Part 2

THE AU AND THE PC

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Nicole Capitaine relaxes in Much Hoole churchyard after the transit

Myles Standish talking to Floor van Leeuwen

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Transits of Venus: New Views of the Solar System and Galaxy
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The Astronomical Unit now

E. M. Standish†

CalTech / Jet Propulsion Laboratory, JPL 301-150, Pasadena, CA 91109, USA
email: ems@smyles.jpl.nasa.gov

Abstract. The Astronomical Unit is one of the most basic units of astronomy: the scale of the solar system. Yet its long and colorful history is sprinkled liberally with incorrect descriptions and mis-quoted definitions – today as much as ever. Over the last half century, the accuracy of the au determinations has improved dramatically: optical (triangulation) methods have given way to modern electronic observations, high-speed computers, and dedicated efforts to improve planetary ephemerides. Typical uncertainties in the value of the au have decreased from many tens of thousands of kilometers to the present level of only a few meters. With the solar system providing a very clean, undisturbed dynamical model, the ephemerides have been used for a variety of exotic physical tests: alternative theories of gravitation, $d(\mathrm{G})/dt$, $d(\mathrm{au})/dt$, etc. In the beginning of this modern era, the author happened to be a witness to a couple of rather key events; more lately, a participant. A couple of these personal experiences are related.

1. Personal recollection

In the autumn of 1962 there was a discrepancy: the new determinations of the value of the au, made using radar measurements, did not agree with the classical determinations, made with optical (photographic) measurements of the asteroid 0433 Eros.

The very first Wednesday afternoon seminar that I attended as a graduate student at Yale University featured three speakers from the astronomy department: Dirk Brouwer described the optical determinations, James Douglas presented the radar values, and Ludwig Oster correctly argued why the effects of the solar corona upon the radar signal were not large enough to account for the discrepancy.

So, the matter was unresolved – an awakening in itself for me.

The next summer in the university's computer center I happened to speak to Brian Marsden: "How are things going?" His reply: "I'm trying to duplicate Rabe's solution, but I can't seem to reproduce his numbers."

Again by chance, in the following winter during a meeting at Yale organized by Brouwer, I happened to overhear Marsden telling Eugene Rabe: "I can't seem to reproduce your results." Rabe had not known of any problem and had no explanation.

The matter was virtually resolved over the next few years, as it was found that 1) the parameters involved in the optical solutions were highly correlated, 2) there were some errors in Rabe's partial derivatives, and 3) the sum-of-squares of the residuals had a very flat minimum. The thesis of J. H. Lieske (1968) provided the final assurance: he collected 8639 observations of Eros, covering the years 1893-1966, taken from 85 different observatories, based upon 106 different catalogues, each reduced to the FK4 stellar catalogue. Lieske adjusted the ephemerides to the observations using an integration of all 9 planets and Eros. The amended parameters were in accord with those from the radar determinations.

† Present address: JPL 301-150, Pasadena, CA, 91109, USA

I had been a non-participating observer of this little step of astronomical progress; it was later that I would take an active part.

It is worthy of note that the 1964 winter meeting started a tradition which was repeated for a number of years; eventually, the meetings, along with a nucleus of the participants, evolved into the American Astronomical Society's Division on Dynamical Astronomy.

2. What is the "au"?

There have been many incorrect descriptions and mis-quoted definitions of the astronomical unit. Even as recently as a month ago, there appeared in a popular magazine, the following:

> " ... table (page 68) says that the astronomical unit (a.u.) is 'based upon the mean Earth-Sun distance' – it's not the mean Earth-Sun distance itself. We now know enough about planetary motions to realize that Earth's average distance from the Sun is not fixed. It changes from one orbit to the next ..."

> " ... astronomers now treat the a.u. as a *defined* quantity rather than a measured one... the a.u. is the radius of an unperturbed circular orbit about the Sun with a period of 365.2568983 days (known as a Gaussian year). This works out to 149,597,870 kilometers ..."

Actually, the au is based upon the Gaussian constant, $k \equiv 0.01720209895$ (exact definition). This, in turn, is an old measurement of the Earth's mean motion.

In physics, one adopts units of length, mass, and time (cgs, e.g.); then, experiments provide the value of the gravitational constant, G. In astronomy, since a period or mean motion is much more easily measured than a distance in the solar system, the adopted units were chosen to be those of a solar mass, a mean solar day, and the gravitational constant ($= k^2$). The au is then the unit of length which is consistent with the other three. As such, it is the result of a convention; it is not a defined quantity.

One equation which relates the au to the other units is Kepler's third law, $n^2a^3 = k^2M$. For a (massless) particle at 1 au from the sun in keplerian motion, we have $a = 1$ and $M = 1$, so that the mean motion is $n = k$. Thus, the period is simply $P = 2\pi/k = 365.2568983...$ days; this is the source of that (irrational) number in the "definition" quoted above.

Incidentally, even in keplerian motion, where "the Earth's average distance from the Sun [would be] fixed", neither the au nor the semi-major axis would be equal to the average distance. In keplerian motion, the mean distance is not the semi=major axis, a; instead, $< r > = a(1 + e^2/2)$. It *is* true, however, that $< 1/r > = 1/a$.

The last statement quoted above is the worst. Nothing "works out" to give the value of the au in kilometers. That number has been a holy grail for a number of centuries and has been the *raison d'etre* for the immense efforts put into the measuring of the transits of Venus, the conjunctions of Mars, the approaches of asteroids, and other endeavors.

As indicated above, the radar determinations of the value of the au expressed in kilometers are now more accurate than the optical determinations. However, both methods have a lot of similarities. In order to measure the au in kilometers, one measures some distance in the solar system, either by optical triangulation methods using earth distances as a baseline, or by recording the travel time of an electromagnetic signal along the path and converting that time into kilometers, given the speed of light. The value of that distance in kilometers is then compared with a corresponding value of the distance in au, obtained from an accurate planetary ephemeris.

The key issue is that accurate planetary ephemerides don't just happen to "work out" from a few equations. Modern ephemerides represent possibly the greatest dynamical system of all time: it has virtually no dust, no static electricity, no friction; it has been accurately measured over a substantial period of time; and it is now accurately modeled with high-speed computers and an understanding of gravitational physics. The modeling of the solar system dynamics is an extensive topic.

3. The creation of modern ephemerides

Back in the 1960's, it became apparent at JPL that the existing ephemerides were not accurate enough to support the increasingly stringent demands of spacecraft navigation. Those involved at that time made decisions that still to this day show a remarkable amount of foresight. The overall system continues to function as well as ever, even with many orders of magnitude increases in accuracy, both of the observational data to which the ephemerides are adjusted and of the resultant ephemerides themselves.

The ephemeris creation process may be looked upon as an attempt to play the part of Mother Nature: she has a set of laws to follow – the equations of motion; she is a very good numerical integrator of those equations; and she started at some time with a set of initial conditions – positions and velocities at some epoch, along with a number of associated constants, such as masses, etc.

The ephemeris creation process has the same three key ingredients:

(a) the Equations of Motion, expressing gravitational physics,
(b) an Integration Program, and
(c) a set of Initial Conditions ($\mathbf{r}, \dot{\mathbf{r}},\ \mathrm{GM}_i,$ etc.).

It is believed, in general, that a) the physics is well-known and b) the integration program has been adequately tested and been shown to be valid. The main key of the ongoing effort of ephemeris improvement, therefore, is c) the set of initial conditions.

The initial conditions are determined by a least-squares adjustment, fitting ephemerides to the set of observational data. As such, the accuracies of the ephemerides are a direct function of the accuracies of the observational data and their reductions.

The reductions follow basic mathematics and physics, for the most part, applying reference frame transformations, tracing the paths of electromagnetic signals, etc. In addition, there are certain adjustment factors, judiciously used where warranted (e.g., a transponder time delay, assumed to have not been previously calibrated.)

So, apart from the reduction procedures, it is the set of observational data which requires the most attention.

4. The observational data

The observational data are the products of many, many dedicated individuals, endowed with ingenuity and dedication: quadrants, telescopes, micrometers, photographic plates, meridian circles, traveling impersonal micrometers, cavity magnetrons, electronic computers, atomic clocks, radio telescopes, interplanetary spacecraft, VLBI, etc. And, the results of this advancing array of technology are reflected in the advance of accuracy in the observational ephemeris data.

References to the different sets of ephemeris data, as well as the data themselves may be found at the following website: http://ssd.jpl.nasa.gov/plan-eph-data/index.html

4.1. *Optical observations*

Until about 50 years ago, the only data used for ephemerides was optical – transit timings, photographs, micrometers, astrolabes. For these, a typical observational error has been on

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the order of one arcsecond [1″], improved over the years with significant effort, to about $0\overset{''}{.}4$ for the innermost four planets. This range corresponds to hundreds of kilometers. For the outer planets, the accuracies are now down to $0\overset{''}{.}2$, and in some cases, even $0\overset{''}{.}1$; here again, these correspond to hundreds, if not thousands, of kilometers.

4.2. *Mercury and Venus radar*

Starting in the 1950's, radar signals were bounced off the surface of the moon at first, then Venus, and then Mercury and Mars. The round-trip times of these signals immediately gave more that an order of magnitude increase in the accuracy of the observational data. Fig. 1 shows radar residuals of Mercury and Venus over the past decades. Even the earliest points show, for the most part, residuals below the 5-km level. And, much of the remaining scatter was caused by the variations in the planet's topography, typically variations of a couple of kilometers. Nowadays, for Venus, a topographic map, obtained from the Pioneer Venus Orbiter spacecraft, is used to eliminate most of that topography from the residuals; residuals are on the order of 1-2 km. For Mercury, an ellipsoidally-shaped planet is adjusted to the residuals.

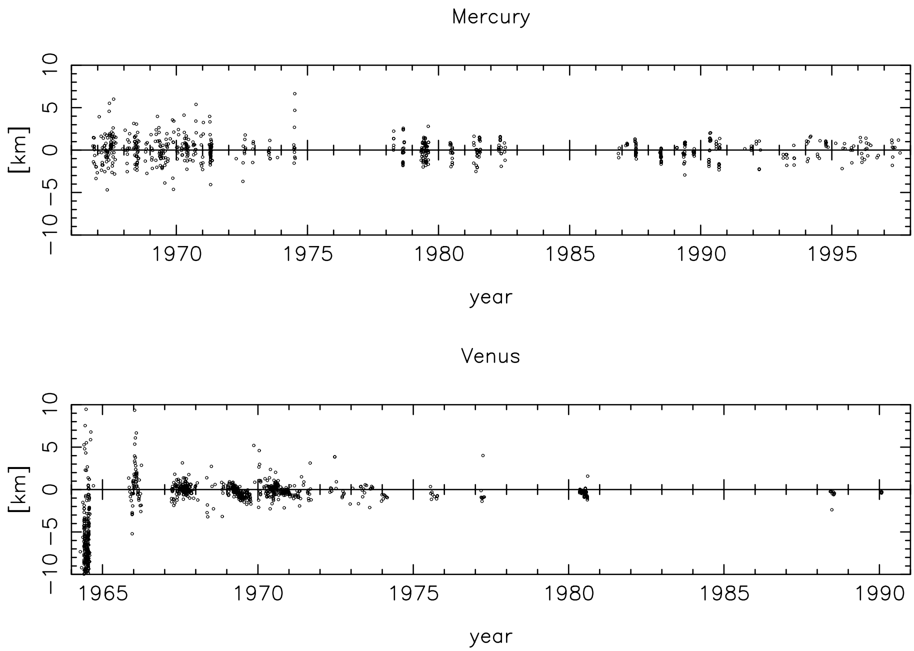

Figure 1. Radar ranging resiuduals of Mercury and Venus.

4.3. *Mars radar closure points*

On Mars, the topographical variations are much more severe. And, with the rapid rotations of that planet, the variations can be seen to change drastically within an observing run of only a few minutes. Fig. 2 shows residuals from two radar tracks on Mars, intentionately offset from each other by about 1.5 km in the vertical direction. They were taken on two different days, separated by over two years, and they have the property that the radar echoes of both days were reflected from spots on Mars with latitudes $-18\overset{\circ}{.}2$ and with longitudes between 280° and 360°. Thus, the two tracks are composed of pairs of echoes where each member of the pair reflected off from the same spot on Mars;

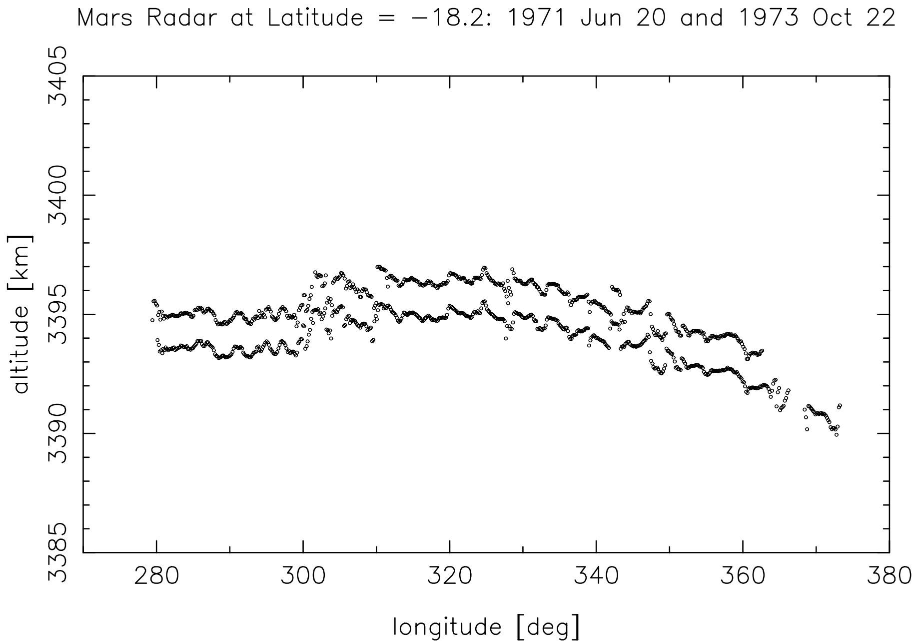

Figure 2. Two sets of Mars ranging residuals, 1971 and 1973, intentionally offset from each other by 1.5 km. On the two days shown, the radar bounced from the same locations on the surface of Mars. If the vertical offset were real, it would indicate an ephemeris drift between the two dates. The similarity of the two tracks shows how accurately one could determine such an offset – to an accuracy well below 100 m.

subtracting one from the other eliminates the topography and measures the ephemeris drift between the two days – determined with an accuracy well below 100 m.

Fig. 3 shows four such radar tracks, again intentionally offset in the vertical direction. These four were taken at differing latitudes, in order to show how the topography can vary as the latitude changes. The peaks of the tracks at longitude 120° are from the south flank of “Arsia Mons”, the southernmost of the three prominent volcanoes, “Tharsis Montes”.

4.4. *Mariner 9 range residuals*

In contrast to the radar-ranging which bounces off from the surface of a planet, the ranging data from a spacecraft are free from the variations in the planet’s topography. Fig. 4 shows the ranging residuals from Mariner 9, in orbit around Mars, 1971–72. The Orbit Determination Program (ODP) at JPL was used to solve for the orbit of the spacecraft with respect to Mars, and the measurements were then reduced to the center of mass of the planet with an uncertainty significantly lower than the uncertainties in the ranging (timing) measurements themselves. For Mariner 9, since the frequency of the signal was relatively low, 2200 MHz, the free electrons in the solar corona contributed significantly to the delay of the signal, especially around the time of Mars’ conjunction in late August, 1972. As a result, the points near the conjunction were severely down-weighted. Models of the solar corona time-delay have been used with moderate success for removing the majority of the delay. However, it has been seen that the density in the corona can change significantly over the span of just an hour or so. Despite such problems, most of the Mariner 9 Mission yielded ranging measurements with uncertainties substantially below 100 m.

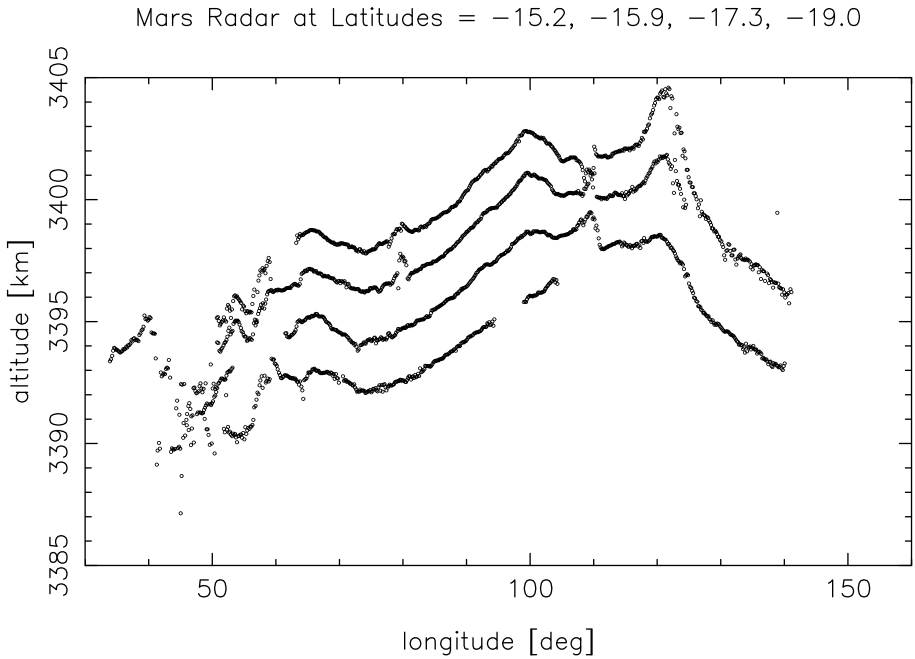

Figure 3. Four sets of Mars ranging residuals, intentionally offset from each other, each at a different latitude on Mars. Near longitude 120°, the tracks run over the south flank of "Arsia Mons", the southernmost of the three prominent volcanoes, "Tharsis Montes". The differences between each set show the variation in topography over the range in latitude.

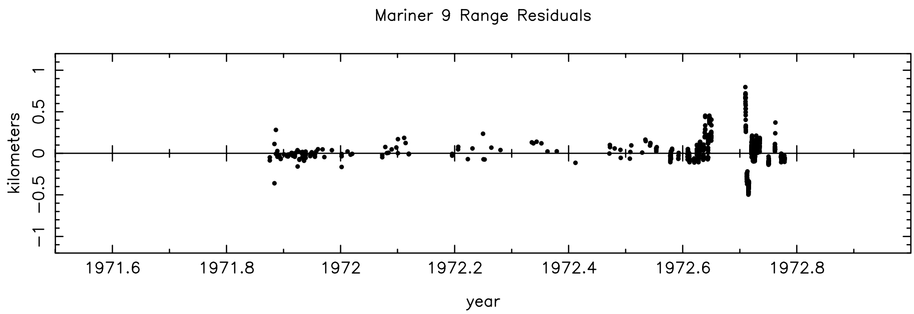

Figure 4. Ranging residuals from the Mariner 9 Spacecraft, 1971–72. Much of the scatter is less than 50 m until the times approaching conjunction when the signal passed through the noisy solar corona.

4.5. *Viking lander range and Doppler residuals*

The Viking Mission sent two spacecraft to Mars, each with an orbiter and a lander. The orbiters had dual frequency transponders; the landers had single frequency ones. Ranges in two frequencies allow the solar corona time-delay to be calibrated because of its dependency upon frequency. Thus, if the orbiter and lander ranges were taken close to each other in time, the delay, calibrated from the orbiter ranges, could be removed from lander ranges. The first plot of Fig. 5 shows the range residuals from the Viking

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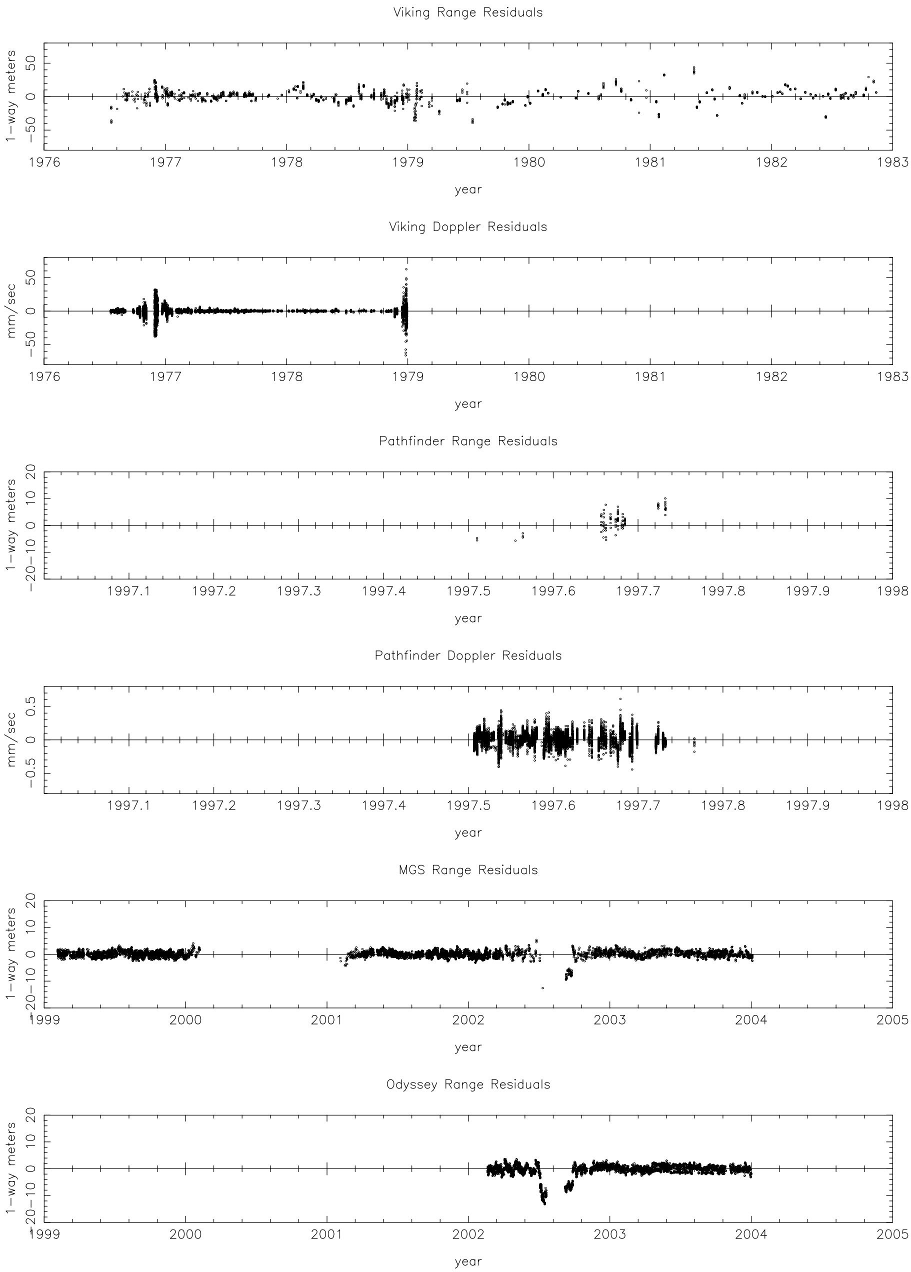

Figure 5. Spacecraft range and Doppler residuals. At the top are the Viking Lander range residuals, with an rms scatter of about 10 m away from the conjunctions. Secondly, Viking Lander Doppler; the noise around the conjunctions is evident. Third and fourth are the Pathfinder ranges and Doppler. The fifth and sixth plots show every tenth point of the over 230,000 range measurements from MGS and Odyssey, respectively. The scatter is about 1.3 m, with the exception of the conjunction in mid-August, 2002.

Landers; these were calibrated from the orbiters' dual frequency data while the orbiters were still active (1976-1980); after that time, a model similar to that used for Mariner 9 was applied. For modeling the lander ranges, one also needs to model the rotation of Mars, correcting the various relevant parameters, as well as determining the locations of the landers upon the surface. Various features of the rotation (precession, seasonal terms, etc.) may be estimated from such data – about 10-m uncertainty.

The second plot of Fig. 5 shows Doppler residuals from the Viking landers; in some sense, these data are redundant, given the existence of the range data.

4.6. *Pathfinder lander range and Doppler residuals*

The lander of the Pathfinder Mission produced a short set of range and Doppler measurements; they are given in the third and fourth plots of Fig. 5. The uncertainties of the ranges are seen to be only a few meters, though there are indications of unmodeled systematic errors, probably due to uncalibrated (and variable) electronic system delays.

4.7. *MGS and Odyssey range residuals*

The most accurate of the Mars data are the range residuals of the MGS and Odyssey orbiting spacecraft. The fifth and sixth plots of Fig. 5 show only every tenth point of the total data set; even so, over 23,000 points are shown. The scatter of these points, excluding those around conjunction in mid-2002, is only 1.3 m, excluding the points within six weeks of the Mars conjunction in mid-August, 2002.

4.8. Δ *VLBI residuals*

The final major set of observational data contains ΔVLBI observations of orbiting spacecraft with respect to the background radio sources, especially those of the (ICRF) International Celestial Reference Frame. Such observations give angular measurements in essentially one dimension: in the direction connecting the two participating radio antennas. Therefore, ΔVLBI observations between the Goldstone and Madrid complexes of the Deep Space Network provide determinations which are almost purely in right ascension, since the latitudes of the two sites are nearly equal. Observations between Goldstone and Canberra, on the other hand, are split about 50–50 between right ascension and declination. Figs 6 and 7 show the ΔVLBI observations presently being fit by the ephemerides of Venus and Mars, respectively. In each figure, two plots are given: the upper in milliarcseconds (mas); the lower in kilometers. The Venus points in Fig. 6, taken of the orbiting Magellan spacecraft, show a scatter of several mas. In contrast, the more recent observations in Fig. 7 show a scatter of less than a single milliarsecond or kilometer: a striking example of technological improvement.

5. The effects of the different types of data

The ephemerides of the four innermost planets and the moon are dominated by the data presented in the preceding section: ranging measurements and ΔVLBI. The ranging measurements, taken over various parts of the planets' orbits, provide all relative distances and angles between the Earth and Mercury, Venus, the Moon, and Mars, thus locking the whole system together. It is also true, though not readily envisioned, that the ranging measurements alone provide accurate mean motions of the planets with respect to inertial space. For a further discussion, see Williams & Standish (1989).

The orientation of the whole system, with respect to some external reference frame, is the only feature *not* provided by the ranging measurements. The orientation is provided by the ΔVLBI measurements which tie the system onto the background ICRF.

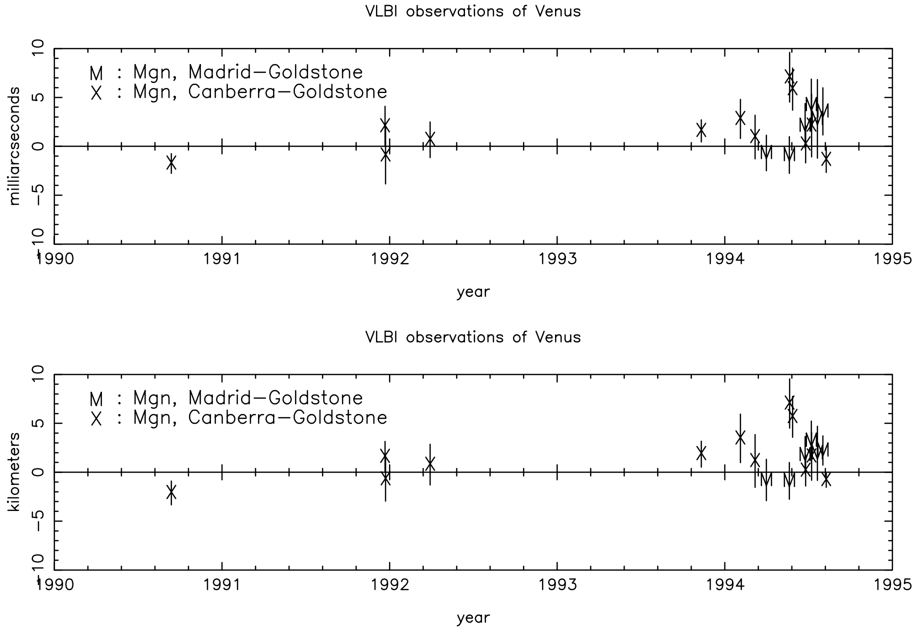

Figure 6. ΔVLBI residuals of Venus from the Magellan orbiting spacecraft, shown both in milliarcseconds and in kilometers. These observations are virtually one-dimensional. Those from Madrid–Goldstone are almost purely in right ascension; those from Canberra–Goldstone are about 50% each in r.a. and dec.

From the ranging and ΔVLBI, then, the relative positions are presently measured down near the 1-m level, and the mean motions are determined at the level of about 10 milliarcseconds/century. The orientation of the system onto the ICRF at the present time is accurate to a fraction of a milliarcsecond. As will be discussed in a later section, however, these accuracies deteriorate in time due to the perturbations of many asteroids whose masses are poorly-known at best, thereby rendering their perturbations not well-modeled.

For Saturn, Uranus, Neptune, and Pluto, there is basically only optical data: meridian circle timings, astrolabe timings, and photographic astrometry. A few various other data points exist, but these provide only momentary fixes in time – not enough for the determination of orbits with periods extending over decades. Jupiter is in between: a few ranges from former missions and some ΔVLBI points from the Galileo mission. So, in contrast to the inner planets, the ephemeris uncertainties for the five outermost planets remain above the 100-km level; substantially more for the outermost ones.

6. Testing with the ephemerides

It is no wonder that the inner solar system attracts those wishing to test various gravitational theories, asking if a modified set of equations of motion (i.e., an alternative theory of gravitation) can better fit the observational data. For instance, the PPN parameters of relativity, β and γ, are conventionally assumed to both be equal to unity; but, since they are programmed explicitly into the equations of motion, it is possible to solve for corrections to them, using the partial derivatives of the ephemeris coordinates with respect to those parameters: $\partial \mathbf{r}_i/\partial\beta$ and $\partial \mathbf{r}_i/\partial\gamma$. Any significant change to β or γ would then indicate a questioning of the original assumption that $\beta = 1$ and $\gamma = 1$.

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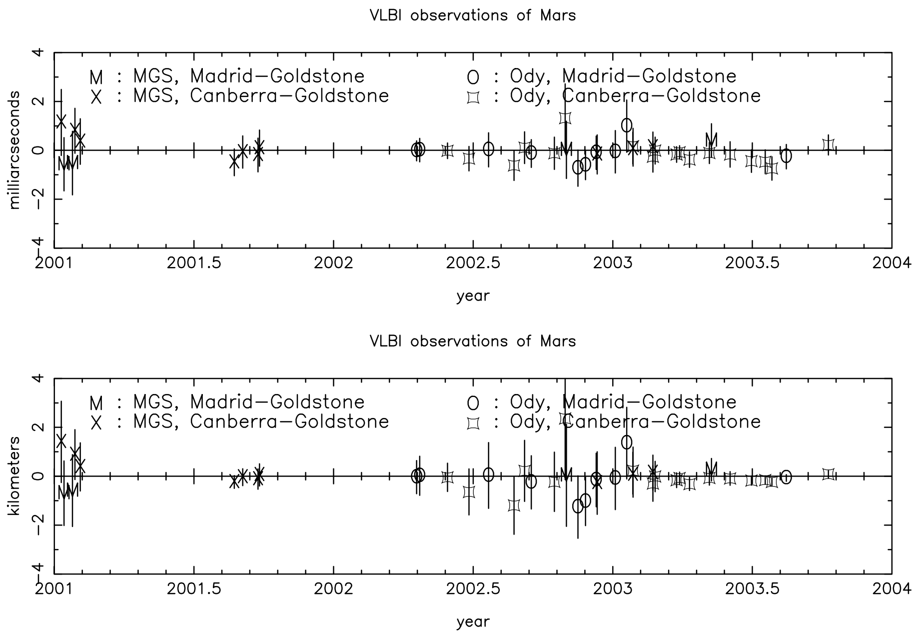

Figure 7. ΔVLBI residuals of Mars from the MGS and Odyssey orbiting spacecraft, shown both in milliarcseconds and in kilometers. These observations are virtually one-dimensional.

The following is a partial list of topics which have been tested, using the planetary and lunar ephemerides, requested by a number of theoretical researchers:

General Relativity : β, γ , J_2(sun)

Modified Newtonian Dynamics

New Weak Forces and Non-Newtonian Gravity

Equivalence Principle

Mach's Principle vs. Equivalence

Sun's gravitational-to-inertial mass ratio

$\dot{G}$

d(au)/dt

Behind all of this testing is the ongoing improvement of modern planetary and lunar ephemerides.

7. Asteroids

Even with such accurate observational data, the planetary motions show rather large uncertainties, for the planets are perturbed by the presence of many asteroids whose masses are quite poorly known. Furthermore, it's not possible to solve for the asteroid masses, other than for the biggest few, because there are too many of them for the data to support such an effort. As a result, the ephemerides of the inner planets, especially that of Mars, will deteriorate over time. Various experiments have shown that the ephemerides have uncertainties at the 1-km level over the span of the observations and growing at the rate of prehaps a km/decade outside that span.

A great deal of effort has been applied in order to represent the asteroid perturbations as well as possible. Studies of the estimations of masses of the most relevant 300 or so asteroids have been made by Fienga (2001) and by Krasinsky *et al.* (2001); Krasinsky

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et al. (2002) have also modeled a ring to represent the perturbations from the remaining thousands of small asteroids.

8. Values of the au

Table 1 is presented in order to emphasize the immense improvements in the determinations of the value of the au over the past century. The values given in the table are the differences from 149,597,870,691 m, the value used in the ephemerides of the late 1990's, JPL's DE403 and DE405 and IAA's EPM2000 (Pitjeva 2001). The optical determinations gave errors of many tens of thousands of kilometers, finally reduced to only 2500 km by the careful extensive work of Lieske.

Table 1. Deteminations of the au [TDB values]

		[meters]	
1931	Spencer Jones	+72,000,000	Eros
1941	Adams	-185,000,000	Stellar Doppler shifts
1942	Brouwer	-19,000,000	Lunar occultations
1950	Rabe	-73,000,000	Eros
1958	False Peak	-130,000,000	radar ghosts
	(me too)	-130,000,000	
1959	(me too)	-140,000,000	
1961	First Real	+1,000,000	radar
		-170,000	
		+2,000,000	
		-2,000,000	
		+130,000	
			→ Venus Rotation au [km]
1964	IAU	+130,000	
1967	PEP	+760	ephemeris
1968	Lieske	+2,530,000	Eros
1969	DE69	+1350	
1976	DE96	+710	
1979	DE200	-31	Viking ('76-'79)
1995	DE403	0	Viking (-'82), LLR, radar
1997	DE405	0	
2000	EPM2000	0	
2004	DExxx	+7	MGS, Odyssey
	$d(\mathrm{au})/dt$	$= +15\ m/yr$?	

The first radar reports were false identifications of signals, thought to be echoes from Venus. Right away, two more groups confirmed this wrong value. The first real radar measurements were in error by only $1000 - 2000$ km, soon to be reduced dramatically by increasing technology and the determination from MIT's PEP ephemeris. Measurements to spacecraft now have brought the value of the au to levels of only a few meters. The

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recent addition of the MGS and Odyssey ranges tends to indicate a value for the au which is a couple of meters shy of 149,597,870,700 m.

At the bottom of the table is the intriguing thought that maybe $d(\text{au})/dt \neq 0$ (Krasinsky & Brumberg 2004). And, at the top is the statement that these are TDB values of the au, not TCB values, recently "recommended" by the IAU.

9. Conclusions

The au has a colorful history, full of mis-quotes, poor definitions, and varied measurements.

• The au is not defined; it is the result of a convention of units, one which has been used for many, many decades in astronomy.

• The determination of the value of the au in kilometers is the result of extensive ephemeris fitting to highly accurate measurements.

• The dominating error source for the four inner planet ephemerides is the perturbations from many asteroids whose masses are poorly known.

• There is still uncertainty in the value of the au: first, from the uncertainties in the ephemerides arising from the poorly-known asteroid masses, and secondly, from the possibility that the length of the au itself may not be constant over time.

Acknowledgements

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Discussion

Dave Monet: There are several experiments such as PANSTARS, LSST, others that really think they are going to find all the asteroids down to a few hundred metres and hand that list to the community. Is that going to help at all?

Myles Standish: The problem as much as anything is not where the asteroids are but their masses. So we need, first of all, an estimation of the diameters, volume - actually, when you get to the small guys I guess it's an estimation of the volume, and then you need the density. Right now for a number of the asteroids what we do is take the estimated volume or diameter and then assign a density according to the taxonomic class. And then we can actually solve for the density of overall taxonomic classes, but you cannot solve for many asteroids. I can try that, but I get a couple of negative masses, a couple densities which are 12; we tend not to believe those.

NICK KOLLERSTROM: You advised us that the mean distance in Keplerian orbit is not the semi-major axis. Did you tell us what it was?

MYLES STANDISH: Yes. The mean distance – it was $a \times (1 + e^2)/2$; that little formula, is that what you meant? It's the semi major axis $\times(1 + e^2)/2$; that's the mean distance in a Keplerian orbit.

DAVID HUGHES: I mean, I love asteroids; what I really would like to know is the total mass of the asteroid belt. This perturbs the orbit of Mars; can you get a handle on this total mass using your work?

MYLES STANDISH: Actually, following Krasinsky of St Petersburg, we have about 20 asteroids which we handle individually – the 20 most important affecting the orbits of Mars and the Earth. Then we have about 300 more which we put into the 3 taxonomic classes, as I've kind of alluded to, and then Krasinsky on top of all that puts a belt of asteroids out there and solves for the mass of the belt, so he has gotten somewhere around a sizable fraction of the mass of Ceres. I think about half the mass of Ceres for that belt. Do you recall Lena?

ELENA PITJEVA: Mass of belt maybe less than half the mass of Ceres; about 50% of Ceres.

MYLES STANDISH: 50% of Ceres – I thought so, yes. So that is an estimate, but you can change. So we have about 300 of the most important, and then another half of a Ceres mass up there. There is a paper by Krasinsky [et al. 2002]; I refer you to that.

JOHN PONSONBY: I'm astonished that you didn't make any mention of pulsar timing as a contributory source of information about the AU. I would have thought this was a way of tying it in with the inertial frame, as well as getting precision measurements because they predict the time of arrival of single pulses to a few microseconds.

MYLES STANDISH: But a few microseconds is 500 metres.

JOHN PONSONBY: Sure, sure. It's not at a metre level, but somewhere along the line I would have thought it was a useful contribution.

MYLES STANDISH: I have used them and looked at pulsar timings. Actually, the ranging swamps them out still, so they really don't contribute. One of the problems is, of course, you have to reduce them to the barycentre of the solar system; that is very poorly known because we don't know the masses of the planets as well as we could. As a matter of fact, there is a little story that when the people at MIT and we were reducing pulsar 19-whatever-it-is, we came up with a different period, a significantly different period, *monstrously different* – and the reason was we had different masses of Neptune in our ephemerides and Neptune puts in a 165-yr period into the barycentre, and with a little piece of that period it looks like a slope and gives you a different period. So, finding the barycentre is one problem, and then of course the σ on the observations is another.

JACQUELINE MITTON: I notice that in conclusion you say that the astronomical unit is not defined. This is a real problem for people like me who write dictionaries where we are obliged to put in a definition, and also, because I often am writing for, or speaking to, children, or advising publishers of magazines, or indeed reading or doing similar to what *Sky & Telescope* did [incorrectly define the AU] which you criticised in a justifiable way. So the question is: okay, there is a technical basis for what we try to understand as the astronomical unit, but for the great public and children under 12 out there, have you come up with a form of words that you find acceptable?

Myles Standish: [laughs] I guess it depends on whom it is acceptable to. I don't know ... I put together the explanation that I showed to make it one or two sentences. Possibly, we could take the sentence that's in the explanatory supplement, and instead of using what they call the year, just use the mean motion, the effective average angular rate going around the sun, but then you have to say that it is also based on an old value, one that is over a century old. I don't know how old the Gaussian constant is ... 150 years or something. But it is not easy; maybe we could work on it.

Dennis McCarthy: Probably you have already solved for the rate of change of the astronomical unit, do you have a number?

Myles Standish: Krasinsky & Bromberg have 15 metres per century in their paper and I am not sure whether that's cosmologically founded, or numerically founded, but I spoke to Dr Pitjeva just before my talk, because I knew you would probably ask me [laughter], and she gets about 5 metres per century

Dennis McCarthy: But your number is from the solutions, from the ephemerides?

Myles Standish: That's where her number comes from, yes. Now, there are other problems with ranging which I didn't want to admit to, but when you go into the electronics of a transponder there is a delay and, as a matter of fact, it's dependent on temperature and everything else. Some of these missions have been very carefully calibrated – the MGS, for instance. Viking was not so much, nor was Odyssey, and actually you put those Odyssey and MGS observations right next to each other, taken at the same time, and there's a couple of metres or so difference between them. So, when you have a solution that stretches from Viking in the 70s to now, then you have a 5-metre discrepancy, you can call it, kind of, an AU-dot. I prefer to call it biases in the equipment. So it's a trade off and we are not sure yet. Maybe with many, many more years of MGS alone we can go after that number.

Jim Message: Can I make one comment and ask one question. About the question of defined: of course there are two possible meanings of saying something is defined or not defined. You can define a concept in the sense of giving a meaning to it, or you can define it in the sense of saying this number is what it is, and I think that we have probably got a little bit of a confusion here, haven't we? I mean what you are saying is that the astronomical unit is not something where we state a number and say this is it. The number comes from the calculation from other assumptions that you have made. The criticism is not to say that the astronomical unit is not a perfectly well-defined concept, in the sense that as you have explained it follows from the equations that you are using. I was just wondering if there was a possible verbal confusion here.

Myles Standish: Well, in the explanatory supplement, or in that quote, they use a term "based upon," and you could say based upon the definition of a numerical value for the mean motion of the Earth, and through Kepler's equation the AU follows. For somebody in school, ...

Jim Message: Well, quite, there's your problem. So it's important to get the concept clear, if youre talking to people who haven't followed the story right through from the 1950s.

Myles Standish: It took me three decades to figure this thing out!

[general laughter!]

Jim Message: I mean, I'm not there yet either, but my question is simply this, the 5 or 7 [metres] that is your present value for the difference of the astronomical unit from the received value: Is there an uncertainty associated with this? What is the σ?

Myles Standish: There is a formal uncertainty, but I would not believe it. The uncertainty just comes from making many, many different solutions, by juggling the different parameters, and weighting the data sets differently, and seeing how much this number jumps around. I was so entranced with the value from 7 or 8 years ago – every time this thing came up plus or minus 6 or 7 [metres], I thought something's wrong. I kept trying to push it back. But now I think we have a real belief that maybe this is ...

Jim Message: But it's not 0? It's not 5 ± 5 [metres]?

Myles Standish: No, I would say 7 ± 2. Now, I know that Dr Pitjeva has put out to another significant figure, so maybe that's significant. I don't know.

Don Kurtz: Myles, can you comment on sources of $\dot{a}$. Why?

Myles Standish: Sources of $\dot{a}$? Why is it believed?

Don Kurtz: No, what's causing the astronomical unit to increase? What's the physical cause of the increase?

Myles Standish: That's a cosmological argument I believe. There's a paper by Krasinsky & Bromberg from St Petersburg, and there is a fairly extensive argument by Bromberg, but I don't know it very well; I probably shouldn't comment.

Don Kurtz: Is there any contribution you could measure from either $\dot{\mathrm{M}}$ from the sun or from accretion onto the sun, or is that just far too small for you still?

Myles Standish: I've tried. We've put in $\dot{\mathrm{M}}$ trying to model the course of hydrogen burning – the mass loss of the sun as it evolves – and to actually solve for anything past that, no. We can get some crazy answers if we do.

Don Kurtz: Something I would like to see (if I could talk you into producing it) would be a nice map of one orbit of the Earth, with the Earth and the Sun in a inertial frame, doing whatever they do in a year, exaggerating the scale to where you can see all these bumps from the perturbations from the asteroids, the planets ... some nice pretty picture to show us how non-Keplerian it really is.

Myles Standish: It is certainly doable.

Don Kurtz: [in a tone of enticement] I'll put it in the proceedings if you do it.

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[general laughter!]

Myles Standish: Oh, boy! [wipes his brow]

[more laughter]

Jaymie Matthews: Apropos to the discussion of $\dot{a}$, and you were talking about biases and the radar ranging measurements, a few years ago there were reports of anomalous timings from, I believe Pioneer and maybe Voyager as well, and I am just curious – I haven't heard much from those groups lately – I just wondered what your sense of what they were measuring was, and what's the consensus of your community on that?

Myles Standish: Yes, I know very much of what you are talking about, and certainly there are some good people trying to figure out what this is all about. The only thing that scares me is how they handle the data right in the beginning, the raw data, because they certainly have looked into many, many different effects and not really been able to explain it. The problem . . . the head guy, kind of would love to see some kind of very exotic explanation, new force or whatever, and I don't think that that has been really justified yet. So that's about all I should say on that, but handling the data is a real touchy issue here.

Walter Brisken: Neptune was discovered by finding these anomalies in the ephemeris. Has there been any recent progress in trying to discover unknown bodies in our solar system this way?

Myles Standish: Not in ten years or so, no. There was a lot of activity maybe 20 years ago – 15 years ago – but most of it was false because the wrong mass of Neptune was being used, and that affects the motion of Uranus. Once you put in the good mass of Neptune and adjust the orbit, the major part of the signature – almost the total signature – is gone. So, there is nothing that we see that really demands some kind of other explanation. Pioneer may be the one example, I don't know. Things *seem* to behave themselves.

Marilyn Head: As an amateur astronomer I was really fascinated. I do minor planet occultations, and this is the first time that I've heard that they are really useful, because what you are talking about – finding the diameter of asteroids, etc. – is useful, and it is important, in order to find out the mass, I assume. So it was just good to hear that, to know that what we are doing makes a contribution.

Myles Standish: I'm sorry, the question is?

Marilyn Head: It was really just a comment. You know the minor planet occultations, were you trying to . . .

Myles Standish: Oh . . . Oh! The occultations of asteroids?

Marilyn Head: Yes.

Myles Standish: Or, the occultation of a star by an asteroid.

Marilyn Head: Yes.

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Myles Standish: Yes, certainly one of the major problems is the volume of an asteroid, because if you have a 20% error in the diameter, you have about a factor of two in volume (close to it) and that can make a big difference. So if the question is: "are these things useful," then, yes. Have you got any more of them?

[laughter!]

Marilyn Head: We try, we try. We get about 1 in 13, I think.

Mikhail Marov: Could you tell us, based on the contemporary estimates for residuals in the motions of Neptune and Uranus, is it possible to estimate the total mass of the Edgeworth-Kuiper belt?

Myles Standish: No, sorry. Especially because the optical observations are really the only measurements we have of Neptune and Uranus – and they exist back only until 1910, at best. It was then that there was a major improvement in observing technique, so the measurements before then are not as good. So, we don't even have a full period of Neptune; we have barely a period of Uranus. So the observation is just not strong enough. I can't put a number on what it would do to the observations, but I would be very, very surprised if we could pull out that signal.

Nicole Capitaine: You provided a number in metres, but generally in astronomical tables what it is provided at first is the value of the astronomical constant in seconds, in time. So what is the first one? Is it the value in seconds, and then you derive the value in metres, or is it the . . .

Myles Standish: No, we actually solve for the value in kilometres and then derive the time. I think the reason could be very apparent. When we take a radar range, of course the measurement is in time. We use the given velocity of light to convert to kilometres, and then we have to convert to AUs to put into the ephemeris system, and that conversion is kilometres per AU. I never used the AU in seconds. It could be done. I mean, it cuts out the middle man, and I know that Irwin Shapiro one time made a comment that maybe we should run the whole ephemeris system using light time as the distance.

Nicole Capitaine: Regarding the dot, the AU-dot, is it related to the timescale, is it in TCB or in TDB?

Myles Standish: Either one. That won't change it . . . well, it will change it in the eighth figure or something. [laughs] We're worried about the sign on the thing!

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