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Updating Navigation Software for Ka-Band Observables—A Progress Report

N. A. Mottinger[1]

This article summarizes the status of determining the components of observable modeling that may need upgrading in navigation software to take advantage of the higher accuracy potentially available through 32-GHz (Ka-band) range, Doppler, and delta-differential one-way ranging (delta-DOR) measurements. Areas investigated include (1) high-precision station-location models, (2) Earth-orientation models, (3) a light-time solution, and (4) spacecraft dynamics modeling. JPL software used for radio very long baseline interferometry (VLBI) applications in geodynamics and astrometry was a reference for high-accuracy station-location models, and JPL software used in precision gravity-field determination provided other insights to improved observable modeling. The study reveals that station-location models in the navigation software are complete to the centimeter level, with the exception of the ocean loading and diurnal and semi-diurnal variations in UT1 and polar motion. Since the last updates to the station-location models in the navigation software (1991), it has been established that there are additional centimeter-level models of tidal terms in UT1 and polar motion that should be added. Improvements in the light-time solution implemented in the gravity-reduction software should be realized in the next-generation navigation software, in which extended numerical precision in representing time exists. The higher-order dynamical models in the gravity-analysis software are being implemented in the navigation software for the Mars Reconnaissance Orbiter mission.

I. Introduction

The update of navigation software for the 32-GHz (Ka-band) observable processing task will develop new and updated observable modeling in the JPL orbit-determination software to take advantage of the higher accuracy potentially available through Ka-band range, Doppler, and delta-differential one-way ranging (delta-DOR) measurements. Relevant models in navigation software—the legacy Orbit Determination Program (ODP) [1] and the next-generation MONTE[2]—have been evaluated to determine if upgrades are necessary to support the higher accuracy in the Ka-band radio metric data. The evaluation has focused on the observable modeling as well as relevant numerical issues. This article documents the status of the investigations conducted in fiscal year 2004 (FY04) on this task.

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[1] Outer Planet/Small Body Flight Dynamics Section.

[2] S. Flanagan, *Architectural Design Document for MONTE—Mission Analysis and Operational Navigation Toolkit Environment*, draft (internal document), Jet Propulsion Laboratory, Pasadena, California, November 29, 2000.

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The following areas were studied to determine if improvements were required:

(1) High-precision station locations.

(2) Earth-orientation parameters.

(3) Light-time solution.

(4) Spacecraft dynamics.

The study is summarized and the identified model improvements are described in this article.

II. Discussion

Three activities were conducted to identify areas where improvements might be needed in the navigation software's observable and spacecraft dynamics modeling to take advantage of the higher accuracy potentially available at 32 GHz (Ka-band):

(1) Assess the accuracy of station-location models in the current navigation software.

(2) Identify higher-accuracy station-location models.

(3) Evaluate modeling in the precision gravity-field estimation software.

The findings of these activities are described below.

A. Navigation Software Station-Location Accuracy Assessment

Station-location models in the current operational navigation software, the Orbit Determination Program (ODP), are described by Moyer [1] and summarized here in Tables 1 and 2. Updates to these models were last made in 1991 and are described by Moyer.[3] This update added four models: solid Earth tides, ocean loading, pole tide, and periodic terms in UT1, which were said to be the last needed to obtain "centimeter level accuracy for Earth fixed and space fixed coordinates of a tracking station on Earth."[4]

The complete list of station-location models in the ODP [1] appears in Tables 1 and 2. These tables specify basic characteristics of each model, its magnitude, and a reference. Table 1 contains models or corrections applied to the station locations in an Earth body-fixed coordinate frame. Table 2 lists the models used to transform the body-fixed location obtained using all the corrections shown in Table 1 to an inertial space-fixed frame (solar system barycentric J2000).

Table 1 lists the five models in the ODP that are applied to the Earth-fixed location (1903.0 pole) and their magnitudes. Characteristics of these vary from plate motion at a few centimeters per year, to polar motion at 2.5 meters per year, to diurnal and semi-diurnal tidal terms of tens of centimeters caused by the Sun and Moon.

Table 2 identifies the components used in the transformation of station locations from Earth-fixed to solar system barycentric space-fixed. These include precession, nutation, true sidereal time, and the instantaneous orientation of the Earth, UT1. The updates needed to the 1980 International Astronomical Union (IAU) nutation model to achieve centimeter-level accuracy in station locations are derived from very

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[3] T. D. Moyer, "Corrections to Earth Fixed Station Coordinates due to Solid Earth Tides, Ocean Loading, and Pole Tide and Calculation of Periodic Terms of UT1," JPL Engineering Memorandum 314-505 (internal document), Jet Propulsion Laboratory, Pasadena, California, July 4, 1991.

[4] Ibid.

Table 1. Navigation software—Earth-fixed station-location models.

Earth-fixed true of date	Component	Coordinate base	Comments	Magnitude	Reference
—	1903.0 position	Mean pole, prime meridian, equator of 1903.0.	Linear scale factor applied, nominally 1.	—	[1, Sect. 5.2.1]
—	Plate motion	Due to Earth-fixed velocity vector in 1903.0 coordinate system.	At epoch supplied in station-location file.	$\sim$5 cm/year	[1, Sect. 5.2.3]
—	Polar motion	Rotate from mean pole, prime meridian, and equator of 1903.0 to true pole, prime meridian and equator of date.	Obtained from EOP file.	20 m per component, 2.5 m/year	[1, Sect. 5.2.5]
—	Solid Earth tides	Earth-fixed Cartesian components in true pole, meridian, and equator of date. 1st- and 2nd-order terms.	1st order use 2nd-degree spherical harmonic (3rd-degree $<$ 1 cm ignored). Uses Love numbers.	$\sim$50 cm, diurnal	[1, Eq. (5-51), 1st order]; [6]
—	—	—	2nd-order terms. K1 diurnal. Others sum to 4 mm are ignored.	1.3 cm, diurnal	[1, Eq. (5-75), K1 term]
—	Ocean loading	True pole, prime meridian, equator of date, radial; 1903 East and North.	Requires user input tide coefficients.	Centimeter-level, diurnal due to ocean tides	[1, Eqs. (5-85) to (5-87) into Eq. (5-36)]; [7]
—	Pole tide	True pole, prime meridian, equator of date, radial; 1903 East and North.	Solid Earth tide caused by polar motion.	$<$2 cm	[1, Eqs. (5-95) to (5-97) into Eq. (5-36)]; [8]

long baseline interferometry (VLBI) processing.[5] These are supplied in the Earth Orientation Parameter (EOP) file provided by the JPL Kalman Earth Orientation Filter (KEOF) program and used in the ODP. Daily values for UT1 also are supplied in the EOP file. Included in the EOP UT1 and the ODP is Yoder's [5] model for short-period terms in UT1, ranging from 5 to 35 days. The maximum possible value of these terms is 2.72 ms or about 1.3 m in equivalent station locations [1, Section 5.3.3.1]. (More discussion on this topic occurs in Section II.B.)

Moyer [1, Section 5.3.3.1] points out, however, that Yoder [5] identified short-period, semi-diurnal, and diurnal ocean tides that result in 0.02- to 0.07-ms semi-diurnal and diurnal UT1 variations. These are equivalent to $\sim$1 to 3 cm in the space-fixed tracking station location, but were not included in the ODP when the short-period UT1 terms described above were implemented in 1991.

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[5] T. Ratcliff, "KEOF Operational EOP Deliveries during MER," JPL Engineering Memorandum (internal document), Jet Propulsion Laboratory, Pasadena, California, July 24, 2003.

Table 2. Navigation software—Earth-fixed to space-fixed station-location models.

Earth-fixed to space-fixed	Component	Coordinate base	Comments	Magnitude	Reference
—	Precession	J2000 equator and equinox to mean equator and equinox of date	—	—	[9]; [1, Sect. 5.3.4]
—	Nutation	Earth mean equator and equinox of date to Earth true equator and equinox of date	—	—	1980 IAU Theory of Nutation; [10] and EOP corrections [1, p. 5-52]
—	B	Space-fixed Earth true equator and equinox of date to Earth-fixed true pole, prime meridian and equator of date	Rotate through true sidereal time	—	Supplement to Astronomical Almanac, 1984; [1, p. 5-67]
—	R	Radio frame to planetary ephemeris frame rotation	Used as needed	—	[1, Sect. 5.3.1]
—	UT1	Periodic terms	41 short period terms of 5–35 day periods	Maximum 2.72 ms or 1.3 m	[5]; [1, Sect. 5.3.3.1]
Geocentric to solar system barycentric	Lorentz transformation	Geocentric, space-fixed	—	∼16 cm, station geocentric radius	[11]; [1, Sect. 4.3.1.1]

Having concluded the first phase of the assessment of station-location model accuracy in the current navigation software (ODP), the next phase involved identifying user inputs to the station-location models identified in Tables 1 and 2. The body-fixed station locations at the 1903.0 equator and pole and plate motion corrections are supplied in files generated by William Folkner.[6] Observed and predicted values of UT1, polar motion, and nutation corrections are obtained from the EOP files updated frequently by the KEOF team.

The only user inputs for the solid Earth and pole tides are two Love numbers and a phase angle for the former, which is nominally zero. Navigation teams maintain these in their ODP input files. The files that were checked used the values specified by Moyer [1, Eq. 5-35]. The ocean loading model, in addition to the Love numbers, requires tables of amplitude and phase angles for each DSN station complex. No operational navigation team was found to have these inputs. Upon noting this, two corrective steps were taken: (1) These tables, which must be the same as those used in the software that determines the station-location values (MODEST [2]), were requested and (2) a memo was written detailing all pertinent station-location inputs that should be included in the file generated by Folkner.

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[6] W. Folkner, Jet Propulsion Laboratory, Pasadena, California. Station-location values are available at a JPL internal Web site.

B. Identify Higher-Accuracy Station-Location Models

The second activity was to determine if higher-accuracy station-location models exist than are currently used in the navigation software. The principal source of this information was the JPL software used for radio interferometry (VLBI) applications in geodynamics and astrometry, MODEST, as documented by Sovers and Jacobs [2].

It was determined that both MODEST and the ODP use the station-location models listed in Tables 1 and 2. Additional models available in MODEST are listed in Table 3, where they are identified as either "Station Location" or "Earth Orientation." The first category parallels the body-fixed models in Table 1, and the second category parallels the geocenter-to-solar system barycenter transformation in Table 2.

MODEST also can be used to evaluate the effects of a wide variety of parameters associated with the reduction of VLBI observables, especially for data sets spanning several decades. Table 3 lists additional MODEST station-location models that may be evaluated to determine if improvements are made to the data processing while obtaining reasonable solutions for these models. If these conditions are satisfied, new station locations and/or models can be generated and used in the navigation software.

Table 3 lists additional MODEST station-location models that may be evaluated to improve the solution. Most of these models are on the order of millimeters, and may have non-tidal or unknown frequencies. Conclusive verification of their measurability is an on-going process. Many have not been determined well enough to model in the navigation software. For some, such as antenna feed and thermal expansion, it may be possible to develop models for use in the navigation software. The large effects due to subreflector focusing are included in the values of the station locations supplied by Folkner, based on assumed focusing characteristics for spacecraft radio metric tracking.

Discussions about the station-location model in MODEST with Richard Gross and Chris Jacobs[7] confirmed that most of the centimeter-level station-location models are implemented in the ODP. However, centimeter-level models originating from diurnal and semi-diurnal tidal terms in UT1 and polar motion are missing. These terms of ~2.3- and ~1.5-centimeter amplitude in UT1 and polar motion, respectively, are described by Ray [3] and Chao [4]. Ray's models are shown in Table 4 [3]. These are the same terms Moyer [1, Section 5.3.3.1] described for UT1 (discussed above), but now they are augmented to include polar motion as well.

Gross also points out that, currently, averaged daily values of UT1 are provided in the EOP files.[8] The diurnal and semi-diurnal UT1 and polar motion terms could be incorporated into the navigation software either by supplying EOP files with hourly values or extending the technique currently used in the ODP to handle the Yoder terms to include these new ones. The former change increases the size of the EOP file; the second requires changes to the navigation software. Before any changes are made, the issue must be thoroughly reviewed.

Jacobs points out that care must be taken when using semi-diurnal and diurnal models to ensure consistency with the tide and nutation models and the frame orientation conventions in the navigation and VLBI software.[9] For example, the value or the polar motion K1 term (9.8 mas) includes conventional offsets that are determined by the set of orientation conventions implied by the set of tidal models used, which are not consistent with those in our navigation and VLBI software.

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[7] R. Gross and C. Jacobs, personal communication, Jet Propulsion Laboratory, Pasadena, California, June 2004.

[8] The EOP file contains daily averaged values of UT1 that include the full Yoder tide model and pole-x and -y positions. The navigation software removes the Yoder [5] UT1 terms to create UT1R. At a given epoch, this is interpolated and the short period terms recomputed and added back in to obtain UT1.

[9] C. Jacobs, personal communication, Jet Propulsion Laboratory, Pasadena, California, September 24, 2004.

Table 3. VLBI parameter estimation software—extended station-location models.

Factor	Component	Comment	Magnitude	Reference
		Station location		
Non-tidal station motion	—	On time scales from seconds to years, local to global	Effects of ground water, snow cover, magnum. Periodic dependencies not known	[2]
—	Atmosphere loading	Seasonal variation	cm	[2]
—	Postglacial rebound	Near ancient glaciers and ice sheets	mm/year	[2]
—	Ocean loading	Non-tidal ocean motion	~1 mm	Gross[a]
Antenna feed rotation	Circularly polarized feed	Causes phase change, cancels for group delay	10^{-13} s/s phase rate for az-el not ha-dec	Liewer[b]
Thermal expansion	—	Diurnal and seasonal temperature variations	5 mm (day to night)	Jacobs[c]
Subreflector	Gravity loading focusing	—	70 mm in 70-m, 9 mm BWG	Jacobs[c] 14 mm in HEF,
Geocenter mass motion	Motion of center of mass of solid Earth	Diurnal and semi-diurnal	~1 cm	[12]
Ocean pole tide	Ocean response to polar motion	Solid Earth deforms from ocean loading	~10% of solid Earth pole tide, ~2 mm max	[8]
		Earth orientation		
Tidal UTPM variations	—	—	—	[2]
—	Solid Earth tide UTPM	62 terms with periods 5 days to 18.6 years	—	[2]
—	Ocean tide UTPM	Diurnal, semi-diurnal, fortnightly, monthly, semi-annual	Terms > 1 μs, diurnal and semi-diurnal	[2]

[a] R. Gross, personal communication, Jet Propulsion Laboratory, Pasadena, California, September 2004.

[b] K. M. Liewer, "Antenna Rotation Corrections to VLBI Data," JPL Interoffice Memorandum 335.4-499 (internal document), Jet Propulsion Laboratory, Pasadena, California, March 29, 1985.

[c] C. Jacobs, personal communication, Jet Propulsion Laboratory, Pasadena, California, June 2004.

Table 4. Tidal variations in UT1 and polar motion [3].[a]

Term	Period, h	ΔUT1		Polar motion				Tidal term definition [13]
				Prograde		Retrograde		
		μs	deg	μas	deg	μas	deg	
Q1	26.868	4.7	26.2	29	76	44	302	Larger lunar elliptic diurnal
O1	25.819	20.5	34.6	139	65	102	307	Lunar diurnal
P1	24.066	6.7	31.9	57	57	880	134	Solar diurnal
K1	23.935	19.8	31.9	169	56	9840	132	Lunisolar with O1 includes lunar declination effect
N2	12.658	4.0	244.3	15	136	37	269	Larger lunar elliptic semi-diurnal
M2	12.421	18.9	246.1	82	125	245	269	Principal lunar, rotation of Earth with respect to Moon, semi-diurnal
S2	12.000	7.4	261.8	29	92	122	303	Principal solar, rotation of Earth with respect to Sun, semi-diurnal
K2	11.967	2.3	263.3	7	92	32	301	Lunisolar modulates M2 and S2 for declination effect of Moon and Sun, semi-diurnal
Total	n/a	84.3	n/a	527	n/a	11,302	n/a	

[a] Conversion to equivalent station-location change: 1 μs UT1 ∼ 0.5 mm, 1 milliarcsec PM ∼ 3 cm (1 μas PM ∼ 0.03 mm).

Jacobs also points that Thomas and Treuhaft[10] identified a ∼3-mm error in the Hellings [11] Lorentz transformation model due to an incorrect treatment of the troposphere correction term in the barycentric frame. Correcting this and ensuring consistent modeling between the navigation and VLBI software is another model update to consider.

A discussion in [2, p. 99] of future model developments in MODEST identifies additional centimeter-level terms at diurnal and semi-diurnal tidal frequencies caused by the motion of the center of mass of the solid Earth due to the motion of the center of mass of the oceans [12]. As explained by Gross,[11] this manifests itself as a motion of the station network (i.e., the terrestrial reference frame) with respect to the center of mass of the entire Earth system.

Another model to consider updating is nutation. Replacing the 1980 IAU model with the IAU 2000 model would significantly reduce the size of the augmentation needed to obtain 1-cm station-location accuracy. However, changes such as this must be studied and implemented carefully to ensure consistency between numerous sets of software, i.e., those that derive station-location estimates and create EOP files and the ODP that uses them.

Another suggestion made was to carefully check the consistency of the station-location modeling in the VLBI and the navigation software. This would begin by taking a single observable and comparing computations for time transformations, station-location models, precession, nutation, and sidereal time between the two sets of software. The consistency check would then be extended to processing a number of observations in which only the final value of the computed observables would be compared. Any discrepancies found would be carefully analyzed with corrective action taken to resolve them.

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[10] R. N. Truehaft and J. B. Thomas, JPL Interoffice Memorandum 335.6-91-016 (internal document), Jet Propulsion Laboratory, Pasadena, California, 1991.

[11] R. Gross, personal communication, Jet Propulsion Laboratory, Pasadena, California, September 21, 2004.

C. Modeling in Precision Gravity Field Estimation Software

The third activity in assessing modeling improvements was a review of the JPL software used in the generation of high-precision gravity fields. A version of the ODP is maintained by Alex Konopliv and Dah-Ning Yuan of JPL for the reduction of radio metric data from Earth and planetary orbiters. They identified several changes that dramatically improved the estimates of the gravity fields and reduced the size of the radio metric Doppler data residuals. These changes included

(1) Extended precision of the light-time solution.

(2) Extended precision of representing time.

(3) Improved spacecraft dynamics modeling.

(4) Improved planetary orientation and polar motion.

While some of these changes were required to support specific properties of the Doppler data used in this analysis, namely short count times (2 s), they may still be applicable for the more general use of the ODP for navigation missions with tighter accuracy requirements. These are summarized in the following subsections.

The ocean loading model is activated in this analysis, with the required amplitude and phase inputs available. The inputs were obtained from JPL's Tracking Systems and Applications Section, but it is not known if they are the current inputs used in MODEST.

1. Extended Light-Time Precision. Extending the ephemeris file readers (spacecraft and planets) from double to quad precision reduced Magellan Doppler residuals by a factor of 100. This was primarily required by the short (2-s) count time of the Doppler observables used in the differenced range observable formulation.

2. Extended Precision of Representing Time. A 25 percent reduction in Magellan Doppler residuals occurred by implementing a scheme in which the time reference was switched from seconds past 2000 (January 1, 2000, 12 hours), to seconds past the epoch of the current trajectory segment. This technique may not be required in the next-generation navigation software, MONTE, due to extended precision in which time is represented.

3. Improved Spacecraft Dynamics Modeling. Modeling antenna gimbaling relative to the phase center and the attitude-dependent variations in solar pressure accelerations (changes in the shadowing among spacecraft components) provided another 25 percent improvement in the residuals. Effects this small may equal those of drag, thermal radiation, and seasonal gravity changes, as well as possibly others, which may have to be modeled to achieve further improvements in the data processing. However, the variation in component shading is being implemented in the ODP for the Mars Reconnaissance Orbiter mission.

4. Improved Planetary Orientation and Polar Motion. Other software modeling changes reported by Konopliv and required for estimating Mars gravity fields include a Mars non-uniform rotation rate and Mars polar motion. Further analyses revealed seasonal terms in the Mars gravity model.

III. Summary

This study has identified a variety of modeling updates that will improve the ability of navigation software to take advantage of the higher accuracy in the Ka-band radio metric data. Confirmation was obtained that many of the basic station-location models are present in the ODP, but additional models are available that should be included to maintain centimeter-level accuracy in station locations.

The modeling changes incorporated in the gravity-estimation version of the ODP indicate that upgrades and improvements are required in a variety of areas to extract the information content of DSN radio metric data. They also indicate that ongoing activities to identify areas where modeling improvements are required to realize the inherent accuracy in future DSN radio systems must be wide in scope and include a wide range of investigators who use these data in their analyses. To this end, a working group has been formed to discuss the topics presented in this article to identify and ensure that reference frames and the parameters required to transform between them are maintained consistently across the software sets used in the overall navigation process. This group will meet periodically to promote discussion and review of the numerous facets of this work to ensure that the potential for higher navigation accuracy at Ka-band becomes a reality.

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