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Closed Orbit Distortion and Correction in the Four-Fold Symmetric NSNS Ring

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U.S. Department of Energy

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DISCLAIMER

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1 Introduction

In the following note we consider the Closed Orbit Distortion (COD) due to random magnetic field and magnet placement errors in the proposed four-fold symmetric NSNS ring. Specifically, we examine the effects of random errors in the

1) Horizontal and Vertical Placement of the Lattice Quadrupoles,

2) Guide Field of the Lattice Dipoles,

3) Rotation (Roll) of the Lattice Dipoles about the Beam Axis.

The analysis is similar to that carried out by Ruggiero [1] for the case of a three-fold symmetric lattice. We assume that the four-fold lattice has parameters specified by Lee [2], and that the distribution of errors is Gaussian with RMS values

$$\sigma_x = 2.5 \times 10^{-4}\,\mathrm{m}, \quad \sigma_y = 2.5 \times 10^{-4}\,\mathrm{m} \tag{1}$$

for the horizontal and vertical placement of the lattice quadrupoles,

$$\sigma_B/B = 2.5 \times 10^{-4}, \tag{2}$$

for the guide field, B, and

$$\sigma_\theta = 2.5 \times 10^{-4}\,\text{radians} \tag{3}$$

for the roll, θ, of the lattice dipoles. The random errors are generated by the Routine "gasdev" found in Numerical Recipies [3], and any errors greater than 2.5 times the RMS value are rejected. Using the generated errors and the lattice parameters from the TWISS file of the MAD program, 101 random distorted closed orbits are calculated. Thin correction dipoles located at the centers of the lattice quadrupoles are then used to correct each of the distorted closed orbits. The required corrections are determined by exciting the array of dipoles with various harmonics and searching for those excitations which minimize the COD. The Simplex Routine "amoeba" [3] is used to find the minimum. As an independent check, the method of 3-bumps [4, 5] is also used to determine the required corrections.

2 Calculation of COD

The distortion of the closed orbit at a position s along the design orbit is given by equation (4.7) of Courant and Snyder [6] which we rewrite here in the form

$$d(s) = \frac{\sqrt{\beta(s)}}{2\sin\pi\nu}\int_s^{s+C} F(s')\sqrt{\beta(s')}\cos\{\pi\nu + \mu(s) - \mu(s')\}\,ds' \qquad (4)$$

where

$$\mu(s) = \int_s^{s+C}\frac{ds'}{\beta(s')}, \quad F(s') = \frac{\Delta B(s')}{B\rho} \qquad (5)$$

$\Delta B(s')$ is the magnetic field error at s', $B\rho$ is the magnetic rigidity, C is the circumference of the design orbit and the other symbols have their usual meanings. If we approximate the errors with n thin elements of length L_j and field ΔB_j, the integral in (4) becomes a sum over the n elements. Thus the distortion of the closed orbit at the position of the ith element becomes

$$d_i = \frac{\sqrt{\beta_i}}{2\sin\pi\nu}\sum_{j=i+1}^{i+n}\phi_j\sqrt{\beta_j}\cos(\pi\nu + \mu_i - \mu_j) \qquad (6)$$

where

$$\phi_j = \frac{\Delta B_j L_j}{B\rho} \qquad (7)$$

is the kick produced by the jth element. We shall assume that the kicks are located in the centers of the dipoles and quadrupoles. The kick in the horizontal plane due to an error, ΔB_j, in the guide field of a lattice dipole is given by

$$\phi_j = \frac{\Delta B_j L}{B\rho} = \frac{\Delta B_j}{B}\theta_B \tag{8}$$

where $L = \rho\theta_B$ is the length of the dipole and θ_B is the bend angle. The kick in the vertical plane due to the roll of a lattice dipole is given by

$$\phi_j = \frac{LB\sin\theta_j}{B\rho} = \theta_B \sin\theta_j \tag{9}$$

where θ_j is the roll angle. A horizontal displacement, Δx_j, of a quadrupole from its nominal position produces a kick in the horizontal plane given by

$$\phi_j = \frac{L_j G_j \Delta x_j}{B\rho} \tag{10}$$

where G_j is the quadrupole gradient and L_j is its length. Similarly, a vertical displacement, Δy_j, of a quadrupole produces a kick in the vertical plane given by

$$\phi_j = \frac{L_j G_j \Delta y_j}{B\rho}. \tag{11}$$

3 Correction of COD

For the correction of the COD we enlarge our set of thin elements to include dipole correctors located at the centers of the lattice quadrupoles. The COD due to both errors and corrections is then given by (6) with the sum taken over the error and correction elements. To minimize the COD we excite the array of dipole correctors with various harmonics such that the kick produced by the jth corrector is

$$\phi_j = \sum_k \frac{A_k}{\sqrt{\beta_j}} \cos\{\psi_k + k\mu_j/\nu\} \tag{12}$$

where A_k and ψ_k are the amplitude and phase of the kth harmonic. In the sum we take $k = 1$ to 20 and employ the Simplex Routine "amoeba" to find the values of A_k and ψ_k that minimize the COD. As an independent check, we also use the method of 3-bumps to minimize the COD. Here, as derived in Ref. [4], the kick required in the jth corrector is given by

$$\phi_j = \left\{ \frac{M_{11}^{(j)}}{M_{12}^{(j)}} + \frac{M_{22}^{(j-1)}}{M_{12}^{(j-1)}} \right\} Y_j - \frac{Y_{j-1}}{M_{12}^{(j-1)}} - \frac{Y_{j+1}}{M_{12}^{(j)}} \tag{13}$$

where $M_{kl}^{(j)}$ are the matrix elements of the transfer matrix from the jth to the $(j+1)$th corrector, and Y_j is the value of the uncorrected COD at the jth corrector.

4 Results

The solid curve in Figure 1a is a typical COD in the horizontal plane; the dashed curve is the corrected COD (using harmonic correction).

The solid curve in Figure 1b shows the dipole kicks required for (harmonic) correction of the COD; the dotted curve shows the kicks due to errors.

The solid curves in Figure 2a show the extreme values of the COD for the entire ensemble of 101 COD's; they all lie within the range of ± 16 mm. The long-dashed curve shows the RMS COD for the ensemble; it is at most 5 mm. The short-dashed curve is the RMS corrected COD (using harmonic correction).

The solid curves in Figure 2b show the extreme values of the required dipole corrector kicks for the entire ensemble of 101 COD's; all of the kicks are within the range of ± 0.4 milliradians. The dashed curve shows the RMS of the kicks for the ensemble; it is at most 0.1 milliradians.

Figures 3–4 are the corresponding figures for the vertical plane.

Figures 5–8 are the corresponding figures for the case in which the 3-bump method is used to correct the COD.

The integrated strength required for a correction dipole to produce kick ϕ_j is

$$\Delta B_j L_j = B\rho\phi_j \tag{14}$$

where $B\rho = 5.6574$ Tm is the magnetic rigidity for protons with 1 GeV kinetic energy. Assuming a maximum value of $\phi_j = 0.4$ milliradians, we obtain

$$\Delta B_j L_j = 23 \times 10^{-4} \text{ Tm}. \tag{15}$$

The ratio of the integrated strength of a correction dipole to that of a lattice dipole is just ϕ_j/θ_B where $\theta_B = 2\pi/32$ is the lattice dipole bend angle. Assuming a maximum value of $\phi_j = 0.4$ milliradians, we get

$$\phi_j/\theta_B = 0.0020, \tag{16}$$

i.e. 0.2 percent of the lattice dipole integrated strength.

5 Closed Orbit Manipulation

During normal operation and tuning of the NSNS ring it may be desirable to produce a deliberate local distortion of the closed orbit; for example, one may wish to adjust the position of the orbit in a collimator, in a particular position monitor, or at a particular loss monitor. The dipole corrector kicks ϕ_{j-1}, ϕ_j, ϕ_{j+1} required to produce a local 3-bump are given by

$$\phi_{j-1} = \frac{Y_j}{M_{12}^{(j-1)}}, \quad \phi_j = -\left\{ \frac{M_{11}^{(j)}}{M_{12}^{(j)}} + \frac{M_{22}^{(j-1)}}{M_{12}^{(j-1)}} \right\} Y_j, \quad \phi_{j+1} = \frac{Y_j}{M_{12}^{(j)}} \tag{17}$$

where $M_{kl}^{(j)}$ are the matrix elements of the transfer matrix from the jth to the $(j+1)$th corrector, and Y_j is the desired change in the position of the closed orbit at the jth corrector. The three kicks required to produce a 3-bump with $Y_j = 10$ mm are plotted for each corrector in Figure 9. Here the squares (diamonds) show the kicks required for horizontal (vertical) 3-bumps; the maximum kick is about 0.8 milliradians.

6 Conclusions

There are two basic conclusions to be drawn from our analysis. The first is that, assuming the errors listed in Section 1, the expected uncorrected closed orbit should lie well within the NSNS ring aperture; specifically, the RMS COD for an ensemble of 101 randomly generated COD's is at most 5 mm as shown in Figures (2a) and (4a). The extreme values of the COD for the ensemble are within ± 16 mm. The second conculsion is that each dipole corrector must be capable of producing a kick of at least 0.4 milliradians. This is a bare minimum which follows from Figures (2b) and (4b) and requires an integrated strength of 23×10^{-4} Tm as shown in Section 4. If one wants to have a safety factor of say two, then an integrated strength of 46×10^{-4} Tm would be required. This would provide 0.8 milliradian kicks and would allow one to produce local 3-bumps of amplitude 10 mm as shown in Section 5.

7 References

1. A.G. Ruggiero, *Closed Orbit Distortion in the NSNS Accumulator Ring*, BNL/NSNS Tech. Note No. 025, February 14, 1997.

2. Y.Y. Lee, *The 4 Fold Symmetric Lattice for the NSNS Accumulator Ring*, BNL/NSNS Tech Note No. 026, February 19, 1997.

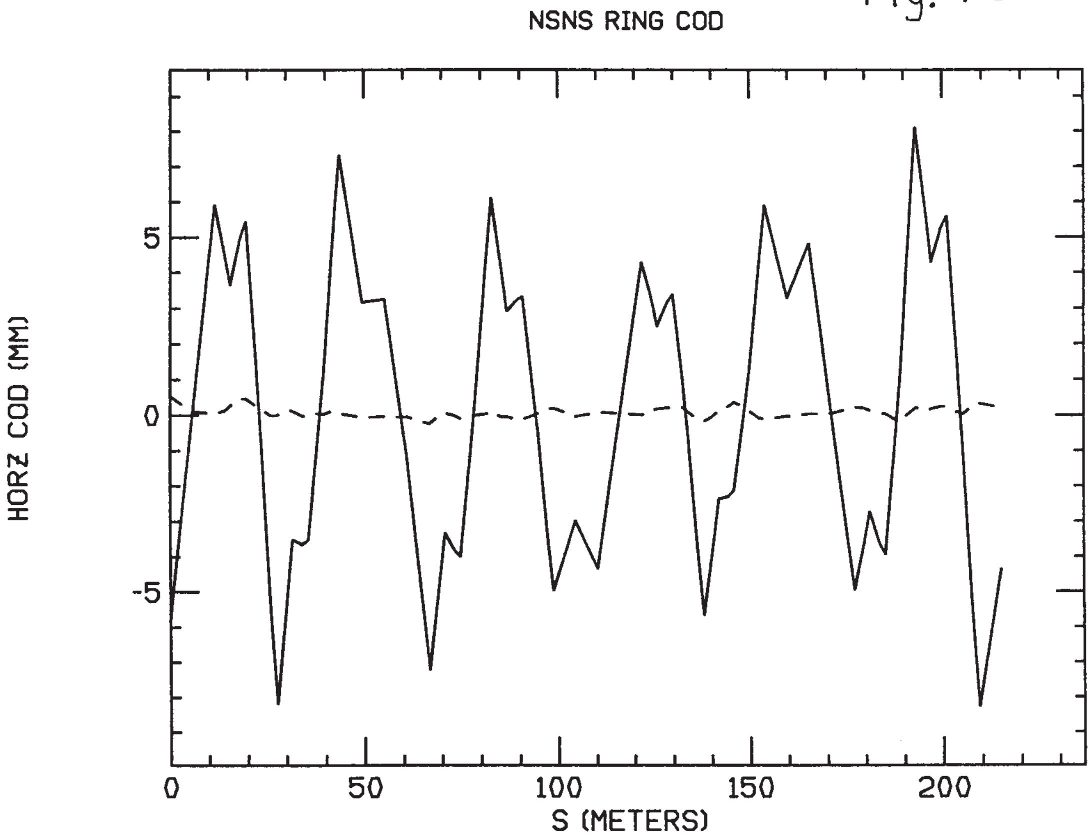
3. W.H. Press, et. al.,*Numerical Recipes in FORTRAN*, 2nd edition, Cambridge University Press, (1992).

4. J. Milutinovic and A.G. Ruggiero, *Closed Orbit Analysis for the AGS Booster*, Booster Tech Note No. 107, February 1, 1988

5. B. Autin, *Lattice Perturbations*, AIP Conference Proceedings No. 127, American Institute of Physics, (1985) 139–200.

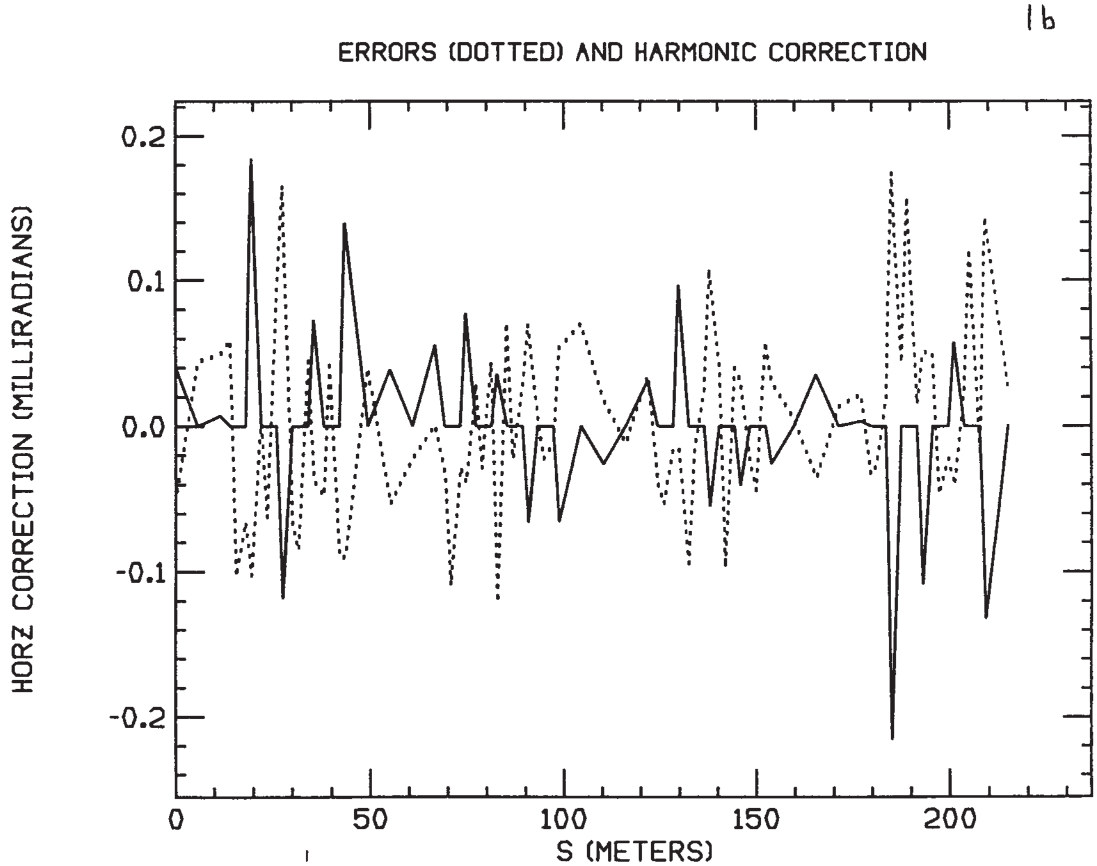
6. E.D. Courant and H.S. Snyder, *Annals of Physics* 3 (1958) 1–48.

Fig. 1a



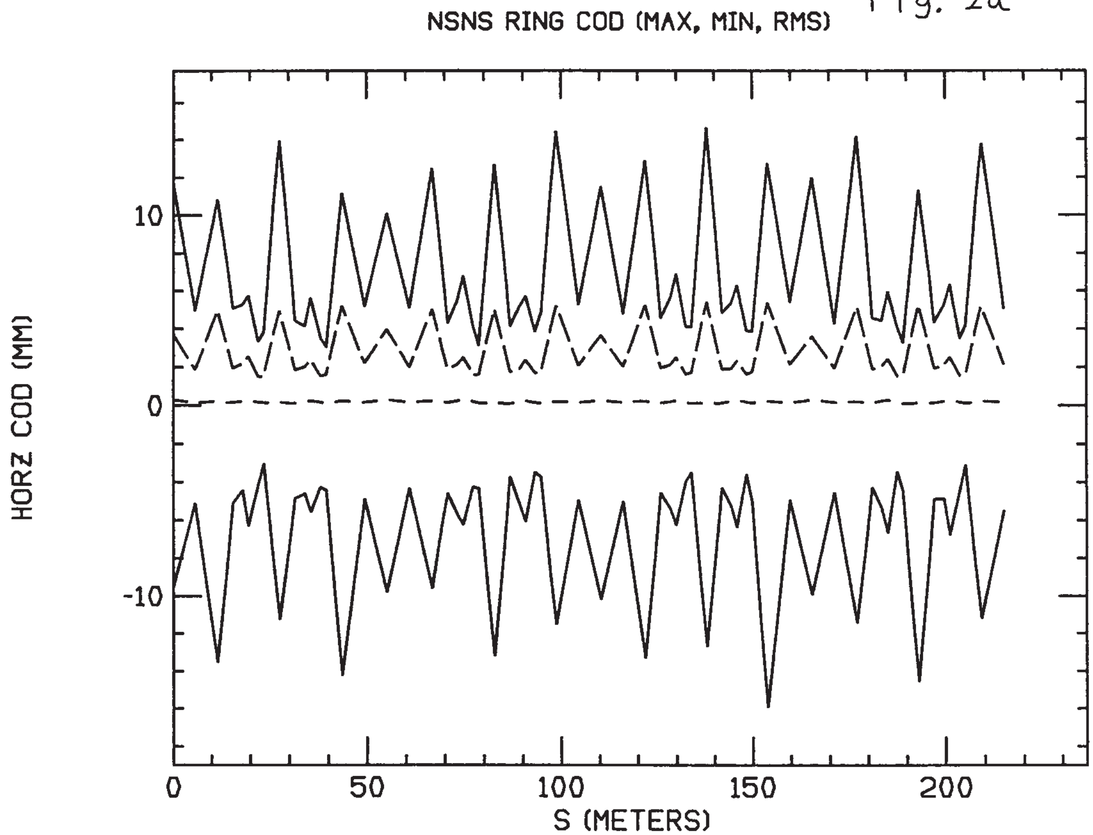
NSNS RING COD
HORZ COD (MM)
5
0
-5
0
50
100
150
200
S (METERS)

1b



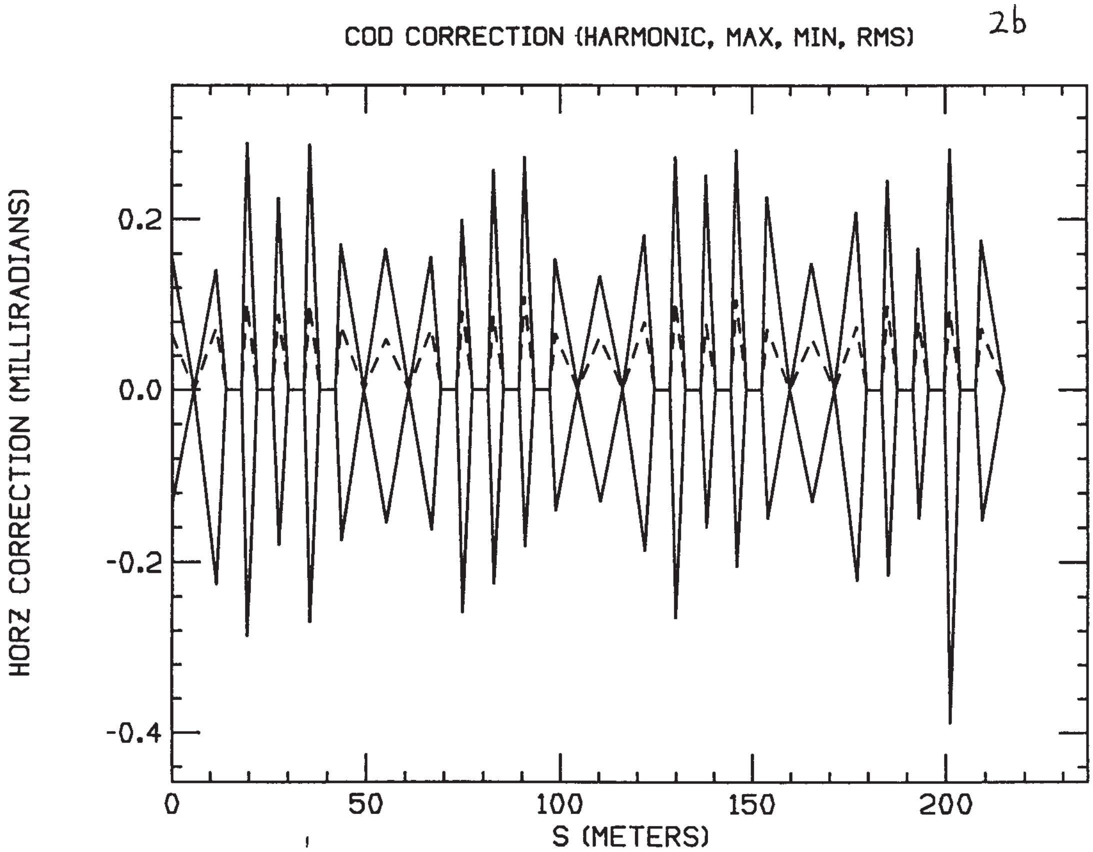
ERRORS (DOTTED) AND HARMONIC CORRECTION
HORZ CORRECTION (MILLIRADIANS)
0.2
0.1
0.0
-0.1
-0.2
0
50
100
150
200
S (METERS)

Fig. 2a



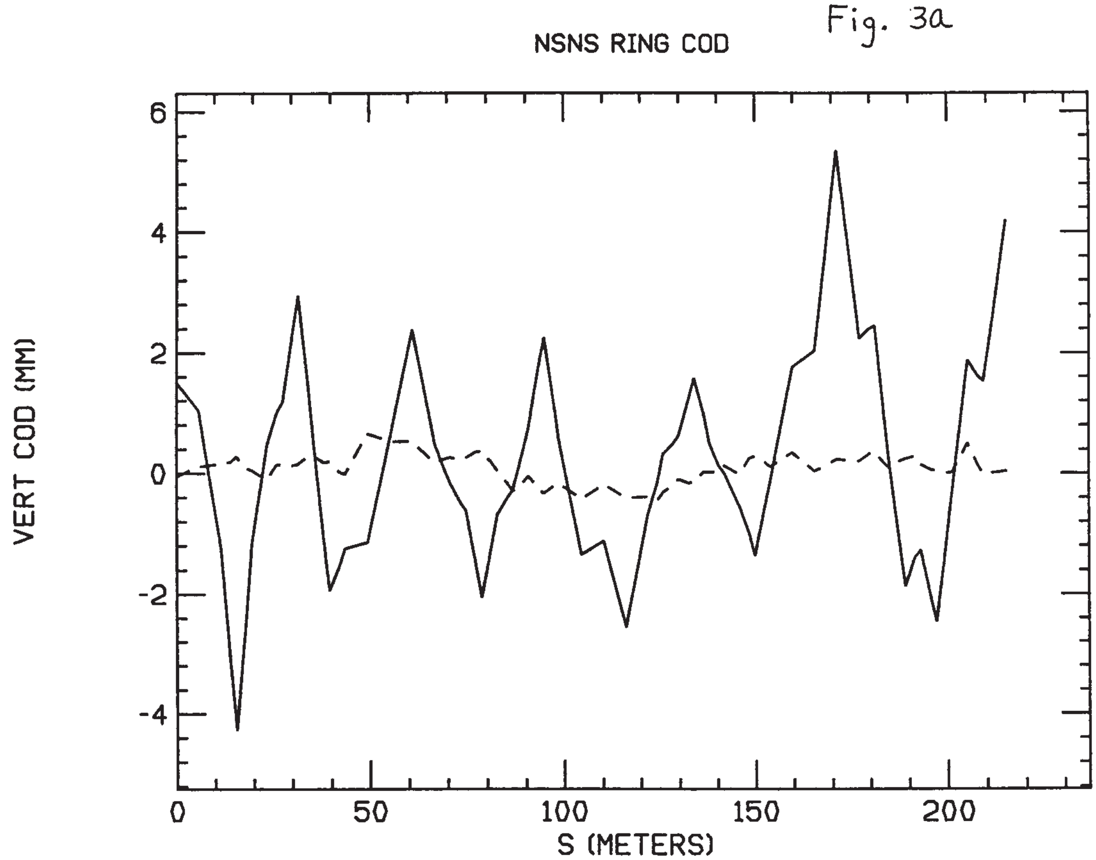
NSNS RING COD (MAX, MIN, RMS)
HORZ COD (MM)
10
0
-10
0
50
100
150
200
S (METERS)

2b



COD CORRECTION (HARMONIC, MAX, MIN, RMS)
HORZ CORRECTION (MILLIRADIANS)
0.2
0.0
-0.2
-0.4
0
50
100
150
200
S (METERS)

Fig. 3a


NSNS RING COD
VERT COD (MM)
6
4
2
0
-2
-4
0
50
100
150
200
S (METERS)

3b

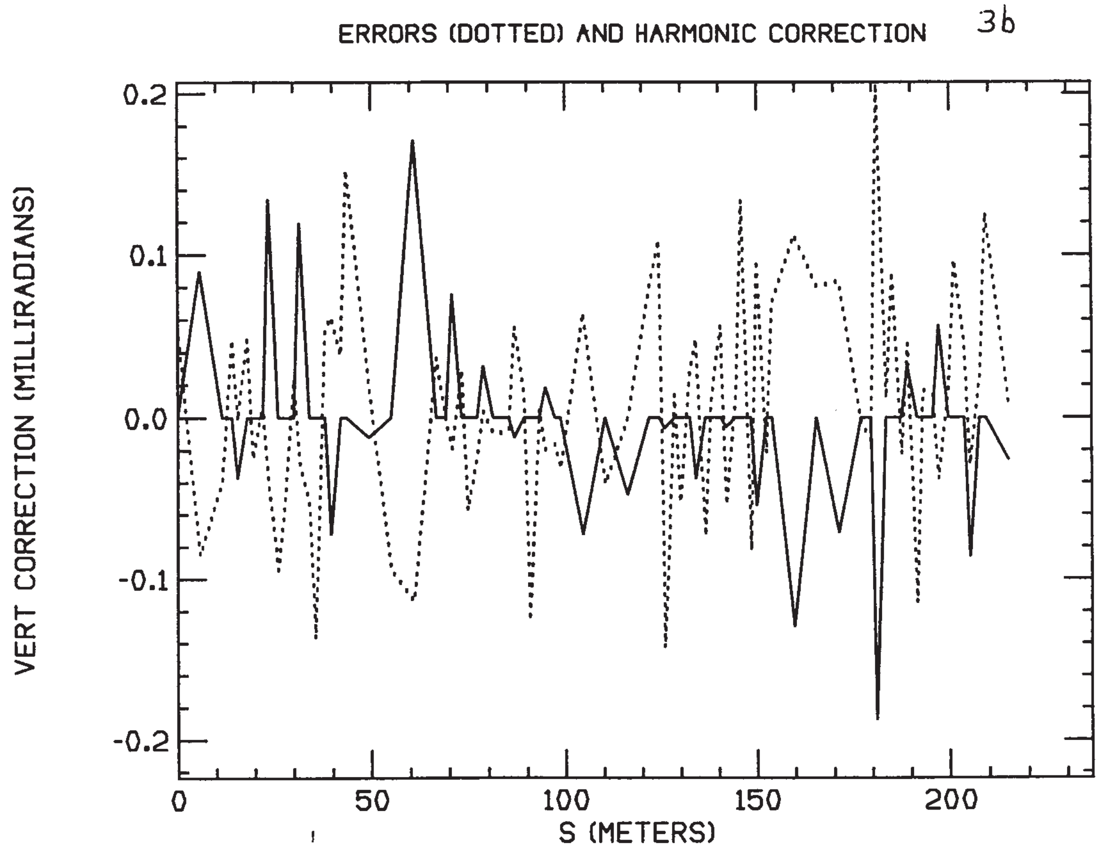
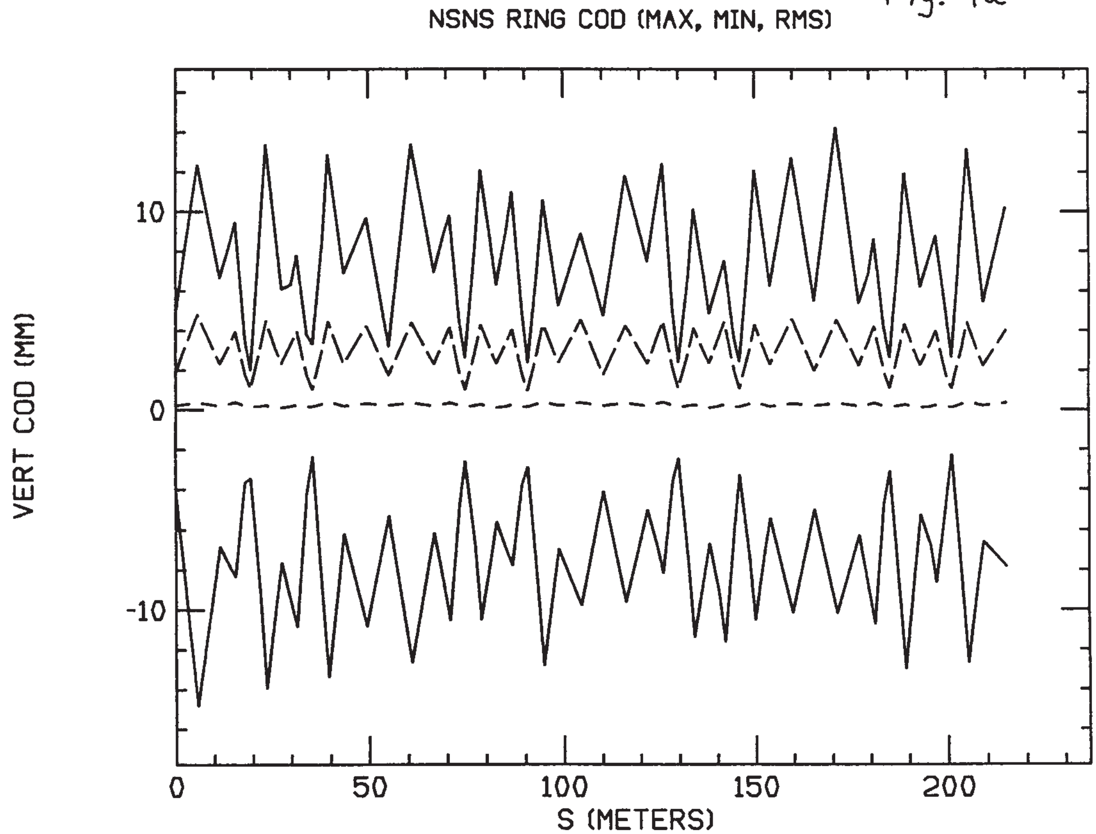

ERRORS (DOTTED) AND HARMONIC CORRECTION
VERT CORRECTION (MILLIRADIANS)
0.2
0.1
0.0
-0.1
-0.2
0
50
100
150
200
S (METERS)

Fig. 4a


NSNS RING COD (MAX, MIN, RMS)
VERT COD (MM)
10
0
-10
0
50
100
150
200
S (METERS)

4b

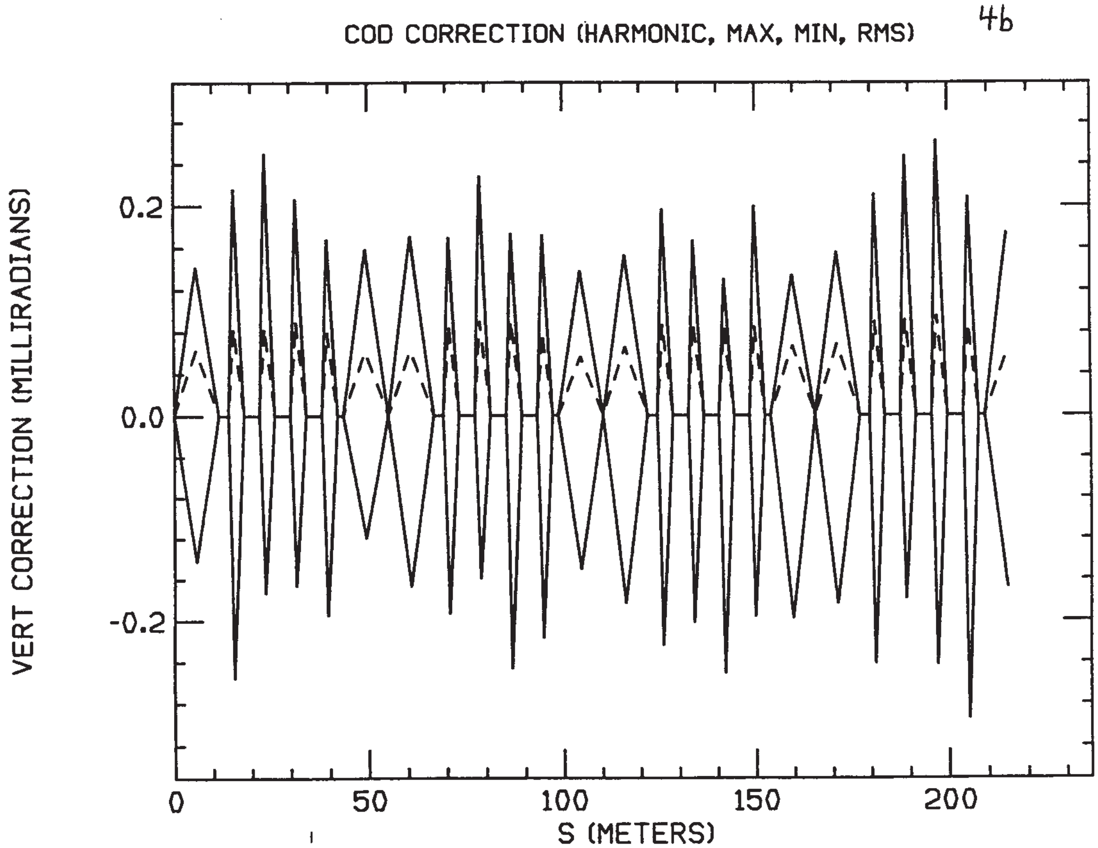
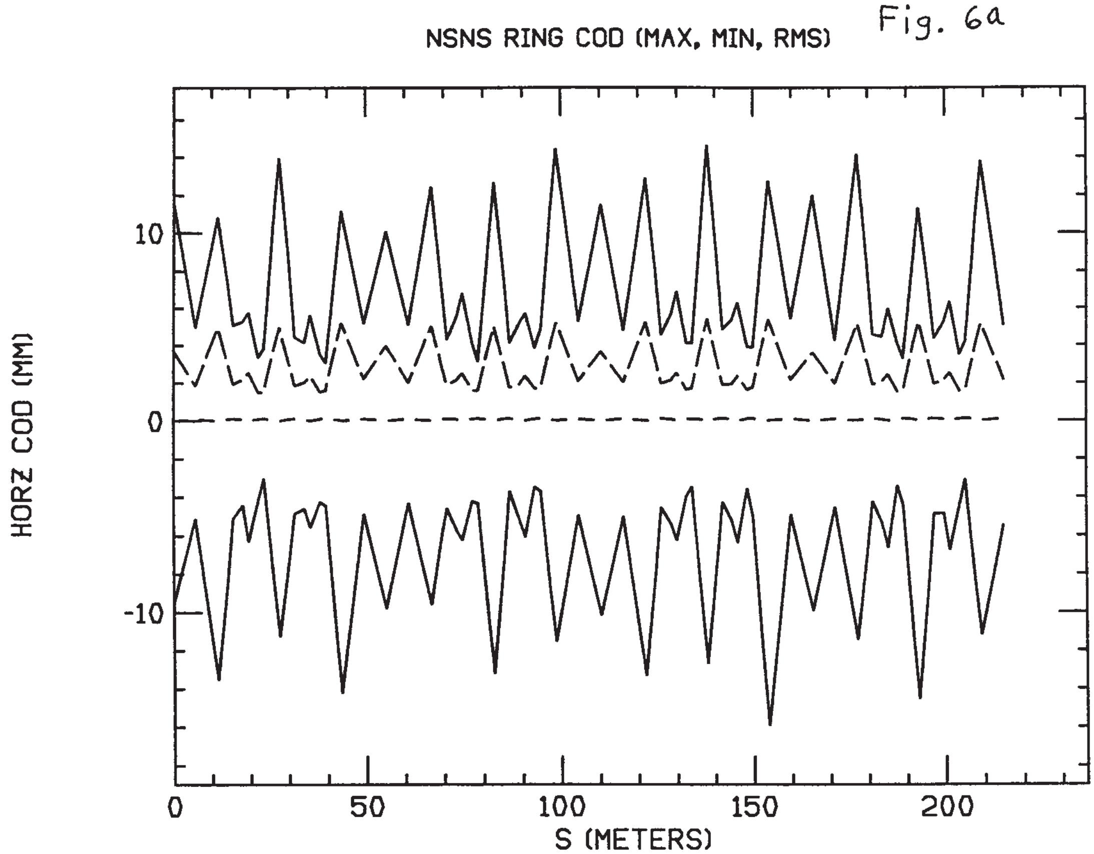

COD CORRECTION (HARMONIC, MAX, MIN, RMS)
VERT CORRECTION (MILLIRADIANS)
0.2
0.0
-0.2
0
50
100
150
200
S (METERS)

Fig. 6a


NSNS RING COD (MAX, MIN, RMS)
HORZ COD (MM)
10
0
-10
0
50
100
150
200
S (METERS)

6b

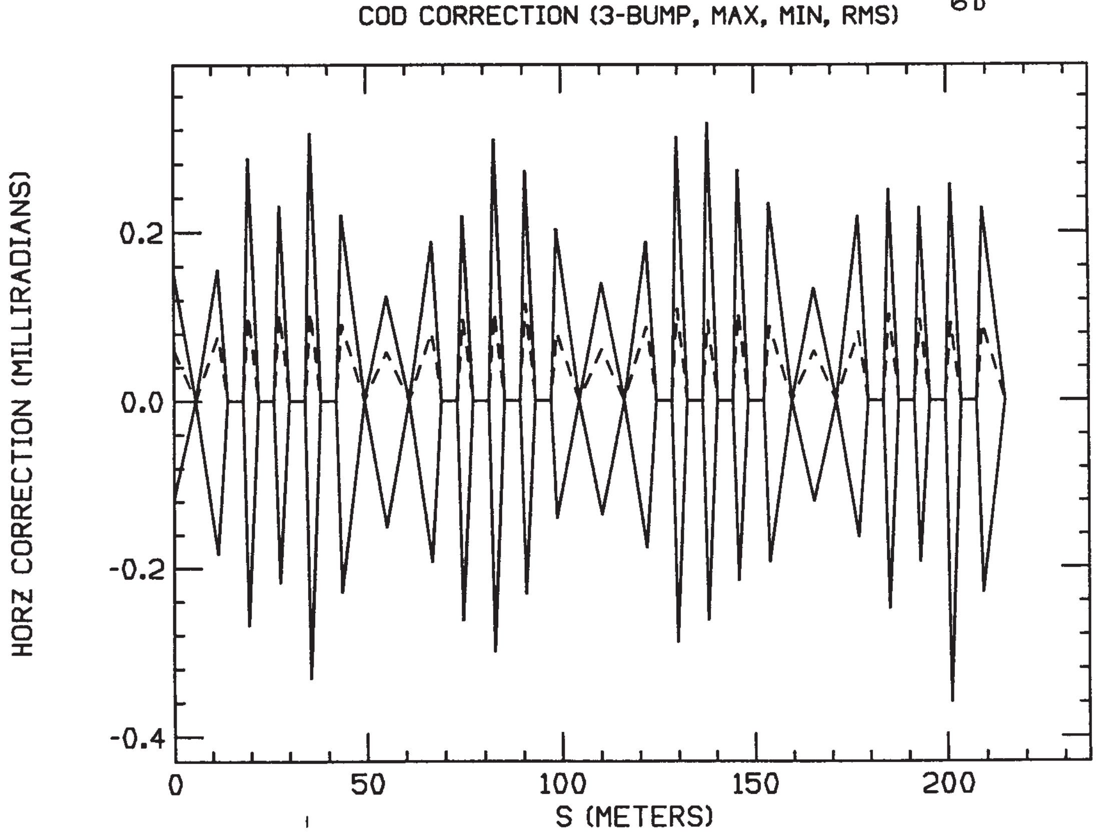
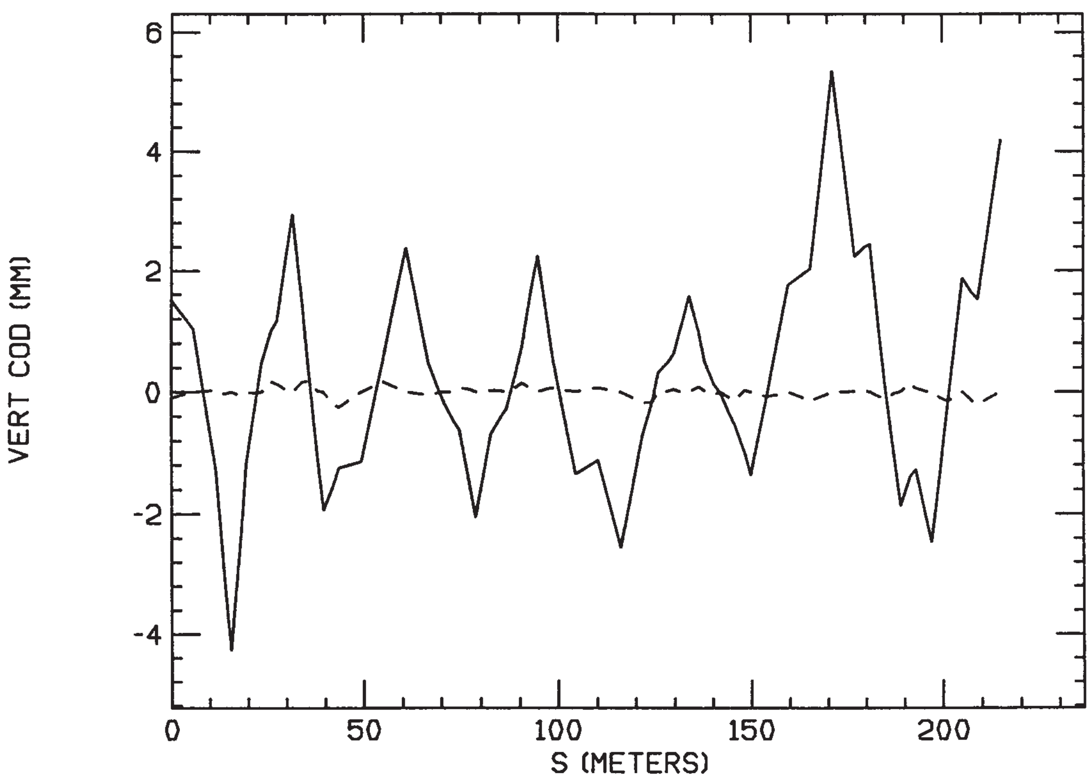

COD CORRECTION (3-BUMP, MAX, MIN, RMS)
HORZ CORRECTION (MILLIRADIANS)
0.2
0.0
-0.2
-0.4
0
50
100
150
200
S (METERS)

Fig. 7a


NSNS RING COD
VERT COD (MM)
S (METERS)
6
4
2
0
-2
-4
0
50
100
150
200

7b

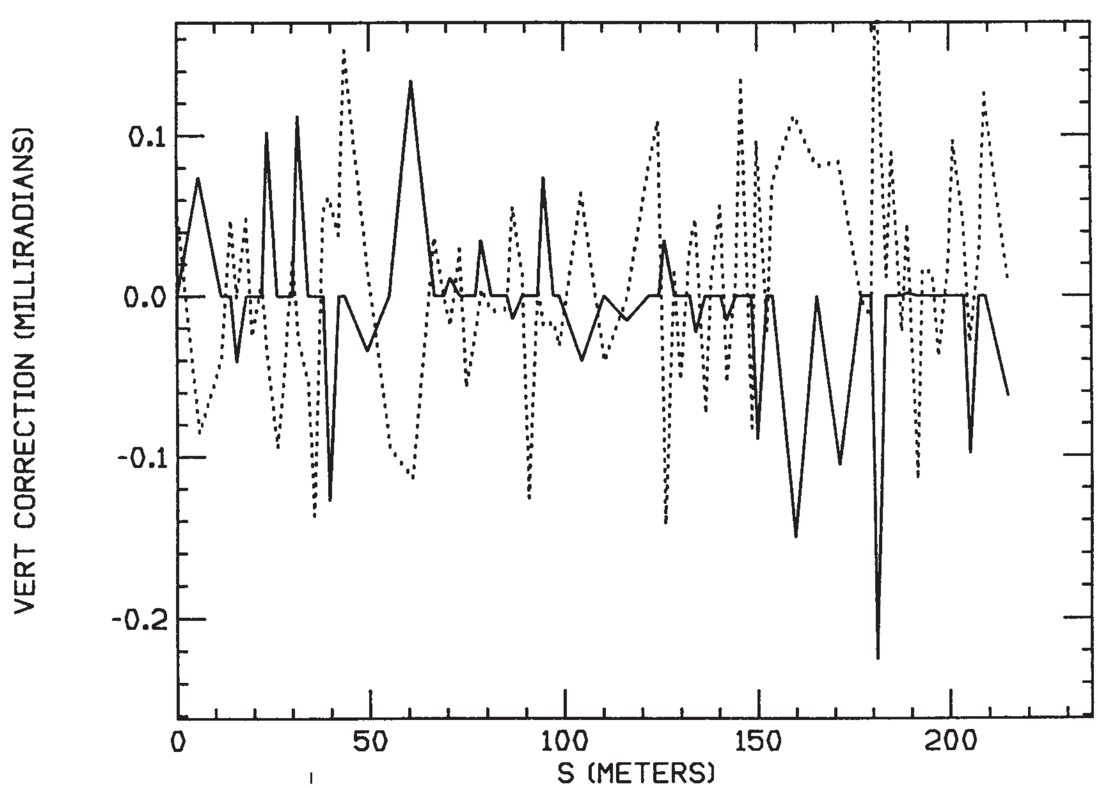

ERRORS (DOTTED) AND 3-BUMP CORRECTION
VERT CORRECTION (MILLIRADIANS)
S (METERS)
0.1
0.0
-0.1
-0.2
0
50
100
150
200

Fig. 8a

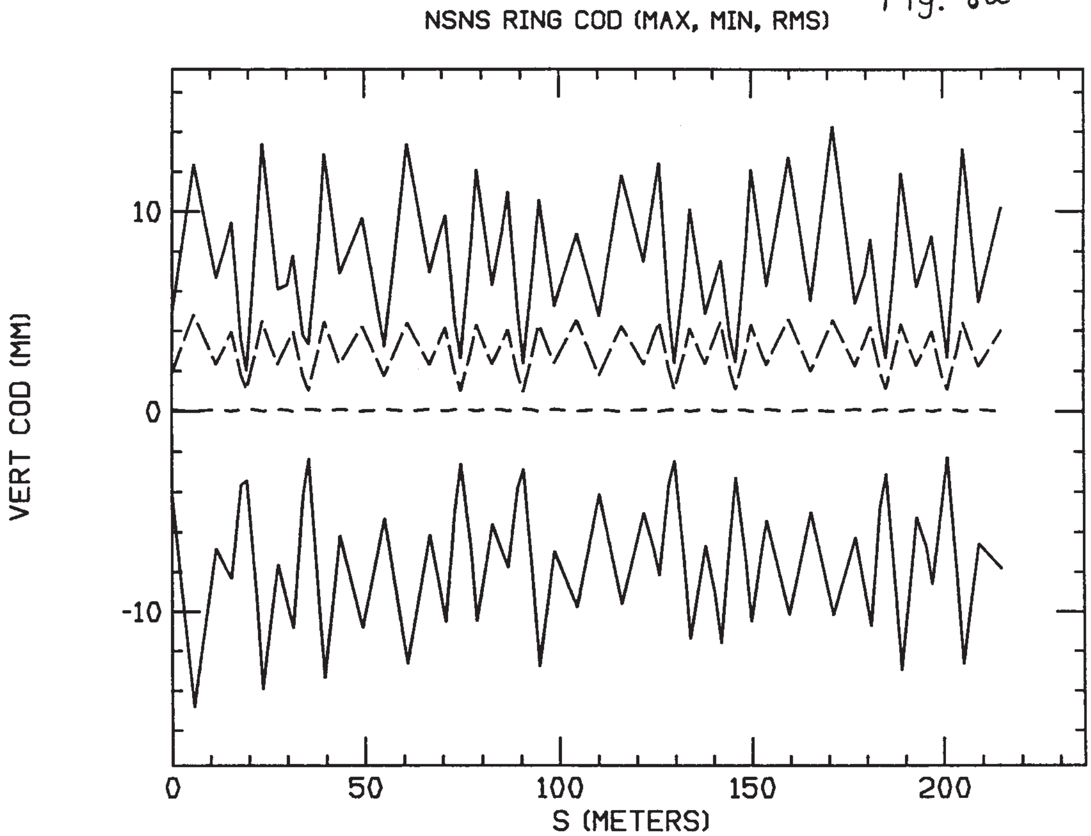

NSNS RING COD (MAX, MIN, RMS)
VERT COD (MM)
10
0
-10
0
50
100
150
200
S (METERS)

Fig. 8b

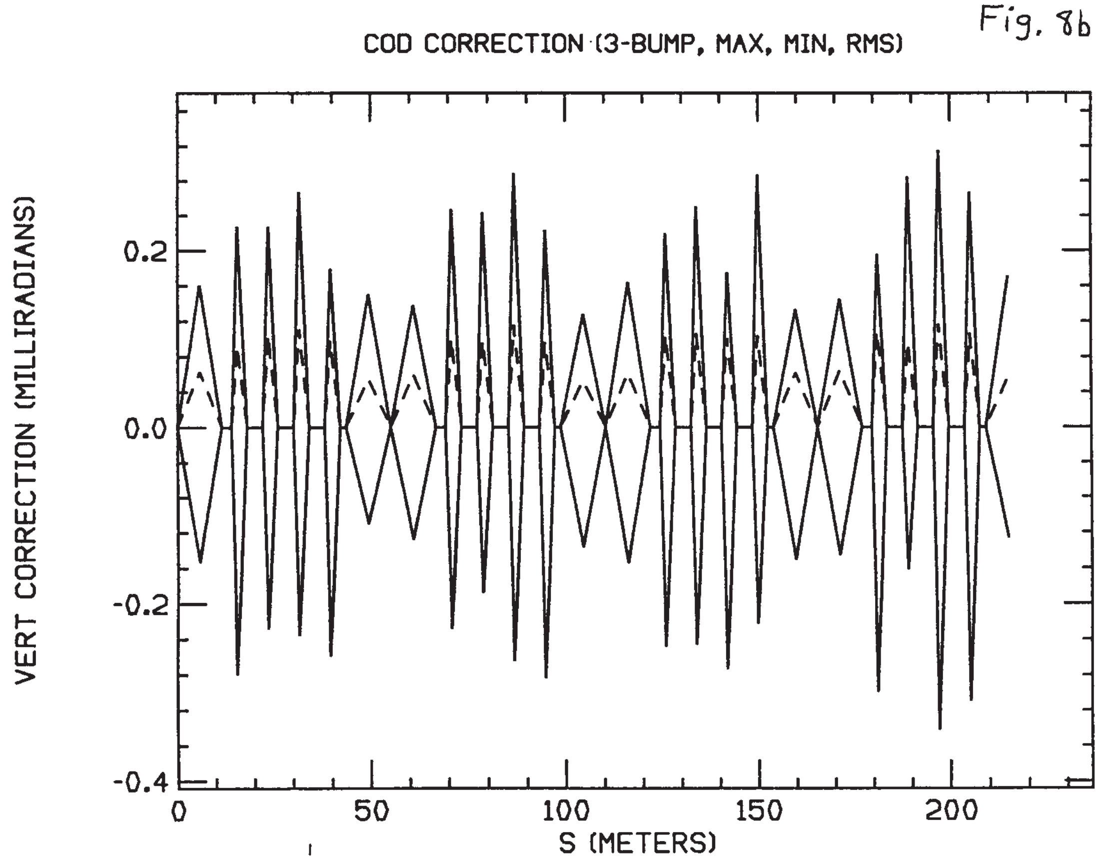
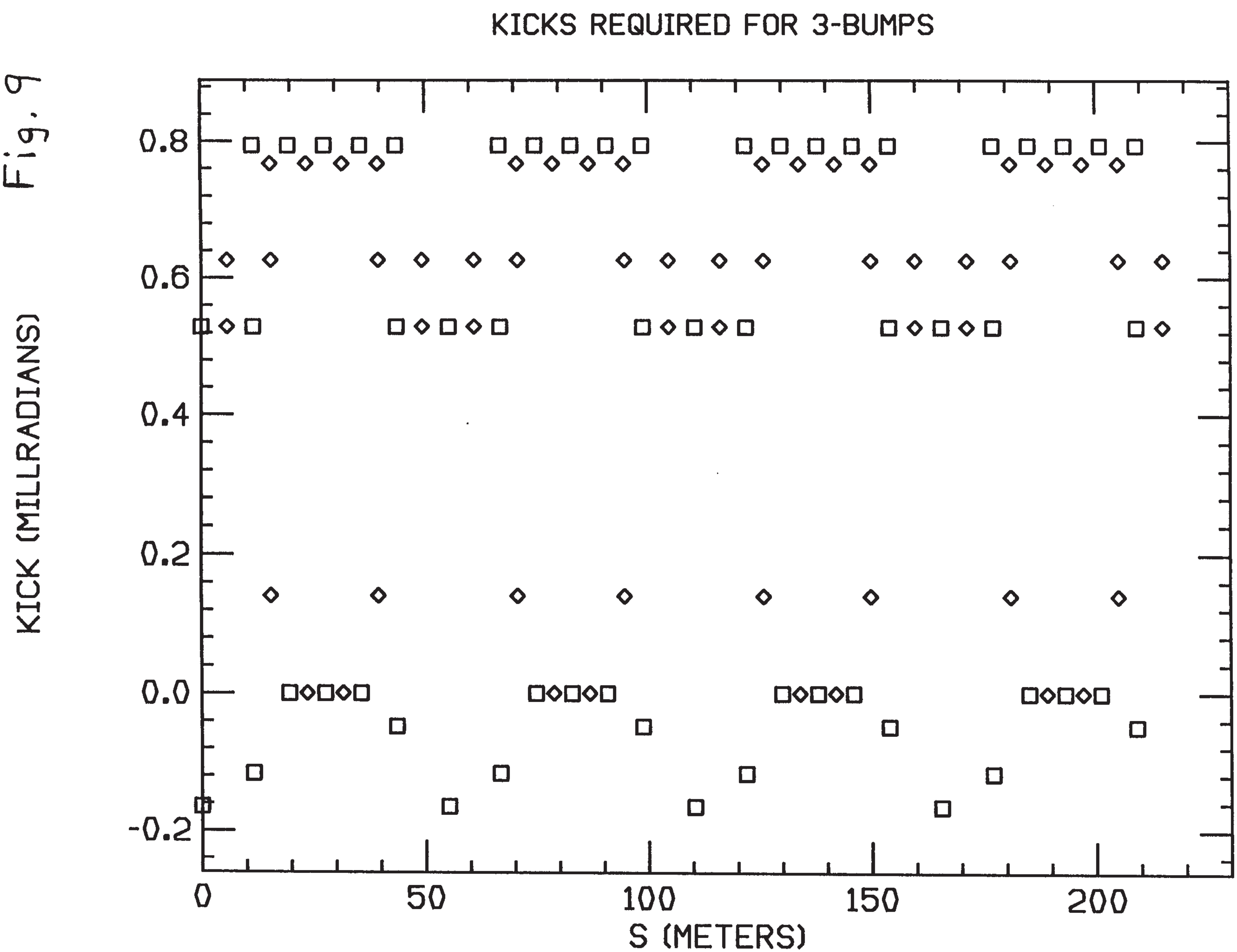

COD CORRECTION (3-BUMP, MAX, MIN, RMS)
VERT CORRECTION (MILLIRADIANS)
0.2
0.0
-0.2
-0.4
0
50
100
150
200
S (METERS)

Fig. 9


KICKS REQUIRED FOR 3-BUMPS
KICK (MILLRADIANS)
0.8
0.6
0.4
0.2
0.0
-0.2
0
50
100
150
200
S (METERS)