I. INTRODUCTION

Inverse synthetic aperture radar (ISAR) is a well-developed technique for producing high resolution images [1, 2]. Three-dimensional (3-D) ISAR images can be obtained by processing coherently the backscattered fields as a function of the frequency and two rotation angles about axes which are mutually orthogonal. When the radar is within the far-field zone of the object, the processing reduces to an interpolation plus a 3-D inverse discrete Fourier transform (DFT) [3]. However, if the radar is located in the near-field of the object, the planar wavefront approximation is not valid and the direct Fourier inversion cannot be used for the image reconstruction. Most of the ISAR algorithms are based on the Fourier transform and as such can tolerate only small amounts of wavefront curvature. Near-field ISAR imaging of large objects using a direct Fourier inversion may result in images which are increasingly unfocused at points which are more distant from the center of rotation [4]. These focusing errors increase dramatically when the synthetic aperture used in the measurement has a large angular extent, being maximum when the object is rotated through 360 deg. Nevertheless, when imaging objects with a narrow-angle synthetic aperture with the direct Fourier inversion, near-field focusing errors introduce a geometric distortion that may be rectified by means of a coordinates transformation.

Mensa, et al. introduced the first two-dimensional (2-D) ISAR algorithm which requires no interpolation and is based on interpreting the 2-D Fourier transform as a one-dimensional circular convolution integral [5]. A 2-D inverse/linear synthetic aperture radar (SAR) processor based on the same principle which accounts for the near-field condition is presented in [6]. An extension of this technique to the 3-D case using a near-field cylindrical system is reported in [7].

Presented here is a 3-D ISAR algorithm based on the use of a near-field focusing function which accounts for the wavefront curvature and the propagation losses. The spatial distribution of the target reflectivity is estimated by means of an azimuth convolution between the near-field focusing function and the frequency domain data, followed by a coherent integration over the frequency band and the synthetic aperture in elevation. The circular convolution in azimuth is performed by applying fast Fourier transform (FFT) techniques, reducing drastically the computing time. Moreover, instead of using a DFT, the focusing function in the azimuth wavenumber domain is evaluated through an asymptotic expansion obtained by the stationary phase method. This asymptotic expansion is further optimized by using working matrices with the points of stationary phase and their second-order derivatives.
The presented algorithm is especially suited for near-field turntable/anechoic chamber imaging using a stepped frequency radar. The measurements are supposed to be fully controlled and therefore factors such as irregular sample spacing, platform position errors and mitigation of RFI have been not investigated. The objective of this work is to develop a rapid and efficient imaging technique for the identification and characterization of radar reflectivity components of complex objects. The practical problem motivating the development of this technique was the formation of a near-field 3-D ISAR image of a 5 m high tree [8]. Conventional techniques based on the polar formatting algorithm or a direct Fourier transform/image rectification were discarded because of the poor quality of the resulting imagery.

This paper is organized as follows. An introduction to 3-D ISAR and its associated formulation is given in Section I. The proposed 3-D near-field ISAR algorithm is discussed in Section III. The computational procedure used in the implementation of the near-field algorithm is addressed in Section IV. An estimate for the spatial resolutions and the required sampling intervals with the proposed imaging technique is given in Section V. Section VI is dedicated to the experimental results undertaken on both simulated and measurement data. For comparison, these results are compared to those obtained with a direct Fourier inversion or far-field algorithm.

II. FORMULATION OF THE PROBLEM

The imaging geometry is shown in Fig. 1. A CW signal is radiated from an antenna, located at a distance $R_0$ from the center of the coordinates system, with a beamwidth sufficiently large to uniformly irradiate a 3-D object. The reflected signal is received by a similar adjacent antenna. The object is positioned on a low reflectivity platform which rotates about the z-axis. The antenna system rotates in the y-z plane forming an angle $\theta$ with the z-axis. Thus, the backscattered fields $E_x(f, \phi, \theta)$ are acquired as a function of three parameters: the frequency $f$ of the CW signal, the azimuth position of the rotating platform $\phi$, and the looking angle of the antenna system $\theta$. Considering that the antenna is located within the near-field region of the object, i.e., it illuminates the object with a spherical wavefront, and its radiation pattern introduces a negligible distortion, then the 3-D complex reflectivity image in cylindrical coordinates $I(\rho, \phi, z)$ can be written as follows [7],

$$I(\rho, \phi, z) = \frac{8}{c^3} \int_{f} \int_{\theta} \int_{\phi} \sin \theta d\theta \sin \phi d\phi \times E_x(f, \phi, \theta) F(\rho, \phi - \phi', z; f, \theta) d\phi'$$

where $F(\cdot)$ is a near-field focusing function (or space-variant matched filter) which can be expressed as

$$F(\rho, \phi, z; f, \theta) = \left( \frac{R}{R_0} \right)^2 \exp\left[2\pi \left( R - R_0 \right) / k \right]$$

$$R = \sqrt{R_0^2 + \rho^2 + z^2 - 2R_0 \rho \cos \phi + z \cos \theta}$$

where $R$ denotes the range to the point with coordinates $(\rho, \phi, z)$, $R_0$ is the range to the center of the coordinates system and zero-phase reference point, and $k$ is the frequency wavenumber. In (1), both the exact near-field phase history and the free-space propagation losses are accounted for by the exponential function and the quadratic term in the amplitude, respectively. It is important to note that the focusing function $F(\cdot)$ is defined only by the measurement geometry and the working frequency. Thus, if calculated once and stored on memory, $F(\cdot)$ could be reused with different data sets measured under the same conditions. This is the case of a fully polarimetric measurement, where four data sets have to be focused using identical processing parameters. The core of this algorithm resides in the calculation of the circular convolution in (1). A description of the approach followed in the algorithm implementation is next.

III. IMAGING ALGORITHM

The circular convolution in azimuth in (1) can be calculated using FFT techniques. In the simplest form, it requires the use of three one-dimensional FFTs and a complex product in the azimuth wavenumber domain $k_\phi$. Instead of using a DFT, the azimuth Fourier transform of the focusing function $F(\cdot)$ may be evaluated by using the method of stationary phase [9]. This approach has the advantage of giving as a result an analytical expression, the evaluation of which can be highly optimized by using working matrices containing the points of stationary phase and their second-order derivatives. Furthermore, the number of points in the azimuth wavenumber domain does not need to be a power of two, thus alleviating the memory requirements and speeding-up the code.
The azimuth Fourier transform of the focusing function $F(\cdot)$ is given by

$$F(\rho,k_\phi,z,f,\theta) = \int_{-\pi}^{\pi} \left( \frac{R(\phi)}{R_0} \right)^2 \exp[j \ p(\phi)] d\phi$$

where

$$p(\phi) = A[R(\phi) - R_0] - k_\phi \phi$$

and

$$R(\phi) = \sqrt{B - C \cos \phi}$$

and

$$A = 2k$$

$$B = R_0^2 + \rho^2 + z^2 - 2R_0z \cos \theta$$

$$C = 2R_0 \rho \sin \theta.$$  

Since the integrand in (4) has no singular points and is a highly oscillating function, the integral can be evaluated by means of the method of stationary phase provided that $A$ is sufficiently large.

Assuming a sampling rate consistent with the Nyquist criterion, the DFT of the focusing function may be expressed as

$$F(p,k_\phi,z,f,\theta) = \sum_{n=-N_0/2}^{N_0/2-1} \left( \frac{R(n \Delta \phi)}{R_0} \right)^2 \exp[j \ p(n \Delta \phi)] \Delta \phi$$

$$k_\phi = \left\{ -\frac{N_0}{2}, -\frac{N_0}{2} + 1, \ldots, \frac{N_0}{2} - 1 \right\}$$

$$\Delta \phi = \frac{2\pi}{N_0}, \ N_0 \text{ even}.$$  

The asymptotic evaluation of this DFT with the method of the stationary phase gives the following result (see the Appendix for more details),

$$F(p,k_\phi,z,f,\theta) \approx \left\{ \frac{\sqrt{2\pi}}{R_0^2} \left( \frac{R^2(\phi_\pm)}{p''(\phi_\pm)} \right)^{1/3} \exp[j p(\phi_\pm)] + \frac{\sqrt{2\pi}}{R_0^2} \left( \frac{R^2(\phi_\pm)}{p''(\phi_\pm)} \right)^{1/3} \exp[j p(\phi_\pm)] \right\},$$

if $k_\phi \leq \hat{k}_\phi$  

$$\left( \frac{2\pi}{|p''(\phi_\pm)|} \right)^{1/3} A\left[ \frac{2}{|p''(\phi_\pm)|} \right] \text{Ai} \left( \frac{2}{|p''(\phi_\pm)|} \right)^{1/3} p'(\phi_\pm),$$

if $k_\phi > \hat{k}_\phi$  

with

$$\hat{k}_\phi = \left| p''(\phi_\pm) \right|^{-1/3}$$

and wherein $\text{Ai}(\cdot)$ denotes the Airy function [10].

In (9), the asymptotic evaluation of the integral in (4) is performed by summing the contribution from two stationary phase points at $\phi = \{\phi_+, \phi_-\}$. In (10),

the major contribution to the integral in (4) comes from a small neighborhood near the point $\phi = \phi_\phi$. In this neighborhood, the second-order derivative $p''(\phi)$ vanishes and,

$$p(\phi) \approx p(\phi_\phi) + p'(\phi_\phi)(\phi - \phi_\phi) + p''(\phi_\phi) \frac{(\phi - \phi_\phi)^3}{3!}.$$  

Substituting $p(\phi)$ with this series expansion, the integral in (4) can be expressed in terms of the Airy function, leading to (10).

If $C \ll B$, i.e., the reflectivity is being estimated at points close to the origin of the coordinates system, then (9) and (10) reduce to a much simpler form and $F(\cdot)$ may be expressed as follows,

$$F(p,k_\phi,z,f,\theta) \approx 2\pi k_\phi \exp \left[ -j \left( 2kR_\rho + k_\phi \frac{\pi}{2} \right) \right]$$

wherein $\eta = A\sqrt{B}/2$ and $J_{k_\phi}(\cdot)$ denotes the Bessel function of integer order $k_\phi$.

Once $F(\cdot)$ has been calculated for each working frequency $f$ and antenna looking angle $\theta$, the reflectivity image in cylindrical coordinates is recovered from the measured data in the azimuth wavenumber domain as

$$I(p,\phi,z) = \frac{8}{c^2} \text{IFFT}_{k_\phi} \left\{ \sum_{f} \sum_{\theta} f^2 \text{FFT}_{k_\phi}[\mathcal{F}(f,\phi,\theta)] \right\}$$

with $[\mathcal{F}]_{k_\phi} = F(p,k_\phi,z,f,\theta)$ for $k_\phi = -N_0/2, -N_0/2 + 1, \ldots, N_0/2 - 1$.

In (14), the evaluation of the near-field focusing function in the azimuth wavenumber domain $[\mathcal{F}(\cdot)]_{k_\phi}$ is associated with most of the computational burden of the algorithm. What follows is a description of the computational procedure used in the implementation of the proposed imaging algorithm.

IV. COMPUTATIONAL PROCEDURE

The near-field 3-D ISAR algorithm presented in Section III may be very demanding in terms of computer power and memory requirements, especially...
when the object being imaged is electrically large. In order to reduce the computational burden, the circular convolution in azimuth in (1) has been implemented with a complex product in the azimuth wavenumber domain. The focusing function \( F(.) \) is evaluated by means of the asymptotic expansions in (9), (10), and (13). This is basically the core of this imaging algorithm, which is the most computer intensive part of the code. The implementation of the first asymptotic expansion may be reduced to reading and interpolating two look-up tables or working matrices with the values of \( p(\phi, \alpha) \) and \( p'(\phi, \alpha) \) as a function of two parameters: \( \alpha \) and \( \beta \). Given these two look-up tables with \( N_\alpha \times N_\beta \) uniformly located samples, the interpolated values may be calculated by using a bilinear interpolation [10]. The second and third asymptotic expansions are of much simpler implementation and can be directly introduced into the code.

The computational procedure for reconstructing a 3-D reflectivity image on the basis of (1) may be presented in the form of the following steps (see flow chart in Fig. 2).

**Step 1** Window the frequency-domain data with the desired weighting function. In the case of an ISAR measurement with the entire rotation of the object, no azimuth window is applied.

**Step 2** Calculate a one-dimensional FFT in azimuth for each frequency and antenna looking angle. As a result, a 3-D array of complex values is obtained.

**Step 3** Create the two look-up tables with the values of \( \{p(\phi, \alpha), p'(\phi, \alpha)\} \) as a function of \( \alpha \) and \( \beta \) on a rectangular grid with \( N_\alpha \times N_\beta \) points. The useful ranges for \( \alpha \) and \( \beta \) are given by

\[
0 \leq \beta \leq \beta_{\text{max}} = \max_{(\alpha,\theta)} \left[ \frac{2R_0 \rho \sin \theta}{R_0^2 + \rho^2 + z^2 - 2R_0 \rho \cos \theta} \right]
\]

**Step 4** Use bilinear interpolation to calculate the focusing function in the azimuth wavenumber domain. Alternatively, if the sampling intervals \( \Delta \alpha \) and \( \Delta \beta \) are small enough, a nearest neighbor interpolation can be used without significant truncation errors.

**Step 5** Calculate the complex product of the near-field focusing function and the measurement data in the azimuth wavenumber domain.

**Step 6** Coherent summation over the antenna looking angle and frequency measured ranges for all pairs \( (\rho, z) \) repeating Steps 4 and 5.

**Step 7** Inverse FFT in azimuth. As a result, the 3-D reflectivity image in cylindrical coordinates \( I(\rho, \phi, z) \) is obtained.

V. RESOLUTION AND SAMPLING CRITERIA

In the resulting 3-D complex reflectivity image, the resolutions in ground-range and cross-range depend on the frequency bandwidth and the angular extent of the synthetic aperture in azimuth, respectively. Thus

\[
\delta_x = \frac{\lambda_c}{4 \sin \left( \frac{\theta}{2} \right)}
\]

\[
\delta_y = \frac{c}{\lambda_c \sin \theta}
\]

where \( W_c \) denotes the angular extent in azimuth, \( \theta_c \) is the frequency bandwidth, and \( \lambda_c \) is the wavelength at the center working frequency. When the ISAR measurement is performed with the entire rotation of the object, equivalent to synthesizing a circular aperture which completely surrounds the object, resolutions in cross-range and ground-range coincide and reach their maximum limit which is approximately \( \lambda_c / 5 \) [5]. The resolution in height depends on the angular extent in elevation and is given by

\[
\delta_z = \frac{\lambda_c}{2(\cos \theta_{\text{min}} - \cos \theta_{\text{max}})}
\]

Assuming the object is confined within a rectangular box of dimensions \( D_x \times D_y \times D_z \) and the
acquired data are calibrated with a canonical target placed at the origin of the coordinates system, the sampling intervals needed to satisfy the Nyquist criterion can be expressed as follows:

$$\Delta f \leq \frac{c}{2\sqrt{D_x^2 + D_y^2 + D_z^2}} \quad (20)$$

$$\Delta \phi \leq \frac{\lambda_{\min}}{2\sqrt{D_x^2 + D_y^2} \sin \theta_{\max}} \quad (21)$$

$$\Delta \theta \leq \frac{\lambda_{\min}}{2\sqrt{D_x^2 + D_y^2 + D_z^2}} \quad (22)$$

where $\lambda_{\min}$ denote the wavelength at the maximum working frequencies, respectively. As expected, the required sampling rates increase with increasing electrical dimensions of the object.

VI. RESULTS

In order to validate the presented algorithm, a number of tests with simulated and real data acquired in the anechoic chamber of the European Microwave Signature Laboratory (EMSL) have been carried out. What follows is the description of the measurement set-ups and the results on simulated and real datasets.

All results have been obtained on a high performance Sun Ultra-Sparc workstation, equipped with a 64 bit CPU and 128 Mbyte of RAM.

A. Numerical Simulations

The target used in this numerical simulation is a 3-D array of $5 \times 5 \times 5$ point scatterers uniformly distributed within a box of 1 m$^3$, as shown in Fig. 4. The range to the center of the coordinates system is $R_c = 2$ m. All scatterers have the same radar cross section (RCS): 0 dBsm. This target is imaged in the frequency range 2 to 6 GHz, sweeping 51 frequency points spaced 80 MHz. A full rotation of the target about the $z$-axis, with 360 azimuth points and a step of 1 deg, is used. The antenna looking angle $\theta$ ranges from 67.5 to 112.5 deg, with 46 antenna positions spaced 1 deg. A 3-D ISAR image has been reconstructed using the presented near-field ISAR algorithm. The projections of this 3-D image onto the $x-y$, $x-z$, and $y-z$ planes are shown in Fig. 5. The array dimensions used in this reconstruction are $N_x = 85$, $N_y = 360$, and $N_z = 121$. This requires approximately 30 Mbyte of internal storage. The overall processing time is 3 h 20 min. The processing time using a DFT code, and not the proposed asymptotic evaluation, for the azimuth Fourier transform of the focusing function is 12 h 13 min. Figs. 6(a)(1-5) show five horizontal slices extracted from the 3-D complex reflectivity image. These slices correspond to the five horizontal planes where the point scatterers are uniformly distributed.

For comparison, reconstructions using both the far-field algorithm (i.e., an interpolation followed by a 3-D inverse DFT) are shown in Figs. 6(b)(1-5). Here, range curvature aberrations introduced by not using the exact phase history term in the focusing function $F(\cdot)$ are evident. Fig. 7 depicts the cross-range, ground-range, and height profiles from the 3-D image generated with the near-field algorithm. As expected, resolutions in cross-range and ground range are both approximately 1 cm. The height resolution is about 6 cm. A Kaiser-Bessel window ($a = 2$) [11] across the aperture in elevation and across frequency is used. These resolutions as well as the reflectivity values at the position of the point scatterers are all in agreement with the predicted ones.

B. Experimental Validation

The presented near-field ISAR algorithm has been validated experimentally using the anechoic chamber of the EMSL [12], a European large-scale facility tailored for 3-D linear and ISAR imaging. Two series of test measurements have been undertaken.
The first measurement set-up consists of a planar array of 49 metallic spheres forming an "S" shape, as shown in Fig. 8(a). The spheres are laid on top of a low reflectivity platform of 2.5 x 2.5 m². All spheres are of the same size: 7.62 cm of diameter. The range to the center of the coordinates system is \( R_c = 9.56 \text{ m} \). The backscattered fields in the HH polarization are acquired in the stepped frequency mode of the HP-8510 ANA within the frequency range 8 to 12 GHz, sweeping 801 frequency points spaced 5 MHz. A full rotation of the target about the z-axis, with 1200 azimuth positions and an angular step of 0.3 deg, is used. This is a 2-D ISAR measurement, and no aperture synthesis in elevation is used. Therefore, no spatial resolution in height is achieved. The antenna looking angle is kept fixed to 45 deg. Once the frequency data set is calibrated, gated in the time domain and the returns from the empty room are...
subtracted, the number of frequency points used in the subsequent processing is decimated by a factor of 8, which still is above the Nyquist sampling rate defined by the target size and measurement geometry. The reference target used in the calibration is a metallic sphere of diameter 30.5 cm positioned at the focus of the chamber. Fig. 8(b) shows the image obtained with the presented near-field ISAR algorithm. As expected, resolutions in cross-range and ground range are both approximately 5 mm. A Kaiser-Bessel window \((a = 2)\) across frequency is used. The overall processing time is 1 min. The processing time using a DFT code, and not the proposed asymptotic evaluation, for the azimuth Fourier transform of the focusing function is 4 min. For comparison, this image is shown along with the one obtained with a far-field ISAR algorithm or direct Fourier inversion; see Fig. 8(c). Again, the better focusing capabilities of the presented algorithm are clearly visible. As expected, aberrations in outer part of the image obtained with the far-field processor are more evident.

The target used in the second test measurement is a 3-D arrangement of eight metallic spheres of diameter 7.62 cm, see Fig. 9 and photograph in Fig. 10(a). The measurement has been conducted with the same angular span in azimuth and elevation, with 61 points equally spaced within the range 0 to 45 deg, acquiring the backscattered fields in the HH polarization at 801 frequency points spaced 5 MHz within the frequency range 8 to 12 GHz. Here, the number of frequency points has been decimated by a factor of 20 after calibration. The range to the center of the coordinates system is again \(R_c = 9.56\) m. The measurement time required in this experiment is approximately 50 h. Note that there are 3721 antenna positions on the 2-D synthetic aperture. A 3-D ISAR image consisting of \(N_h = 61\) horizontal slices on a polar raster with \(N_p = 101\) and \(N_e = 480\) has
been reconstructed and is shown in Fig. 10(b). The processing time is 3 h 27 min. Achieved resolutions, as expected, are about 2 cm in the cross-range and height directions, and 4 cm in the ground-range direction.

VII. CONCLUSIONS

This paper has described a new 3-D ISAR algorithm which accounts for wavefront curvature. The core of the algorithm resides in the calculation of a near-field focusing, which is convoluted with the measurement data in the azimuth domain. An efficient computational procedure based on FFT codes and an asymptotic evaluation with the method of stationary phase has been introduced. This asymptotic evaluation is optimized by using working matrices with the points of stationary phase and their second-order derivatives. Experimental results with the presented near-field ISAR algorithm show a remarkable performance in terms of focusing capabilities and spatial stability of its impulse response.

APPENDIX

Solution of the Fourier integral in (4) using the method of stationary phase [9] takes the form,

\[
\mathcal{F}(\rho, k_\phi; f, \theta) \simeq \frac{\sqrt{2\pi}}{R_0^2} \left\{ \frac{R^2(\phi_-)}{\sqrt{p''(\phi_-)}} \exp[jp(\phi_-)] + \frac{R^2(\phi_+)}{\sqrt{p''(\phi_+)}} \exp[jp(\phi_+)] \right\}
\]

where \( \phi_- \) and \( \phi_+ \) are two stationary phase points determined by the equations,

\[
p'(\phi_-) = \left. \frac{\partial p(\phi)}{\partial \phi} \right|_{\phi_-} = A^2 \frac{C \sin \phi_-}{2\sqrt{B - C \cos \phi_-}} - k_\rho = 0
\]

\[
p'(\phi_+) = \left. \frac{\partial p(\phi)}{\partial \phi} \right|_{\phi_+} = A^2 \frac{C \sin \phi_+}{2\sqrt{B - C \cos \phi_+}} - k_\rho = 0
\]

which, after some algebraical manipulations, result in

\[
\phi_\pm = \arccos \left[ \frac{2\alpha^2 \pm \sqrt{\beta^2 - 4\alpha^2(1 - \alpha^2)}}{\beta} \right]
\]

\[
p(\phi_\pm) = \gamma \left[ \sqrt{1 - \left[ 2\alpha^2 \pm \sqrt{\beta^2 - 4\alpha^2(1 - \alpha^2)} \right]} - \alpha \phi_\pm \right] - 2kR_0
\]

\[
p''(\phi_\pm) = \pm \gamma \frac{\sqrt{\beta^2 - 4\alpha^2(1 - \alpha^2)}}{2\sqrt{1 - \left[ 2\alpha^2 \pm \sqrt{\beta^2 - 4\alpha^2(1 - \alpha^2)} \right]}}
\]

\[
R(\phi_\pm) = \frac{\gamma}{A} \sqrt{1 - \left[ 2\alpha^2 \pm \sqrt{\beta^2 - 4\alpha^2(1 - \alpha^2)} \right]}
\]
with
\[ \alpha = \frac{k_b}{\gamma}, \quad \beta = \frac{C}{B}, \quad \text{and} \quad \gamma = A\sqrt{B}. \] (30)

The approximation in (23) is satisfactory if the function \( p''(\cdot) \) does not vanish at the stationary phase points. From (24) and (25), it can be shown that the two stationary phase points converge to a single point as \( k \) increases, which is given by
\[ \phi_0 = \arccos \left[ \frac{1 - \sqrt{1 - \beta^2}}{\beta} \right]. \] (31)

As in any asymptotic expansion, it is difficult to give precise conditions for the validity of (23). However, the following gives some indication of the range of \( k \), where the error is small compared with \( F(\cdot) \).

If \( k > \hat{k} \), then the major contribution to the integral (4) comes from a small neighborhood near the point \( \phi = \phi_0 \). In this neighborhood, \( p''(\phi) \) vanishes and the following higher order series expansion
\[ p(\phi) \approx p(\phi_0) + p'(\phi_0)(\phi - \phi_0) + p''(\phi_0)(\phi - \phi_0)^3 \] (33)

must be used in the asymptotic evaluation of (4), leading to
\[ F(\phi, k, z; f, \theta) \approx 2\pi \left( \frac{R(\phi_0)}{R_a} \right)^2 \exp[jp(\phi_0)] \left( \frac{2}{|p''(\phi_0)|} \right)^{(1/3)} \times Ai \left( -\frac{2}{|p''(\phi_0)|} \right)^{(1/3)} p'(\phi_0) \] (34)

wherein \( Ai(\cdot) \) denotes the Airy function [10], and
\[ p(\phi_0) = \gamma[(1 - \beta^2)^{1/4} - \alpha \phi_0] - 2kR_a \] (35)
\[ p'(\phi_0) = \gamma \left[ -\alpha + \sqrt{1 - \frac{1 - \beta^2}{2}} \right] \] (36)
\[ p''(\phi_0) = -\gamma \sqrt{1 - \frac{1 - \beta^2}{2}} \] (37)
\[ \phi_0 = \arccos \left[ \frac{1 - \sqrt{1 - \beta^2}}{\beta} \right] \] (38)
\[ R(\phi_0) = \frac{\gamma}{A}(1 - \beta^2)^{(1/4)} \] (39)

provided that
\[ \hat{k} < k \leq \frac{N_0}{2}. \] (40)

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