1: 4.544nm / +127.4deg signal mean: 2214cnts
time: 72118s C1: 12.35nm A1: 2.792nm / +113.3deg signal mean: 2221cnts
time: 72126s C1: 9.979nm A1: 2.68nm / -7.9deg signal mean: 2216cnts
time: 72134s C1: 11.6nm A1: 6.093nm / +53.2deg signal mean: 2219cnts
time: 72141s C1: -15.43nm A1: 2.935nm / +81.8deg signal mean: 2186cnts
time: 72149s C1: 9.432nm A1: 1.026nm / -150.2deg signal mean: 2208cnts
time: 72157s C1: 14.08nm A1: 3.486nm / +39.9deg signal mean: 2213cnts
time: 72165s C1: 16.82nm A1: 2.352nm / -37.8deg signal mean: 2223cnts
time: 72172s C1: 14.51nm A1: 1.271nm / +38.8deg signal mean: 2225cnts
time: 72180s C1: 16.17nm A1: 4.618nm / -18.5deg signal mean: 2223cnts
time: 72188s C1: 12.75nm A1: 1.764nm / +52.3deg signal mean: 2207cnts
time: 72196s C1: 12.95nm A1: 5.547nm / +52.6deg signal mean: 2210cnts
time: 72204s C1: 13.41nm A1: 1.523nm / +2.6deg signal mean: 2210cnts
time: 72211s C1: 15.93nm A1: 375.8pm / +102.5deg signal mean: 2224cnts
time: 72219s C1: 15.36nm A1: 4.018nm / +99.8deg signal mean: 2230cnts
time: 72227s C1: 13.61nm A1: 1.628nm / -34.3deg signal mean: 2212cnts
time: 72235s C1: 16.81nm A1: 2.084nm / -31.7deg signal mean: 2217cnts
time: 72243s C1: 12.6nm A1: 2.118nm / +22.6deg signal mean: 2222cnts
time: 72250s C1: 12.54nm A1: 1.82nm / -61.7deg signal mean: 2211cnts
time: 72258s C1: 12.85nm A1: 746.7pm / -43.1deg signal mean: 2208cnts
time: 72266s C1: 12.14nm A1: 254.8pm / -63.2deg signal mean: 2220cnts
time: 72274s C1: 12.04nm A1: 2.224nm / +49.4deg signal mean: 2203cnts
time: 72282s C1: 9.621nm A1: 3.419nm / -36deg signal mean: 2216cnts
time: 72290s C1: 13.2nm A1: 1.308nm / +68.6deg signal mean: 2216cnts
time: 72298s C1: 14.34nm A1: 2.003nm / +34.4deg signal mean: 2217cnts
time: 72306s C1: 14.94nm A1: 1.391nm / +57.5deg signal mean: 2228cnts
time: 72313s C1: 14.6nm A1: 1.245nm / +109.6deg signal mean: 2224cnts
time: 72321s C1: 13.39nm A1: 3.929nm / +23deg signal mean: 2236cnts
time: 72329s C1: 12.75nm A1: 5.694nm / -18.8deg signal mean: 2218cnts
time: 72337s C1: 12.57nm A1: 899pm / -38.8deg signal mean: 2233cnts
time: 72344s C1: 10.48nm A1: 2.431nm / +153.3deg signal mean: 2232cnts
time: 72352s C1: 14.55nm A1: 2.461nm / +3.6deg signal mean: 2228cnts
time: 72360s C1: 12.26nm A1: 1.003nm / -65.5deg signal mean: 2232cnts
time: 72368s C1: 14.61nm A1: 2.214nm / -88deg signal mean: 2224cnts
time: 72376s C1: 12.1nm A1: 492.2pm / -167.9deg signal mean: 2220cnts
time: 72383s C1: 14.04nm A1: 3.318nm / -131.7deg signal mean: 2232cnts
time: 72391s C1: 12.31nm A1: 1.481nm / -151.1deg signal mean: 2232cnts
time: 72399s C1: 12.35nm A1: 4.071nm / 40deg signal mean: 2235cnts
time: 72407s C1: 9.751nm A1: 3.475nm / -31deg signal mean: 2201cnts
time: 72415s C1: 11.39nm A1: 1.322nm / +0deg signal mean: 2200cnts
time: 72422s C1: 11.25nm A1: 2.801nm / +33.1deg signal mean: 2231cnts
    
```

The screenshot shows the 'STEM CsCorrector GUI (service) V2.95p12' interface. Key elements include:

- Top Panel:** 'File Debug Tableau Dialog' with a 'corr A1' button circled in red.
- Parameter Table:**

| StigmA1 | Stigm | extra | User BSh | BeamTilt |
|---------|--------|--------|----------|----------|
| -0.268 | -4.328 | +0.000 | -79.115 | -25.834 |
| -1.027 | -5.197 | +0.000 | -10.015 | +24.132 |
- Image View:** A central window showing a spot pattern with a red circle around a specific spot. Below it, a status bar reads: 'C1: 8.967nm A1: 3.024nm / +51deg signal mean: 2233cnts'.
- Config Analysis Panel:** On the right, showing 'SHMAG', 'TEM off', 'X500K', 'X600K', 'X800K' and various acquisition parameters like 'Nyquist frequency' (0.68) and 'Outer tableau tilt' (18).
- Single Channel control Panel:** At the bottom, showing a grid of controls for Hexapole (Hexapole11, Hexapole12), Dipole (Dipole11X to Dipole12Y), Qpole (QpoleX, QpoleY), Hpole (HpoleX, HpoleY), BShift (BShiftX, BShiftY), and Tlens (Tlens12 to Tlens22).

Use the Spot function to get an continuous measurement of A1 (2-fold astig) and C1 (Focus). Manually adjust these to 0-5nm and 5-10nm respectively

3.5

Corrector Tune of 2nd Order Aberrations

Ensure all (or nearly all) of the tableau measurements are used. If more than 3 or 4 are rejected – the result is unreliable. Discard and run again.

```
Tab pressed.
# 1 C1: 2.396nm A1: 5.258nm / +26.5deg signal mean: 2252cnts
# 2 C1: 5.329nm A1: 5.355nm / -58.2deg signal mean: 2515cnts
# 3 C1: 9.662nm A1: 10.09nm / -87.4deg signal mean: 2379cnts
# 4 C1: 7.85nm A1: 9.438nm / -102.7deg signal mean: 2236cnts
# 5 C1: 5.553nm A1: 4.302nm / -28.8deg signal mean: 2120cnts
# 6 C1: 3.14nm A1: 2.84nm / -115.6deg signal mean: 2100cnts
# 7 C1: 3.058nm A1: 2.797nm / -54.2deg signal mean: 2170cnts
# 8 C1: -954pm A1: 3.174nm -11.7deg signal mean: 2384cnts
# 9 C1: -3.159nm A1: 4.179nm / -54.6deg signal mean: 2653cnts
#10 C1: 1.528nm A1: 7.241nm / -13.8deg signal mean: 2822cnts
#11 C1: -482.1pm A1: 1.864nm / +35deg signal mean: 2895cnts
#12 C1: 3.34nm A1: 3.839nm / -73deg signal mean: 2811cnts
#13 C1: 7.517nm A1: 6.981nm / -25.9deg signal mean: 2677cnts
#14 C1: 2.867nm A1: 4.578nm / -12.8deg signal mean: 2331cnts
#15 C1: 4.92nm A1: 2.538nm / -43.2deg signal mean: 2136cnts
#16 C1: 1.896nm A1: 996.7pm / +68.2deg signal mean: 2266cnts
#17 C1: 2.246nm A1: 3.922nm / -55.5deg signal mean: 2475cnts
#18 C1: 2.204nm A1: 2.937nm / -27.4deg signal mean: 2251cnts
dTime: 73773s Date: Fri Jan 5 01:53:42 2018
```

```
1st order measured! (not used:)
Satt: 3.897nm Sused: 3.897nm (1.122%)
C1: 2.3nm (95%: 4.9nm)
A1: 3.69nm / +7.7deg (95%: 6.06nm)
A2: 24.24nm / -156deg (95%: 45.7nm)
B2: 61.61nm / +44.5deg (95%: 29.2nm)
C3: 2.322um (95%: 1.71um)
A3: 707.3nm / -152.2deg (95%: 1.74um)
S3: 1.474um / +111.2deg (95%: 753nm)
A4: 50.33um / +74.8deg (95%: 72.7um)
Btn 'Accept Aberr' pressed.
Btn 'B2' pressed.
```

A2=24 +/- 48nm OK
 B2=62 +/- 29nm Not OK
 Correct B2 by clicking OK
 and pressing the B2 button

Run a Standard Tableau and Use an 18mrad tilt angle. This will give you reliable 2nd order aberration values. Ignore all 3rd order and higher values.



Corrector Tune of 2nd Order Aberrations ctd

- Continue tuning 2nd order aberrations until the A2 and B2 values are within the target range (both <50nm).
- Only then move on to correcting 3rd order aberrations.

```
1st order measured! (not used:)  
Sall: 3.141nm Sused: 3.141nm (0.9042%)  
C1: 8.456nm (95%: 2.68nm)  
A1: 3.064nm / -35.9deg (95%: 5.68nm)  
A2: 29.99nm / -139.2deg (95%: 42.8nm)  
B2: 25.86nm / -50.9deg (95%: 19.9nm)  
C3: -968.1nm (95%: 1.08um)  
A3: 507.6nm / +33deg (95%: 1.63um)  
S3: 350.6nm / +127.9deg (95%: 614nm)  
A4: 44.91um / +121.3deg (95%: 68.1um)
```

□

Target Values

C1 5-10nm

A1 5nm

A2 <50nm

B2 <50nm

Ignore 3rd order

Corrector Tune of 3rd Order Aberrations

If more than 2 or 3 measurements are Rejected, run the tableau again. Focus on fixing A3 and S3 (ignore 1st and 2nd order) C3 will bounce around – change C3 at the end when you have a feel for the typical value.

```
#10 C1: 5.43nm A1: 6.197nm / -49.3deg signal mean: 2132cnts
#11 C1: 6.582nm A1: 8.607nm / -37.1deg signal mean: 2215cnts
#12 C1: 3.887nm A1: 3.492nm / -31.7deg signal mean: 2489cnts
#13 C1: 6.235nm A1: 3.924nm / -39.8deg signal mean: 2348cnts
#14 C1: 7.29nm A1: 5.551nm / -34.8deg signal mean: 2426cnts
#15 C1: 6.162nm A1: 9.505nm / -26.1deg signal mean: 2248cnts
#16 C1: 678pm A1: 3.233nm / -25.5deg signal mean: 2123cnts
#17 C1: 2.658nm A1: 5.461nm / -2deg signal mean: 2197cnts
#18 C1: 2.711nm A1: 2.936nm / -12.5deg signal mean: 2487cnts
#19 C1: 4.864nm A1: 5.952nm / -21.6deg signal mean: 2811cnts
#20 C1: 5.817nm A1: 2.747nm / -36.2deg signal mean: 2848cnts
#21 C1: 3.654nm A1: 6.381nm / -74.1deg signal mean: 2627cnts
#22 C1: 3.74nm A1: 3.508nm / -65.9deg signal mean: 2169cnts
dTime: 72928s Date: Fri Jan 5 01:39:37 2018
```

1st order measured! (not used:)

```
Salt: 2.617nm Sused: 2.617nm (0.7534%)
C1: 4.544nm (95%: 2.65nm)
A1: 2.754nm / -31deg (95%: 4.52nm)
A2: 31.76nm / -65deg (95%: 45.1nm)
B2: 17.2nm / 6.5deg (95%: 40.2nm)
C3: -869.9nm (95%: 2.68um)
A3: 690.5nm / -69.5deg (95%: 771nm)
S3: 638.8nm / +21.6deg (95%: 282nm)
A4: 25.22um / +17.6deg (95%: 24.4um)
D4: 7.789um / +73.1deg (95%: 13.5um)
B4: 13.22um / -138.6deg (95%: 27.1um)
C5: 2mm (95%: 3.32mm)
A5: 1.013mm / +84deg (95%: 885um)
Btn 'Accept Aberr' pressed.
Btn 'S3' pressed.
```

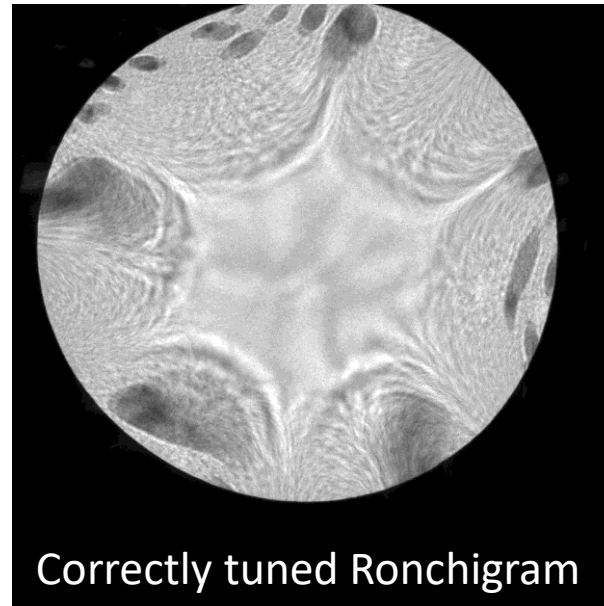
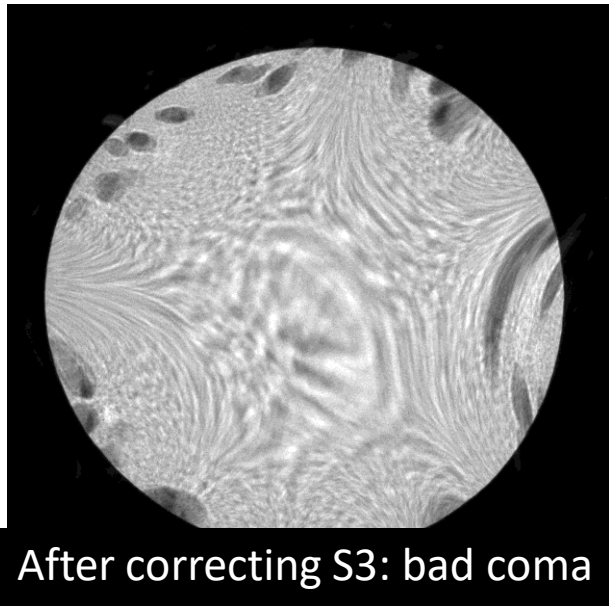
C3 – make any changes at the end
A3 – OK within error
S3 – Can be fixed.
Press OK then S3

Select 24 or 27mrad tilt angle and use the Extended Tableau

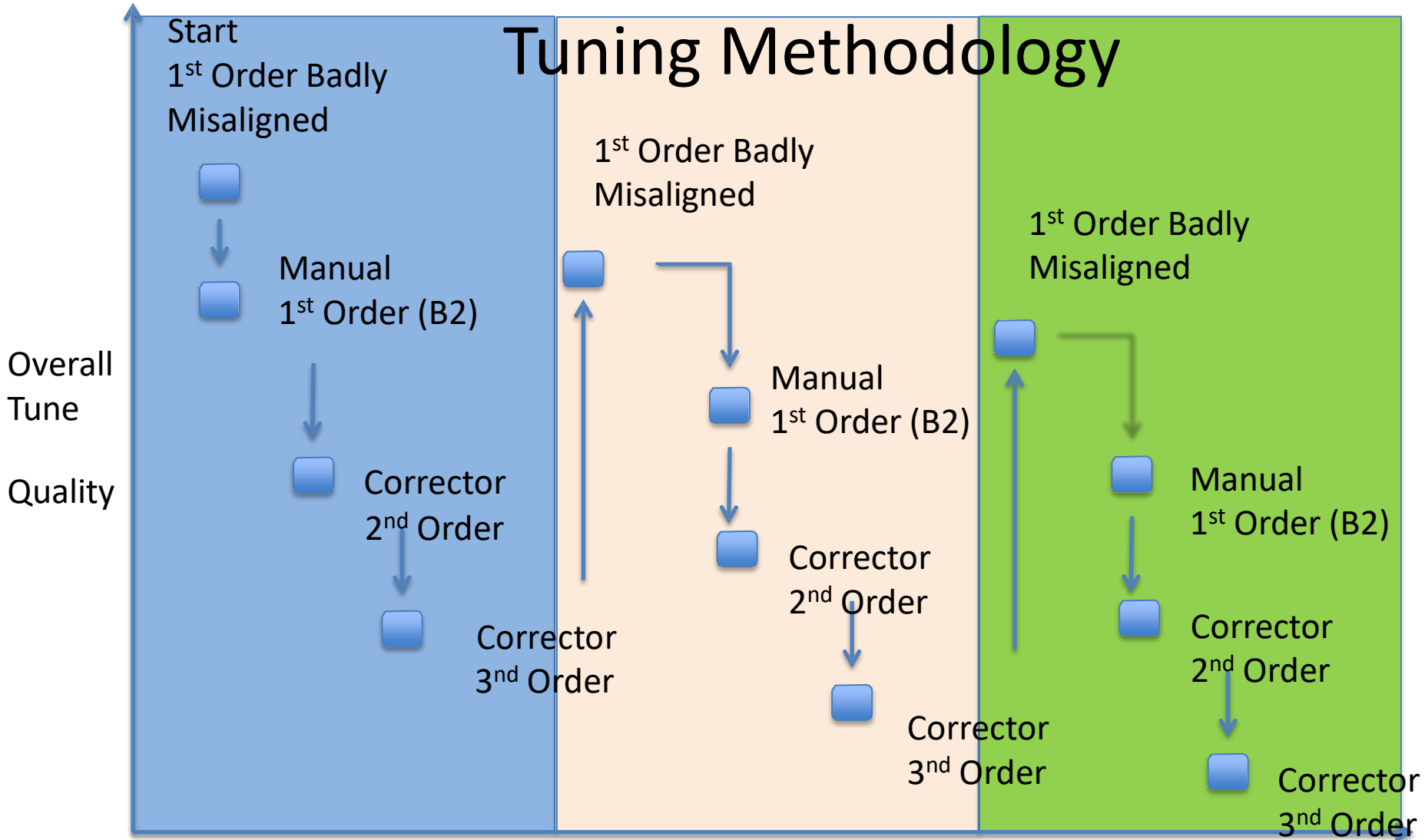
3.5

After Correcting 3rd order Aberrations

- Correct whichever is the worst aberration (A3 or S3). Corrections will ruin 1st and 2nd order alignments.
- Correct these by generating a Ronchigram and manually correct C1 (focus), A1 (2-fold astig) and B2 (coma).



Tuning Methodology



After Completing the nth Tune

- After fixing 1st order aberrations, run one or more Standard Tableaux and fix 2nd order.
- Then run an Extended Tableaux and fix third order aberrations – Repeat the tuning cycle to converge on target values. An unstable microscope will not converge.

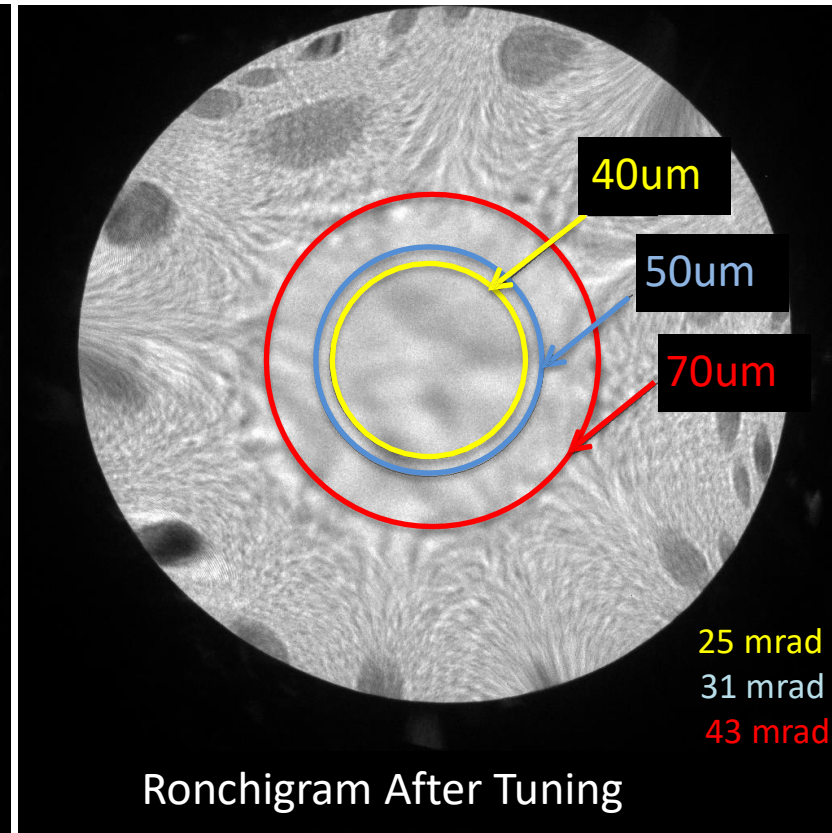
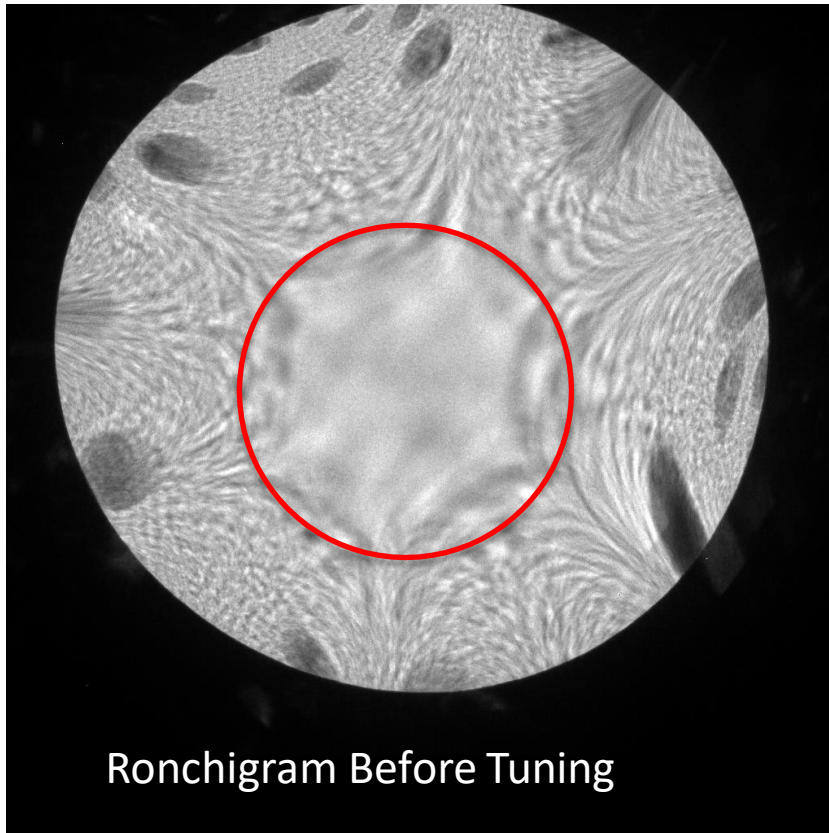
```
1st order measured! (not used:)
Sall: 3.913nm Sused: 3.913nm (1.126%)
C1: 2.614nm (95%: 3.97nm)
A1: 1.813nm / +45.5deg (95%: 6.74nm)
A2: 65.71nm / +122.6deg (95%: 67.5nm)
B2: 36.21nm / +53.4deg (95%: 60.1nm)
C3: 3.034um (95%: 4.02um)
A3: 461.2nm / -64.9deg (95%: 1.15um)
S3: 552.1nm / +72.6deg (95%: 422nm)
A4: 42.84um / +117.2deg (95%: 36.5um)
D4: 11.48um / +62.6deg (95%: 20.2um)
B4: 20.74um / -98.2deg (95%: 40.6um)
C5: 599.6um (95%: 4.97mm)
A5: 1.602mm / +104.5deg (95%: 1.32mm)
□
```

- Only trust 1st and 2nd order values from a Standard Tableau.
- Only trust 3rd order values from an Extended Tableau – results shown left.
- Here A2 is higher than target (<50nm) – ignore it (note the large error). The value in the previous Standard Tableau was <50nm.
- C3 bounced around a bit during tuning, but the average was 3um – which is on target.
- A3 and S3 are <1um – which is fine.
- **The Ronchigram appearance/size is more important than the numbers.**



The Goal of Tuning

- The aim of tuning the corrector is to produce a very large aberration-free region within a symmetric Ronchigram.



Closing Remarks.

1. Minimise the amount of work the software has to do during tuning, by manually correcting focus (C1), 2-fold astigmatism (A1) and coma (B2) as well as possible, before asking the software to correct those values.
2. Monitor the hexapole values HpoIX and HpoIY, especially when correcting A2 (3-fold astigmatism). Keep the values to within +/- 10um. If the values become very large, then heating/hysteresis may result in an unstable tune. If the values move slightly outside the +/-10um range during tuning eg +/-15um, then avoid changing them immediately, as they may move back towards zero during subsequent tunes. However, if they move outside that range significantly, reset them by choosing Reset A2. This may mess up the tune somewhat – so go back to stage 1 (Manual correction) and proceed from there.
3. Low voltage (60-80kV). Good tunes are much more difficult at low voltage, as minor variances have a much bigger effect. I routinely switch to 80kV on Friday pm. Allow the weekend to magnetically and thermally equilibrate, then tune the following Monday. However, I find this tune is not very stable and by Mon pm/Tues the Ronchigram has reduced in size. I reserve all the low resolution work, such as EDS mapping, for Mon and Tues. Then on Wed am I again retune the corrector. This results in a very stable tune for the remainder of the week. I reserve all high resolution work – eg graphene ring imaging - from Wed-Fri. In general, 200kV tunes are much easier. If I tune on a Monday (after switching to 200kV on Friday), the tune is very stable thereafter and will not need to be redone.
4. Microscope stability is critically important when tuning. Beam shower the specimen – there can be no contamination occurring during tuning. Always degauss (Lens Relax) the column twice before attempting a tune. Ensure the microscope is at standard focus and adjust the height to focus. Large changes in specimen height can result in subsequent focus drift. Ideally complete all major stage and height adjustments the night before tuning, to allow settling. At the start of tuning, monitor the focus and astigmatism for 30s or more to ensure that it is not changing. If it is, give it 30mins settling time and try again.
5. For high performance STEM, avoid using Low Mag mode if humanly possible. Low Mag mode turns off the objective lens (1kW of power). If you must use Low Mag – eg to find a FIB section, switch into Low Mag, find the region as quickly as possible (<20s), then switch back out immediately. In Low Mag mode the objective lens begins to cool, causing thermal drift. After using Low Mag, degauss the column (twice). DO NOT use Low Mag within 1hr of tuning. Even after degaussing, the objective lens may still be (thermally) unstable for 30 or more minutes.
6. When doing routine STEM, if you change spot size, the condenser lens crossover will move (relative to the corrector) and the Ronchigram will be degraded. Degauss the column twice then manually correct the A1, C1 and B2 in the Ronchigram. If you have a cold FEG microscope an alternative approach to changing spot size is to change the FEG extraction voltage, to change the probe current. Here the condenser lens crossover does not move (much) and the Ronchigram will not a retune – unless doing high res.

