MARS EXPRESS AND VENUS EXPRESS RANGE RESIDUALS FOR IMPROVING PLANETARY EPHEMERIDES

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ABSTRACT

During the time that Mars Express (MEX) and Venus Express (VEX) have been orbiting their planetary namesakes, range residuals have been and continue to be routinely computed from the ranging measurements, with the aid of the JPL DE 405 planetary ephemerides. The trends over time of these residuals reflect the errors in the planets' geocentric distances as derived from the ephemerides. The residuals are provided to both JPL and the **I**nstitut de **M**écanique **C**éleste et de **C**alcul des **É**phémérides (IMCCE) for the purpose of improving the accuracy of the planets' ephemerides.

The most recently developed and released planetary ephemerides of both institutes, DE 421 from JPL and INPOP08 (**I**ntégrateur **N**umérique **P**lanétaire de l'**O**bservatoire de **P**aris) from IMCCE exploit the MEX and VEX data, up to October 2007 for DE 421 and up to April 2008 for INPOP08. The range residuals through to the end of June 2009, computed using these ephemerides, show the quality of the fits and the prediction accuracies since the data cut-off dates. The VEX data are especially useful since they are the only measurements related to Venus since 1999.

Since August 2008, VEX and directionally, near-by quasar differential one-way range (DOR) measurements have been acquired from one hour long intervals of two-station tracking during most months. Each occasion provides one or two delta differential one-way range (δDOR) data points that can be used to improve a component of Venus' location on the plane-of-sky. These data are not so useful as the range residuals but may help tie the planetary ephemeris to the International Celestial Reference Frame (ICRF).

1. INTRODUCTION

MEX and VEX tracking comprises two-way coherent Doppler and range measurements. The Doppler data are converted to range-rate: the component of the spacecraft's velocity relative to the ground station along the direction from the station to the spacecraft. The determination of the spacecraft's orbits uses only the range-rate data since, under normal circumstances, the additional inclusion of the range data leads to only insignificant improvement in the accuracy of the orbit solutions.

Within the orbit determination, the computed values of the observables rely on high fidelity modelling of the dynamics and the signal path [1], [2]. As part of this modelling, the orbital states of Mars and Venus are taken from the JPL DE 405 planetary ephemerides [3]. Based upon the orbits determined from the Doppler data, computed values of the range observables are found and the residuals formed, the differences between the observed (O) and computed (C) values in the sense (O-C). Over time these range residuals exhibit a signature whose predominant contribution is the error in the computed topocentric distance from the ground station to the spacecraft. This is virtually the same as the error in the distance from the Earth to the planet as given by the planetary ephemerides. The range residuals are therefore derived data that are very useful for studies to improve the accuracy of planetary ephemerides.

The extent to which the ephemerides can be improved depends upon the accuracy of the residuals. For most of the time, the main factor influencing the accuracy is the error in the determination of the orbits of the spacecraft. Other contributions to the errors in the residuals arise from imperfect knowledge and stability of the group delay of the on-board transponders, inaccuracies in the calibrations of the station equipment delays and deficiencies in correcting for atmospheric delays, especially those due to the troposphere. Also, substantial errors can occur during periods of superior solar conjunction due to additional noise and biases on the radiometric data from the passage of the signal through a region of high and variable electron density within the solar corona [4].

2. MEX ORBIT DETERMINATION

MEX, the first European mission to Mars, was launched on 2nd June 2003 and inserted into Mars orbit on 25 December 2003. The mission is presently extended until the end of 2009 and a further extension is expected to be announced in autumn 2009.

The operational orbit (Fig. 1) is near polar and elliptic with an apoapsis altitude of a little over 10000 km and a periapsis altitude that has varied between 250 km and 340 km. The orbital period averaged 6.72 hours (11:3 resonance) until late in 2007 when a series of five manoeuvres at periapsis increased the period to 6.84 hours (18:5 resonance). In early 2009, a further two manoeuvres again increased the period to 6.895 hours (25:7 resonance). The pericentre precesses so that, over time, all sub-satellite latitudes can be viewed from relatively low altitude.

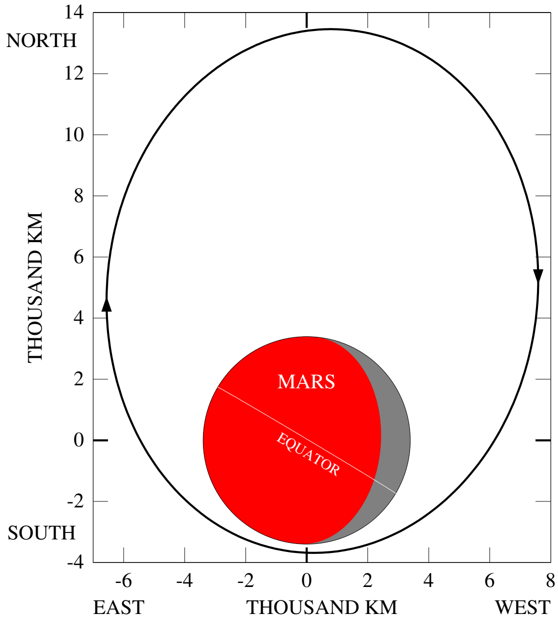

Fig. 1. MEX orbit on 10/09/2007 seen from Earth

MEX is tracked with both ESA 35 m deep space antennas and those of the NASA Deep Space Network (DSN) (mainly at the Goldstone complex), in almost equal proportions in terms of tracking duration (Fig. 2 & Table 1). Most of the ESA tracking is from New Norcia (NNO) in Western Australia, the rest from Cebreros, near Madrid in Spain.

DSN range measurements of MEX are made at intervals of 3 minutes 27 seconds. ESA raw ranging measurements are made every second. The standard procedure is to extract one ESA raw data point every 20 minutes. So the quantity of DSN range data and hence range residuals is far higher than the quantity of ESA range residuals.

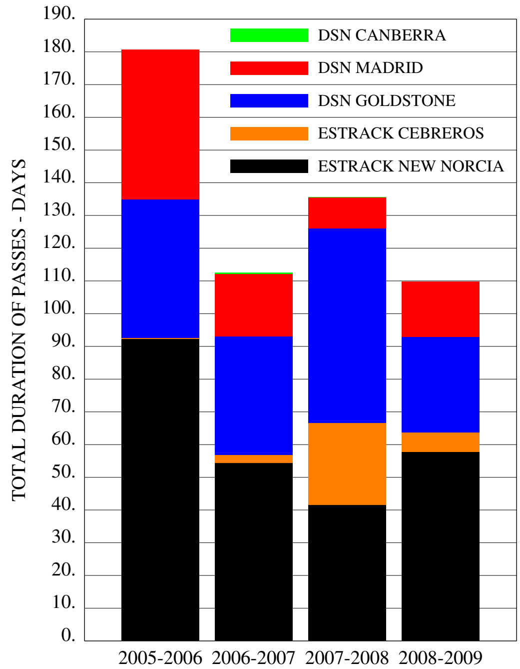

Fig. 2. MEX station support starting on 5th March

The standard deviation of range residuals for individual passes gives a good indication of the random noise on the measurements. For ESA data, the average standard deviation of the (two-way) residuals is less than 1 m. For NASA/DSN data it is below 0.5 m.

MEX is equipped with a fixed high-gain antenna (HGA) that must be pointed towards the Earth during tracking passes. The primary science data collection is around periapsis passage when the spacecraft is usually put into an attitude, for example with the payload boresights nadir pointing, such that the HGA is not Earth-pointing. For orbit determination purposes, the information content within the Doppler data is highest around periapsis so the orbit solution accuracy is adversely affected by the lack of such data. The orbit determination accuracy is also limited by other factors; most notably the imperfect calibration of perturbing velocity increments (usually in the range of 2-8 mms^{-1}) caused by thrusting, on average every 4th orbital revolution in the vicinity of apoapsis, to off-load the accumulated angular momentum of the reaction wheels, and also the problems in accurately modelling small forces due to solar radiation pressure and the tiny but highly variable atmospheric drag at each periapsis passage.

The accuracy is also dependent on the orbital geometry, particularly on the angle between the orbit normal and the line-of-sight from the Earth [5]. The most unfavourable situation occurs when the orbit is viewed close to face-on.

Table 1. MEX station usage between 5th March 2005 and 5th May 2009

Ground station			Number of passes	Pass duration total (days)	Percentage of total duration	
ESA	New Norcia		1225	253.644	46.0	52.1
	Cebreros		280	34.049	6.2	
NASA DSN	Goldstone	DSS 14	200	28.479	5.2	31.0
		DSS 15	500	87.496	15.9	
		DSS 24	100	13.593	2.5	
		DSS 25	160	25.193	4.6	
		DSS 26	113	16.440	3.0	
	Canberra	DSS 43	4	0.382	0.1	0.1
		DSS 45	1	0.018	0.003	
	Madrid	DSS 54	103	15.832	2.9	16.8
		DSS 55	97	13.927	2.5	
		DSS 63	213	34.038	6.2	
		DSS 65	205	28.887	5.2	
Total			3201	551.979		

Early in the MEX operational mission, routine orbit determinations were made twice per week based on tracking data arcs of 5-7 days duration, corresponding to approximately 18-25 orbital revolutions, with a typical overlap of 2 days between successive arcs. Nowadays, orbit determination is made weekly using an arc of about 10 days duration and therefore with similar overlaps. The differences between the values of common range residuals computed from successive orbit determinations provides an indication of the effect of orbit determination errors on the accuracy of the residuals. Outside of periods of superior solar conjunction (see section 4.3), these differences are almost always below 3 m. The range residuals that are retained are taken from the earlier of each overlapping solution.

2.1 MEX range residuals using DE 405

Fig. 3 is a plot of the 95858 MEX two-way range residuals from 5th March 2005 until 30th June 2009. The peaks during the superior solar conjunctions in autumn 2006 and at the end of 2008 actually reached 2300 m and 700 m respectively. Ignoring these intervals, the signature shows that the error in the predicted value (over about 10-15 years) from the DE 405 ephemerides of the Earth-Mars distance has varied between -200 m and +170 m. The obvious periodic component in Fig. 3 is the synodic period of Mars.

During September 2006, MEX experienced long eclipses and to conserve power the on-board transmitter was switched on only occasionally. Very few tracking data were acquired and when ranging measurements were available they were used together with the Doppler data for orbit determination. This explains the first data gap in Fig. 3. The second gap is between 8th November and 7th December 2006. At the request of the Mars Global Surveyor (MGS) project, MEX ranging was not performed so as to guarantee no interference with communications to MGS that had been lost (and which were never recovered).

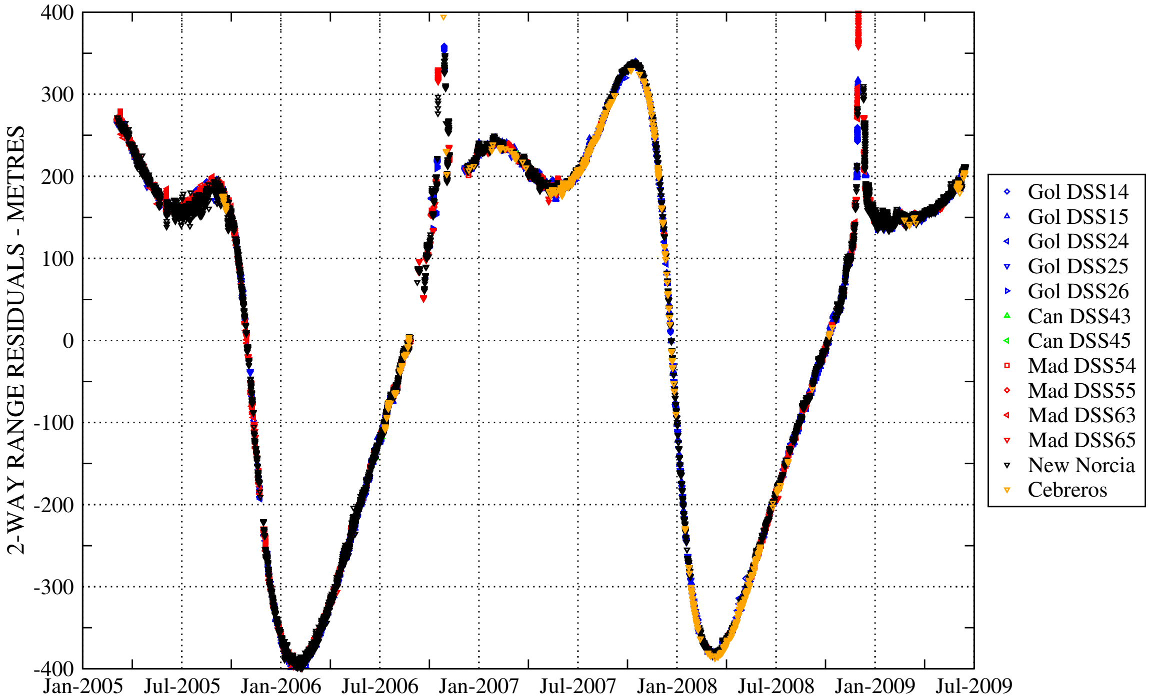

Fig. 3. MEX range residuals using DE 405 planetary ephemerides

3. VEX ORBIT DETERMINATION

VEX, the first European mission to Venus, was launched on 9th November 2005 and inserted into Venus orbit on 11th April 2006. Like MEX, its mission is presently extended until the end of 2009 and a further extension is expected to be announced in autumn 2009.

The operational orbit (Fig. 4) is polar and highly elliptic. There is hardly any precession of the line of apsides so the periapsis, whose argument, at the time of writing, is 91° with respect to the planet's equator, remains close to the planet's north pole. The apoapsis altitude is about 66500 km and the periapsis altitude has been controlled to stay within the range between 185 km and 390 km. The orbital period is nominally 24 hours and the maximum excursion has never been more than 6 minutes.

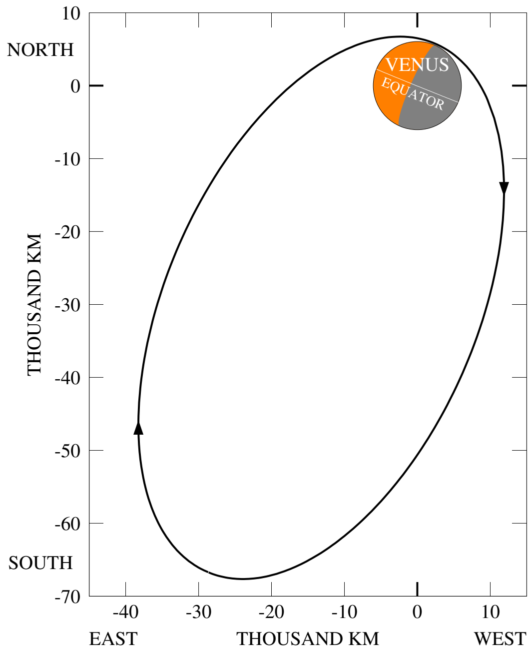

Fig. 4. VEX orbit on 24-25/05/2009 seen from Earth

The primary ground station supporting VEX is Cebreros, which tracks the spacecraft almost every day. Between 27th April 2006 and 5th May 2009, there were 1046 Cebreros passes whose accumulated duration of 367.2 days accounts for 97.0% of the total tracking duration. New Norcia has provided two-way coherent radiometric data during 39 passes and NASA DSN stations during 45 passes, of which 22 were made with the 70 m antenna of DSS 43 at Canberra, many of them during the superior solar conjunction in autumn 2006.

The sampling rates of the range data and the random noise on the measurements are the same as for MEX.

Every orbital revolution, in the vicinity of apoapsis but not within ground station visibility, the momentum of the reaction wheels is off-loaded by thrusting. The perturbing ΔV into the orbit is typically in the range 10-25 mms^{-1} which is substantially higher than for the MEX wheel off-loadings. The spacecraft attitude and the direction of the thrust are chosen so that the manoeuvres help to control the orbit phasing. The control is such that the signal elevation from the daily Cebreros passes rises to 10° (when telecommanding may start) always close to 2 hours after periapsis passage. The pass ends either 10 hours later, close to apoapsis, or at 10° descending elevation, whichever is earlier. So tracking data are almost never acquired during the descending leg of the orbit, and only rarely around periapsis from an Australian station.

VEX has two fixed HGAs mounted on opposite faces. For thermal reasons, the Sun must not shine on one of these faces, so the seasonal use of each antenna is driven by the angle between the Sun and Earth subtended at the spacecraft. During 3-4 weeks around each quadrature, when the Sun-Venus-Earth angle is close to 90°, the spacecraft tends to become too warm for one of the scientific instruments when in the attitude needed for communications. To avoid this, Earth contact periods are skipped and tracking passes on alternate days are the norm, which leads to degradation in the accuracy of the orbit solutions.

The combination of the unfavourable pattern of tracking data arcs, imperfect calibration of the wheel off-loadings and deficiencies in modelling forces due to solar radiation pressure, together with the variable dependency on the orbital plane orientation with respect to the line-of-sight from Earth cause the accuracy of the orbit determination to be worse than that for MEX. One difference from MEX is that for the overwhelming majority of the mission duration, with the periapsis altitude above 200 km, no discernible atmospheric drag is detected during periapsis passage. Even down to 185 km altitude the drag force is exceedingly small[1].

Routine VEX orbit determination is made weekly using tracking arcs of 10 days duration, corresponding to 10 orbital revolutions, with an overlap of 3 days between successive arcs. Typical values of the differences between range residuals derived from successive orbit solutions are a few metres but, occasionally, the differences can reach as high as 10 m. During quadrature, the differences are sometimes substantially higher and at periods of superior solar conjunction they can become considerable.

3.1 VEX range residuals using DE 405

Fig. 5 is a plot of the 28882 VEX two-way range residuals from 27th April 2006 until 30th June 2009. The sharp peaks in autumn 2006 and mid-2008 occur at periods of superior solar conjunction. At the middle of the second conjunction, VEX was not tracked at all between 6th and 11th June inclusive.

The signature shows that the error in the predicted value from the DE 405 ephemerides of the Earth-Venus distance has varied between -300 m and +280 m. The periodic component in Fig. 5 is the synodic period of Venus.

1. It is planned to allow the natural perturbations to cause the periapsis altitude to fall to a minimum of 175 km in October 2009 when further radio science investigations will be made of the tenuous upper atmosphere of Venus.

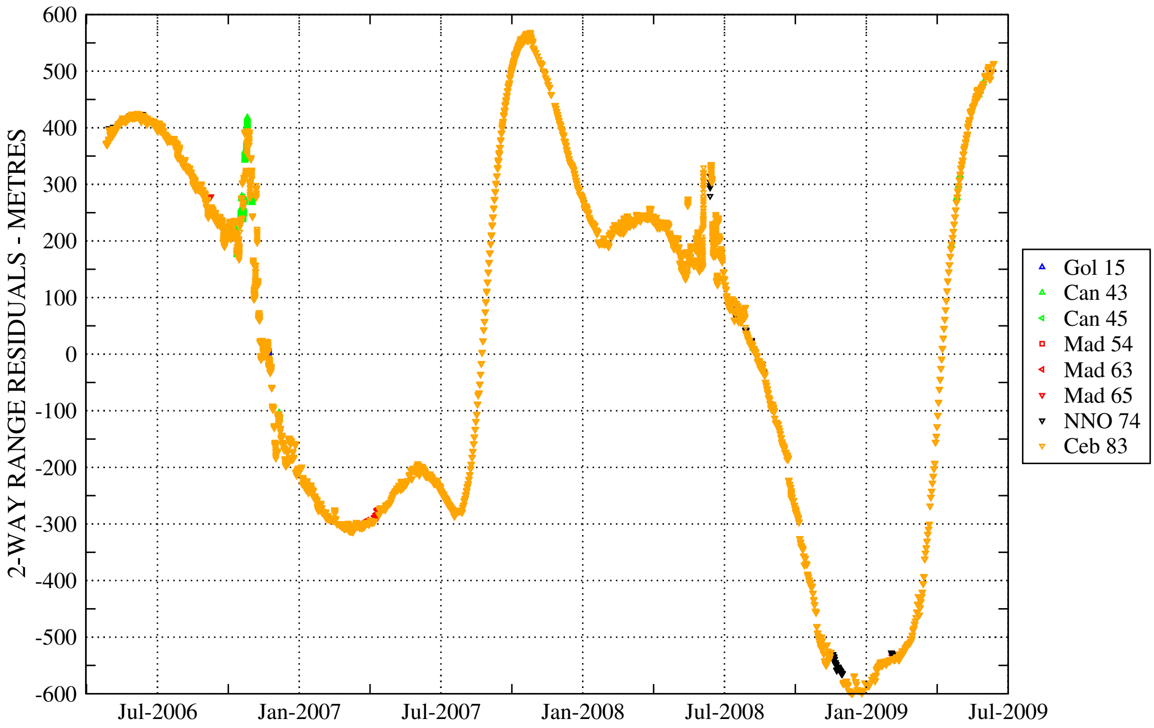

Fig. 5. VEX range residuals using DE 405 planetary ephemerides

4. ACCURACY OF THE RANGE RESIDUALS

In addition to the imperfections in orbit determination results, there are a number of other sources of error in the evaluation of range residuals that are addressed in the following sections.

4.1 Spacecraft transponder group delay

Subtracted from each range measurement is the nominal value of the group delay of the on-board transponder. For MEX, the value corresponding to the normally used X-band up- and downlink signals is 2076 nanoseconds (~622 m). For VEX, that has a virtually identical transponder, the value is 2085 ns (~625 m).

The nominal value is the average value measured at different occasions on ground before launch in the course of RF compatibility tests by the transponder manufacturer and ESA. The delay cannot be measured or estimated later during flight. From the variations in measured values, ostensibly made under identical conditions, it is thought that the systematic error of the nominal value should not be larger than 30 ns (~10 m). In addition, it is known that the group delay is not perfectly stable and can fluctuate by a few ns, depending upon variations in a number of parameters such as temperature and signal strength.

4.2 Ground station equipment delays

Range measurements are modelled of the signal path to and from the location of the ground antenna. This is defined to be at the intersection of the two axes of the antenna - in the case of all the antennas supporting MEX and VEX, the intersection of the azimuth and elevation axes. Therefore, corrections have to be applied, consisting of the purely geometric one accounting for the double reflection of the signal at the main and sub-reflector (118.59 ns at both NNO and Cebreros) plus the delay within the station electronics to and from the tracking receiver.

The latter delay is usually measured before each tracking pass by transmitting and receiving the signal through a calibration loop. For the ESA deep space stations, the calibration value varies from day to day over a range of up to about 5 ns (~1.5 m). For the DSN stations, JPL subtracts the calibration value before providing ESOC with the range data. For the so-called remote stations at Goldstone, DSS 24, 25 and 26, which are situated a long way from the measurement electronics, the subtraction is relative to a large, nominal delay of 77 µs. It is not sufficiently accurate to subtract the total measured delay because the measurement time tag is affected. This part of the calibration has then to be applied within the software that computes the residuals.

The use of many different stations to track MEX allows to analyse the consistency of the data. The left side of Fig. 6 shows a magnified view of the MEX range residuals between 31st October and 5th December 2007. On average, the NNO residuals are off-set about 1-2 m higher than the Goldstone residuals (using 5 different antennas). Slightly more marked is the negative off-set of about 3 m for the Cebreros residuals. During this period, an X-band high power amplifier was used at Cebreros to boost the uplink signal and the average ground station calibration value was 4763 ns (1428 m).

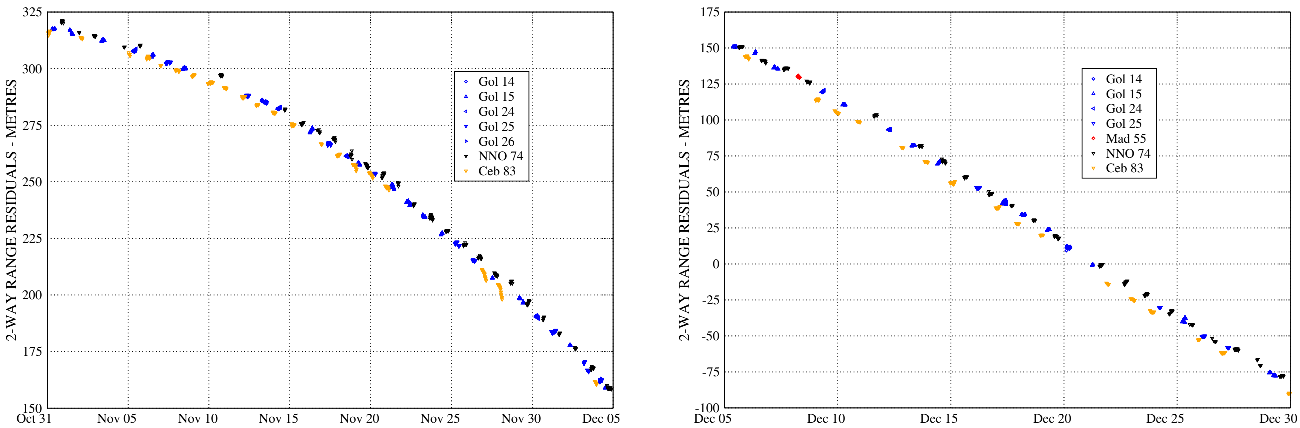

Fig. 6. MEX range residuals during November (left) and December (right) 2007

The situation during the following 25 days was slightly different, as shown on the right side of Fig. 6. During this period, a low power amplifier was used at Cebreros and the average ground station calibration value was 4780 ns (1433 m). The change in calibration value is explained by the change in equipment but the negative off-set in the range residuals is noticeably larger than in the previous period, being 5-6 metres on average.

There are two possible explanations that would account for the different off-set in the range residuals. The simplest is that the group delay of the on-board transponder is about 10 ns (3 m) smaller when the received signal strength corresponds to the lower uplink power. The alternative explanation, that is deemed less likely, is the following. Part of the signal path of the calibration loop is not common to the signal path when tracking. This part includes a reflective converter that turns around the calibration signal. The correction for the delay in this part of the loop is assumed constant at 76.81 ns (or 59.87 ns at NNO) and is based partly on scale drawings and partly on measurements of the group delay within the reflective converter when the station was commissioned. But no measurements were made of the stability of this group delay at different signal strengths.

4.3 Velocity errors in planetary ephemerides

Two-way Doppler data are not prone to systematic errors: in the routine orbit determination no bias is assumed or estimated in the range-rate modelling. Yet any error in the planet's geocentric range-rate, as computed from the planetary ephemerides, does cause a bias, albeit usually quite small.

The highest slope of the VEX range residuals in Fig. 5 occurred in August-September 2007, after Venus inferior solar conjunction (18th August), and corresponded to a range-rate bias of 0.2 mms^{-1}. This value is quite substantial compared with the standard deviation of the range-rate noise (over an integration interval of 1 minute) for individual passes, that is usually in the range 0.04-0.07 mms^{-1}. The left side of Fig. 7 is a magnified view of the range residuals computed from one orbit solution within this period. During the course of each tracking pass the residuals are flat.

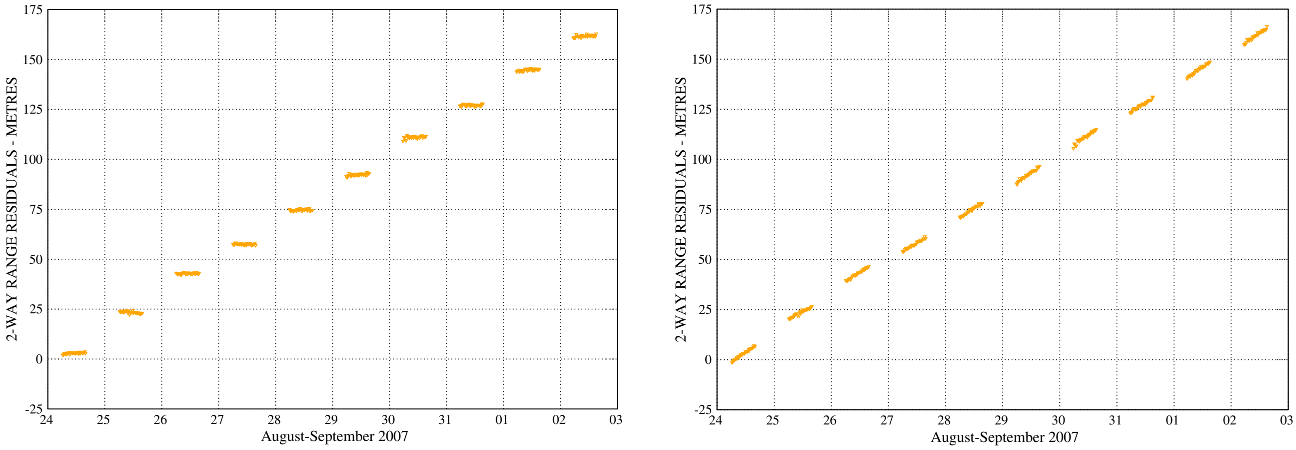

Fig. 7. VEX Cebreros range residuals without (left) and with (right) assumed range-rate bias

As a test, the orbit determination was repeated with a bias of 0.2 mms^{-1} applied to the computed range-rate observables. The main changes in the results were slightly different calibration estimates for the ΔV components from the daily momentum desaturations and differences in the estimated position of the spacecraft up to a maximum of about 5 m.

The range residuals that were subsequently computed from the orbit solution are shown plotted on the right side of Fig. 7. The slope exhibited over the duration of individual passes matches the overall slope over all ten passes.

So, ignoring any range-rate modelling bias within the orbit determination does not have any significant influence on the overall trend seen in the range residuals.

4.4 Superior solar conjunction

During the time that MEX and VEX range residuals have been generated and archived, each mission has experienced two superior solar conjunctions. Some details related to the Sun-Earth-probe (SEP) angle are listed in Table 2.

Table 2. MEX and VEX superior solar conjunctions

Date of minimum SEP angle	Spacecraft	minimum SEP angle	Days SEP angle < 10°
23rd October 2006	MEX	0.39°	61
27th October 2006	VEX	0.95°	78
9th June 2008	VEX	0.04°	73
5th December 2008	MEX	0.46°	70

The effects on spacecraft radiometric data at the first two conjunctions have been described in [4]. The signals to and from the spacecraft pass through the solar corona surrounding the Sun. The free electrons in the plasma cause a group delay on ranging measurements. Since the electron density increases with decreasing distance from the Sun, following, at least approximately, an inverse square law, the delay increases as the SEP angle diminishes.

No solar corona model was applied when computing the range residuals, so the increased delay is the cause of the peaks in Figs. 3 and 5. The existing solar corona models that could be used to correct the range residuals are not very accurate. They cannot take into account the quite large day-to-day variations in the signal delay caused by short-term fluctuations in solar activity like sunspot formation, flares and coronal mass ejections, all of which can influence the surrounding electron density.

A secondary cause of increased errors in range residuals at solar conjunction is due to the main effect on Doppler measurements of a substantial increase in noise. When the SEP angle falls to about 1°, the measurement noise typically increases up to two orders of magnitude higher than is usual at large SEP angles. The accuracy of range residuals is then indirectly and adversely affected by a degradation in the accuracy of the orbit determination solutions.

It is left up to the analyst who is concerned with the improvement of planetary ephemerides to decide whether to omit range residuals during periods of solar conjunction or to apply a solar corona model, including the possibility of additionally estimating free parameters of such a model.

4.5 Corrections for atmospheric effects

Range observables are corrected for the additional delays on both the up-link and down-link due to atmospheric refraction.

The contribution to the delay due to the ionosphere is inversely proportional to the signal frequency. For both MEX and VEX the tracking is at the high-frequency X-band (7.17 GHz for the up-link and 8.42 GHz for the down-link). So a typical one-way correction is of the order of only 10 cm. The size of the error in the applied correction is insignificant compared to the other error sources discussed here.

The contribution to the one-way delay due to the troposphere is almost always between 2.1-2.3 m in the zenith direction and reaches ~12 m at 10° elevation. VEX and MEX range measurements below 15° elevation are usually discarded so the largest delays are avoided. For the ESA tracking data, the corrections are based on processing meteorological data from a weather station located close to the antenna and functions for mapping to any elevation. This leads to quite precise calibrations for the larger, dry component of the troposphere but slightly imperfect calibrations for the smaller, but more variable, wet component. It is thought that the total calibration error rarely exceeds 10 cm in the zenith direction so that, even at relatively low elevation, any systematic error contribution should be less than 50 cm.

5. DE 421 AND INPOP08 PLANETARY EPHEMERIDES

The most recently released planetary ephemerides are DE 421 [6] from JPL and INPOP08 [7] from IMCCE. For both ephemerides, over the interval 2005-2009 inclusive, the maximum heliocentric position differences from DE 405 are 1.2 km for Venus, 1.5 km for the Earth-Moon barycentre and 1.9 km for Mars. According to [6], the Venus orbit accuracy is now about 200 m and through 2008 the Earth and Mars orbit accuracies are expected to be better than 300 m and DE 421 is expected to predict the Earth-Mars range with an accuracy of about 15 m.

MEX and VEX range residual data were used in the fits of both ephemerides: in the case of DE 421 up to a data cut-off in October 2007 and for INPOP08 a later data cut-off in April 2008. For Mars, range data from NASA orbiters were also fit. According to [7], for an overlapping period during the spring of 2005, the systematic differences between MEX INPOP08 range residuals and those of Mars Global Surveyor and Mars Odyssey are just 3.5 m. This suggests that the MEX range residual error estimates previously mentioned appear realistic and perhaps a little conservative.

The VEX range residuals are particularly valuable because they are the only spacecraft data available for improving the Venus ephemeris since the last of the Magellan VLBI measurements in 1994, except for two data points derived from Cassini in 1998-1999. But this also means that there is no independent means to verify their accuracy and to confirm that any biases are small. However, as is emphasised in [7], the residuals corresponding to earlier measurements of Venus that resulted from the fitting of an ephemeris (INPOP06) that did not use the VEX data hardly changed with the fit of INPOP08. This means that the VEX data are consistent with the older data and their addition in the fit does not degrade the Venus ephemeris over a long time interval into the past.

Fig. 8 shows the differences in the Earth-Venus and Earth-Mars distances, computed from the two ephemerides, for 2005-2009. The small high frequency oscillations have the Moon's orbital period. The Venus distance difference is well below 10 m and actually remains at this level up to beyond 2014. The Mars distance difference begins to grow after the data cut-offs. By the end of 2013 the difference reaches a maximum of 170 m.

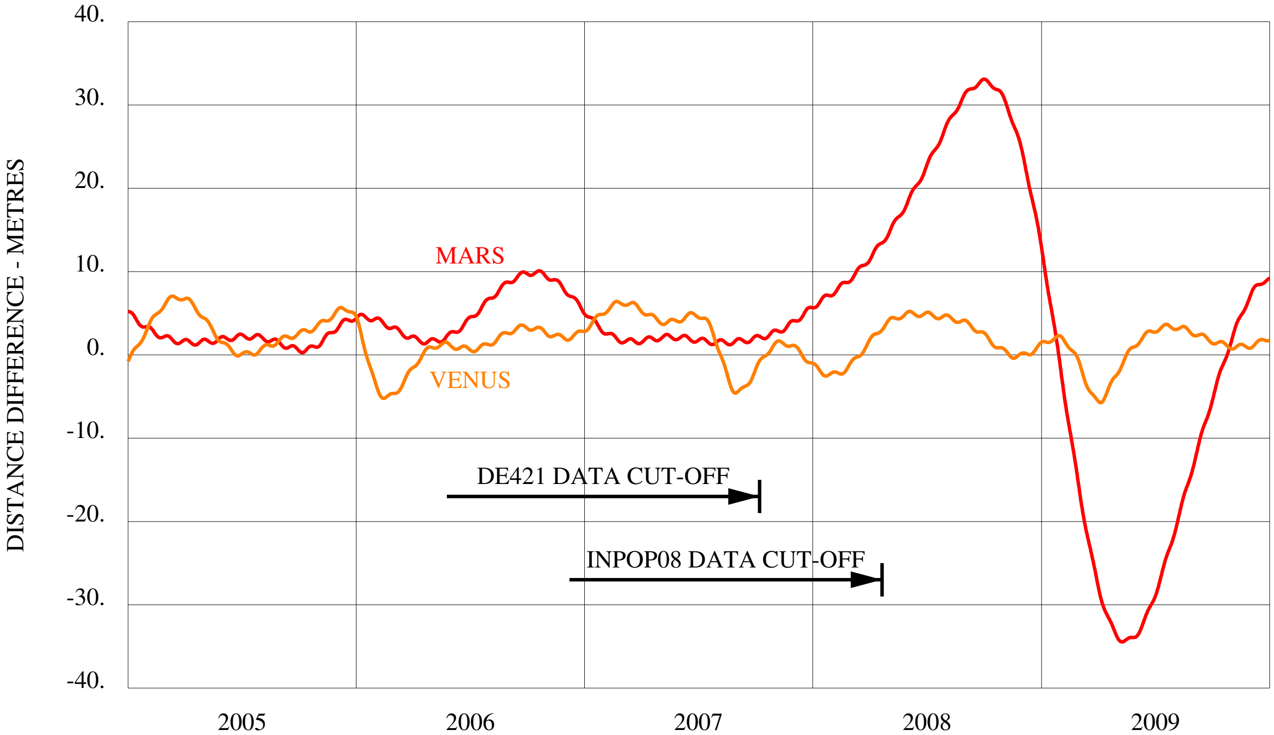

Fig. 8. Geocentric distance differences: INPOP08 minus DE 421

The MEX and VEX range residuals were recomputed using the DE 421 and INPOP08 ephemerides in place of DE 405. The results for MEX are shown in Fig. 9. Data have been omitted when the SEP angle was less than 10°.

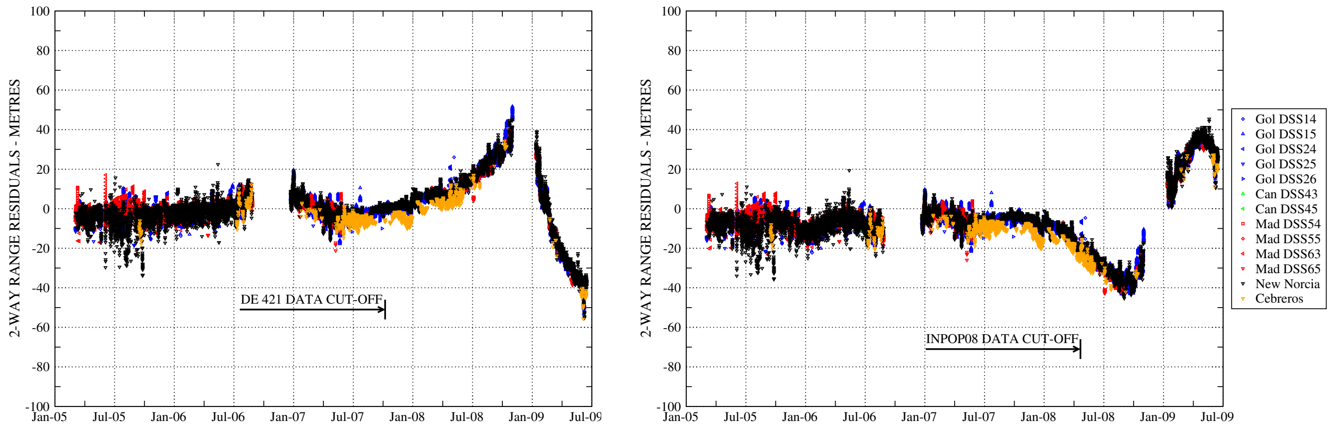

Fig. 9. MEX range residuals using DE 421 (left) and INPOP08 (right)

Up to the data cut-offs, the scatter in the 2-way residuals is about ± 10 m, i.e. ± 5 m for the Earth-Mars distance, and there appears to be a small negative bias in the residuals against INPOP08. A plot from JPL [8] shows even flatter residuals against DE 421 than those in Fig. 9 because a solar corona correction has been applied over the whole range of SEP angles.

After the data cut-offs, the prediction errors start, but in opposite senses for the two ephemerides. As is pointed out in [6] and, at length in [7], the main problem in establishing good prediction accuracy for the Mars ephemeris is the large uncertainty in the masses of several asteroids that significantly perturb the planet’s motion. Continued range measurements of Mars orbiters and astrometric observations of asteroid-asteroid encounters should lead to prediction improvement in the next few years.

The VEX range residuals against DE 421 and INPOP08 are shown in Fig. 10, again with gaps around the superior solar conjunctions.

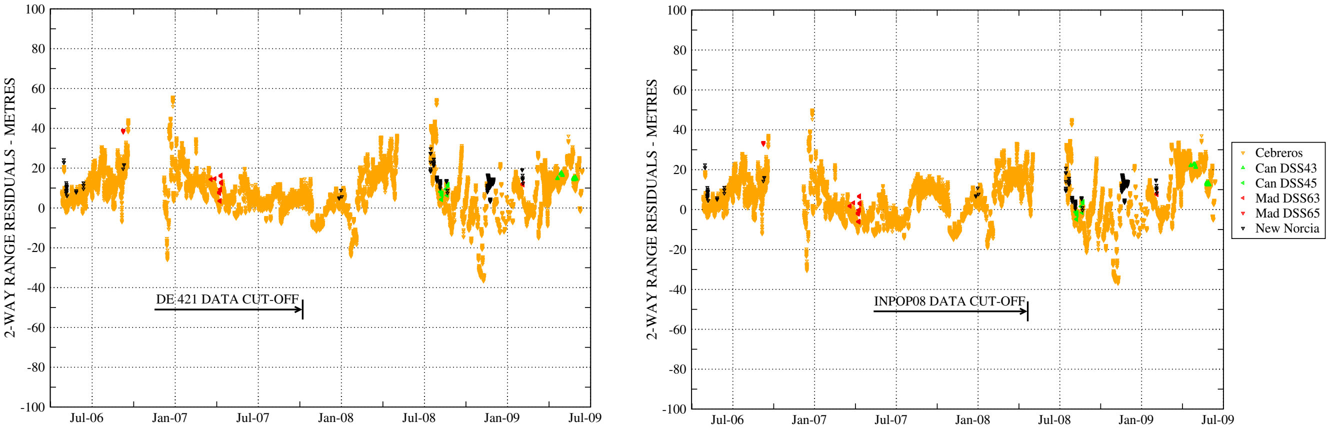

Fig. 10. VEX range residuals using DE 421 (left) and INPOP08 (right)

Since the difference in the Earth-Venus distance between the two ephemerides is continuously small, the two sets of residuals are almost identical. A modest improvement in their appearance could probably be achieved by applying a solar corona correction model at moderately low SEP angles. The scatter of the residuals is higher than for MEX and this is attributed to the worse accuracy in the determination of the VEX orbit. The asteroids have little influence on the motion of Venus and there is no obvious difference in the quality of the data fits between the intervals before and after the data cut-off dates. It will be interesting to see whether the prediction error remains small over the next few years.

6. VEX δDOR DATA

δDOR data are a refined type of VLBI measurements [9]. Such data are the double differences between the arrival time of the spacecraft signal at two widely separated stations and the arrival time of the signal from a quasar in a near-by direction. In effect, each data point is an accurate measure of the component of the angular separation on the plane-of-sky between the quasar (whose direction is very precisely known) and spacecraft, in the plane containing the baseline between the two stations. The accuracy of such data expressed in time units can be converted to an angular measure by multiplying by the speed of light and dividing by the length of the baseline.

One VEX δDOR data point from 2007 was used in the fit for DE 421.

Since August 2008, on nominally one occasion each month (but with 3 exceptions), VEX raw DOR measurements have been acquired at NNO and Cebreros whose baseline length is 11650 km. The data are correlated at ESOC [10]. Usually, each occasion finally allows the reduction to two δDOR data points. Up to and including June 2009, 14 such data sets have been provided to JPL for Venus ephemeris improvement purposes.

The VEX transponder does not have the capability to generate DOR tones, so the harmonics of the telemetry subcarrier have to be used, which limits the total spanned frequency bandwidth. δDOR accuracy is directly proportional to the bandwidth and consequently the VEX data are not so accurate as the δDOR data acquired by NASA from its Mars orbiters. The other main factor affecting the accuracy is the flux level from the calibration quasar. Estimates made at ESOC of the 1σ error of the delivered data lie in the range 0.22 to 0.57 ns or, equivalently, 5.7 to 14.6 nanoradians. Taking into account the variation in the geocentric distance to Venus, the 1σ errors on the plane-of-sky lie between 0.5 - 2.6 km. An additional, smaller, contribution arises from the component in the same direction of the orbit determination error of the spacecraft relative to Venus.

VEX δDOR data are therefore of considerably less strength for improving the Venus ephemeris than the range residuals. But they do provide measurements in an orthogonal direction and, over time, could help to reduce systematic errors. Also, a subset of the quasars defines the orientation of the ICRF, so δDOR data can help to tie the planetary ephemeris to this frame. JPL intends to include the VEX δDOR data in the fit for generating new ephemerides [8].

In the near future, the tracking data receivers at the ESA deep space stations will be enhanced to allow a much larger bandwidth between the frequency channels within which the measurements are made. This will have little influence on VEX δDOR accuracy but is expected to lead to a substantial improvement in δDOR accuracy for spacecraft whose transponders can generate DOR tones.

VEX DOR measurement passes are firmly scheduled once per month through to the end of 2009 and a preliminary schedule already exists for a continuation through the first half of 2010.

6. CONCLUSIONS

For improving planetary ephemerides, range residuals differ from other data types in that they are derived via a process that relies on modelling rather than merely a reduction of raw measurements. The various contributions to the errors from the modelling and in the range measurements themselves have been described and the quality of the fits to the recent DE 421 and INPOP08 ephemerides confirm the expected overall accuracy of the residuals. The errors are almost two orders of magnitude smaller than the peak-to-peak excursions seen in their signatures against the still widely used DE 405 ephemerides.

The VEX data alone and the MEX data together with corresponding range measurements of NASA Mars orbiters have helped in the development of new Venus and Mars ephemerides whose contemporary position accuracy is an order of magnitude better than that predicted from DE 405. Nevertheless, at least for the foreseeable future, DE 405 will continue to be used in MEX and VEX orbit determinations since its present deficiencies have no significant impact on meeting their required accuracies. Also, any change could impact external users of orbital products. Some instrument teams use planetary ephemerides for transforming reconstructed orbital data that are provided as an aid for their science data interpretation. For strict consistency, the same ephemerides should be used as the ones employed for operations.

It is the intention to continue generating MEX and VEX range residuals for as long as the spacecraft survive with a ranging capability. Only time will tell which of DE 421 and INPOP08 has the better prediction accuracy. In any case, the problems with the modelling of the asteroid perturbations on the motion of Mars will necessitate quite frequent generation of a new Mars ephemeris if the present accuracy in the knowledge of its position is to be maintained.

Future ESA interplanetary missions will use more modern planetary ephemerides. Hitherto, only development ephemerides released for export by JPL have ever been used. In the last few years, the modelling and techniques for generating ephemerides at IMCCE have reached a state-of-the-art that makes its products fully “competitive” with those of JPL, so that the ephemerides user now has a real choice. For Gaia, it has already been agreed that the same version of an INPOP planetary ephemerides will be used both for the spacecraft navigation and within the processes used by the science team to reduce and interpret the payload data. In response to the lobby of “European ephemerides for European space missions” a future trend away from JPL ephemerides in favour of IMCCE ephemerides appears inevitable.

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