Proceedings of The Institute of Acoustics

STABILISATION METHODS FOR ACTIVE SONARS

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1. Introduction

This paper aims to introduce and discuss some of the problems associated with providing stabilisation for shipborne, active sonars. The findings are of general application although the need for stabilisation obviously becomes greater as the accuracy capability of a given system increases; high resolution, sector scanning equipment certainly requires to be isolated from the movements of its ship transport in order to achieve good results in open ocean conditions.

An effective and proven method of separating ship and transducer motion is to provide an electro-mechanically stablised platform which compensates a sonar's search position in sympathy with measured ship's movement. However, such an arrangement is costly to install and maintain and it is for these reasons that alternative methods have received attention, especially in recent years. Several possible techniques are considered in the following text where the individual merits and drawbacks of each scheme are compared. Finally a novel method is suggested which uses arrays of transducers both to transmit and receive and employs electronic beamshifting of the array directional patterns to apply the necessary geometric corrections. Under general conditions this stabilisation system only yields results comparable to a stablised platform if measures are taken to provide individual axial rotations of the transducers and to carefully control the shape of the transmit and receive beam patterns. Such restraints are liable to render this approach to stablilisation unattractive, especially to commercial users.

2. Achieving Stablisation

2.1. The Problem

Fig 1 illustrates how ship motion may be reduced to six components, three rotational (yaw, pitch and roll) and three translational (heave, surge and sway) related to a fixed axis system within the vessel. Of these components, all translational movements may be neglected for most stablisation purposes; as the sonar range increases the relative effect of heave, surge and sway in producing angular error and target loss decreases and becomes insignificiant when compared to the influence of rotational motion. Thus the stabilisation problem reduces to removing the effects of yaw, pitch and roll.

2.2. Possible Methods

a) Stablilised Platform

A stabilised platform provides direct physical compensation for the sonar transducers by sensing the three rotational components of vessel motion and then employing an electro-mechanical feedback system to move the platform which itself has three orthogonal axes of rotational freedom. Such an arrangement, though conceptually simple, is expensive and needs regular maintenance to avoid unreliable operation.

b) Display Corrections

All sonars present data to an operator using some form of display. Display correction has been widely used in marine radar systems to produce improved accuracy of results. Reference 1. The nature and feasibility of such correction when applied to a particular sonar will depend on the type of display and on the given application. The corrective power is limited since no physical, compensatory movement of the transducers or their beam patterns is involved. To achieve meaningful results display modification can only be incorporated as a refinement to other, more powerful techniques.

c) Discontinuous Transmission

If ship's motion is considered as three component rotations, a method of stabilisation can be postulated where the three rotations are monitored and it is arranged that the sonar only transmits when it is in the correct position within given accuracy limits. Unfortunately, even when considering just one motion such as roll, the time period involved immediately renders the technique unuseable - a typical roll period can be of the order of ten seconds for a large vessel. This means that a sonar would be in its correct position only once every five seconds. Also, the rotational speed of the vessel is greatest when passing through the zero roll angle position so that this stabilised zone for the sonar is maintained for a short time only. An angular speed of 18 degrees per second for a seagoing vessel is quoted in Reference 2. Taking an accuracy target of $\mp$ 1 degree, this would then necessitate limiting the working range of the sonar to the region of 80m.

It can be seen that discontinuous transmission is not workable even to compensate for roll alone, since it severely reduces data rate and maximum range. Consideration of pitch and yaw simultaneously with roll serves to amplify this conclusion.

d) Electronic Beamshifting

Electronic beamshifting has been successfully employed to stabilise vertical echosounders. Reference 3,4. The principle of electronic deflection of array patterns is well known and no further details will be given here. An apparent requirement for the implimentation of the method to sonar stabilisation is transducer arrays both for transmission and reception. Now assuming we can deflect the sonar directional patterns, we can consider how the process can be applied in more general cases than that of simple echo sounders. To do this an understanding of the three dimensional geometry of the situation is necessary.

Fig. 2 shows a fan-beam, beamwidth θ_H, lying in the horizontal plane and trained to point at an angle A to the roll axis of a ship. The transducers are centred at the point 1, which is taken to be the centre of buoyancy of the ship.

If the effect of roll is dealt with first, the ship is allowed to roll through the angle R so that the beam moves from its original position (position 1 in the diagram) to position 2. This motion moves the central axis of the beam through an angle A_C, measured in the horizontal plane, and also through an angle B_C, measured in the vertical plane containing its new position. Thus the train angle of the beam in the horizontal plane is now $(A - A_c)$ and it is inclined to the horizontal plane by the angle B_C.

Next consider the motion of the end positions of the fan beam, labelled as L and M on Fig. 2 If parallel planes of reference to those used to define the movement of the centre of the beam are taken, then the point L has moved by angular amounts A_L and B_L and point M by A_M and B_M, where:

$$A_L > A_C > A_M$$

and

$$B_L > B_C > B_M$$

This effect is produced because, in addition to its angular displacement, the centre of the beam undergoes a rotation in moving from position 1 to position 2.

The amount of movement of each part of the beam depends on the size of the roll angle R, the initial train angle A and the position of the particular section of the beam within the angle θ_H. If the beam were trained along the roll axis so that A is zero, then rolling simply produces rotation about the central axis. If $A = 90^o$, the beam is just rotated in the vertical plane passing through the centre.

Rotation about the pitch axis produces exactly the same type of motion on a beam originally on position 1, only in this case the conic angle of the movement of the beam centre is $(90 - A)^o$. So the effect of roll and pitch combined is to cause rotation about the central axis together with two net angular displacements of the beam centre, one being measured in the horizontal plane, the other in the vertical plane containing the final position of the beam axis.

Yaw brings about a direct alteration in the horizontal SPACE reference angle of the beam but the value of the train angle A measured with respect to the ship, is unaffected.

In order to show the combined result of yaw, pitch and roll it is expendient to use a spherical diagram as illustrated in Fig.3. The ship has its centre of buoyancy at the centre, O, of the sphere of radius R, with the sonar also placed at O. All the planes shown are Great Circle sections of the sphere and the intersection of these planes with the front face of the sphere are indicated by the full-line semi-elliptic curves. To aid description, the planes are numbered on the front face of the sphere and these numbers are used in the text.

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The horizontal plane (1) originally contains the fore-and-aft and athwartships axes of the ship, as shown. The sonar beam is trained at angles A and B in the horizontal and vertical planes respectively so that the initial position of the fan beam is in the vertical plane (3). After yawing through the angle Y has occurred, the fore-and-aft and athwartships axes move to positions FG and HJ and the fan beam moves into plane 4, which is again vertical. Plane 2 is vertical and now contains the fore-and-aft axis so that pitching can take place in this plane about the athwartships axis, taking the fore-and-aft axis to position KL. To complete the motion, rolling is introduced about this pitched axis, causing the athwartships axis to move to MN.

Plane 5 should now be recognised as the final position of plane 1 and plane 6 contains the resting place of the plane of the fan beam. Line OA, originally normal to the horizontal plane and fixed to the ship, has moved to a position OB, normal to plane 5.

The motion of the beam has altered its space reference angles in the horizontal and vertical planes from A to A' (both measured from the ship's ORIGINAL heading) and B to B' respectively, and has caused rotation of the fan about its central axis. Having now arrived at this understanding of the motion of the beam it is possible to consider correcting its position to effect stabilisation.

Take again the simple example of rolling motion applied to a horizontal fan beam as in Fig 2. Fig. 4 shows the fan beam drawn again in the same search position but this time as one axis of a rectangular cross-sectional beam which has a beamwidth θ_V on the vertical plane.

At the given range, the surface area of the nose of the beam is shown as the section PQST. Consider PQST to be insonified by a transmitter beam having beamwidths θ_V and θ_H and which is produced by a line of transducers lying in the plane of θ_V. This will enable the beam pattern to be deflected electronically in the vertical plane. In addition, a rectanular receiver beam, beamwidths θ_V and θ_H, covers PQST but this time beam deflection is possible in the plane of θ_H, which is horizontal.

Now consider the situation after rolling through the angle R. The angular movement of various parts of the beam is different, as was explained earlier, since the whole beamshape has been rotated about its central axis. It is therefore not possible to simply employ beamshifts on transmission and reception and larger beamwidths in the non-steerable planes of the transducers in order to return the area covered by both beams to its original position. This technique can be used in the vertical echo-sounder case because only the vertical depth below the ship is being measured and rotation of the beam due to yaw is ignored.

Intuitive thinking suggests, though, that if the beams were rotated about their central axis by an amount equal and opposite to the rotation produced by rolling, then beamshifts through the angles B_C and A_C (as previously defined) on reception and transmission respectively would stabilise the sonar. This is assuming that the beams are made the required amount wider in the non-steerable planes for a given maximum roll angle.

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The fact that this arrangement is not geometically possible can be clearly demonstrated by the use of the (x y z) co-ordinate system initially positioned as in Fig. 4. The x-axis points along the central axis of the beam, the y-axis in the direction of the line of the transmitter array and the z-axis along the line of the elements in the receiver array. After rolling through the angle R, the transducers and (x y z) have rotated so that the x, y and z axes point along Ox_1, Oy_1 and Oz_1. If a rotation about the Ox_1 axis is now performed, so that Oy_1 moves to Oy_2 and Oz_1 to Oz_2 the angle B_C is subtended by the x z and x_1z_2 planes and angle A_C exists between planes x y and x_1y_2.

In this position the transmitting array lies along Oy_2. So beam-shifting on transmission can be achieved in the x_1y_1 plane but movement through the desired angle B_C cannot be achieved. For this to occur, the z_2-axis would have to lie in the original xz plane so that plane x_1y_1 is normal to plane xz. This situation can be achieved, of course, by rotating the transducers about Ox_1 until the z_2-axis lies in the xy plane. On the other hand, if this is done, the y_2-axis cannot lie in the xy plane and so beamshifting normal to plane xy cannot be achieved simultaneously on reception and the desired stabilisation cannot be achieved. Also note that since A_C is measured in the horizontal plane it is not the actual beamshift angle required for the receiver beam.

The angle that must be moved through is directly related to the size of A_C but it is measured in the x_1y_2 plane after the y_2-axis has been moved by rotating about Ox_1 so that Oy_2 lies in the xy plane.

The argument of this last paragraph shows in fact that the method of stabilisation being considered here is workable if the correct individual rotations are applied to the transmitting and receiving arrays. Fig 5. through to Fig 13 illustrate this concept applied to a general but ideal case.

In Fig 5 the horizontal and vertical planes (1 and 2) shown in Fig. 3 have been drawn in a plane normal to the page so that only their front edges are visable. This is done to avoid adding unnecessary complication to later diagrams. The central planes (3 and 7) are shown of a rectangular cross-section beamshape which is pointing with its central axis along the same direction as that of the fan beam in Fig. 3. The beamwidths of a separate transmitter and receiver are θ_V and θ_H in planes 3 and 7 respectively. On transmission, beamshifting can take place in plane 3 and on reception it is possible in plan 7. The transmitter and receiver arrays can be rotated separately, each about a central axis normal to its face. In the diagram the required search sector is outlined by the dotted curves on the front face of the sphere.

Fig. 5 shows the effect of the ship's yaw, pitch and roll on the beams where:

A is the train angle of the sonar measured in the horizontal plane relative to the ship's fore-and-aft axis.
B is the angle of declination of the sonar below the horizontal plane.
Y is the yaw angle of the ship from a fixed heading.
P is the pitch angle measured in a vertical plane about the ship's athwartships axis.
R is the ship's roll angle measured about the pitched fore-and-aft axis.

Now it is necessary to treat the transmitter and receiver beams separately.

Transmitter

The transmitting array is rotated about its central axis so that plane 8 moves into plane 10 (Fig.7) where plane 10 is normal to plane 7. A beamshift on transmission is also utilised through the angle T (Fig. 8) which causes the transmitter beam to move within plane 10 until the beam's axis lies in plane 7.

The final orientation of the transmitter is shown by means of its central, planar axes in Fig. 9. It is seen that the central plane of the beam, in the plane normal to the one in which beamshifting occurs, now lies in plane 7. Plane 7 also contains the central plane of the beam when in its original position.

Receiver.

A similar procedure to the one just described can be carried out with the receiver beam. A rotation through the angle R_R about the central axis of the receiving array takes plane 9 into plane 11 (Fig. 10) so that the plane in which the receiver beamshift takes place (11) is now normal to plane 3. Beamshifting through the angle R_L (Fig.11) takes the central axis of the receiver beam into plane 3. Fig. 12 shows the final position of the receiver beam.

The angle T_B indicated in Fig.8 is a measure of the displacement of the central axis of the transmitter beam in plane 7 after its position has been modified using the angles T_R and T_L in the manner explained. So in order that the required sector of sea is always insonified by the transmitter beam, the beamwidth in the plane normal to the one in which beamshifting takes place must be increased from θ_H to θ_T where

$$\theta_T = \theta_H + (2 \times T_{B_{max}}).$$

Here, $T_{B_{max}}$ is the maximum value T_B takes with a given range of values of the angles Y, R, P, A and B.

Similarly, the increased beamwidth, θ_R, required for the receiver in the non-steerable plane is

$$\theta_R = \theta_V + (2 \times R_{B_{max}})$$

Angle R_B for the receiver corresponds to angle T_B for the transmitter and R_B is shown in Fig. 12.

In Fig 13 an ideal situation is drawn where only the original sonar search section is covered by both the stabilised transmitter and receiver beams. To achieve this result it must be assumed that the beams have rectangular cross-sections and that they can be electronically deflected, the transmitter subtending solid angles of θ_V and θ_T and the receiver solid angles equal to θ_H and θ_R, as shown.

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3. Conclusions

Several stabilisation methods for shipborne sonar have been investigated. no technique has been found to match the versatility of performance of a stabilised platform which has associated cost and maintenance problem. Of the remaining possibilities, the most attractive is a process involving electronic beamshifting both on transmission and reception together with individual axial rotations of the separate transducer arrays required. Drawbacks inherent in this stabilisation setup are:

The need for separate transducer arrays to transmit and receive.
Careful control required of transducer beam patterns.
Overscanning produces beam pattern distortion if deflection angles become large.
Complex compution required to convert measured ship motion to necessary beamshifts, maximum beam angles and transducer axial rotations.
Rotation of transducer arrays involves mechanical motion or matrix switching of elements in a complex pattern.

The overall conclusion must be that, except in certain simple cases, a stabilised platform still represents the best method of correcting high resolution and shipborne sonar for the effects of ship motion.

4. References

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FIG.1 Components of ship motion.

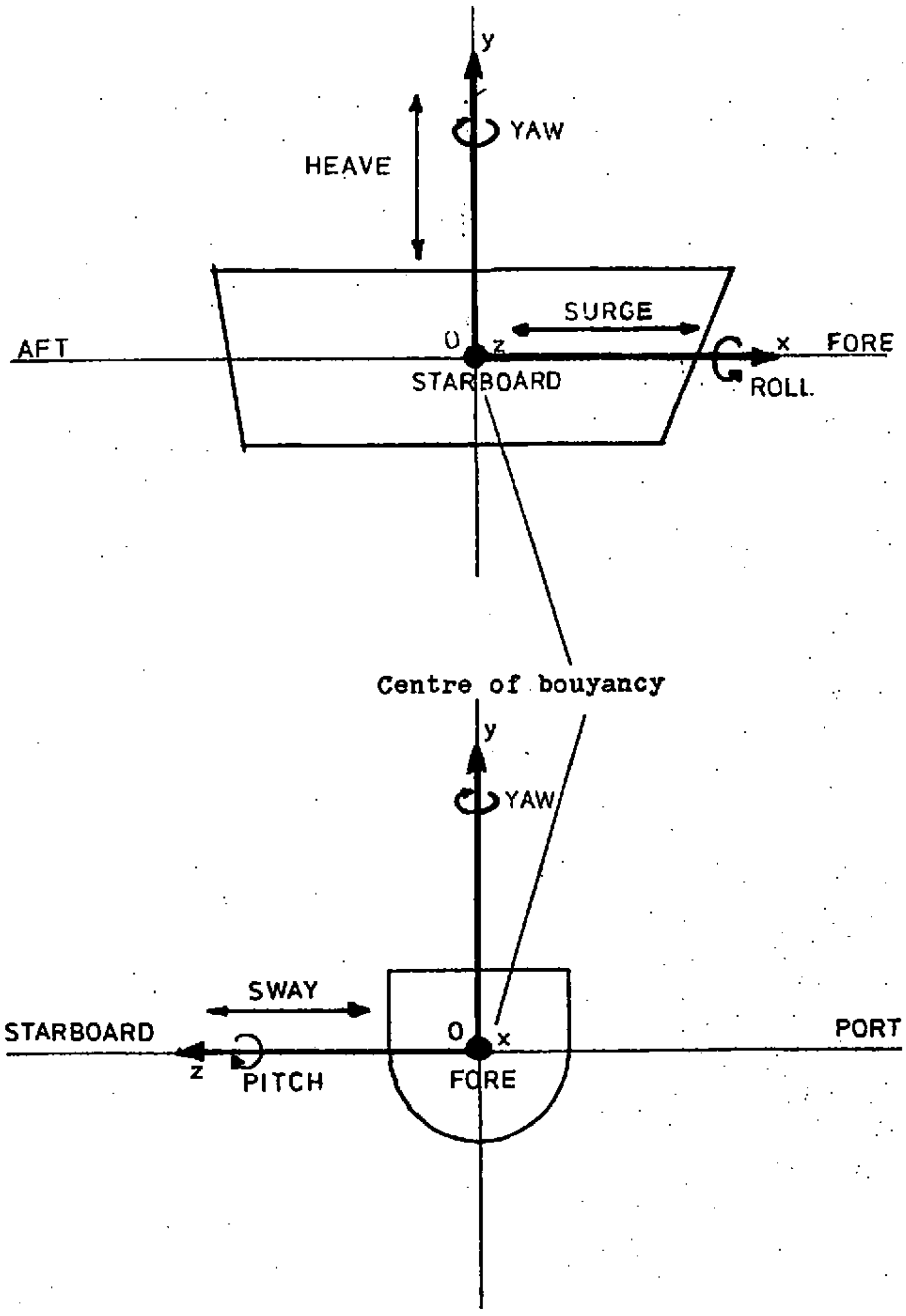
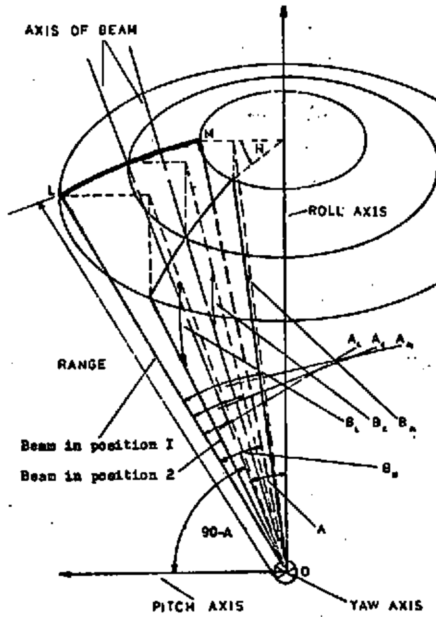


FIG. 2



The plane of the paper contains the ROLL and PITCH axes; the YAW axis is vertically down into the page.

Fig. 3 Effect of yaw, pitch and roll on a vertical fan beam

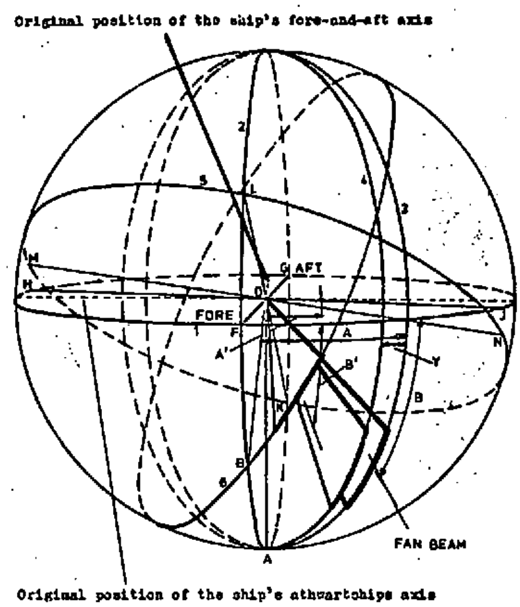


FIG. 4

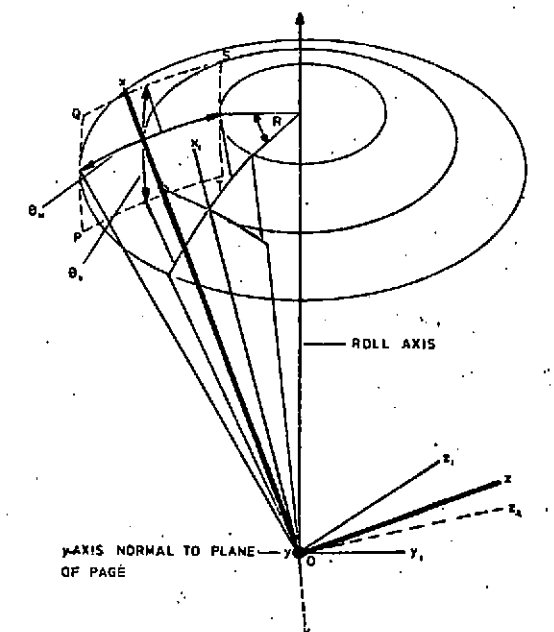


Fig. 5 Reference position of search sector

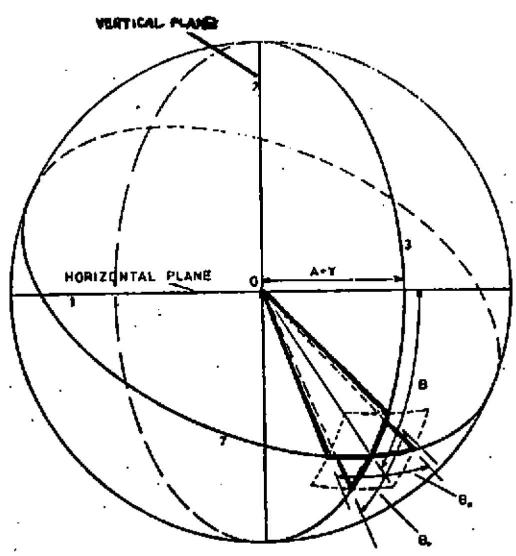


Fig. 6 Movement of search sector due to yaw, pitch and roll

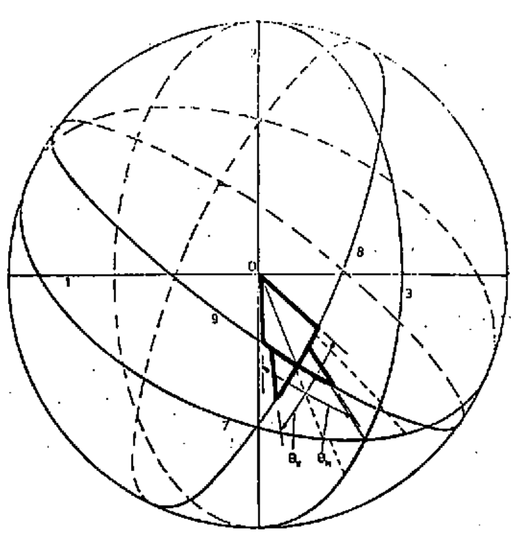


Fig. 7 Rotation of transmitter beam

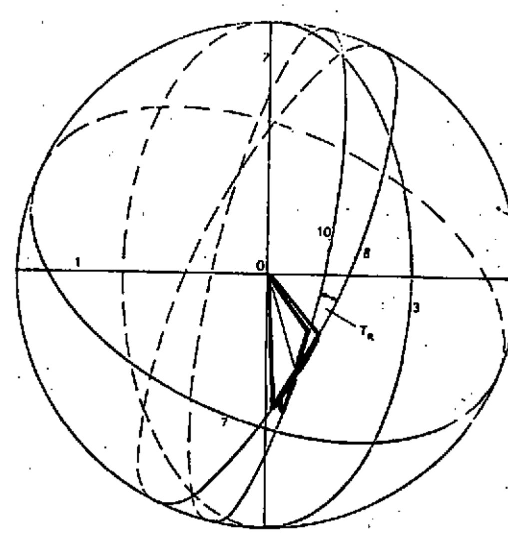


Fig. 8 Transmitter beamshift

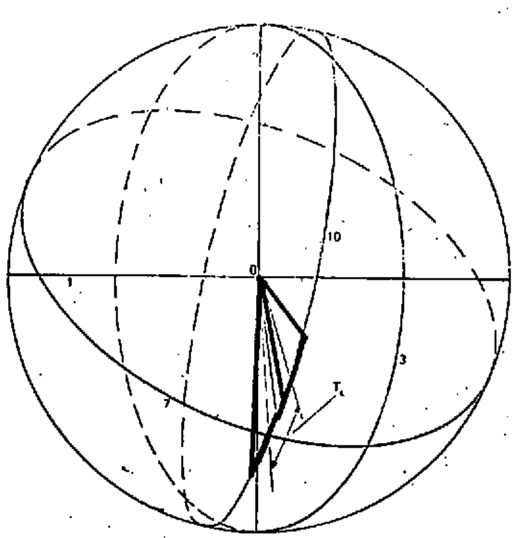


Fig. 9 Stabilized position of transmitter beam

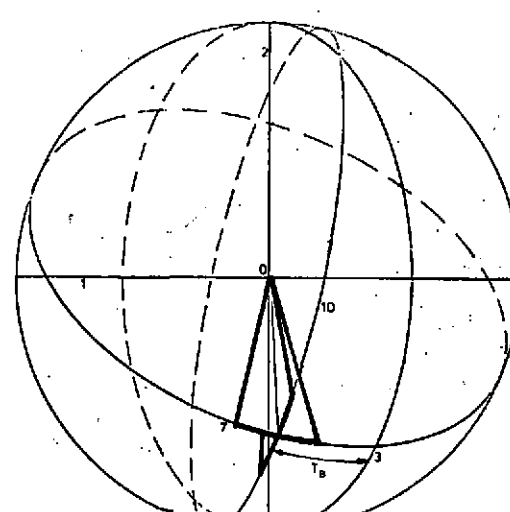


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Fig. 10 Receiver rotation.

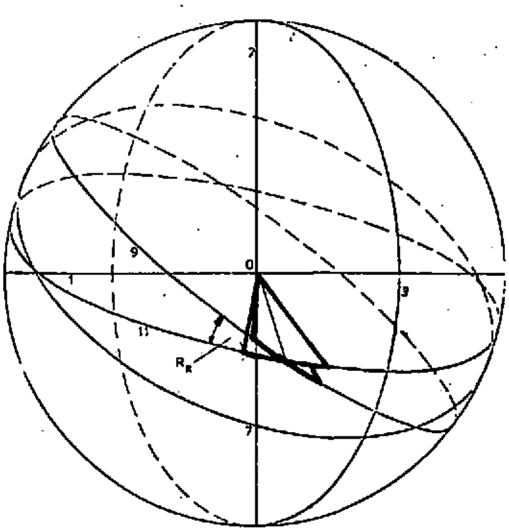

Fig. 11 Receiver beamshift

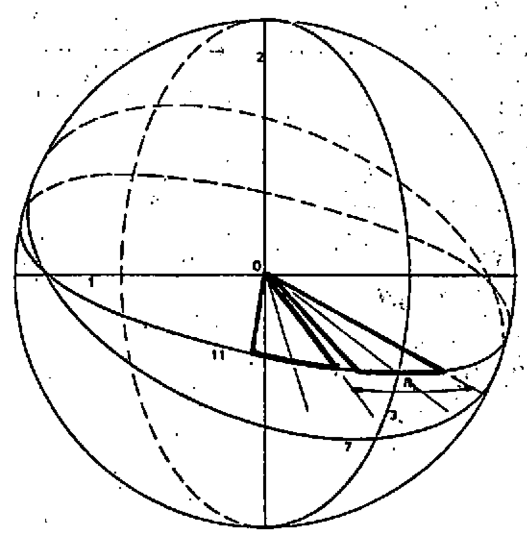

Fig. 12 Stabilized position of receiver beam

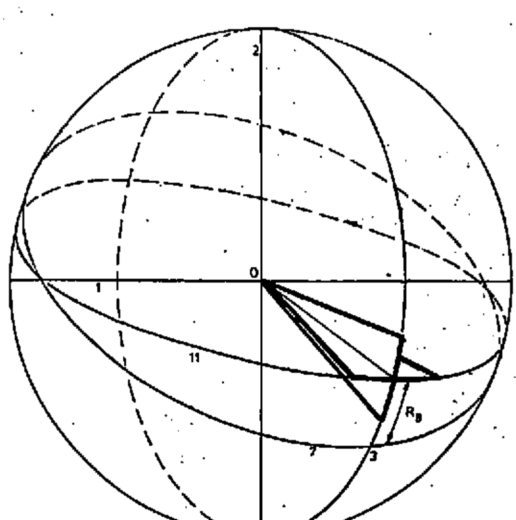

FIG. 13