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5 APPARATUS FOR DETERMINING A WATER CRAFT'S OWN SPEED

The invention relates to an apparatus for determining a water craft's own speed by Doppler measurement, of the generic type defined in the precharacterizing clause of claim 1.

In the case of such so-called Doppler logs, sound energy is transmitted at the transmission frequency f_s at an inclination angle α to the movement plane of the water craft, is reflected from the seabed or from the water, and the reflected components of the sound energy are received again, with their frequency being shifted through the so-called Doppler frequency shift f_D with respect to the transmission frequency f_s . The velocity v of the vehicle is determined from the Doppler frequency shift f_D using

$$f_D = 2 \frac{v}{c} \cdot f_s \cdot \cos \alpha$$

where c is the speed of sound in the water. If the inclination angle α of the transmission and reception direction, which is normally referred to as the main lobe direction of the antenna, is adjusted by shifting the phase of the drive to the individual transducers, then the measured Doppler frequency shift is independent of the speed of sound c and the installation of the antenna in the water craft becomes simpler, since the antenna may be in the form of a flat antenna which is aligned parallel to the movement plane of the water craft.

In the case of a known Doppler log (DE 1 798 276 C1), the antenna transducers are split into groups which are operated in parallel, with the transducers in each group being fed with a rotating field from a polyphase generator whose rotating field revolves cyclically at the transmission frequency f_s . The rotation direction of the rotating field determines whether the main lobe direction, which is inclined with respect to the movement plane of the water craft, of the antenna is directed ahead of the marine vessel or astern of the marine vessel. The transmission frequency f_s is defined, and is fixed, by the antenna design, that is to say by the distance between the transducers that are operated in phase, and the desired inclination angle α of the main lobe direction of the antenna, which is normally between 45° and 60° .

In the case of one known Doppler log (US 5 694 372), the antenna is a so-called flat array comprising a multiplicity of electroacoustic transducers arranged in rows and columns. All of the transducers, which are located at equal intervals one behind the other in the row (y direction) on the one hand, and all the transducers which are located at equal intervals one behind the other in columns (X direction) on the other hand are electrically connected to one another and are connected to a beamformer for the X direction and to a beamformer for the Y direction. The transducers which are connected to one another are normally referred to as staves. During reception, the output signals from the staves are phase shifted in the correct phase, and are added in phase, in the X and Y beamformers. During transmission, the transmission signal which is applied to the staves is shifted through the same phase angle from one stave to the next, with the phase angle of 360° being split uniformly between the staves. The definition of the phase shading also defines the transmission frequency of the transmission signal and

the inclination angle of the main lobe direction of the direction characteristic of the flat array with respect to the horizontal plane, the so-called emission and transmission angle of the Doppler log.

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The invention is based on the object of improving an apparatus of the type mentioned in the introduction, such that its field of operation both with respect to the type of waterway and the waterway conditions as well as the type of vehicle is expanded, with precise velocity measurement being ensured in each application.

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According to the invention, the object is achieved by the features of claim 1.

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The apparatus according to the invention has the advantage that the Doppler measurement need not be carried out at a fixed predetermined operating frequency, with the operating range of the apparatus thus being fixed invariably, but the operating range can be matched to the respectively prevailing conditions by selection of a different transmission frequency. For example, it is possible to switch to a high transmission frequency in shallow water, allowing precise Doppler measurement even in shallow water. In deeper waterways, a sufficiently great measurement depth can be achieved by switching to a low transmission frequency, because of the reduced attenuation of the sound waves. Overall, the capability to switch between different transmission frequencies makes it possible to produce an apparatus with an operating range from one to several hundred meters, thus making it possible to carry out precision measurement from shallow waterways to deep waterways.

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In all cases, the inclination angle of the main lobe direction of the antenna with respect to the movement plane of the water craft remains the same.

As a result of this operating range flexibility, the apparatus according to the invention can be used with equally good measurement results both in surface vessels as well as in submarines and small autonomously operating underwater vehicles, so-called AUVs or drones, which frequently travel at a relatively short distance from the seabed. In many water craft, Doppler logs are normally operated in parallel with further electroacoustic transmitting and receiving devices installed in the water craft, such as sonar systems. The capability to switch the transmission frequency of the Doppler log makes it possible to avoid frequency-dependent conflicts between transmission and/or reception operation of the sonar systems and the Doppler log, and to operate all of them in parallel, without interruption. However, the broadband transducers also allow sound waves at different transmission frequencies to be emitted at the same time, if this is necessary in specific applications.

Expedient embodiments of the apparatus according to the invention, together with advantageous developments and refinements of the invention, are specified in the further claims.

According to one advantageous embodiment of the invention, the transducers which are driven in phase in the various groups are each connected to a common power amplifier, that is to say they are hard-wired to the power amplifiers. Independently of the setting of the transmission frequency, only as many power amplifiers are therefore required as the number of groups of transducers operated in parallel in the antenna. Despite the capability for transmission frequency switching and the multiple emission of transmission frequencies, only a low level of power amplifier complexity is therefore required in comparison to conventional Doppler logs.

According to one advantageous embodiment of the invention, the transducers are produced from a piezoelectric composite material, so-called composite, in which a multiplicity of ceramic elements are embedded in a polymer, with metallic surfaces making contact with their end faces. The antenna can be produced at low cost from this composite material, since all that is necessary to form its transducer is to etch the transducer electrodes out of the metallic surfaces. The antenna obtained in this way has a transmission and reception characteristic with a wide frequency bandwidth, high transmission power, high reception sensitivity and low sidelobes.

According to one preferred embodiment of the invention, in order to form at least one antenna, a sector is provided in a plate composed of composite material with metallic surfaces, and the transducers in the antenna are formed by etching the metallic surfaces of the plate in such a manner that rectangular electrodes in the form of strips are created, with long strips and narrower strip width, and are arranged in rows, leaving gaps when seen in the strip width. The strip length is in this case aligned at right angles to the projection line of the desired main lobe direction of the antenna onto the plate plane.

According to one preferred embodiment of the invention, a total of four sectors are provided on the plate, each form an antenna, and are offset through a circumferential angle of 90° with respect to one another. The alignment of the longitudinal edges of the electrode surfaces, which are in the form of strips, in the four different sectors is thus likewise offset through a circumferential angle of 90° , so that the strip length, that is to say the longitudinal edges of the electrodes, run parallel to one another in each

case two mutually opposite sectors. A design such as this allows simultaneous transmission and reception of sound waves in four main lobe directions offset through 90° with respect to one another. When, according to one
5 advantageous embodiment of the invention, the plate is arranged on the vehicle such that the four main lobe directions point ahead, astern, to port and to starboard of the water craft, then this results in an antenna configuration which can be produced at low cost
10 for a Doppler log which operates on the basis of the known "Janus principle". Because of the capability to switch the transmission frequencies, all four antennas can be operated selectively at the same transmission frequency, or each can be operated at different lengths
15 of the available transmission frequencies. In the latter case, antennas are preferably driven sequentially for transmission, and are then switched for simultaneous reception. The use of different transmission frequencies reliably prevents mutual
20 "crosstalk" between the antennas.

Successive driving of the individual antennas during transmission has the advantage that there is no need to use one set of power amplifiers in each case for all
25 the antennas, but the same set of power amplifiers can be connected to all four antennas by means of appropriate switching elements. Since power amplifiers for transmission operation are expensive components, the reduction in the number of power amplifiers, in
30 this case by a factor of four, very considerably reduces the total costs.

The provision of four separate antennas on the same composite material plate can be achieved at low cost by
35 means of a wet-chemical process, and leads to a small antenna configuration, based on the Janus principle. It is, of course, possible to form a total other than four of antennas on the plate, in which case the offset

angle of the antennas in the circumferential direction is determined by the number of antennas.

- According to one advantageous embodiment of the invention, the antennas are designed identically in all sectors of the plate. That electrode in the form of a strip which has the greatest strip length, that is to say the longest longitudinal edge, is arranged in the center. Successive electrodes are decreased symmetrically in steps, starting from the central electrode, toward the two outer electrodes. This results in a design with so-called mechanical shading in order to suppress sidelobes, that is to say a variable acoustic power output of the transducers, decreasing from the center of the antenna toward the edge. The magnitude of the steps of the strip length of individual electrodes is chosen to correspond to the desired shading.
- In order to additionally reduce sidelobes which occur transversely to the main lobe direction, the individual sectors according to one advantageous embodiment of the invention have concave curvature in the direction of the strip length of the electrodes. This results in the plate, which is occupied by four sectors and is composed of composite material, being approximately in the form of a hollow mirror. Since the influence of the curvature on the sidelobes is frequency-dependent, it is necessary to choose the curvature such that it is optimized for all the transmission frequencies which can be selected.

The invention will be described in more detail in the following text with reference to one exemplary embodiment, which is illustrated in the drawing, in which:

- Figure 1 shows a side view, in the form of a detail, of a vessel with a Doppler log, illustrated schematically,
- Figure 2 shows a plan view of the antenna configuration of the Doppler log shown in Figure 1,
- Figure 3 shows a section, in the form of a detail, along the line III-III in Figure 2, illustrated schematically,
- Figure 4 shows a section along the line IV-IV in Figure 2, illustrated schematically,
- Figure 5 shows a schematic illustration, in the form of a detail, of the hard wiring of the transducers in an antenna to power amplifiers in the antenna configuration shown in Figure 2,
- Figure 6 shows a table for the phase shading of the transducers in the antenna shown in Figure 5,
- Figure 7 shows a table for the phase shading of the transducers in a modified antenna with twelve transducers per transducer group.
- The surface vessel which is illustrated in the form of a schematic detail in Figure 1 as an exemplary embodiment of a general water craft is equipped with a Doppler log by means of which the surface vessel's own speed is measured over ground or through the water. The Doppler log, which operates on the so-called Janus principle, has an antenna configuration 11 as illustrated in the form of a plan view in Figure 2, which is attached to the bottom of the vessel hull, with an antenna plane aligned parallel to the movement direction of the surface vessel. The antenna configuration 11 has four antennas 111, 112, 113 and 114, which are arranged rotated through 90° with respect to one another. Each antenna 111 to 114 has a

directional characteristic with a main lobe direction 12 for transmission and reception of sound waves, also referred to as the main lobe of the directional characteristic, which is inclined through an inclination angle α with respect to the antenna plane, with the main lobe direction 12 of the antenna 111 pointing ahead, the main lobe direction 12 of the antenna 112 pointing astern, the main lobe direction 12 of the antenna 113 pointing to port, and the main lobe direction 12 of the antenna 114 pointing to starboard. The four antennas 111 to 114 are required when the aim is to transmit in all four directions at the same time. If this is unnecessary, then two of the four antennas 111, which are aligned at right angles to one another, are sufficient, for example the top and right-hand antenna 111 in Figure 2, since their main lobe directions 12 can be scanned to starboard and astern by varying the phase shading of the transducers 13. However, electronic switching means are then required in order to carry out the phase switching. Each antenna 111 to 114 has a multiplicity of electroacoustic transducers 13, which are arranged in a row or rows at equal intervals and are driven, for example, by a polyphase generator with phase shading at one transmission frequency. The transducers 13 in the antennas 111 and 112 and the transducers 13 in the antennas 113 and 114 are, however, each driven in antiphase with the same phase shifts. The emission angle α , that is to say the inclination angle α of the main lobe direction 12 with respect to the antenna plane, is governed by the distance d between the transducers 13 and the wavelength λ of the transmission frequency.

Each of the four identically configured antennas 111 to 114 is formed in one sector of a plate 18 composed of a piezoelectric composite material, so-called composite.

Piezoelectric composite materials and their production are known, and are described by way of example in DE 30 21 449 A1 or US 5 950 291. The plate 18 has a multiplicity of ceramic elements 14, which are separated from one another, are composed of a piezoelectric or electrostrictive ceramic, are embedded in a polymer 15, and have contact made with their end faces by a metallic surface, which is applied to the upper face of the plate 18, and by a metallic surface which is applied to the lower face of the plate 18. The section illustrations shown in Figures 3 and 4 show the configuration of the plate 18 composed of composite material, with Figure 3 showing a section III-III as shown in Figure 2, and Figure 4 showing a section IV-IV as shown in Figure 2 of the antenna 111. The column-like ceramic elements 14 are polarized at right angles to the plate plane, are preferably arranged like a matrix in rows and columns, and are isolated from one another by the polymer 15. The metallic surfaces on the upper face and/or lower face of the plate 18 are etched to form electrodes 16, 17, and the plurality of ceramic elements 14 are in each case combined to form a transducer 13. As can be seen from Figures 3 and 4, each transducer 13 in the illustrated exemplary embodiment has two ceramic elements 14 which are arranged alongside one another (Figure 3), and a different number of ceramic elements 14 (Figure 4) arranged transversely with respect to them. The etching process is carried out in such a way that rectangular electrodes 16, 17 are created in the form of strips, with a long strip length and a shorter strip width, with longitudinal edges arranged in a row or rows, leaving a separating gap free. The longitudinal edges are in this case aligned at right angles to the projection line of the main lobe direction 12 of the antenna 111 on to the plate 18. In the exemplary embodiment illustrated in Figures 3 and 4, electrodes 16, 17 in the form of strips are etched out of the

metallic surface, in an identical form, on both sides of the plate 18. However, it is sufficient for the electrodes 16 or 17 in the form of strips to be formed from one of the two metallic surfaces of the plate 18.

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In the exemplary embodiment shown in Figure 2, each antenna 111 to 114 comprises a total of twenty-four transducers 13 arranged in the main lobe direction 12 of the antennas 111 to 114 with a separation distance d (Figure 5), with these transducers 13 being formed by the configuration, in the form of strips, of the electrodes 16, 17 from the ceramic elements 14 described above. As can be seen in Figure 2, the length of the electrodes 16, 17, which are in the form of strips, of successive transducers 13 is decreased symmetrically in steps from the two central transducers 13 toward the two outer transducers 13, so that the transducers 13 have a different number of ceramic elements 14. This mechanical configuration of the transducers 13 results in the antenna having an acoustic power output which decreases from the center toward the edge, and is referred to as so-called amplitude shading. This mechanical shading largely suppresses unavoidable sidelobes in the directional characteristic of the antennas 111 to 114, which do not point in the main lobe direction 12, for interference-free operation.

The total number of transducers 13 in each antenna 111 to 114 is split into groups 20 with the same number of transducers, that is to say with the same number of transducers 13 (Figure 5), with the transducers 13 in one group 20 being driven with phase shading via power amplifiers 19. All the groups 20 are operated in parallel, so that the transducers 13 in each group 20 are fed with the same phase shifts. In the described exemplary embodiment of the antennas 111 to 114 with twenty-four transducers 13, the transducers 13 are, by

way of example and as is illustrated in the form of a detail in Figure 5, split into four groups 20 of six transducers 13 each, which are numbered successively from No. 1 to No. 6 in each group 20 in Figure 5. The transducers 13 which are driven in phase in each group 20 are hard-wired to in each case one power amplifier 19. The number of transducers in the parallel-operated groups 20 is chosen to be six so that a number of subgroups 21, in this case two, can be formed, each having the same number of transducers 13, in this case three, within each of the groups 20.

The circuitry for the antennas 111 to 114 is configured such that sound waves can be emitted at different transmission frequencies, and this can be done without any loss of power as a result of the broadband characteristic of the transducers 13, which is achieved by the physical design of the transducers 13 as described above. As mentioned initially, there is a fixed relationship between the transducer separation d between the transducers 13, the inclination angle α of the main lobe direction 12 and the wavelength λ of the transmission frequency f_s , in accordance with the known equation:

$$\cos \alpha = \frac{\varphi \cdot \lambda}{2\pi \cdot d} \text{ where } \lambda = \frac{c}{f_s},$$

where φ is the phase shift and c is the speed of sound in water. The transducer separation d is fixed, and the inclination angle α of the main lobe direction 12 of the antennas 111 to 114 must be maintained. The transducers 13 within the groups 20 are therefore split into at least two subgroups 21, which can be operated in parallel and have the same number of transducers 13. The circuitry for each of the subgroups 21 which are operated in parallel is connected to the same power amplifiers 19, and these are driven with the same phase

shifts, which are fixed for each transmission frequency f_s . While the transmission frequency f_s which corresponds to the lowest transmission frequency is applied to the transducers 13 in the groups 20 which are operated in parallel, the transducers 13 in the subgroups 21 which are operated in parallel are driven at a second transmission frequency, which is an integer multiple of the lowest transmission frequency f_s . The integer multiple is governed by the number of subgroups 21 which are operated in parallel. When driven at the second transmission frequency, the reduced number of transducers 13 which are driven with a phase shift in one subgroup 21 must accordingly have their phase shading changed, corresponding to the multiple of the frequency, in comparison to the phase shading of the transducers 13, which are operated at the lowest transmission frequency f_s , in the groups 20. In the described example, with four groups 20 of six transducers 13 each, the six transducers 13 in each group 20 are split into two subgroups 21 of three transducers each. As shown in the table in Figure 6, the six transducers 13 in one group 20 have the transmission frequency f_s applied to them, with the transducers Nos. 1 to 6 each being fed phase-shifted through 60° with respect to one another. The circuitry for this is illustrated in Figure 5. The possible second transmission frequency is now $2f_s$ because of the two subgroups 21 which are formed in each group 20. In accordance with what has already been stated, the transducers Nos. 1 to 3 and the transducers Nos. 4 to 6 in each group 20 have their circuitry combined in each case to form a subgroup 21 for operation of the antenna 111 to 114 at the second transmission frequency $2f_s$. The transducers Nos. 1 to 3 in the subgroup 21 are now each fed with a phase shift of $2 \times 60^\circ = 120^\circ$ via the power amplifiers 19. The transducers Nos. 4 to 6 in the second subgroup 21 in the group 20 are likewise fed

with a phase shift of $2 \times 60^\circ = 120^\circ$ via the power amplifiers 19, as is illustrated in Figure 5.

The table in Figure 7 shows the same illustration as that in the table in Figure 6, for a modified antenna with twelve transducers 13 per group 20 that is operated in parallel. As can be seen without any further explanation from the table, this number of transducers provide the capability to operate the antennas 111 to 114 at four different transmission frequencies, which differ by an integer multiple. In the exemplary embodiment shown in Figure 2, by way of example, a different transmission frequency can therefore be chosen for each antenna 111 to 114. It is also possible to operate all the antennas 111 to 114 at the same transmission frequency, and to select one of the transmission frequencies f_s , $2f_s$, $3f_s$, $4f_s$ that are available, whose frequency band does not overlap that of a sonar system which is operated in parallel in the surface vessel. Furthermore, it is possible to operate all the antennas 111 to 114, or individual antennas 111 to 114 at a plurality of selected transmission frequencies, or at all of the available transmission frequencies. As shown in the table in Figure 7, the twelve transducers 13 in the groups 20 which are operated in parallel are each fed with the frequency f_s , each phase-shifted through 30° with respect to one another. In order to emit the transmission frequency $2f_s$, two subgroups 21 of six transducers 13 each are formed in each transducer group 20, with the transducers 13 in each subgroup 21 being fed with a phase shift through $2 \times 30^\circ = 60^\circ$ with respect to one another. In order to emit the transmission frequency $3f_s$, the circuitry for the total of twelve transducers 13 in each transducer group 20 is combined to form three subgroups 21 of four transducers 13 each, with the transducers 13 in each subgroup 21 being fed at the frequency $3f_s$, phase-shifted through $3 \times 30^\circ = 90^\circ$ with

respect to one another. In order to emit the transmission frequency $4f_s$, finally, the transducers 13 in each group 20 are combined to form four subgroups 21 of three transducers 13 each, which are fed at the frequency $4f_s$, phase-shifted through $4 \times 30^\circ = 120^\circ$ with respect to one another. As can easily be seen, the multiplication of the lowest transmission frequency f_s at which the Doppler log can be operated is governed by the number of subgroups 21 formed in the circuitry.

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The Doppler log according to the invention can be used not only to determine the surface vessel's own speed, but is also particularly suitable, because of the small size of the antenna configuration 11 as shown in Figure 2, for use in submarines and in particular in autonomously operating or remotely controlled underwater vehicles, so-called drones or AUVs, alternatively ROVs, which are physically small. The diameter of the plate 18 can be reduced to about 100 mm for AUVs. It is, of course, possible for the plate 18 to also be rectangular. For submarines and AUVs, the plate 18 is likewise attached to the bottom of the vehicle body, so that the plate 18 is arranged parallel to a plane which is covered by the longitudinal axis and lateral axis of the underwater vehicle. In order to suppress or to largely reduce sidelobes which occur transversely with respect to the main lobe direction 12 of the antennas 111 to 114, the plate 18 is mechanically curved, thus resulting in it having a shape similar to a hollow mirror. The curvature is chosen such that an optimum reduction in these side lobes is achieved for all possible transmission frequencies.

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PATENT CLAIMS

1. An apparatus for determining a water craft's (10) own speed by Doppler measurement with at least one antenna (111 to 114) which is arranged on the water
10 craft (10), comprises a multiplicity of electroacoustic transducers (13) which are arranged in a row or rows at equal intervals and have a broadband transmission and reception characteristic, and, as a result of the transducers (13) being driven with a phase shift, has a
15 main lobe direction (12), which is inclined through an angle (α) with respect to the plane covered by the vehicle longitudinal axis and lateral axis, for the transmission and reception of sound waves, characterized in that the total number of transducers
20 (13) is split into groups (20) which can be operated in parallel and have the same numbers of transducers, with the total number of transducers (13) being chosen such that the transducers (13) within the group (20) can be combined to form subgroups (21), which can be operated
25 in parallel and have the same numbers of transducers, and such that, if the main lobe direction (12) of the antenna (111 to 114) is not changed, the transducers (13) in the groups (20) which are operated in parallel are driven selectively at a first transmission
30 frequency (f_s) and/or the transducers (13) in the subgroups (21) which are operated in parallel are driven at at least one second transmission frequency, which is an integer multiple of the first transmission frequency (f_s), with the multiplication factor being
35 determined by the number of subgroups (21) which are operated in parallel in each group (20).

2. The apparatus as claimed in claim 1, characterized in that the first transmission frequency (f_s) is a lowest frequency which is predetermined by the main lobe direction (12) and the transducer separation (d).

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3. The apparatus as claimed in claim 1 or 2, characterized in that transducers (13) which are driven in phase in the various groups (20) are each permanently connected to a common power amplifier (19).

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4. The apparatus as claimed in one of claims 1 to 3, characterized in that the transducers (13) are produced from a composite material with a multiplicity of ceramic elements (14), which are embedded in a polymer (15) and are composed of a piezoelectric or electrostrictive ceramic, with electrodes (16, 17) making contact with their end faces.

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5. The apparatus as claimed in claim 4, characterized in that the antenna (111 to 114) is formed in a sector of a plate (18) composed of composite material, and the electrodes (16, 17) which make contact with the ceramic elements (14) on at least one end face are in the form of strips with a strip length which is greater than the strip width, and are arranged in a row or rows with a column separation, seen in the strip width, with the strip length being aligned at right angles to the projection line of the desired main lobe direction (12) of the antenna (111 to 114) on to the plate plane.

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6. The apparatus as claimed in claim 5, characterized in that the strip length of the successive electrodes (16, 17) in the row decreases, starting from the central electrode (16, 17), toward the two outer electrodes.

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7. The apparatus as claimed in claim 5 or 6, characterized in that the sector has concave curvature

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in the direction of the strip length of the electrodes (16, 17).

8. The apparatus as claimed in claim 7, characterized
5 in that the curvature of the sector is matched to the frequency range covered by the transmission frequencies.

9. The apparatus as claimed in one of claims 5 to 8,
10 characterized in that four sectors are provided on the plate (18), each form an antenna (111 to 114), and are offset through a circumferential angle of 90° with respect to one another.

15 10. The apparatus as claimed in claim 9, characterized in that the plate (18) is arranged on the vehicle (10) such that, of the main lobe directions (12) of the antennas (111 to 114) formed from the sectors, one points ahead, one astern, one to starboard and one to
20 port.

11. The apparatus as claimed in one of claims 5 to 10, characterized in that two sectors are provided on the plate (18), each form an antenna (111), and are rotated
25 through a circumferential angle of 90° with respect to one another.