ALIGNMENT IN SHIPS

BY

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This article explains briefly existing methods of alignment, and goes on to explain two other methods, one of which may be introduced into the Service. It also highlights some of the problems and factors affecting alignment in ships, in an endeavour to give a background against which a particular alignment problem can be judged.

In this article ships can be taken to include submarines and other floating vessels; also equipment refers to weapon equipment or any other mechanical equipment.

The author has just completed a Feasibility Study with the British Aircraft Corporation on the Application of Electrolevels to H.M. Ships for Alignment. The study report concludes that Electrolevels could be successfully applied to ships for alignment purposes, and a policy decision will shortly be taken on whether these recommendations should be implemented. Certain of the photographs are reproduced by kind permission of B.A.C.

SHIP DATUMS

Two datums are defined in every ship. The Training Master Datum Plane (TMDP) a vertical type plane, is normally defined by three plates on the forecastle over a base length of approximately 100 feet, two of which are on the same level, and the third of which is elevated as much as possible on some strong structure. The installation of the TMDP occurs before the superstructure is erected in the ship, and a line parallel to the ship's building centre line is defined throughout the length of the ship, with two plates for the Forward Datum and two for the Aft Datum. After the erection of the superstructure the third plate is installed relative to each datum plane. With the obliteration of the forward to aft line of sight, there is currently no way of checking the alignment of forward and aft datums, other than by a series of optical transfers over the length of the ship, with the ship in tilt-test conditions.

The Master Level Plane (ML) is a horizontal type plane defined by a Master Level Datum Plate installed in different places in different ships (gyro room, sonar compartment, boiler room, etc.), and it denotes the ship's designed waterplane under normal seagoing conditions.

The fact that these datums are related to the ship's centre line and waterplane are of no real consequence, as the datums are only used as arbitrary reference planes for equipment alignment.

In order to check alignment of a weapon system it is necessary to put the ship in tilt-test conditions (BR983). This requires the ship to be docked down to within one foot of the blocks, waterborne, shored, and in as representative a condition as possible, i.e., stored, ammunitioned, fuelled, etc. With the ship 'wedged' in this unnatural condition it is frequently not absolutely steady, but it is possible to use gravity bubbles to set up a theodolite, or compare two levels (with a clinometer) in the ship without unacceptable changes of gravity bubble due to ships motion. In contractor's yards dock gates are often not water-tight, and weapon alignment has to be conducted in the time permitted by tidal conditions. Thus the alignment is frequently carried out in great haste which obviously affects the accuracy of the results obtained.

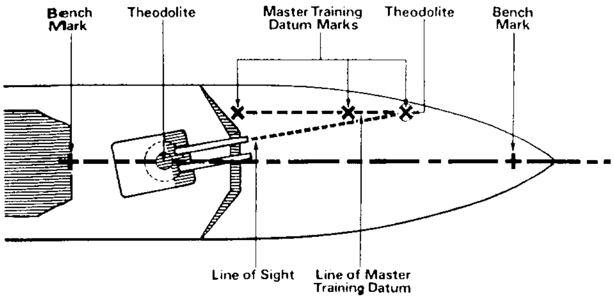

FIG. 1—DIAGRAM SHOWING THE PRINCIPLE OF TRAINING ALIGNMENT INCLUDING TMDP

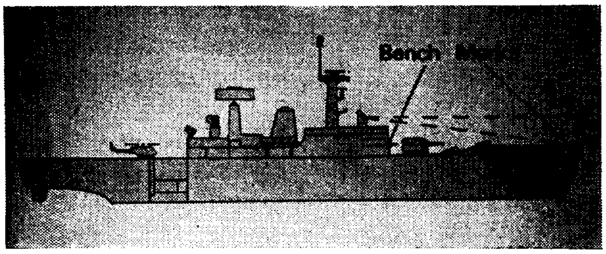

FIG. 2—DIAGRAM SHOWING THE PRINCIPLE OF ELEVATION ALIGNMENT

Training

When a theodolite, set up in the TMDP, is in line of sight with the equipment, e.g. gun mounting or director, it is possible using benchmarks and a theodolite in the plane of the mounting, to check the training alignment of the equipment. by the principle of equal and opposite angles (FIG. 1).

In order to check alignment of equipment not within line of sight of the theodolite mounted over the TMDP, it is necessary to transfer the plane by the collimation of two theodolites transferring the datum as far as line of sight permits, and as often as necessary to sight the datum in the required position. This can be a very lengthy operation and involve considerable numbers of theodolite transfers all of which contribute both instrument and human errors, in the transferred datum, or 'secondary' TMDP. Once established it is unlikely to be checked as it is very difficult to prove whether it is accurate or not. Errors of up to $\frac{1}{2}$-degree have been found in some transferred datums.

Elevation

Elevation alignment is achieved by comparing the level of the equipment with the level at ML at a defined training position. (FIG. 2.) Comparison is achieved by transfer of ML to a convenient place on the equipment using two clinometers. Frequently voice communication is used to control the adjustment of the transfer level clinometer until it is reacting identically to the master clino in sensing any movement. The clino mounted on the equipment is then compared with the transferred ML clino, and thus, using the benchmarks, elevation alignment can be achieved.

Tilt

Tilt, or verticality, is determined by comparing the level of a mounting or pad with the level at master level over various training angles. In gunnery systems it is normal to measure the relative tilt between mountings, directors, gyro stabilizers, etc., and to endeavour to reduce the relative tilt in the system to a minimum. This can be achieved by the use of tilt rings on directors and gyro stabilizers. Master level is not relevant in this problem, but is in some systems, notably GWS.2.

Planing off the Theodolite

This operation is an essential pre-requisite of training alignment and the use of theodolites on board ships. The first stage is to plane off the theodolite with respect to true horizontal. This is done using the gravity bubbles provided and the theodolite is revolved as necessary to ensure it is training in the earth's plane or true horizontal. It is then necessary to set corrections on the theodolite such that it trains 'in the plane of the ship' (as defined by the ML plane). This is done by measuring the level of the ML datum using a clino in two directions —fore and aft and athwartships, and then by adjusting the footscrews on the theodolite to set the same level in the same two directions. Equipment theodolites are always planed off to the roller path.

Summary

The problem is, therefore, to achieve alignment of equipment throughout the ship in training, elevation, and tilt, above or below decks and for rotatable and non-rotatable equipment to an accuracy of one minute of arc.

DISTORTION OF SHIPS

No discussion of alignment in ships can ignore the effects of distortion of ships' structure. Very little is known of the way in which ships distort and by how much.

Nowadays with the lightweight construction of ships it is not an easy concept to consider a ship as a rigid body; anyone walking along a deck can feel the distortion occurring as his weight is applied. Simple strength of materials theory states that there will be a deflection when any force, however small, is applied to any material, regardless of how large is its modulus of elasticity. Consequently, it is more important than ever for datums to be mounted in the strongest areas of the ship where the least distortion can be expected, and if it is necessary for a man to read a theodolite or clino, the deck on which he stands must be rigid such that his weight does not affect the instrument.

For the most accurate measurements the longest possible base lengths should be used. A measurement of 1 minute of arc is equivalent to a deflection of 0·0035 inches over one foot or 0·35 inches over 100 feet; 0·35 inches is a measurement which can be obtained with ease and accuracy, and thus every attempt is made to achieve as long a base length as possible. For the measurement of level the alternative to producing a long base length is to have surfaces which are flat to a very high standard, and the surface of the measuring instrument (usually a clinometer) must be equally flat. Clinometers are approximately 6 inches long, and in order to measure level to an accuracy of 1 minute of arc, the combined clino and datum error must not exceed 0·00175 inches. A speck of dirt or a burr is quite sufficient to produce such an error, consequently the greatest care must be taken of the surface of both clinos and datums.

N.B. If a burr on one of the surfaces is evident, great care must be taken in its removal, since the level of the measuring surface itself may be changed by thoughtless rubbing with emery cloth or worse still by filing.

Temperature Induced Distortion

In a recently published report the effects of temperature variations throughout the ship in terms of induced stresses and distortion were studied. The effects of the sun heating the upper parts of the ship with the ship afloat in cold seawater; or with one side of a ship in shade and the other in full sunlight, etc., were the kind of problems considered. Computed deformations indicate that curvatures in the vertical plane of about 0·1 minute of arc per foot length, and in the horizontal plane of up to 0·02 minute of arc per foot length may be expected, i.e., for a *Leander* Class frigate temperature induced distortions under bad conditions could be as much as 35 minutes vertical and 8 minutes horizontal. The present state of the art does not permit any correction due to temperature induced distortion, but it is worth knowing that such effects exist, and are significant in alignment terms.

Distortion Induced During Ship Construction

Anyone who has seen a ship building and who has witnessed the way in which bulkheads are pulled into position, often with great force, welded, and then released, will realize that the built-in stresses in the ship's structure can be considerable. There is of course no method of stress relief, except to take the ship to sea and allow it to 'work out' its building stresses. Thus datums secured on the ship during building may become misaligned during the early part of the ship's seagoing life.

Distortion due to Ship Motion

At sea, ships obviously distort due to ship motion but no results have been quantified on this kind of distortion. What does seem clear is that the distortion at sea is normally elastic, such that the structure will return to its original position when the motion ceases. For ships in normal harbour conditions it is reasonable to consider them as a rigid body, and motion-induced distortion is negligible.

Distortion due to Ship Loading

Tilt-test conditions define the requirements for ship loading. In one ship the bow was measured to rise by 40 minutes having defuelled and de-ammunitioned, and when re-loaded correct alignment was restored. This problem is impossible to solve during ship construction as datums have to be secured at an early stage to permit weapon installation, when there is no 'load' onboard.

It is worth noting that particularly with a ship on the blocks, and to a lesser extent in tilt-test conditions the ship is in an 'unnatural' condition under a greater or lesser form of restraint which is likely to induce distortion. This was recently shown in the alignment of part of a DLG's handling system, which was set up with the ship on the blocks in dry dock, and had to be re-set with the ship waterborne. Thus the most 'natural' condition under which to check alignment would be floating in relatively calm water in harbour. However, existing methods of alignment employ gravity bubbles which can only be used when ship motion is prevented.

Overall System Alignment Accuracy

All too frequently, a system is designed without a systematic approach to alignment. Each unit of the system is designed to the highest possible accuracy and combined together, and the result is an inefficient, inaccurate system. It is essential that consideration should be given to an agreed overall system alignment policy which takes into account all relevant factors, e.g., accuracy of input data, stabilization accuracy, data transmission accuracy, mechanical accuracy, etc. A statistical approach to the combination of these accuracies is then necessary, followed by the derivation of the required accuracy for each unit in the system. This is the logical and most efficient way to approach overall system accuracy and alignment.

Conclusions

It is important to realize just how small 1, 2 and 3 minutes of arc are, and how difficult it is to achieve and maintain this alignment in ships. When approaching an alignment problem involving small angles all the relevant factors must be taken into account. Before rejecting a system merely because the results are outside the tolerance laid down in the specification, the questions which have to be asked are:

Is this tolerance reasonable considering the equipment and its installation in the ship?

How was the alignment measured, and are any of the factors mentioned in preceding paragraphs relevant?

It is quite wrong to hold the alignment team at fault when a misalignment is found, unless all the other factors which could contribute to a misalignment can be dismissed or there is clear evidence that the team was in error in some way.

Having read of some of the reasons for misalignment, the conclusion may seem inescapable that alignment in ships is impossible to any accuracy! The proof of the pudding is that in gunnery systems where alignment is so vital to the system success rate, it *is* possible to achieve consistent and good results, and it is, therefore, reasonable to conclude that the alignment problem is not as impossible as it might appear.

OTHER ALIGNMENT TECHNIQUES

Precision Indicator of the Meridian (PIM)

This system employs a sensitive rate gyroscope which is used for detecting the horizontal component of the earth's rate of rotation. The gyro is mounted under a theodolite so that its output axis is parallel to the training axis of the theodolite. The gyroscope is directly coupled to the theodolite head and rotates with it. (FIG. 3.)

The theodolite is set up for level, and the position of north determined by detecting earth's rate. The scale on the theodolite is set up to the gyro's spin axis, thereby permitting the theodolite to measure angles relative to north to a very high accuracy.

This system has been used for alignment of tunnels and for setting up army weapons in the field. The system is not really practical for alignment in ships as the gyro is so sensitive that even under the most still conditions it senses ship motion which is large compared with earth's rate and is, therefore, very significant. Successful trials have been carried out with ships 'on the blocks' docked right down and well shored. Under these 'unnatural' conditions it is possible to set up the PIM over the TMDP, sight down the three-master datum plates, and determine the relationship of the plane to north. The equipment can be taken anywhere in the ship and set up to transfer the plane to a high degree of accuracy, setting on the same angular displacement from north.

FIG. 3—PIM BEING SET UP FOR USE IN TUNNEL ALIGNMENT

The Talyvel

The 'Talyvel' is a device which uses a plumb line in conjunction

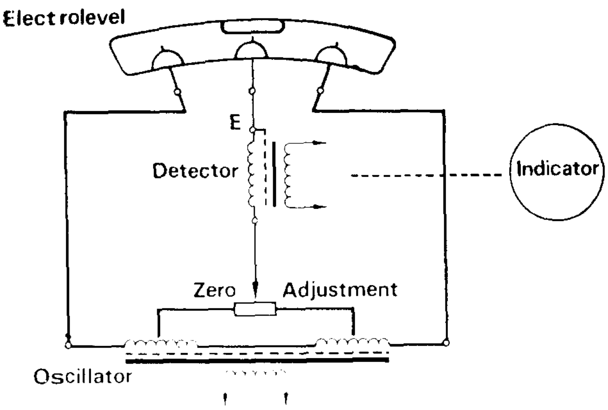

FIG. 4—ELECTROLEVEL SHOWING THE BRIDGE CIRCUIT USED TO SIGNAL THE OUTPUT—SCHEMATIC

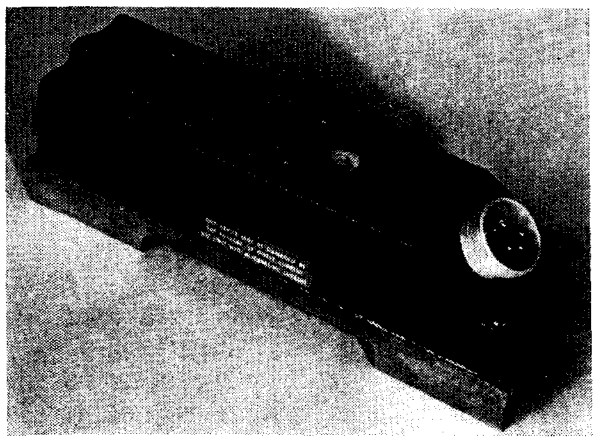

FIG. 5—A MOUNTED ELECTROLEVEL ON A ROBUST STEEL BLOCK WITH PRECISION SURFACES, A CENTRING BUBBLE AND OUTPUT SOCKET

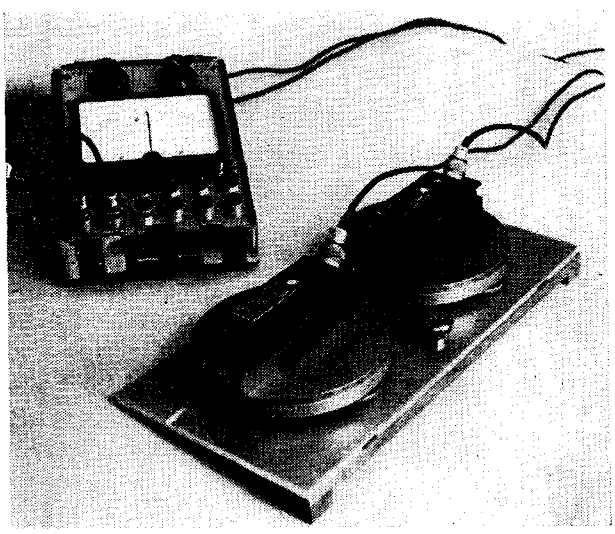

FIG. 6—TWO ELECTROLEVELS MOUNTED IN THE SAME PLANE AND IN TRAINING ALIGNMENT. THE DIFFERENCE READING IS ZERO

with an electrical detecting system to sense its precise attitude with respect to its housing. The electrical signal is amplified and used to operate a meter. The plumb line in the instrument is called a pendulum, and an inductive bridge circuit is used to obtain the electrical signal indicating its attitude. The outputs of two Talyvels can be differenced in a similar manner to the electrolevel, to indicate a misalignment. This device has been used in the alignment of some of the GWS.1 handling system.

Electrolevels

An electrolevel is a special type of spirit level filled with a conducting liquid, and fitted with three electrodes which signal the position of the bubble to a very high accuracy, typically with a resolution of one second of arc. The electrolevel output is processed and displayed on a conventional galvanometer or a pen recorder. Normally electrolevels are used in pairs, and by taking the difference of outputs between two electrolevels the effects of harbour ship motions can be removed leaving a measure of misalignment only, i.e.

{Electrolevel Signal A + Ship Motion} −
{Electrolevel Signal B + Ship Motion} =
Signal corresponding to (A–B)

i.e., effects of ship motion are removed.

Thus a direct comparison of the level of two surfaces is obtained. (FIGS. 4 and 5.)

If two electrolevels are parallel in training, and the ship on which they are mounted is heeled through an arc of 6 degrees (3 degrees to port—3 degrees to starboard) using weights, then the difference of the two outputs remains constant. Slight misalign-

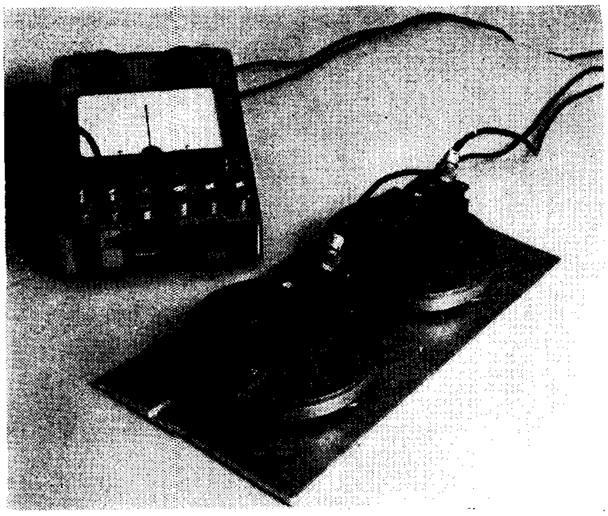

FIG. 7—THE DECK PLANE HAS BEEN INCLINED THROUGH AN ANGLE NORMAL TO THE TRAINING AXIS, AND THE DIFFERENCE READING REMAINS ZERO WHEN THE ELECTROLEVELS ARE PARALLEL IN TRAINING

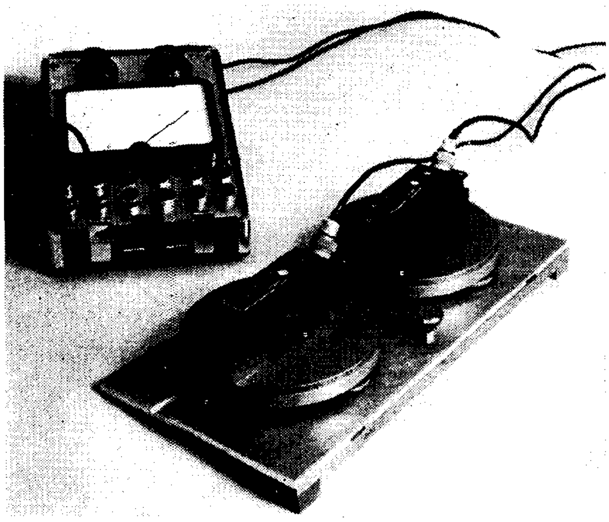

FIG. 8—THE DECK PLANE HAS BEEN INCLINED BUT THE DIFFERENCE OF ELECTROLEVEL OUTPUTS IS NOT ZERO AND IT CAN BE SEEN THAT THE ELECTROLEVELS ARE NOT IN TRAINING ALIGNMENT

ments are detected by the system such that, after heeling, the difference meter will show a reading corresponding to approximately 1/10th of the actual training misalignment (sine angle of heel (6 degrees) = 1/10th). (FIGS. 6, 7, 8). The arc of 6 degrees is the compromise between practicality and accuracy. Thus two training datums anywhere in the ship can be compared. From the above there are two modes of use of an electrolevel:

(*i*) The direct comparison in *level* of two surfaces anywhere in the ship, with or without a line of sight, giving a remote electrical readout.

(*ii*) The comparison of two *training* datums anywhere in the ship, with or without a line of sight giving a remote electrical read-out, by heeling the ship.

Under normal harbour conditions it can be assumed that the ship moves as a rigid body, and that accelerations sensed by the electrolevel at point A are the same as those sensed by another electrolevel at point B somewhere else in the ship. It is possible to achieve a difference reading of better than 10 arc seconds. Difference in height will cause slightly different accelerations; temperature difference will affect the response of the electrolevels: but these effects and others have been quantified, and in the production equipment their effects will be negligible. Any bubble bias or other electrolevel error can be established by turning the electrolevel through 180 degrees and due allowance made (c.f. clino and clino plane errors).

Application of Electrolevels to H.M. Ships for Alignment

A mounted electrolevel is approximately 6 inches in length and has a very accurately machined base for level measurement, and edge for training measurement. It would be possible to use the device in this form for alignment, but it is obvious that particularly for training this method suffers from all the problems of the short base length.

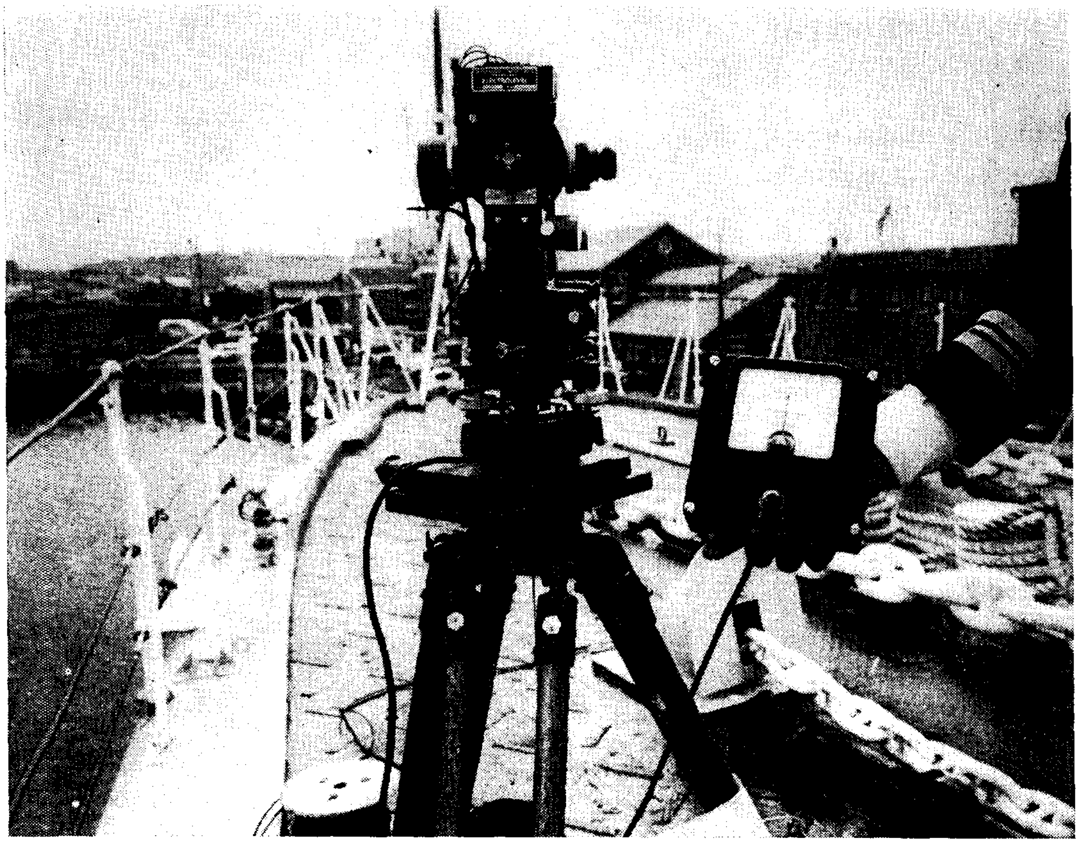

FIG. 9—AN ELECTROLEVEL BUILT INTO A THEODOLITE FOR TRIAL PURPOSES ONLY. THE DIFFERENCE METER ALTHOUGH MARKED IN MICRO-AMPERES WAS, IN FACT, CALIBRATED IN MINUTES OF ARC

In order to overcome this problem an electrolevel has been built into a theodolite, such that the electrolevel trains in the same plane as the theodolite and is aligned with the theodolite's telescope. It is a precision job to build and set up the theodolite in this way, but it will be possible to verify that the electrolevel is aligned with the theodolite's line of sight, by a simple dockside test. (FIG. 9.)

Using this instrument it is possible to set up the theodolite over the TMDP, and plane it off in the ship's plane using electrolevels as a level comparator. An electrolevel mounted on the ML datum is differenced with the electrolevel built into the theodolite, fore and aft and athwartships, and the theodolite footscrews adjusted until the difference meter reading is zero. This operation is both simple and accurate, and it ensures that the theodolite trains in the plane of the ship. (FIG. 10.)

Now that the theodolite has been set up it is possible to align equipments anywhere in the ship, whether a line of sight to the theodolite exists or not. Where the equipment reference can be sighted from the theodolite, its coordinates in training and elevation can be read off, and thence equipment alignment achieved.

If, however, the equipment reference is not within line of sight of the theodolite, then alignment transfer is necessary using the electrolevel. Another (secondary) theodolite with electrolevel built in, is set up adjacent to the equipment to be aligned within line of sight of the equipment reference, and planed off in the plane of the ship in the manner described above (against ML). The electrolevel output of the secondary theodolite is differenced with the output of the electrolevel in the theodolite mounted over the TMDP. By training the secondary theodolite, the difference between the two electrolevel readings can

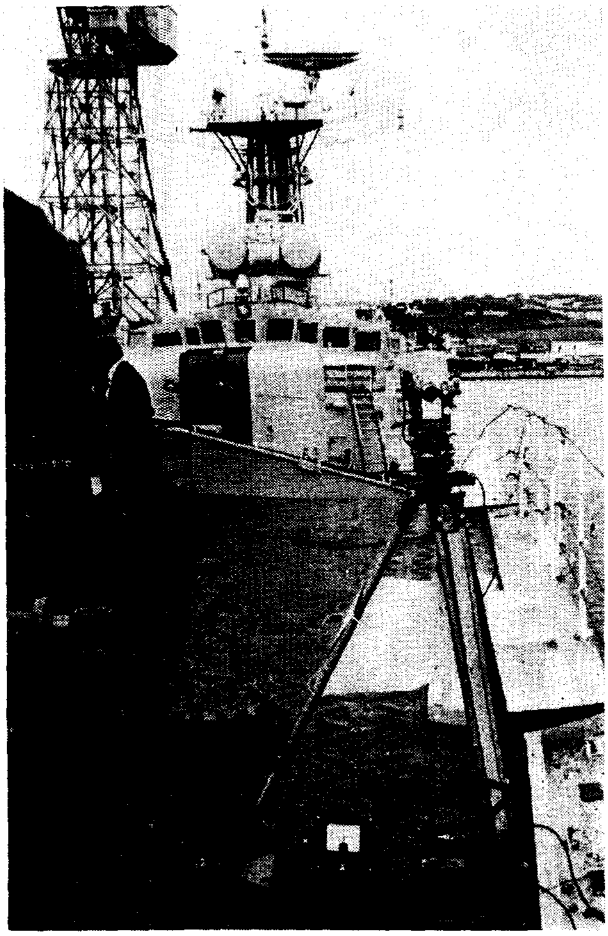

FIG. 10—THE THEODOLITE, WITH ELECTROLEVEL BUILT IN, SET UP OVER THE TMDP SIGHTING THE SECOND PLATE UNDERNEATH THE TOP STEP OF THE LADDER AT THE FORWARD SCREEN, AND ALSO SIGHTING THE THIRD PLATE ABOVE THE OUTBOARD PORT BRIDGE WINDOW, IN A TYPE 12 FRIGATE

be altered until it is a minimum. The ship is then rolled through 6 degrees and with the difference reading remaining constant, the two theodolites are parallel, i.e., both aligned in the TMDP. Equipment alignment can then proceed in exactly the same manner as if a line of sight between TMDP and equipment exists. (FIG. 11.)

Thus one has the advantage of the theodolite which can sight long base lengths such as define the TMDP, combined with the ability to measure angles to great accuracy, and the electrolevel which enables the theodolite to be set up on a moving ship and can be used to transfer both training and level alignment.

Elevation

The use of the electrolevel does not significantly alter the technique for measuring elevation. The range of the electrolevel likely to be most suitable for use in ships is $\pm$ 40 minutes of arc. In order to give the widest possible range, it is possible to mount an electrolevel on a clinometer, and adjust the clino through accurately measurable angles such that the electrolevel is maintained within range. The output of an electrolevel so mounted can be checked with the output of another electrolevel anywhere in the ship. (FIG. 12.)

Tilt

The use of the electrolevel does not significantly alter the tilt-test technique; but the advantages listed below obviously accrue.

Equipment References

An alignment reference is required on each equipment which requires to be aligned, and this reference must be in a known relationship with the line of sight or bore axis of the equipment, to the accuracy the system demands. Some equipments already have suitable references; in the case of a turret or director the bore sight telescope will be used, and a sight taken on the crosswires to define training and elevation. Usually it will only be possible to check the reference in the factory, and so some careful thought will have to be given as to how it is designed, and how its manufacture is achieved.

Two additional thoughts: in order to achieve a longer base length for the setting up of a 'secondary' theodolite in the TMDP in a gyro room for example, it is possible to arrange a series of holes in bulkheads to permit a sight to be

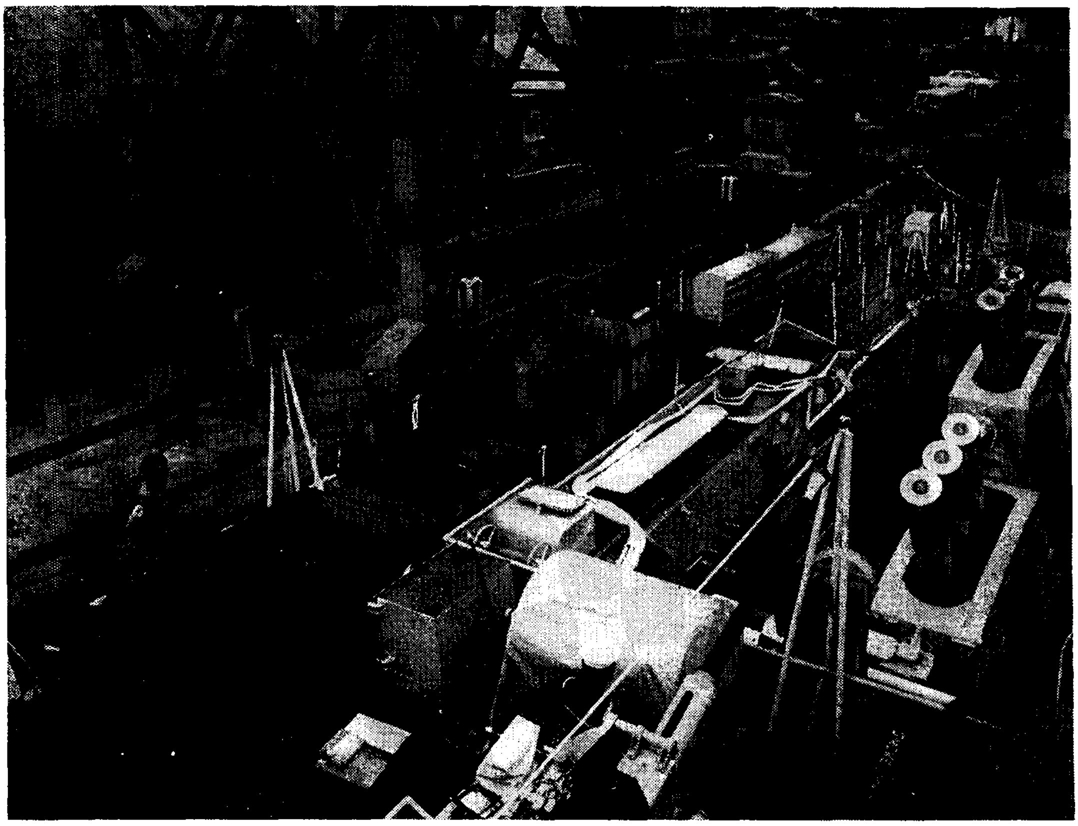

FIG. 11—THE 4-TON SKIPS USED TO HEEL THE SHIP THROUGH 3 DEGREES. A TYPE 12 FRIGATE REQUIRES 24 TONS TO ACHIEVE THE REQUIRED HEEL

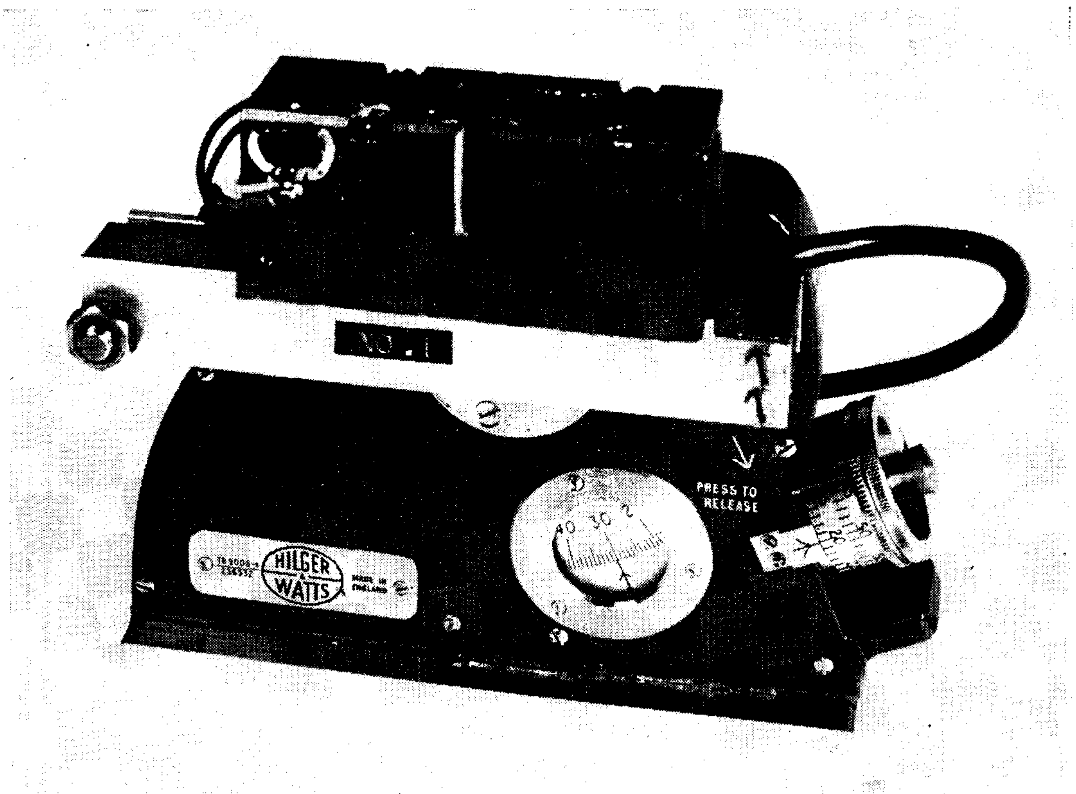

FIG. 12—AN ELECTROLEVEL BUILT INTO A CLINOMETER

Task / Method	Time Taken (Days) in Ship With 1 Gun Mounting and 1 Director					
	Docking	Tilt Test	Training Alignment	Elevation Alignment	Un-Docking	Total
Clinometers And Theodolites (Present)	$\frac{1}{2}$	$\frac{1}{2}$	1	1	$\frac{1}{2}$	$3\frac{1}{2}$
Electrolevels	0 (No Need to Dock) ←	——— 1 Day ———			→ 0 (No Need to Dock)	1

FIG. 13—COMPARISON BETWEEN THE TIME TAKEN FOR WEAPON SYSTEM ALIGNMENT USING PRESENT DAY METHODS AND WITH THE USE OF ELECTROLEVELS

taken over a longer distance. The holes need only be small and cover plates could be provided when not in use. This technique is already used in other navies who assess the damage control hazard as negligible. Alternatively, it is possible to build an optical mirror into the ship's structure which creates an infinitely long base length for a theodolite sight.

Conclusion

This system has evolved as a result of the application of a new technique, to well established alignment procedures with obvious advantages:

(*a*) That alignment can be carried out in a normal alongside berth with no special facilities, and without many of the restrictions imposed by tilt-test conditions.

(*b*) There will be a considerable reduction in time taken for alignment (50 per cent at least), and both dockyard and ship planning will be greatly simplified. (FIG. 13.)

(*c*) That alignment can be established simply, and re-checked as required. Equipment elevation and training can always be referred direct to the respective master datum.

(*d*) The system can be used for alignment of equipment on the upper deck or in the double bottoms with equal ease and accuracy.

(*e*) The system has self-checking facilities which do not exist in present alignment procedures, and will enable alignment to be checked stage by stage to ensure that any human or equipment errors are detected, and therefore corrected.

Trials have been carried out on 2 DLGs, 2 *Leander* Class frigates, and a Type 12 frigate, and all the results confirm that the electrolevel system can be successfully applied to alignment in H.M. ships, with an accuracy validated to $\pm$ 1 min. of arc in training, elevation and tilt.