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Inventor	Jeffrey A. Szelag et al

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PROCESS FOR ASSEMBLY OF MULTIMODE HYDROPHONE CERAMIC STACK

STATEMENT OF GOVERNMENT INTEREST

[0001] The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

CROSS REFERENCE TO OTHER PATENT APPLICATIONS

[0002] None.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

[0003] The present invention relates to a method of assembly for a multimode acoustic hydrophone.

(2) Description of the Prior Art

[0004] An acoustic hydrophone can transfer underwater pressure waves to electrical energy. As a result, an output charge can be monitored from piezoelectric material with the operation similar to using an underwater microphone. Typically, hydrophones are used as omni-directionsl sensors or are used as directional sensors in an array format.

[0005] The design of a multimode hydrophone was originally disclosed in United States Patent No. 3,290,646. In the reference, a multimode hydrophone includes a piezoelectric stack and associated electronics that can provide directional receiving responses. For other hydrophones, it has been shown that if an axial stress is non-uniform on any of the ceramic rings; a bearing to a source of an incoming pressure wave indicated by a hydrophone varies erratically. The hydrophones therefore become useless devices.

[0006] **FIG. 1** thru **FIG. 12** chart a performance difference of a hydrophone that does not have uniform axial stress/voltage on each ring, when the hydrophone is assembled and **FIG. 13** thru **FIG. 24** chart a performance difference of a hydrophone that does have uniform axial stress/voltage on each ring when the hydrophone is assembled. The plots depict bearing error relative to a known source location as a function of frequency. Each curve represents a different azimuth angle. In total, there are azimuthal measurements made every thirty degrees around a 360 degree circle.

[0007] To have an accurate hydrophone, it is desirable that each curve be as close to zero as possible in order to indicate that a bearing to a source is accurate. As shown in **FIG. 13** thru **FIG. 24**, the hydrophone is much more accurate than the hydrophone shown in **FIG. 1** thru **FIG. 12** since the curves in **FIG. 13** thru **FIG. 24** are at approximately zero plus or minus 10 degrees. The curves in **FIG. 1** thru **FIG. 12** have large excursions (greater than thirty degrees and less than thirty degrees) at numerous frequencies. The difference between the hydrophones in **FIG. 1** thru **FIG. 12** and the hydrophones in **FIG. 13** thru **FIG. 24** are an applied axial compression of each of the five tangentially-poled ceramic rings.

[0008] A hydrophone **10** of the prior art is shown in **FIG. 25.** The hydrophone **10** includes tangentially-poled ceramic (lead-zirconate titanate) rings **12**, a Delrin washers **14,** a LC-800 washers **16,** 26 AWG insulated wire **18,** a stainless steel flange **20,** an end cap **22,** 30 AWG uninsulated bus wire **24,** solder joints **26,** ¼-28 socket head screw **28,** and a phenolic feed through assembly **30.**

[0009] The direction of assembly is axially from right to left when the hydrophone is assembled. The ceramic rings **12** are slid on a shaft (flange) and capped with the socket head screw **28** which imparts an axial compression on the ceramic ring stack. If compression is asymmetric on the five rings; the performance is indicative as these plots are shown in **FIG. 1** thru **FIG. 12.** If the compression is uniform on all the rings; the performance improves to be indicative of those plots shown in **FIG. 13** thru **FIG. 24.**

[0010] Numerous references detail the assembly of ceramic rings. In Butler (United States Patent No. 4,326,275) ceramic discs are mounted to brass flexural discs using a conductive epoxy on adjoining surfaces. The ceramic discs have approximately the same thickness as the brass flexural discs but are slightly smaller in diameter so that the discs fit within hollow cavities by the closing of rings by the flexural discs.

[0011] Congdon (United States Patent No. 5,018,116) discloses a hydrophone with a ceramic stack, which includes an outer rubber boot covering the ceramic stack. Between the stack and the inner surface of the boot is a layer of polyurethane elastomer which bonds the boot to the stack and serves as an acoustical transfer agent to transfer sound pressure waves to the stack.

[0012] Purcell et al. (United States Patent No. 6,584,039) discloses an axial drive resonant pipe projector that contains a ceramic stack piezoelectric drive element, rings, and a watertight seal to seal the stack from seawater. A Neoprene boot isolates active components from seawater and is bonded to the stack by epoxy. Restraining clamps are clamped on a central boss of the end plates at either end of the stack with a stack of ceramic rings that may be varied or a single piezoelectric cylinder.

[0013] Birchak et al. (United States Patent No. 6,594,199) discloses a hydrophone with a mounting portion having yoke legs which extend parallel to a longitudinal axis of a stack of piezoelectric crystals, instead of extending perpendicular to the axis as in the hydrophone. The hydrophone also includes an opening formed between the mounting portion and the membrane enclosing the stack, for even or symmetrical application of fluid pressure to the crystals.

[0014] Butler et al. (United States Patent No. 6,950,373) discloses a piezoelectric ceramic stack of four elements driving a transmission line for asymmetric drive, consecutive mode excitation. The electrically inactive section to the right of the piezoelectric section may be constructed from an acoustically satisfactory material, and connected. A material that matches the impedance between the piezoelectric ceramic material and the medium, such as water, would be one example.

[0015] Butler et al. (United States Patent No. 7,372,776) discloses a schematic of a five ring transducer array. The five transducer array rings may be 1.5 inches high; each with a total array height if approximately nine inches; including the isolation gaps and end caps. The diameter of the array may be six inches and the eight piezoelectric stacks of each ring are sandwiched between eight aluminum pistons and common centrally disposed between steel mass.

[0016] Hama (United States Patent No. 7,418,102) discloses an echo sounder with a front mass, a layered product of piezoelectric ceramics. The piezoelectric ceramics have a ring shape and are layered in such a manner to define an inner space. The layered product of the ceramics is sandwiched between the front mass and the rear mass. A compressive force is exerted on the layered product of ceramics.

[0017] Porzio (United States Patent No. 7,495,370) discloses a transducer configuration wherein the head mass includes a piezoceramic receiver such as a monolithic ceramic disk that acts as both a hydrophone and the head mass for a second ceramic body, which takes the form of a composite tape-cast ceramic stack.

[0018] Porzio (United States Patent No. 7,535,801) discloses a driver in the form of a stack of piezoelectric rings. The driver may be magnetostrictive material that can provide a selected vibratory frequency through the excitation provided by oscillatory magnetic fields. The driver may be made of a lead-zirconate-titanate ceramic, terfernol-D or other electrostrictive, magnetostrictive, piezoceramic or piezomagnetic solid state material. The transducer may be operated as a projector of acoustic signals of a desired frequency but may also be operated as an acoustic receiver or hydrophone.

[0019] Goodemote (United States Patent No. 7,583,010) discloses a hybrid transducer that includes a headmass, tailmass, and an active structure disposed intermediate the headmass and the tailmass. The active structure is a low defect, high dielectric, modified pZT-5H type ceramic material.

[0020] Butler et al. (United States Patent No. 8,599,648) discloses a continuous piezoelectric ring in contact with a shell through spaced apart supports. The ring is shown with eight margins or gaps on the electrode surface allowing a piezoelectric mode of excitation of the monopole, dipole and quadrupole modes and also allowing incremental steering every 45 degrees. The use of more and wider margins allows excitation of the piezoelectric ring in the higher coupled piezoelectric mode of operation.

[0021] Alternatives processes attempted in the past have provided inconsistent results of hydrophone performance. Previously, ceramic rings and interstitial layers have been stacked onto the shaft and a measurement of the overshoot of the stack relative to the top surface was used for setting the compression. This method, although physically repeatable, does not provide repeatable results in the performance of the hydrophones.

SUMMARY OF THE INVENTION

[0022] It is therefore a primary object and general purpose of the present invention to provide a method of assembly of a hydrophone in which an axial compression of the ceramic rings of the hydrophone can be equalized.

[0023] It is therefore a further object of the present invention to provide a method of assembly of a hydrophone in which the hydrophone can be used across a wide range of frequencies.

[0024] It is therefore a still further object of the present invention to provide a method of assembly for a comparatively smaller transducer that is easier to handle, install and less costly to manufacture than existing transducers.

[0025] In order to attain the objects of the invention, a method of assembly of a hydrophone is provided in which the method utilizes an array of tangentially poled ceramic rings. The hydrophone is assembled by stacking the ceramic rings, Delrin washers and LC-800 washers such that a top edge of a composite stack slightly extends beyond a top of a hydrophone flange.

[0026] The method is functional in that the results of hydrophone performance are varied because this method does not include a determination of axial compression of each of the ceramic rings. Instead, the stack is measured in total where compression among each ring would not be measurable. By measuring the voltage on each ceramic ring of the composite stack while an end cap and a cap screw are installed; the axial compression of each ceramic ring is quantified; thereby, providing an opportunity to equalize the axial compression of each ceramic ring to yield an accurately performing hydrophone.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] Reference is made to the accompanying drawings in which is shown an illustrative embodiment of the invention, from which its novel features and advantages will be apparent, wherein corresponding reference characters indicate corresponding parts throughout the several views of the drawings and wherein:

[0028] **FIG. 1** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of zero degrees;

[0029] **FIG. 2** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of thirty degrees;

[0030] **FIG. 3** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of sixty degrees;

[0031] **FIG. 4** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of ninety degrees;

[0032] **FIG. 5** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of one hundred and twenty degrees;

[0033] **FIG. 6** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of one hundred and fifty degrees;

[0034] **FIG. 7** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of one hundred and eighty degrees;

[0035] **FIG. 8** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of two hundred and ten degrees;

[0036] **FIG. 9** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of two hundred and forty degrees;

[0037] **FIG. 10** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of two hundred and seventy degrees;

[0038] **FIG. 11** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of three hundred degrees;

[0039] **FIG. 12** depicts a performance difference between a hydrophone that does not have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of three hundred and thirty degrees;

[0040] **FIG. 13** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of zero degrees;

[0041] **FIG. 14** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of thirty degrees;

[0042] **FIG. 15** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of sixty degrees;

[0043] **FIG. 16** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of ninety degrees;

[0044] **FIG. 17** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of one hundred and twenty degrees;

[0045] **FIG. 18** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of one hundred and fifty degrees;

[0046] **FIG. 19** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of one hundred and eighty degrees;

[0047] **FIG. 20** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of two hundred and ten degrees;

[0048] **FIG. 21** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of two hundred and forty degrees;

[0049] **FIG. 22** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of two hundred and seventy degrees;

[0050] **FIG. 23** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of three hundred degrees;

[0051] **FIG. 24** depicts a performance difference between a hydrophone that does have uniform axial stress/voltage on each ring when assembled with the parameters of bearing error and coded frequency with an azimuth of three hundred and thirty degrees;

[0052] **FIG. 25** depicts a prior art hydrophone;

[0053] **FIG. 26** depicts the individual components of the hydrophone of the present invention prior to assembly; and

[0054] **FIG. 27** depicts a cut-away view of the hydrophone of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0055] Referring to **FIG. 26** and **FIG. 27**, a hydrophone **100** of the present invention is provided. Prior to assembly, the components of the hydrophone **100** are sized for precision. The hydrophone **100** is assembled by stacking ceramic rings **102**, washers **104**, and LC-800 washers **106** such that a top edge of a composite stack with an end cap **108** and a cap screw **110** extends beyond a top of a hydrophone flange **200** by 0.030 to 0.060 inches.

[0056] Each of the ceramic rings **102** preferably has a length of 0.475 inches and are hollowed with a thickness of .125 inches. Each of the ceramic rings **102** is sized to be slidable (by thousandths of an inch) on the flange **200.**

[0057] The tangentially poled ceramic rings **102** are poled where consecutive sections (arcs) of the ring have an opposite polarity; thereby, dividing the ring into sections with two sections defining a quadrant. Being tangentially poled is a method of separating the ceramic cylinder into consecutive sections that have the opposite polarity; thus allowing the formation of quadrants which are required to operate as multimode hydrophones. When the quadrants are added, a widespread directionality is achieved in the results can be used to determine a bearing of incoming pressure waves.

[0058] The washers **104** are made from Delrin. Delrin is a nylon-like material that can be easily machined yet is rigid enough to provide the interstitial layers with a stiffness required to transfer an axial stress uniformly through the ceramic rings.

[0059] The LC-800 washers **106** provide adequate compliancy for mounting between ceramic cylinders or rings in that the LC-800 material maintains constant mechanical properties over a wide range of temperatures and pressures. LC-800 is also an acoustic decoupling material which isolates each of the rings so that the rings can perform independently.

[0060] The hydrophone flange **200** is preferably a solid stainless steel rod connected to electronics such as a data processor. The flange **200** preferably has a 3 inch length and 0.55 inch diameter. The flange also includes a tapped indent **202** that allows insertion of the cap screw **110**.

[0061] The method is inventive in that the individual ceramic rings **102** are tested after assembly in order to confirm uniform axial stress. Voltage measurements are made by probes connectable to electrodes on the ceramic rings **102**. Each of the ceramic rings **102**, when the hydrophone **100** is energized, should measure to approximately one volt with a matching tolerance of approximately one tenth of a volt per ring when matched with other ceramic rings. If the matching tolerance is not met; the hydrophone **100** is disassembled to but not including the ceramic ring **102** which had the correct tolerance of one tenth of a volt to an adjacent ceramic ring. The other ceramic rings **102** are reassembled onto with the end cap **108** tightened with a minimal first torque.

[0062] If the tolerance between the ceramic rings **102** still does not have the correct matching tolerance; the hydrophone **100** is dissembled in the previously described manner of disassembly and retested until all of the ceramic rings have the correct matching tolerance. Once the matching tolerance is correct for all of the ceramic rings **102**; then the end cap **108** is tightened to specifications at a second torque such that there is a uniform compression between the ceramic rings.

[0063] Electrical connection of the 26 AWG insulated wire **18** and the 30 AWG uninsulated bus wire **24** to the components of the hydrophone **100** for electrical operation of the hydrophone is known to those skilled in the art. Series voltage of the hydrophone **100** is not a consideration; however, parallel voltage with a correct matching tolerance is an important consideration for the hydrophone **100**. Testing of the hydrophone **100** occurs after electrical connection of the bus wires. Disassembly for testing and retesting includes disconnecting the 26 AWG insulated wire **18** and the 30 AWG uninsulated bus wire **24.**

[0064] After a voltage measurement is made, the cap screw **110** is tightened to compress the assembly of the ceramic rings **102** and other components. Tightening is to bottom out the cap screw **110** in the indent **202** of the flange **200.** A normal "hand-tight" torque is used to tighten at the first torque and to loosen or "back-out" the cap screw **110** out of the flange **200** until there is a uniform voltage between all of the ceramic rings **102.** Once the matching tolerance is correct for all of the ceramic rings **102;** then the end cap **108** is tightened at a second torque such that there is a uniform compression between the ceramic rings and that a top edge of a composite stack with an end cap **108** and a cap screw **110** extends beyond a top of a hydrophone flange **200** by 0.030 to 0.060 inches.

[0065] The method is functional in that the results of hydrophone performance are varied because this method does not include a determination of axial compression of each of the ceramic rings **102.** Instead, the composite stack is measured in total where compression among each ring would not be measurable. By measuring a voltage on each ceramic ring **102** of the composite stack while an end cap **110** and a ¼-28 socket head cap screw are installed; the axial compression of each ceramic ring is quantified; thereby, providing an opportunity to equalize the axial compression of each ceramic ring to yield an accurately performing hydrophone.

[0066] The magnitude of the voltage is important to a lesser degree than the deviation between the voltages measured on each ring. A deviation, or range, of voltage of plus/minus 0.1 VDC between all five rings, will produce an accurate hydrophone, such as the results depicted in **FIGS. 13 – 24.**

[0067] The piezoelectric portion of the invention described and reflected in **FIG. 27** is approximately seven inches in length, less than an inch in diameter and weighs less than three pounds. A prior art hydrophone, generally as shown in **FIG. 25**, that covers the same frequencies is twenty-four inches in length, six inches in diameter and weighs thirty-five pounds.

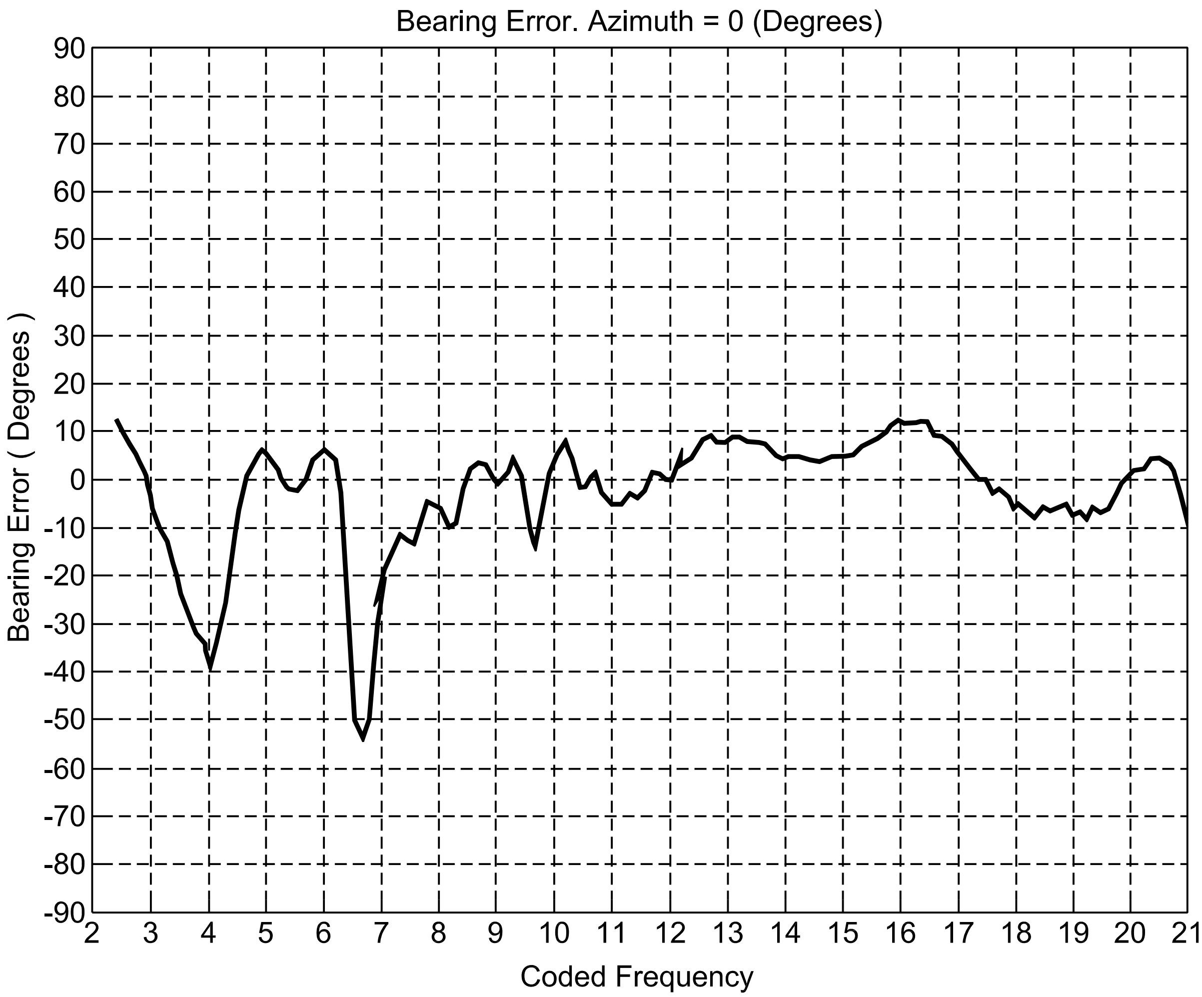
[0068] The foregoing description of the preferred embodiments of the invention has been presented for purposes of illustration and description only. It is not intended to be exhaustive or to limit the invention to the precise form disclosed; and obviously many modifications and variations are possible in light of the above teaching.

[0069] It will be understood that many additional changes in the details, materials, steps and arrangement of parts, which have been herein described and illustrated in order to explain the nature of the invention, may be made by those skilled in the art within the principle and scope of the invention as expressed in the appended claims.

PROCESS FOR ASSEMBLY OF MULTIMODE HYDROPHONE CERAMIC STACK

ABSTRACT OF THE DISCLOSURE

A method of assembling a hydrophone is provided in which the method stacks ceramic rings, delirin washers, and LC-800 washers such that a top edge of a composite stack extends beyond a top of a hydrophone flange. By measuring the voltage on each ceramic ring while an end cap and a socket head cap screw are installed; the axial compression of each ceramic ring is quantified; thereby, providing an opportunity to equalize the axial compression of each ceramic ring to yield an accurately performing hydrophone.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Bearing Error (Degrees)
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-60
-70
-80
-90
2
3
4
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11
12
13
14
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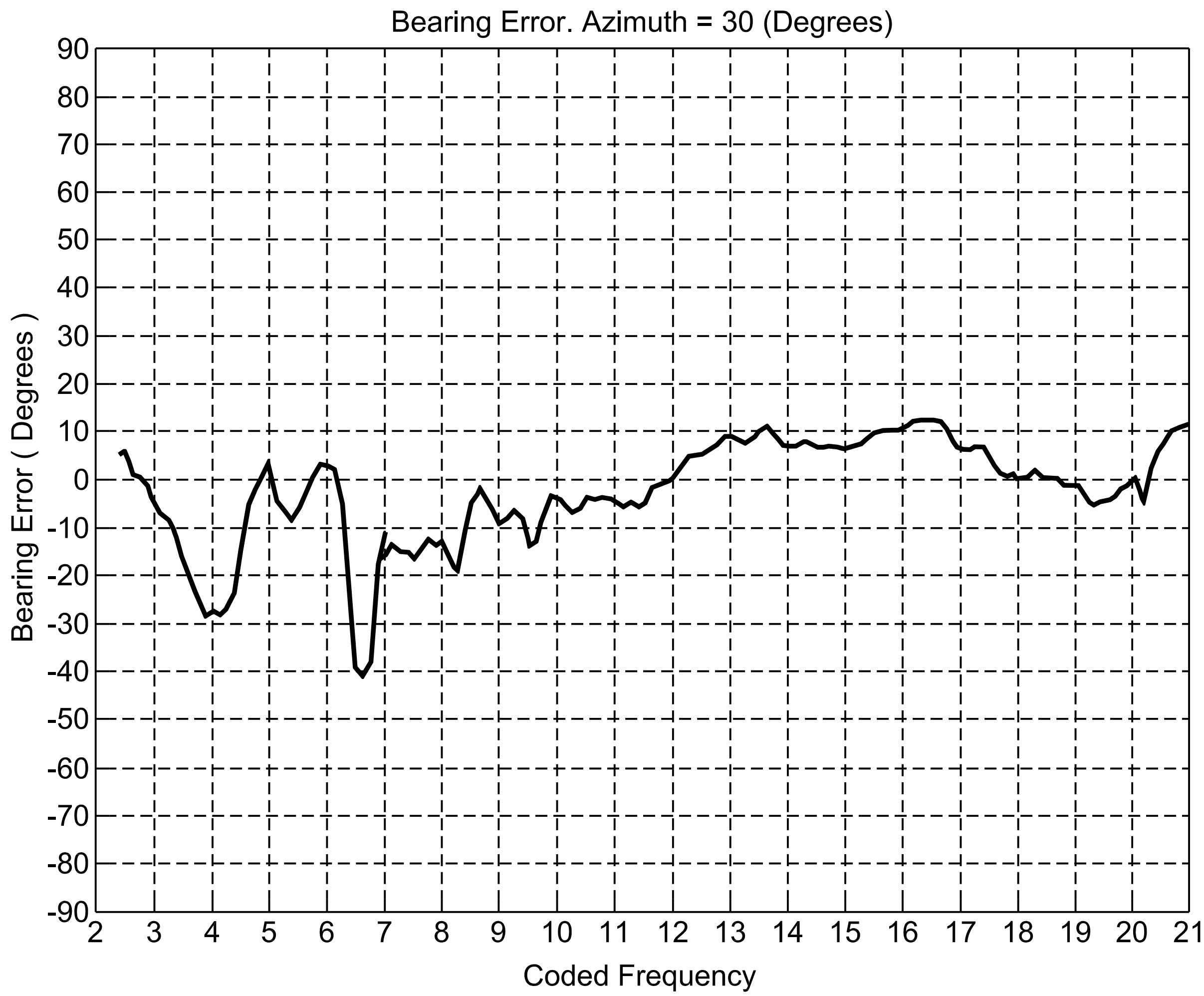
18
19
20
21
Coded Frequency

FIG. 1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Bearing Error (Degrees)
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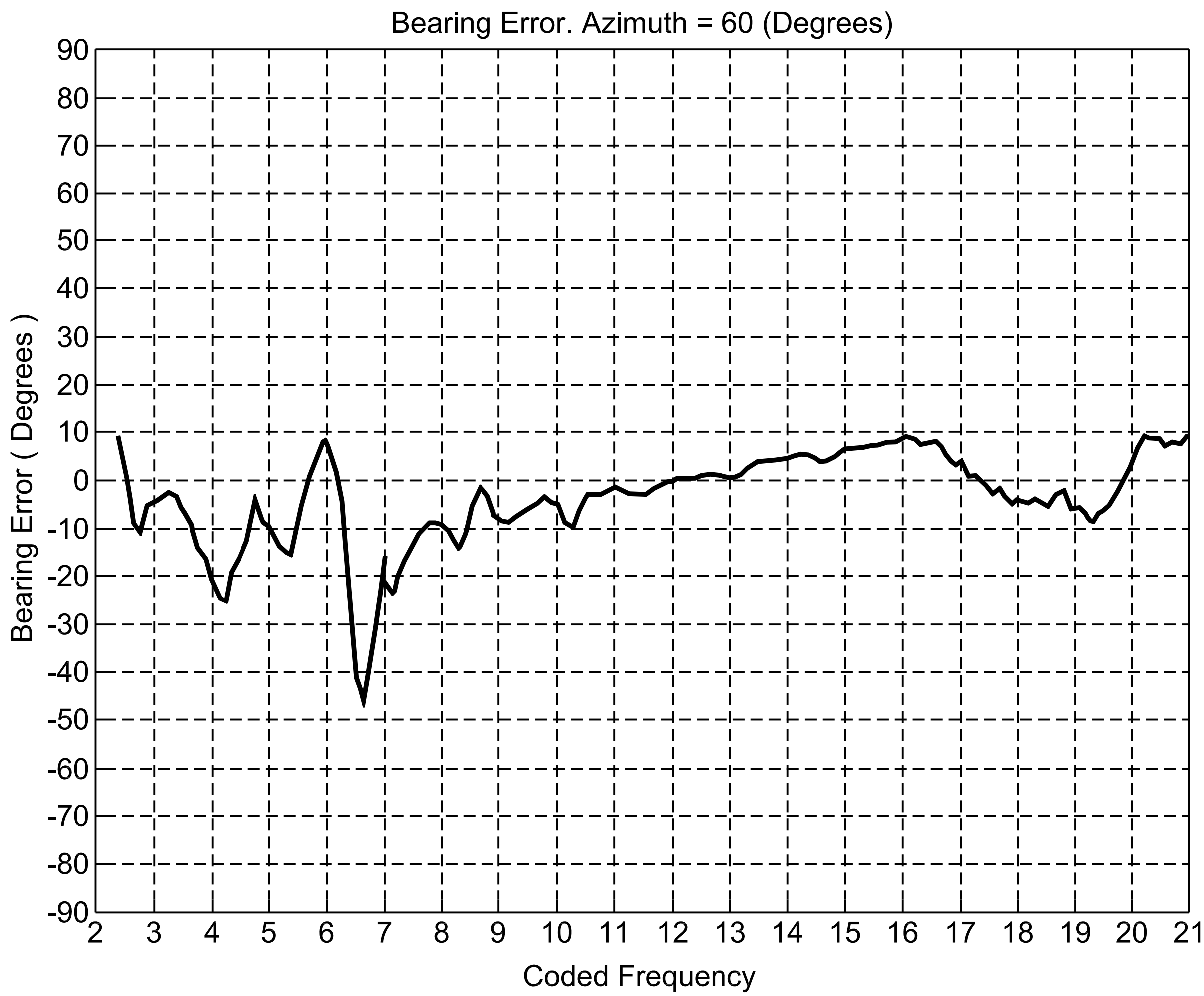
-60
-70
-80
-90
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Coded Frequency

FIG. 2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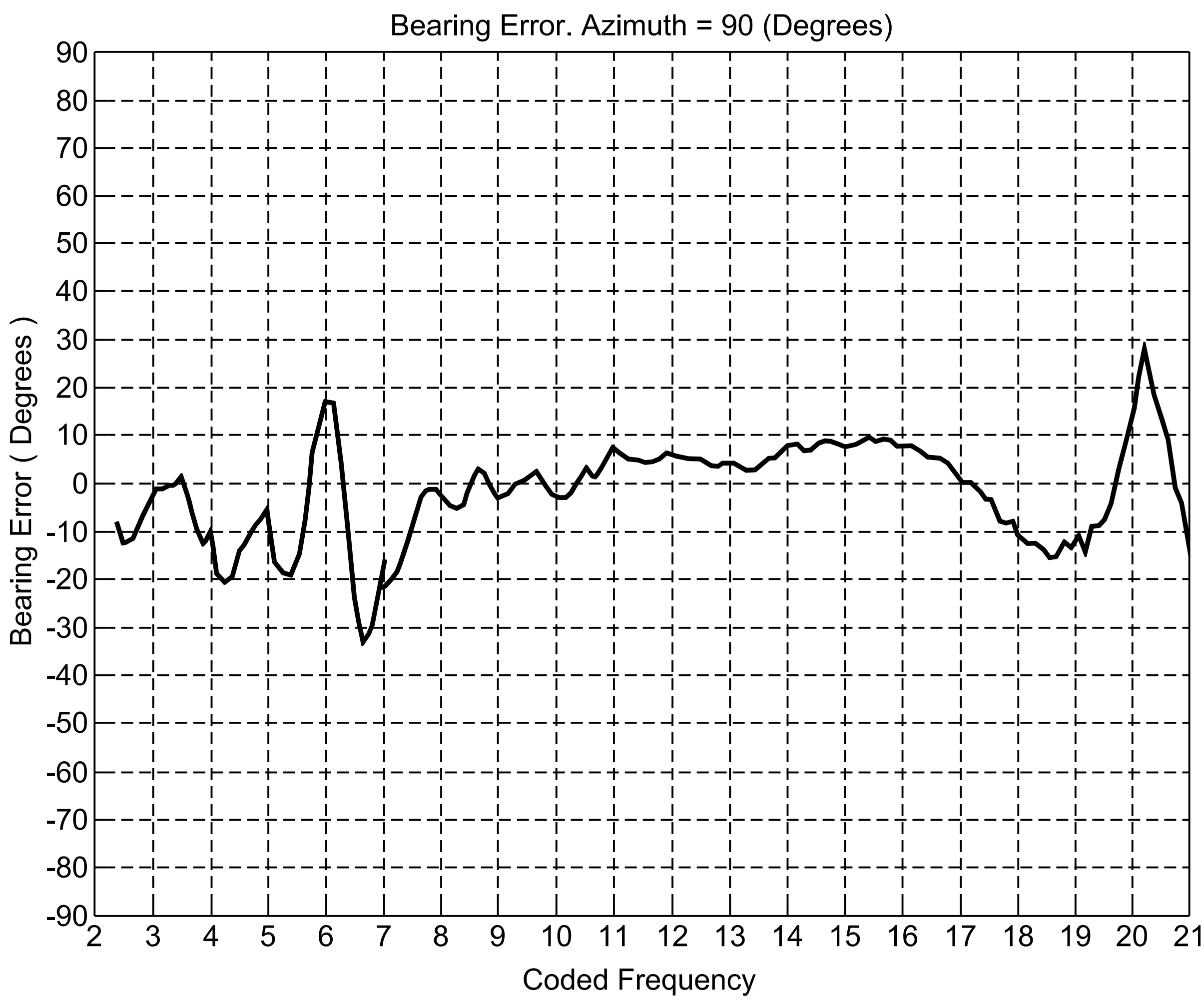
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 3



Bearing Error. Azimuth = 90 (Degrees)
Bearing Error (Degrees)
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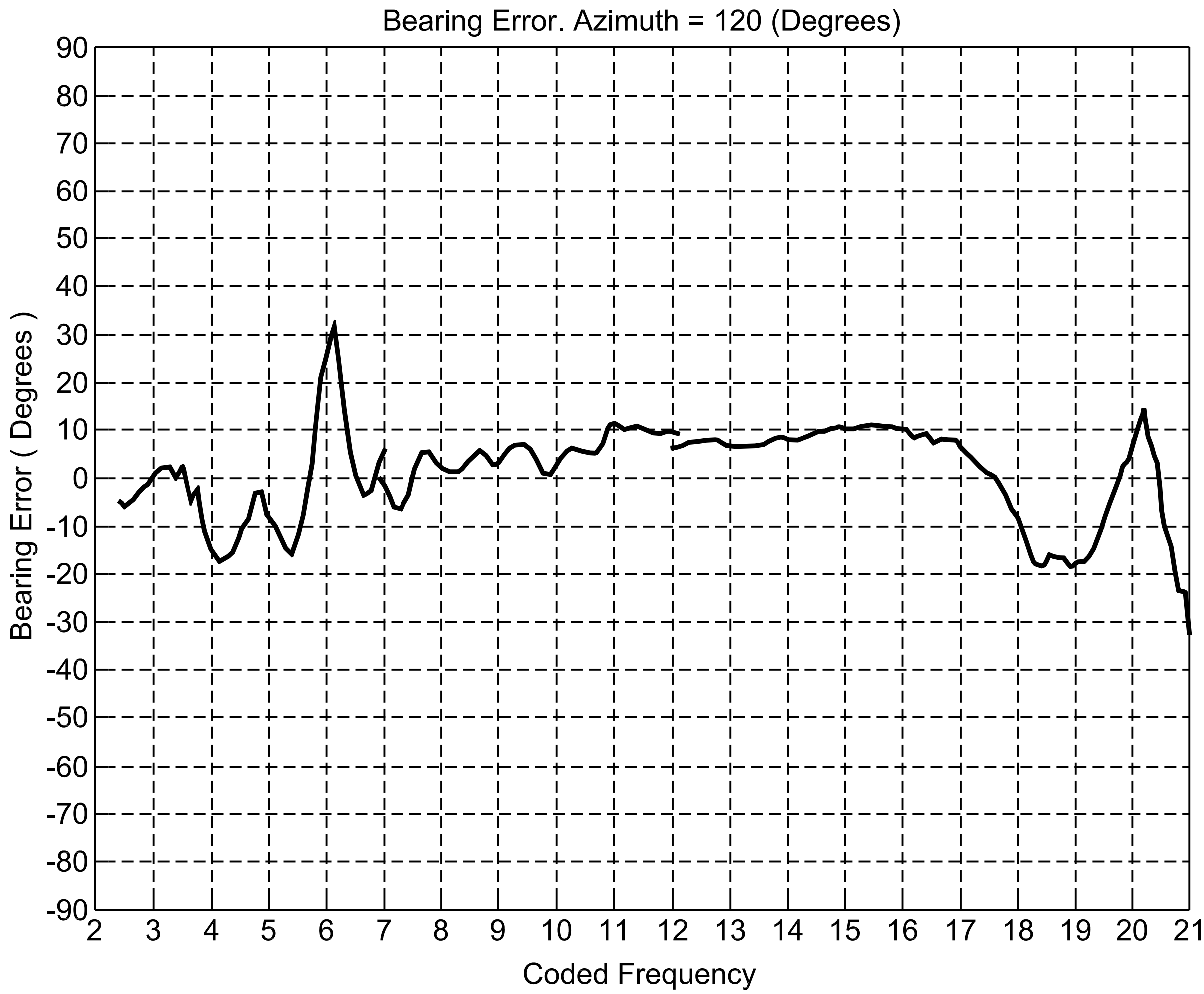
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Coded Frequency

FIG. 4



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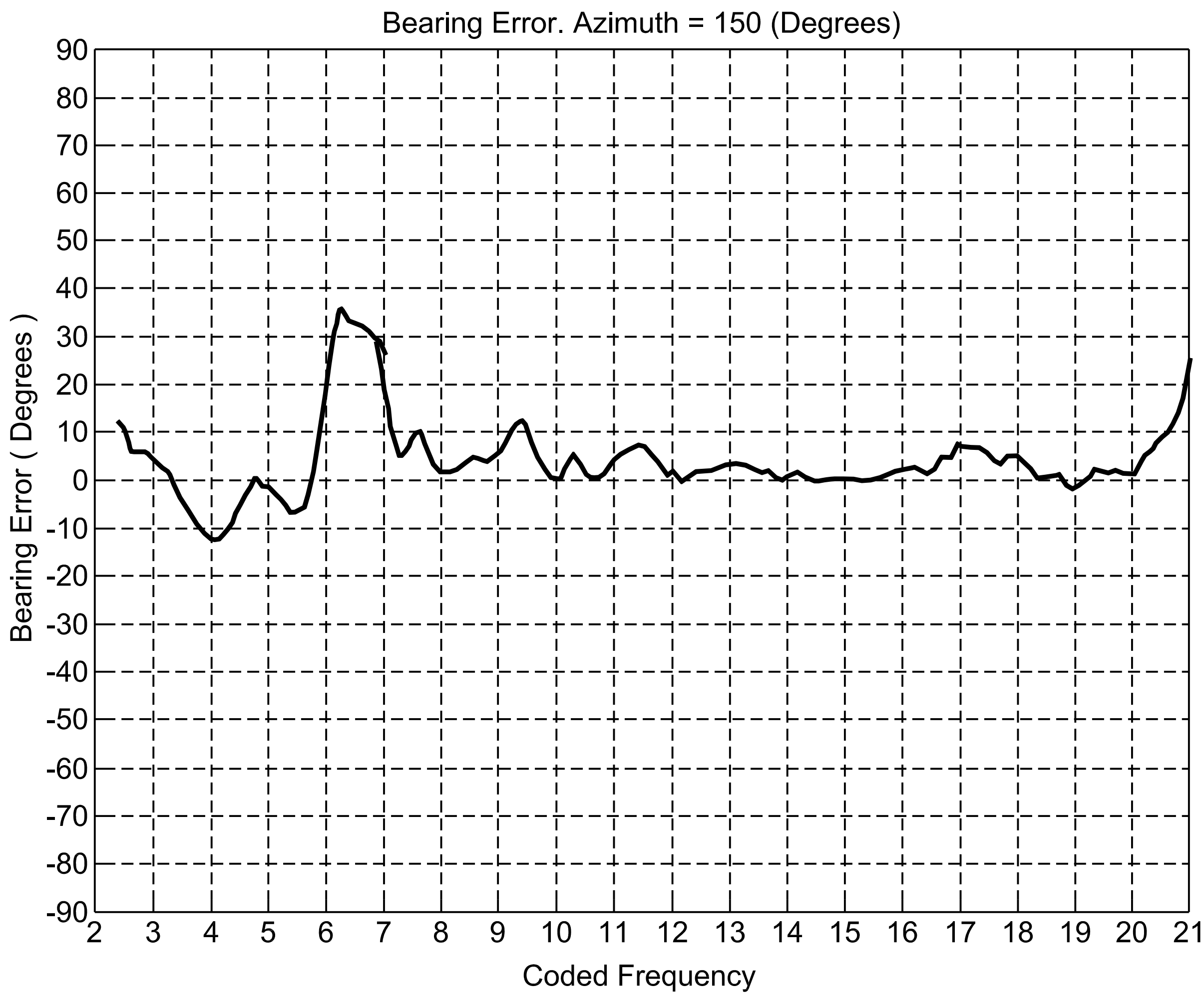
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
Bearing Error (Degrees)
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 5



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30
20
10
0
-10
-20
-30
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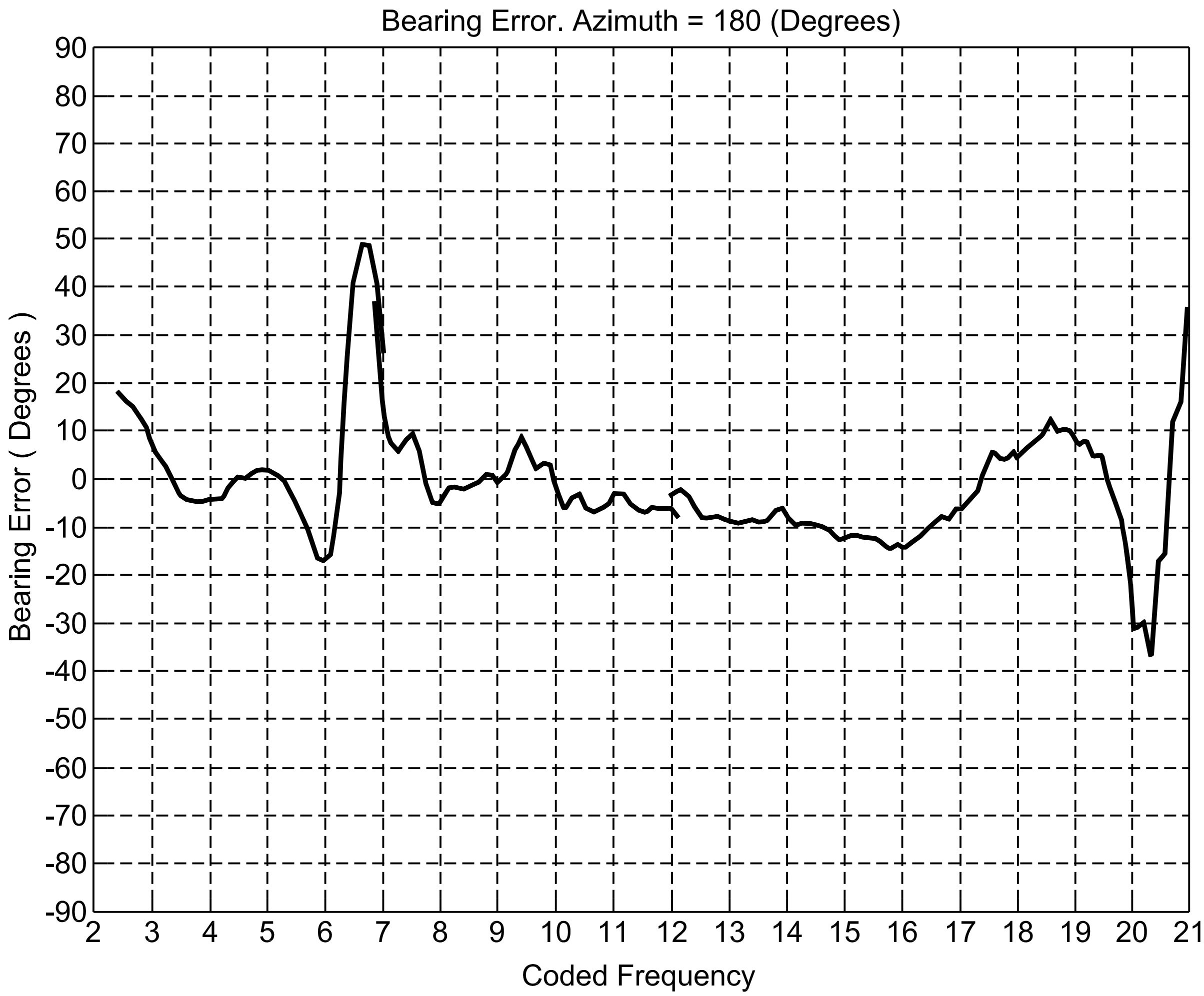
-60
-70
-80
-90
Bearing Error (Degrees)
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 6



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Bearing Error (Degrees)
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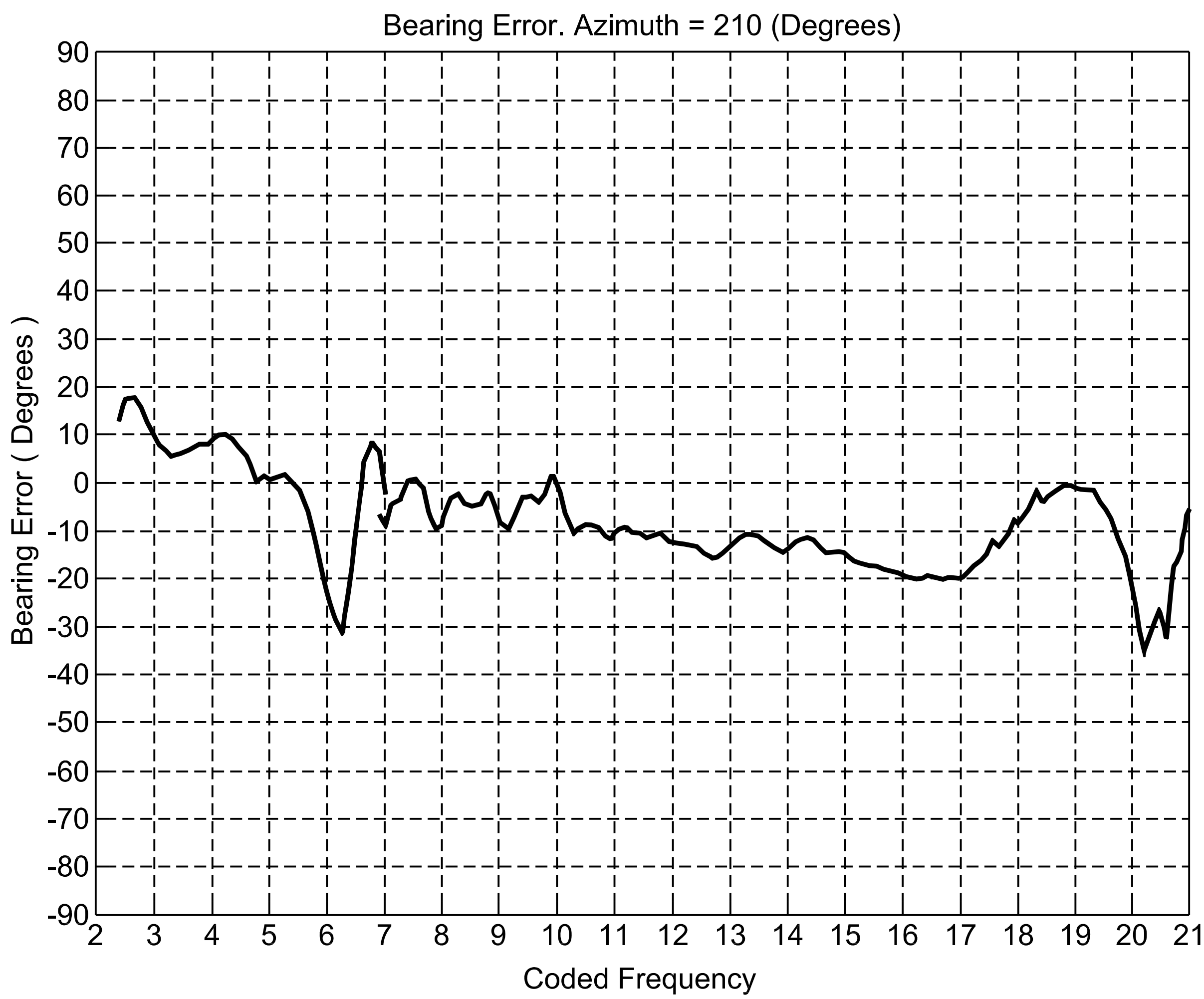
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 7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Bearing Error (Degrees)
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-70
-80
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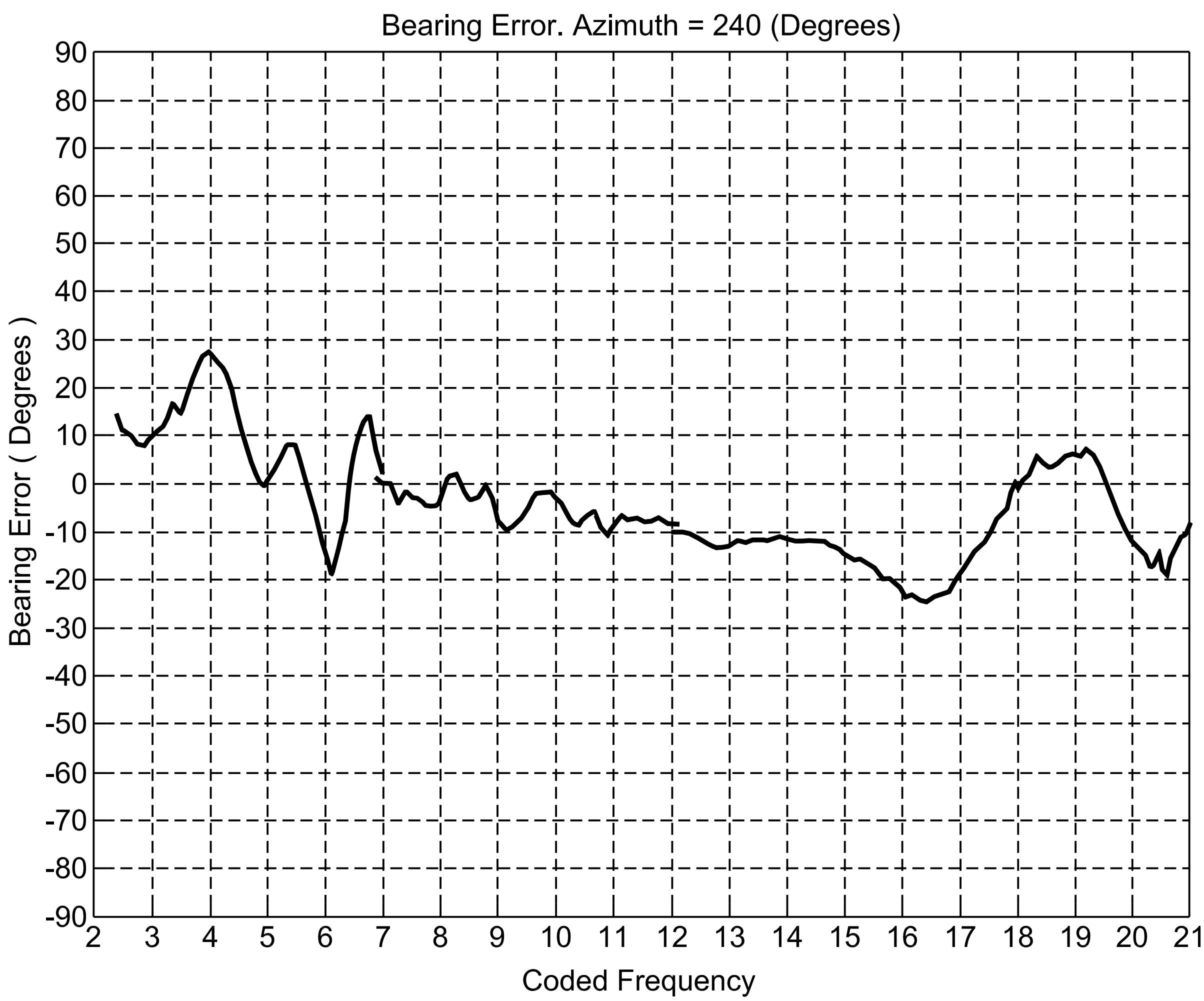
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 8



Bearing Error. Azimuth = 240 (Degrees)
Bearing Error (Degrees)
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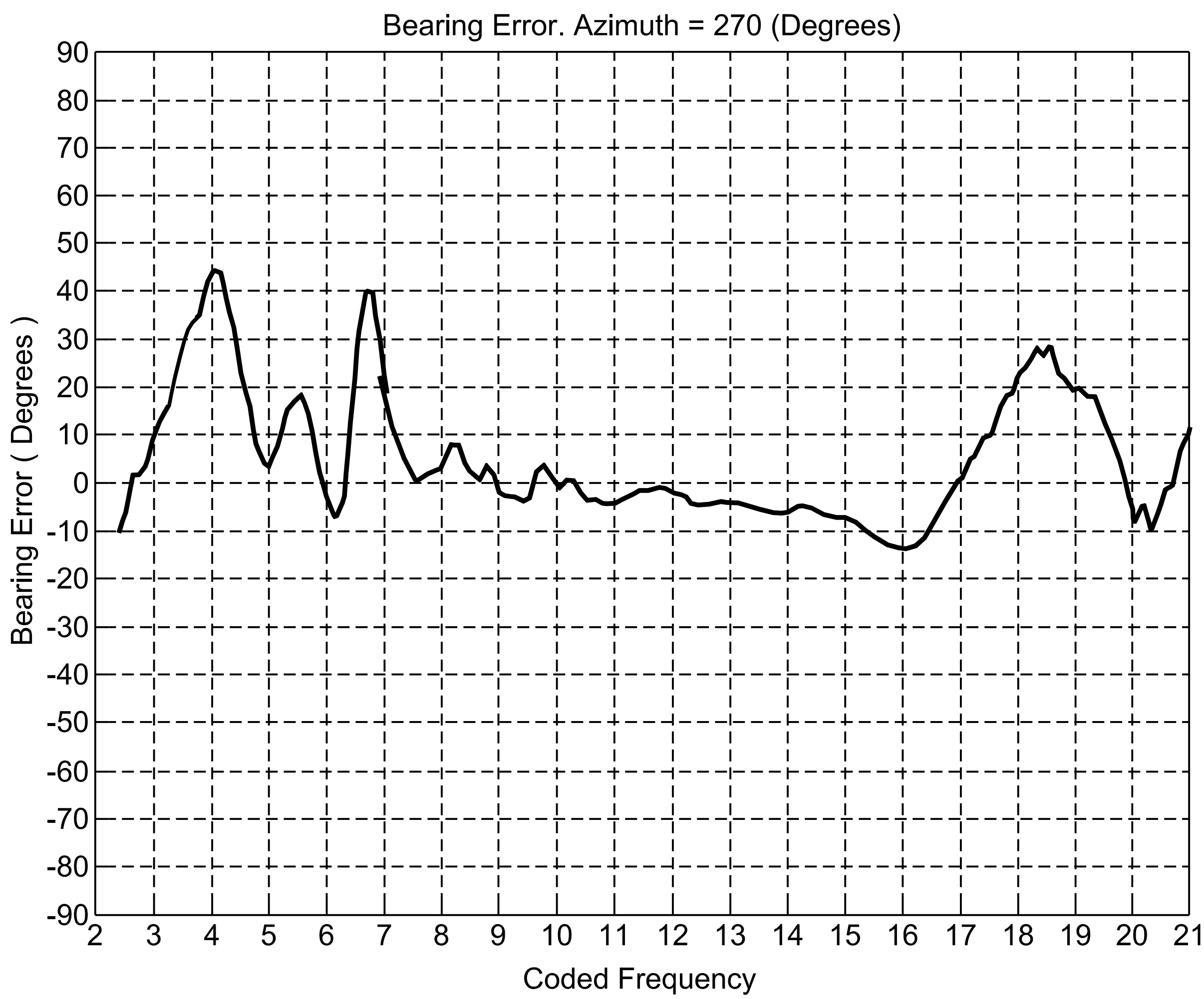
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Coded Frequency

FIG. 9



Bearing Error. Azimuth = 270 (Degrees)
Bearing Error (Degrees)
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60
50
40
30
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10
0
-10
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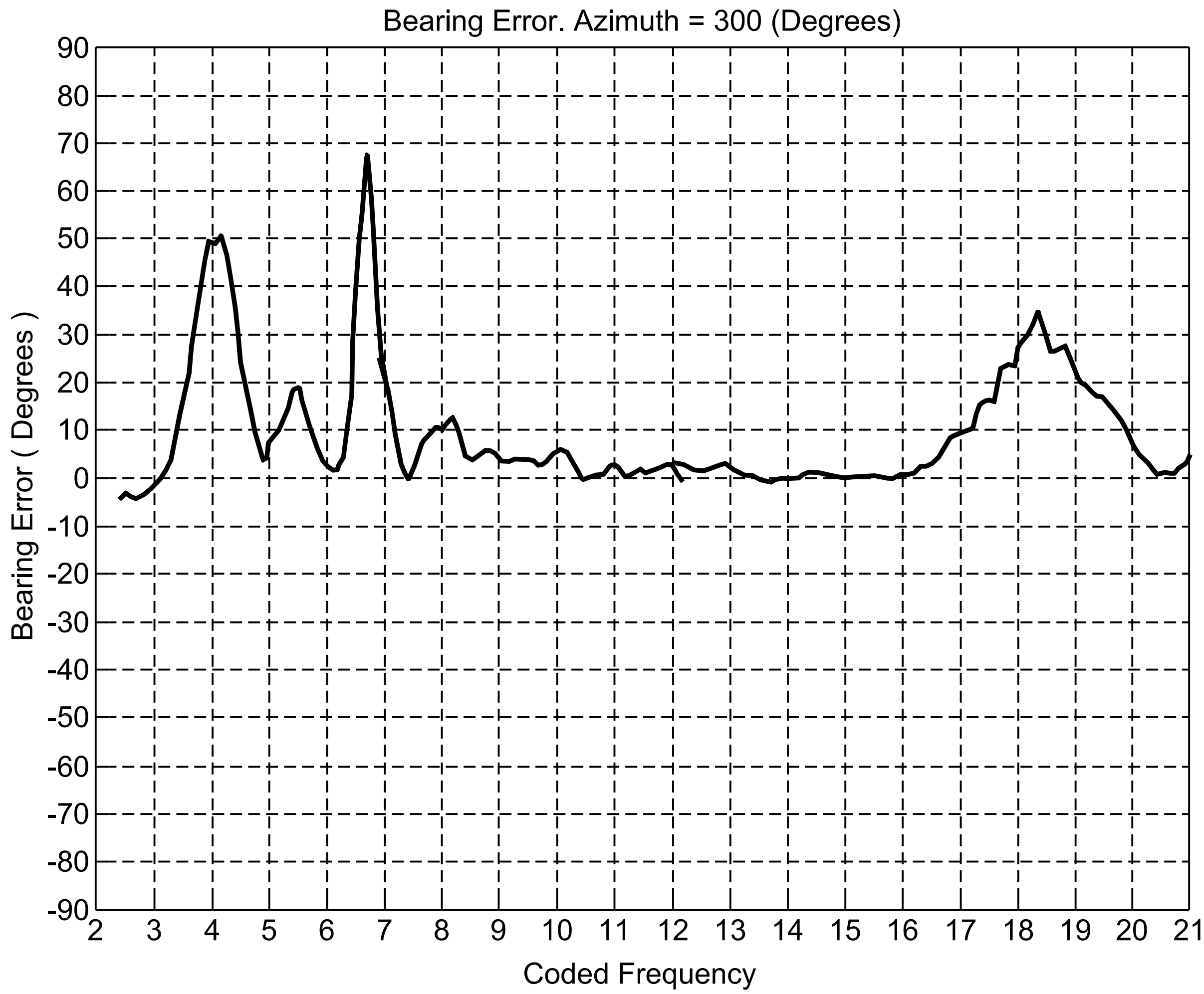
-60
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 10



Bearing Error. Azimuth = 300 (Degrees)
Bearing Error (Degrees)
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80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 11

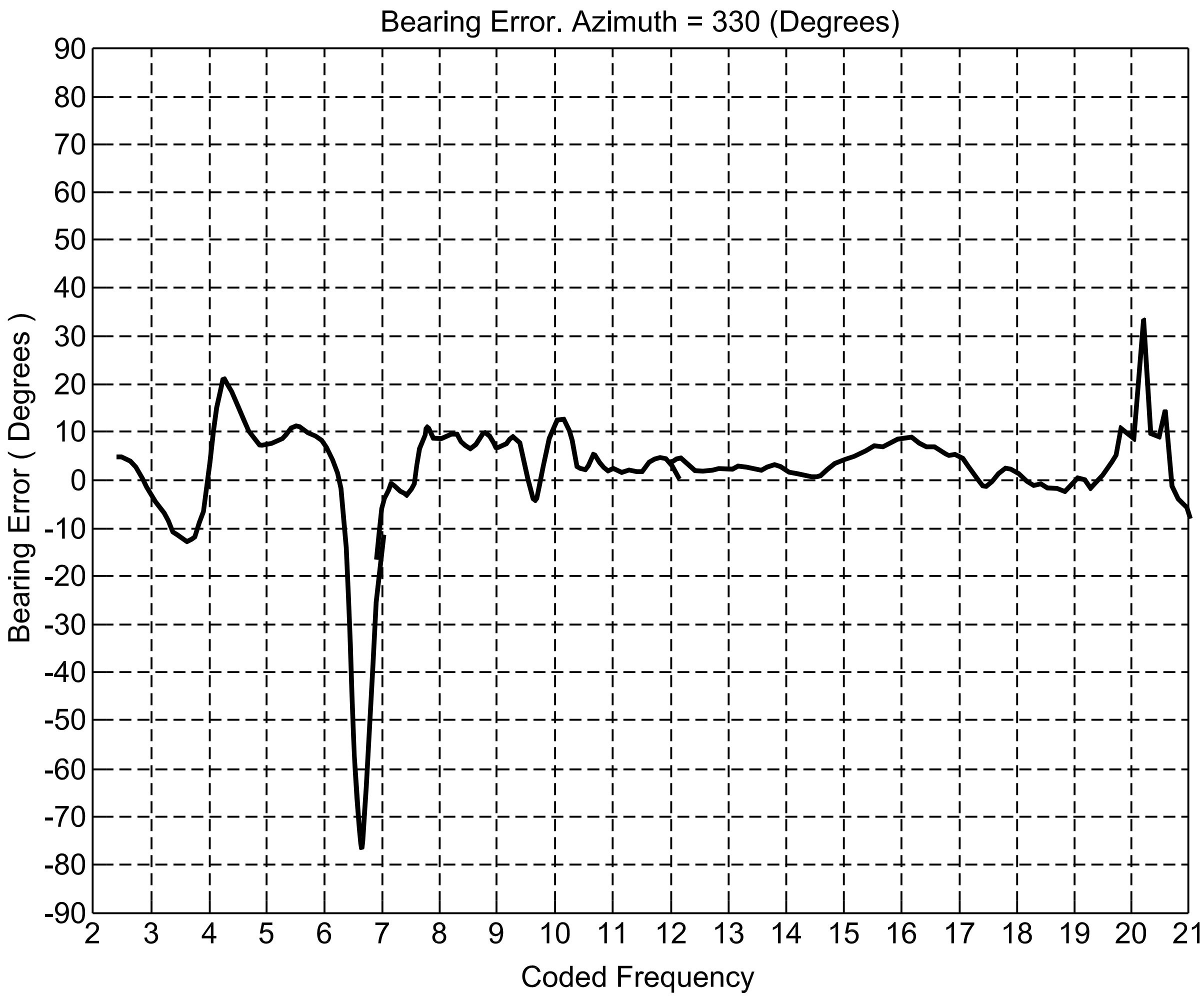

Bearing Error. Azimuth = 330 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Coded Frequency

FIG. 12

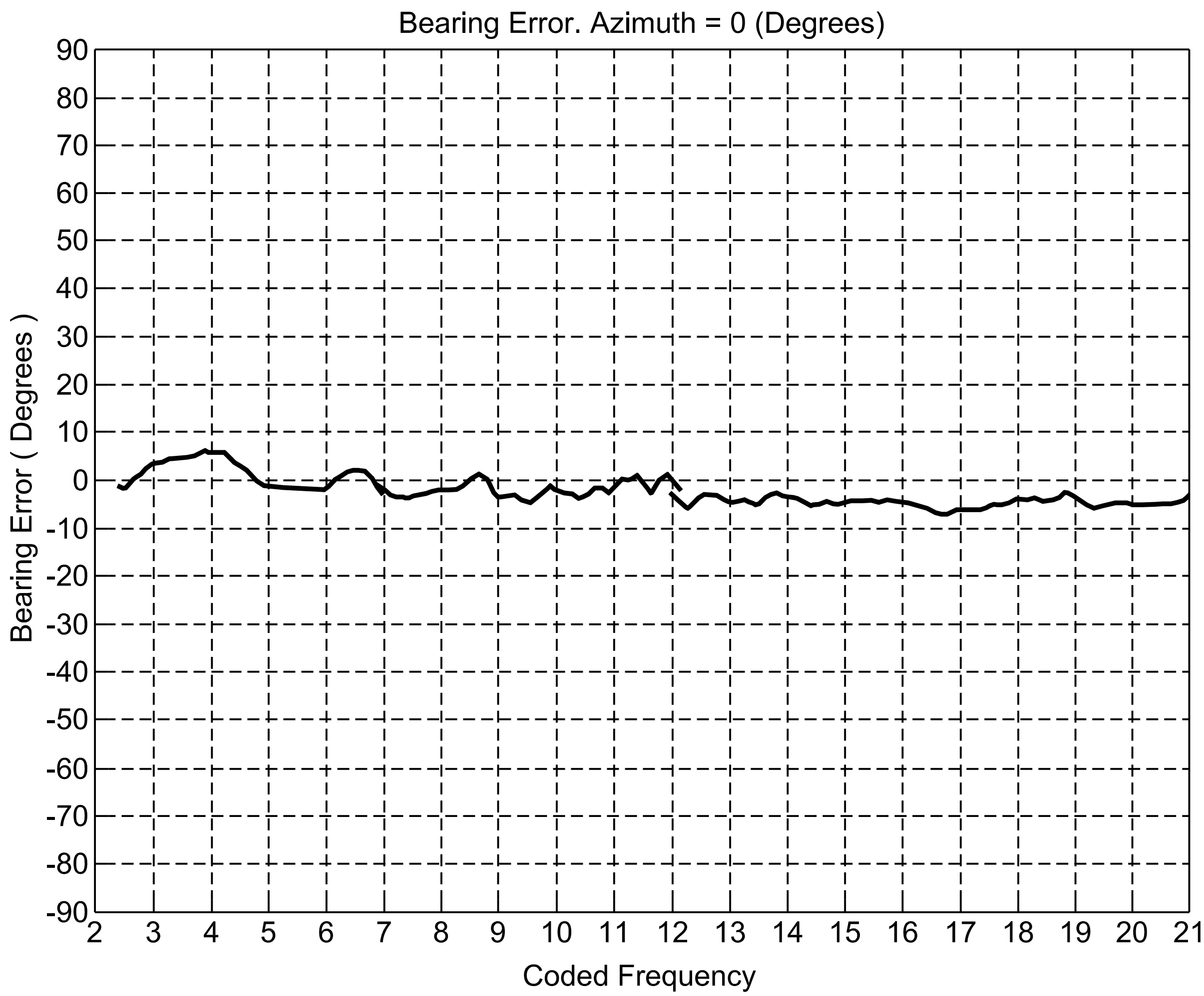
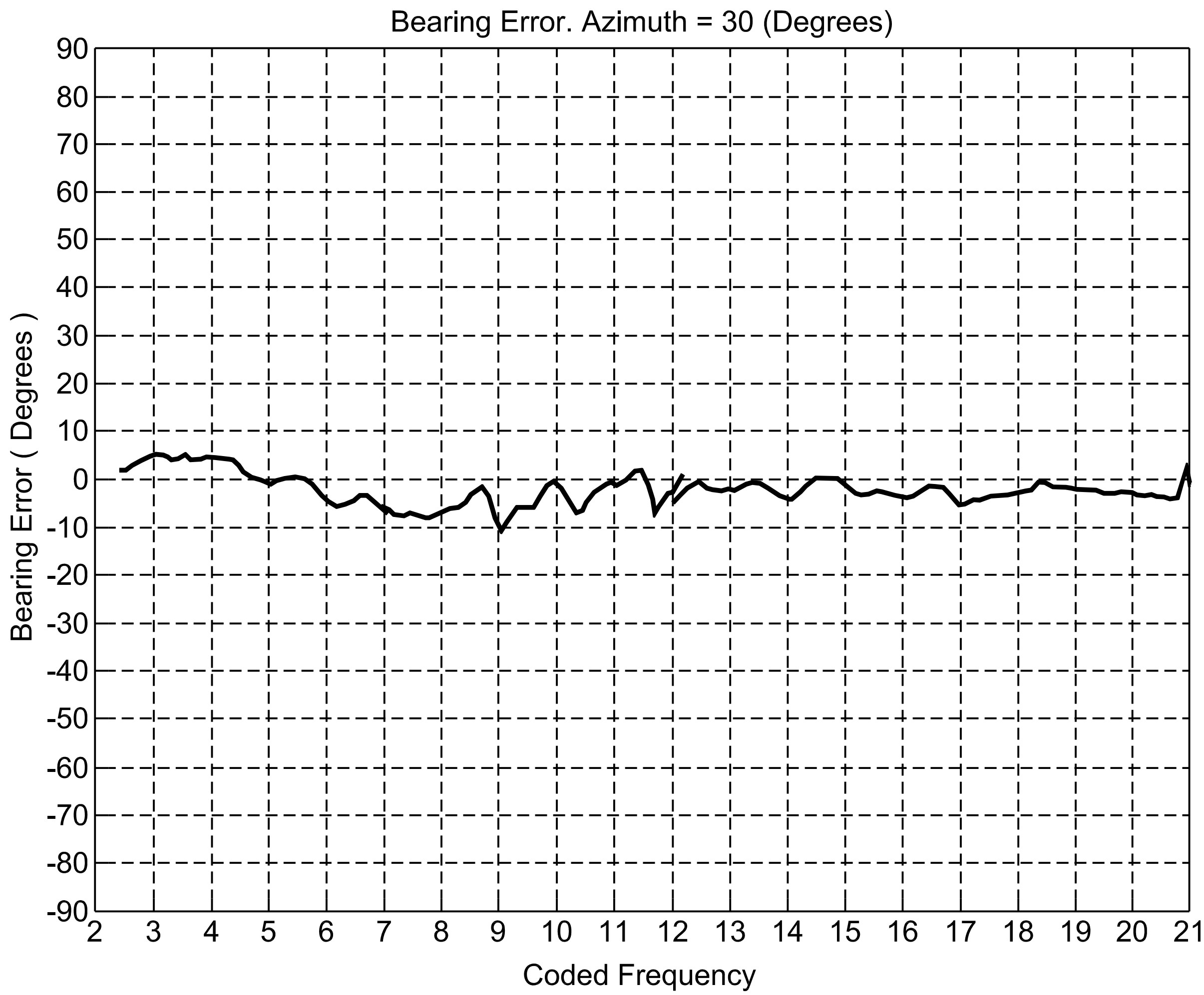
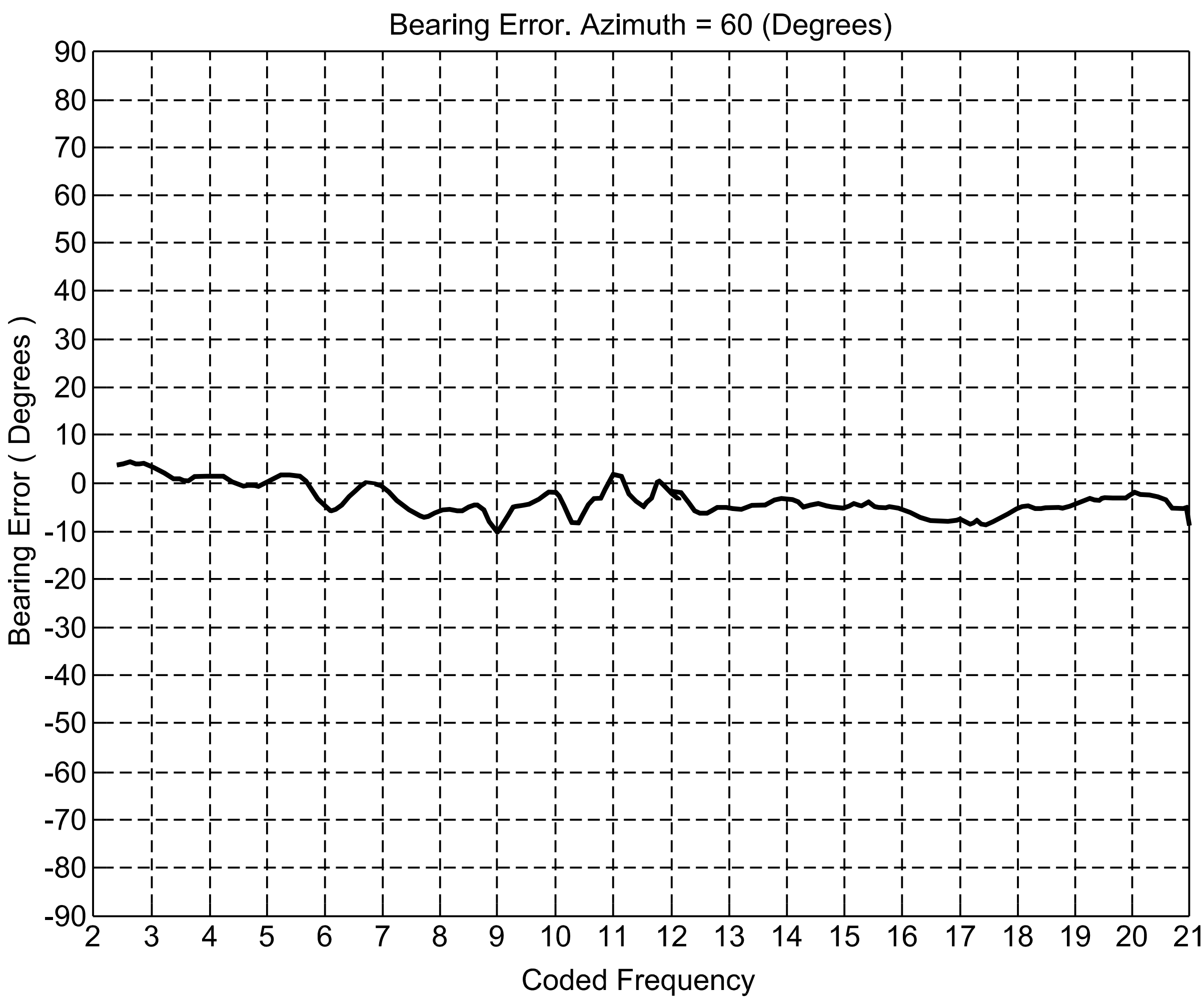

Bearing Error. Azimuth = 0 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 13



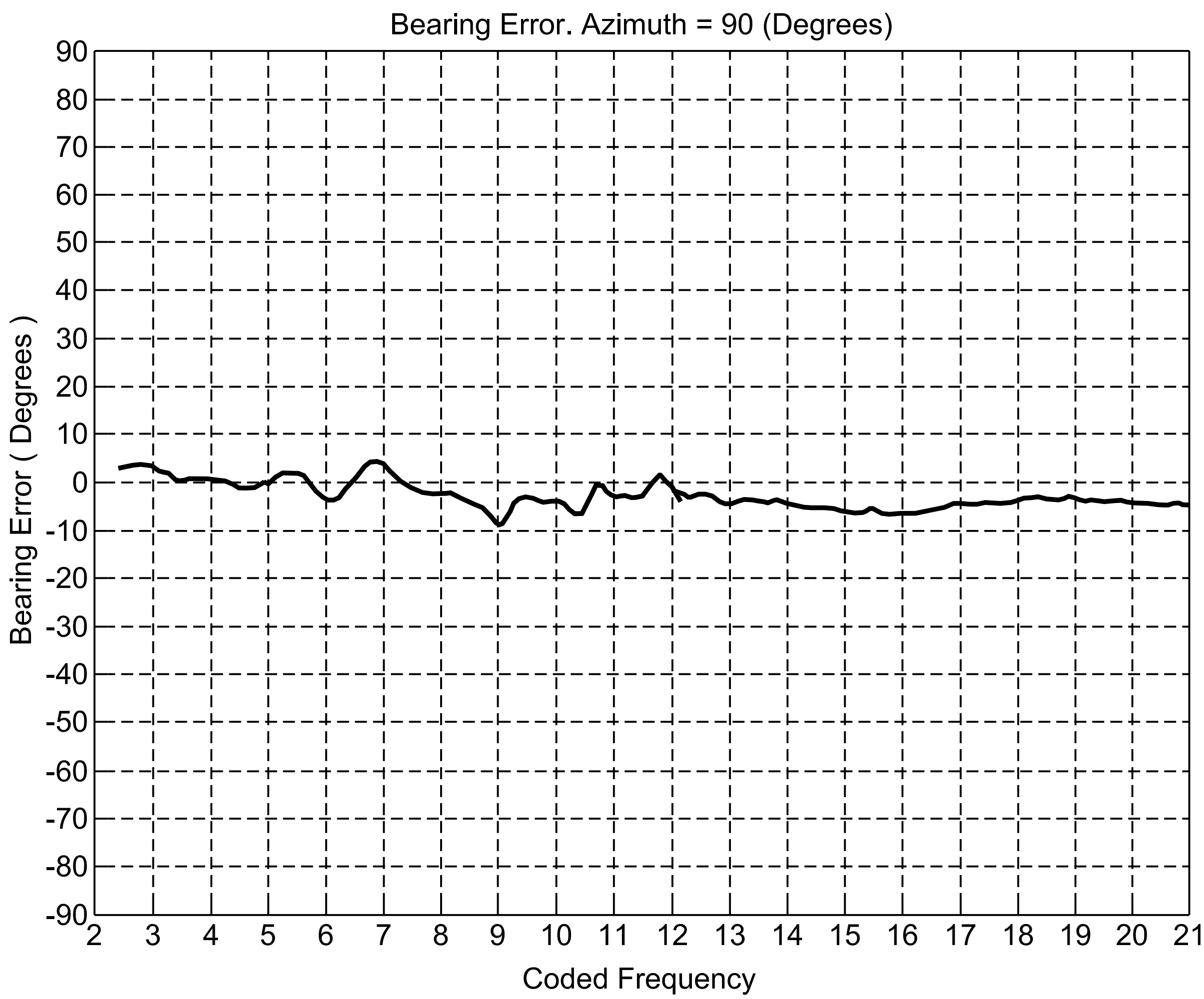
Bearing Error. Azimuth = 30 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 14



Bearing Error. Azimuth = 60 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 15



Bearing Error. Azimuth = 90 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 16

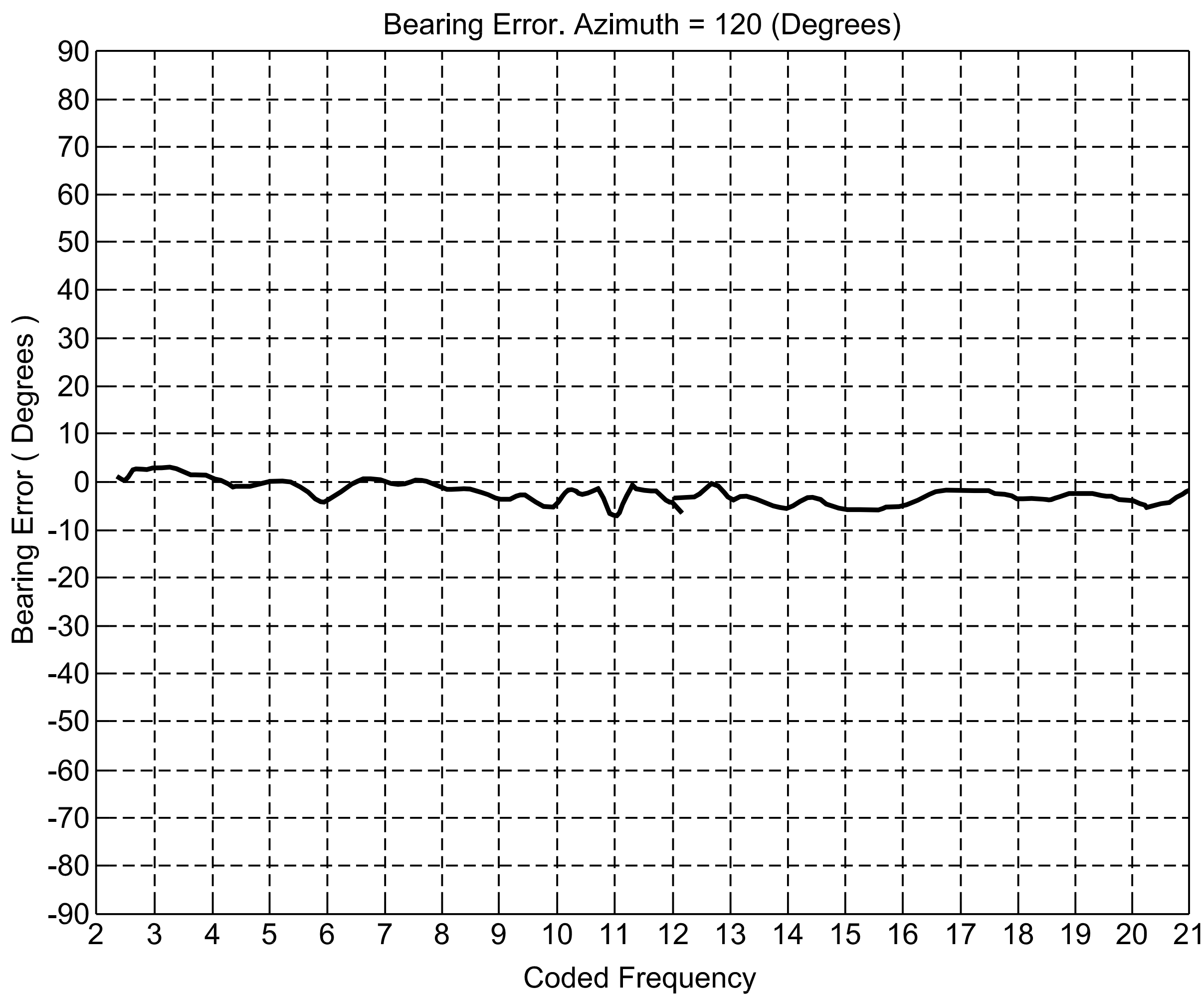

Bearing Error. Azimuth = 120 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 17

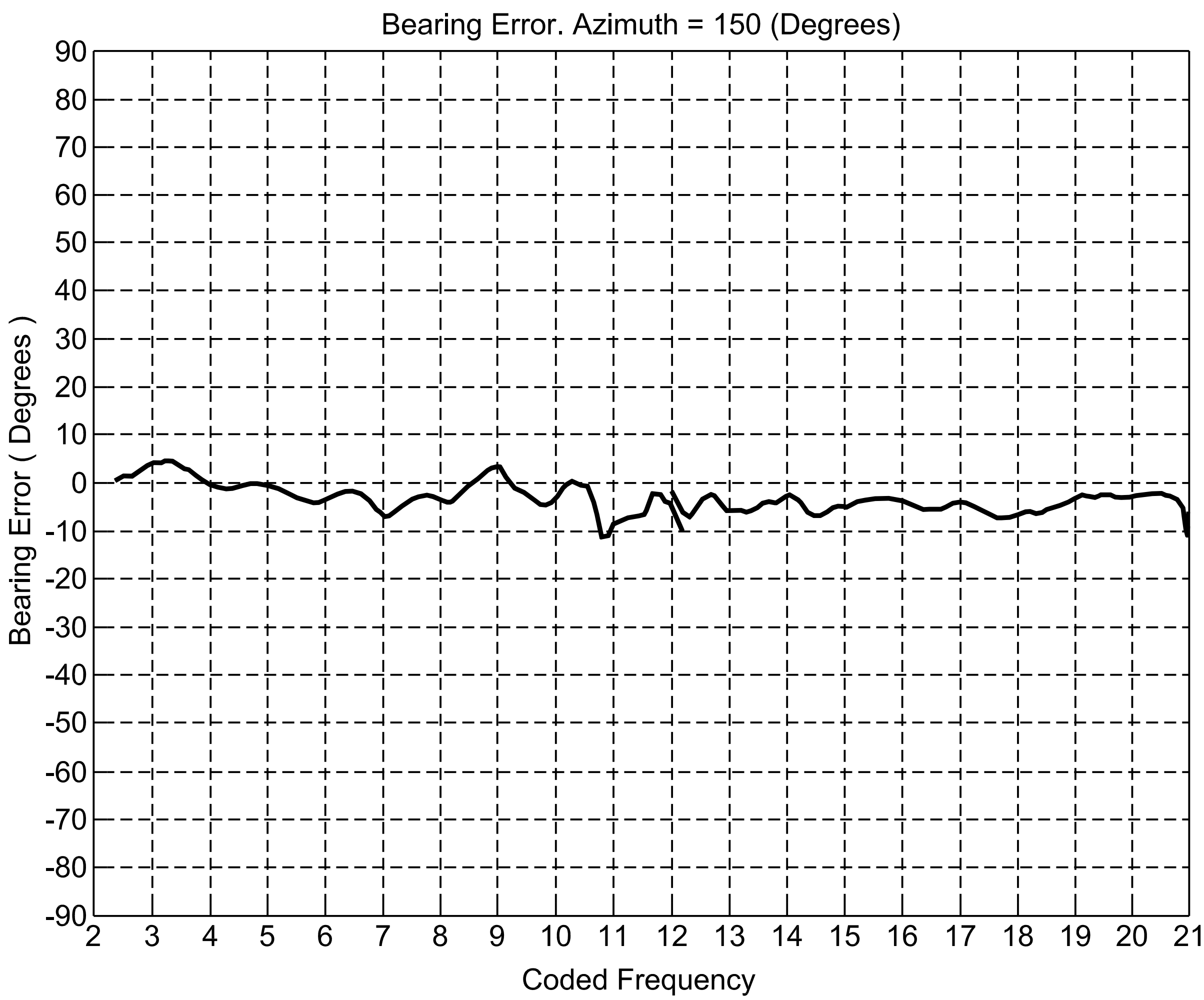
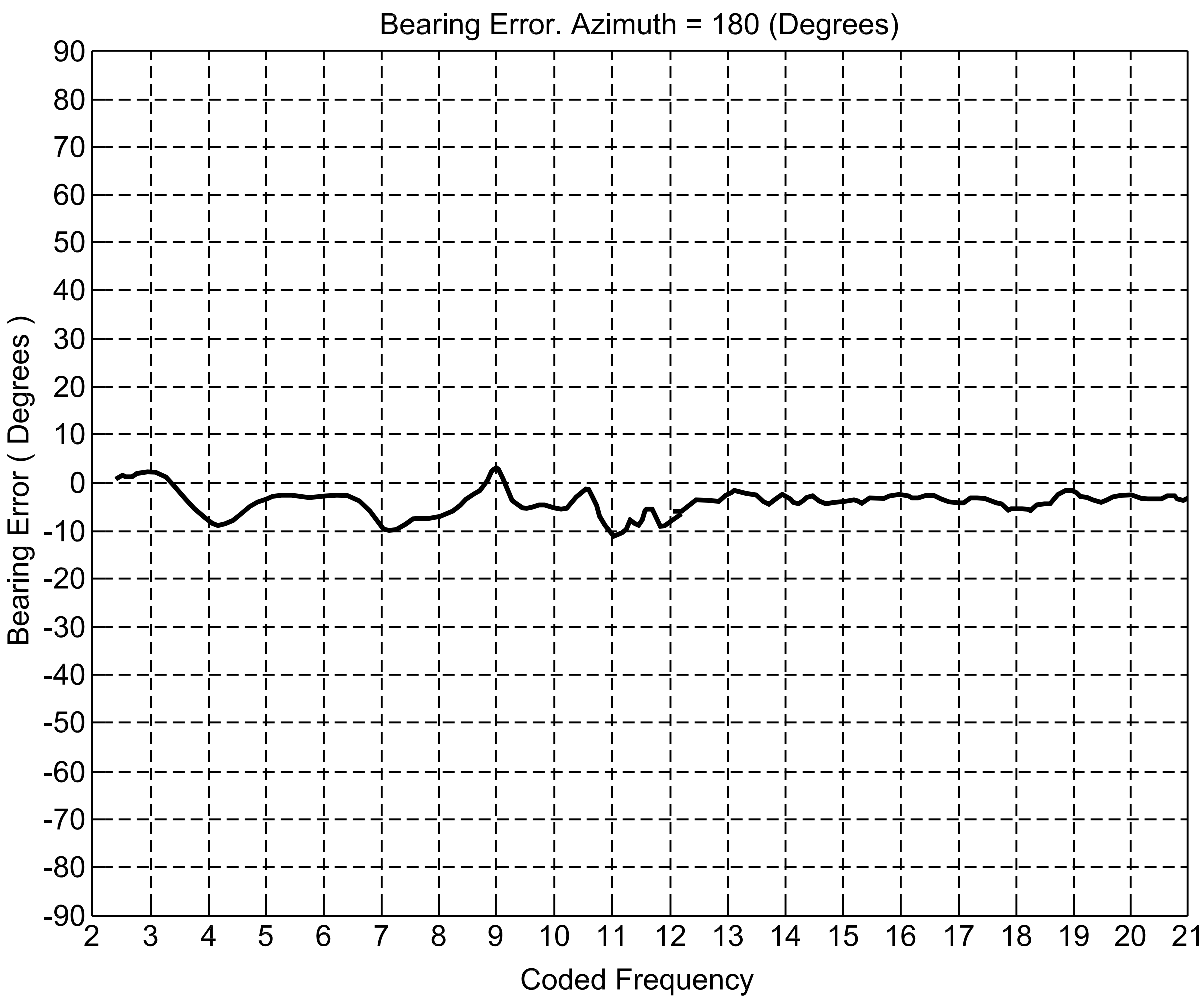
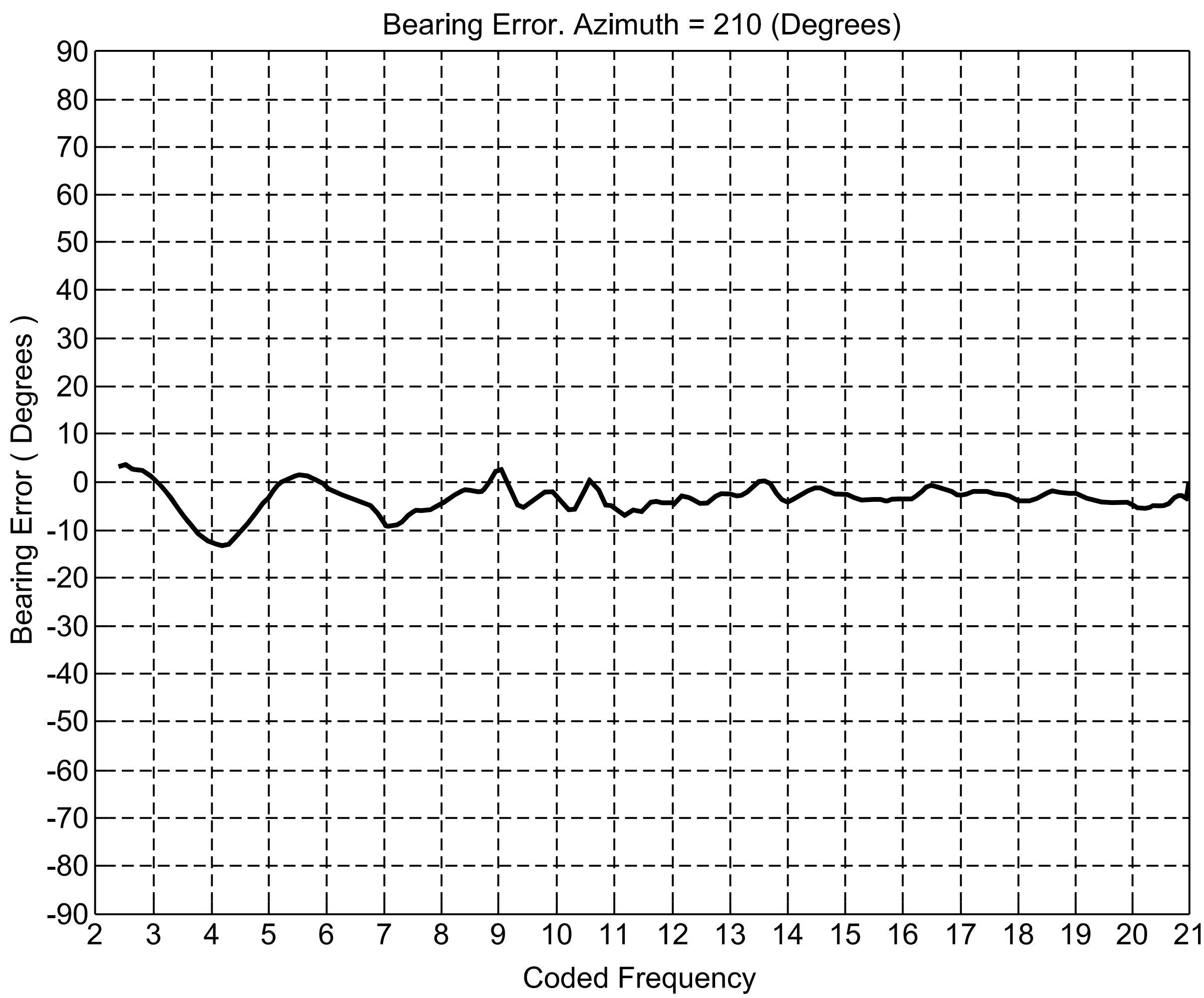

Bearing Error. Azimuth = 150 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 18



Bearing Error. Azimuth = 180 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 19



Bearing Error. Azimuth = 210 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
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6
7
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9
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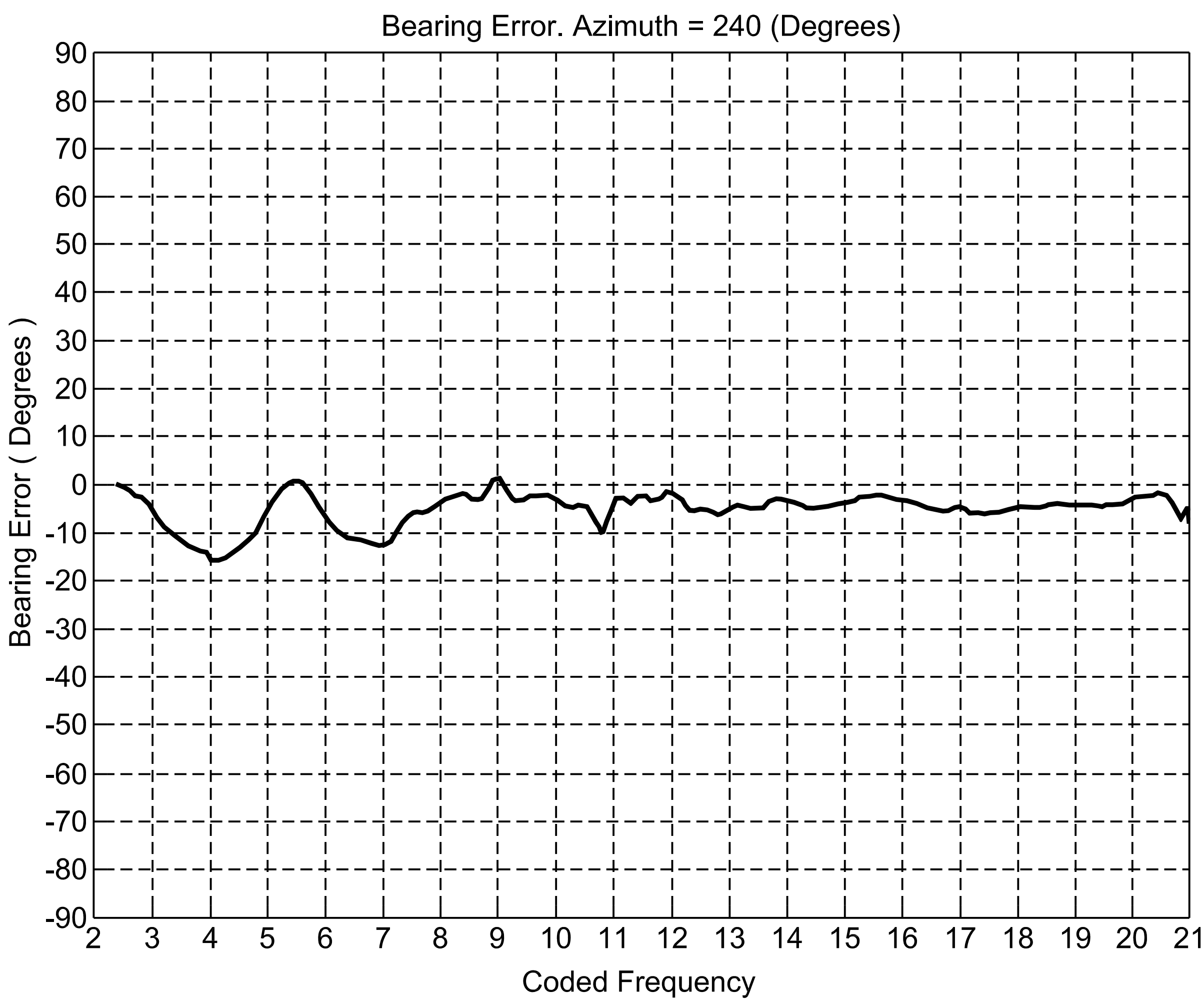
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 20


Bearing Error. Azimuth = 240 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
5
6
7
8
9
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11
12
13
14
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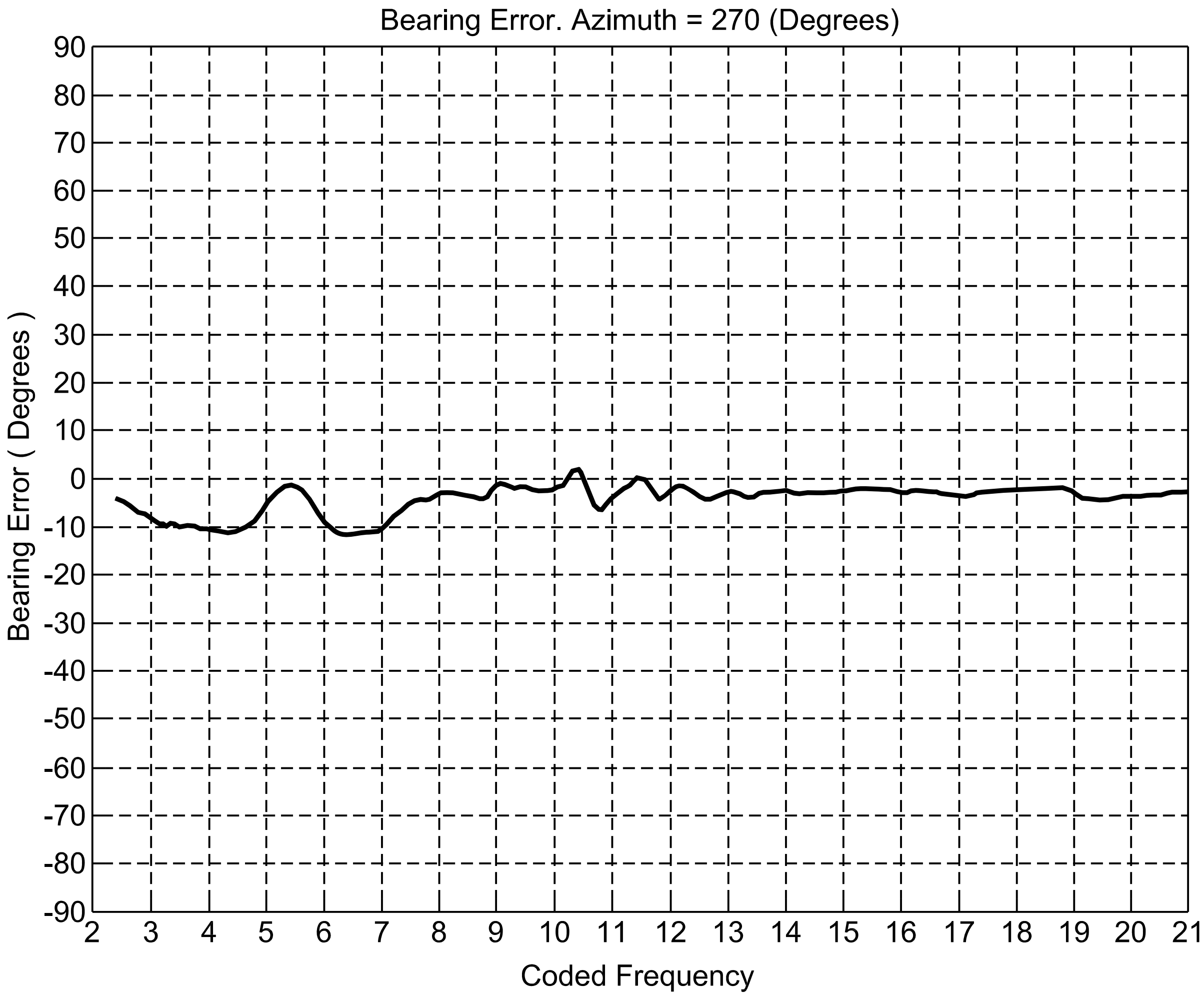
16
17
18
19
20
21
Coded Frequency

FIG. 21



Bearing Error. Azimuth = 270 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
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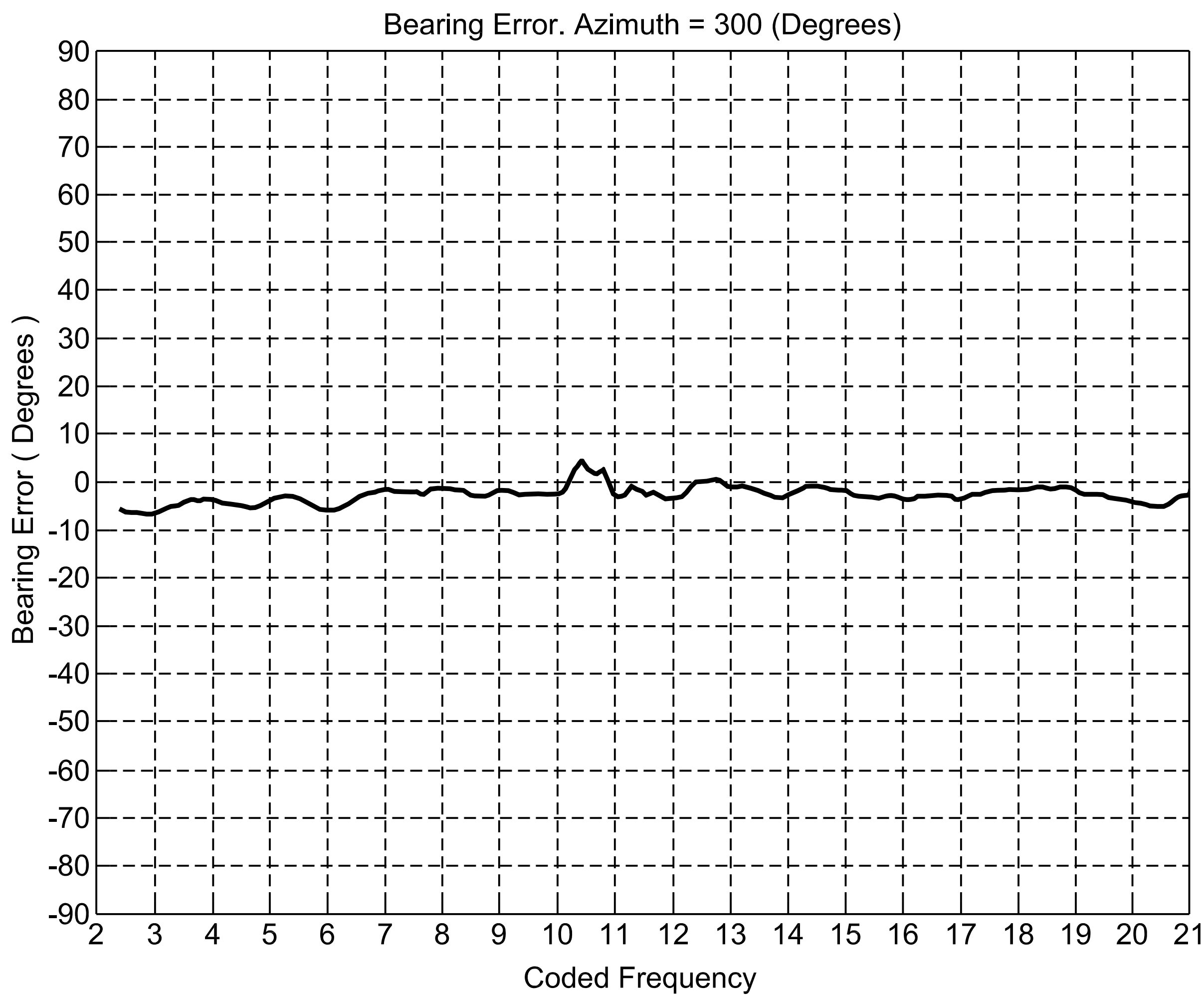
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 22



Bearing Error. Azimuth = 300 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
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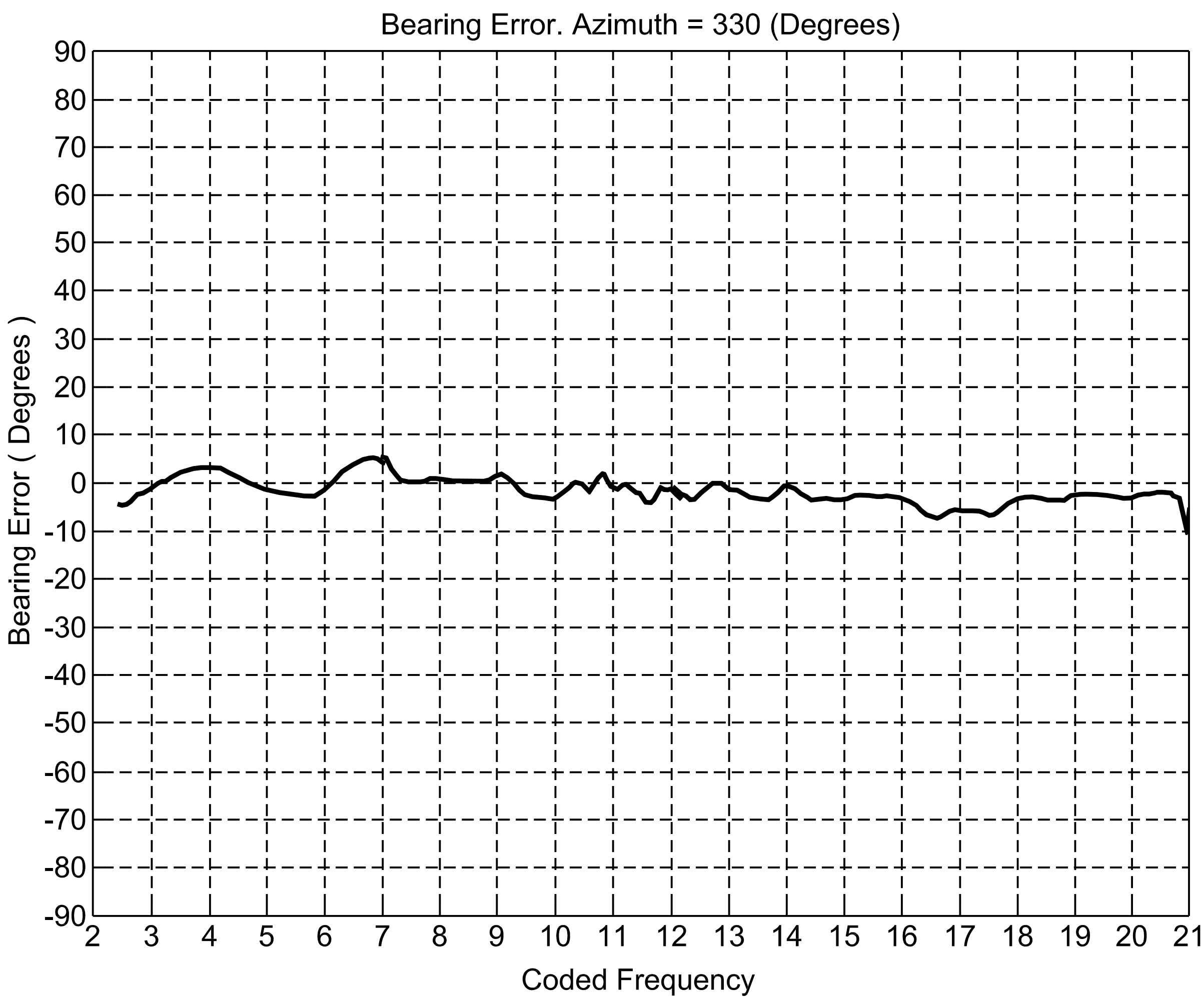
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 23


Bearing Error. Azimuth = 330 (Degrees)
Bearing Error (Degrees)
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
2
3
4
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6
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11
12
13
14
15
16
17
18
19
20
21
Coded Frequency

FIG. 24

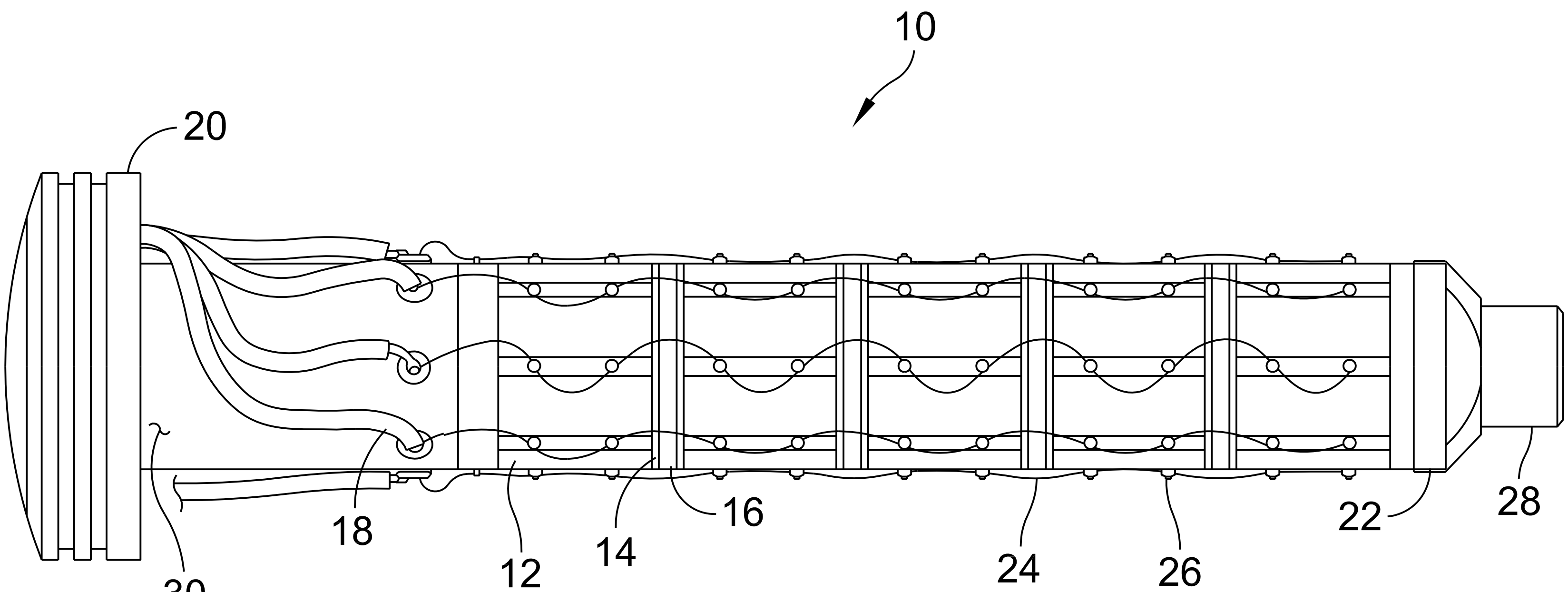

FIG. 25
(PRIOR ART)

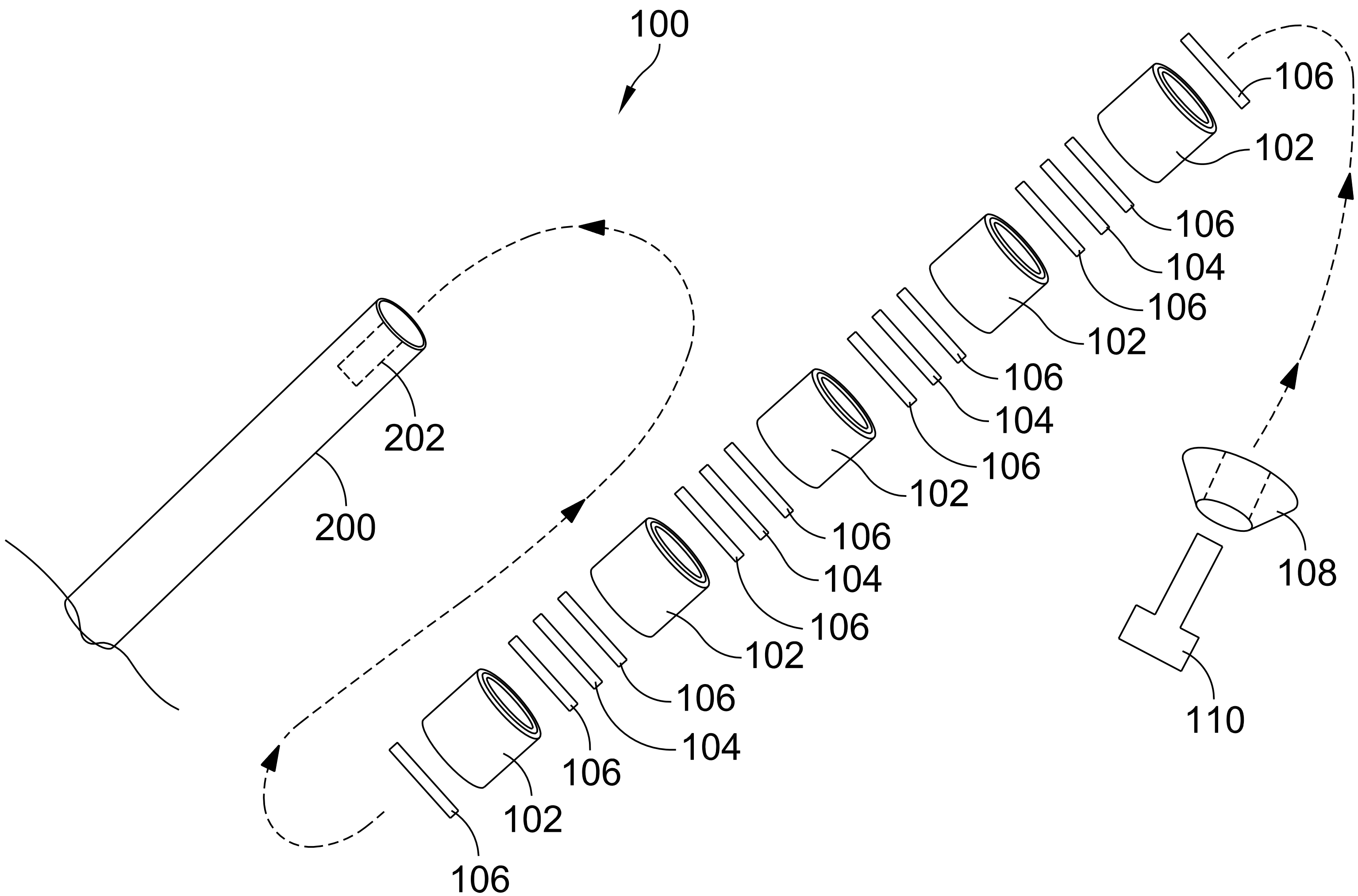
100
106
102
106
104
106
102
106
104
106
102
106
104
106
102
106
104
106
102
106
108
110
202
200

FIG. 26

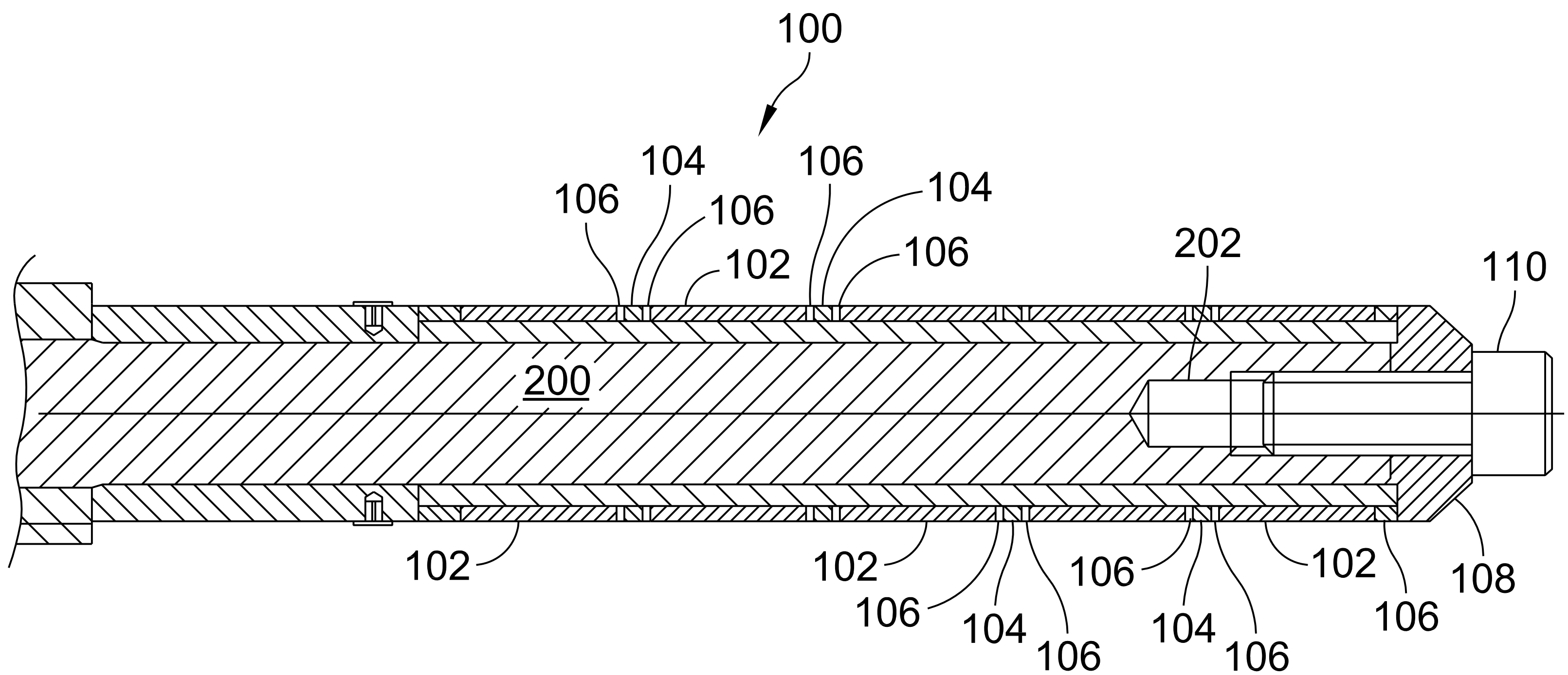
100
106
104
106
102
106
104
106
202
110
200
102
102
106
104
106
106
104
106
102
106
108

FIG. 27