EXTENDING ESA'S NAPEOS S/W SYSTEM FOR OCEAN TIDE PARAMETER RECOVERY

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Abstract: *Ocean tides represent a fairly large source of perturbations in the motion of a close Earth satellite. Its 250 km altitude orbit makes GOCE the most sensitive satellite to ocean tide perturbations and a test-bed for the application of classical orbit perturbation analysis methods to recover tidal parameters. Several analysis procedures can be devised, but the direct numerical integration of the orbital motion with an extensive force model remains a fundamental tool. The means to perform this type of analysis has been identified in ESA's NAPEOS S/W system. This is a portable navigation software system for Earth Observation missions, providing many capabilities, among which orbit determination and prediction and parameter estimation. NAPEOS is fully written in Fortran 90. The estimation of ocean tide parameters, however, is not currently implemented in the system. Although none of the authors has been involved in any phase of the development of the system, it was decided to take up the challenge and implement this capability. Eighteen modules of NAPEOS were modified, in particular the BAHN and MULTIARC programs for normal equation stacking and handling. We report on the analysis methodology and on the strategy used to perform the upgrade and provide some validation results.*

Keywords: *Satellite Geodesy, Inverse problems, Orbit determination, Ocean tides, Software.*

1 Introduction

Accurate models of the tidal field over the oceans have been available in the recent years both as a result of extensive numerical integrations of the Laplace tidal equations, e.g. the FES series of models [1], or from the analysis of satellite altimetry data, as exemplified by the CSR [2] and the GOT [3] series of models. The recent GOCE mission and the allied GRACE mission, however, represent two space geodetic missions which, due to their low altitude, are ideally suited to tidal analysis, except for aliasing problems associated with sun-synchronicity. Its approximately 250 km altitude orbit makes GOCE the most sensitive satellite to ocean tide perturbations. To recover tidal parameters an estimation scheme based on the direct numerical integration of the orbital motion with an extensive force model is a fundamental tool.

As part of the GOCE-Italy project [4] [5], the CISAS group carried out the task of GOCE fully-dynamic precise orbit determination (POD) using ESA's state-of-the-art NAPEOS S/W system. The results obtained for one-day arcs covering a period of over one year show an average post-fit RMS of the undifferenced GPS carrier phase observations below 8 mm for most of the arcs [6]. Figure 1 shows the relationship between the post-fit RMS and the three-dimensional position difference RMS with respect to the official, reduced-dynamics GOCE project orbits. Except for a limited number of cases, which were not thoroughly investigated, low post-fit arcs are associated with orbits which compare within around 5 cm with respect to the official orbits. This encouraging result shows that state-of-the-art orbit accuracies can be obtained through a densely-parameterized, fully dynamic POD approach using NAPEOS. However,we believe that the comparison with the reduced dynamics and also with the kinematic PSO project orbits can be further improved through a detailed analysis of the ocean tide perturbations. In fact, both PSO-type orbits can absorb tidal perturbations signal that the NAPEOS force model, however densely prameterized, cannot. It becomes therefore of importance to be able to solve for ocean tide coefficients with NAPEOS. The upgrade
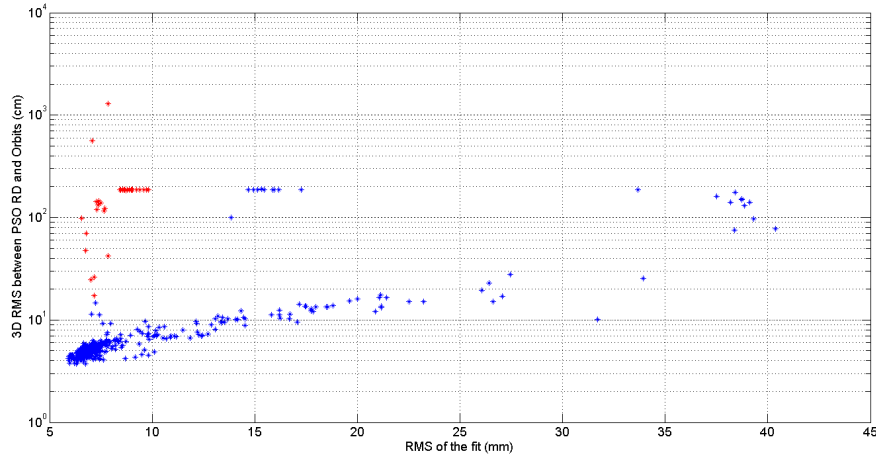
Figure 1: Comparison of the 3D rms distance between the orbits determined with NAPEOS and the official reduced dynamic orbits as a function of the NAPEOS rms of fit.

of NAPEOS to this capability is discussed in this contribution. After a brief description of NAPEOS S/W system given in Section 2, we give a summary of the perturbation model due to ocean tides in Section 3. An extensive description of the upgrade to the several modules of NAPEOS is provided in Section 4, while results on the validation of the upgrade are given in Section 5.

2 NAPEOS overview

The NAPEOS (NAvigation Package for Earth Observation Satellites) software system developed by ESA is a portable navigation software system for Earth Observation satellite missions, providing many capabilities, among which orbit determination and prediction, manoeuvre-planning and parameter estimation. NAPEOS can process a wide variety of observation data types (currently, 34 data types) including angles, range, range-rate, altimetry, satellite-to-satellite range and range-rate, GNSS data [7] [8].

NAPEOS is structured as a collection of component libraries and programs. Its main characteristics are

- it is fully written in Fortran90 following an object oriented methodology that allows the decomposition of the system according to the key abstractions in the problem domain [8],
- a user frendly GUI based on Tcl/Tk,
- a modular structure that minimizes the coupling among components, thus easing its replacement by another one with the same functionalities,
- a highly flexible design providing the capability to adapt the system to new constraints and guarantee its extension to other missions of interest without drastic software changes,
- an automatic execution capability of a sequence of tasks interactively defined by the user.

Figure 2 represents, at functional level, the basic architecture of the NAPEOS software system [8]. The elements in the diagram represent the main components of the NAPEOS functional chain. The diagram is at the same time a somewhat incomplete representation of the operational components of the system.

The UML diagram in Fig. 3 shows the relationships among the different NAPEOS components. The use relationship between different subsystems (libraries) is represented by arrows pointing to the element being used by another. Clearly, the elements at the bottom are subsystem components providing support
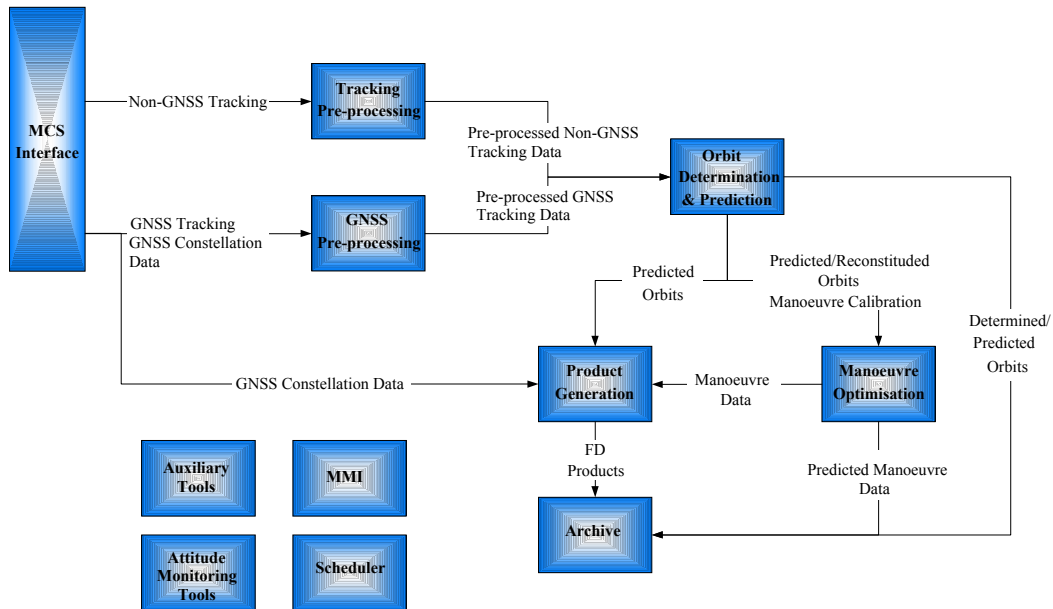
functionality to almost all other subsystems.

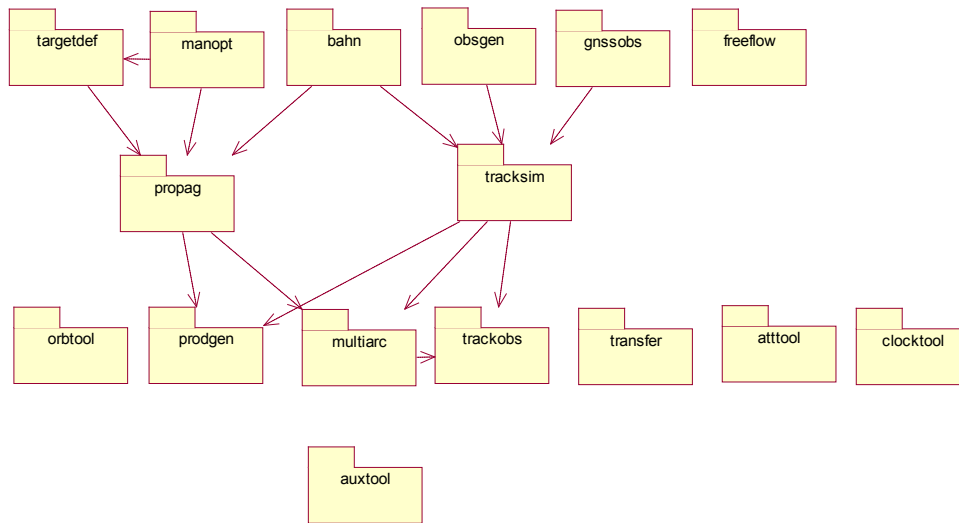**Figure 2: NAPEOS functional architecture [8]**

Figure 3: NAPEOS subsystem overview [8]

3   Ocean tides

In this Section we provide a brief summary of ocean tide modeling as implemented in NAPEOS. We focus on the definition of the time-varying corrections to the Stokes coefficients in the spherical harmonics representation of the gravitational field in terms of the harmonic coefficients of the tide height field expansion. We also provide expressions for the partials with respect to these ocean tide harmonic coefficients.

3.1 Parametrization of the ocean tide potential

The general expression of the ocean tide potential is given as an explicit function of the fully-normalized temporal variations $\Delta \bar{C}_{lp}(t)$ and $\Delta \bar{S}_{lp}(t)$ of the Stokes coefficients of the geopotential and can be written as

$$V_{OT}(r, \lambda, \phi) = \frac{GM}{r} \sum_l \sum_p \left(\frac{a}{r}\right)^l [\Delta \bar{C}_{lp}(t) \cos(p\lambda) + \Delta \bar{S}_{lp}(t) \sin(p\lambda)] \bar{P}_{lp}(\sin \phi), \tag{1}$$

where r, λ and ϕ are respectively the radial distance, the longitude and the latitute of the field point, l and p are the degree and order of the spherical harmonics expansion, $\bar{P}_{lp}(\sin \phi)$ is the fully normalized associated Lengendre function of degree l and order p, GM is the gravitational parameter of the Earth and a its equatorial radius.

We can write the Stokes coefficients variations $\Delta \bar{C}_{lp}(t)$ and $\Delta \bar{S}_{lp}(t)$ in terms of the prograde ($+$) and retrograde ($-$) harmonic coefficients $\tilde{C}_{lp}^{\mathbf{k}+}, \tilde{C}_{lp}^{\mathbf{k}-}, \tilde{S}_{lp}^{\mathbf{k}+}, \tilde{S}_{lp}^{\mathbf{k}-}$ of the spherical harmonics expansion of the tide height field as follows

$$\Delta \bar{C}_{lp}(t) = F_{lp} \sum_{\mathbf{k}} [(\tilde{C}_{lp}^{\mathbf{k}+} + \tilde{C}_{lp}^{\mathbf{k}-}) \cos \Theta_{\mathbf{k}}(t) + (\tilde{S}_{lp}^{\mathbf{k}+} + \tilde{S}_{lp}^{\mathbf{k}-}) \sin \Theta_{\mathbf{k}}(t)], \tag{2}$$

$$\Delta \bar{S}_{lp}(t) = F_{lp} \sum_{\mathbf{k}} [(\tilde{S}_{lp}^{\mathbf{k}+} - \tilde{S}_{lp}^{\mathbf{k}-}) \cos \Theta_{\mathbf{k}}(t) - (\tilde{C}_{lp}^{\mathbf{k}+} - \tilde{C}_{lp}^{\mathbf{k}-}) \sin \Theta_{\mathbf{k}}(t)], \tag{3}$$

where $\Theta_{\mathbf{k}}(t)$ is the Doodson argument of the tidal constituent $\mathbf{k}$ (see [9]) and the normalization factor F_{lp} is given by

$$F_{lp} = \frac{4\pi G \rho_w}{g} \frac{1 + k_l'}{2l+1} \sqrt{\frac{(l+p)!}{(2 - \delta_{0p})(2l+1)(l-p)!}}, \tag{4}$$

where k_l' is the loading Love number of order l, ρ_w is the ocean water density and g is the gravitational acceleration at the Earth surface.

The harmonic coefficients $\tilde{C}_{lp}^{\mathbf{k}+}, \tilde{C}_{lp}^{\mathbf{k}-}, \tilde{S}_{lp}^{\mathbf{k}+}, \tilde{S}_{lp}^{\mathbf{k}-}$ form the set of parameter to be estimated in tidal analysis. Each of these parameters is uniquely defined by specifying five indices: its degree and order, its Doodson number, its harmonic type and its chirality, as shown in Tab. 1.

Table 1: List of indices identifying a given tidal harmonic coefficient

Index	Description
Tidal constituent	Doodson number of the tidal constituents $\mathbf{k}$
Degree	Degree of harmonic coefficient
Order	Order of harmonic coefficient
Harmonic type	C or S
Chirality	$+$ for a prograde coefficient, $-$ for a retrograde one

3.2 Ocean tides partials

The ocean tide model described in the previous section was already implemented in NAPEOS. However, as already stated, the estimation of ocean tide parameters is not currently implemented. In general, given the observations O_i, the correspondig computed values C_i and the vector $\mathbf{P}$ of parameters to be determined, the basic problem of parameter estimation is to determine a solution to the equations

$$O_i - C_i = - \sum_j \frac{\partial C_i}{\partial P_j} dP_j + dO_i, \tag{5}$$

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where i denotes the ith observation, dP_j is the correction to the jth parameter and dO_i is the error of observation associated with the ith measurement. Defining with $\mathbf{P}_{OT}$ the vector of tidal parameters as

$$\mathbf{P}_{OT} = \left(\begin{array}{cccc} \tilde{C}_{lp}^{\mathbf{k}+} & \tilde{C}_{lp}^{\mathbf{k}-} & \tilde{S}_{lp}^{\mathbf{k}+} & \tilde{S}_{lp}^{\mathbf{k}-} \end{array} \right), \tag{6}$$

to estimate the harmonic coefficients we have to compute the partials $\partial C_i / \partial \mathbf{P}_{OT}$. Clearly, the harmonic coefficients $\tilde{C}_{lp}^{\mathbf{k}+}, \tilde{C}_{lp}^{\mathbf{k}-}, \tilde{S}_{lp}^{\mathbf{k}+}, \tilde{S}_{lp}^{\mathbf{k}-}$ are dynamical parameters affecting the motion of the satellite. This implies that we can write

$$\frac{\partial C_i}{\partial \mathbf{P}_{OT}} = \frac{\partial C_i}{\partial \mathbf{X}_r} \frac{\partial \mathbf{X}_r}{\partial \mathbf{P}_{OT}}, \tag{7}$$

where $\mathbf{X}_r = (\mathbf{r}_r, \mathbf{v}_r)$ is the satellite dynamical state vector. The partials of C_i with respect to the satellite state vector were already implemented in NAPEOS. The partials $\partial \mathbf{X}_r / \partial \mathbf{P}_{OT}$ are called variational partials and are obtained from the numerical integration of the variational equations

$$\frac{d}{dt}\left(\frac{\partial \mathbf{r}_r}{\partial \mathbf{P}_{OT}} \right) = \frac{\partial \mathbf{v}_r}{\partial \mathbf{P}_{OT}}, \tag{8}$$

$$\frac{d}{dt}\left(\frac{\partial \mathbf{v}_r}{\partial \mathbf{P}_{OT}} \right) = \frac{\partial \mathbf{a}_r}{\partial \mathbf{r}_r} \frac{\partial \mathbf{r}_r}{\partial \mathbf{P}_{OT}} + \frac{\partial \mathbf{a}_r}{\partial \mathbf{P}_{OT}}, \tag{9}$$

where $\mathbf{a}_r$ is the acceleration on the satellite. The implicit partials $\partial \mathbf{a}_r / \partial \mathbf{r}_r$ were already implemented in NAPEOS. On the contrary, the explict partials $\partial \mathbf{a}_r / \partial \mathbf{P}_{OT}$ had to be implemented. Recognizing that $\mathbf{a}_r = \nabla V_{OT}$, where V_{OT} is given by Eq. 1, and developing the partials using the chain rule we can write the partials as

$$\frac{\partial \Delta \bar{C}_{lp}(t)}{\partial \mathbf{P}_{OT}} = \left(\begin{array}{cccc} \frac{\partial \Delta \bar{C}_{lp}(t)}{\partial \tilde{C}_{lp}^{\mathbf{k}+}} & \frac{\partial \Delta \bar{C}_{lp}(t)}{\partial \tilde{C}_{lp}^{\mathbf{k}-}} & \frac{\partial \Delta \bar{C}_{lp}(t)}{\partial \tilde{S}_{lp}^{\mathbf{k}+}} & \frac{\partial \Delta \bar{C}_{lp}(t)}{\partial \tilde{S}_{lp}^{\mathbf{k}-}} \end{array} \right), \tag{10}$$

$$\frac{\partial \Delta \bar{S}_{lp}(t)}{\partial \mathbf{P}_{OT}} = \left(\begin{array}{cccc} \frac{\partial \Delta \bar{S}_{lp}(t)}{\partial \tilde{C}_{lp}^{\mathbf{k}+}} & \frac{\partial \Delta \bar{S}_{lp}(t)}{\partial \tilde{C}_{lp}^{\mathbf{k}-}} & \frac{\partial \Delta \bar{S}_{lp}(t)}{\partial \tilde{S}_{lp}^{\mathbf{k}+}} & \frac{\partial \Delta \bar{S}_{lp}(t)}{\partial \tilde{S}_{lp}^{\mathbf{k}-}} \end{array} \right). \tag{11}$$

Explicitly the partials of the Stokes coefficient variations due to ocean tides with respect to the harmonic coefficients at a specified tidal frequency $\mathbf{k}$ are

$$\begin{aligned}
\frac{\partial \Delta \bar{C}_{lp}(t)}{\partial \tilde{C}_{lp}^{\mathbf{k}+}} &= F_{lp}\cos\Theta_{\mathbf{k}}(t), & \frac{\partial \Delta \bar{C}_{lp}(t)}{\partial \tilde{C}_{lp}^{\mathbf{k}-}} &= F_{lp}\cos\Theta_{\mathbf{k}}(t), \\
\frac{\partial \Delta \bar{C}_{lp}(t)}{\partial \tilde{S}_{lp}^{\mathbf{k}+}} &= F_{lp}\sin\Theta_{\mathbf{k}}(t), & \frac{\partial \Delta \bar{C}_{lp}(t)}{\partial \tilde{S}_{lp}^{\mathbf{k}-}} &= F_{lp}\sin\Theta_{\mathbf{k}}(t), \\
\frac{\partial \Delta \bar{S}_{lp}(t)}{\partial \tilde{C}_{lp}^{\mathbf{k}+}} &= -F_{lp}\sin\Theta_{\mathbf{k}}(t), & \frac{\partial \Delta \bar{S}_{lp}(t)}{\partial \tilde{C}_{lp}^{\mathbf{k}-}} &= F_{lp}\sin\Theta_{\mathbf{k}}(t), \\
\frac{\partial \Delta \bar{S}_{lp}(t)}{\partial \tilde{S}_{lp}^{\mathbf{k}+}} &= F_{lp}\cos\Theta_{\mathbf{k}}(t), & \frac{\partial \Delta \bar{S}_{lp}(t)}{\partial \tilde{S}_{lp}^{\mathbf{k}-}} &= -F_{lp}\cos\Theta_{\mathbf{k}}(t).
\end{aligned} \tag{12}$$

These are the partials to be implemented in NAPEOS in order to integrate the variational equations to allow the estimation of the harmonics tidal coefficients.

4 NAPEOS software upgrade

The harmonic tide coefficients are a particular set of parameters, like geopotential coefficients or station position, that can only be estimated processing observations over a long span of time (from months to years). It is not practical in these cases to process a unique long orbit determination arc because this would require long computation times, inverting large matrices and having to deal with huge observation datasets. From the computational point of view in fact this task can conveniently be performed using normal equation stacking

and handling. In this way both arc and common parameters are estimated on each shorter arc (usually a daily arc) and the normal equations are stored in memory. Then the normal equations are combined togheter pre-eliminating the arc parameters and solving for the common parameters.

Taking advantage of the modularity and flexibility of NAPEOS, the software has been accurately analized to clearly identify the components that have to be modified to include the capability of estimating the ocean tide parameters. The base components (libraries) involved are essentially four, that is *multiarc*, *tracksim*, *propag* and *bahn*. The main programs affected by this upgrading were BAHN and MULTIARC: a total of eighteen Fortran90 modules of NAPEOS have been modified as shown in Table 2.

Table 2: List of modified NAPEOS module and associated libraries

Library	Module name
multiarc	`MApa_Parameter`
	`MAs_Record`
	`MAio_ReadWrite`
	`MAux_Aux`
	`MApr_Processor`
	`MAsn_Sinex`
tracksim	`TSpc_CentralBodyParameters`
propag	`OPti_Tides`
	`OPsa_Satellites`
	`OPin_Integration`
	`OPac_Acceleration`
	`OPgp_GeoPot`
bahn	`BApc_CentralBodyParameters`
	`BApm_ParametersManagement`
	`BApg_GnssParamters`
	`BApa_Parameters`
	`BAco_Computation`
	`BAne_NEQExport`

The main program BAHN is responsible for the determination, by means of weighted least-squared fitting, of the orbit of a set of satellites orbiting around the Earth, using tracking observations of those satellites. The estimated orbit is uniquely defined by an initial state vector and epoch plus the list of force models applied, together with parameters associated with these models (extended state vector). It is able to estimate all arc-dependant parameters required, and in addition it is able to generate observation and normal equations for global parameters to be estimated by the program MULTIARC. Figure 4 shows the relationship between the program BAHN and the other NAPEOS libraries.

BAHN manages the estimation of parameters subdividing them into six families as shown in Tab. 3. It is clear that the harmonic tide coefficients are members of the central body family: the parameters of this family, together with the satellite parameters, must have their variational partials propagated. In the NAPEOS architecture the numerical integration task is handled by a substructure inside the *satellite global structure* that contains also all the information on the force model acting on a given satellite. In this way, when estimating a parameter belonging to satellite family the new value of the parameter must be updated at each iteration only in the force model section contained in the satellite global structure. In the case of the estimation of a central body parameter the question is more complicated due to the distinctive feature of this family. The new value in fact has to be updated at each iteration both in the force model section of satellite global structure
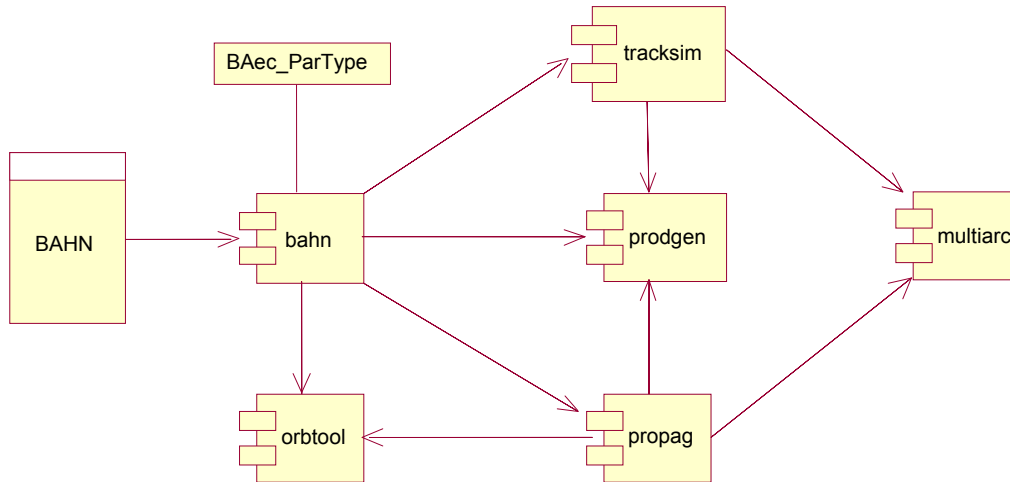
Figure 4: Relationship between BAHN and the other libraries of NAPEOS S/W [8]

and in the database of central body parameters. The ocean tide coefficients are stored in a structure inside a module that computes the corrections to the Stokes coefficients due to solid and ocean tides. Therefore new procedures interfacing the *propag* and *bahn* components have been developed. Moreover the satellite global structure has been extended by adding new parameters substructures specifically designed for the central body parameters family. In this way the handling of variational equations has been managed more easily by adopting the same schema used for the satellite parameter family. The new capability of estimate the ocean tide coefficients can be easily extended to estimate other central body parameters like the Stokes coefficients and solid Earth tide parameters.

The currently available version of the NAPEOS GUI was already prepared to accept the harmonic tide coefficients as estimable parameters (see Fig. 5). On this GUI the name of the tide must be given. The four coefficients C^+ (prograde cosine), C^- (retrogade cosine), S^+ (prograde sine) and S^- (retrograde sine) are estimated for every tidal constituent selected. In the central body parameters list a lower limit in degree and order (*index 1* and *index 2* respectively) and a higher limit in degree and order (*index 3* and *index 4* respectively) must be given.

In the following the list of the specific changes for each module is given including also the new procedures with their descriptions. The naming convention is the same as used in NAPEOS, i.e., all public objects and procedures belonging to one module start with the same first four letters of the module name (the first two capital letters identify the component or library). Concerning the abbreviation in the rest of the document, I stands for integer*4, R for real*8 , L for logical and D for derived types in the Fortran sense. In the first column of each table the name contained within parentheses indicate, where present, the public name of the procedure.

4.1 **MApa_Parameter**

This module contains the definition and the manipulation of all parameters that can be managed by NAPEOS. Any low level parameter `MApa_ParType` belonging to one of the families shown in Tab. 3 is defined in this module. The ocean tide parameters, originally not treated by NAPEOS, have been specified here.

Table 3: The six families of estimable parameters of NAPEOS S/W

Parameter family	Parameter type
Central body	Stokes coefficients, ocean tide coefficients, *GM*, k_2
Earth orientation	x_p, y_p, $\dot{x}_p$, $\dot{y}_p$, UT1$-$UTC, lenght of day
Satellite	position, velocity, solar radiation pressure coefficients, empirical acceleration, aerodinamic coefficients, albedo and infrared coefficients
Transponder	clock bias, transponder bias, transponder ambiguity
Station	station position, atmospheric delay, station clock bias
GNSS	GNSS clock bias, GNSS clock drift, GNSS ambiguity
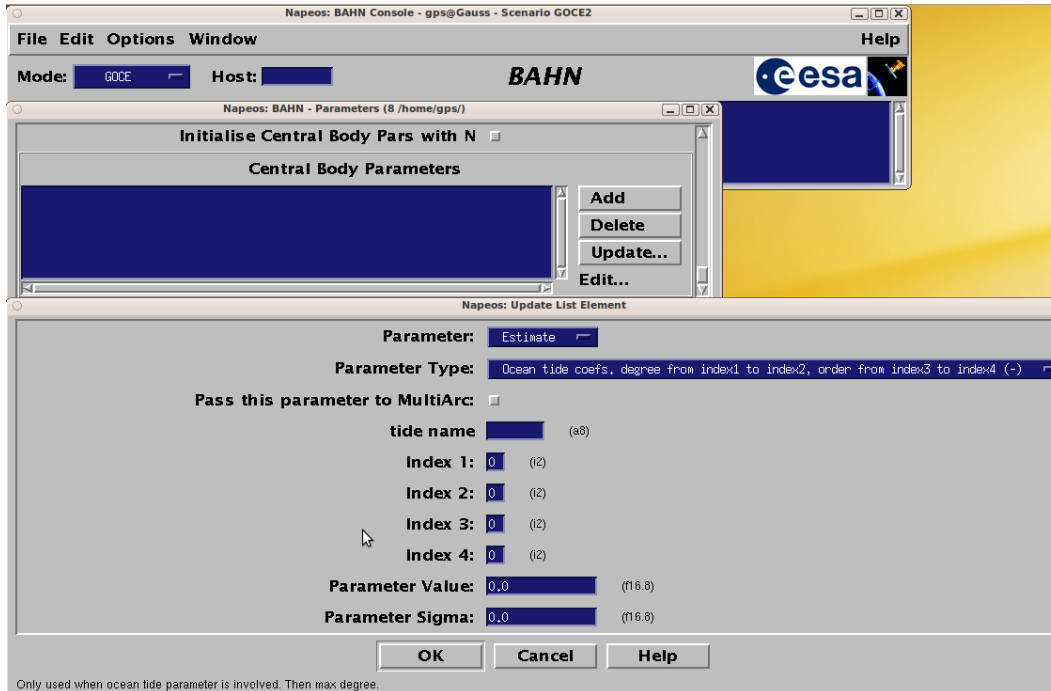
Figure 5: NAPEOS GUI for setting the estimation of ocean tide parameters in BAHN

`MApa_Parameter`	Type	Origin	Description
`MApa_otide`	parameter (I)	new	name for ocean tide parameter
`MApa_nTypes`	parameter (I)	modified	added the ocean tide parameter to the total number of known parameters
`MApa_IType`	parameter (D)	modified	added row to specify ocean tide parameter description
`parObsTraceability`	parameter (L)	modified	added row to specify ocean tide parameter observability with respect to an observation type

4.2 `MAs_Record`

This module contains the data structures and the record definition for normal and observation equations. The data structure to hold a parameter definition record as been changed adding the information that qualifies the ocean tide coefficients (see Tab. 1).

MAs_Record	Type	Origin	Description
MAs_ParType	variable (D)	modified	added the characteristics given in Tab. 1 to the data structure

4.3 MAio_ReadWrite

This module is responsible for the handling of observation and normal equations reading and writing. The procedure managing the reading and writing of the normal equations file have been modified adding the information that qualify the ocean tide coefficients (see Tab. 1)

MAio_ReadWrite	Type	Origin	Description
ReadParOne (MAio_ReadPar)	procedure	modified	added the characteristics given in Tab. 1 to the READ statement
WriteParOne (MAio_WritePar)	procedure	modified	added the characteristics given in Tab. 1 to the WRITE statement

4.4 MAux_Aux

This module contains auxiliary functions and procedures for MULTIARC. The upgrade let the main program to recognize and handle the new parameters.

MAux_Aux	Type	Origin	Description
IsSimilar (MAux_IsSimilar)	function	modified	added call to MAux_IsOtidePar
MAux_IsOtidePar	function	new	Returns whether the parameter is an ocean tide parameter

4.5 MApr_Processor

This module is responsible for the processing of the normal and observation equations and their solution. The change involved only the procedure that deals with the output report.

MApr_Processor	Type	Origin	Description
WriteSolution	procedure	rewrited	write the solution of the multiarc problem including ocean tide coefficients

4.6 MAsn_Sinex

This module handle SINEX format input and output. The change involved only the procedure that deals with the return of the parameter information to write to a SINEX file.

MAsn_Sinex	Type	Origin	Description
MAsn_SinexInfo	function	modified	added info on ocean tide parameters

4.7 TSpc_CentralBodyParameters

This module manages central body family parameters (MApa_cbParFamily type). The information qualifying the ocean tide parameters have been added to the derived type that define the central body family TSpc_ParType. The procedure that deals with the loading of parameters from the steering file generated by the GUI has been modified adding the reading of the ocean tide parameters.

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TSpc_CentralBodyParameters	Type	Origin	Description
TSpc_ParType	variable	modified	added to central body family type the following `tidename`: Doodson argument `degree` `order` `harmonic`: 1 = C, 2 = S `sign`: -1 = -, +1 = +
TSpc_tide	parameter (I)	new	added to set `TSpc_ParType` values from GUI
TSpc_ReadPar	procedure	modified	added the read of ocean tide parameters
TSpc_ParameterDescription	procedure	modified	added description of ocean tide parameters
ExpandGridOceanTidePar	procedure	new	expand the grid of ocean tide parameters defined by min-max degree and min-max order
CheckPar	procedure	new	check if parameter is already set before or if parameter is not estimable
AssignParameterMany (=)	operator	new	overloading operator
AssignParameterManyMany (=)	operator	new	overloading operator

4.8 OPti_Tides

This module calculates corrections to the coefficients of the gravity field due to both ocean and solid tides. The ocean tide coefficients read from the input file are stored in this module. Addding the new capability of estimate these parameters, new procedures for setting and retriving the ocean tide coefficients has been coded. Moreover subroutine for computing the partials derivatives of geopotential coefficient corrections due to ocean tides with respect to the ocean tide coefficients has been added.

OPti_Tides	Type	Origin	Description
OceanTidesCorr	procedure	modified	corrected error (missing factor 2 in the computation of zonal correction)
OPti_IsParameterPresent	function	new	checks whether the provided ocean tide parameter of given degree, order and tidal constituent is present in the `OTide` database structure
OPti_GetOtideValues	procedure	new	provided ocean tide parameter of degree, order and tidal constituent return the corresponding values in the following order: C^+, S^+, C^-, S^-
OPti_SetOceanTideCoefficient	procedure	new	set value of an ocean tide parameter in the `OTide` database structure given the tidal constituent, degree, order, and the mask C^+, S^+, C^-, S^-
OPti_GetConstituentIndex	procedure	new	provided tidal constituent return the corresponding index of constituent in database
OPti_GetPerturbationIndex	procedure	new	provided constituent index, order and degree, return the corresponding index of constituent in database
OPti_DotideCorrDp	procedure	new	computes partials derivatives of geopotential coefficient corrections due to ocean tides wrt ocean tide coefficient

4.9 OPsa_Satellites

This module contains the satellite structure definition and all related procedures. The satellite global structure contains all the information on the satellites currently activated and the force model acting on them. Moreover this structure is responsible for the numerical integration of the orbits and variational partials. In this structure two new derived types specific for the central body parameter family have been added. The ocean tide

substructure has been extended including these new derived types. In this way the ocean tide coefficients can be treated as satellite parameters and their variational partials can be propagated. In case that new central body family parameters, like Stokes coefficients, have to be estimated it is necessary to modify and extend both the new derived types (`OPsa_pcParType` and `OPsa_pcSingleParType`) and the procedure associated to them.

OPsa_Satellites	Type	Origin	Description
OPsa_pcParType	variable (D)	new	specific central body parameter list type
OPsa_pcSingleParType	variable (D)	new	single central body parameter type (loaded from `OPsa_pcParType`)
OPsa_TidesType	variable (D)	modified	added `OTide` of type `OPsa_pcParType`
OPsa_numSatPcPar	parameter (I)	new	number of central body propagation parameters
OPsa_satPcParId	parameter (I)	new	central body propagation parameters identification
DoneOne (OPsa_Done)	procedure	modified	added call to `DoneSinglePcPar`
OPsa_InitSingleSatPcPar	procedure	new	allocates, sets epochs and resets values for a single parameter
OPsa_SetSatPcPar	procedure	new	dump data from a `MApa_ParType` to a `OPsa_pcParType`
OPsa_IsSatPcPar	function	new	determine wether the satellite structure has parameter `MAtype` of central body type
OPsa_GetSatPcPar	procedure	new	finds within satellite structure a certain parameter type of central body family and points the output variable to it
OPsa_GetPcDxDp	procedure	new	extract partial with respect to a central body parameter from previously interpolated point
DoneSinglePcPar	procedure	new	Deallocates a satellite parameter structure

4.10 `OPin_Integration`

This module performs single-satellite integration using a numerical method for solving first-order differential equations. The driver procedure for the initialization of numerical integration now interfaces with the new method of module `OPsa_Satellites` allowing the correct initialization of the integration variables contained in the `OPsa_SatType` derived type.

OPin_Integration	Type	Origin	Description
InitIntegVariable	procedure	modified	allocates integration structure and set initial values: added pointer to a central body parameter (`OPsa_pcParType`) to the satellite structure

4.11 `OPac_Acceleration`

This module loads in the satellite structure the values of the derivatives with respect to time of every integration parameter. The procedure for computing the geopotential acceleration has been changed adding a call to subroutine that computes the partials with respect to every estimated ocean tide parameters.

OPac_Acceleration	Type	Origin	Description
GetGravity	procedure	modified	added call to subroutine for computation of partials with respect to ocean tide parameters

4.12 `OPgp_GeoPot`

This module contains all the data types and subroutines that deal with the Earth potential. Arrays for storing the partials of gravitational acceleration with respect to geopotential coefficients have been added following

the storage schema of the geopotential coefficients. In this way the correct degree and order can be easily retrieved.

OPgp_GeoPot	Type	Origin	Description
OPgp_Init	procedure	modified	added allocation of arrays storing partials with respect to geopotential coefficients
OPgp_AccelGeoPot	procedure	modified	added arrays storing partials with respect to geopotential coefficients
OPgp_DaDpGeoPotOtide	procedure	new	computes partials derivatives of acceleration from non-spherical earth potential with respect to ocean tide parameters
OPgp_Done	procedure	modified	added deallocation of arrays storing partials with respect to geopotential coefficients

4.13 `BApc_CentralBodyParameters`

This module contains the subroutines which drive the management of central body parameters family within BAHN. All the central body parameters (of derived type `TSpc_ParType`) that can be estimated or considered are stored in this module. The procedure for expanding the central body parameters loaded from `TSpc_ReadPar` has been extended adding the ocean tide coefficients. The parameters are expanded taking into account the ocean tide coefficients stored in the database (input), the cut with respect to the gravitational potential and with respect to the ocean tide force model acting on the selected satellite. Central body family is peculiar because its parameters are stored in this module but at the same time are present in the database and in the satellite class for propagation. When a parameter of this family is estimated, its value changes during the iteration process. The new value has to be updated in every location of the code that use it. For this reason new procedures interfacing with the satellite structure have been added to initialize the satellite structure (for propagation) with the value of parameter retrieved from this module and to change the value of coefficients contained in `OPti_Tides`. Moreover the procedures updating the parameter values in this module and interfacing with *multiarc* have been modified.

BApc_CentralBodyParameters	Type	Origin	Description
BApc_InitPar	procedure	modified	added call to `InitSatPar` to initialize parameter values in satellite structure for propagation
ExpandPar	procedure	modified	added expansion of ocean tide coefficients checking their presence on Dynamic Ocean Tide Model (input file)
InitSatPar	procedure	new	initialize parameter values in satellite structure for propagation
GetNumOTideSatPar	procedure	new	get the number of central body parameters of type ocean tide that participate to satellite structure (`BApr_SatType`)
BApc_UpdWithMAPar	procedure	modified	updates value and sigma with parameters coming from NEQ equations: added ocean tide parameters
BApc_UpdPar	procedure	modified	add call to `UpdDbPar` and `UpdSatPar`
UpdDbPar	procedure	new	updates the value of the parameter in the central body database
UpdSatPar	procedure	new	updates the value of the parameter in the satellite structure for (`BApr_SatType`) propagation
UpdSatParOtide	procedure	new	updates the values of the ocean tide parameter in the satellite structure for propagation
BApc_DyDp	function	modified	returns the partials of the observation with respect to a central body parameter: added ocean tide partials
BApc_DxDp	function	modified	returns the partials of the state vector with respect to a central body parameter

4.14 `BApm_ParametersManagement`

This module contains the subroutines which drive the whole management of parameters. The high-level family parameters are always managed from this common interface to all families of parameters. Also low level parameters (`MApa_ParType` and estimated parameters are managed throught this common interface. Originally the maximum number of parameters for observation type was set hard coded. Now this value is computed in `BApa_Parameters` allowing the allocation of the temporal structure necessary for the correct initialization of BAHN.

`BApm_ParametersManagement`	Type	Origin	Description
`tempEstConPar`	variable (D)	modified	changed from fixed to allocatable the temporal structures to store estimated and consider parameters previously found
`tempBiasesPar`	variable (D)	modified	changed from fixed to allocatable the temporal structures to store bias parameters previously found
`BApm_tempParAllocate`	procedure	new	allocates temporal structures to store estimated, consider and bias parameters
`BApm_tempParDone`	procedure	new	deallocates temporal structures
`BApm_ParamReport`	procedure	modified	change output format to print ocean tide coefficient information

4.15 `BApg_GnssParameters`

This module contains the subroutines which drive the management of GNSS parameters family (clocks and ambiguities). New procedure for counting the correct number of GNSS parameter have been added.

`BApg_GnssParameters`	Type	Origin	Description
`BApg_GetNumModuleOtherPars`	procedure	new	get number of non GNSS estimated clock parameters
`BApg_GetNumParEstimateClocks`	procedure	new	get number of GNSS clock estimated parameters (per epoch) in the process
`BApg_GetNumModuleISBArrays`	procedure	new	get number of GNSS intersystem biases (number of receivers)
`BApg_GetNumModuleAmbArrays`	procedure	new	get number of GNSS ambiguities arrays (number of receivers)
`BApg_GetNumModuleFixedClocks`	procedure	new	get number of GNSS clock fixed parameters (per epoch) in the process

4.16 `BApa_Parameters`

This module handles low level parameters `MApa_ParType` using a linked list schema.

`BApa_Parameters`	Type	Origin	Description
`BApa_maxNumParsPerObs`	variable (I)	modified	changed from PARAMETER type to variable type
`BApa_SetMaxNumParsPerObs`	procedure	new	get number of low level parameters

4.17 `BAco_Computation`

This module contains subroutines to accumulate the normal equations and the observation equations using generic observations and their related parameters.

BAco_Computation	Type	Origin	Description
BAco_Init	procedure	modified	added calls to BApm_tempParDone and BApm_tempParAllocate

4.18 **BAne_NEQExport**

This module manages the writing of the normal equation file. The change involved only the multiarc structure for writing the normal equations file.

BAne_NEQExport	Type	Origin	Description
ConvertParBA2MA	procedure	modified	added saved ocean tide parameters information to multiarc structure MAs_ParType

5 Software upgrade validation

Different internal consistency tests have been carried out on the estimated GOCE orbits to validate the implementation carried out on NAPEOS of the estimation of the ocean tide parameters. We can summarize these activities as follows:

- because parts of the BAHN program involving the numerical integration of the variational equations has been modified to account for the partials with respect to the ocean tide parameters, GOCE precise orbits obtained with the pre-modification software have been compared with the precise orbits obtained with the upgraded software, the estimated orbits yielding 3D differences on the order of the micrometer;
- because the MULTIARC program has been modified in order to recognize the tidal parameters as multiarc parameters and write them in the NEQ (Normal EQuation) file, a comparison has been performed to verify the agreement between the results obtained from a MULTIARC test-case provided by ESA before and after the software upgrade, and this showed no differences;
- a 21-day run has been performed to process daily arcs with BAHN and combining the ensuing normal equations with MULTIARC to solve for a set of ocean tide coefficients; given the short period of time of the global arc the solution obtained is not comparable with the model used (FES 2004), but the order of magnitude of each single coefficient is the same.

Concerning the last item, it is well known that in order to have a good tidal solution it is necessary to operate on very long global arcs and select the subset of tidal parameters according to their observability along the specific satellite orbits, accounting for its sensitivity the spectral characteristics of the tidal perturbations. This will be part of the next phase of the investigation.

6 Conclusions

The NAPEOS S/W system developed by ESA has been adopted by the GOCE-Italy consortium for the recovery of ocean tide parameters from the perturbation analysis of the orbit of GOCE due to its state-of-the-art precise orbit determination capability. However, lacking the capability of solving for the ocean tide parameters, it has been necessary to carry out an extension of the system to implement this capability. We have reported on the specific modifications to a large series of elements constituting the NAPEOS S/W system and the successful validation of the resulting, upgraded version. As a side benefit, the nature of the modifications applied to NAPEOS is such that the system can now be easily extended to estimate other central body parameters, like Stokes and solid Earth tides coefficients. This will be part of a future extension of NAPEOS.

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