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Benjauthrit

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(54) BEAM WAVEGUIDE ANTENNA WITH INDEPENDENTLY STEERABLE ANTENNA BEAMS AND METHOD OF COMPENSATING FOR PLANETARY ABERRATION IN ANTENNA BEAM TRACKING OF SPACECRAFT

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(51) **Int. Cl.**^{7} **H01Q 19/10**
(52) **U.S. Cl.** .... **343/839**; 343/761; 343/781 CA
(58) **Field of Search** .... 343/839, 761, 343/781 CA, 840, 837, 757, 758

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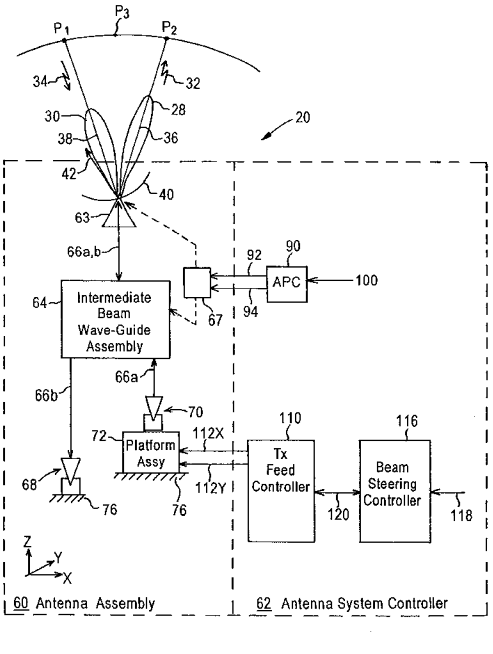
(57) ABSTRACT

An antenna assembly for forming and directing a transmit beam, and for controlling receive and transmit beam tracking of a spacecraft in the presence of planetary aberration. The assembly includes a main reflector, a sub-reflector centered along an optical axis of the main reflector, and a moveable transmit feed for directing electromagnetic radiation along a longitudinal axis thereof. The assembly also includes an intermediate beam waveguide assembly arranged between the moveable transmit feed and the main reflector, wherein the intermediate beam waveguide assembly includes fixed and moveable optical components for guiding electromagnetic beam energy between the moveable transmit feed and the main reflector. A beam steering mechanism is coupled with the moveable transmit feed for angularly displacing the transmit beam from the optical axis by displacing the moveable transmit feed in a direction substantially orthogonal to the longitudinal axis of the transmit feed.

9 Claims, 10 Drawing Sheets



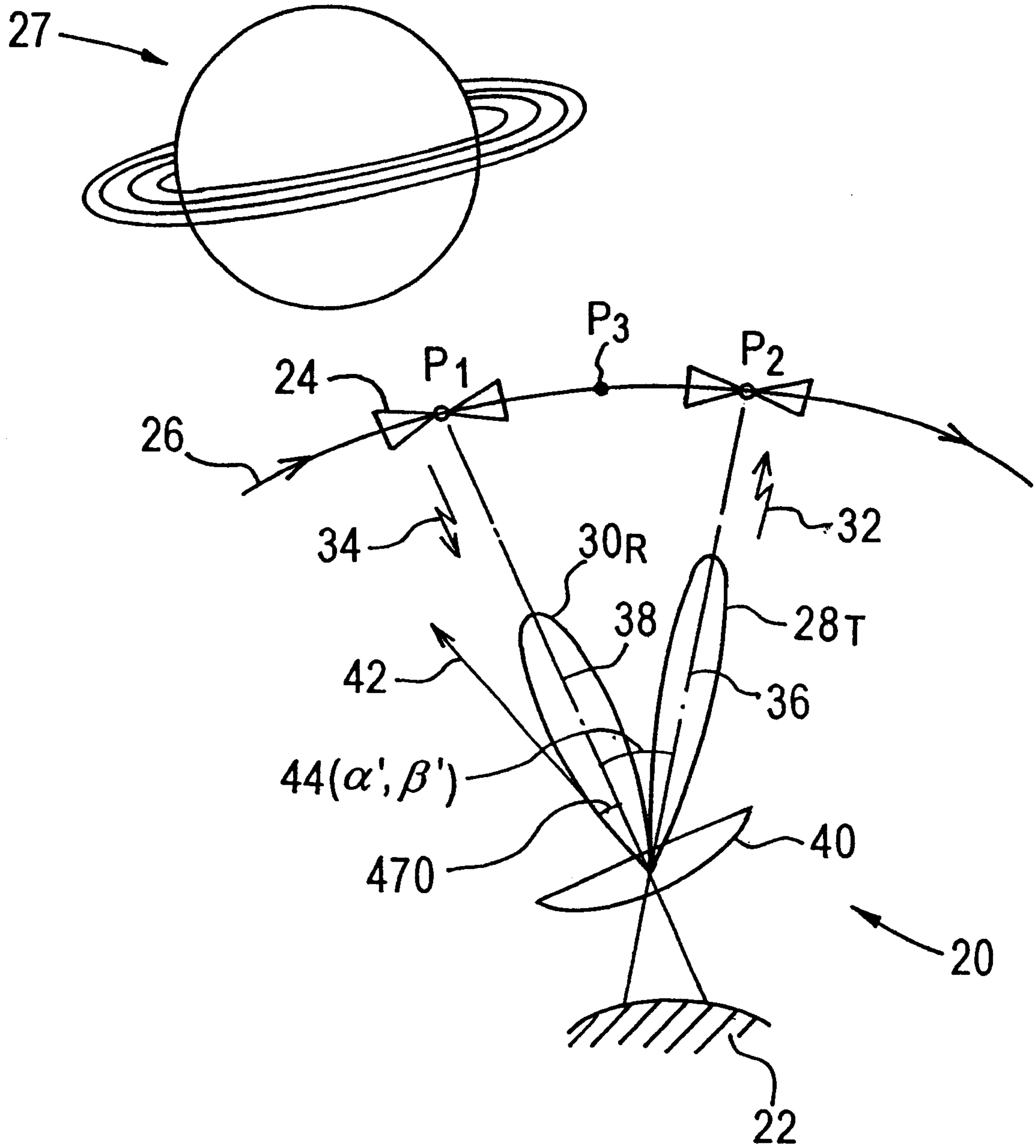


FIG. 1

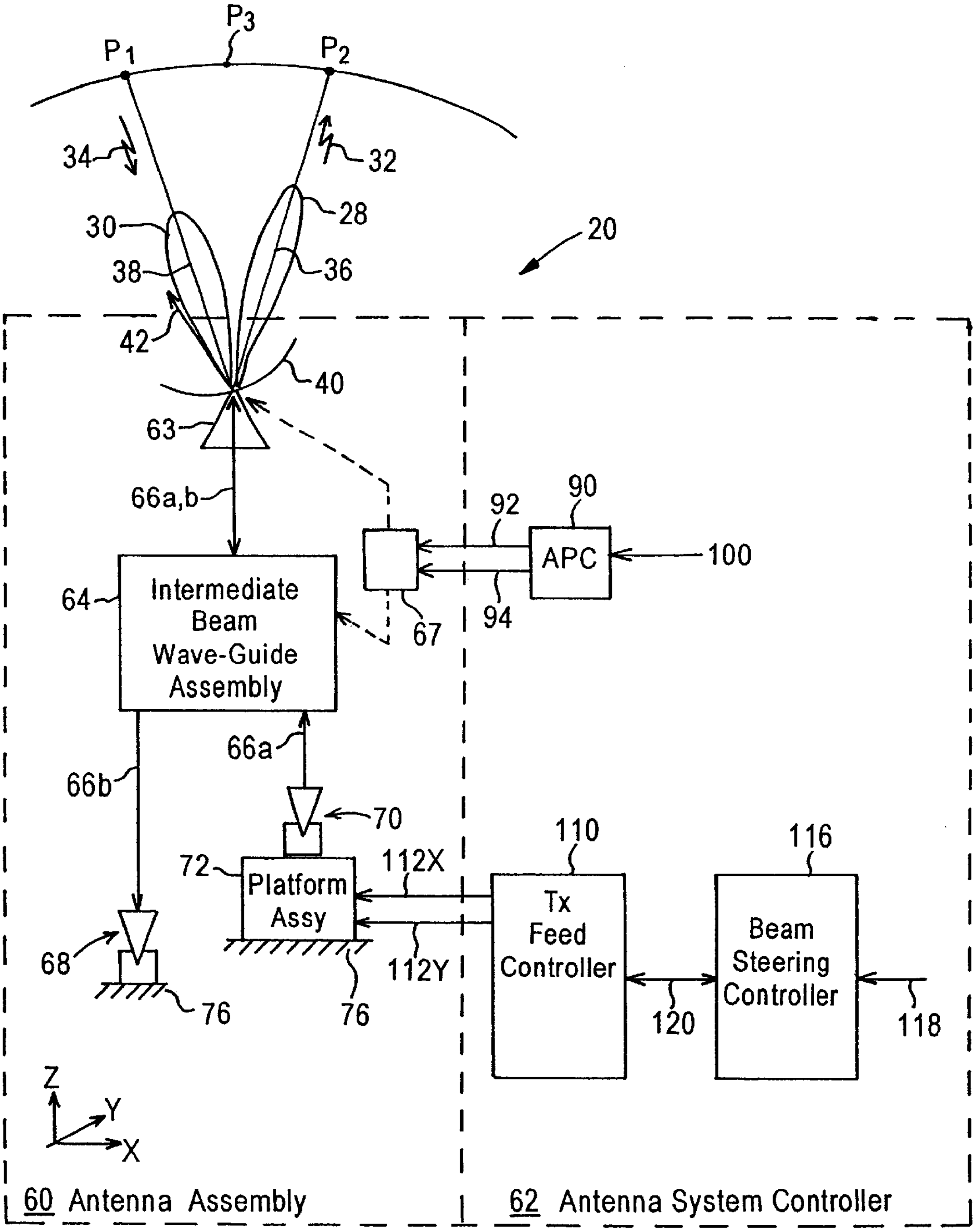

P_3
P_1
P_2
34
32
30
28
38
36
20
42
40
63
66a,b
92
90
APC
100
64
Intermediate Beam Wave-Guide Assembly
67
94
66a
66b
70
110
116
72
Platform Assy
112X
112Y
Tx Feed Controller
Beam Steering Controller
68
76
76
120
118
Z
Y
X
60 Antenna Assembly
62 Antenna System Controller

FIG. 2

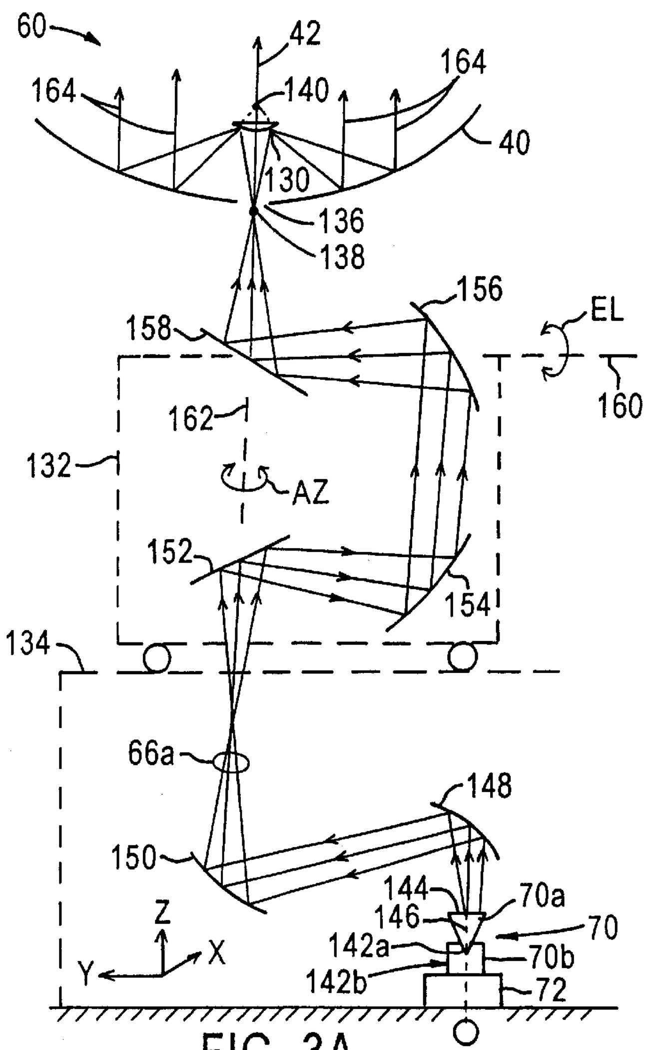

60
42
164
140
164
40
130
136
138
156
158
EL
160
162
132
AZ
152
154
134
66a
148
150
144
146
70a
70
142a
70b
142b
72
Z
Y
X

FIG. 3A

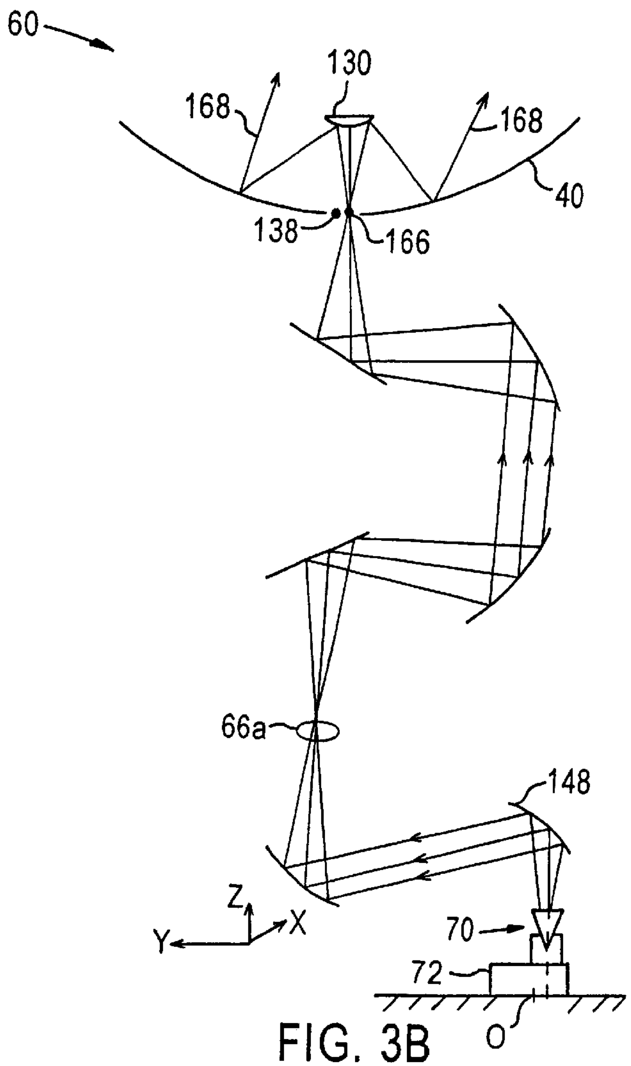

60
130
168
168
40
138
166
66a
148
Z
Y
X
70
72
O

FIG. 3B

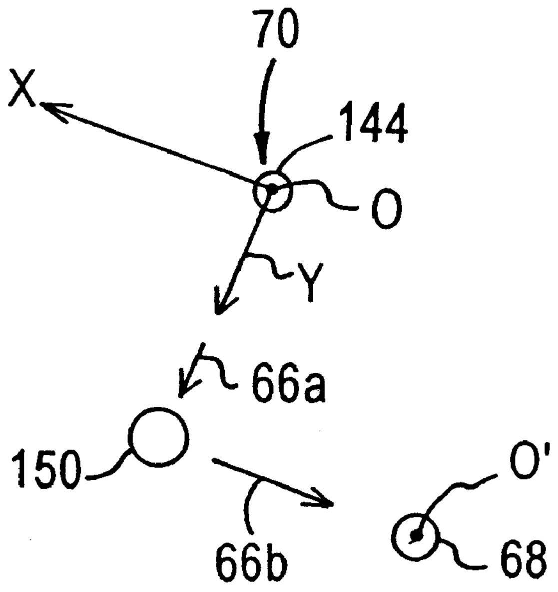


FIG. 3C

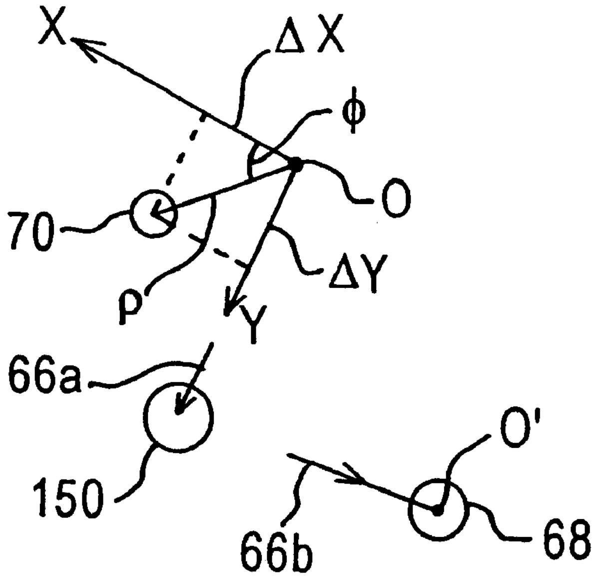


FIG. 3D

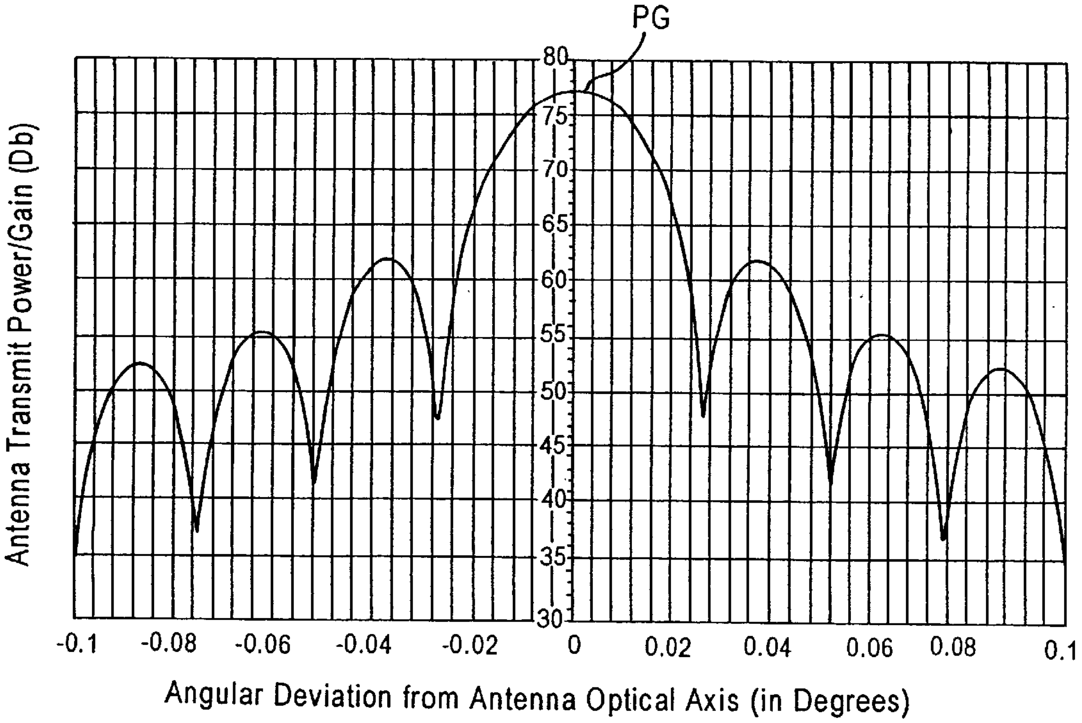

PG
Antenna Transmit Power/Gain (Db)
80
75
70
65
60
55
50
45
40
35
30
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
Angular Deviation from Antenna Optical Axis (in Degrees)

FIG. 3E

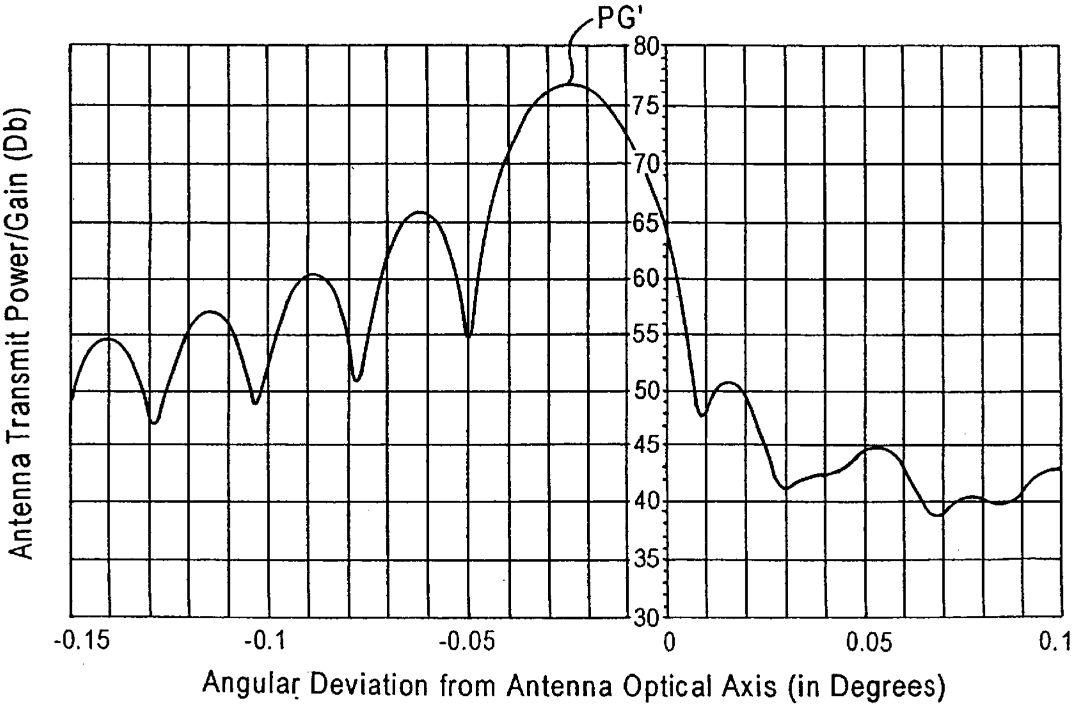

PG'
Antenna Transmit Power/Gain (Db)
80
75
70
65
60
55
50
45
40
35
30
-0.15
-0.1
-0.05
0
0.05
0.1
Angular Deviation from Antenna Optical Axis (in Degrees)

FIG. 3F

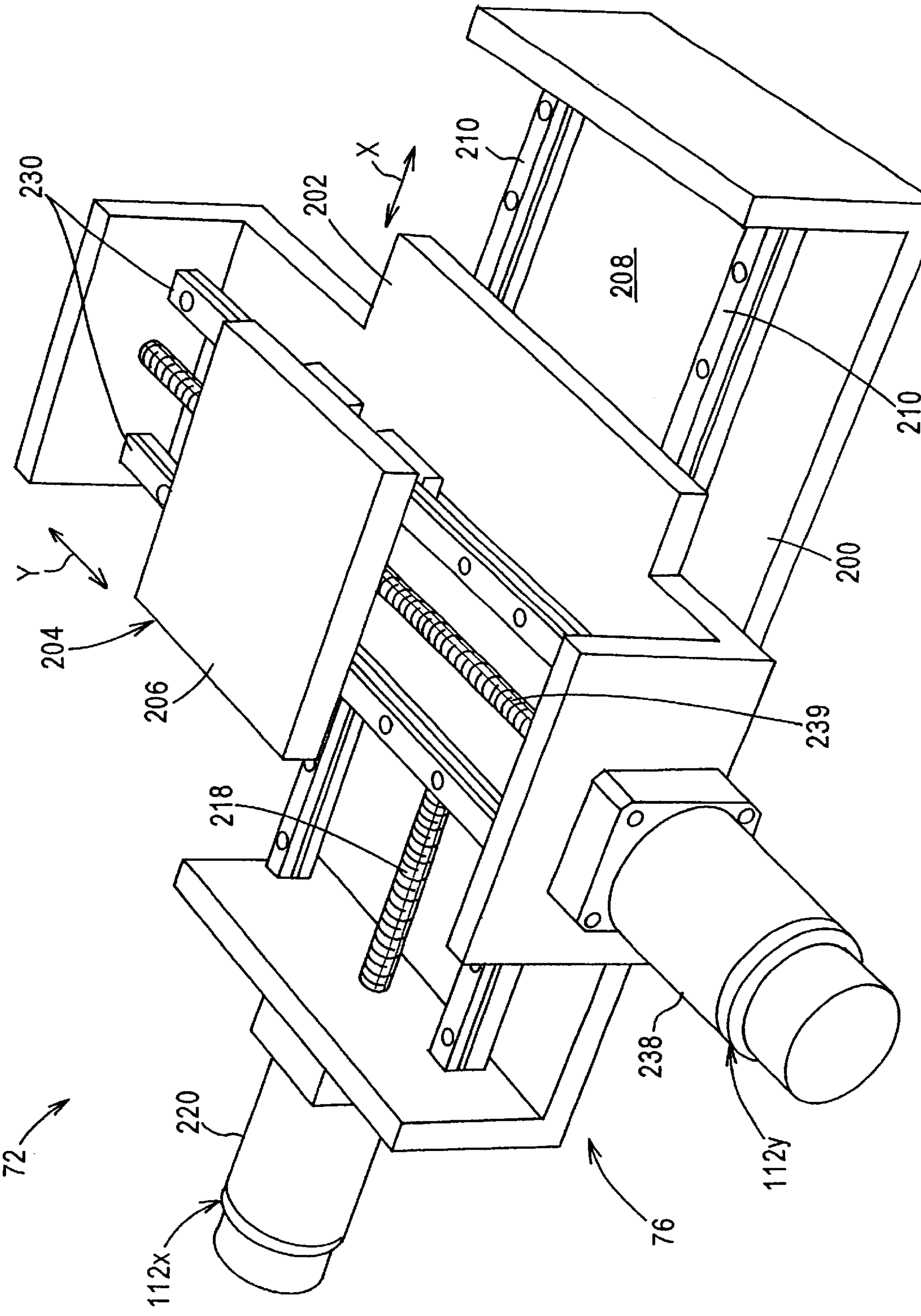

230
202
X
210
208
210
200
Y
204
206
239
218
238
112y
220
72
76
112x

FIG. 4

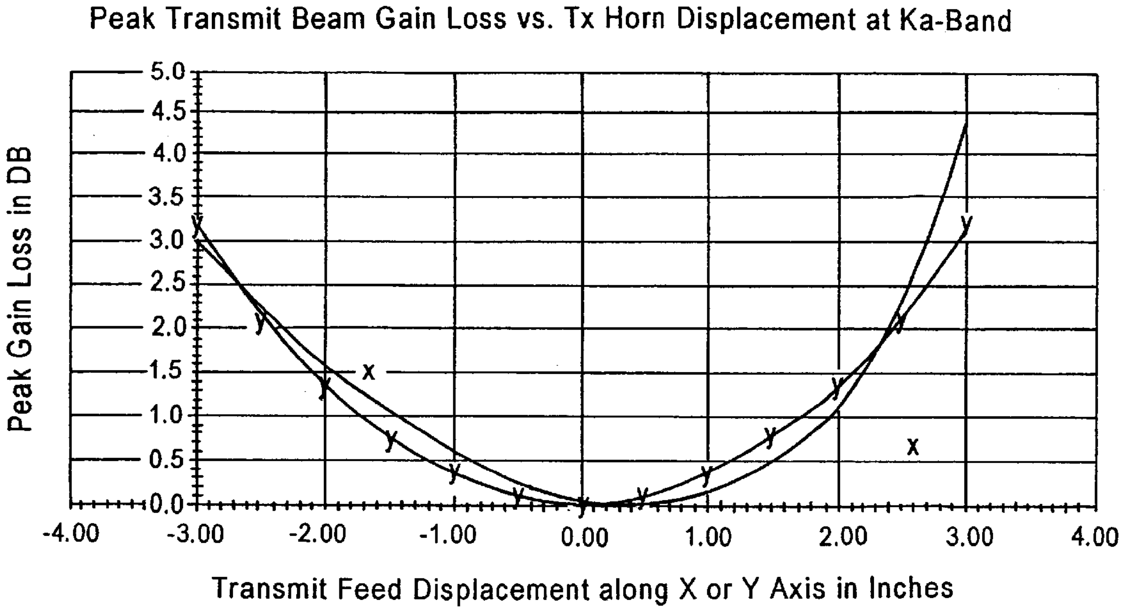

Peak Transmit Beam Gain Loss vs. Tx Horn Displacement at Ka-Band
Peak Gain Loss in DB
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-4.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00
Transmit Feed Displacement along X or Y Axis in Inches
x
y

FIG. 5A

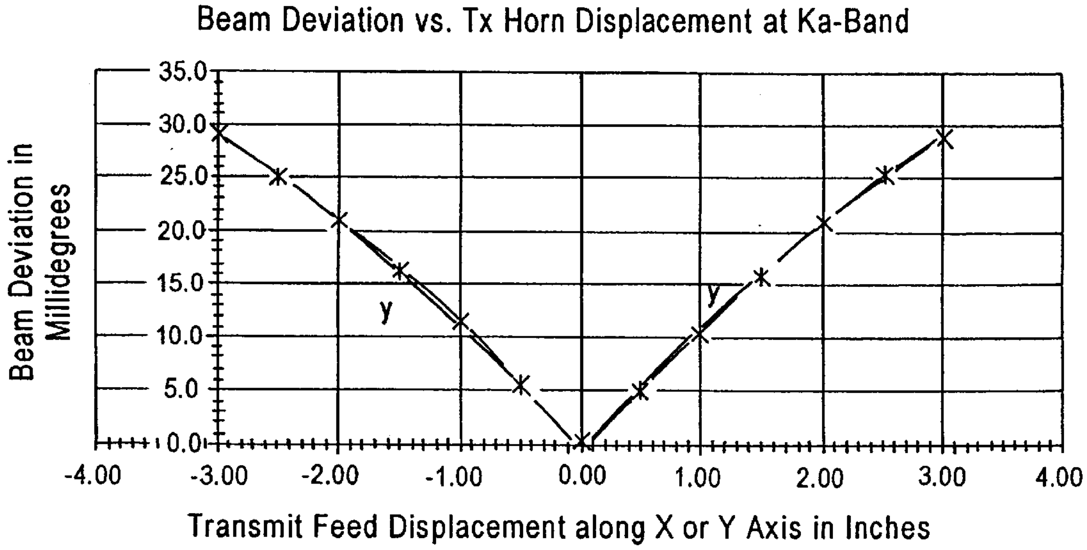

Beam Deviation vs. Tx Horn Displacement at Ka-Band
Beam Deviation in Millidegrees
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
-4.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00
Transmit Feed Displacement along X or Y Axis in Inches
y

FIG. 5B

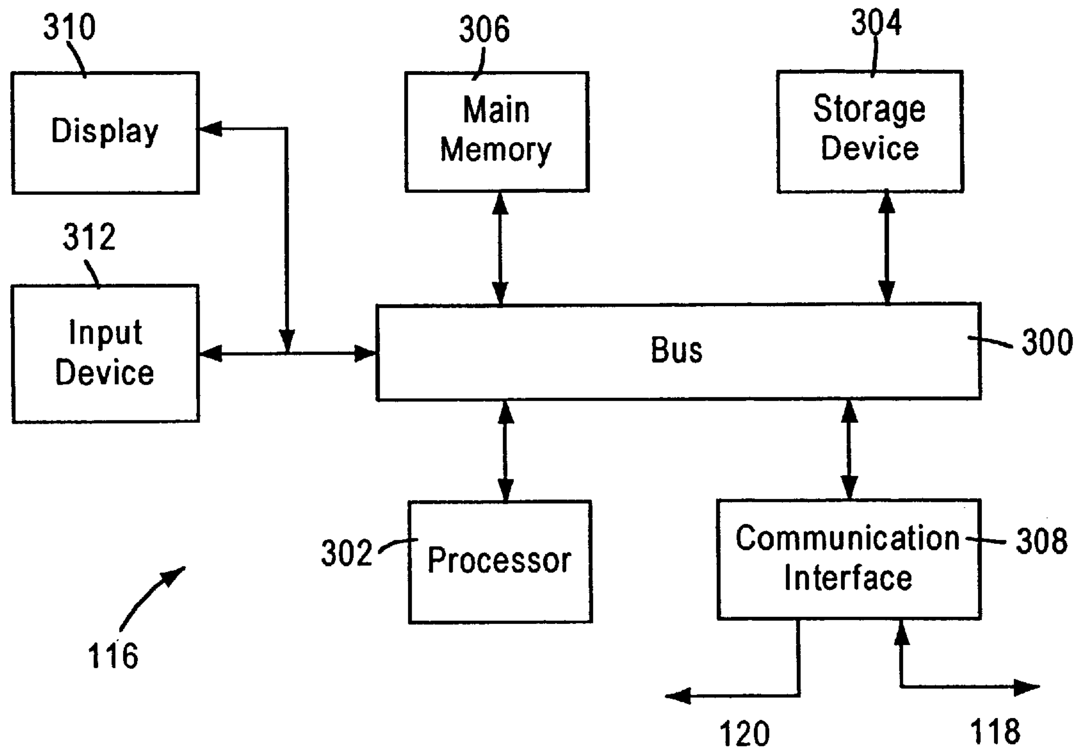

310
Display
306
Main Memory
304
Storage Device
312
Input Device
Bus
300
302
Processor
Communication Interface
308
116
120
118

FIG. 6A

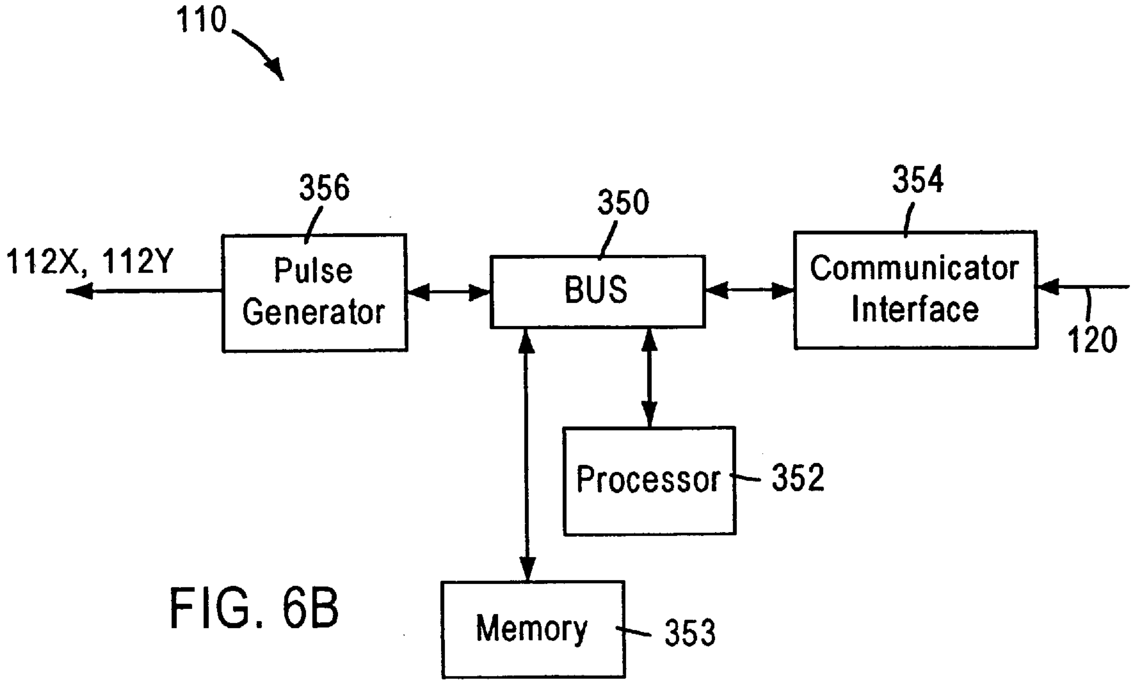
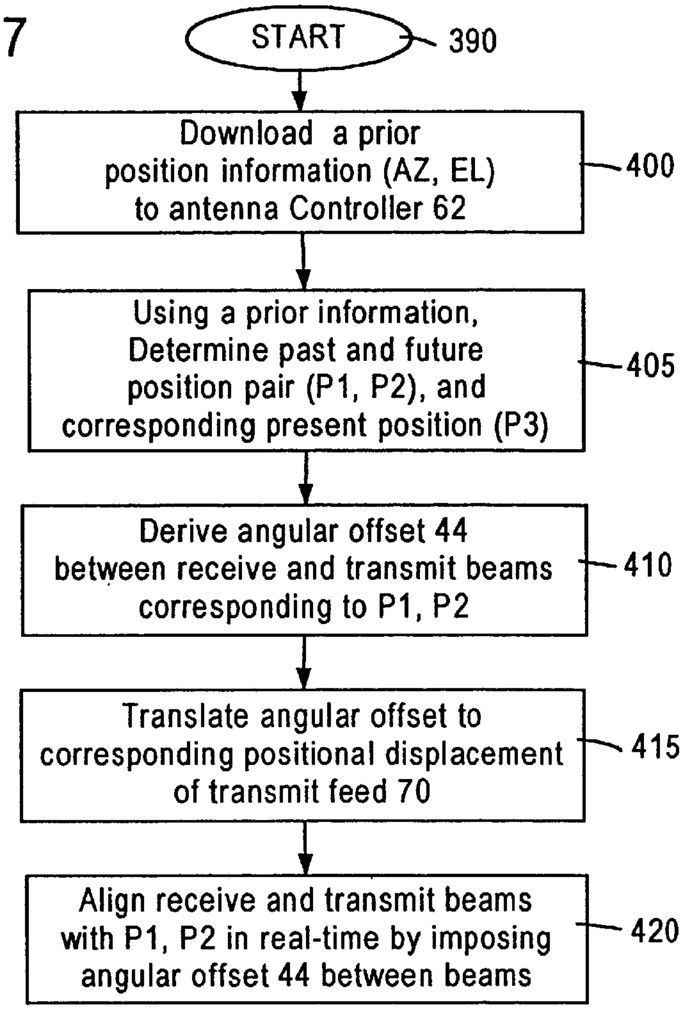
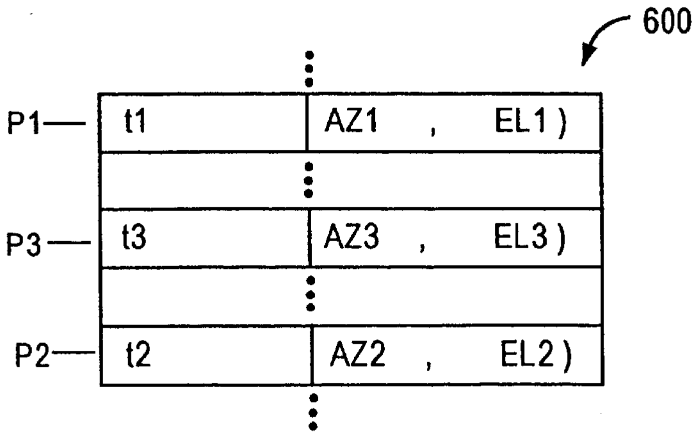

110
356
350
354
112X, 112Y
Pulse Generator
BUS
Communicator Interface
120
Processor
352
Memory
353

FIG. 6B

FIG. 7





⋮		
P1	t1	AZ1 , EL1)
	⋮	
P3	t3	AZ3 , EL3)
	⋮	
P2	t2	AZ2 , EL2)
⋮		

FIG. 8

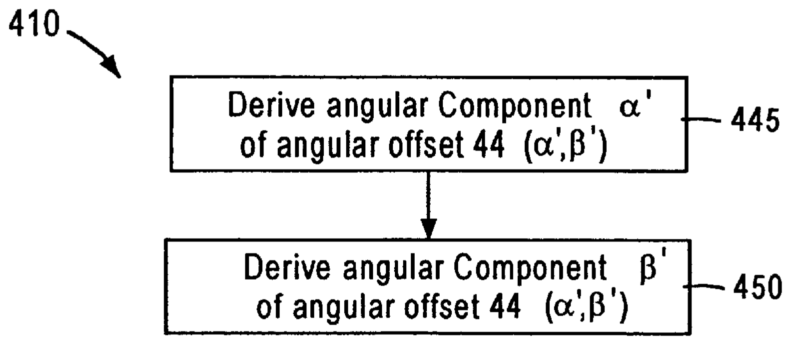


FIG. 9

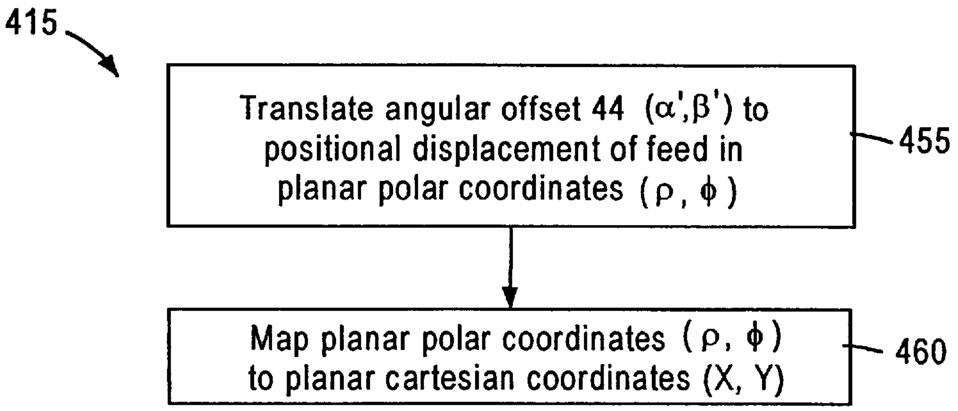


FIG. 10

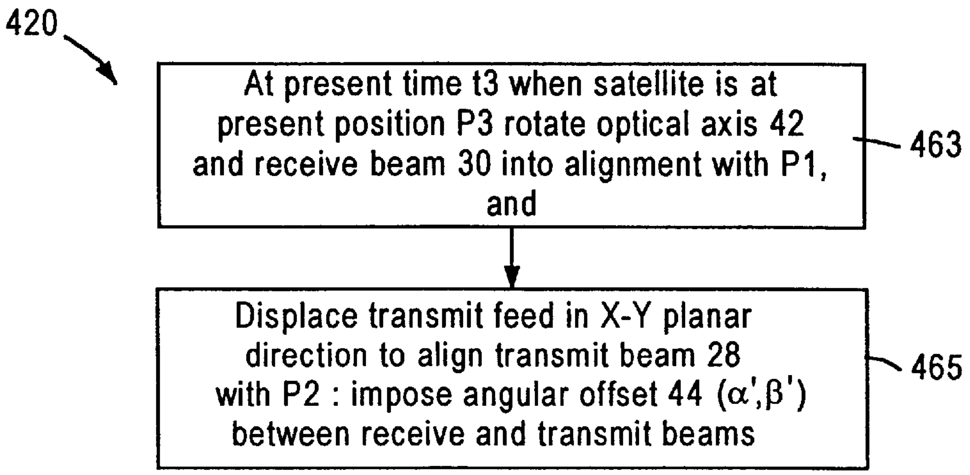


FIG. 11

BEAM WAVEGUIDE ANTENNA WITH INDEPENDENTLY STEERABLE ANTENNA BEAMS AND METHOD OF COMPENSATING FOR PLANETARY ABERRATION IN ANTENNA BEAM TRACKING OF SPACECRAFT

This application is a Divisional of application Ser. No. 09/361,355 filed Jul. 27, 1999.

FIELD OF THE INVENTION

The present invention generally relates to a terrestrial beam waveguide antenna and, more particularly, to such an antenna forming a transmit beam, wherein the transmit beam is independently steerable with respect to a receive beam formed by the antenna.

The present invention also generally relates to a method of and apparatus for controlling a terrestrial beam waveguide antenna and, more particularly, to a method of and apparatus for controlling receive and transmit beams of such an antenna to compensate for planetary aberration in the beam tracking of a spacecraft.

BACKGROUND OF THE INVENTION

Terrestrial stations for spacecraft communications typically include a large aperture antenna for communicating with a spacecraft. Such an antenna typically includes a beam waveguide assembly having a main reflector and a sub-reflector centered on an optical axis of the main reflector, e.g., a Cassegrain antenna. The beam waveguide assembly forms and directs a reciprocal pair of main antenna beams along the optical axis. The main antenna beams typically include a transmit beam for transmitting an uplink signal to and a receive beam for receiving a down-link signal from the spacecraft. To track the spacecraft, the main reflector and the sub-reflector, which are fixed relative to each other and rotate together, along with other optical components of the beam waveguide assembly, are typically driven by motors and servo-mechanisms in at least two rotational directions, e.g., azimuth (AZ) and elevation (EL), so as to align the main beams with the spacecraft. In this manner, the receive and transmit beams are both aligned with the same position of the spacecraft at a given point in time.

A Cassegrain antenna of sufficiently high gain to track a distant spacecraft includes large and correspondingly heavy beam waveguide components, e.g., a main reflector thirty-five meters in diameter, thus necessitating correspondingly bulky and relatively complex motors and servo-mechanisms to rotate such heavy components. Antenna beam tracking accuracy, i.e., alignment accuracy between the main beams and a tracked spacecraft position, is critical when using such a high gain antenna because even a small alignment error, e.g., on the order of millidegrees, results in a significant reduction in peak antenna gain. This criticality is even more pronounced when the antenna is used to track an interplanetary spacecraft because a signal communicated between such a distant spacecraft and the antenna experiences substantial propagational attenuation, i.e., signal attenuation proportional to the square of the distance between the antenna and the spacecraft.

Although the conventional antenna arrangement described above may suffice for communicating with a spacecraft relatively near to the earth, e.g., occupying low, medium and high earth orbits, its use for communicating with a relatively distant, e.g., interplanetary, spacecraft is limited and problematic. Effective communication with the relatively distant spacecraft is complicated in part by a phenomenon referred to as planetary aberration—the phenomenon by which objects in space, as viewed from the earth, are not where they appear to be. Planetary aberration arises as a result of 1) a component of relative motion between the spacecraft and the antenna, specifically, a component of the spacecraft's velocity orthogonal to a line-of-site between the spacecraft and the antenna, and 2) the finite time taken for the uplink and down-link signals to travel between the spacecraft and the antenna due to the finite speed with which the signals propagate through space. The finite time taken for the uplink and down-link signals to travel round-trip between the spacecraft and the antenna is referred to as the round-trip light travel time (RTLT).

The effect of planetary aberration can be appreciated in view of an astronomical coordinate system referred to as the right ascension (RA) and declination (DEC) coordinate system. RA/DEC coordinates define a position on what is referred to as a celestial sphere. The celestial sphere is a two dimensional projection of the sky on a sphere—the celestial sphere—surrounding the earth. Planetary aberration arises because the spacecraft moves in the RA/DEC coordinate system, and thus changes its position over time on the celestial sphere as observed from a point fixed on the earth, i.e., the antenna. The spacecraft changes its RA/DEC position because of its component of orthogonal velocity, without which the spacecraft would tend to maintain a single RA/DEC position and thus move directly toward or away from the antenna.

As will become apparent from the following example, compensating for planetary aberration in the receive and transmit beam tracking of the spacecraft requires an angular separation between the receive and transmit beams. The conventional beam waveguide antenna system disadvantageously includes colinearly aligned receive and transmit beams, i.e., receive and transmit beams aligned in the same direction, and is without a mechanism for imposing such angular separation between the receive and transmit beams, i.e., for splitting the receive and transmit beams apart to compensate for planetary aberration.

The following example serves to illustrate the detrimental effect planetary aberration has on communication between the spacecraft and the colinearly aligned receive and transmit beams of the conventional antenna. Assume a spacecraft initially transmits a down-link signal from a past or previous spacecraft position, and in the finite time taken for the down-link signal to travel to the antenna, i.e., half a RTLT, the spacecraft moves to a present spacecraft position at a present time. Assume at the present time the receive beam of the antenna, along with the optical axis and transmit beam, is aligned with the past spacecraft position to receive the down-link signal arriving therefrom, and, contemporaneous with the arrival of the down-link signal, an uplink signal is transmitted from the antenna via the transmit beam. Assume also in the finite time taken for-the uplink signal to arrive at the past spacecraft position, i.e., half a RTLT, the spacecraft moves from the second spacecraft position to a future spacecraft position, i.e., in one RTLT, the spacecraft moves from the past spacecraft position, through the present spacecraft position, and on to the future spacecraft position.

For a relatively near spacecraft, one RTLT is relatively short, e.g., fractions of a second, and the displacement of the spacecraft in RA/DEC coordinates between the past and future positions is negligible with respect to the beam coverage of the receive and transmit beams. Consequently, effective communication can occur even though the uplink signal is transmitted toward the past spacecraft position, and not along a direction intersecting the future spacecraft position, because both spacecraft positions are covered by the transmit beam.

On the other hand, for a relatively distant spacecraft, the one RTLT is relatively large, e.g., 160 minutes for a spacecraft near the planet Saturn, thus leading to an appreciable spacecraft displacement between the past and future spacecraft positions. In this case, the transmit beam coverage does not necessarily encompass the more widely separated positions, a situation worsened by the requirement for a highly directive, i.e., high gain, antenna beam. Without some form of correction or compensation to account for the separation of positions due to planetary aberration, signal loss can be significant, e.g., up to 25 dB. This is due to the colinear alignment of the receive and transmit beams of the antenna with past, present or future positions of the spacecraft. Consequently, ineffective communication results since the uplink signal is transmitted toward the incorrect spacecraft position (e.g., the past position), as a result of this colinear alignment of the receive and transmit beams of the antenna.

For the relatively distant spacecraft, effective communication thus requires simultaneous alignment of the downlink and uplink signals with the respective past and future positions of the spacecraft at the present time, i.e., simultaneous alignment of the receive and transmit beams with respective spaced-apart spacecraft positions coinciding with times half a RTLT previous to and half a RTLT after the present time. Conventionally, achievement of such spaced alignment disadvantageously requires two antennas—one antenna providing receive beam tracking of the past position, and the other antenna providing transmit beam tracking of the future position—because of the colinear receive and transmit beam arrangement of the conventional antenna.

Accordingly, there is a need for a high-gain beam waveguide antenna having a beam steering capability independent of and in addition to the conventional rotational mechanisms used for antenna beam steering.

There is also a need for a high-gain beam waveguide antenna having receive and transmit main beams independently steerable with respect to each other and the optical axis of the antenna.

There is a further need in a beam waveguide antenna system to control the receive and transmit beam tracking of a spacecraft moving along a space trajectory to compensate for appreciable planetary aberration.

There is an even further need for using a single antenna system forming receive and transmit beams to beam-track a spacecraft moving along a spacecraft trajectory to compensate for planetary aberration.

There is also a need to reduce the effects of propagational attenuation of a signal transmitted between a spacecraft and an antenna system.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to independently steer the transmit beam of a high-gain, beam waveguide antenna with respect to a receive beam formed by the antenna. This object also includes independently steering the transmit beam with respect to an optical axis of the antenna.

A related object of the present invention is to control independent steering of a transmit beam formed by a terrestrial, high-gain, beam waveguide antenna with respect to an optical axis of the antenna and a receive beam formed by the antenna, to compensate for appreciable planetary aberration in the receive and transmit beam tracking of a spacecraft moving along a space trajectory.

Another object of the present invention is the improvement of a conventional, high-gain, beam waveguide antenna having a conventional beam steering mechanism for steering together receive and transmit beams formed by the antenna, the improvement including the addition of a beam steering mechanism for independently steering the transmit beam with respect to the receive beam.

Another object of the present invention is to reduce the effects of propagational attenuation of a signal transmitted between a spacecraft and an antenna system.

These and other objects of the present invention are achieved through an improvement to a conventional, high-gain beam waveguide antenna system. The improved antenna system includes a beam waveguide having conventional components, including a large main reflector, a sub-reflector centered along an optical axis of the main reflector, a fixed receive feed associated with a receive beam formed by the antenna system, and an intermediate beam waveguide assembly positioned between the fixed receive feed and the main reflector for guiding beam energy there between. A conventional beam steering mechanism coupled with the main reflector and moveable components of the intermediate beam waveguide assembly steers together the optical axis of the main reflector, the receive beam and a transmit beam formed by the antenna system.

The improvement in accordance with the present invention includes a moveable transmit feed, associated with the transmit beam. Controlled displacement of the moveable transmit feed, in a planar direction perpendicular to a beam feeding axis of the transmit feed, advantageously produces a corresponding angular displacement of the transmit beam from both the optical axis and the receive beam. The improvement also includes electrically driven actuators coupled with the moveable transmit feed for controllably displacing the transmit feed responsive to a control signal derived by a beam steering controller executing beam steering control software of the present invention. Advantageously, the electrically driven actuators are small, light, readily available, and easy to control because the transmit feed is much smaller and lighter than the large main reflector. As a result, high resolution transmit beam steering, on the order of millidegrees, is easily attained with fine displacements of the moveable transmit feed using the actuators coupled thereto.

The foregoing objects of the present invention are achieved by an antenna assembly for forming and directing a transmit beam. The assembly includes a main reflector, a sub-reflector centered along an optical axis of the main reflector, and a moveable transmit feed for directing electromagnetic radiation along a longitudinal axis of the transmit feed. The assembly also includes an intermediate beam waveguide assembly positioned between the moveable transmit feed and the main reflector, wherein the intermediate beam waveguide assembly includes fixed and moveable optical components for guiding electromagnetic beam energy between the moveable transmit feed and the main reflector. A beam steering mechanism is coupled with the moveable transmit feed for angularly displacing the transmit beam from the optical axis by displacing the moveable transmit feed in a direction substantially orthogonal to the longitudinal axis of the transmit feed.

The foregoing and other objects of the present invention are achieved by a method of controlling the improved antenna of the present invention to compensate for appreciable planetary aberration in receive and transmit beam tracking of a spacecraft moving along a space trajectory. In the method, the transmit and receive beams of the improved antenna respectively transmit an uplink signal to and receive a down-link signal from the spacecraft. The down-link and uplink signals travel round-trip between the spacecraft and the antenna in one RTLT.

The method includes aligning the receive beam at a present time with a past position of the spacecraft coinciding with where the spacecraft was half a RTLT before the present time. The method includes contemporaneously aligning the transmit beam with a future position of the spacecraft coinciding with where the spacecraft will be half a RTLT after the present time. When so aligned, an angular displacement between the receive and transmit beams compensates for planetary aberration. The contemporaneous step of aligning the transmit beam includes the step of displacing the transmit feed of the antenna in a planar direction, thus angularly displacing the transmit beam from the receive beam and into alignment with the future position of the spacecraft.

The foregoing and other objects of the present invention are achieved by a method of controlling a terrestrial antenna system to compensate for planetary aberration including the steps of 1) aligning a receive beam of the antenna system at a present time with a past position of a spacecraft, and 2) aligning a transmit beam of the antenna system with a future position of the spacecraft spaced from the past position, wherein a down-link signal and an uplink signal can be simultaneously received from the past position of the spacecraft and transmitted to the future position of the spacecraft by the antenna system, respectively.

The foregoing and other objects of the present invention are achieved by a method of compensating for planetary aberration in an antenna system. The antenna system includes a beam waveguide and a transmit feed for forming and directing a transmit beam. The transmit beam is used to transfer a signal between the transmit feed and a spacecraft. The method includes angularly displacing the transmit beam from an optical axis of the beam waveguide responsive to a displacement of the transmit feed in a direction orthogonal to an axis of the transmit feed. Such displacement of the transmit feed aligns the transmit beam with a future position of the spacecraft, wherein the spacecraft moves from a present position to the future position during the approximate time taken for the transfer of the signal between the antenna system and the spacecraft.

The foregoing and other objects of the present invention are achieved by an antenna system controller for a terrestrial antenna adapted to form and direct transmit and receive beams for respectively transmitting a signal to and receiving a signal form a spacecraft. The antenna system controller includes a processor, an interface coupled to the processor, and a memory coupled to the processor. The memory stores sequences of instructions which, when executed by the processor, causes the processor to 1) identify temporally spaced first and second apriori positions of the spacecraft corresponding to a round-trip travel time of the signals between the spacecraft and the terrestrial antenna, and 2) derive an angular displacement between the receive and transmit beams to contemporaneously align the receive and transmit beams with spacecraft positions.

The above and still further objects, features and advantages of the present invention will become apparent upon consideration of the following detailed description of a specific embodiment thereof, especially when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a high-level operational diagram of an embodiment of an antenna system in accordance with the present invention;

FIG. **2** is a high-level block diagram of the antenna system of FIG. **1**;

FIG. **3**A is a schematic diagram of an arrangement of the beam waveguide optics of the antenna assembly of FIG. **1**;

FIG. **3**B is a schematic diagram of the antenna assembly of FIG. **3**A with a transmit feed displaced from an origin;

FIG. **3**C is a partial plan view of the antenna assembly of FIG. **3**A with the transmit feed positioned at the origin;

FIG. **3**D is a partial plan view of the antenna assembly of FIG. **3**A with the transmit feed displaced from the origin;

FIG. **3**E is a diagram of an antenna gain pattern for the antenna assembly of FIG. **3**A with the transmit feed coincident with the origin;

FIG. **3**F is a diagram of an antenna gain pattern for the antenna assembly of FIG. **3**A with the transmit feed displaced from the origin;

FIG. **4** is a perspective view of an embodiment of a platform assembly;

FIG. **5**A is a diagram of a plot of predicted peak transmit beam gain loss versus transmit feed displacement along X and Y axes for the antenna assembly of FIG. **3**A;

FIG. **5**B is a diagram of a plot of predicted beam deviation from a reference axis versus transmit feed displacement along the X and Y axes;

FIG. **6**A is a block diagram of the beam steering controller of FIG. **2**;

FIG. **6**B is a block diagram of an embodiment of the transmit feed controller of FIG. **2**;

FIG. **7** is a high-level flow diagram of a method used to control the antenna system of FIG. **1**;

FIG. **8** is an illustration of an exemplary format for the apriori spacecraft trajectory information used in the method of FIG. **7**; and

FIGS. **9**–**11** are flow diagrams expanding on the method steps of FIG. **7**.

BEST MODE FOR CARRYING OUT THE INVENTION

In the following description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, that the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to avoid unnecessarily obscuring the present invention.

FIG. **1** is a high-level operational diagram of an embodiment of an antenna system **20** operable in accordance with the principles of the present invention. As illustrated, antenna system **20**, positioned at a predetermined terrestrial location **22**, tracks a spacecraft **24** along its predetermined interplanetary trajectory **26**. Trajectory **26** brings spacecraft **24** into the neighborhood of a distant planet **27**, e.g., Saturn—in one intended application of the present invention. Antenna system **20** forms a transmit beam **28** and a receive beam **30** for respectively transmitting an electromagnetic (EM) uplink signal **32** to and receiving an EM down-link signal **34** from spacecraft **24**. Transmit beam **28** is approximately symmetrical about a beam axis **36** thereof substantially aligned with a peak gain of the transmit beam **28**. Similarly, receive beam **30** is approximately symmetrical about a beam axis **38** thereof substantially aligned with a peak gain of the receive beam **30**.

Antenna system **20** includes a Cassegrain high-gain antenna assembly having a large main reflector **40**, e.g., thirty-five meters in diameter, and a sub-reflector, not shown, aligned with an optical axis **42** of main reflector **40**. In addition to a conventional beam steering mechanism, antenna system **20** advantageously includes a beam steering mechanism capable of angularly separating, i.e., angularly splitting, the receive and transmit beams **30**,**28** by a predetermined angle **44**. Antenna system **20** is thus capable of simultaneously aligning receive and transmit beams **30**,**28** with a first (i.e., past) spacecraft position p1 and a second (i.e., future) spacecraft position p2 having spaced-apart RA/DEC position coordinates.

More specifically, transmit beam **28** is independently steerable in azimuth and elevation with respect to both receive beam **30** and optical axis **42** of main reflector **40**, to impose angular offset or split **44** between receive and transmit beams **30**,**28** aligned respectively with the first and second spacecraft positions. It should be appreciated that an antenna beam is said to be aligned with, i.e., pointed at or in the direction of, the spacecraft when a peak gain of the beam is substantially aligned with the spacecraft; this occurs when the beam axis (e.g., beam axis **36** or **38**) is substantially aligned with the spacecraft.

In providing independent steering of transmit beam **28** relative to receive beam **30** and optical axis **42**, antenna system **20** overcomes complications associated with planetary aberration to permit effective, contemporaneous reception of down-link signal **34** from and transmission of uplink signal **32** to distant spacecraft **24** at the spaced past and future positions p1, p2, as the following brief operational example illustrates.

To provide a basic understanding of the invention the following operational example is provided and the structure which provides this functionality is described in detail following the operational example. At an instant in time corresponding to a present time, receive beam **30** is steered into alignment with past position p1 where the spacecraft was half a RTLT prior to the present time, and contemporaneously, transmit beam **28** is steered into alignment with future position p2 where spacecraft **24** will be half a RTLT after the present time—spacecraft **26** moves from past positions p1 to future position p2 in one RTLT of uplink signal **32** and down-link signal **34** between satellite **24** and antenna system **20**. Down-link signal **34** transmitted by spacecraft **24** from past position p1 is received via receive beam **30**. Similarly, uplink signal **32** is transmitted to spacecraft **24** at future position p2 via transmit beam **28**. Angular offset or split **44** required between receive and transmit beams **30**,**28** arises due to planetary aberration since past and future positions p1,p2 have spaced-apart RA/DEC position coordinates; as described previously, the separation in positions arises from the relative component of spacecraft velocity orthogonal to the line-of-sight between the spacecraft and antenna system **20**.

As illustrated above, antenna system **20** advantageously compensates for planetary aberration by angularly splitting receive and transmit beams to respectively align the same with respective positions p1,p2. Importantly, aligning the peak gains of the receive and transmit beams with respective positions p1,p2 also reduces detrimental effects caused by propagational attenuation of down-link and uplink signals **34**,**32**. Such can be appreciated considering that planetary aberration can require an angular offset **44** of, for example, up to 30 millidegrees for a spacecraft travelling near Saturn, while each of high-gain receive and transmit beams **30**,**28** has an exemplary 3 dB beam-width (i.e., a full beam-width 3 dB down from the peak gain point of the beam) of approximately 15 millidegrees.

With reference to FIG. **2**, antenna system **20** includes an antenna assembly **60** and an antenna system controller **62**. Antenna assembly **60** includes both conventional Cassegrain, beam-wave guiding optics, and improvements in accordance with the present invention, to form and direct receive and transmit beams **30**,**28**. The conventional beam waveguide optics include a high gain, parabolic main reflector **40** rotatable in both azimuthal and elevational directions. Main reflector **40** is supported above ground by a main reflector support **63**. The conventional beam waveguide optics also include an intermediate beam waveguide **64**. Waveguide **64** guides both an uplink or transmit EM beam **66***a* and a down-link or receive EM beam **66***b* through antenna assembly **60** and feeds the EM beams to and from main reflector **40**, respectively.

A conventional fixed receive feed **68** receives EM beam **66***b* from waveguide **64**. More specifically, down-link signal **34** received via receive beam **30** is directed by main reflector **40** and optics associated therewith to intermediate beam waveguide assembly **64**. Assembly **64** guides down-link signal **34** from main reflector **40** to an input aperture of receive feed **68**. Conventional motors and servomechanisms, indicated generally as reference numeral **67**, are coupled to main reflector **40**, main reflector support **63**, and moveable optical components within beam waveguide assembly **64**, as will be described. Motors and servomechanisms **67** rotate optical axis **42** of main reflector **40** in both azimuthal and elevational directions responsive to a pair of respective azimuthal and elevational control signals **92**,**94**, as is known in the art.

An improvement to antenna assembly **60** in accordance with the present invention includes a conventional moveable transmit feed **70** (described more fully later) to independently steer transmit beam **28** with respect to optical axis **42** and receive beam **30**. Moveable transmit feed **70** radiates the uplink signal, i.e., EM beam **66***a*, toward intermediate beam waveguide assembly **64**. Intermediate beam waveguide assembly **64** guides beam **66***a* input thereto, along an optical path within antenna assembly **60**, to an output of waveguide assembly **64**. Beam waveguide assembly **64** directs beam **66***a* to main reflector **40**, from where uplink signal **32** is transmitted into space via transmit beam **28**.

The improvement includes a platform assembly **72** for moveably supporting transmit feed **70**. Specifically, a moveable upper surface or platform of platform assembly **72** supports transmit feed **70**, whereas a lower surface of the platform assembly rests upon a fixed surface **76**. Platform assembly **72** displaces transmit feed **70** supported thereby responsive to a pair of actuator control signals **112***x*,**112***y* indicative of transmit feed displacement, and provided from antenna system controller **62**, as described in detail below. As will be described more fully, an independent, controlled displacement of transmit feed **70** in a planar direction results in a correspondingly controlled angular offset between transmit beam **28** and both optical axis **42** and receive beam **30**.

Antenna system controller **62** includes both conventional beam steering control components and improvements in accordance with the present invention, which work together to control antenna assembly **60**. Antenna system controller **62** thus controls antenna assembly **60** to track spacecraft **24** and to compensate for planetary aberration. Conventionally, an antenna pointing controller (APC) **90** derives azimuthal and elevational control signal pair **92**,**94** responsive to apriori spacecraft trajectory information provided to APC **90** over an interface **100**.

In accordance with the present invention, a transmit feed position controller **110** and a beam steering controller **116** together control the movements or displacements of moveable transmit feed **70**. Transmit feed position controller **110** derives actuator control signal pair **112***x*,**112***y* responsive to transmit feed displacement commands issued thereto over an interface **120**. High-level beam steering controller **116** controls the independent beam steering of transmit beam **30** to correct for planetary aberration, and derives the transmit feed displacement commands issued to controller **110** responsive to the apriori spacecraft trajectory information supplied thereto via an interface **118**. Both APC **90** and beam steering controller **116** receive a signal indicative of accurate real-time, e.g., Greenwich Mean Time (GMT), and are thus time-synchronized. Feed controller **110** is also time-synchronized with controller **116** to provide controlled, real-time displacements of transmit feed **70**.

FIGS. **3**A and **3**B are schematic diagrams of an embodiment of a construction of the beam waveguide optics of antenna assembly **60**. The conventional beam waveguide optics include parabolic main reflector **40** and a hyperbolic sub-reflector **130**, both supported above an upper edifice **132**. Upper edifice **132** is rotatively coupled to and above a fixed lower edifice **134**. Main reflector **40** includes a central opening **136** through which beam energy is directed, and sub-reflector **130** is fixedly centered along optical axis **42** of main reflector **40**. Optical axis **42** extends through both a first focus point **138** and a second focus point **140** of the combined sub-reflector **130** and main reflector **40**.

Moveable transmit feed **70**, located within fixed lower edifice **134**, provides the source of EM beam energy for beam **66***a* in the transmit direction. Transmit feed **70** includes a transmit horn **70***a* coupled to a supporting transmit guide or feed assembly **70***b*. Transmit horn **70***a* includes an EM input **142***a*, an EM output aperture **144**, and a horn shaped body between input **142***a* and output aperture **144**. Output aperture **144** is centered along a central, longitudinal axis **146** of transmit horn **70***a*. Longitudinal axis **146** extends in a direction parallel with the Z-axis, as depicted in FIG. **3**A.

A transmitter of antenna system **20**, not shown, initially supplies uplink signal **32** to an input **142***b* of transmit guide or feed assembly **70***b*. Transmit feed assembly **70***b* couples uplink signal **32** to input **142***a* of transmit horn **70***a*. The horn shaped body of transmit horn **70***a* guides uplink signal **32** from input **142***a* to output aperture **144**, from where the uplink signal is radiated, in the direction of longitudinal axis **146**, toward intermediate beam waveguide assembly **64**.

Intermediate beam waveguide assembly **64** is conventional, and includes optical components within both lower edifice **134** and upper edifice **132**. Intermediate waveguide assembly **64** guides beam **66***a* from an input end thereof proximate aperture **144**, along a path through antenna assembly **60**, to an output end of the intermediate waveguide assembly proximate opening **136** of main reflector **40**. Beam **66***a* exiting the output end of assembly **64** is directed through opening **136** toward a convex outer surface of sub-reflector **130**, to be reflected thereby back toward an inner concave surface of main reflector **40**. This inner concave surface reflects beam energy incident thereto into space as a main antenna beam, e.g., transmit beam **30**, in the direction of a main beam axis, e.g., transmit beam axis **36**.

Beam waveguide assembly **64** includes, in series along the direction of guided beam **66***a*, 1) a hyperbolic mirror **148** and an elliptic mirror **150** disposed within edifice **134**, and 2) a plane mirror **152**, an elliptic mirror **154**, an elliptic mirror **156**, and a plane mirror **158** disposed within edifice **132**. As is known, main reflector **40**, sub-reflector **130** and the mirrors of beam waveguide assembly **64** are moveable with respect to an elevational axis **160** and an azimuthal axis **162** to correspondingly steer receiver and transmit beams **30**,**28** in elevational and azimuthal directions.

An important aspect of the present invention is the layout arrangement or positioning of moveable transmit feed **70** and fixed receive feed **68** with respect to mirror **150**. Such is depicted in FIG. **3**C—a partial plan view of antenna assembly **60** of FIG. **3**A—wherein transmit feed **70** is positioned at an origin O of an X-Y plane defined by an X axis and a Y axis, and receive feed **68** is fixed at an origin O'. Transmit feed origin O is concentric with mirror **150**, and the Y-axis is directed radially inward from origin O toward mirror **150**, i.e., an inward radial displacement or movement of transmit feed **70** form origin O toward mirror **150** coincides with a positive-Y displacement of the transmit feed. The X axis is orthogonal to the Y-axis, in a conventional right-handed Cartesian coordinate system with the Z-axis directed upwardly, i.e., out of the plane of FIG. **3**C. Receive feed **68** is fixed at position O', also concentric with mirror **150**.

Receive and transmit beams **30**,**28** are aligned with optical axis **42** with receive and transmit feeds **68**,**70** positioned at respective origins O',O. Operationally, with longitudinal axis **146** of moveable transmit feed **70** positioned as depicted in FIGS. **3**A and **3**C, i.e., aligned with origin O of the X-Y plane, beam **66***a* exiting aperture **144** impinges upon a central region of mirror **148**, and from there traces a centralized path through intermediate waveguide assembly **64**, as indicated in FIG. **3**A by the rays between mirrors. It is to be appreciated that although beam **66***a* diverges and converges along its path responsive to its interaction with the various optical components, an axis of the beam is nevertheless centralized with respect to the guiding optical components. Importantly, since beam **66***a* follows the path depicted in FIG. **3**A throughout assembly **64**, the beam exits the assembly in the direction of optical axis **42** and is centrally directed through first focus point **138**. Main reflector **40** and sub-reflector **130** focus centralized beam **66***a* incident thereto into a main transmit beam, i.e., transmit beam **28**, in the direction of optical axis **42**, as indicated by rays **164**.

FIG. **3**E is a plot of antenna transmit power/gain versus angular deviation from optical axis **42** for antenna assembly **20** arranged as depicted in FIGS. **3**A and **3**C, and operating at a transmit frequency of approximately 22 Ghz. The peak transmit gain PG plotted in FIG. **3**E is aligned with optical axis **42** because transmit feed **70** is positioned at origin O, as depicted in FIGS. **3**A and **3**C.

Displacement of transmit feed **70** in the X-Y plane, i.e., in the X and/or Y directions, independently steers transmit beam **28** angularly away from optical axis **42** in either or both azimuthal and elevational directions. More specifically and by way of example, displacement of longitudinal axis **146** of feed **70** from origin O by an amount ΔX in the X-direction and an amount ΔY in the Y-direction, as depicted in FIG. 3D, imposes an angular offset between transmit beam **28** and optical axis **42**.

The causal effect between displacement of transmit feed **70** and angular displacement of transmit beam **30** is explained with reference back to FIG. 3B. Beam **66***a*, originating from displaced transmit feed **70**, impinges upon a portion of mirror **148** correspondingly displaced from the central region thereof, and from there traces a correspondingly displaced path, i.e., displaced with respect to the centralized path of FIG. 3A, through the optical components of the beam waveguide assembly. Unlike FIG. 3A, displacement of beam **66***a* throughout assembly **64** causes beam **66***a* to exit assembly **64** displaced from first focus point **138** in the -Y-direction. Beam **66***a* is directed through a displaced beam convergence point **166**, as depicted in FIG. 3B. Main reflector **40** and sub-reflector **130** generally focus displaced or offset beam **66***a* incident thereto into a transmit beam angularly offset from optical axis **42**, as indicated by rays **168**. The magnitude and direction of the angular offset between the main beam and optical axis **42** is a function of the magnitude and direction of the displacement of longitudinal axis **146** of feed **70** in the X-Y planar direction. In this manner, control of transmit feed displacement responsively controls the angular offset of transmit beam **28** from optical axis **42** in azimuth and elevation.

Another example of the above described angular offset is illustrated in FIG. 3F. FIG. 3F is a plot of antenna transmit power/gain versus angular deviation from optical axis **42** for antenna assembly **20** transmitting at approximately 22 Ghz, and arranged with transmit feed **70** offset approximately 1.66 inches from origin O in the X-direction. The 1.66 inch displacement between transmit feed **70** and origin O causes a 25 millidegree angular offset between the peak transmit gain PG' and optical axis **42**, as depicted in FIG. 3F.

It is to be understood that in the beam waveguide optics of antenna assembly **60**, interaction with and control of receive and transmit EM beams **66***b*,**66***a* is reciprocal, i.e., the same, with respect to both the receive and transmit beam-path directions, with the exception that receive feed **68** is fixed. The receive and transmit beams trace equivalent but reverse paths through the beam waveguide optics of assembly **64**, and are thus equivalently influenced thereby. With regard to the receive beam path, down-link signal **34** received by receive beam **30** from a predetermined direction, is directed by main reflector **40** and sub-reflector **130** to intermediate waveguide assembly **64**. Waveguide assembly **64** in turn directs beam **66***b* from main reflector **40** to receive feed **68** positioned at O'. Receive feed **68** directs beam energy collected thereby to a receiver of antenna system **20**, not shown.

In brief summary, the preferred embodiment includes moveable transmit feed **70** and fixed receive feed **68** within edifice **134** to feed the beam waveguide assembly **64**. Receive beam **30** is steerable through conventional beam steering techniques previously discussed, e.g., using APC **90** and motors and servomechanisms **67** controlled thereby, whereas transmit beam **28** is independently steerable through controlled displacement of transmit feed **70**. Transmit beam **28** is also steerable using the conventional technique.

FIG. 4 is a perspective view of platform assembly **72** used to support and displace transmit feed **70**. Platform assembly **72** is a commercially available product sold by, for example, Parker Hannifin Corporation located in Pennsylvania. Platform assembly **72** supports transmit feed **70** and is adapted to displace the position of transmit feed **70** in a planar direction, e.g., in the X-Y plane. Platform assembly **72** is a vertically stacked structure including a base **200** fixed or resting on surface **76**. An X-translation table **202** disposed above and slidingly coupled to base **200** is displaceable in the X-direction. A Y-translation table **204** disposed above and slidingly coupled to X-translation table **202** is displaceable in the Y-direction. Transmit feed **70** is supported by an upper surface **206** of Y-translation table **204** and is displaced therewith.

An upper surface **208** of base **200** includes a pair of parallel rails **210** extending in the X-direction. A set of parallel legs, not shown, depend vertically from a lower surface of X-translation table **202**. The set of parallel legs slidingly engage parallel rails **210**, whereby X-translation table **202** can be driven to slide in the X-direction. A first actuator assembly includes a motor **220** fixed to base **200**, and a threaded rod **218** rotatably driven by motor **220**. Threaded drive rod **218** is rotatably coupled to X-translation table **202**, whereby X-translation table **202** is driven to slide in the X-direction responsive to a rotative displacement of threaded drive rod **218** by motor **220**. Specifically, X-translation table **202** is displaced in opposing X-directions responsive to bi-directional rotative displacement of threaded rod **218** by motor **220**.

Similar to the above arrangement, a pair of parallel rails **230** extending in the Y-direction are fixed relative to X-translation table **202**. Y-translation table **206** is driven to slide along rails **230** by a second actuator including a motor **238** and an associated threaded rod **239** coupled to Y-translation table **204**.

Actuator control signals **112***x*,**112***y* are provided to respective control inputs of motors **220**,**238** to control the rotative displacement imparted by these motors to respective drive shafts **218**,**239**, to thus control the displacements of respective X- and Y-translation tables **202**,**204**. Actuator control signals **112***x*,**112***y* control the number of revolutions, the angular velocity, and the angular acceleration of respective drive shafts **218**,**239**. In this manner, actuator control signals **112***x*,**112***y* control the magnitude, velocity, and acceleration of the X and Y displacements of feed **70**.

FIGS. 5A and 5B are predicted performance curves for antenna assembly **20** operating at a Ka band frequency, e.g., 34 GHz, and with a main reflector diameter of 35 meters. FIG. 5A is a plot of peak transmit beam gain loss versus transmit feed displacement along the X and Y axes. FIG. 5B is a plot of beam deviation, i.e., angular displacement from a reference axis, versus transmit feed displacement along the X and Y axes. Significantly, at a beam deviation or angular displacement of twenty millidegrees, corresponding to a feed displacement of approximately two inches from origin O, peak transmit beam gain loss is less than 1.5 dB. Such performance permits the beam tracking of a distant spacecraft in the presence of planetary aberration in accordance with the present invention. For instance, transmitter power, and thus the power of the uplink signal, can be increased to compensate for the relatively small decrease in peak-gain loss of transmit beam **28** resulting from the angular displacement of the transmit beam from optical axis **42** of the antenna.

In antenna system **20**, APC **90** and beam steering controller **116** control the beam forming/directing components of antenna assembly **60**. FIG. 6A is a block diagram of an embodiment of controller **116**. Controller **116** is a general purpose computer, e.g., a personal computer, as is known in the art. The controller includes a bus **300** for communicating information and a processor **302** coupled with bus **300** for processing information. A storage device **304**, e.g., a disk, is provided and coupled to bus **300** for storing static information and instructions for processor **302**. Controller **116** further includes a main memory **306** coupled to bus **300** for storing instructions to be executed by processor **302**, and for storing the apriori spacecraft position information downloaded via interface **118**. Main memory **306** is also used for storing temporary variables or other intermediate information during execution of instructions executed by processor **302**.

Controller **116** includes a two-way data communication interface **308** coupled to bus **300**. Communication interface **308** includes interfaces **120**,**118**. Controller **116** includes a display **310** for displaying information, e.g., status, to antenna system operators. Operators enter information into controller **116** with an input device **312**.

Processor **302** executes sequences of instructions contained in main memory **306**. Such instructions are read into memory **306** from another computer-readable medium, such as storage device **304**. Execution of the sequences of instructions contained in memory **306** causes processor **302** to perform various method and operational steps of the present invention. In alternative embodiments, hard-wired circuitry can be used in place of or in combination with software instructions to implement the invention.

Controller **110** directly controls the movement of transmit feed **70**. An embodiment of transmit feed controller **110** is depicted in FIG. **6**B. Feed controller **110** includes a bus **350** coupled with the following components: a processor **352**; a main memory **353** for storing program instructions executed by processor **352**; a communication interface **354** for receiving beam steering commands from controller **116**; and, a pulse generator **356** for generating control signals **112***x*, **112***y*. Processor **352** translates transmit feed displacement commands received via interface **120** to pulse generator commands, including displacement magnitude, velocity and acceleration commands. Processor **352** issues the pulse generator commands to pulse generator **356**. Pulse generator **356** derives pulsed, actuator control signals **112***x*,**112***y* in real-time responsive to the pulse generator commands issued thereto.

As mentioned above, antenna system controller **62** (FIG. **2**) derives control signals and commands for controlling antenna assembly **60**. Specifically, APC **90** derives antenna steering control signals **92**,**94** while controllers **110** and **116** derive actuator control signals and **112***x*,**112***y* to control the position of transmit feed **70**. The following exemplary sequence of method steps describes the derivation and application of these control signals, and the control of antenna assembly **60** to thereby compensate for planetary aberration in the beam tracking of spacecraft **24**.

FIG. **7** is a high level flow diagram for controlling antenna assembly **60** to compensate for planetary aberration. At step **390**, the process is started. At step **400**, apriori spacecraft trajectory information corresponding to trajectory **26** is downloaded from an external source, not shown, to controllers **90**,**116** via respective interfaces **100**,**118**.

Next, at step **405**, controller **116** uses the apriori trajectory information to determine an apriori past position, e.g. p**1**, and an apriori future position, e.g., p**2**, corresponding to an apriori present time and an associated apriori present position, e.g., p**3**, using the RTLT of down-link and uplink signals **34**,**32** between antenna assembly **60** and spacecraft located at apriori present position p**3**. This preparatory step **405** can occur at any time before spacecraft **24** is actually at present position p**3**.

Next, at preparatory step **410**, controller **116** derives an angular offset between receive and transmit beams **30**,**28**, e.g., angular offset **44**, corresponding to an alignment of receive and transmit beams **30**,**28** with respective past and future positions p**1**,p**2**

Next, at preparatory step **415**, controller **116** translates angular offset **44** to a corresponding positional displacement of moveable transmit feed **70** from origin O. Such displacement imposes the required angular offset **44** between receive and transmit beams **30**,**28**, when receive beam **30** is aligned with past position p**1**.

The next step, step **420**, is a real-time step, wherein antenna system **20** steers receive and transmit beams **30**,**28** into alignment with respective past and future positions p**1**,p**2** at the real-time occurrence of the present time, when spacecraft **24** is actually at the present position p**3** along trajectory **26**. Antenna system **20** imposes angular offset **44** between receive and transmit beams **30**,**28**, and in doing so, aligns receive beam **30** with position p**1** to receive downlink signal **34** arriving therefrom, and aligns transmit beam **28** so as to transmit uplink signal **32** in the direction of future position p**2**. It is to be understood that steps **400**–**420** are continuously repeated for positions p_n, p_{n+1} so as to maintain alignment between receive and transmit beams **30**,**28** and successive respective past and future positions (e.g., p**1**,p**2**) as spacecraft **24** traverses trajectory **26**. In this manner, receive and transmit beams **30**,**28** of antenna system **20** continuously track spacecraft **24** along trajectory **26** and continuously compensate for planetary aberration.

Method steps **400**–**420** are now explained more fully with reference to additional FIGS. **9**, **10** and **11**, wherein high-level method steps **410**, **415**, and **420** are respectively depicted in greater detail. In step **400**, apriori spacecraft trajectory information is downloaded into the memories of APC controller **90** and controller **116**. The apriori information is formatted to include a time-ordered list or series of successive spacecraft position entries **600** corresponding to trajectory **26** of spacecraft **24**, as depicted in FIG. **8**. Each of the entries includes the following:

1) an apriori (e.g., predicted) spacecraft position in AZ and EL coordinates, e.g., p**1**=AZ**1**, EL**1** etc., and
2) an associated time index or time reference indicative of a predicted real-time when spacecraft **24** will arrive at the associated AZ and EL, e.g., at real-time t**1**, spacecraft **24** will be at position p**1** (AZ**1**, EL**1**), etc.

Such information is conventional and can be downloaded to controllers **90**,**116** in advance or when needed thereby. Importantly, the time indexing of each of the entries permits a relatively straight forward identification of a future position once a past (or present) spacecraft position is identified. The future position is found by looking ahead in the position/time entries a predetermined amount of time. For example, once past position p**1** and time index t**1** associated therewith are identified, future position p**2** is determined by adding the appropriate RTLT to t**1**, to thus establish time index t**2**, which is then available as an index by which associated future position p**2** can be accessed. It is to be understood the positions of the spacecraft can be provided in AZ and EL coordinates, in RA/DEC coordinates, or in any other suitable coordinate system, so long as appropriate mathematical conversions there between and derivations therefrom ultimately permit the derivation of the transmit feed displacements required to align receive and transmit beams **30**,**28** with ascertained past and future positions p**1**,p**2**, in accordance with the present invention.

Importantly, antenna system controller **62** also uses the time indexes for real-time tracking of spacecraft **24**. More specifically, since APC **90** and controller **116** are time synchronized with each other and with real-time, each controller can determine in real-time the past, present and future positions p**1**–p**3** of spacecraft **24** corresponding to an instant in real-time by comparing the real-time to the time indexes associated with the apriori position entries.

As described above, at step **405**, controller **116** identifies apriori past, future, and present positions p**1**(AZ1, EL1), p**2**(AZ2, EL2) and p**3**(AZ3, EL3).

At step **410**, controller **116** derives angular offset **44**. A pair of angular coordinates or components α',β' define angular offset **44**, as illustrated in FIG. **1**. Controller **116** derives angular components α',β' at respective steps **445** and **450** (FIG. **9**) in accordance with the following equations:

$$\alpha'=[(\Delta EL)^2+(\Delta XEL)^2]^{1/2}$$

$$\beta'=\tan^{-1}(\Delta EL, \Delta XEL)$$

where $\Delta EL=EL2-EL1$, and $\Delta XEL=(AZ2-AZ1) * \cos(ELAVG)$, and where $ELAVG=(EL1+EL2)/2$

At step **415**, controller **116** translates angular offset **44**(α', β') to a corresponding positional displacement of transmit feed **70** from origin O, as described previously. More specifically, at step **455** (FIG. **10**), controller **116** translates or maps angular offset **44**((α',β') to a corresponding positional displacement of feed **70** defined in terms of planar polar coordinates ρ,ϕ, illustrated in FIG. **3**D. As depicted in FIG. **3**D, The displacement of transmit feed **70** from origin O includes a magnitude ρ and a direction ϕ, defined relative to the X-axis. This translation from angular offset **44**(α',β') to positional displacement ρ,ϕ proceeds in accordance with the following equations:

$$\rho=[(\Delta X)^2+(\Delta Y)^2]^{1/2}$$

where ΔX and ΔY represent displacements of transmit feed **70** in respective X and Y directions (see FIG. **3**D), and

$$\phi=-\beta'-(AZ-\phi_{stn})+EL+n\pi/2;\ n=-1$$

where AZ and EL represent AZ1 and EL1, and ϕ_{stn} is a constant depending on the location of antenna assembly **60**.

At step **460**, controller **116** translates transmit feed displacement ρ,ϕ into corresponding X and Y displacements ΔX, ΔY. This translation is necessary because in the preferred embodiment, platform assembly **72** is incrementally displaceable in X and Y directions by respective actuator assemblies thereof.

After completing preparatory steps **415**–**460**, antenna system controller **62** has available thereto the information required to align in real-time receive and transmit beams **30**,**28** with past and future positions p**1**,p**2**, to thus compensate for planetary aberration. APC **90** controls real-time steering of optical axis **42**, and both receive and transmit beams **30**,**28** therewith, while controller **116**, along with feed controller **110**, controls real-time independent steering of transmit beam **28**. Overall, real-time synchronization existing between APC **90**, controller **116**, and transmit feed controller **110** permits coordinated beam steering control of receive and transmit beams **30**,**28** by antenna assembly **62**.

Specifically, at the real-time occurrence of present time t**3**, i.e., at the time when down-link signal **34** arrives at antenna system **20** from the direction of past position p**1**, antenna system **20** performs the following steps:

1) at step **463** (FIG. **11**), APC **90** steers receive beam **30** into alignment with past position p**1** to receive the down-link signal arriving therefrom. Such steering requires APC **90** to drive optical axis **42** of antenna assembly **62** in azimuthal and elevational directions to bring receive beam **30** into alignment with past position p**1**; and

2) at step **465**, transmit beam **28** is steered into alignment with position p**2**. Specifically, controller **116** issues a transmit feed X,Y displacement command to transmit feed controller **110**. The X,Y displacement command includes the transmit feed X and Y displacements $\Delta X,\Delta Y$ required to impose angular offset **44**(α',β') between receive and transmit beams **30**,**28**, with receive beam **30** aligned with past position p**1** (see step **463**). The X,Y displacement command also includes a time entry indicative of the real-time when such displacements $\Delta X,\Delta Y$ must be imposed by feed controller **110**. Feed controller **110** generates in real-time actuator control signals **112**x,**112**y indicative of transmit feed displacement responsive to the X,Y displacement command. Platform assembly **72** appropriately displaces transmit feed **70** from origin O in the X-Y plane responsive to supplied actuator control signals **112**x, **112**y, as depicted in FIG. **3**D. The planar displacement thus imposed between receive and transmit feeds **68**,**70** correspondingly imposes angular offset **44**(α',β') between receive and transmit beams **30**,**28**, to compensate for planetary aberration.

In accordance with the present invention, antenna system **20** continuously tracks spacecraft **24** as the spacecraft moves along its trajectory **26**, to compensate for planetary aberration throughout the trajectory. Accordingly, APC **90** continuously steers receive beam **30** in real-time to track successive past positions of spacecraft **24**. Contemporaneously, controller **116** and feed controller **110** steer transmit beam **28** to track successive future positions of spacecraft **24**, associated with the successive past positions, by continuously updating angular offset **44** (α',β'), in response to updating of displacements $\Delta X,\Delta Y$ of transmit feed **30**. It can thus be appreciated that method steps **400**–**465** are repeatedly traversed to provide such continuous updating to beam track the movement of spacecraft **24** along its trajectory **26**.

In practice, an angular alignment error **470** (see FIG. **1**) typically arises between optical axis **42** and receive beam **28**, when receive beam **28** is aligned with position p**1**. Angular alignment error **470** arises because of systemic errors in antenna assembly **60**. At least two factors contribute to these systemic errors; imperfections in motors and servomechanisms **67** leading to imperfect steering of optical axis **42** by APC **90**, and imperfections in the optical components of the beam waveguide assembly leading to an angular offset error between optical axis **42** and the direction of receive beam **30** (and transmit beam **28**).

In the present invention, a bore-sighting calibration procedure quantifies angular alignment error **470**, thus leading to subsequent compensation thereof. One such calibration procedure includes receive beam tracking of a distant radio source having a known location, such as a star. More specifically, APC **90** steers optical axis **42** into alignment with the positional coordinates, e.g., AZ and EL or RA/DEC, of a known star. APC **90** systematically displaces, i.e., nutates, optical axis **42** with respect the position of the known star source. A receiver (not shown), coupled to an output of receive feed **68** and to APC **90** monitors radio signal power received from the star via receive beam **30**, while optical axis **42** is nutated. A maximum received signal is detected and a corresponding angular offset, e.g., angular offset **470**, identified. Angular offset **470** is stored in APC **90** memory as an angular alignment error, i.e., adjustment factor, for use during subsequent tracking of spacecraft **24**. APC **90** applies the adjustment factor as necessary throughout method steps **400–465** to fine tune the alignment of receive and transmit beams **30**,**28** with respective positions p**1**,p**2**. For example, at step **463** APC **90** steers receive beam **30** into calibrated alignment with position p**1** by incorporation of the adjustment factor into AZ and EL control signal pair **92**,**94**.

An antenna system for and method of compensating for planetary aberration in the receive and transmit beam tracking of a spacecraft has been described. Advantageously, receive and transmit beams formed by the antenna system are angularly separated or split to contemporaneously align the receive and transmit beams with separated past and future positions of the satellite. By concurrently aligning the peak gains of the receive and transmit beams with respective down-link and uplink signals transmitted between the antenna system and the spacecraft, the antenna system advantageously reduces the effect of propagational attenuation of such signals.

While there have been described and illustrated specific embodiments of the invention, it will be clear that variations in the details of the embodiments specifically illustrated and described may be made without departing from the true spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. An antenna assembly for forming and directing a transmit beam, comprising:

a main reflector;

a sub-reflector centered along an optical axis of said main reflector;

a moveable transmit feed for directing electromagnetic radiation along a longitudinal axis thereof;

an intermediate beam waveguide assembly positioned between said moveable transmit feed and said main reflector, said intermediate beam waveguide assembly including fixed and moveable optical components for guiding electromagnetic beam energy between said moveable transmit feed and said main reflector; and

a first beam steering mechanism coupled with said moveable transmit feed for angularly displacing the transmit beam from said optical axis by displacing said moveable transmit feed in a direction substantially orthogonal to said longitudinal axis thereof.

2. The antenna assembly of claim **1**, comprising a fixed receive feed for receiving electromagnetic beam energy directed thereto by said intermediate beam waveguide assembly, said receive feed being associated with a receive beam.

3. The antenna assembly of claim **2**, wherein said first beam steering mechanism includes an actuator coupled with said moveable transmit feed, said actuator being adapted to impart a displacement to said moveable transmit feed in said orthogonal direction responsive to an actuator control signal supplied to an input of said actuator and being indicative of said displacement.

4. The antenna assembly of claim **3**, wherein said moveable transmit feed is driven in first and second orthogonal directions by said actuator to displace said moveable transmit feed in a planar direction substantially orthogonal to said longitudinal axis of said moveable transmit feed.

5. The antenna assembly of claim **4**, comprising a first controller for deriving said actuator control signal responsive to a displacement command supplied to an input of said first controller.

6. The antenna assembly of claim **5**, comprising a second controller for deriving said displacement command.

7. The antenna assembly of claim **6**, comprising a second beam steering mechanism coupled with said main reflector, said sub-reflector and said moveable optical components of said intermediate waveguide assembly, for rotating said main reflector, said sub-reflector and said moveable optical components about first and second orthogonal rotational axes to correspondingly rotate together said receive and transmit beams about said rotational axes.

8. The antenna assembly of claim **7**, wherein said first and second orthogonal axes correspond to azimuthal and elevational axes.

9. The antenna assembly of claim **8**, wherein said second beam steering mechanism includes a motor and a servomechanism assembly for rotating said main reflector, said sub-reflector and said moveable optical components responsive to control signal indicative of a rotational displacement, said second beam steering mechanism including a controller for deriving said control signal indicative of said rotational displacement.

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