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(71) Applicant: **BAE Systems PLC**
London SW1Y 5AD (GB)

(72) Inventor: **The designation of the inventor has not yet been filed**

(74) Representative: **BAE SYSTEMS plc**
Group IP Department
Lancaster House
P.O. Box 87
Farnborough Aerospace Centre
Farnborough, Hampshire GU14 6YU (GB)

(54) Structure

(57) A structure, and a method for modifying the design of a structure, are provided such that the structure comprises features designed to minimise the radar cross-section of the structure at one or more predetermined frequencies. A structure is provided having an inclined surface, wherein the angle of inclination of the surface is selected in order to minimise the radar cross-section of the structure. In the particular case of a wind turbine tower, the radar cross-section of the tower may be minimised by careful selection of the angle of inclination of a conical portion of the tower. Ideally, the tower is constructed entirely in the form of a truncated cone.

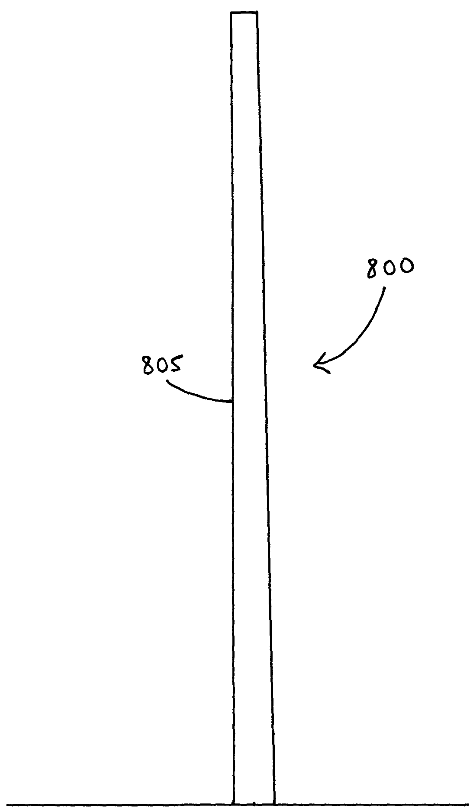

Figure 8

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Description

[0001] This invention relates to structures which conventionally have large radar signatures and in particular, but not exclusively, to improved structures having structural features that serve to reduce their radar cross-section (RCS).

[0002] Currently, approximately 47% of planning applications for wind farms in the United Kingdom are objected to on the basis of their potential to cause interference to radar signals. Consequently, a number of government-sponsored projects have focussed either on mitigating these effects by improved radar signal processing or through the development of wind turbines with reduced radar signatures.

[0003] The magnitude with which a particular object scatters radar energy is characterised in terms of its radar cross section (RCS). The RCS of an object is dependent on the size and shape of the object and on the material from which it is made. In respect of a particular radar installation, the RCS of an object is also dependent on the relative positions of the transmitting and receiving antenna apertures of the installation, and on the angle of polarisation of the electromagnetic (EM) wave incident on the object.

[0004] From a first aspect, the present invention resides in a structure, at least a portion of which comprises an inclined surface, wherein the angle of inclination of the inclined surface is selected to minimise the radar cross section of the structure at one or more predetermined frequencies.

[0005] The inventors in the present case have realised that the RCS of a structure can be significantly reduced, in particular for a structure comprising a tower, by arranging for at least a portion of the outer surface of the tower to be inclined relative to the vertical, to some extent. The angle of inclination is calculated to minimise the RCS of the tower over one or more selected frequency bands.

[0006] Preferably, the angle of inclination is selected to correspond to an angle for which a minima occurs in the sidelobes formed in a scattering pattern of incident electromagnetic radiation of said one or more predetermined frequencies. This refinement is often able to provide a further reduction in RCS over that provided by merely inclining the surface by some arbitrary angle.

[0007] Ideally, a tower in the shape of a truncated cone can be provided with an angle of slope for the sides of the cone designed to minimise the RCS. However, a very tall conical structure may in practise require a very wide base. Preferably, in a compromise arrangement, the structure comprises a conical section supported on a cylindrical section.

[0008] Whereas it is known to provide structures in the form of towers made using at least one conical section, such structures are designed primarily for their aerodynamic and load-bearing properties, not in order to minimise their RCS. According to the present invention, with careful selection of the shape of a structure, in particular of the angle of inclination of the surface of the structure, the RCS of that structure may be minimised.

[0009] A structure such as a tower comprising cylindrical and/or conical sections, and hence having a circular cross-section, is likely to have a substantially uniform RCS over a range of azimuthal angles, that is, the RCS will not have been minimised in respect of any one direction. However, if it is known that the RCS of the structure needs to be minimised in only one direction, for example because the structure is likely to be in the field of view of a single radar installation at a single known location, cross-sections other than circular may be used, subject to aerodynamic and other considerations, to further reduce the RCS of the structure in that one direction.

[0010] From a second aspect, the present invention resides in a wind turbine having a tower that comprises a substantially conical section, wherein the angle of inclination of the surface of the conical section is selected to minimise the radar cross section of the tower at one or more predetermined frequencies.

[0011] Typical shaping angles vary according to the height of the tower and the relative geometries of the cone and cylinder portions (if required). Substantial reductions in monostatic RCS, preferably in the range of 10-20dBsm, are achievable using cone slope angles of less than 2° for most tower geometries at the frequencies of interest. Preferably, an angle is selected which gives good reductions in more than one frequency band in order to minimise the impact of the structure on the most widely deployed radar installations.

[0012] From a third aspect, the present invention resides in a tower, in the shape of a truncated cone, wherein the angle of inclination of the surface of the tower is selected to minimise the radar cross-section of the tower at one or more predetermined frequencies.

[0013] Preferred embodiments of the present invention will now be described in more detail, by way of example only, with reference to the accompanying drawings of which:

Figure 1 is a representation of the structure of a known wind turbine tower;

Figure 2 illustrates the principles of backscattering of incident radar radiation by a cylindrical structure;

Figure 3 is a graph showing a typical sidelobe pattern in backscattered radiation by an electrically large cylinder at varying angles of inclination;

Figure 4 shows how the RCS (at 3GHz) of a conventional wind turbine tower may be varied through changes to the shape of a conical portion of the tower according to preferred embodiments of the present invention;

Figure 5 shows how the RCS (at 10GHz) of a conventional wind turbine tower may be varied through changes to the shape of a conical portion of the tower according to preferred embodiments of the present invention;

Figure 6 is a 2D plot showing how the RCS of the conical portion of a tower varies with both angle of inclination and frequency;

Figure 7 shows plots of the RCS of a conical portion of a tower at two different frequencies for the purpose of finding an optimum base diameter and hence slope angle according to preferred embodiments of the present invention; and

Figure 8 shows a preferred structure for a tower, in particular a wind turbine tower, devised according to preferred embodiments of the present invention.

[0014] A preferred embodiment of the present invention will now be described in the context of a wind turbine. Wind turbines are often deployed in open and exposed locations such as coastal or mountainous areas, and in large numbers forming so-called wind farms. Such locations are often likely to be within the field of coverage of coastal radar or air traffic control radar installations.

[0015] A wind turbine, for example one manufactured by Vestas Technology™, is a large structure comprising a tower, a nacelle to house a generator, and a two or three-blade rotor. The tower itself is approximately 80 metres tall. The inventors in the present case have modelled the electromagnetic properties of one of the wind turbines of Vestas Technology™, the V82 turbine, using a BAE SYSTEMS pic proprietary physical optics computer program called "MITRE". The MITRE software was used to evaluate the monostatic (i.e. the transmit and receive antennas are collocated) radar cross-section (RCS) of the V82 turbine at 3GHz in order to predict the magnitude of backscatter from the object. A commercially available hybrid computer program product called "FEKO" was used to perform the same evaluation of the V82 turbine at 10GHz. These frequencies were selected to correspond to those of the radars of the major UK operators which may be broken down into two distinct bands: 2.7-3.1GHz, covering air defence, civil and military air traffic control primary surveillance radars, and marine Vessel Traffic Services (VTS); and 9.1-9.41 GHz covering marine navigation radars, both shore-based and aboard civil/military small/large craft. In practise, a majority of the objections to proposed wind farm installations are raised by the operators of these radar types and it is highly probable that the same frequencies will be critical in other non-UK wind farm construction projects.

[0016] The results of the evaluations show that, from an RCS perspective, wind turbines can be considered to consist of four scattering component types: the blades (of which there are three on the V82 turbine); the nacelle, that houses the generator; the nosecone; and the tower. The predictions of backscatter generated by MITRE and FEKO for each of these component types were compared against those calculated using simple geometric optics-derived formulae for these components represented as simple shapes.

[0017] For the V82 turbine the RCS was found to be of the order of 57dBsm at 3GHz, increasing to 62dBsm as the object 'appears' electrically larger at 10GHz (approximating the 9.1-9.41GHz band). This is an enormous radar signature; greater than, for example, typical RCS values for naval ships at most orientation angles. The greater proportion of the RCS, around 75% in the case of the V82, is a result of backscatter of radar energy from the tower. The structure of a V82 tower is represented in Figure 1.

[0018] Referring to Figure 1, the known tower structure 100 comprises a cylindrical portion 105, typically of rolled steel construction, 3.65m in diameter and 54m in length, supporting a truncated conical section 110, also of rolled steel construction, 24m in length. The overall height of the tower is typically 78m.

[0019] Since the greater part of the monostatic RCS of a wind turbine is derived from the tower, reduction in the RCS of the tower is considered critical to the development of a reduced radar signature wind turbine.

[0020] There are a number of known methods for evaluating RCS for simple structures such as that of a wind turbine tower. In particular, the text book "Radar Cross Section", by E. F. Knott, J. F. Shaeffer, M. T. Tuley, Second Edition, Artech House, 1993, describes a general method for predicting RCS. Features of the "MITRE" software referred to above are described in a paper by A M Woods, C D Sillence and K D Carmody, entitled "Efficient Radar Cross Section Calculations on Airframe Geometries at High Frequencies", Proc. Second Test and Evaluation International Aerospace Forum, AIAA, London, 1996. However, irrespective of the technique used for evaluating RCS of a structure, the inventors in the present case have found that by adjusting the angle of inclination of a surface of a structure, for example a wind turbine tower that comprises a section that is conical in shape, the RCS of the structure may be minimised. The principles of RCS evaluation that demonstrate the beneficial effects of the present invention will now be described in outline with reference to Figure 2.

[0021] Referring to Figure 2, if the structure is assumed to be a simple upright cylinder 205, and an illuminating radar signal 210 is incident on the cylinder 205 from a horizontal direction, the microwave energy of the radar signal 210 will arrive and be scattered in phase along an infinitely thin "line" 215 running all the way along the length of the cylinder. In practise, coherent scattering, as modelled using evaluation techniques based upon physical optics, is assumed to result from plane wave illumination of a surface where the curvature of the surface is such that the total phase variation (over that surface) in a reflected wave 220 is less than one eighth of a wavelength - the so termed "Stationary Phase Zone". This zone forms a band 225 whose extent around the cylinder

205 either side of the "line" 215 varies as a function of frequency, being wider at low frequencies. The width of this band may be determined by conventional techniques, such as those referenced above, at each of the frequency bands of interest. However, the inventors in the present case have found that if the angle of the incident radar wave is changed slightly so that the incident radiation is no longer normally incident but is elevated or depressed, then specular scattering from the cylinder 205 no longer reaches the receiving aperture of the radar. The scattering is then governed by returns from the sidelobes in the scattered radiation. Within an overall sidelobe envelope, the sidelobes are periodic with increasing angle from normal incidence and hence at some angles the RCS may be significantly lower than at other angles that differ by only a fraction of a degree. The periodicity of the sidelobes is governed by discontinuities in the currents induced on the surface of the cylinder 205, in this example caused by the ends 230 of the cylinder. Hence, long cylinders yield very narrow sidelobes with high periodicity with increasing angle, while short cylinders yield wide sidelobes with low periodicity. A typical sidelobe envelope and periodic sidelobe pattern for a cylinder is shown in Figure 3.

[0022] Referring to Figure 3, it can be seen from the steeply sloping section 300 of the sidelobe envelope that even a small angle of inclination from normal incidence, of only one or two degrees, results in a significant reduction in RCS. However, as will be emphasised below and as can be seen from Figure 3, within the overall sidelobe envelope the periodic sidelobe pattern varies significantly with very small variations in angle of inclination, providing an opportunity, in a preferred embodiment of the present invention, for fine tuning of RCS through careful choice of angle. These effects occur similarly if, instead of tilting the angle of illuminating radiation of a cylinder 205 by a small angle away from normal incidence, the illumination remains horizontal but the sides of the cylinder are sloped to form a cone. In this case the RCS differs somewhat as the radius varies linearly along the length of the cone in addition to the effect on the RCS of a transverse electromagnetic wave being off-normal.

[0023] The inventors in the present case have developed a simple mathematical routine, based to some extent on principles described in the published references cited above, to predict the RCS of a wind turbine tower as a function of frequency and angle, i.e. for a tower comprising a truncated cone portion supported on top of a cylindrical portion. By careful selection of the cone and cylinder heights and the cone angle, the present inventors have demonstrated that it is possible to ensure that the radar cross section of the tower, from the perspective of a particular radar receiving aperture, is minimised for the two preferred frequency bands mentioned above. This is achieved by ensuring that illumination of the cone portion from the horizontal direction at both those frequency bands results in scattered radiation at or near respective minima in the sidelobe pattern within the sidelobe envelope. This gives rise to a greater reduction in RCS than would be achieved by simply altering the geometry of a tower from a simple cylinder to a cone of arbitrary slope angle. In that instance, the arbitrarily chosen slope angle may correspond to a sidelobe maxima being detected at the radar receiving aperture rather than a minima in the sidelobe pattern.

[0024] In summary, the reductions in radar cross section achievable according to preferred embodiments of the present invention, relative to the RCS of a simple cylinder, are of two types. Firstly, conversion of the simple cylinder into a truncated cone of an arbitrary cone angle, typically of 1 or 2 degrees, results in a significant reduction in the radar cross section consistent with the overall sidelobe envelope. Secondly, the sidelobe radiation pattern within that sidelobe envelope consists of a series of maxima and minima as described previously and hence the RCS can be further reduced, from the perspective of a particular radar receiving aperture, if a cone angle is chosen so that radiation scattered from the cone and detected by the radar is at or near a minima in the sidelobe pattern at the frequency bands of interest. This is possible because the variation in periodicity of the sidelobes with cone angle is frequency dependent. This variation in periodicity and other aspects will now be demonstrated and described with reference to figures 4, 5 and 6. These figures are provided in the context of an existing design of wind turbine tower having a cylindrical portion and a conical portion in the proportion (54m to 24m respectively) as described above with reference to Figure 1.

[0025] Referring firstly to Figure 4, assuming illumination by radiation of a frequency of 3GHz - the lower of the two radar bands of interest - three graphs 400, 405 and 410 of RCS are provided. The graph 400 shows how the RCS (sidelobe pattern) of the smaller conical portion of the tower would vary if its slope angle were to be varied between 0° and 1°. The graph 405 shows the RCS of the cylindrical portion as being fixed at approximately 56dBsm; the cylinder surface being of fixed slope. The graph 410 shows how the total RCS for the tower would vary if the slope angle of the conical portion were varied between 0° and 1°, taking account of the contributions from the cylindrical portion and the conical portion. It can be seen that for a wind turbine tower according to an existing design, where the cylindrical portion is significantly longer than the conical portion, the total RCS of the tower reduces only slightly as the slope of the conical portion is increased from 0° to 0.2° but negligibly thereafter. However, Figure 4 does emphasise that if the tower can be designed so as to comprise as great a proportion as possible in the form of a cone, the RCS of the tower would reduce much more considerably with increasing slope angle of the cone, in the limit corresponding to a plot similar to that shown in the graph 400 if the tower were to comprise only a conical portion.

[0026] Referring to Figure 5, a similar set of graphs 500, 505 and 510 are provided to those of Figure 4 in respect of the same tower design, on the basis of illumination by radiation of frequency 10GHz - approximating the higher of the two radar bands of interest. It can be seen, in particular, by comparing the periodicity in the sidelobe pattern 400 of Figure 4 with the pattern 500 of Figure 5, that the periodicity in the sidelobe pattern relating to the conical portion increases with increasing frequency of illuminating radiation. This provides an opportunity for finding an optimal slope angle corresponding to sidelobe minima at two different frequencies.

[0027] Referring to Figure 6, a 2D plot is provided showing how RCS varies with slope angle of the conical portion of a tower and with frequency, showing in particular the increase in periodicity of the sidelobe pattern of scattered radiation with increasing illumination frequency.

[0028] In practise, a preferred process for designing a tower or other similar structure having minimal overall RCS at one or more frequencies, according to preferred embodiments of the present invention, would use RCS graphs similar to those generated in Figure 4, 5 or 6 through modelling of the structure with known RCS evaluation techniques as described and referenced above. However, taking account of practical constraints in the configuration of a tower, in particular, the graphs 400 and 500 in Figure 4 and 5 respectively may be converted to show the variation of RCS for a conical portion in terms of the base diameter of the cone, rather than in terms of the angle of slope, for each frequency of interest. The converted graphs may then be shown on the same plot in order to identify an optimal base diameter (slope angle) for the cone, as shown for example in Figure 7.

[0029] Referring to Figure 7, a graph 700 of RCS for a cone for 3GHz radar and a graph 705 of RCS for a cone for 10GHz radar are shown. It is a relatively simple exercise to identify an optimal base diameter 710 for the cone, in this example at approximately 4.15m, corresponding to a slope angle of approximately 0.6°, if necessary within a practically convenient range of diameters, that results in a minimal overall RCS. Figure 7 demonstrates that it is possible to construct a tower, in particular a wind turbine tower, comprised only of a truncated cone that with slope angle chosen according the method described above minimises radar cross-section at both the main radar frequency bands in the UK. A preferred tower structure resulting from this method is shown in Figure 8.

[0030] Referring to Figure 8, a tower 800 is shown to comprise a truncated cone (a frustum) having a surface 805 whose angle of inclination is selected according to preferred embodiments of the present invention to minimise the radar cross-section of the tower at two radar frequency bands.

[0031] Preferably, an automated process may be implemented to identify the optimal base diameter/slope angle by the solution of simultaneous equations, one for each frequency, or by means of an iterative technique.

[0032] It can be seen from the above that, in the ideal case, a tower is comprised solely of a simple truncated cone, but in practise some cylindrical part may be required to ensure that the diameter of the tower base does not exceed the maximum permitted diameter for transport by road, for example. As a further practical constraint, the upper diameter of the truncated cone for use in a wind turbine tower is typically set at around 2.4m for the purposes of interfacing with the nacelle. However, according to the present invention, such constraints may be taken into account in providing effective means of RCS reduction for a wind turbine tower, and for similar structures, by shaping. Conveniently, parameters defining the design of a minimal-RCS structure, a tower for example, may be calculated and listed in tables so that the process of tower design may be reduced to one of looking up slope angles or other parameters defining the structure according to the frequency or combination of frequencies for which RCS is to be minimised.

[0033] Whereas there may be scope for reducing the RCS of an existing structure by making a slight modification to a part of the structure, for example by altering the angle of slope of a conical section of the structure, or replacing that section, it may be that the dominant contribution to RCS arises from a part of the structure that cannot be economically changed. For example, if the cylindrical portion of an existing wind turbine tower is the dominant contributor to overall RCS, then subtle changes in the slope of a conical section supported by the cylinder may make little difference to the overall RCS of the tower. This was demonstrated above with reference to Figure 4 and Figure 5. However, although an expensive solution in practice, cladding of the cylindrical portion to create a more conical overall shape, at an angle of slope selected according to the present invention, may have a beneficial effect in reducing the overall RCS of the structure. Preferably the shaping of a structure according to the present invention may be combined with the use of radar absorbent materials, in particular when applied at least to that part of the structure making the largest contribution to the overall RCS of the structure, for example to the cylindrical portion of a wind turbine tower, to further reduce the radar signature of the structure beyond that achievable through shaping alone.

[0034] The present invention may be applied, potentially, to any structure in which shaping has the potential to yield significant RCS reduction.

Claims

1. A structure, at least a portion of which comprises an inclined surface, wherein the angle of inclination of the inclined surface is selected to minimise the radar cross section of the structure at one or more predetermined frequencies.

2. A structure according to Claim 1, wherein the angle of inclination is selected to correspond to an angle for which a minima occurs in the sidelobes formed in a scattering pattern of incident electromagnetic

radiation of said one or more predetermined frequencies.

3. A structure according to Claim 1 or Claim 2, comprising a substantially conical section.

4. A structure according to Claim 3, in the form of a tower comprising a substantially cylindrical section supporting said substantially conical section.

5. A wind turbine having a tower that comprises a substantially conical section, wherein the angle of inclination of the surface of the conical section is selected to minimise the radar cross section of the tower at one or more predetermined frequencies.

6. A wind turbine according to Claim 5, wherein the angle of inclination is selected to correspond to an angle for which a minima occurs in the sidelobes formed in a scattering pattern of incident electromagnetic radiation of said one or more predetermined frequencies.

7. A wind turbine according to Claim 5 or Claim 6, wherein the tower further comprises a substantially cylindrical section.

8. A tower, in the shape of a truncated cone, wherein the angle of inclination of the surface of the tower is selected to minimise the radar cross-section of the tower at one or more predetermined frequencies.

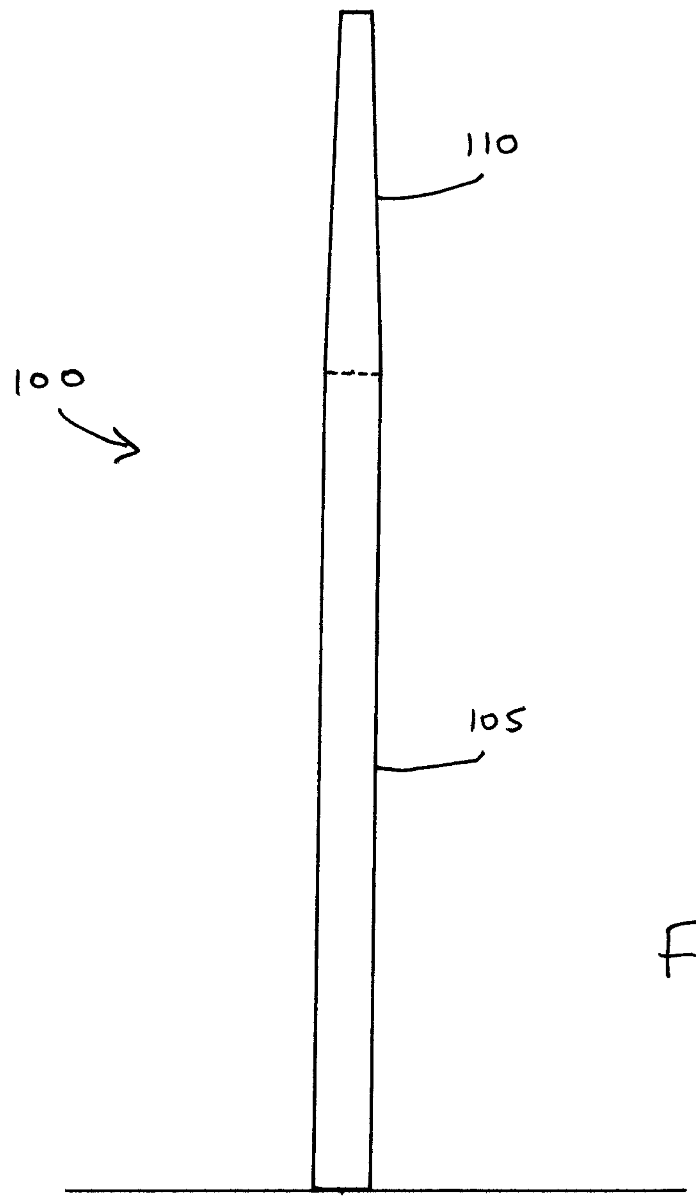

Figure 1

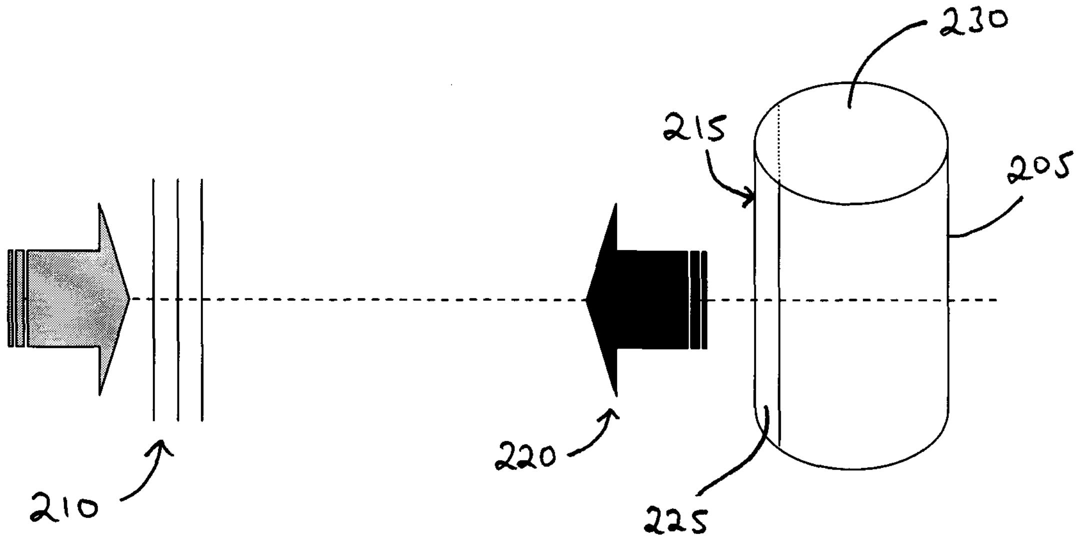

Figure 2

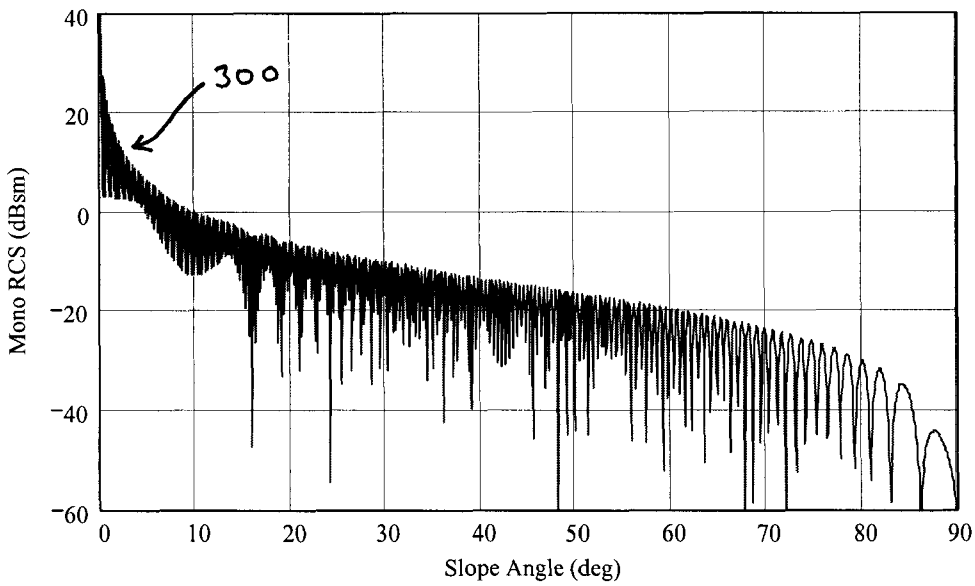

Figure 3

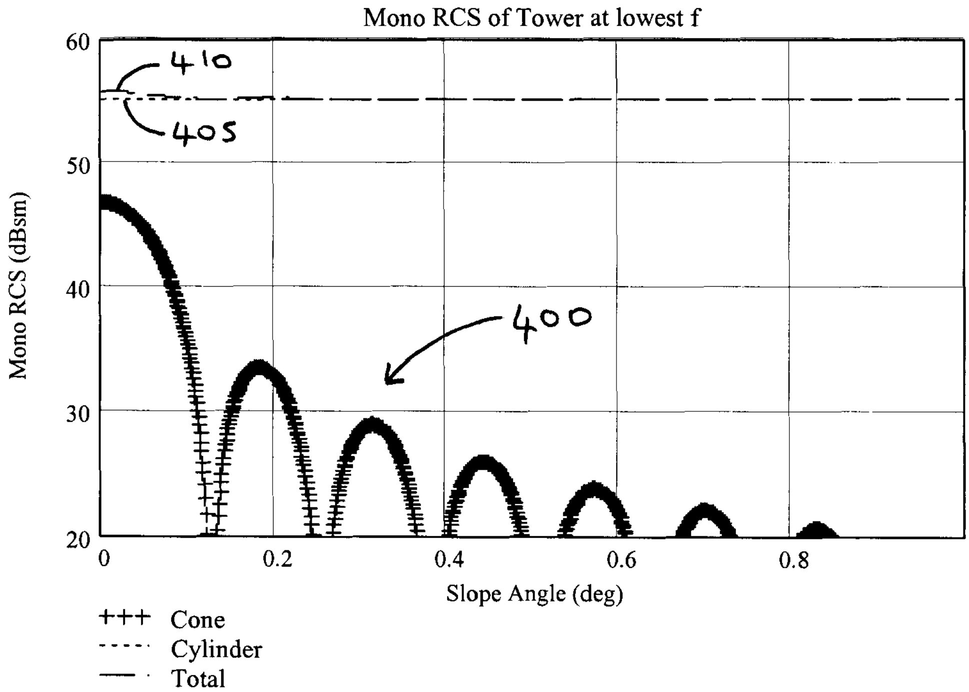

Figure 4

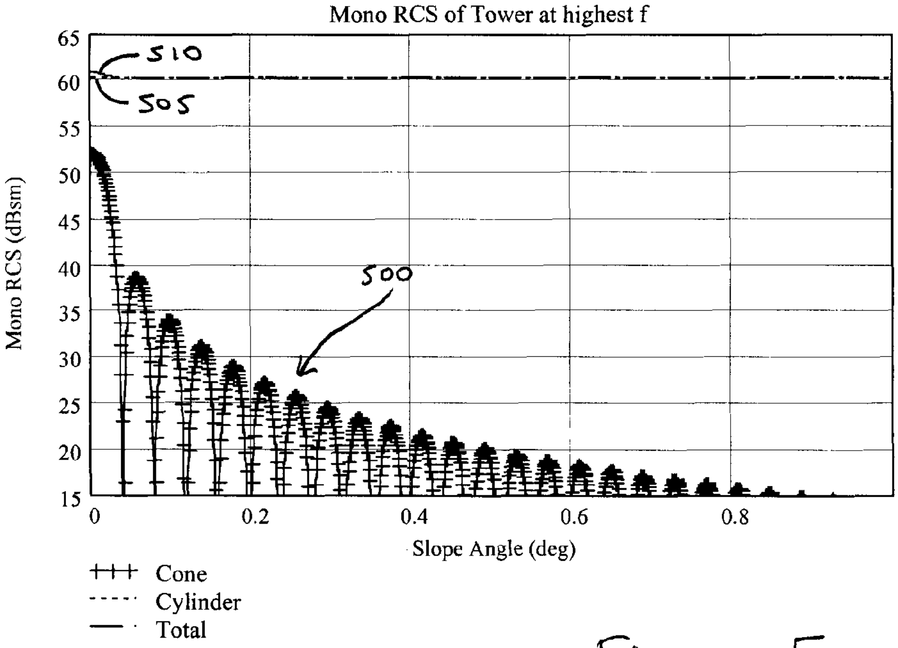

Figure 5

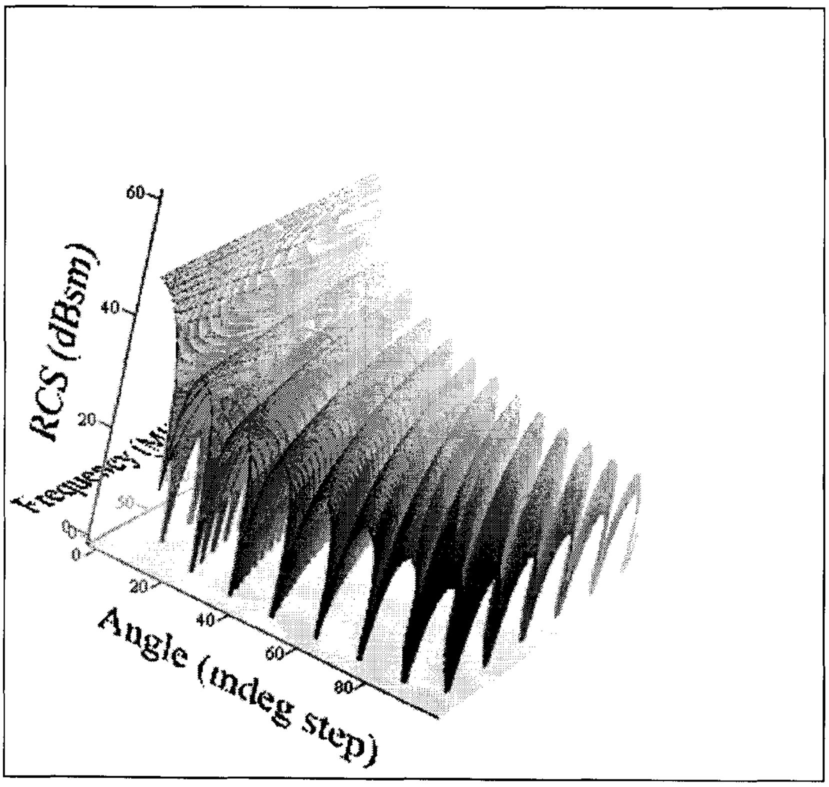

Figure 6

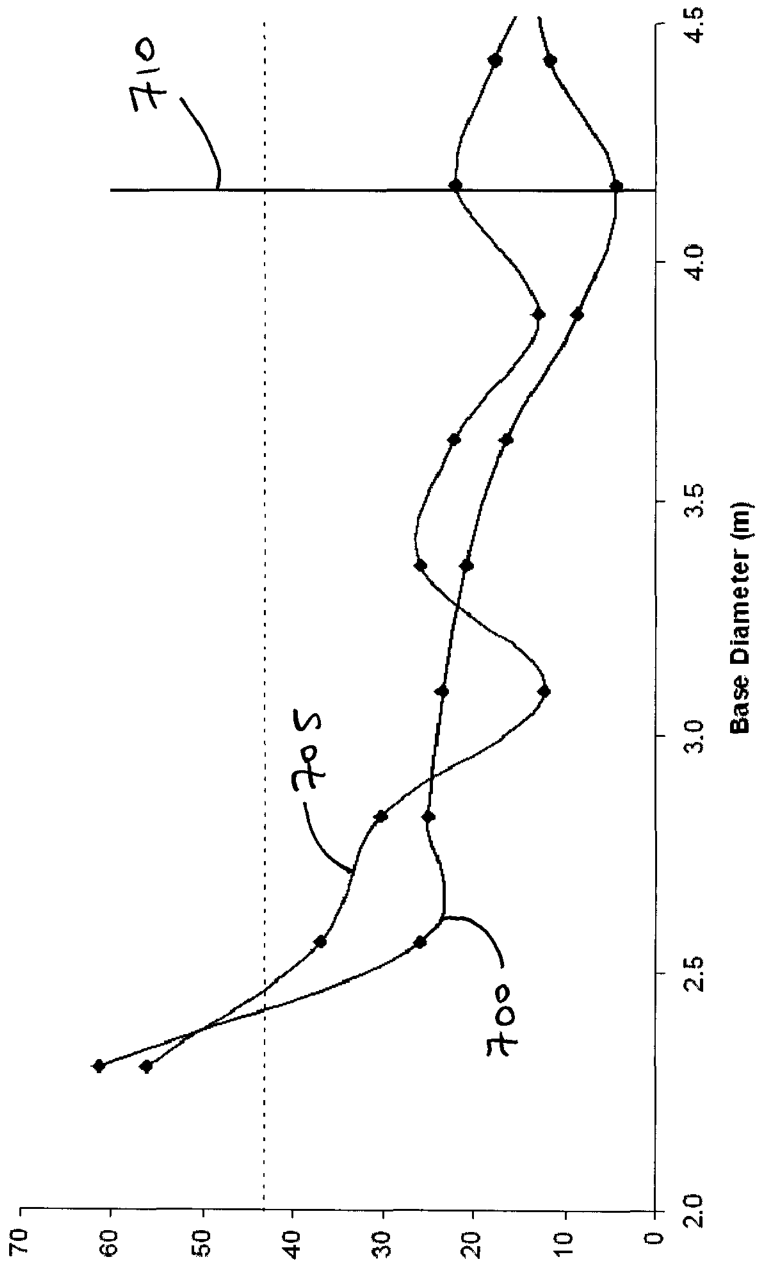
Monostatic RCS (dBsm)
Base Diameter (m)
0
10
20
30
40
50
60
70
2.0
2.5
3.0
3.5
4.0
4.5
700
705
710

Figure 7

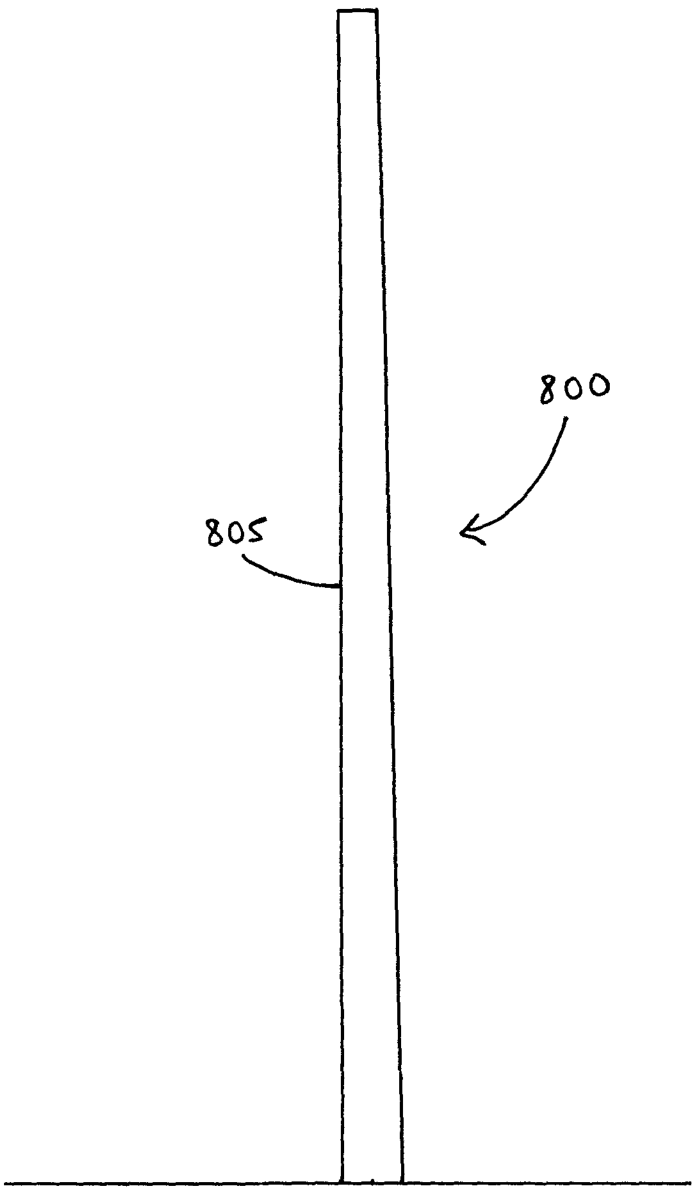

Figure 8

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EUROPEAN SEARCH REPORT

Application Number
EP 06 27 0086

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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The present search report has been drawn up for all claims

3

Place of search	Date of completion of the search	Examiner
The Hague	11 January 2007	Wattiaux, Véronique

CATEGORY OF CITED DOCUMENTS

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X	WO 2004/068630 A2 (BAE SYSTEMS INFORMATION [US]; MARSAN LYNN A [US]; URBANIK EDWARD A [US]) 12 August 2004 (2004-08-12) * the whole document * -----	1	
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