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BESTUUR DER WATERWEGEN
DIENST DER KUST
HYDROGRAFIE
OOSTENDE

M2 TIDAL REDUCTION METHOD FOR
COASTAL ZONES 53444_

by

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1. INTRODUCTION

The M2 reduction method was developed by the since then disbanded Advisory Department of the Rijkswaterstaat at Flushing (Adviesdienst Vlissingen) of the former Directorate for water management and water resources (Directie waterhuishouding en waterbeweging). [1].

The M2 reduction method has been accepted as the standard method for tidal reduction for the mouths of the Eastern and Western Scheldt and the Belgian coast by the following governmental services in the Netherlands:

- A. De dienst der Hydrografie van de Koninklijke Marine
 - B. Het Directoraat Generaal voor Scheepvaart en Maritieme Zaken, district Scheldemond, afdeling Hydras.
 - C. Rijkswaterstaat, Directie Zeeland, Meetdienst.
- and in Belgium: Dienst der Kust, afdeling Hydrografie.

The measurements service of the T.V. Zeebouw Zeezand located in Zeebrugge took part in these studies during the entire length of the project.

The choice as standard method is the result of study and discussion within a working committee in which the above-mentioned services were represented and where various reduction methods were considered. In comparing methods, special attention was paid to accuracy and ease of use. In terms of accuracy, it was stipulated that the error in the water level generated by the reduction method be no larger than 1 cm. for both average deviation and standard deviation [2 thru 6].

The discussion of this reduction method is divided into four sections, namely: the theory, the measurements, aspects of quality control and the hydrographical reduction chart (the final product).

2. THEORY

2.1 Description of the theory.

Simply put the principles of the M2 reduction method may be

formulated as follows:

Determine the water level at a "random" location at sea based on the water level at a reference location by manipulating the reference water level with the help of three factors. These three factors are:

- A. A factor determined by the differences in mean sea level.
- B. An amplitude factor.
- C. A phase factor.

In the appendices 1 thru 3 each factor is graphically presented.

2.2 Mathematical formulation of the theory.

The principle of the M2 reduction method may be mathematically formulated as follows:

$$Z_t = \Delta Z + F_1 * C_t - F_2 \quad (1)$$

where

ΔZ = Mean sea level difference factor

F_1 = Amplitude factor.

F_2 = Phase factor.

Z_t = The calculated value of sea level height at a "random" location in meters, related to the N.A.P. datum at the time t

$C_t - F_2$ = The measured value of sea level height at the reference location in meters, again related to N.A.P. at the time $t - F_2$.

2.3 Limiting conditions when using the reduction method.

The use of this method of tidal reduction is limited by the following restriction:

To achieve a reasonable level of accuracy the variation in sea level (tide) in both the reference and sea locations must be similar to one another.

In appendix 4 examples of similar and dissimilar sea level curves are shown.

Practically speaking, the above-mentioned limiting condition has the following effects:

- A. The region within which a reference location may safely be used will be "limited".
- B. This restricted region will be larger depending on whether there are fewer banks and shoals in the intertidal area.

2.4 A further specification of the factors.

The factors mentioned in paragraphs 2.2 and 2.3 may be further determined as follows:

- A. Values of mean sea level for a number of locations along the coast in the area of interest are given in table 1. These mean sea level values have been taken from [7].

Table 1. Mean sea level in meters related to N.A.P.

Location	Mean sea level
Nieuwpoort	- 0.10
Oostende	- 0.09
Zeebrugge	- 0.09
Cadzand	- 0.05
Vlissingen	- 0.06

In view of the marginal differences in mean sea level, the factor pertaining to mean sea level difference may be neglected.

The M2 component (2-day, lunar tide) is the most significant harmonic component in the region under consideration. This is the reason that the factors F_1 and F_2 are determined as given below and also the motivation behind the name of this method.

- B. The multiplier is given as:

$$F_1 = \frac{A}{B} \quad (2)$$

where,

A = The amplitude of the M2 component at the location at sea in cm.

B = The amplitude of the M2 component at the reference location in cm.

C. The phase factor is given as:

$$F_2 = F_M - F_R$$

where,

F_M = The phase of the M2 component at the location at sea
in minutes.

F_R = The phase of the M2 component at the reference
location
in minutes.

2.5 Summary

When the factors determined from equations (2) and (3) have been substituted in equation (1) we get

$$Z_t = \frac{A}{B} * C_{t_R} \quad (4)$$

where

$$t_R = t - (F_M - F_R) \quad (5)$$

3. THE MEASUREMENTS

3.1 In general

The reason for taking measurements is to determine the factors A, B, F_M and F_R according to the paragraphs 2.4 and 2.5.

To this end the following measurements had to be made:

- A. Water levels at the reference locations.
- B. Water levels at the locations at sea.

No separate measurement campaign had to be carried out to determine the water levels at the reference locations, since water levels are continually registered at a sufficient number of coastal locations. These may serve as reference stations. On the other hand, it was necessary to carry out accurate datum level measurements, in order to verify the height difference between N.A.P. (New Amsterdam's Benchmark) in the Netherlands and T.A.W. (The Second General Benchmark Survey) in Belgium.

To measure water levels at sea, a number of measurement campaigns were carried out. These campaigns may be split into three separate phases:

- A. Preparations
- B. The measurements themselves
- C. Data-analysis.

The measurements will now be considered on the basis of these three phases.

3.2 Preparations.

The preparations for the water level measurements at the locations at sea consisted of the determination of the duration and location of the measurements and the readying of personnel and material to carry them out. The services taking part in the project were, without serious difficulty, able to guarantee the necessary logistic support.

The fact that the M2 amplitude and phase had to be determined was, of course, most important in ascertaining the duration of the measurements. The measurements would be carried out during an entire springs-neaps cycle.

This implied a measurement length of at least 30 days.

Aside from the length of the measurements, the time of the year also played a role. The measurements were conducted in the spring and summer as far as possible in order to avoid measuring under stormy conditions.

A sampling interval of 15 minutes was chosen. This interval was deemed sufficient to reproduce the variations in water level with the necessary accuracy and to ensure that reliable analyses could be made.

Significant with respect to the choice of measuring locations were:

- A. The boundaries of the area under study.
- B. The number and the lie with respect to one another of the measuring points.

The boundaries were chosen in relation to the boundaries of the participating Government Services. The region covers the Belgian coast from the French border to the mouth of the Eastern Scheldt and stretches some 30 km out to sea.

The number and lie of the measuring points was determined from practical experience, budgetary limitations and the use of the measurements for other purposes.

In appendix 5 a map is given showing the locations of the measurements carried out to date. The first measurements were made in 1982 and the last in 1986. Appendix 5 reveals that the entire region has not yet been measured. Measurements will be carried out in the future before the Belgian coast between Oostende and the French border, in the West-hinder area and just to the North of the Mouth of the Eastern Scheldt.

3.3 Practical considerations.

The Dutch measurements were conducted using pressure sensors, placed on the sea bed [8, 9]. The pressure sensing device used, the DAG 6000, is shown in appendix 6. The DAG 6000 tide gauge consists of a water tight drum with lid, fitted out with hooks to enable its being suspended in a framework. The drum is made from cast bronze, thus making the device insensitive to corrosion. The pressure sensor is on the underside and there is further a battery compartment, an electronics section and room for a data cassette, where the pressure data is recorded. The DAG 6000 instruments were placed on the sea bed and marked at the surface with a buoy. In our case, the devices were retrieved after a months measurements.

The Belgian measurements, carried out with Aanderaa equipment, could first be begun in 1985. Of these, six series fell within the group that could immediately be used.

These were then used as control measurements. The rest of the measurements carried out and those still to be carried out will serve to fill in the blank spaces in the western section of the reduction chart.

3.4 Data analyses.

The data analyses consisted of the following steps for those measurements made in the reference locations:

- A. The choice of reference sites for the investigation of the measurements at the locations at sea.
- B. Harmonic analyses of the reference water levels for each period of measurement to determine the M2 components.

- C. Harmonic analyses of the reference water levels in 1983 to determine the M2 components.

Analyses of the data collected from the locations at sea consisted of the following steps:

- A. The cassettes, containing pressure data, were read out. Pressure values were recorded at 15 minute intervals.
- B. The pressure values were corrected for the specific weight of sea water, barometric pressure and mean sea level. This correction inherently implies the translation of pressures into water levels.
- C. The water levels were presented graphically for visual control and possible correction.
- D. Harmonic analyses of the water level data to determine the M2 components (amplitude and phase).
- E. The M2 component varies with time as a result of variations in the angle between the lunar trajectory and the equator. It was therefore deemed necessary to normalize the M2 component to the year 1983. In that year the angle had an average value of $23^{\circ}27'$, for a length of the ascending node of 90° . The normalization procedure could then be carried out as follows:

The equation below was used to determine the M2 amplitude:

$$A = B * \frac{a}{b} \quad (6)$$

where,

A = M2 amplitude (norm 1983) for the location at sea

B = M2 amplitude (norm 1983) for the reference location

a = M2 amplitude (measurement period) for the location at sea

b = M2 amplitude (measurement period) for the reference location.

For the M2 phase: The M2 phase difference between 1983 and the period of measurements at the reference location was added to the M2 phase for the measurement period at the location at sea.

4. QUALITY CONTROL

After the factors A, B, F_M and F_R have been determined, the equation given in paragraph 2.5 can be verified.

This check carried out for the most part by Rijkswaterstaat and the Dienst Der Kust, implies the determination of the difference between the computed and the measured water levels.

It may be expressed as:

$$\Delta h = Z_t \text{ calculated} - Z_t \text{ measured}$$

where,

Δh = the difference between the water level Z_t calculated with equations (4) and (5) and the measured water level Z_t .

Z_t = the water level at a location at sea, given in m.
relative to N.A.P. at time t.

For all measuring points and for the entire period of measurements Δh has been determined at intervals of 15 minutes. The standard deviation of Δh , the percentage of Δh values between ± 1 dm and the maximum and minimum values of Δh are given in appendix 7. The following general conclusion may be drawn on the basis of these results:

The largest standard deviation is 7 cm and the mean of the deviation 10, -10 cm (in percentage) reaches 95.90%.

The M2 method of reduction meets the stipulated degree of accuracy.

5. THE HYDROGRAPHIC REDUCTION CHART

5.1 Product development.

After it had been determined that the accuracy requirements had been met, the product itself could be developed. This product, the reduction chart - M2 method, is shown in appendix 8. The development was carried out in the following steps:

- A. The results of the measurements, the M2 amplitudes and phases are recorded in the chart, whereby their relationship to one another is made visible through the use of iso-contours.

In this way it is possible to determine the M2 values (and therefore the water levels) at an arbitrary point.

- B. Eight reference locations have been chosen, and the area within which each reference location is applicable is delimited based on the results of the quality control. The three Belgian reference locations are part of the Vlaamse Banken Network, and the five Dutch locations form part of the ZEGE net. In these networks, water level information is automatically collected and stored in a Data base. Efforts are presently being made to couple the above-mentioned networks.
- C. Rijkswaterstaat makes use of N.A.P. as chart datum, and this is also used as reference level for the chart. The other services use GLLWS (the average lowest low tide at springs). The realisation of the latter reference level in the reduction chart made it necessary to present iso-contours of GLLWS (Z_0 in cm in relation to N.A.P.). During production of the first version of the chart it became apparent that the Belgian GLLWS, at the Dutch-Belgian border, was about 2 dm lower than the Dutch GLLWS datum. Additional investigation showed that this difference is due to a difference in the way low tide is defined when determining the value of GLLWS. As a result, the frequency with which low tide comes to lie beneath chart datum at Vlissingen is 6,7% of the time, where as for Oostende and Zeebrugge this happens 0,6% of the time. With the help of a text, the situation described above is made clear in the reduction chart itself.
- D. The theoretical background is reiterated in the lower right hand corner of the chart, as an instruction for the user. The value of Z_0 , i.e. the difference in height between N.A.P. and GLLWS, determined with the help of equation (4), had also been presented.
- E. A few additional finishing touches to the reduction chart, such as header, geographic and UTM coördinates, depth contours, etc. are then made. Lay-out was provided for by the Dienst der Kust, Hydrographic office.

F. In a plenary sitting of the working committee on the 13th of May 1986, the decision was made to officially begin using the reduction chart as of the 1st. of January 1987. Therefore, since this date, the chart is to be considered valid in those areas where the ISO-contours are clearly defined.

5.2 The practical use of the reduction chart.

The use of the reduction chart by those services mentioned in paragraph 1, may be summed up as follows:

- A. In those areas where hydrographic surveys are carried out, a number of points are registered on the reduction chart, there where the water level is to be calculated, and being themselves representative for a certain portion of the area. With the help of these points, the M2 amplitude and phase can be read directly from the reduction chart.
- B. For the points mentioned under A., the corresponding reference location(s) along with M2 amplitude and phase are additionally determined. The water levels for the period in question at these reference locations are shifted from the data base of the measuring network to a computerfile and readied.
- C. Equations (4) and (5) are programmed. This program reads the reference water levels and requests that the necessary M2 values be fed in by hand. After this, the desired water level at sea is calculated and stored on file for further use.

Furthermore, plans^{*} exist to store the basic data of the reduction chart in matrix form in the computer, and to re-edit the analyses software. This will be done in such a way that, based on the location and moment in time of a particular sounding, the choice of reference location, the determination of the M2 values and the determination of the water level at the location(s) at sea will be carried out automatically.

* Meanwhile a tidal reduction model has been developed in the "Dienst der Kusthavens-Hydrografie" for some more details about this model, we want to refer to the annexed Addendum.

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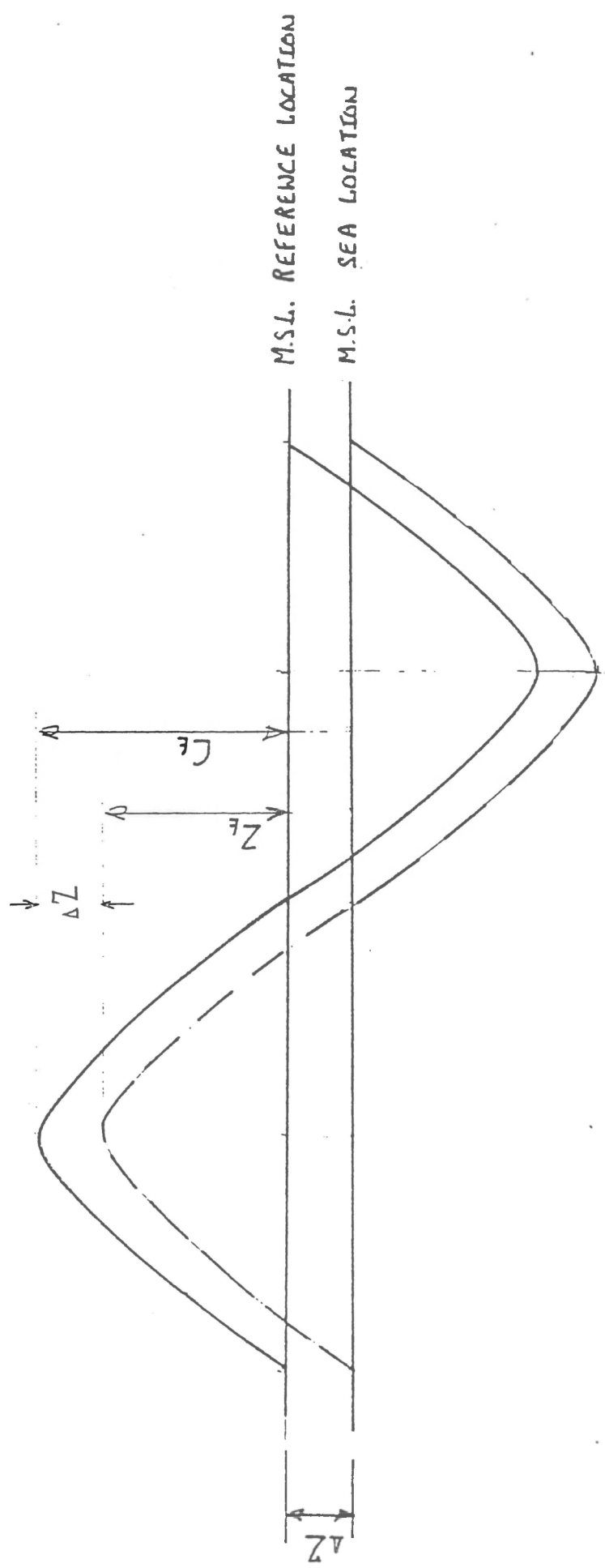
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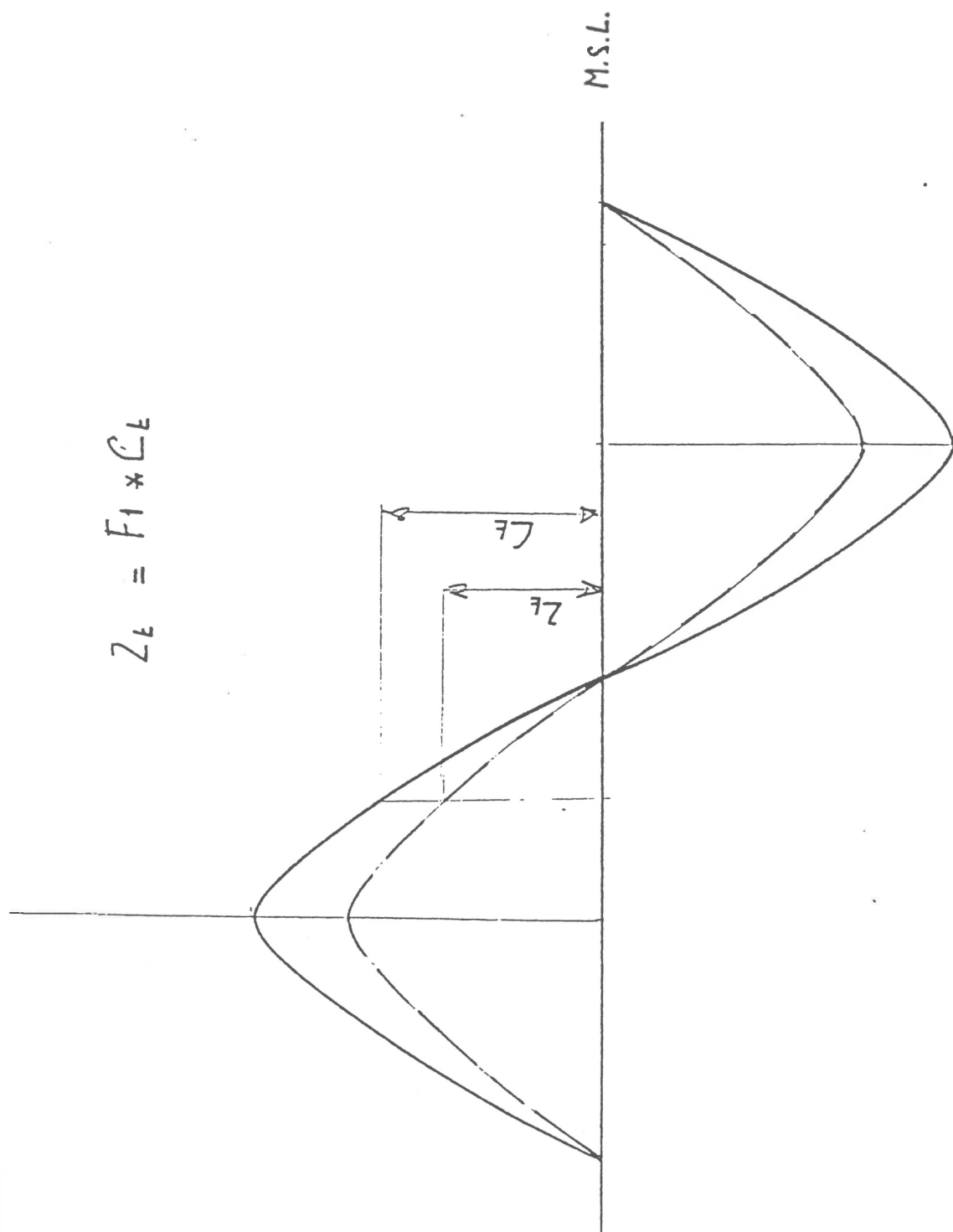
$$Z_L = C_L - \Delta Z$$



— REFERENCE LOCATION

- - - SEA LOCATION

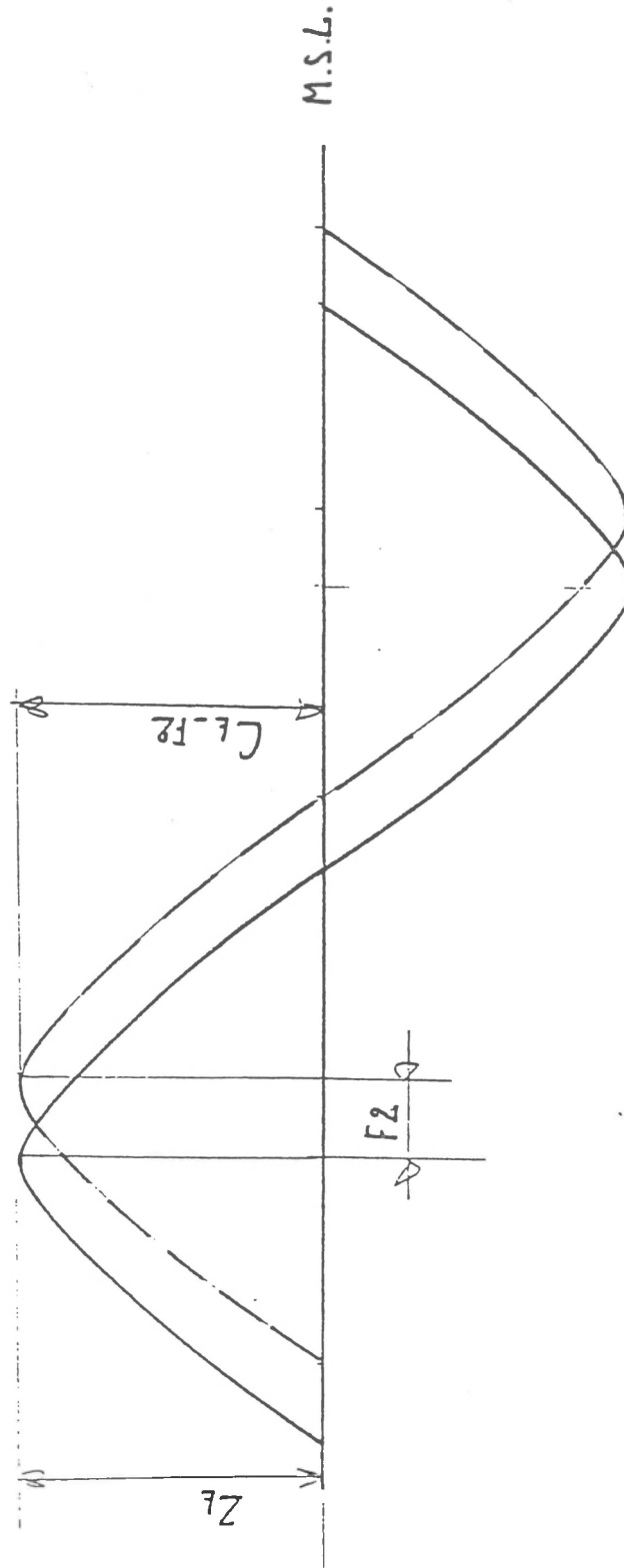
$$Z_L = F_1 * C_L$$



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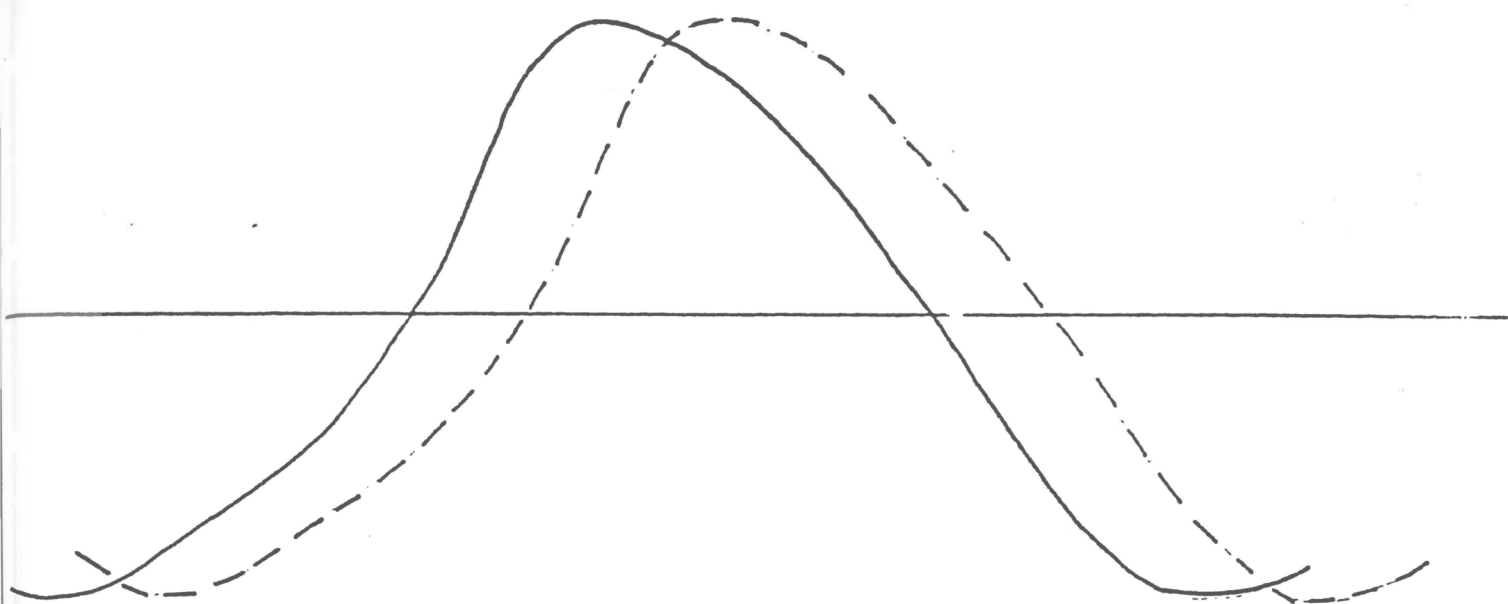
SEA LOCATION

$$Z_L = C_L - F_L$$



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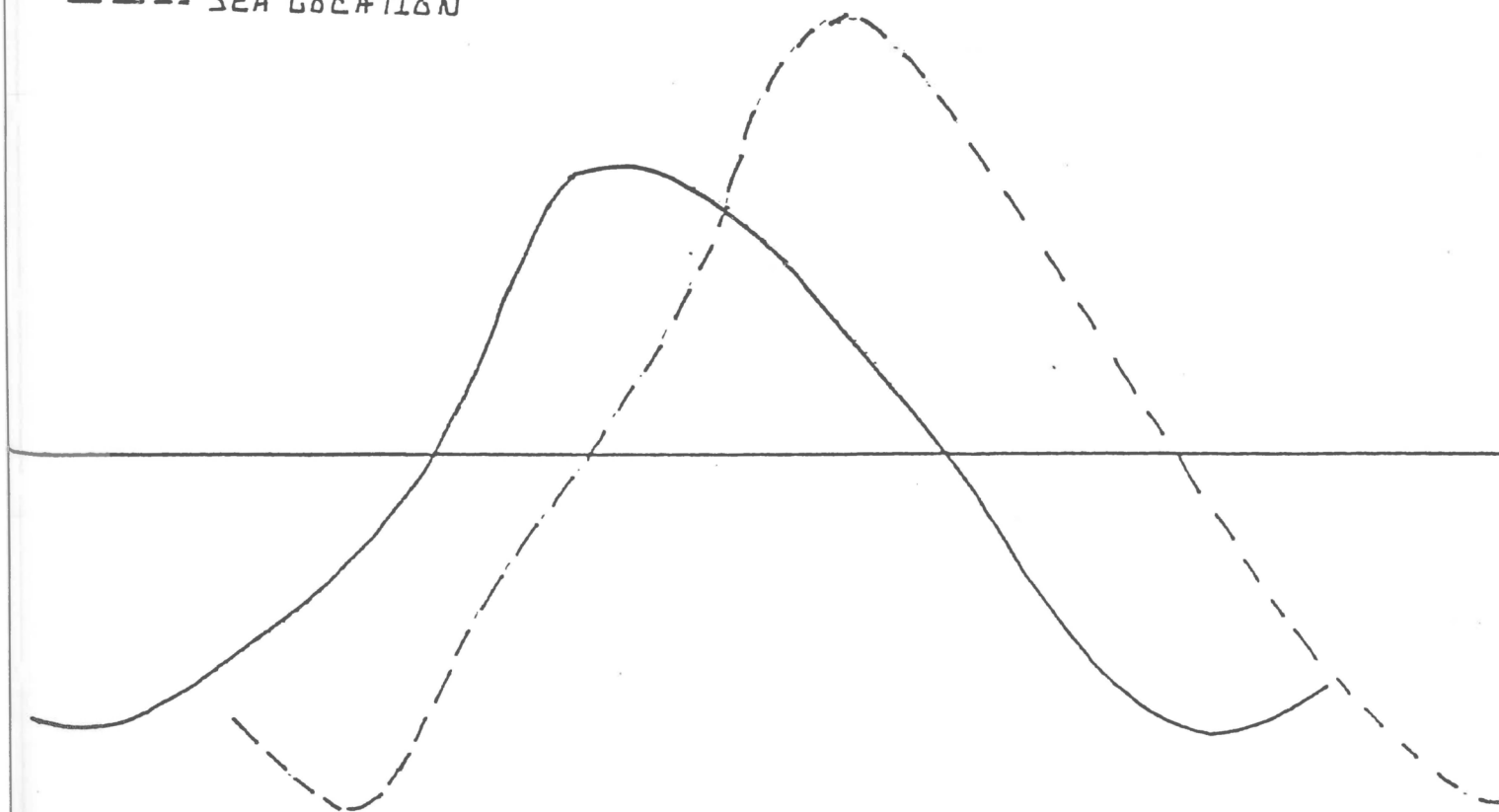
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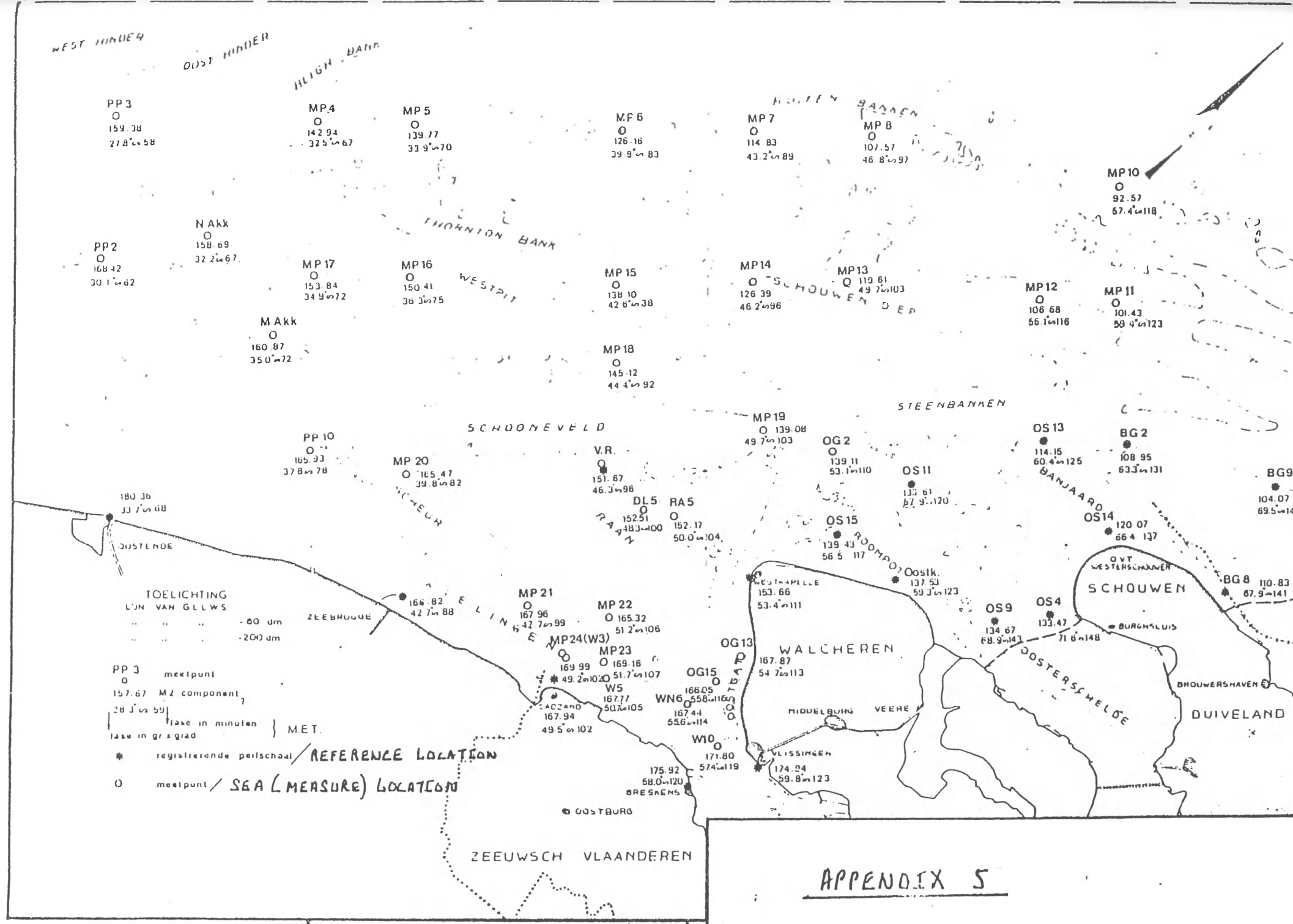
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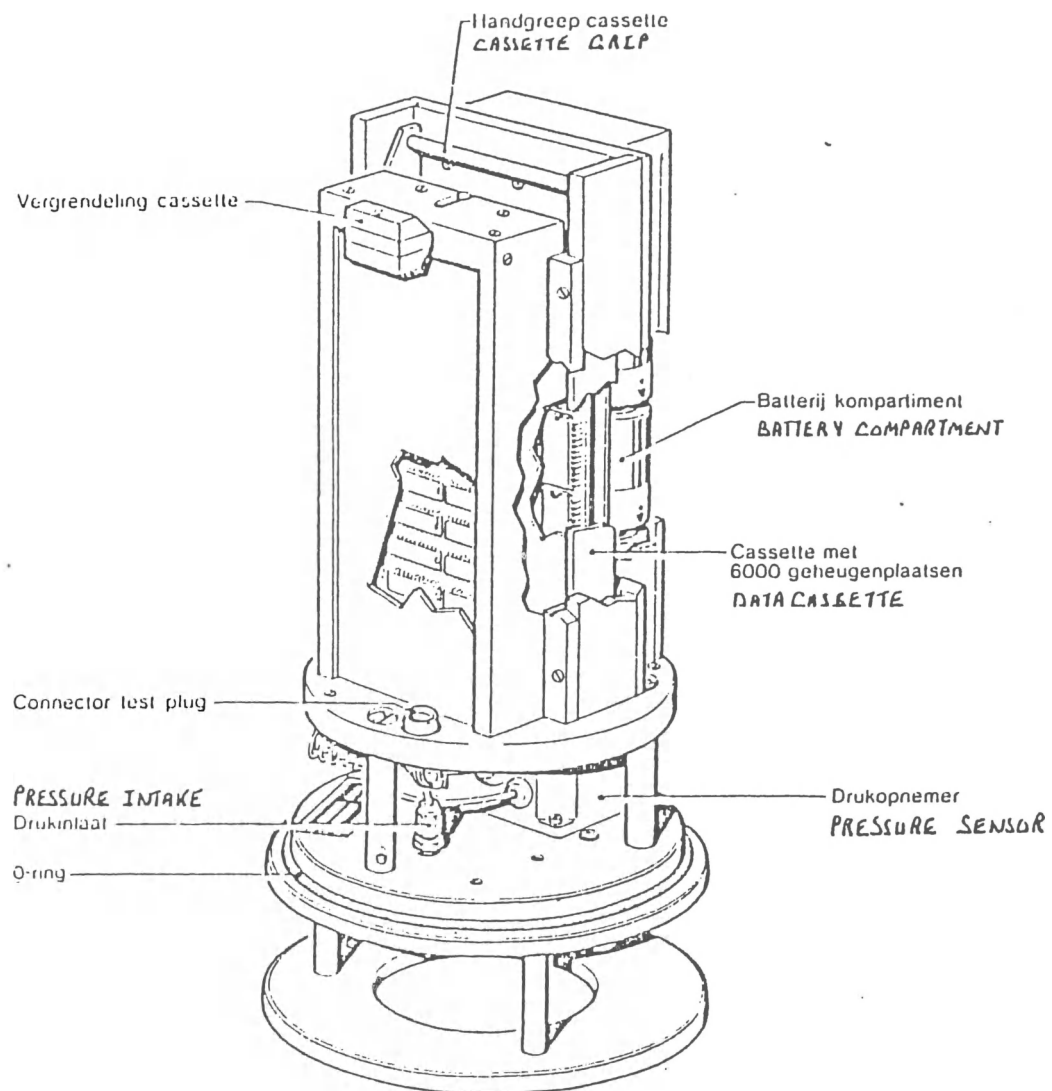
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- - - SEA LOCATION

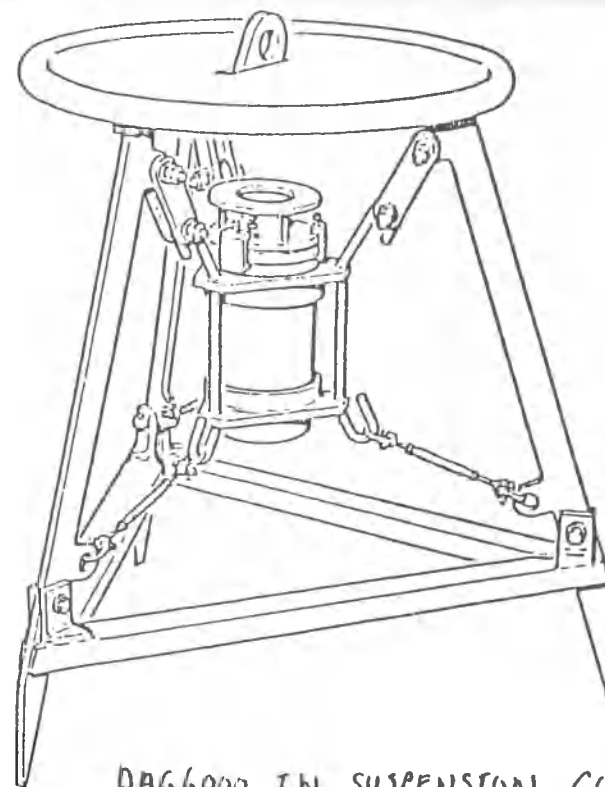


DISSIMILAR TREND

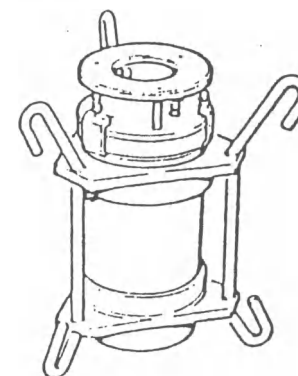




DAG6000 - KERN



DAG6000 IN SUSPENSION CONSTRUCTION



DAG6000 WITH LID AND HOOKS

Quality Control

REF. P.	SEA P.	S	% 10, -10	MAX Δh cm	MIN Δh cm	NUMBER Δh
QOST.	PP2	4	98%	18(1)	-20(1)	797
QOST.	PP3	4	97%	16(1)	-17(1)	797
QOST.	PP4	6	88%	21(2)	-17(1)	797
QOST.	PP9	6	91%	21(2)	-17(1)	797
QOST.	PP10	6	92%	23(2)	-18(2)	797
QOST.	M. AKKAERT	4	97%	18(1)	-12(1)	797
QOST.	N. AKKAERT	3	99%	11(1)	-11(1)	797
ZEEBR.	PP4	5	94%	18(1)	-16(1)	797
ZEEBR.	PP9	4	98%	15(1)	-20(1)	797
ZEEBR.	PP10	4	98%	13(1)	-22(1)	797
V.R.	MP6	5	96%	18(1)	-16(2)	797
V.R.	MP13	6	90%	21(1)	-21(1)	797
V.R.	MP14	5	94%	16(2)	-16(2)	798
V.R.	MP19	4	99%	9(4)	-15(1)	797
V.R.	MP21	4	98%	12(1)	-16(1)	797
V.R.	MP22	4	98%	10(1)	-21(1)	797
V.R.	MP23	4	97%	12(1)	-20(1)	797
V.R.	W3	4	99%	12(1)	-15(1)	797
V.R.	MP24	4	98%	13(1)	-21(1)	797
V.R.	RAS	3	99%	10(1)	-18(1)	797
V.R.	OG2	5	95%	18(1)	-17(1)	797
CADZ.	MP21	2	99%	17(1)	-12(1)	797
CADZ.	MP22	2	100%	18(1)	-13(1)	797
CADZ.	MP23	4	97%	12(1)	-20(1)	797
CADZ.	W3	3	100%	49(1)	-8(3)	797
CADZ.	MP24	2	99%	13(1)	-13(1)	797
CADZ.	M. AKKAERT	5	96%	45(1)	-13(1)	797
CADZ.	N. AKKAERT	6	92%	41(1)	-16(1)	797
CADZ.	RAS	5	97%	22(1)	-19(1)	797
CADZ.	V.R. (DAG6000)	4	98%	19(1)	-20(1)	797
WESTK.	MP7	7	83%	22(3)	-25(1)	797
WESTK.	MP13	6	89%	23(1)	-18(2)	797
WESTK.	MP14	6	92%	20(1)	-25(1)	797
WESTK.	MP19	4	98%	16(1)	-12(1)	797
WESTK.	V.R. (DAG6000)	5	97%	17(2)	-36(1)	797
WESTK.	RAS	3	98%	18(1)	-30(1)	797
WESTK.	OG2	5	96%	19(1)	-29(1)	798
OS15	MP7	6	93%	15(1)	-18(2)	797
OS15	MP8	7	86%	21(2)	-20(1)	797
OS15	MP13	5	98%	18(1)	-14(2)	797
OS15	MP14	4	99%	11(2)	-16(1)	797
OS15	RAS	4	98%	13(3)	-18(1)	797
OS15	OG2	2	100%	9(1)	-9(1)	797
OS15	V.R. (DAG6000)	5	95%	17(2)	-16(1)	797
OS13	MP11	4	98%	12(1)	-16(3)	797
OS13	MP12	3	99%	10(1)	-13(2)	797
BG2	MP8	6	90%	29(1)	-21(1)	797
BG2	MP11	4	98%	10(6)	-20(1)	797
BG2	MP12	4	99%	17(1)	-17(1)	797
BG2	MP10.1	5	96%	13(1)	-15(1)	797
BG2	MP10.2	5	96%	14(1)	-16(1)	797