Comparison of some tidal prediction programs
and accuracy assessment of tidal gravity predictions

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1. Introduction

The strongest precision requirements concerns tidal gravity prediction. It is a reason why we shall investigate this tidal component. The comparison work is not exhaustive as we did not include the VAV (Venedikov and Vieira, 2004) or the BAYTAP-G (Tamura et al., 1991) approaches.

Two main approaches will be compared here:

- PREDICT (Wenzel, 1996) and T-soft (Van Camp and Vauterin, 2005);
- MT80w and MT80Tw (ICET, http://www.astro.oma.be/ICET/).

We shall follow the different steps required to obtain an accurate gravity tides prediction from the simple case of the astronomical tides to the tides on the real Earth

The accuracy of the tidal prediction will depend on the number of terms used in the Tidal Potential development. We shall see that other refinements are also required.

The tidal potential development have been computed with an increasing complexity: Doodson (1921) 378 terms, Cartwright-Edden (CTE505, 1973) 505 terms, Buellesfeld (1985) 656 terms, Tamura (TAM1200, 1987) 1,200 terms, Xi-Qin-Wen (1989) 2,933 terms, Roosbeek (1996) 6,499 terms and Hartmann-Wenzel (HW95, 1995) 12,935 terms. Recently Kudryatsev (2004) proposed a tidal potential development KSM03 with 28,806 terms.

PREDICT is the most versatile application and can use all the existing tidal potentials from Doodson up to Hartmann-Wenzel HW95. T-soft uses the same programming as PREDICT but is restricted to the TAM1200 tidal potential.

The MT80w is restricted to the CTE505 potential and MT80Tw can use TAM1200 and CTE505.

We shall compare the results of the different software for the station Hannover (λ=9°.7144E, φ= 52°.3868N, h=110m) during the year 1990. The peak to peak amplitude of the gravity tides reaches 2,200nms^{-2}. We shall call it the "tidal range" (TR)

To compare different tidal predictions we generally fit a linear regression between the results to obtain a scale factor and a RMS error. We can also give the range of the differences.

2. The astronomical tides

The first step is the precise evaluation of the direct influence of the Moon, the Sun and the planets, generally called the "astronomical tides". It is based on the developments of the tidal potential (Melchior, 1978). To derive a tidal prediction we have to consider a scale factor often referred as "Doodson" constant, a geometrical part depending on the position at the surface of the Earth (geodetic coefficients), which is different for each tidal component, and the harmonic part, which is a sum of sinusoidal terms. The development of the tidal potential provides for each term a normalised amplitude and an argument which is a linear combination of the astronomical arguments of the celestial bodies.

Only 6 arguments are required for the Luni-solar tides. The fundamental variables chosen by Doodson are

$\dot{\tau}$ = 14.49205 (period of 24h50m) for the mean lunar time τ

The orbital motion of the Moon requires 3 supplementary variables i.e.

$\dot{s}$ = 0.544902 (period of 27.321 days) s defines the position of the Moon on its orbit. It corresponds to the variation of the declination of the Moon (tropic month)
$\dot{p}$ = 0.00464 (period of 8.847 years) associated to the revolution of the mean lunar perigee.
$\dot{N}$ = (period of 18.613 years) corresponding to the retrograde revolution of the lunar node.

As the mean solar and lunar times (t et τ) are linked to the sidereal time t' by the relation

$\dot{t}' = \dot{t} + \dot{h} = \dot{\tau} + \dot{s}$

The solar terms will be expressed through the relation $\dot{t} = \dot{\tau} + \dot{s} - \dot{h}$

The apparent motion of the Sun is expressed by
$\dot{h}$ = (period of 365.25 days) tropic year
$\dot{p}_s$ = (20,940 years) period of rotation of the perihelion of the terrestrial orbit.

The Doodson variables are expressed as polynomial functions of the elapsed time, expressed in fraction of Julian century, since an initial epoch which is now J2000.0 corresponding to "Julian" date 2451545.0. The moment of the tidal prediction is thus converted in fraction of julian century since J2000.0. The amplitude of the main tidal terms is also changing slowly with time and since Tamura the main tidal constituents are given with a linear trend.
Some care should be taken when computing the Doodson arguments.
τ is not directly accessible but is computed by the relation
$\tau = 15°.t + \alpha_m - s + \lambda$
where t is the hour in UT and α_m is the right ascension of an fictitious object defining UT, and λ the longitude. The tidal prediction is thus expressed in UT at the point of longitude λ.
α_m replaces h because we want to use the "true" position of Moon and Sun and not the "apparent" one when we compute the hour angle α-α_m of a celestial body of right ascension α.
We consider thus that the gravitational attraction is acting instantaneously. The difference corresponds to the aberration term of 20".5 i.e. a phase shift of 0°.01 for the semi-diurnal waves or, at mid latitude, a global error that can reach 0.25nms^{-2} or 10^{-4} of the tidal amplitude.
One should use the dynamical time t_D, which is a linear time scale, in all arguments except α_m where the universal time t_u is used.
The universal time t_u is not a linear time scale and in practice one uses the UTC which is a linear time scale periodically readjusted on t_u.
The difference between t_d and UTC is given by an initial offset plus the sum of all the "leap" seconds applied to UTC since its instauration.
In the equation of τ we have still to correct t for the residual difference between t_u and UTC as the leap second jumps are already taken into account in α_m. This correction is always smaller than one second and will also affect the tidal prediction at the 10^{-4} level.
Concerning the planetary influences, Tamura was the first to introduce tidal terms coming from Jupiter and Venus.
Roosbeek and Hartmann-Wenzel introduced additional arguments for Mars, Mercury and Saturn to arrive to a total of 11 astronomic elements.

2.1 The planetary terms in Tamura and Wenzel

A direct comparison of the Tamura's formula with Wenzel ones for the planetary terms is not easy as the two authors are not using the same arguments to define the Jupiter and Venus positions.
Tamura argument f_7 is referring to Jupiter's opposition and f_8 to Venus superior conjunction.

Wenzel argument k_{10} is the mean longitude of Jupiter and k_8 the mean longitude of Venus.
It is easy to convert from one system to the other as

$$f_8 = 180° - (h - k_8)$$

and

$$f_7 = h - k_{10}$$

where h is the mean longitude of the sun.
For Jupiter there is no difficulty but there is a contradiction for Venus

From the first order expression in PREDICT with origin in JD 2451545.0

$h = 280°.47 + 360007.70*DTM$

$k_8 = 181°.98 + 585192.13*DTM$

we get

$f_8 = 81°.51 + 225184.4*DTM$

In Tamura, 1987 we have

$f_8 = 81°.5 + 22518.44*TD$

with DTM=TD/10

We see that at the first order in TD the definition is identical. It should be noted that an initial phase of 180° is equivalent to a change of sign of the term. It will matter only for terms where the argument k_8 is multiplied by an odd number. Among the few terms generated from Venus only term 984 has an odd argument (-1) for k_8. Its sign should be changed with respect to original Tamura work, when the program PREDICT is used (Ducarme and Xi, 2006).

2.2 Intercomparison of the softwares with a same tidal development

Comparison of PREDICT and MT80Tw with TAM1200:

extrema –0.01/+0.02nms^{-2} (< 10^{-5} TR)
scale factor 0.9999869
RMS error 0.0028nms^{-2}

Comparison PREDICT and MT80Tw with CTE505

extrema –0.15/+0.2nms^{-2} (< 10^{-4} TR)
scale factor 0.9998970
RMS error 0.0487nms^{-2}

Comparison PREDICT and MT80w with CTE505

extrema –0.2/+0.4nms^{-2} (< 210^{-4} TR)
scale factor 1.0000030
RMS error 0.1610 nms^{-2}

2.3 Intercomparison of the tidal developments for a same software

Comparison of HW95 and TAM1200 with PREDICT:

Extrema –0.4/+0.4nms^{-2} (< 210^{-4} TR)
scale factor 1.0000044
RMS error 0.0799nms^{-2}

Comparison of TAM1200 and CTE505 with MT80Tw

Extrema –1.5/+1.5nms^{-2} (<7.10^{-4} TR)
scale factor 0.9996702
RMS error 0.3347 nms^{-2}

2.4 Conclusions

The programming with TAM1200 is perfectly equivalent in PREDICT and MT80Tw. Even the old versionMT80w referred to J1900.0 is still valid to much better than 10^{-3}TR.
If we consider that HW95 is the most precise tidal development we see clearly the reduction of the precision with TAM1200 at the level of 2.10^{-4}TR ($0.5nm/s^2$) and CTE505 at the level of 7.10^{-4} TR ($1.5nm/s^2$).
The choice of the software and tidal development will thus depend of the required precision of the tidal gravity prediction around $10nms^{-2}$ for field work and better than $1nms^{-2}$ for absolute gravity measurements, for which special attention has to be paid to the LP part of the spectrum which can easily produce systematic errors. On the contrary for field differential measurements LP tides will cancel.

3. Elastic response of the Earth (the Earth tides)

Astronomical tides are only valid for a rigid Earth. For an elastic Earth it is necessary to take into account the deformation of the Earth and the additional change of potential induced by this deformation. For tidal gravity predictions this amplitude factor is called δ. The rigid Earth corresponds to $\delta = 1$. The computations are made under the assumption that all the waves inside a tidal "group" have one and the same δ factor. Tidal groups are formed by the waves in the vicinity of the main tidal constituents. The number and the limits of the groups are quite arbitrary for tidal prediction but for tidal analysis the Rayleigh criterion of commensurability of the periods on the time interval covered by the data set put constrains on the number of groups that one can consider.
The fundamental tidal potential W_2 is an harmonic function of degree 2. Doodson introduced already terms deriving from W_3 and since Tamura the potential W_4 is included. Each potential of degree n produces terms of order k with $0 \leq k \leq n$. The order fixes the frequency of the corresponding harmonic terms i.e. the tidal "families": 0 (LP), 1 (D), 2 (SD), 3 (TD), 4 (QT),….As a consequence in the LP tides one can find terms coming from W_2^0 , W_3^0 , W_4^0 ,… and in the ter-diurnal band terms from W_3^3 , W_4^3 ,…
As the Earth response will be different for each degree and order, it will be necessary to carefully separate the different degrees in each tidal family.
Finally attention should be paid to the fact that in the diurnal band the elastic response is not constant but that there exists a resonance, due to the liquid core (NDFW), close to the sidereal frequency, corresponding to wave K_1. For gravity the response is diminished of 2% for K_1 and increased by 10% on ψ_1. This fact is indeed included in the models.
Finally there is a permanent tide called M_0S_0 which requires a specific treatment. Tidal gravity corrections should apply the so called "zero tide" convention defined by IAG. It means that we can only correct the corresponding astronomical tide by applying a tidal factor equal to 1. This is automatically the case for the MT80 programs but for PREDICT and T-soft it is necessary to define a special tidal group M_0S_0 with $\delta = 1$
We shall investigate three questions:

- discrepancies between the different elastic models;
- influence of the LP, D and SD terms associated with W_3 and W_4;
- liquid core resonance

3.1 Comparison of the Earth response models

PREDICT is using latitude dependent tidal parameters for an elliptical, rotating, inelastic and oceanless Earth computed from the Wahr-Dehant-Zschau model (Dehant, 1987).

MT80Tw can be used with the model DPREMZ, Wahr-Dehant-Zschau, Dehant, 1987) and the DDW, Dehant-Defraigne-Wahr (Dehant et al., 1999) models, either hydrostatic (HYDR) or non-hydrostatic and inelastic(NHYDR).
The comparisons are made with the TAM1200 potential.

Comparison of NHYDR and HYDR:

Extrema –2./+1.nms^{-2} (< 10^{-3} TR)
scale factor 1.0015464
RMS error 0.1718

Comparison of NHYDR and DPREMZ

Extrema –2./+1.nms^{-2} (< 10^{-3} TR)
scale factor 1.0014897
RMS error 0.202

Comparison of DPREMZ and HYDR

Extrema –0.3./+0.4nms^{-2} (< $2 10^{-4}$ TR)
scale factor 1.0000565
RMS error 0.1156

The fit shows that the model NONHYDR differs significantly from the two others at the level of 0.15%. After the fit the discrepancies are reduced to –0.5/+0.5nms^{-2}. HYDR and DPREMZ are very close except for the LP tides , with $\delta = 1.157$ for HYDR and $\delta = 1.154$ for DPREMZ.

3.2 Treatment of W_3^k ($0 \leq k < 2$) and W_4^J ($0 \leq j < 3$) terms

These terms are very weak and, except for W_4^3, are mixed up inside the main LP, D and SD groups. However their amplitude factors differ systematically from these of the W_2 potential:
$\delta_2 \cong 1.155$ (LP), 1.15 (D) outside the resonance or 1.16 (SD) while $\delta_3 \cong 1.07$ $\delta_4 \cong 1.04$.
The W_4^3 terms will appear kept inside the ter-diurnal family.
To take into account this systematic difference it is conventionally accepted to multiply these terms by the ratio δ_3/δ_2 or δ_4/δ_2 between the tidal factor corresponding to their harmonic degree and the tidal factor corresponding to the main wave of their group. For what concerns the elastic response of the Earth this procedure is indeed perfectly correct.
Neglecting this correction will introduce systematic effects at the level of ±1.nms^{-2} (0.5 10^{-3} TR) and a RMS error of 0.61nms^{-2}.
Due to oceanic loading the problem of the LP, D and SD terms deriving from W_3 and W_4, becomes also more complicated. The oceanic loading effects are much lower on these constituents than on the tides excited by W_2. The analysis of the terms generated by W_3^1 and W_3^2 performed on the long records of superconducting gravimeters provided amplitude factors close to 1.07 and very small phase differences. Using as reference the modeled tidal factors δ_m, it is thus more correct to multiply the terms coming from $W_{3,4}^1$ and $W_{3,4}^2$ by $\delta_{3,4}/\delta_m$. If observed tidal factors are available it is necessary to check how they were obtained. Most of the tidal analysis programs include a correction of the terms generated by W_3^1 and W_3^2. Their amplitude in the tidal potential is multiplied by the ratio δ_3/δ_2 or δ_4/δ_2. It is thus better to use the same normalization in the tidal prediction. A more correct procedure, used in the program VAV, is to treat these terms as a separate group mixed up inside the wave groups generated by W_2^1 or W_2^2. Then the observed tidal factors δ_{obs} are free from any influence of the $W_{3,4}$ terms and it is better to apply in the tidal prediction the ratio $\delta_{3,4}/\delta_{obs}$ to the terms coming from $W_{3,4}^1$ and $W_{3,4}^2$.

For example a difference of 20% on the tidal amplitude factor of the SD waves used as reference to normalize the $W_{3,4}^{1,2}$ will produce a peak to peak difference of 2.10^{-4}TR ($0.4nms^{-2}$).

3.2 Influence of the NDFW in the diurnal band

The liquid core resonance is taken into account in the different models of the Earth response to the tidal forces, but with slightly different resonance parameters. It is concentrated on π_1, P_1, K_1 on one side of the resonance and ψ_1 and φ_1 on the other one. K_1 amplitude factor is reduced of 2% and ψ_1 is amplified of 10%.

As a first comparison one can enter the same model $\delta = 1$ on all the waves

Comparison of PREDICT and MT80Tw:

Extrema –0.1/+0.1nms^{-2} (< 0.5 10^{-4} TR)
scale factor 0.9999269
RMS error 0.0518

The differences are concentrated around ψ_1 and are due to the fact that a different ratio $\delta_{TD}/\ \delta_D$ is used in PREDICT and MT80Tw.

However generally for a tidal prediction we have only parameters for the main tidal groups i.e Q_1, O_1, P_1, K_1, N_2, M_2, S_2, K_2. In this case ψ_1 and φ_1 are mixed up with K_1 and will receive the same tidal parameters as the main wave of this group. However due to the resonance the effective amplitude factor of ψ_1 is higher by more than 10% and 3% for φ_1. It is thus useful to introduce the resonance by multiplying the amplitude inside by the theoretical resonance factors $\delta_{\psi 1}/\delta_{K1}$ or $\delta_{\varphi 1}/\delta_{K1}$. This correction is effectively implemented in PREDICT, T-soft and MT80Tw. Neglecting this correction will produce residues at the level of ±0.6nms^{-2} (3.10^{-4}TD) and a RMS error of 0.322nms^{-2}.

The intercomparison of the results when the K_1 group is not split but the theoretical resonance is introduced is given below.

Comparison of PREDICT and T-soft

Extrema –0.05/+0.05nms^{-2} (< 0.2 10^{-4} TR)
scale factor 0.9999899
RMS error 0.0220

Comparison of PREDICT and MT80Tw

Extrema –0.2./+0.2nms^{-2} (< 10^{-4} TR)
scale factor 0.9999268
RMS error 0.0518

It is clear that PREDICT and T-soft are based on the same models and formula. However most of the remaining discrepancy is concentrated in the TD and QD bands, where on the contrary there is no power left in MT80Tw. MT80Tw and PREDICT agree within 10^{-4}TD. Most of the discrepancy arises in the vicinity of ψ_1 where the reference models for the resonance have a significant difference.

3.3 Magnitude of the different effects

	Error	**RMS (nms^{-2})**
1. Choice of the elastic model	10^{-3}TR	0.1 to 0.2
2. Influence of W_3 and W_4 on LP, D and SD	5. 10^{-4}TR	0.610
3. Without considering resonance on ψ_1	3. 10^{-4}TR	0.322

residual effect on the difference between PREDICT and MT80Tw after correction of the effects 2 and 3, due to the discrepancy between the reference models used for the correction.

Effects 2 & 3	$1.0\,10^{-4}$TR	0.085
Effect 2 only	$0.5\,10^{-4}$TR	0.052

The conclusion is that the programs PREDICT and MT80Tw agree at the level of 10^{-4}TR for the computation of the gravity tides on an elastic Earth.

4. Tidal gravity prediction on the real Earth

The main problem for tidal gravity prediction is that the Earth tides are strongly perturbed by the influence of the oceanic tides which modify the tidal parameters distribution at the surface of the Earth. The oceanic tides produce a direct attraction due to the moving water masses, a flexure of the crust and an additional change of the potential due to the mass redistribution.

The ocean tides models of the main tidal constituents are given over a grid and each cell is characterized by its amplitude and phase. The tidal loading is evaluated according to a convolution of the ocean tide model with the Green's functions derived by Farrell (Farrell, 1972). The result called the load vector $\mathbf{L}(L,\lambda)$, where λ characterize the phase difference between the oceanic effect an the Earth tides vector for each wave (Figure 1). It is also possible to compute the equivalent tidal parameters δ_m, α_m that will be introduced in the tidal prediction program: $\mathbf{A}_{\mathbf{m}}(\delta_m.A_{theo}, \alpha_m) = \mathbf{R}(R,0) + \mathbf{L}(L,\lambda)$, with the notations of Fig. 1.

The effect can reach up to 10% of the Earth body tides, but is generally at the level of a few percent. The uncertainties and contradictions between different ocean tides models are such that the dispersion of the corresponding modeled tidal parameters δ_m, α_m is generally at the level of a few tenths of a per cent. In coastal areas it can easily exceed 1%. To demonstrate it we computed modeled tidal factors using 9 different ocean tides models (SCW80, ORI96, CSR3, CSR4, FES95, FES02, NAO99, GOT00 and TPX06). The standard deviation on the amplitude factors σ_δ and the phase differences σ_α is given in the table 1 for three regions: Siberia between 83° and 143° east longitude, Atlantic coast of France, Southern and Eastern Europe.

From Table 1 it is clearly seen that the standard deviation of one model is lower than 0.15% on the diurnal waves.

In the semi-diurnal band the standard deviation is lower than 0.2% inside Siberia and slightly larger close to the Pacific coast. The standard deviation is the same on the in phase and out of phase components and thus in amplitude and phase. In West Europe stations located at 100km from the Atlantic coast of France have standard deviations close to 1% for the out of phase component and thus on the phase. For Mordelles, located in Britanny, the errors are even larger than 1% on both components. For Etna which is far from the Atlantic Ocean the standard deviation is lower than 0.15%. It is clear that the use of the mean of the 9 models will be affected by a RMS error three times lower. It should be necessary to study systematically all the continents in order to identify areas where the contradiction between models are larger. In these regions some models are probably more suitable. For example along the Atlantic coast of France, Timofeev et al. (2006) recommend the use of CSR3, CSR4 or FES02 on the basis of tidal gravity observations.

Table 1: standard deviation of the tidal factors modelled by 9 different ocean tides models

STATION	O_1		K_1		M_2	
	σ_δ	σ_α	σ_δ	σ_α	σ_δ	σ_α
Novosibirsk	0.00112	0.049°	0.00096	0.045°	0.00180	0.094°
Talaya	0.00100	0.068°	0.00083	0.036°	0.00151	0.076°
Khabarovsk	0.00139	0.095°	0.00078	0.039°	0.00157	0.101°
Y.Sakhalinsk	0.00121	0.095°	0.00057	0.058°	0.00230	0.120°
Menesplet (F)	0.00115	0.068°			0.00186	0.404°
Chize (F)	0.00116	0.067°			0.00212	0.357°
Mordelles (F)	0.00141	0.077°			0.01194	0.776°
Etna	0.00128	0.065°	0.00117	0.073°	0.00136	0.068°
Pecny (9 maps)	0.00099	0.047°	0.00099	0.055°	0.00168	0.042°
(8 maps)					0.00084	0.022°

We can expect that, except in very unfavorable conditions, the standard deviation of the modeled tidal factors is at the level of 0.2%. The use of the mean of several models will increase the precision up to 0.1%.
If we take into account the disagreement between the different models of the elastic response of the Earth at the 0.1% level, we obtain an error budget close to 0.15% of the TR.

A better solution is indeed to perform tidal gravity observations to determine the quantities δ_{obs}, α_{obs}. However the calibration of the best instruments are also questionable at the level of 0.1% and very often calibration errors still exists at the level of 0.2%, even in the GGP network (Ducarme et al., 2002). Moreover to be able to separate the main tidal components a minimum of six months to one year of observations is required.
To summarize, without special care, it is very difficult to ensure an accuracy better the 0.2% of the TR.

5. Conclusions

It is rather easy to insure an accuracy of 1nm/s^2 for the prediction of the astronomical tides and all the tested software can achieve it.
For an elastic Earth, it is essential to introduce the effect of the liquid core resonance (0.03%) on one hand and the difference of elastic response for the terms deriving from the potentials of degree 3 and 4 (0.05%) on the other hand. These errors can be corrected with a precision better than 0.01%. However there are still discrepancies at the level of 0.1% between Earth models, according to the underlying hypotheses, such as hydrostatic or non-hydrostatic, elastic or anelastic.
On the real Earth the main perturbation is the ocean tides loading and attraction effect. Using the most recent ocean tides models and avoiding coastal areas, one can expect a precision of 0.1% of the tidal loading computations. Keeping in mind the two main error sources (Earth response and ocean loading) we reach an error budget of 0.15% of the TR, as a minimum. It is a reason why accurate tidal gravity observations can still be useful. However a determination

of the tidal parameters is difficult to achieve with accuracy better than 0.2% and the 0.1% level is exceptional (Francis, 1997; Palinkas, 2006).
For the while an accuracy of 0.2% of TR seems to be accessible either by direct observation of the tidal parameters or by modeling of the ocean tides loading and attraction effects.

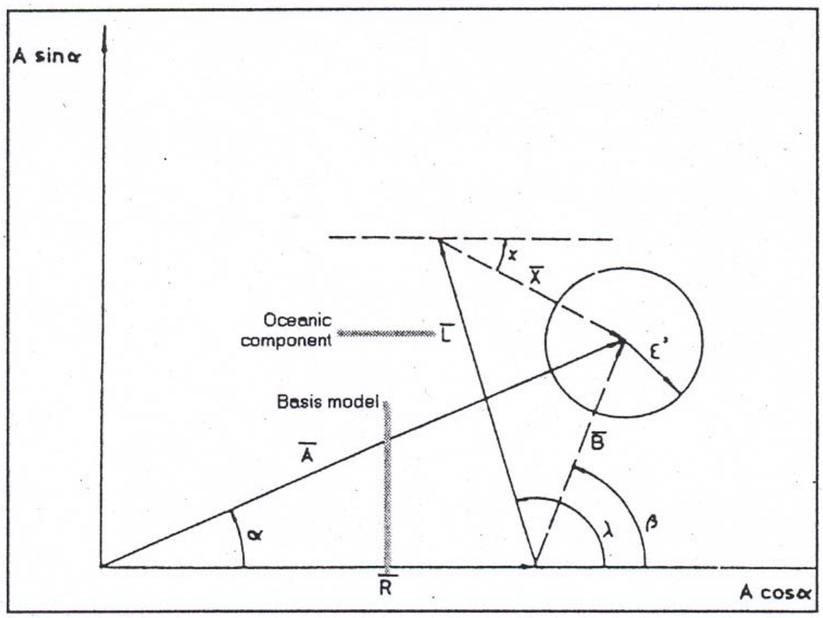

Fig. 1: Relationship between the observed tidal amplitude vector $\mathbf{A}(A,\alpha)$, the Earth model $\mathbf{R}(A_{theo}\delta_{theo},0)$, the computed ocean tides load vector $\mathbf{L}(L,\lambda)$, the tidal residue $\mathbf{B}(B,\beta)$ and the corrected residue $\mathbf{X}(X,\chi)$:

$$\mathbf{B}(B,\beta) = \mathbf{A}(A_{\text{theo}}\delta_{\text{obs}},\alpha) - \mathbf{R}(R,0)$$

$$\mathbf{X}(X,\chi) = \mathbf{B}(B,\beta) - \mathbf{L}(L,\lambda)$$

A_{theo} is the astronomical tidal amplitude, δ_{obs} is the observed tidal amplitude factor, α is the observed phase difference.

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