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The size, shape and orientation of the asteroid Vesta based on data from the Dawn mission

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ABSTRACT

The aim of this paper is to study the size, shape, and orientation of the asteroid Vesta based on the Dawn spacecraft observations. In this line, three main reference surfaces are defined; the geoid, reference ellipsoid, and best-fit ellipsoid. To be consistent with International Astronomical Union (IAU) standards, all the computations are done in the Claudia Double–Prime coordinate system. The geoid and its potential value W_0 are computed by fitting an equipotential surface to the shape of Vesta in a least-squares sense regarding the topographic bias effect. We find that the topographic bias effect on the geoid potential value as well as the geoidal and topographic heights is significant. The geoid potential value W_0 is estimated equal to 68709 ± 24 $\mathrm{m}^2/\mathrm{s}^2$. The reference ellipsoid is defined as an equipotential ellipsoid which best fits the geoid. The reference ellipsoid is computed based on the fundamental geodetic constants which define a geodetic reference system (GRS). The semi-axes of the triaxial reference ellipsoid are found to be equal to 280413 ± 104 m, 274572 ± 102 m, and 231253 ± 86 m with the equatorial semi-major axis longitude 8.29°E, while the semi-axes of the biaxial reference ellipsoid are 278556 ± 117 m and 229921 ± 76 m. The results show that the geoidal heights with respect to the triaxial reference ellipsoid are significantly different from the geoidal heights with respect to the biaxial reference ellipsoid. The parameters of the best-fit ellipsoid are estimated by fitting geometrical ellipsoids with various degrees of freedom to Vesta's shape in a least-squares sense. We report the semi-axes of the general best-fit ellipsoid with 9 degrees of freedom equal to 284562 ± 75 m, 277248 ± 73 m, and 226405 ± 57 m. Regarding the orientation of Vesta, we find that the angle between the equatorial semi-major axis of the general best-fit ellipsoid and the X-axis of the coordinate system is $9.17° \pm 0.47$, and the angle between its polar axis and the Z-axis is equal to $0.63° \pm 0.05$. Furthermore, the spherical harmonic coefficients of the shape model of Vesta up to degree 180 are computed, giving the ability to estimate the parameters of the general best-fit ellipsoid. The significant differences observed between the parameters of the general best-fit ellipsoid derived from the spherical harmonic coefficients of the shape model, and those derived from the fitting are due to the large polar and equatorial flattenings of Vesta. We estimate that the offset of the center of figure from the center of mass is 1350 ± 53 m, and the mean radius of Vesta is 261403 ± 39 m.

1. Introduction

The solar system owes its beauty not only to the Sun and its planets, but also to its asteroid belt located between the orbits of the planets Mars and Jupiter. As known, the existence of every body in our universe is somehow correlated to the others, where our planet Earth is not an exception. This fact motivates the study of bodies in our (the planet Earth's) surrounding. The study of the planets and celestial bodies would help elevate our understanding not only on those bodies but also on the planet Earth. As a matter of fact, it is the evolution of these celestial bodies that scores the line for the evolution of Earth. In this line, we chose to work on the asteroid named Vesta in a sense of studying its size, shape and orientation. Vesta, minor-planet designation 4 Vesta, is the third largest by volume and the second largest by mass asteroid in the solar system's asteroid belt. The outcome of studying the size and shape of celestial bodies directly sheds light on quite a lot of applications in geodesy and geophysics such as; providing basis for geodetic and cartographic studies (e.g., Seidelmann et al., 2007), providing constraints on the internal structure (e.g.,

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Kiefer et al., 1996), tectonic evolution (e.g., Simons et al., 1997), crustal and lithospheric thickness (e.g., Neumann et al., 2004; Wieczorek and Zuber, 2004), and thermal and rotational evolution (e.g., Zuber et al., 2000). Conventionally, three main reference surfaces are defined for approximating the shape of the celestial bodies. These reference surfaces are the geoid, reference ellipsoid, and best-fit ellipsoid (e.g., Torge and Müller, 2012). It is worth noting studies carried out regarding the reference surfaces of celestial bodies, namely the planet Mars (e.g., Burša and Šíma, 1989; Smith et al., 1999; Wieczorek, 2007; Ardalan et al., 2010), the planet Venus (e.g., Burša and Šíma, 1989; Wieczorek, 2007; Ardalan and Karimi, 2014), the planet Mercury (e.g., Anderson et al., 1996; Perry et al., 2015; Karimi et al., 2016), the Moon (e.g., Burša and Šíma, 1989; Ardalan and Karimi, 2014), and some asteroids (e.g., Burša and Vanýsek, 1996; Drummond and Christou, 2008; Ermakov et al., 2014; Park et al., 2014).

The geoid is defined as an equipotential surface of the gravity field that possesses a specific gravity potential value W_0. In the case of the planet Earth, W_0 is chosen from a geoid that best fits the global mean sea level (Gauss, 1828; Listing, 1873). For other celestial bodies, due to the absence of oceans, W_0 is chosen more arbitrary (Wieczorek, 2007; Ardalan et al., 2010). However, W_0 should be selected such that the geoid could well approximate the planet's shape and reflect its geophysical and geological properties. Therefore, it has been suggested by Ardalan et al. (2010), Ardalan and Karimi (2014) and Karimi et al. (2016) that W_0 aught to be selected such that the geoid best fits the shape of the celestial body. This choice of W_0 for planets is more consistent with the Gauss–Listing definition for the geoid of the Earth enabling the best approximation for the planets figure (Ardalan et al., 2010; Ardalan and Karimi, 2014; Karimi et al., 2016). The geoid is used in geodesy, cartography, and oceanography as a reference surface for heights and depths. The geoid opens one's hand to a variety of applications in geophysics and geology. To give a flavor of its various applications, one could name its use in determining the planetopotential topography (the height of the planet's surface with respect to the geoid's surface) and slope of the planet's terrain. The correlation between the geoid and topography can help compute the crustal and lithospheric thickness (e.g., Wieczorek and Zuber, 2004). The second concept under consideration in the present study is the reference ellipsoid which is defined as an equipotential ellipsoid that best fits the geoid. The reference ellipsoid is determined based on the Somigliana–Pizzetti theory (Pizzetti, 1894; Somigliana, 1930). The parameters of the reference ellipsoid are computed using the fundamental geodetic constants which define the geodetic reference system (GRS). In order to make geodetic results mutually comparable and to provide coherent results to other sciences such as geophysics and astronomy, GRSs are established by recommendation of the International Union of Geodesy and Geophysics (IUGG). For example, for the planet Earth, the GRS 1980 has been adopted at the XVII General Assembly of the IUGG in Canberra, December 1979, by Resolution N°7 (Moritz, 2000). The GRS can be defined by four or six fundamental constants. These constant parameters for the 4-parameter GRS are $\{GM, \omega, W_0, \overline{C}_{20}\}$, while for the 6-parameter GRS are $\{GM, \omega, W_0, \overline{C}_{20}, \overline{C}_{22}, \overline{S}_{22}\}$, where GM is the planetocentric gravitational constant, ω is the angular velocity, and $\overline{C}_{20}$, $\overline{C}_{22}$, and $\overline{S}_{22}$ are the fully normalized spherical harmonic coefficients of the gravity model (Burša and Fialova, 1993; Burša and Vanýsek, 1996; Grafarend and Ardalan, 1999; Karimi et al., 2016). It is important to note that there exists other choices for the constant parameters. A choice for the 4-parameter GRS is $\{GM, \omega, a, \overline{C}_{20}\}$, and a choice for the 6-parameter GRS is $\{GM, \omega, a, \overline{C}_{20}, \overline{C}_{22}, \overline{S}_{22}\}$, where a is the equatorial semi-major axis of the reference ellipsoid (Moritz, 2000; Karimi et al., 2016). The 4-parameter GRS is suitable for a celestial body which its equatorial flattening in comparison with its polar flattening is small, like the planet Earth (Moritz, 2000), while the 6-parameter GRS is suitable for a celestial body that its equatorial flattening in comparison with its polar flattening is quite significant, like the planet Mercury (Karimi et al., 2016). The reference ellipsoid is used for producing the normal gravity field which serves as a reference for the actual external gravity field before enabling the computation of the gravity anomalies for geophysical applications. The geoidal heights and gravity anomalies are usually referred to the reference ellipsoid; therefore the reference ellipsoid must be very close to the geoid to produce the gravity anomalies and geoidal heights for reasonable and interpretable geophysical results. It should be noted that the reference ellipsoid is an approximation of the planet's shape in hydrostatic equilibrium (Torge and Müller, 2012). Therefore, the deviations of the actual shape from the reference ellipsoid can reflect the planet's geodynamical and geophysical characteristics. The best-fit ellipsoid is defined as a geometrical ellipsoid which best fits the actual shape of the celestial body. The main difference between the reference ellipsoid and the best-fit ellipsoid is that the reference ellipsoid is an equipotential ellipsoid, while the best-fit ellipsoid is not an equipotential ellipsoid. The best-fit ellipsoid can be used for describing positions on the curved surface of the celestial bodies. By performing a comparison between the reference ellipsoid and the best-fit ellipsoid, one could show the geophysical and geodynamical properties of the celestial body together with its hydrostatic equilibrium state.

To determine the geoid, reference ellipsoid, and best-fit ellipsoid of Vesta, its shape and gravity models need to be in hand. The primary attempts for determining the shape model of Vesta is based on the images provided from the Hubble Space Telescope (Thomas et al., 1997). Recently, more accurate and higher resolution shape models have been obtained using images from the Framing Camera of the Dawn spacecraft. The Dawn mission was launched in September 2007 promoted by NASA's Jet Propulsion Laboratory (Russell et al., 2004, 2012). Two different techniques in two independent centers have been employed to produce the shape models of Vesta; the stereophotoclinometry (SPC) technique in the Planetary Science Institute (PSI) (Gaskell, 2012), and the stereophotogrammetry (SPG) technique in the German Aerospace Center (DLR) (Jaumann et al., 2012). It has been reported by Ermakov (2016) that the SPG-based shape models have discontinuities at poles, are more oblate than the SPC-based shape models, and strongly deviate from isotropy at high spherical harmonic degrees. One of the latest available shape models of Vesta based on the SPC technique is the GASKELL_SHAPE_POST_VESTA shape model (Gaskell, 2012), and one of the latest available shape models of Vesta based on the SPG technique is the DLR_HAMO_DTM shape model (Preusker et al., 2014). Both models are available from http://dawndata.igpp.ucla.edu/tw.jsp?section=geometry. The GASKELL_SHAPE_POST_VESTA shape model is based on images from all phases of the Dawn mission, including Survey Orbit, High Altitude Mapping Orbit (HAMO), Low Altitude Mapping Orbit (LAMO) and HAMO-2 (Ermakov et al., 2014; Konopliv et al., 2014), while the DLR_HAMO_DTM shape model is based on images from the HAMO and HAMO-2 phases (Preusker et al., 2014). Since more images have been used to produce the GASKELL_SHAPE_POST_VESTA shape model, in this work we use the GASKELL_SHAPE_POST_VESTA shape model. However, at the time being one cannot exactly specify which model is closer to reality due to the lack of an absolute reference.

The VESTA20H gravity model in terms of the spherical harmonics up to degree 20 has been determined based on radiometric Doppler and range data and optical landmark tracking issued by the Dawn spacecraft (Konopliv et al., 2014). It has been indicated in Konopliv et al. (2014) that the gravity errors increase significantly when all degree 20 coefficients are included. It has also been reported by Russell et al. (2015) that the VESTA20H gravity