Earth Tides

Svend Saxov[1]) *og P. Melchior*[2])

Måling af tidejord

Af Svend Saxov.

Tidevandets bevægelser, ebbe og flod, har været kendt langt tilbage i tiden, og når man tager i betragtning, dels at ca. 71 % af jordens overflade er dækket af hav, dels hvilken betydning havene har haft som forbindelsesvej, forstår man, hvor vigtigt det har været at kunne forudsige tidevandets bevægelser.

Tidevandsbevægelserne fremkaldes som bekendt af variationerne i tiltrækningskraften mellem jorden på den ene side og solen og månen på den anden side. På grund af månens rotation om jorden og jordens rotation om solen forekommer der ændringer i tidevandets bevægelser, omend den periodiske længde er fastlagt; men da de fysiske love, hvormed tidevandets bevægelser kan beskrives, er ganske godt kendt, er det muligt med meget stor nøjagtighed at forudberegne og forudsige tidevandets bevægelser.

De tiltrækningskræfter, som solen og månen udøver på jorden, virker ikke alene på havene, men også på den faste del af jordens overflade. Vi går med andre ord rundt på en

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gyngende overflade. Heldigvis er denne bevægelse så lille og foregår så langsomt, at vi ikke mærker til den, men på den anden side er bevægelsen stor nok til, at den kan måles. Det er denne bevægelse, som har fået benævnelsen tidejord — Earth tides —. I det efterfølgende afsnit af professor P. Melchior, leder af International Earth Tide Centre i Bruxelles, fremgår det, at tidejordsstudier har stor betydning for en lang række emner. Dette er en af grundene til, at tidejordsstudier udgjorde en vigtig andel i det internationale Upper Mantle Project og også indgår i det nu løbende internationale Geodynamics Project.

Tidejordsmålinger kan udføres på flere måder; ved målinger på Færøerne (ligesom i Aarhus, på Bornholm og i Godhavn) er benyttet et langtidsregistrerende gravimeter. For at opnå de mest pålidelige registreringer har gravimetret været opstillet ca. 6 måneder på hvert af målestederne.

At langtidsregistreringer er både nødvendige og ønskelige, skyldes først og fremmest de periodiske variationer i påvirkningerne af sol og måne, jordens rotation og ændringen heraf, forstyrrelser udefra såsom jordskælv, storme og strømafbrydelser. På figur 1 vises et udsnit af målingerne på Bornholm, hvor der optræder jordskælv såvel som strømafbrydelse.

De matematiske udtryk for tidejordsbevægelserne er ganske komplicerede, hvilket ikke mindst skyldes, at problemet er af potentialteoretisk art. Det må derfor være tilstrækkeligt at nævne de enkelte periodiske faktorer, som de også optræder i beskrivelsesarket for station 0821 Faeroe, se figur 3.

Først nævnes de faktorer, som har en periode på ca. $^1/_2$ døgn; de har alle et 2-tal påhæftet. Derpå følger de faktorer, som har en periode pa ca. 1 døgn; de har alle et 1-tal påhæftet. M2 (12.42 time), N2 (12.66 time) og L2 (12.19 time) er alle fremkaldt af månen; S2 (12.00 time) skyldes solen, medens K2 (11.97 time) har såvel sol- som måneårsag. O1 (25.82 time), Q1 (26.87 time), J1 (23.10 time) og OO1 (22.30 time) skyldes månen; P1 (24.07 time) skyldes solen, mendens K1 (23.93 time) har såvel sol- som måneårsag. Eftersom perioderne ligger dels

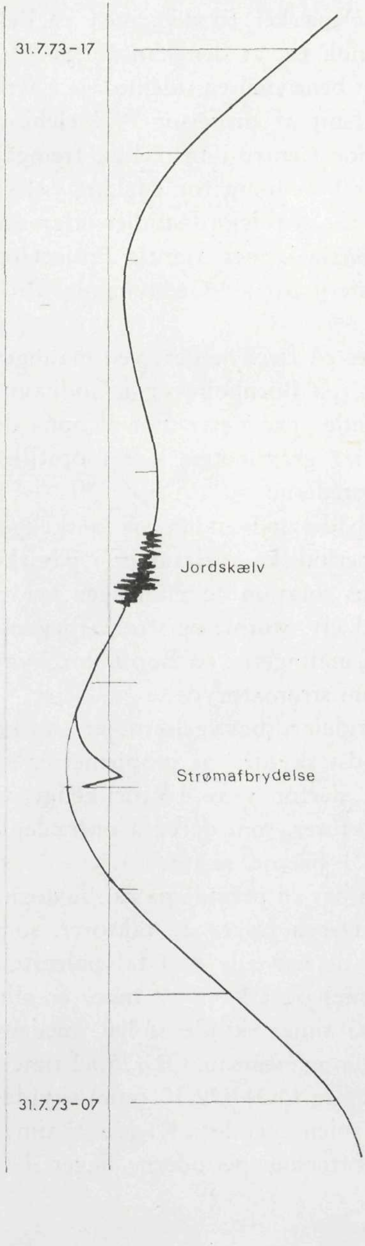

Fig. 1: *Udsnit af tidejordsregistreringen fra Bornholm. Registreringen dækker perioden 31. juli 1973 fra kl. 07.00 til kl. 17.00. Man ser, at der har været en strømafbrydelse kl. 10, og at der har været et jordskælv ved 12-tiden.*

1. mynd: Úrskurður av skrásetingini av flóð og fjøru á landi á Bornholm. Skrásetingin fevnir um tíðarskeiðið 31. juli 1973 frá kl. 07.00 til kl. 17.

Her sæst at streymslit hevur verið kl. 10 og jarðskjálvti umleið kl. 12.

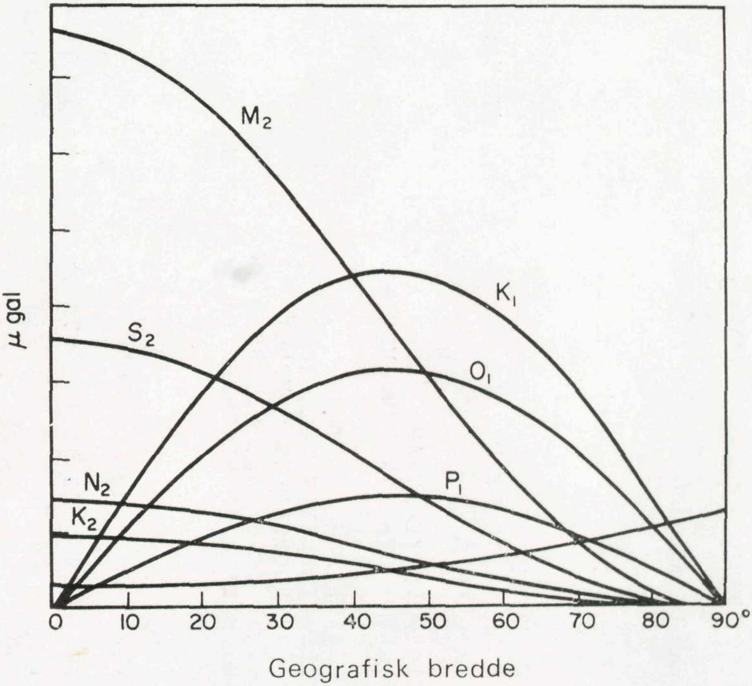

Fig. 2: *Diagram over de periodiske faktorers afhængighed af den geografiske bredde.*
2. *mynd:* Strikumynd av hvussu teir skeiðbundu luttøkutættirnir eru bundnir at breiddarstigunum.

mellem 11.97 og 12.66 time dels mellem 22.30 og 26.87 time, indser man bedre, hvorfor det er nødvendigt med lange måleserier.

Bestemmelsen af de nævnte 11 faktorer skal foretages på forskellige steder på jorden, idet faktorerne er afhængige af den geografiske breddeværdi. I diagramform er dette vist i figur 2.

I professor Melchiors tekst optræder to betegnelser, h og k; disse er sammen med et tredie, l, defineret af den engelske fysiker A. E. H. Love (1863—1940) og kaldes derfor Love's tal. Definitionen af h og k lyder således:

Fig. 3: *De beregnede periodiske faktorer efter 180 dages observations-periode.*

3. mynd: Teir roknaðu skeiðbundnu luttøkutættirnir eftir 180 daga eftirlitstíð.

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TRANS EUROPEAN PROFILE                                      STATION FAEROE

STATION 0821 FAEROE              COMPOSANTE VERTICALE              DANEMARK
        MORKEDAL RADAR STATION        BASALTE
62 04 N      06 57 W             H 700 M          P 45 M          D 2KM
GRAVIMETRE GEODYNAMICS 730 P.MELCHIOR/J.T.KUO-TRANS EUROPEAN PROFILES
CALIBRATION                  BRUXELLES - STATION FONDAMENTALE
INSTALLATION                 B.DUCARME/N.BREINER
MAINTENANCE                  PRLT. JAKOBSEN
METHODE DES MOINDRES CARRES / FILTRES VENEDIKOV SUR LECTURES HORAIRES
POTENTIEL CARTWRIGHT TAYLER EDDEN / DEVELOPPEMENT COMPLET
CORRECTION D INERTIE PROPORTIONNELLE AU CARRE DES VITESSES
CALCUL      CENTRE INTERNATIONAL DES MAREES TERRESTRES /FAGS/ BRUXELLES

FACTEUR D ECHELLE   0.31272
TRAINAGE   O1  1.29   M2  1.59   O1/M2 0.81
CORRECTION D ATTENUATION   M2/O1 1.01811

GEO 730    73  6 18   73 11  9   73 11 14   73 12 8   73 12 10   73 12 16

NOMBRE TOTAL DE JOURS 180
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GROUPE	SYMBOLE	AMPLITUDE EPOQUE CENTRALE	PHASE	FACT.AMPL.	EQM	DEPHASAGE	EQM	AMPLITUDE MOYENNE
1- 62	Q1	4.7977	26.42	1.1355	0.0192	-2.03	0.97	5.1450
63- 88	O1	30.1319	338.07	1.1384	0.0038	0.95	0.19	29.3383
89-110	M1	0.7764	26.71	0.9812	0.1107	15.30	6.46	3.4331
111-120	P1	14.2021	93.29	1.2066	0.0085	1.67	0.40	14.6735
121-143	S1K1	44.4192	268.13	1.1926	0.0027	1.47	0.13	44.0584
144-165	J1	2.4314	221.15	1.1785	0.0418	-1.29	2.04	2.9128
166-197	OO1	1.5556	18.01	1.0083	0.0914	-0.39	5.21	1.4469

ERREUR Q.M. D 4.226012

GROUPE	SYMBOLE	AMPLITUDE EPOQUE CENTRALE	PHASE	FACT.AMPL.	EQM	DEPHASAGE	EQM	AMPLITUDE MOYENNE
198-236	2N2	0.1798	271.48	1.5078	0.0684	10.87	2.64	0.8023
237-260	N2	4.5659	122.21	1.5521	0.0134	5.27	0.50	4.2491
261-286	M2	26.6243	67.45	1.6077	0.0027	-0.32	0.10	26.6814
287-300	L2	0.3502	175.35	2.4242	0.1746	0.53	4.19	0.6525
301-309	S2	11.2002	161.48	1.4883	0.0058	-7.55	0.23	11.5585
310-347	K2	3.4324	168.17	1.5234	0.0205	-6.19	0.78	3.2772

ERREUR Q.M. SD 1.865565

O1/K1 0.9545 1-O1/1-K1 0.7185 M2/O1 1.4122
EPOQUE DE REFERENCE TJJ* 2441942.0

h er forholdet mellem tidejordshøjden og den tilsvarende statiske tidevandshøjde;

k er forholdet mellem potentialtilvæksten (fremkaldt af deformationen) og det deformerende potential;

Numerisk falder h mellem 0.60 og 0.53, og k mellem 0.29 og 0.24. Det har været sædvane at sætte h = 0.58 og k = 0.29, hvilket giver h = 2k. Professor Melchior's analyse af de nyere data giver imidlertid k = 0.4989h, altså en mindre ændring fra 0.5h. Det er dog troligt, at yderligere måledata vil ændre denne værdi.

Tidligere blev langt de fleste tidejordsmålinger udført i mineskakter, hvilket skyldes, at man gerne ville være uafhængig af atmosfæriske forstyrrelser og af temperaturvariationer. Dette betød også, at langt de fleste stationer blev etableret i England, Sverige, Finland og Tyskland, og at disse stationer stort set var beliggende i ensartede geologiske forhold. Den stigende forståelse for tidejordsmålinger og den samtidige udvikling inden for elektronikken og observationsteknikken har gjort det muligt at opnå en betydelig bedre fordeling af målestationer, således at man dels har fået en bedre nord-syd-gående fordeling, fra Spitsbergen til Antarktis, dels stationer på såvel kontinenter som oceaniske øer. I denne forbindelse indgår Færøerne sammen med Island og Grønland i en profilforbindelse mellem Europa og Nordamerika. Endvidere kan måleapparaturet nu afskærmes så stærkt, at stationerne kan etableres på jordoverfladen, blot undergrunden er fast. Station 0821 Faeroe stod direkte på klippen.

Laboratoriet for Geofysik ved Aarhus Universitet fik af det internationale center i Bruxelles stillet et geodynamics-gravimeter til rådighed. Af Statens Naturvidenskabelige Forskningsråd blev bevilget det fornødne beløb til stationens etablering, og ved velvilje fra Forsvarsministeriet blev det muligt at oprette stationen i tilknytning til flyvestation Thorshavn.

Selve etableringen af tidejordsstationen blev foretaget i et samarbejde mellem Dr. B. Ducarme fra Bruxelles og ingeniør

Niels Breiner fra laboratoriet. Det daglige tilsyn med målestationen blev varetaget af premierløjtnant C. Jacobsen fra flyvestation Thorshavn. Registreringerne blev med regelmæssige mellemrum sendt til centret i Bruxelles, hvor hele beregningsprocessen finder sted på computer og efter et internationalt vedtaget regneprogram. Et eksempel på databehandlingen ses i figur 3. Station 0821 Faeroe var i funktion i den sidste halvdel af 1973.

Earth Tides in 1974

By P. Melchior.

A. *Introduction*

The Earth tides research field has been much enlarged since 1957 when, with the impulse of the International Geophysical Year, a program was developed for the continuous registration of this phenomenon.

At that epoch, the problem could be considered as restricted to some special investigation on the physics of the Earth's interior. Its importance resulted from the fact that it is the only known geophysical phenomenon for which one is able to compute a priori, and with very high precision, the acting forces as well as their frequencies (tidal frequencies are known with eight digits exact!). Owing to the smallness of the measured amplitudes, it seemed however to be without real pratical meaning for other research fields.

The development of new techniques, with always higher precision requirements has radically changed this view in the six different fields as described here:

1. *Fundamental Astronomy*

The unicity of the precession-nutations phenomenon and of the diurnal tesseral earth tides has been understood and demonstrated. This is of particular importance with respect to the liquid core dynamical effects (see § 6).

A similar relation must exist between the Moon's librations and the tidal deformations of the Moon.

The determination of the irregularities of the rotation of the Earth, including the polar motion, derived from doppler tracking of satellites, laser measurements of the Earth-Moon distance or by very long base interferometry implies a very precise determination of the total earth tide.

On the other hand the phase lag of the semi-diurnal sectorial earth tides is a basic factor producing the secular retardation of the Earth's rotation and it is a parameter representative of the Earth's viscosity (see § 6).

There is now some hope that we could be able to derive it in the next ten years.

2. *Space Dynamics*

a) The perturbing effects of tidal variations of the Earth potential on artificial satellite orbits have been derived from the observations themselves by R. Newton and by Y. Kozai. They amount to as much as 50 meters on a satellite position.

b) As laser distance measurements to the Moon and satellites will have ratings of some centimeters and as the radial tidal deformation reaches an amplitude of 30 to 40 cm, the latter must be taken into account. But (as reported by J. Derral Mulholland to Cospar) a simple analytical elastic earth-model being insufficient to calculate exactly this tidal deformation, experimental measurements are necessary at the sites concerned.

3. *Gravimetry*

Absolute determinations of g are made now with a precision of nearly one microgal (10^{-9}) (Sakuma, Faller). The comparison of such determinations made at different sites and at different epochs also depends upon the precision with which the tidal correction can be given. Special high precision gravity profiles presently developed (Scandinavia) request a comparable precision. Here again a simple analytical model is not sufficient.

In equatorial regions, the tidal variations of gravity amount to 0.4 milligal. If the local elastic factors and local phase lags are not measured in a reasonable number of stations, systematic errors of 10 % can be expected.

In the same way, when high precision gravity base lines are developel (a recent example is the new line Port Moresby — Hobart), the tidal parameters (amplitude *and* phase) must be measured at these stations to insure that no systematic errors, even little, can be introduced in the base line through some erroneous tidal corrections.

4. *Oceanography*

Ocean-continent interaction are carefully investigated in Marine Geodesy. Transcontinental tidal profiles are now under way in the United States, in Europe and in Asia in order to determine with precision the loading effects produced by the oceanic tides on the upper crust.

The Asiatic profile just undertaken already, gives quite different results than the European profile because the distribution of oceanic tides in the Atlantic Ocean is mostly of semi-diurnal type while it is of diurnal type in the China Sea.

There is a serious hope that one will be able to solve the *inverse problem*, that is to improve the cotidal and corange charts on the basis of the amplitudes and phases observed on the mainland for the solid earth tide (J. T. Kuo's programme).

5. *Tectonics*

Harmonic constants (amplitude and phase) of the main tidal waves determined at many places could perhaps give new informations on the limits of the plates constituting the earth's crust.

Stations have been occupied on the Philippine plate to check if this is a reasonable possibility.

6. *Physics of the Earth's interior*

To describe easily the global elastic behaviour of the Earth one uses convenient fundamental parameters called Love's numbers.

The determination of these numbers is evidently a basic goal in the earth's tide study.

As indicated by Poincaré and later on by Jeffreys, Jeffreys-Vicente and Molodensky, a resonance due to dynamical effects in the liquid core causes a perturbation in the Love's numbers values for waves having their frequency near the resonance.

Therefore we carefully separate these waves from the other ones by harmonic analysis. New invstigations are presently under way at the International Earth Tide Center on six very long series (3000 to 4000 days) obtained with quartz horizontal pendulums to try to determine the fine structure of the diurnal spectrum.

On the other hand, the measure of the eventual lag of the tides with respect to the acting potential should give basic informations on the viscosity of the Earth. The present results show a clear regional distribution but the extension of the world net will help to understand correctly this effect.

B. *Program of measurements*

1. *Results of 14 years observations (1960—1974)*

A great part of these investigations have been conducted under supervision or with support of the International

Centre of Earth Tides located at Brussels. This Centre was founded in 1958 under the direction of P. Melchior.

New instruments (quartz horizontal pendulums VM), calibration devices, methods of computation, computer programs have been developed at the Centre.

Presently Bruxelles Centre is a fundamental world point for calibration of instruments (tiltmeters and gravimeters).

The new problem arising now is the determination of radial tidal deformation which is necessary to correct laser distance measurements. This deformation is described by the first Love number called h. It can not be determined directly but current earth tide measurements give two simple arithmetic combinations containing h:

the ratio of observed to theoretical tidal amplitude measured with a gravimeter:

$\delta = 1 + h - {}^{3}/_{2}\, k$ (vertical component)

and the similar ratio measured with a tiltmeter:

$\gamma = 1 + k - h$ (horizontal component)

Thus, for h determination, it should be necessary to install not only gravimeters but also horizontal pendulums or vertical pendulums.

Horizontal pendulums are cheap and of easy maintenance (once a week) but one needs a 50 meters deep place to install them. If one can find a mine in the vicinity of laser stations, it could be done.

Vertical pendulums are very expensive and one has to drill a borehole 50 meters deep to have a good installation. The borehole is also expensive but not so much as a special galery. But the azimut of the instrument must be controlled at the moment of the installation at such a depth. Until now nothing has yet been published or available to have a clear idea of the performances of this instrument (calibration, phase lag etc....).

From present experience, european stations equipped with

VM horizontal quartz pendulums have given very consistent results in EW component, for the diurnal tidal waves called K_1 (period 1 sidereal day), P_1 (period 1 solar day) and O_1 (period 1 lunar day). O_1 is practically static and not disturbed by indirect oceanic effects. Mean values for 14 stations (18.056 days of observations) are just now:

	γ (K_1)	γ (O_1)
arithmetic mean	0.7429	0.6788
weight is number of days	0.7449	0.6797
weight according to m. s. e.	0.7494	0.6759
m. s. e. on the mean	0.0045	0.0056

in agreement with a Molodensky Earth's model with a liquid core.

For gravimeters the situation is more complex because some instruments, although excellent, seem to have been uncorrectly calibrated.

After some discussion and eliminations, I got for 18 stations (10.512 days of observation):

	δ (K_1)	δ (O_1)
arithmetic mean	1.1485	1.1628
weight is number of days	1.1466	1.1627
weight according to m. s. e.	1.1327	1.1638
m. s. e. on the mean	0.0028	0.0008

also in agreement with Molodensky model.

From these data we can derive following values:

	K_1			O_1		
	h	k	k/h	h	k	k/h
arithmetic mean	0.474	0.217	0.458	0.638	0.317	0.497
number of days weight	0.458	0.208	0.454	0.647	0.323	0.499
m. s. e. weight	0.486	0.236	0.485	0.645	0.321	0.497
m. s. e. on h is nearly		0.016				
on k		0.010				
on k/h		0.024				

As a theoretical relation gives (for $C/Ma^2 = 0{,}333$):

$$k/h = 0.4989$$

in the case of homothetic deformations and, without this assumption:

$$k/h < 0.4989$$

we can be satisfied with O_1 value.

Consequently, as a first approximation I should recommend to adopt $k/h = 0.499$ and check the values of h and k at each place from tidal gravity variations only which should indicate if there is any anomalous behaviour at the place concerned.

Such a check is necessary because the known numerical results concern presently only one part of Europe. As an exemple Scandinavia is giving quite different results for gravimeters but not for pendulums.

2. *The Trans World Tidal Gravity Profile*

Several North American profiles have been completed by John T. Kuo covering United States and South East of Canada. They are tied with Bruxelles station (calibrations are in agreement within 0,5 % between Bruxelles and New York).

Several European profiles are also completed by B. Ducarme and P. Melchior from South of France, Italy, Austria through Germany, Switzerland, Belgium, Holland, Denmark and England. New stations are planned in Spain, Portugal and Scandinavia. A separate profile has been made in Finland (T. Honkasalo). All the instruments have been calibrated at Bruxelles for amplitude and phase.

To solve the different described problems, it is of primary importance that the different transcontinental profiles will be tied together.

A first positive step has been completed by making a 6 months period of observation at Torshavn/Faroe.

This should allow to tie Europe with North America as stations are now occupied in Iceland (Reykjavik) and in Greenland (Godhavn) and later on in the Labrador.

The »Trans World Profile I« has been undertaken in november 1973 from Bruxelles to Asia and includes already nine stations: Cairo, Hyderabad, New Delhi, Kathmandu, Bangkok, Chiang Mai, Manila, Hong Kong and Port Moresby.

One month observations made by UCLA at Baguio (100 km north of Manila), Saïgon and Delhi has been reanalysed by the new methods and gives results in close agreement with ours.

This experience will be continued in Australia in 1975 (Darwin, Alice Springs, Broken Hill, Canberra, Perth, Charters Tower, Hobart).

Bruxelles has been tied to Japan by T. Sato in 1974, using two different gravimeters.

A project exists also to make measurements in South America in 1976 or 1977, with the cooperation of the Geodetic Institute of Tucuman University (J. C. Usandivaras).

PRELIMINARY REMARKS CONCERNING THE RESULTS OBTAINED AT TORSHAVN (Faeroe)

The measurements performed at Torshavn must be considered as a tentative to solve the inverse problem of oceanography as described in point 4.

The numerical results obtained here show a very different behaviour in function of the tidal frequencies.

1. *the Diurnal waves*

   are not very much disturbed for such a central oceanic situation as amplitude factors and phases do not differ very much from their continental values. The disturbance however is bigger for K_1 than for O_1.

2. *the Semi-Diurnal waves*

   have highly disturbed amplitude factors, 13 % higher than their values observed in Western Europe. However the phase is practically zero for M_2 while there is an important lag for S_2. This depends upon the exact location of the amphidromic point of the North Atlantic Ocean. These results have to be considered together with those obtained in England, Norway, Iceland, Greenland and Spitsbergen, in relation with the available cotidal charts of the Atlantic Ocean.

ABSTRACT

In the first part (in Danish) there is given a short description of the Earth Tide problem and the factors involved. In the second part (in English) are presented the development of the work of the International Centre of Earth Tides for 1974 and the Establishment of the Trans World Tidal Gravity Profile, of which station 0821 Faeroe is a member.

The preliminary results for station 0821 Faeroe show that the Diurnal waves are not very much disturbed, while the Semi-Diurnal waves are considerably affected by oceanic tidal loading effects, all compared with continental stations.

REFERENCES

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Melchior, P., Physique et dynamique planétaires, Vol. 2, Vander, Louvain, 1971.

ÚRTAK

Í fyrra parti (á donskum) verður í stuttum greitt frá fyribrigdinum flóð og fjøra á landi og luttøkutáttunum. Í seinna parti (á enskum) er sagt frá hvussu arbeiðið hjá »International Center of Earth Tide« í 1974 tók seg upp og frá stovnsetingini av »Trans World Tidal Gravity Profile« har sum Føroyar eru limur í støðini 0821.

Fyribils úrslitini frá støðini 0821 Faroe vísa at samdøgursaldurnar eru ikki nógv órógvaðar, meðan hálv-samdøgurs aldurnar eru munandi ávirkaðar av tyngingini av flóð og fjøru í havinum, alt samanborið við støðir inni á meginlandinum.