PLANETARY SYSTEM GMS IN THE JPL PLANETARY EPHEMERIDES

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ABSTRACT. Fundamental to JPL planetary ephemeris development are the values of the planetary system GMs. Currently, all but the GM of the Pluto system have been determined with data obtained from spacecraft. This article gives an overview of the sources of the GM values in previous and current ephemerides.

1. INTRODUCTION

The GMs of the planetary systems within the solar system are fundamental constants needed for the development of the planetary ephemerides or more correctly the ephemerides of the planetary system barycenters. Except for Mercury and Venus, the GMs of the systems are the sum total of the planet and the planetary satellite GMs. The basic method for determining the GMs is the measurement of the gravitational effects produced by the planets and satellites on the motion of other bodies in the solar system. Prior to the advent of interplanetary spacecraft, the other bodies were planets, satellites, and asteroids. After the 14 December 1962 flyby of Venus by Mariner 2, spacecraft were added to the list of bodies. With the exception of the dwarf planet Pluto, the determination of the GMs of all planetary systems incorporate spacecraft data. The primary type of this data is Earthbased Doppler tracking of the spacecraft near a planet or satellite.

2. MERCURY

The Mariner 10 spacecraft had three flybys of Mercury: March 1974, September 1974, and March 1975. Howard et al. (1974a) determined the GM using tracking from the first flyby. The second flyby produced no usable data. Anderson et al. (1987) combined the data from the first and third flybys to improve the GM estimate. The Messenger spacecraft on its way to enter orbit about Mercury in 2011 has also had three flybys: January and October 2008, September 2009. Smith et al. (2010) analyzed tracking from the first 2 flybys to obtain a GM value. Taylor (2009) estimated the GM using the data from all 3 flybys.

3. VENUS

The Mariner 2 flyby of Venus in 1962 was the first successful planetary encounter by a spacecraft. Anderson et al. (1964) fit the Doppler acquired during the flyby to obtain a GM estimate; crude processing procedures were used but a rather reasonable result was obtained. Data from subsequent flybys by Mariner 5 in 1967 and Mariner 10 in 1974 were also analyzed to produce GM estimates (Anderson et al., 1967; Anderson and Efron, 1969; Howard et al., 1974b). With the arrival of Pioneer Venus Orbiter (PVO) in 1978, work on the development of a gravity field model for Venus began. Sjogren et al. (1990) used the PVO Doppler tracking to estimate the GM. Later Konopliv and Sjogren (1994) combined the PVO data with tracking from the Magellan orbiting spacecraft to develop a 60 degree and order gravity field and obtain an associated GM. Konopliv and Sjogren (1996) extended the gravity field to degree and order 180 and revised the GM estimate.

4. EARTH-MOON

Estimates of the Earth and Moon GMs are found during development of the gravitational field models of those bodies from tracking of Earth and lunar orbiters. The current best estimate of the Earth GM is quite accurate (Ries et al., 1992); note that because the Ries value was determined in the geocentric metric, it must be converted to the barycentric metric before it can be used with the planetary ephemerides. Konopliv et al. (2001) obtained an estimate of the Moon GM along with an estimate of the lunar gravity field from the orbiting Lunar Prospector spacecraft. The accuracy of that GM and gravity field, however, is limited because of lack of tracking data over the far side of the Moon.

The Earth-Moon system GM is found together with the lunar orbit using Lunar Laser Ranging (LLR) measurements (Williams et al., 2009; Williams, 2010). This system GM is currently more accurate than the sum of the separate Earth and Moon GMs from the gravity field work. The Earth-Moon mass ratio is determined as one of the parameters when fitting ephemerides of solar system bodies from observations which include ranging data. These data are sensitive to the motion of the Earth about the Earth-Moon system barycenter. Konopliv et al. (2002) obtained a value as part of their work on the gravity field and orbit of the asteroid Eros using data from the NEAR spacecraft. Relying on radar range to Mercury and Venus and ranging to several spacecraft at Mars, Folkner et al. (2008) improved the mass ratio during the development of the DE421 planetary ephemerides. The mass ratio combined with the system GM yields the GMs of the individual bodies.

5. MARS

Doppler tracking of Mariner 4 during its 1964 flyby of Mars yielded the first Martian GM estimate based on spacecraft data (Null, 1969). Following the 1971 insertion of Mariner 9 into Martian orbit, Born (1974) found the Mars GM and a low order and degree gravity field from the tracking. Konopliv and Sjogren (1995) followed by developing a 50 degree and order gravity field and associated Mars GM from the combination of Mariner 9 and Viking Doppler. They also estimated the GMs of the satellites thus producing a true system GM estimate. Yuan et al. (2001) extended the gravity field to 75th degree and order using the Mariner 9, Viking, and Mars Global Surveyor (MGS) data, and Konopliv et al. (2006) developed a 95 degree and order gravity field model from the MGS and Mars Odyssey tracking data. Recently, Konopliv et al. (2010) added data from the Mars Reconnaissance Orbiter to that from the MGS and Mars Odyssey to improve the gravity field reaching degree and order 110.

6. JUPITER

The Pioneer 10 and Pioneer 11 flybys of Jupiter in 1973 and 1974, respectively, provided Doppler tracking to estimate the GM of the Jovian system including the GMs of the Galilean satellites (Null, 1976). Campbell and Synnott (1985) added the 1979 Voyager 1 and Voyager 2 tracking to that from the Pioneers to update the GMs. Jacobson (2005) extended Campbell and Synnott's work to include tracking from the 1992 Ulysses flyby and the Galileo orbiting spacecraft to revise the system and Galilean satellite GMs. A GM for Amalthea was also determined, but its value is less than the uncertainty in the total system GM.

7. SATURN

The first spacecraft to visit Saturn was Pioneer 11 in 1979. Null et al. (1981) used the Doppler tracking to get the GMs of the system and Rhea, Titan, and Iapetus; GMs for the other satellites were taken from Kozai (1976). Campbell and Anderson (1989) added the tracking from the 1980 and 1981 Voyager 1 and Voyager 2 encounters to that from Pioneer and determined the system, Rhea, Titan, and Iapetus GMs; again the Kozai GMs were assumed for the other satellites. Jacobson et al. (2006) extended Campbell and Anderson's work by adding data from the Cassini orbiting spacecraft and Earth-based observations of Saturn's Lagrangian satellites to obtain the system GM as well as the GMs of all of the major satellites.

8. URANUS AND NEPTUNE

The Voyager 2 flybys of Uranus in 1986 and Neptune in 1989 provide the data to determine the GMs in those planetary systems. Jacobson et al. (1992) estimated the Uranian system and major satellite GMs from the Voyager tracking, the Voyager satellite imaging, and Uranian satellite astrometry over the period 1960–1985. Jacobson (2007) updated the analysis with improved data processing techniques and and an extension of the astrometry to cover 1911–2006. In a procedure analogous to that used for Uranus, Jacobson et al. (1991) obtained the Neptune and Triton GMs from an analysis of Voyager tracking, Voyager imaging, and satellite astrometric observations from 1847 to 1988. Jacobson (2009) extended that earlier work by improving the data processing, adding astrometry through 2008, including the satellite Proteus in the system, and incorporating all available observations of Proteus.

9. PLUTO

No spacecraft have yet visited the Pluto system; the New Horizons spacecraft is planned to arrive in 2015. Consequently, the GMs of the bodies in the system must be determined from observations of the motions of Pluto's satellites. Prior to the discovery of Nix and Hydra in 2005, analysis of the motion of Charon produced estimates of the system GM (Harrington and Christy, 1981; Tholen, 1985; Null and Owen, 1996; Olkin et al., 2003). Subsequent to the Nix and Hydra discovery, observations of all three satellites have been used (Tholen et al., 2008, 2010; Brozovic and Jacobson, 2010).

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