9th International Particle Accelerator Conference IPAC2018, Vancouver, BC, Canada JACoW Publishing
ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPAF009

OPTIMISING RESPONSE MATRIX MEASUREMENTS FOR LOCO ANALYSIS

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Abstract

The Linear Optics from Closed Orbit (LOCO) method is a common tool for determining storage ring lattice functions and requires a measured BPM to Corrector response matrix. For very large rings with many correctors, such measurements can be time consuming. The following study investigates how the number of correctors and the signal-to-noise ratio (SNR) affects the LOCO analysis results. For the Australian Synchrotron, the results show that four distributed correctors per plane with a SNR of >1000 is sufficient to fit the betatron functions to an accuracy of less than 0.2%.

INTRODUCTION

For many storage ring based light sources, characterisation of the linear optics is achieve by using an Orbit Response Matrix (ORM) method called Linear Optics from Closed Orbits (LOCO) [1]. In the past year the Australian Synchrotron has commissioned its Fast Orbit Feedback System (FOFB) [2] and there are plans to extend the FOFB system to drive the fast correctors to quickly measure the orbit response matrix as has been shown at DIAMOND and ALBA [3, 4] using sinusoidal excitation of corrector magnets. Another method to reduce the measurement time is to reduce the number of correctors used in LOCO. The following investigation shows how corrector selection and measurement signal to noise ratio (SNR [1]) affects the LOCO results.

EFFECT OF CORRECTOR SELECTION

Correctors are used to perturb the storage ring and the relationship to the resulting closed orbit pattern is given by the ORM. When using the LOCO method to determine the lattice parameters of a storage ring, the constraints of the optimisation problem in LOCO are the position measurements at the BPMs and *NOT* the correctors themselves. Therefore the use of multiple correctors should only serve to reduce any "noise" in the problem. The locations of the BPMs in relation to the magnets for the AS are shown in Figure 1.

A typical LOCO fit at the AS will have 200 fit parameters (mostly skew quadrupole components), and the current process of using 42 horizontal correctors and 56 vertical correctors results in a highly over-constrained problem with 19208 constraints and only 200 parameters. A Monte Carlo analysis was employed to investigate the relationship between the accuracy of the LOCO-derived results and the selection of the correctors in the ORM (input for LOCO analysis).

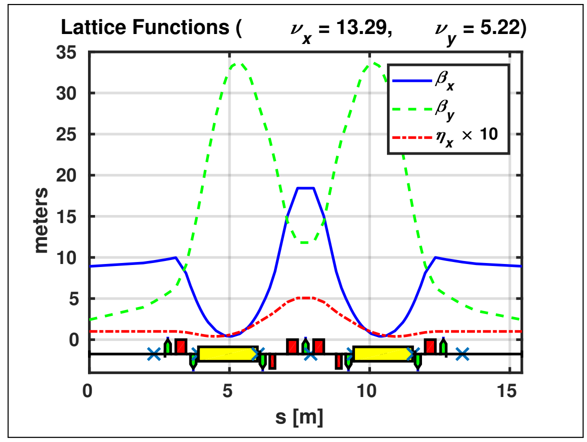

Figure 1: One out of 14 sectors of the AS Storage Ring. The "X" marks the BPM locations, upright green pentagons represent sextupoles with horizontal correctors and inverted green pentagons represent sextupoles with vertical correctors. There are 3 families of quadrupoles: QFA (outer pair), QDA and QFB (inner pair).

The Monte Carlo analysis consisted of 100 lattices with different quadrupole (k) and skew quadrupole (k') perturbations distributed across all multipole magnets (quadrupoles and sextupoles). For each sample a response matrix and dispersion function of the perturbed lattice was generated (with and without measurement noise, σ_{noise}). To simplify the problem in this first set of analysis, the dispersion function is *not* used in the analysis. The fit parameters are k in the quadrupole magnets and k' in quadrupole and sextupole magnets. With these conditions 12 LOCO input files are create with different combinations of correctors resulting in a total of 1200 LOCO input files per simulation. Each simulation takes 10 hours computed on ASCI [5] with 48 cores. The combination of correctors used in the LOCO anaysis was either: *sequential groupings* (e.g. [1,2,3,4] or [1,2,...,32]), or *distributed groupings*(e.g. [1,11,21,32] or [1,6,11,16,...,32,37]). Figure 2 outlines the method of the study where the difference in the Twiss parameters and quadrupole values for (a) and (b) are compared.

The difference between the model (a) and the LOCO fitted model (b) is quantified by plotting the standard deviation of the relative error of the Twiss parameters ($\delta\beta_{x,y}$), absolute error of the emittance coupling ($\Delta\epsilon_c$) and the absolute error of the tilt angle ($\Delta\phi$).

Two data sets are created with peak amplitudes of 50 μm and 250 μm with a corresponding in-plane/out-plane SNR of 1567/29 and 313/6 respectively when the measurement noise is set to σ_{noise} = 50 nm. The two data sets are also processed without the addition of noise. Without noise both

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[1] Defined here as average signal divided by the standard deviation of the noise: μ/σ

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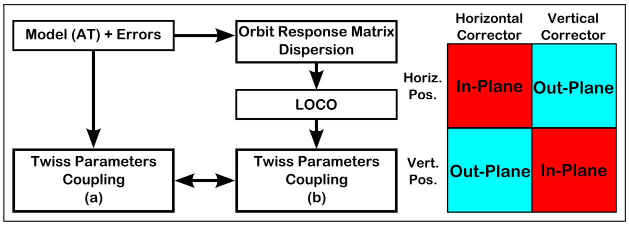

Figure 2: Left diagram describing the comparison between the model based lattice parameters and the derived parameters using LOCO. Accelerator Toolbox (AT) is used to do all the simulations. The ORM can be split into two sections, in-plane and out-plane as shown on the diagram on the right. The SNR is calculated by computing the average amplitude, μ, of the ORM in-plane and out-plane.

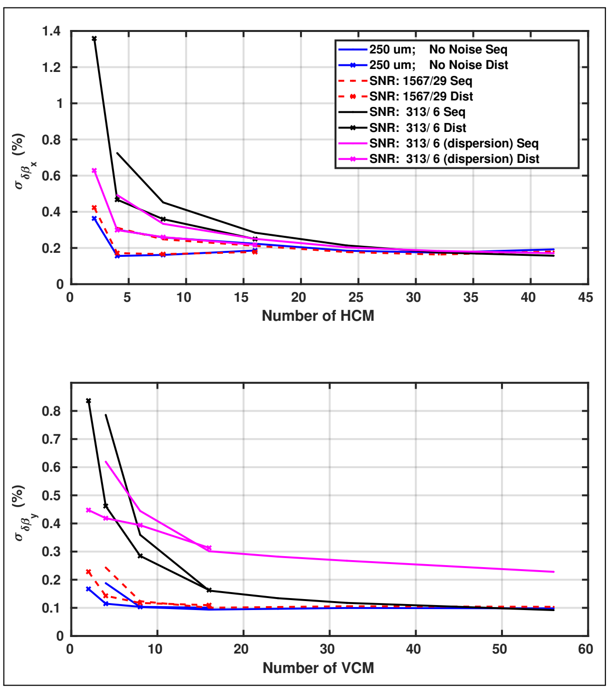

Figure 3: Errors in $\beta_{x/y}$ decreases with more correctors. For ORM's with very large SNR the benefit of using more than 16 sequential or 4 distributed correctors negligible. With four correctors in each plane the ORM this will yield errors < 0.2%.

results were virtually identical and therefore only the noise free case with a peak amplitude of 250 μm has been shown in Figures 3 and 4. Both figures show decreasing errors when using an increasing number of correctors (sequential and distributed alike). In both cases there are clear benefits of distributing the correctors. With a large SNR of 1567/29 there is no advantage in using more than four correctors per plane. With a lower SNR of 313/6 the errors are larger and it is clearly better to use more correctors, however even in this case there is no advantage in using more than 16 correctors per plane.

When the dispersion function is included in the fit (with a horizontal and vertical dispersion weighting of 10 and 1 respectively), the conclusion is the same as before with regard to the number of correctors. Including the dispersion function does significantly improve the accuracy of the lattice coupling at the expense of the accuracy of $\beta_{x/y}$. This agrees with previous experience in coupling control [6–8]. Moreover the weighting of the dispersion also has a direct effect on the fit of k'. This aspect is currently under investigation.

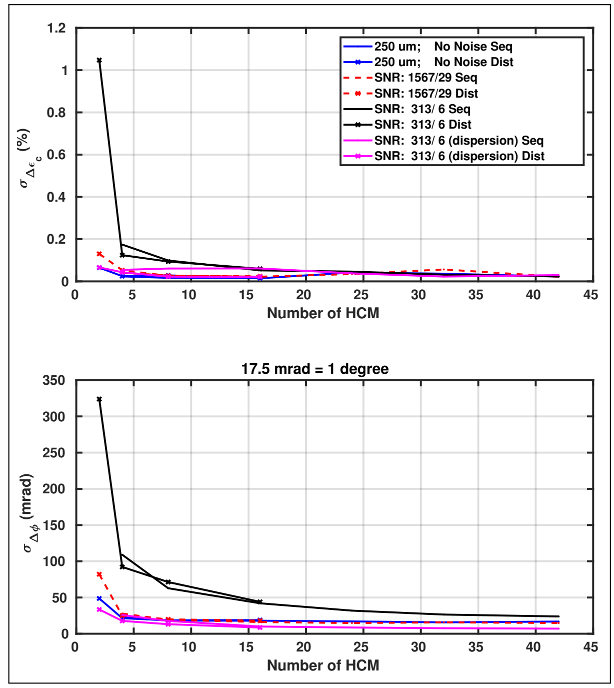

Figure 4: The fit of the emittance coupling (ϵ_c) value and tilt angle (ϕ) shows that using more than four correctors does not improve the results. In these simulations the average global emittance coupling is 0.6% and with four correctors per plane, the coupling error is 0.05% compared to the best at 0.02%. The inclusion of dispersion halves the tilt errors.

What has also been clear throughout the investigation is that the accuracy of the fit is dependent on the SNR of the ORM and dispersion measurements.

EFFECT OF THE SNR

To investigate the relationship between the SNR and the accuracy of the fit, simulations with an SNR of 157, 313, 940 and 1567 was computed (without including dispersion in the fits). Figure 5 displays the three corrector cases: all correctors, 16 distributed corr/plane and 4 distributed corr/plane. The results show qualitatively that increasing the number of correctors from 4 to 16, decreases the error by a factor $\approx \sqrt{4} = 2$ while going from 4 to 42 correctors decrease the error by factor $\approx \sqrt{10} = 3$. This implies that the additional correctors does indeed have an averaging effect by reducing the "noise" in the optimisation problem and is more apparent for measurements with low SNR. The inverse relation ship between the SNR and the accuracy of $\beta_{x,y}$ indicates that for the AS, exceeding a SNR of 1000 (peak amplitude of 150 μm) shows little benefit. Moreover above this SNR the

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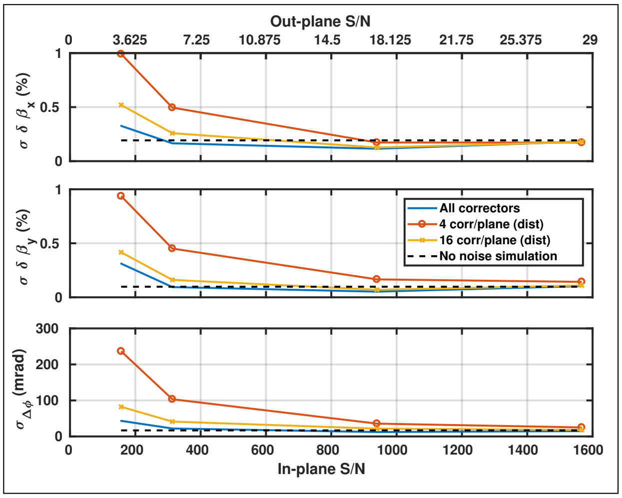

Figure 5: The results show decreasing errors with increasing signal to noise ratio (SNR; defined as μ/σ). There are two sets of SNR: the in-plane and the out-plane ORM SNR.

relative error between 4 or 42 correctors does not change significantly.

MACHINE MEASUREMENTS

To verify the above conclusions, a set of 30 Δk and $\Delta k'$ perturbations is applied to the storage ring. For each set of perturbations the ORM, dispersion function, tunes and beam tilt, ϕ, is measured. Following the same procedure as the simulations, Figure 6 shows the differences between the LOCO-derived and measured tunes and tilt. The SNR of these measurements is 313/6. The results support the conclusions that has been drawn from the simulations. As concluded previously, with this lower SNR, 16 distributed correctors per plane is sufficient.

CONCLUSION

With the Matlab implementation of LOCO, when measurements have a SNR of >1000, there is little benefit in using more than 4 distributed correctors per plane. If coupling is critical, then measuring the dispersion function with an equivalent SNR is also required. Future investigation is under-way in a few areas: are these findings universal or particular to the Australian Synchrotron; what effect does weighting the dispersion have on the accuracy of lattice coupling; do the above conclusions hold for very low coupling lattices (<0.1%). The obvious benefit of these results are a significant reduction in the time required to measure the ORM for LOCO analysis. At the AS the ORM measurement can be reduced from ten minutes to one minute. For larger storage rings the time savings could be even greater.

ACKNOWLEDGEMENTS

The author would like to thank Rohan Dowd for discussion on coupling analysis and the Operators at the AS who helped collect the measured data.

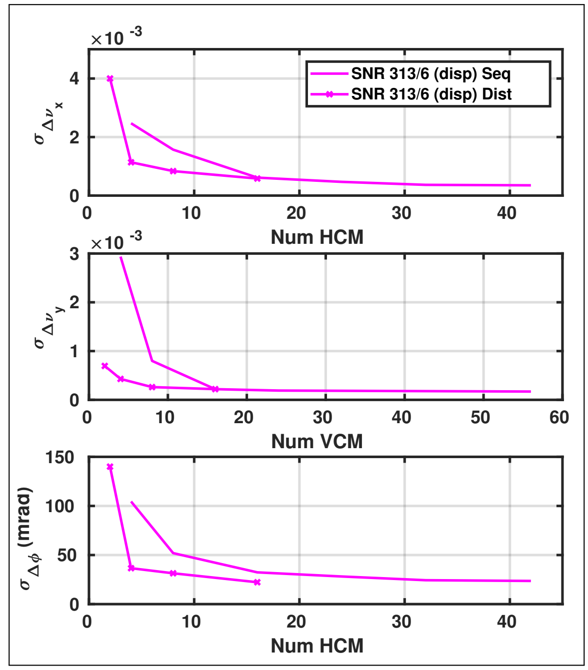

Figure 6: Standard deviation calculated from a sample size of 30. Plots show the spread in the difference between the LOCO-derived and measured tunes and beam tilt, ϕ, at a xray pinhole camera.

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