Planetary Solar Time and Seasons

Mike Allison
GISS Lunch Seminar
2014 January 15 – 18:00 UTC
MJD 5 6672.8
MSD 4 9782.7

NASA Goddard Institute for Space Studies

Pluto as seen from Charon
by space artist Ron Miller

Planetary Solar Time and Seasons – Related Papers Published

First simple algorithim for Mars lander time

- Allison, M. 1997. Accurate analytic representations of solar time and seasons on Mars with applications to the Pathfinder/Surveyor missions. *Geophys.Res.Lett.* 24,1967-1970.

Mars Fictitious Mean Sun

- Allison, M. and M. McEwen 2000. A post-Pathfinder evaluation of areocentric solar coordinates with improved timing recipes for Mars seasonal/diurnal climate studies. *Planet. Space Sci.* 48, 215-235.

Titan solar coordinate algorithm

- Allison, M., D.H. Atkinson, M.K. Bird, M.G. Tomasko 2004. Titan zonal wind corroboration via the Huygens DISR solar zenith angle measurement. *ESA SP–544* (A. Wilson, Ed.), pp. 125-130.

"Paleo-Titan" study

- Aharonson, O., A.G. Hayes, J.I. Lunine, R.D. Lorenz, M.D. Allison, and C. Elachi. 2009. An asymmetric distribution of lakes on Titan as a possible consequence of orbital forcing. *Nature Geosi.* 2, 851–854.

In preparation:

- Allison, M. (Drafted 2014). Revised planetocentric mean elements and solar timing constants for Mars. [Based on a newly published update to the Mars pole precession and prime meridian.]

GISS/Columbia collaborators and assistants on planetary solar timing/simulation work over many years:

- **Wei Zhou**
- **Noam Solomon**
- **Megan McEwen**
- **Jeremy Ross**
- **Joe Ferrier**
- **Rob Schmunk**

With significant intellectual/moral encouragement from:

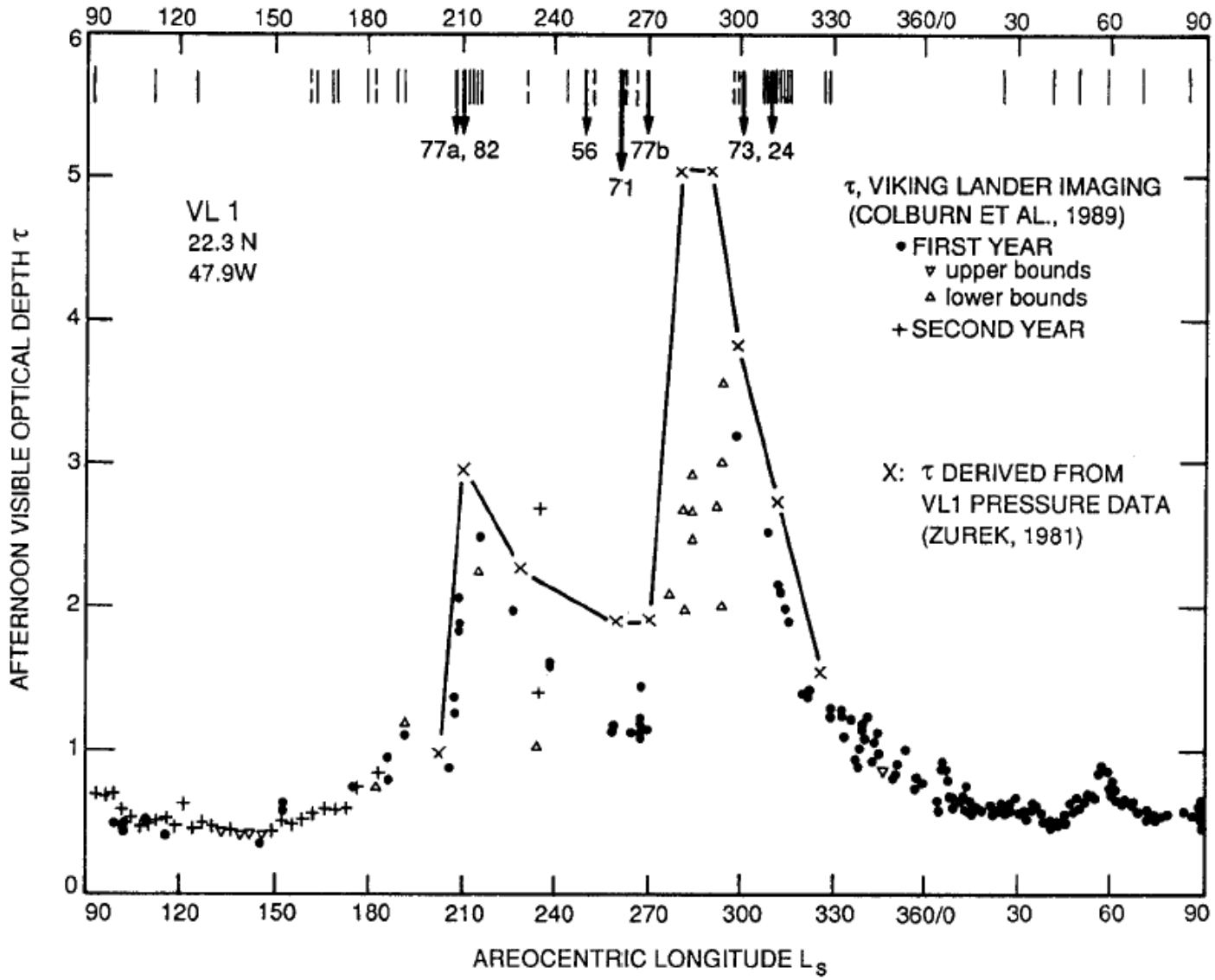
- **Tony Del Genio (GISS)**
- **Larry Travis (GISS)**
- **Gary Russell (GISS)**
- **Mike Bird (Universität Bonn)**
- **Bill Blume (JPL – astronavigation)**
- **Rich Zurek (JPL – Mars projects)**
- **Tom Duxbury (JPL and George Mason University)**
- **Oded Aharonson (CalTech)**

Some Goals for this Talk on Planetary Solar Time and Seasons

- Review some nuts and bolts for the efficient calculation of the planet-centered solar position for climate modeling or data analysis … including seasonal, diurnal, and multi-millenial/paleoclimate changes.

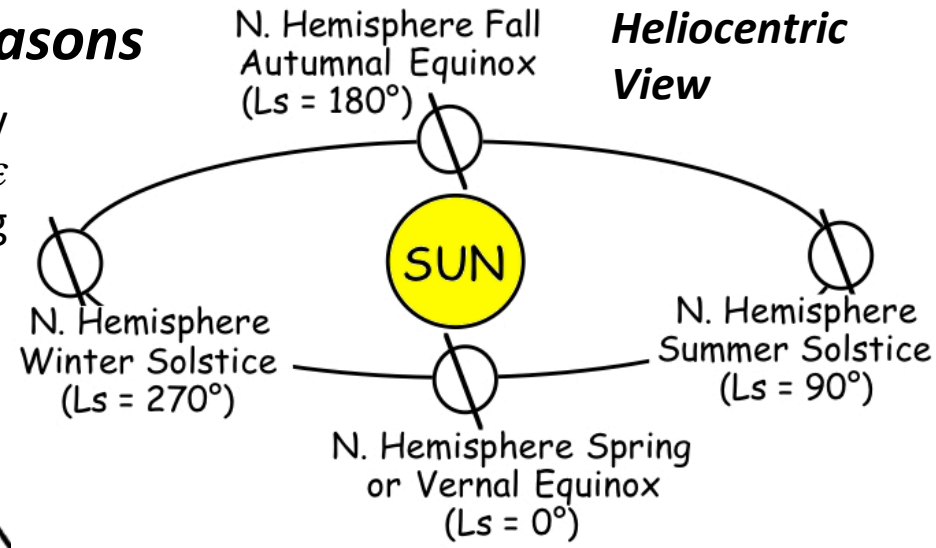
- Outline some of the ways that terrestrial timing methods and standards might be (or have already been) applied to other planets.

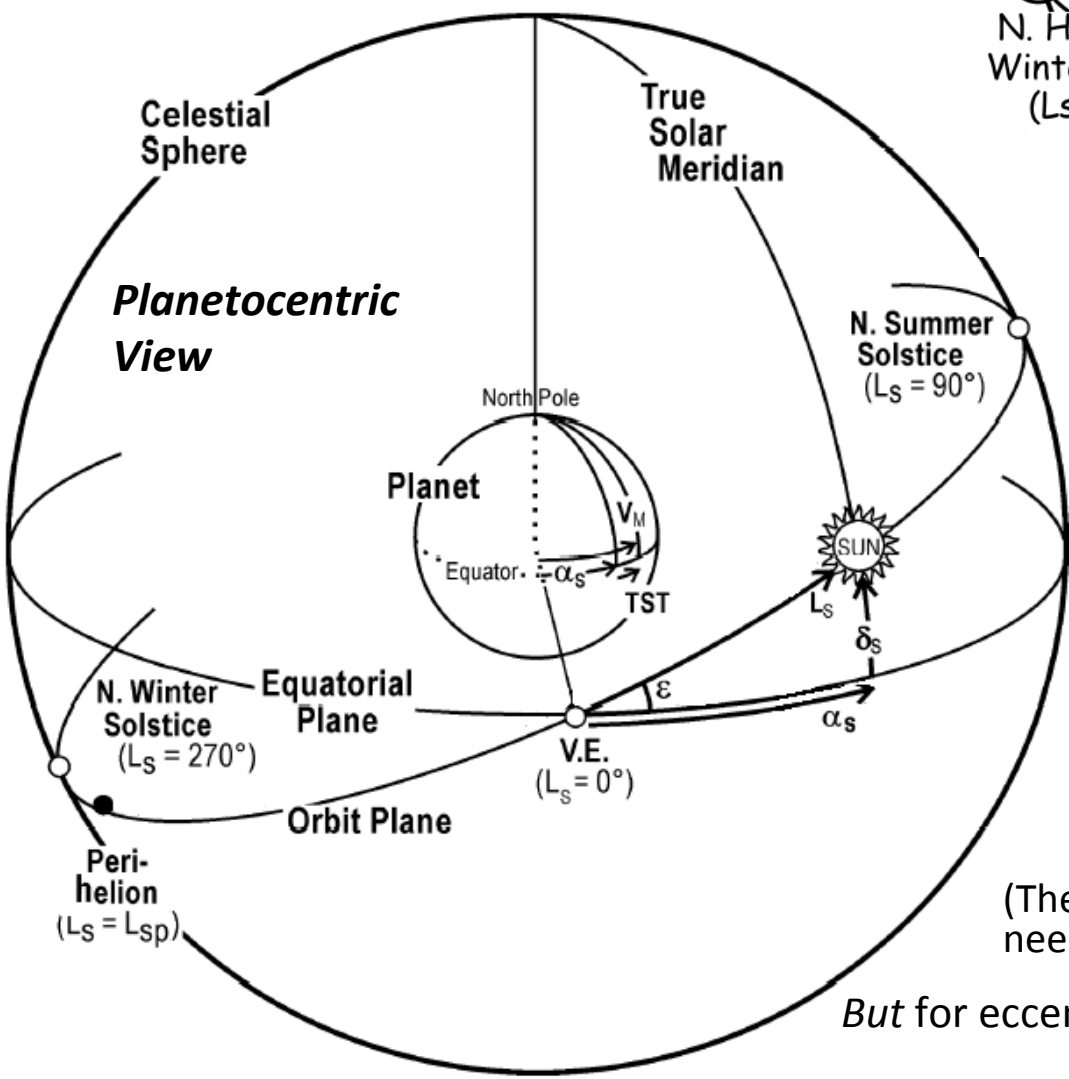
- Review some of the special nomenclature and reference standards adopted for astronomical (and Earth historical) timing. And along the way . . . provide some (possibly amusing) tour of a few foibles and peculiarities to the subject … a few maybe relevant to extraterrestrial or paleo circumstances.


90 120 150 180 210 240 270 300 330 360/0 30 60 90
77a, 82
56
77b
71
73, 24
VL 1
22.3 N
47.9W
τ, VIKING LANDER IMAGING
(COLBURN ET AL., 1989)
• FIRST YEAR
▿ upper bounds
▵ lower bounds
+ SECOND YEAR
X: τ DERIVED FROM
VL1 PRESSURE DATA
(ZUREK, 1981)
AFTERNOON VISIBLE OPTICAL DEPTH τ
0 1 2 3 4 5 6
AREOCENTRIC LONGITUDE L_s

The Astronomical Reason for the Seasons

Primarily – the obliquity (tilt) of the planetary spin axis with respect to the plane of the orbit ε . . . along with the variable solar distance along the eccentric orbit. *Ls* is the standard index.





Given the *planetocentric solar longitude* (referenced to the vernal equinox), the position of the Sun on the planet's celestial sphere is given by the indicated legs of the right spherical triangle with hypotenuse *Ls,* along with the angle ε :

$$\delta_S = \mathrm{Sin}^{-1}(\mathrm{Sin}\,\varepsilon \cdot \mathrm{Sin}\,L_S) \qquad \text{and}$$

$$\alpha_S = \mathrm{Tan}^{-1}(\mathrm{Cos}\,\varepsilon \cdot \mathrm{Tan}\,L_S),$$

$$= L_S + \frac{180^\circ}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \left(-\mathrm{Tan}^2 \frac{\varepsilon}{2}\right)^n \cdot \mathrm{Sin}(2nL_S)$$

(The series avoids the tangent infinities and the need to test for the proper quadrant.)

But for eccentric orbits, *Ls* advances unevenly with time.

Calculation of Time and Distance on Orbit

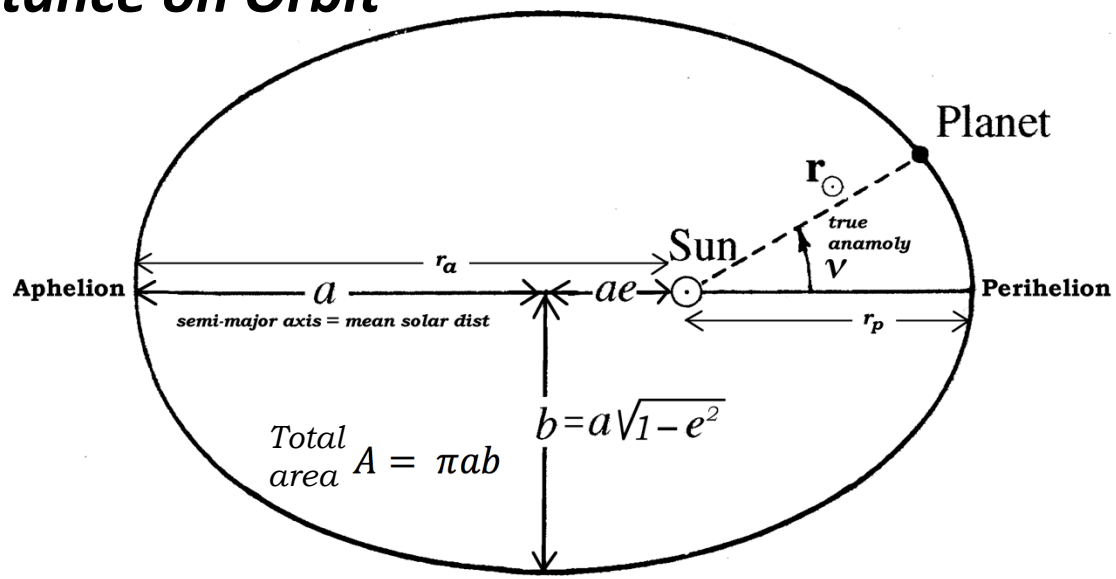
We may approach the calculation of a planet's time-of-season *Ls* as a special form of the Kepler problem, with the instantaneous solar distance given by the ellipse equation

$$r_\odot = \frac{a\ (1-e^2)}{1+e\ Cos\ \nu}$$

where the *geometric** **mean distance** $a = \frac{1}{2}(r_a + r_p)$

the orbital **eccentricity** $e = 1 - r_p/a$

and the **true anomaly** ν is the orbital longitude eastward from perihelion.



By Kepler's 3rd Law, the **orbit period**

$$\tau_{orb} = 2\,\pi \left[\frac{a^3}{k^2(1+m_p/M_\odot)}\right]^{\frac{1}{2}} \text{ ephemeris day}$$

where k = 0.01720209895 $AU^{3/2}d^{-1}$.

By Kepler's 2nd Law, equal areas $dA = \frac{1}{2}r^2 d\nu$ are swept out by the radius vector in equal times as $\frac{1}{2}r^2\frac{d\nu}{dt} = \frac{\pi\, a^2}{\tau_{orb}}(1-e^2)^{\frac{1}{2}}$ Then with the ellipse eqn:

$$dt = \frac{\tau_{orb}}{2\,\pi}\frac{(1-e^2)^{\frac{3}{2}}}{(1+e\ Cos\ \nu)^2}d\nu$$

which integrates to

$$t = t_p + \frac{\tau_{orb}}{2\,\pi}\left\{2\,Tan^{-1}\left[\frac{(1-e^2)^{1/2}}{1+e}\ Tan\frac{\nu}{2}\right] - \frac{(1-e^2)^{1/2}e\ Sin\ \nu}{(1+e\ Cos\ \nu)}\right\} + \tau_{orb}\cdot IntegerPart\left[\frac{\nu}{180°}\right]$$

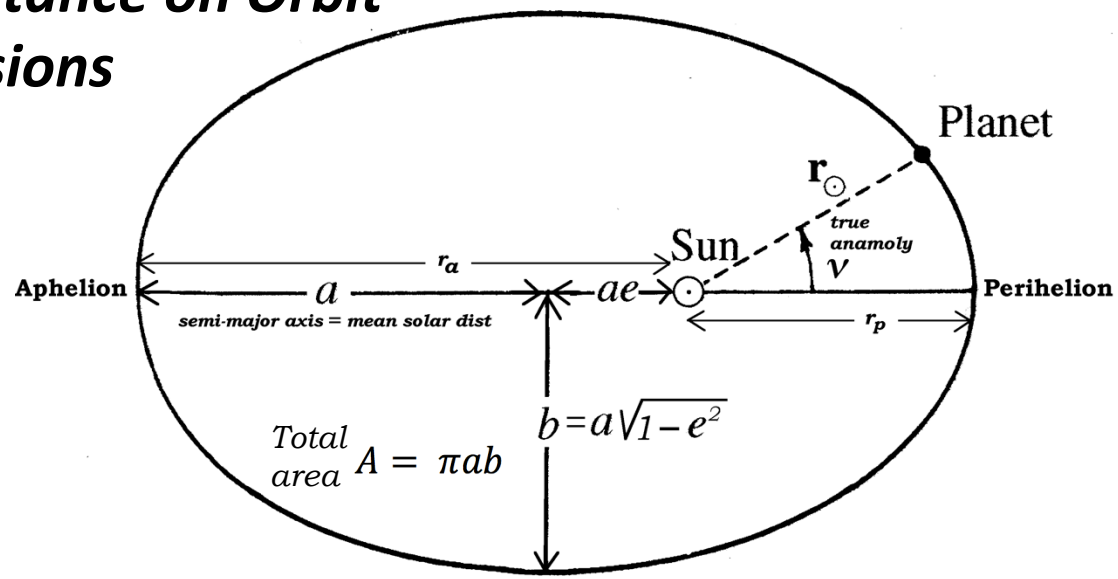
where t_p is the time of perihelion.

Then with $\nu \rightarrow L_s - L_{sp}$, where L_{sp} is the planetocentric solar longitude at perihelion, the time of season is specified. (Beebe, Suggs, and Little, 1986.) *However . . .*

**Time*-mean distance $\frac{1}{\tau_{orb}}\int_0^{\tau_{orb}} r_\odot\, dt = a\left(1+\frac{1}{2}e^2\right)$

Calculation of Time and Distance on Orbit via Mean Element Expansions

There are *many* other ways of solving the Kepler problem which can also be applied to the calculation of planetary seasons. But in fact, both *e* and *Lsp* change slowly with time, and if their secular variation is admitted, the two-body solution is no longer closed.



Another approach utilizes the orbital ***mean anomaly*** $M = [(t_0 - t_p) + (t - t_0)]\, n_{anom}$ where $t_p = t_0 - M(t_0)/n_{anom}$ is the indicated time of perihelion passage and n_{anom} the mean rate of motion corresponding to the anomalistic orbit period $\tau_{anom} = 360°/n_{anom}$.

Now the Fourier-Bessel series for the "equation of center" in terms of *M* and *e* is (e.g. to sixth order) given as

$$\begin{aligned}(\nu - M) &= (2e - \tfrac{1}{4}\, e^3 + \tfrac{5}{96}\, e^5) \sin M \\ &+ (\tfrac{5}{4}\, e^2 - \tfrac{11}{24}\, e^4 + \tfrac{17}{192}\, e^6) \sin 2M \\ &+ (\tfrac{13}{12}\, e^3 - \tfrac{43}{63}\, e^5) \sin 3M + (\tfrac{103}{96}\, e^4 - \tfrac{451}{480}\, e^6) \sin 4M \\ &+ (\tfrac{1097}{960}\, e^5) \sin 5M + (\tfrac{1223}{960}\, e^6) \sin 6M + O(e^7).\end{aligned}$$

(convergent for $e < 0.66274$)

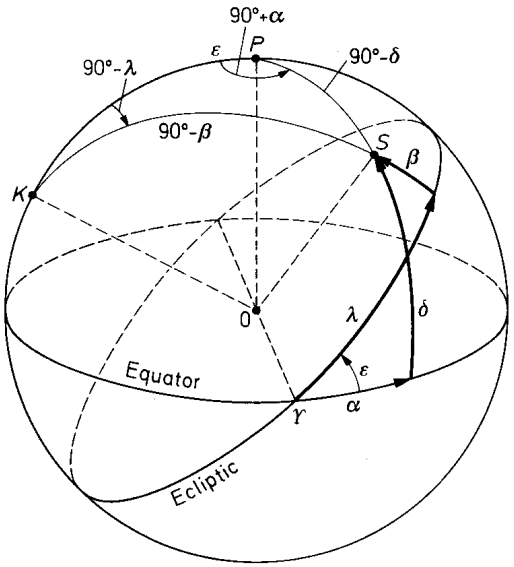
Then with $\nu \rightarrow L_s - L_{sp}$ the seasonal timing reduces to simple arithmetic!

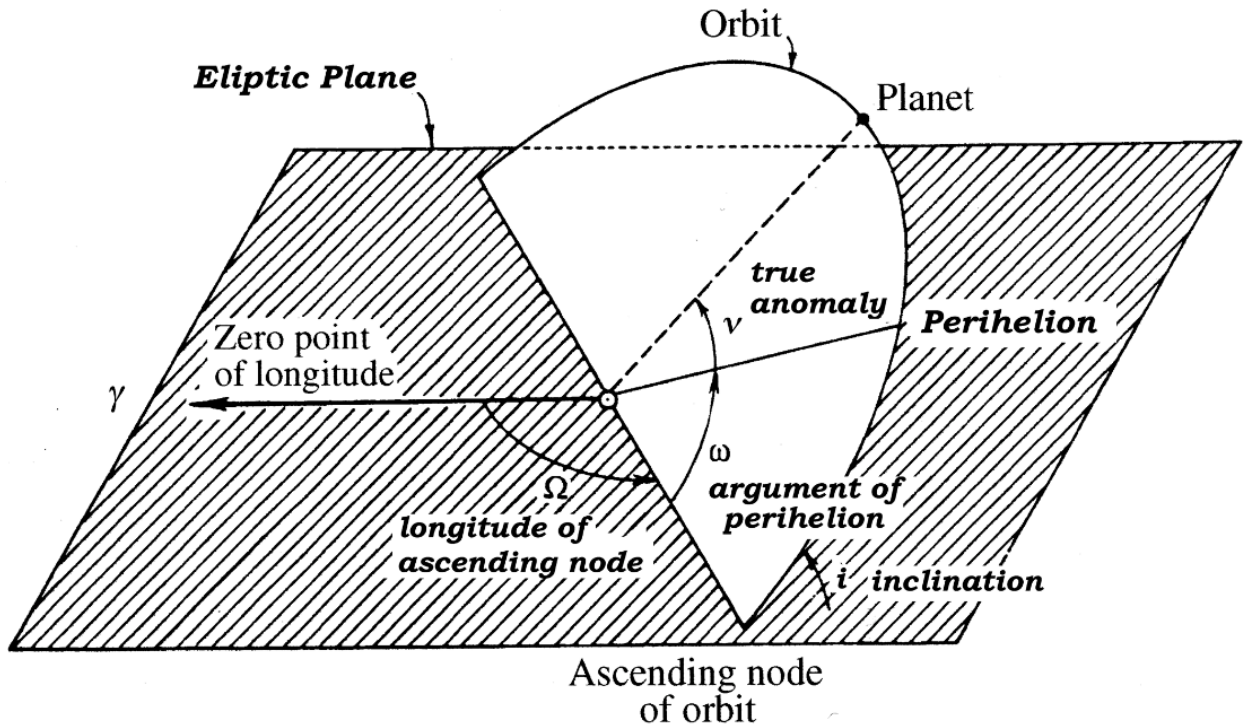
For more details, see Allison and McEwen (2000).

'Speed and direction,' she repeated, 'it's everything . . . it tells you everything you need to know . . . if you can find out.'

– Carol Hill, *The Eleven Million Mile High Dancer*

Orbits and Elements





In general, six elements are needed to describe an orbit in space. And several different choices are possible. *a* and *e* describe the size and shape of the orbit. *I*, Ω, and ω describe its orientation. A sixth element is needed to set the time on orbit, such as the mean anomaly *M* specifying the mean motion with respect to perihelion.

Mean Element Representations of Planetary Orbits

For "short-term" (centennial/millenial) applications, recommend

Astron. Astrophys. (282, 663–683; 1994)

Numerical expressions for precession formulae and mean elements for the Moon and the planets

ASTRONOMY AND ASTROPHYSICS

J.L. Simon[1], P. Bretagnon[1], J. Chapront[1], M. Chapront-Touzé[1], G. Francou[1], and J. Laskar[2]

[1] Bureau des Longitudes, URA 707, 77 Avenue Denfert-Rochereau, F-75014 Paris, France
[2] Bureau des Longitudes, JE 337, 3 Rue Mazarine, F-75006, Paris, France

Provides polynomial expressions for classical and elliptical mean elements of the eight major planets valid over ±6000 yr, for both the fixed (J2000) ecliptic and the dynamical ecliptic and equinox of date, along with harmonic expressions for the major planetary perturbations.

5.8.4. Mean elements of Mars

fixed (J2000) equinox and ecliptic

$$a = 1.5236793419 + 3\,10^{-10}t\,,$$

$$\lambda = 355^\circ.43299958 + 689050774''.93988t + 0''.94264t^2 - 0''.01043t^3\,, \qquad (\lambda \equiv L - \tilde{\omega})$$

$$e = 0.0934006477 + 0.0009048438t - 80641\,10^{-10}t^2 - 2519\,10^{-10}t^3 + 124\,10^{-10}t^4 - 10\,10^{-10}t^5\,,$$

$$\varpi = 336^\circ.06023395 + 15980''.45908t - 62''.32800t^2 + 1''.86464t^3 - 0''.04603t^4 - 0''.00164t^5\,,$$

$$i = 1^\circ.84972648 - 293''.31722t - 8''.11830t^2 - 0''.10326t^3 - 0''.00153t^4 + 0''.00048t^5\,,$$

$$\Omega = 49^\circ.55809321 - 10620''.90088t - 230''.57416t^2 - 7''.06942t^3 - 0''.68920t^4 - 0''.05829t^5\,,$$

Mean Element Representations of Planetary Orbits

For *long* term (~ 10 million yr) applications, recommend

Icarus (88, 266–291; 1998)

The Chaotic Motion of the Solar System: A Numerical Estimate of the Size of the Chaotic Zones

J. LASKAR

SCMC du Bureau des Longitudes, UA 707 du CNRS, 77 Avenue Denfert-Rochereau, F75014 Paris, France

Provides tables of the ten largest terms for the amplitudes, phases, and frequencies of the complex elliptical element representation of the major planet orbits, for multi-million yr time scales. Using complex variable arithmetic, these can be converted to i, Ω, e, ω as needed paleoclimate studies. (The paper also verifies the robust chaotic nature of the Solar System!)

The *long* (Myr) term evolution of planetary obliquity and Lsp can then be computed using the analytic solution technique developed for Mars by

J. Geophys. Res. (79, 3375–3386; 1975)

Climatic Variations on Mars
1. Astronomical Theory of Insolation

WILLIAM R. WARD[1]

Division of Geological and Planetary Sciences, California Institute of Technology Pasadena, California 91109

But beware of the factor 2 change in the complex variable definitions!

IAU recommended (α , δ , W) coordinates for planetary spin poles are published approximately every three years in *Celestial Mechanics & Dynamical Astronomy.*

Table 1 Recommended values for the direction of the north pole of rotation and the prime meridian of the Sun and planets

α_0, δ_0 are ICRF equatorial coordinates at epoch J2000.0.
Approximate coordinates of the north pole of the invariable plane are $\alpha_0 = 273°.85$, $\delta_0 =$
T = interval in Julian centuries (of 36525 days) from the standard epoch
d = interval in days from the standard epoch
The standard epoch is JD 2451545.0, i.e. 2000 January 1 12 hours TDB

Sun

$\alpha_0 = 286°.13$
$\delta_0 = 63°.87$
$W = 84°.176 + 14°.1844000d$ (a)

Mercury

$\alpha_0 = 281.0097 - 0.0328T$
$\delta_0 = 61.4143 - 0.0049T$
$W = 329.5469 + 6.1385025d$
$+0°.00993822 \sin(M1)$
$-0°.00104581 \sin(M2)$
$-0°.00010280 \sin(M3)$
$-0°.00002364 \sin(M4)$
$-0°.00000532 \sin(M5)$

where

$M1 = 174°.791086 + 4°.092335d$
$M2 = 349°.582171 + 8°.184670d$
$M3 = 164°.373257 + 12°.277005d$
$M4 = 339°.164343 + 16°.369340d$
$M5 = 153°.955429 + 20°.461675d$ (b)

Mercury spin pole coordinates now incorporate non-zero obliquity and librations by Margot (2009).

Venus

$\alpha_0 = 272.76$
$\delta_0 = 67.16$
$W = 160.20 - 1.4813688d$ (c)

Earth

$\alpha_0 = 0.00 - 0.641T$
$\delta_0 = 90.00 - 0.557T$
$W = 190.147 + 360.9856235d$

Mars

$\alpha_0 = 317.68143 - 0.1061T$
$\delta_0 = 52.88650 - 0.0609T$
$W = 176.630 + 350.89198226d$ (d)

Mars pole vector and prime meridian will be revised with lander radio tracking by Kuchynka *et al.* (2014)

Jupiter

$\alpha_0 = 268.056595 - 0.006499T + 0°.000117 \sin Ja + 0°.000938 \sin Jb$
$+ 0.001432 \sin Jc + 0.000030 \sin Jd + 0.002150 \sin Je$
$\delta_0 = 64.495303 + 0.002413T + 0.000050 \cos Ja + 0.000404 \cos Jb$
$+ 0.000617 \cos Jc - 0.000013 \cos Jd + 0.000926 \cos Je$
$W = 284.95 + 870.5360000d$ (e)

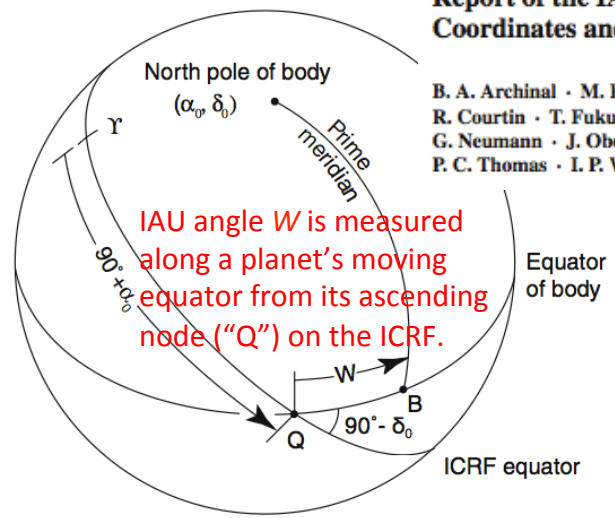
where $Ja = 99°.360714 + 4850°.4046T$, $Jb = 175°.895369 + 1191°.9605T$,
$Jc = 300°.323162 + 262°.5475T$, $Jd = 114°.012305 + 6070°.2476T$,
$Je = 49°.511251 + 64°.3000T$

Celest Mech Dyn Astr
DOI 10.1007/s10569-010-9320-4

SPECIAL REPORT

Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2009

B. A. Archinal · M. F. A'Hearn · E. Bowell · A. Conrad · G. J. Consolmagno · R. Courtin · T. Fukushima · D. Hestroffer · J. L. Hilton · G. A. Krasinsky · G. Neumann · J. Oberst · P. K. Seidelmann · P. Stooke · D. J. Tholen · P. C. Thomas · I. P. Williams



IAU angle W is measured along a planet's moving equator from its ascending node ("Q") on the ICRF.

Conversion to planetocentric angles requires specification of the planetary orbits.

Table 1 continued

Saturn

$\alpha_0 = 40.589 - 0.036T$
$\delta_0 = 83.537 - 0.004T$
$W = 38.90 + 810.7939024d$ (e)

Saturn has problems (poorly constrained internal rotation)

Uranus

$\alpha_0 = 257.311$
$\delta_0 = -15.175$
$W = 203.81 - 501.1600928d$ (e)

Pluto (now listed with dwarf planets)

Neptune

$\alpha_0 = 299.36 + 0.70 \sin N$
$\delta_0 = 43.46 - 0.51 \cos N$
$W = 253.18 + 536.3128492d - 0.48 \sin N$ (e)
$N = 357.85 + 52.316T$

$\alpha = 132°.993$
$\delta_0 = -6°.163$
$W = 237°.305 + 56°.3625225\ d$

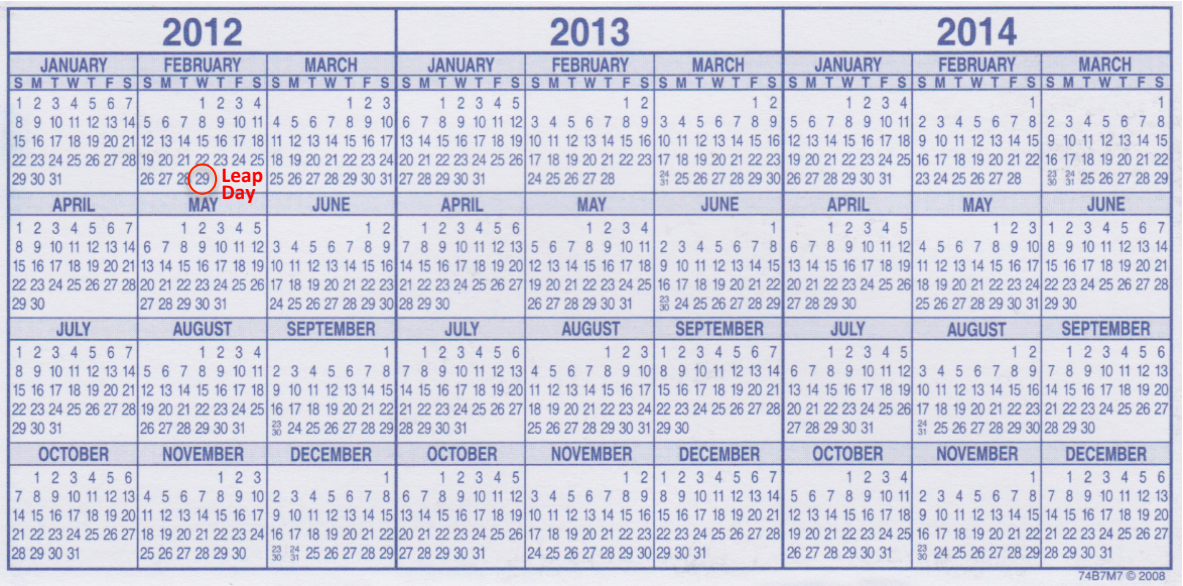
(a) The equation W for the Sun is now corrected for light travel time and removing the aberration correction. See the Appendix in Seidelmann et al. (2007)
(b) The 20° meridian is defined by the crater Hun Kal
(c) The 0° meridian is defined by the central peak in the crater Ariadne
(d) The 0° meridian is defined by the crater Airy-0
(e) The equations for W for Jupiter, Saturn, Uranus and Neptune refer to the rotation of their magnetic fields (System III). On Jupiter, System I ($W_I = 67°.1 + 877°.900d$) refers to the mean atmospheric equatorial rotation; System II ($W_{II} = 43°.3 + 870°.270d$) refers to the mean atmospheric rotation north of the south component of the north equatorial belt, and south of the north component of the south equatorial belt

Five Parameters Defining Planetary Solar Time and Seasons

	Obliquity Eqtr-to-Orbit ε	Eccentricity Solar Orbit e	Planetocentric Solar Lon @ Perihelion L_{sp}	Solar Rotation Period d_{sol}	Tropical Orbit Period T_{trop}
Mercury	0°.04	0.206	8°.0	$175^{d}.94$	$87^{d}.969$
Venus	2°.64	0.007	253°.8	$-116^{d}.75$	$224^{d}.700$
Earth	23°.44	0.017	282°.9	$24^{h}00^{m}00^{s}.000$	$365^{d}.2422$
Mars	25°.19	0.093	251°.0	$24^{h}39^{m}35^{s}.244$	$686^{d}.9726$
Jupiter	3°.13	0.048	57°.1	$9^{h}55^{m}35^{s}.244$	$11^{Jy}.863$
Saturn	26°.73	0.056	279°.5	$10^{h}31^{m}58^{s}$?	$29^{Jy}.457$
Uranus	82°.23	0.046	185°.5	$-17^{h}14^{m}22^{s}$	$84^{Jy}.020$
Neptune	27°.85	0.009	2°.2	$16^{h}06^{m}37^{s}$	$164^{Jy}.772$
Pluto	57°.46	0.249	184°.5	$-153^{h}17^{m}$	$248^{Jy}.368$
Eris	78°	0.442	?	?	$558^{Jy}.7$

From *Les Tres Riches Heures Du Duc de Berry*, painted by the Limbourg brothers, c.1416.

The Gregorian Calendar



2012			2013			2014		
JANUARY	FEBRUARY	MARCH	JANUARY	FEBRUARY	MARCH	JANUARY	FEBRUARY	MARCH
S M T W T F S	S M T W T F S	S M T W T F S	S M T W T F S	S M T W T F S	S M T W T F S	S M T W T F S	S M T W T F S	S M T W T F S
1 2 3 4 5 6 7	1 2 3 4	1 2 3	1 2 3 4 5	1 2	1 2	1 2 3 4	1	1
8 9 10 11 12 13 14	5 6 7 8 9 10 11	4 5 6 7 8 9 10	6 7 8 9 10 11 12	3 4 5 6 7 8 9	3 4 5 6 7 8 9	5 6 7 8 9 10 11	2 3 4 5 6 7 8	2 3 4 5 6 7 8
15 16 17 18 19 20 21	12 13 14 15 16 17 18	11 12 13 14 15 16 17	13 14 15 16 17 18 19	10 11 12 13 14 15 16	10 11 12 13 14 15 16	12 13 14 15 16 17 18	9 10 11 12 13 14 15	9 10 11 12 13 14 15
22 23 24 25 26 27 28	19 20 21 22 23 24 25	18 19 20 21 22 23 24	20 21 22 23 24 25 26	17 18 19 20 21 22 23	17 18 19 20 21 22 23	19 20 21 22 23 24 25	16 17 18 19 20 21 22	16 17 18 19 20 21 22
29 30 31	26 27 28 29 (Leap Day)	25 26 27 28 29 30 31	27 28 29 30 31	24 25 26 27 28	24 31 25 26 27 28 29 30	26 27 28 29 30 31	23 24 25 26 27 28	23 30 24 31 25 26 27 28 29
APRIL	MAY	JUNE	APRIL	MAY	JUNE	APRIL	MAY	JUNE
1 2 3 4 5 6 7	1 2 3 4 5	1 2	1 2 3 4 5 6	1 2 3 4	1	1 2 3 4 5	1 2 3	1 2 3 4 5 6 7
8 9 10 11 12 13 14	6 7 8 9 10 11 12	3 4 5 6 7 8 9	7 8 9 10 11 12 13	5 6 7 8 9 10 11	2 3 4 5 6 7 8	6 7 8 9 10 11 12	4 5 6 7 8 9 10	8 9 10 11 12 13 14
15 16 17 18 19 20 21	13 14 15 16 17 18 19	10 11 12 13 14 15 16	14 15 16 17 18 19 20	12 13 14 15 16 17 18	9 10 11 12 13 14 15	13 14 15 16 17 18 19	11 12 13 14 15 16 17	15 16 17 18 19 20 21
22 23 24 25 26 27 28	20 21 22 23 24 25 26	17 18 19 20 21 22 23	21 22 23 24 25 26 27	19 20 21 22 23 24 25	16 17 18 19 20 21 22	20 21 22 23 24 25 26	18 19 20 21 22 23 24	22 23 24 25 26 27 28
29 30	27 28 29 30 31	24 25 26 27 28 29 30	28 29 30	26 27 28 29 30 31	23 30 24 25 26 27 28 29	27 28 29 30	25 26 27 28 29 30 31	29 30
JULY	AUGUST	SEPTEMBER	JULY	AUGUST	SEPTEMBER	JULY	AUGUST	SEPTEMBER
1 2 3 4 5 6 7	1 2 3 4	1	1 2 3 4 5 6	1 2 3	1 2 3 4 5 6 7	1 2 3 4 5	1 2	1 2 3 4 5 6
8 9 10 11 12 13 14	5 6 7 8 9 10 11	2 3 4 5 6 7 8	7 8 9 10 11 12 13	4 5 6 7 8 9 10	8 9 10 11 12 13 14	6 7 8 9 10 11 12	3 4 5 6 7 8 9	7 8 9 10 11 12 13
15 16 17 18 19 20 21	12 13 14 15 16 17 18	9 10 11 12 13 14 15	14 15 16 17 18 19 20	11 12 13 14 15 16 17	15 16 17 18 19 20 21	13 14 15 16 17 18 19	10 11 12 13 14 15 16	14 15 16 17 18 19 20
22 23 24 25 26 27 28	19 20 21 22 23 24 25	16 17 18 19 20 21 22	21 22 23 24 25 26 27	18 19 20 21 22 23 24	22 23 24 25 26 27 28	20 21 22 23 24 25 26	17 18 19 20 21 22 23	21 22 23 24 25 26 27
29 30 31	26 27 28 29 30 31	23 30 24 25 26 27 28 29	28 29 30 31	25 26 27 28 29 30 31	29 30	27 28 29 30 31	24 31 25 26 27 28 29 30	28 29 30
OCTOBER	NOVEMBER	DECEMBER	OCTOBER	NOVEMBER	DECEMBER	OCTOBER	NOVEMBER	DECEMBER
1 2 3 4 5 6	1 2 3	1	1 2 3 4 5	1 2	1 2 3 4 5 6 7	1 2 3 4	1	1 2 3 4 5 6
7 8 9 10 11 12 13	4 5 6 7 8 9 10	2 3 4 5 6 7 8	6 7 8 9 10 11 12	3 4 5 6 7 8 9	8 9 10 11 12 13 14	5 6 7 8 9 10 11	2 3 4 5 6 7 8	7 8 9 10 11 12 13
14 15 16 17 18 19 20	11 12 13 14 15 16 17	9 10 11 12 13 14 15	13 14 15 16 17 18 19	10 11 12 13 14 15 16	15 16 17 18 19 20 21	12 13 14 15 16 17 18	9 10 11 12 13 14 15	14 15 16 17 18 19 20
21 22 23 24 25 26 27	18 19 20 21 22 23 24	16 17 18 19 20 21 22	20 21 22 23 24 25 26	17 18 19 20 21 22 23	22 23 24 25 26 27 28	19 20 21 22 23 24 25	16 17 18 19 20 21 22	21 22 23 24 25 26 27
28 29 30 31	25 26 27 28 29 30	23 30 24 31 25 26 27 28 29	27 28 29 30 31	24 25 26 27 28 29 30	29 30 31	26 27 28 29 30 31	23 30 24 25 26 27 28 29	28 29 30 31

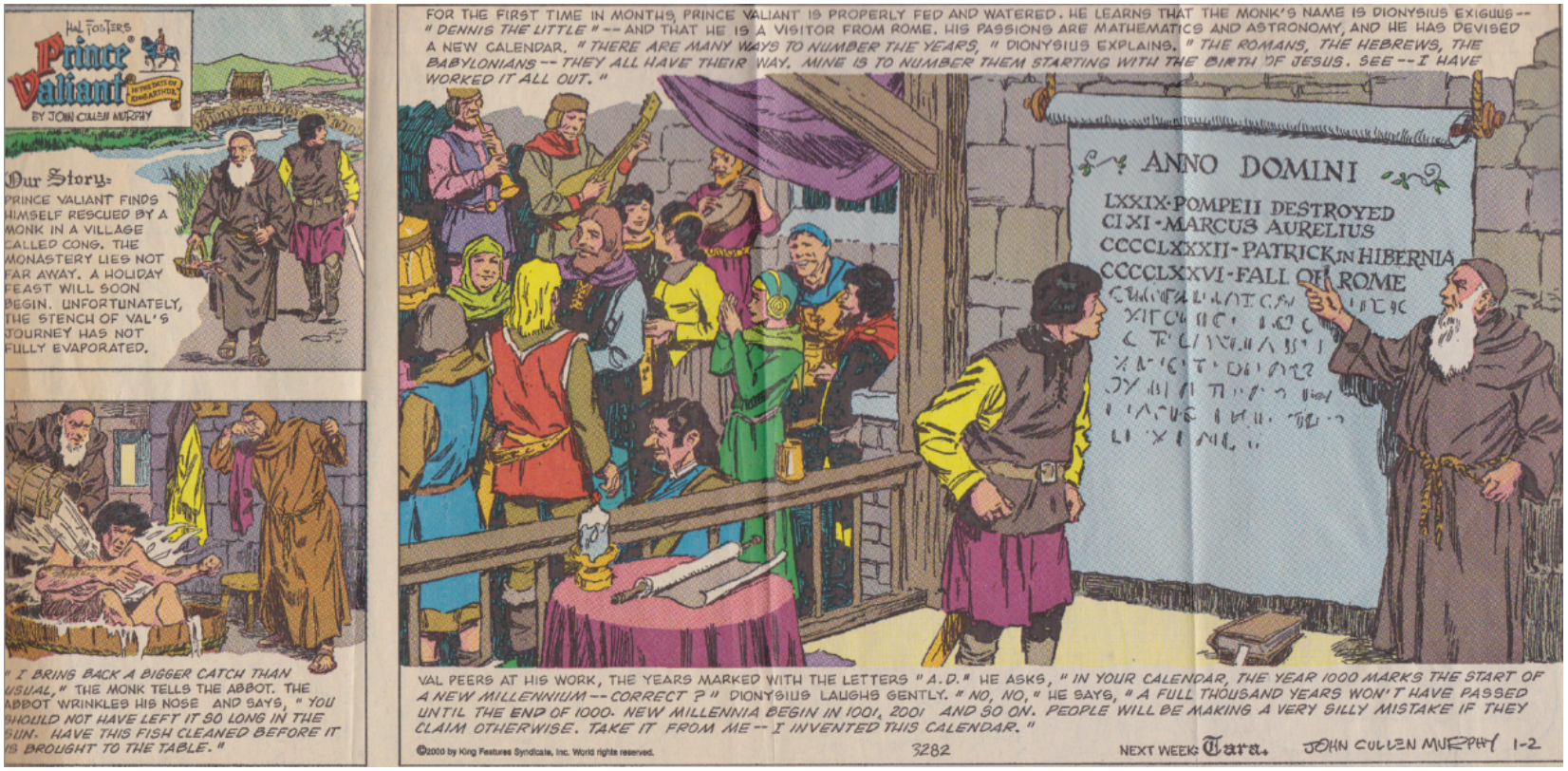
74B7M7 © 2008

A modification of the 12 month (average 365.25 day) Julian Calendar by Pope Gregory XIII (as invented by physician-astronomer Aloysius Lilius, also advised by Christopher Clavius). Established (in Catholic countries) on the day following 1582 Oct 4 (Julian), designated 1582 Oct 15, thereby resetting the vernal equinox to March 20 / 21.

Every year exactly divisible by 4 is a leap year, *except* for centurial years which are not exactly divisible by 400. (2000 is a leap year, 1900 and 2100 are not.) The resulting average calendar year length of 365 + 97/400 = 365.242500 days closely approximates the current tropical year of 365.24219 days.

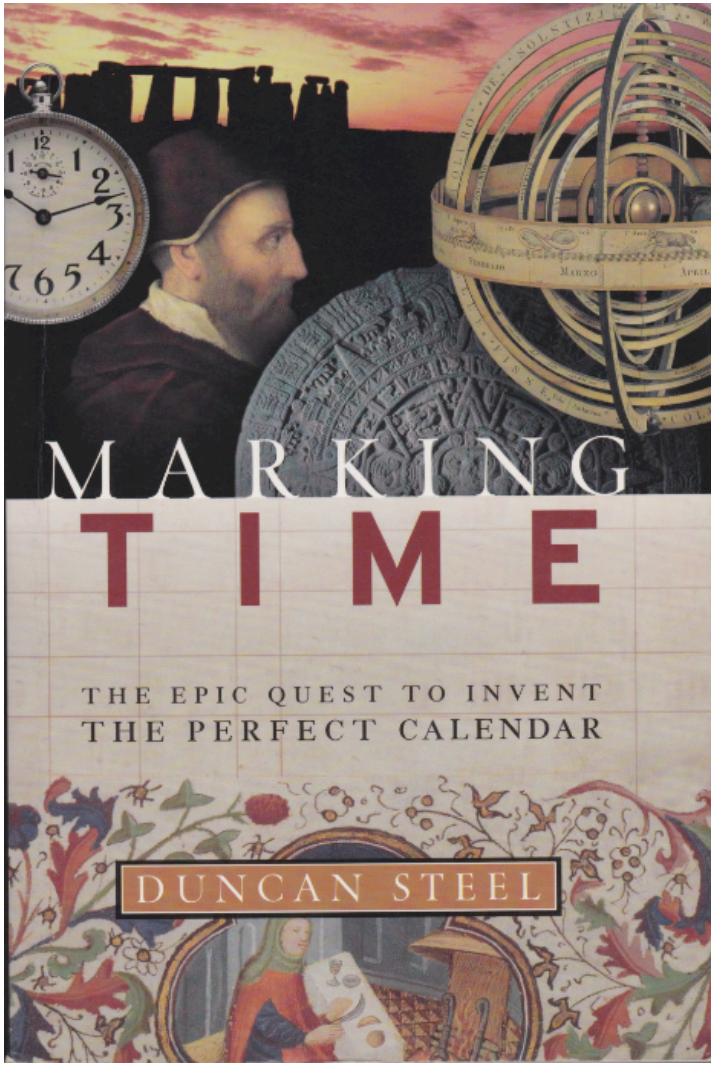
However, Duncan Steel argues that the unstated intent of Pop Gregory's reform was to match the Vernal Equinox year of 365.2524 d, to stabilize the dating of Easter.

Year Number Epochs

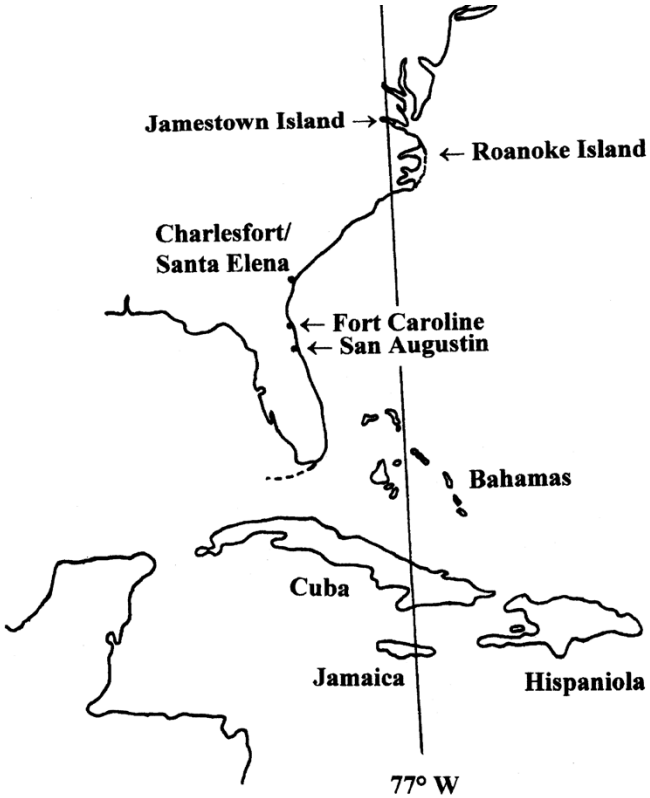


The year number epoch for the ("Anno Domini") Christian calendar was established by the 6th-century scholar Dionysius Exiguus. (1 A.D. is no longer regarded as an accurate birth date for Jesus.) In the A.D./B.C. (or secular C.E./B.C.E.) designation, there is no year zero, and therefore the "new millennium" really began on January 1, 2001.

However, astronomers often define a year 0 = 1 B.C., with prior years then designated with negative numbers. The lunisolar Hebrew calendar is dated from the "Era of Creation" (Era Mundi) , dated -3760 Oct 7. The Islamic calendar dates from the flight of Mohammed on +622 July 16. The old Roman calendar dated from –752.



One of the better, technically informed books on the history of the calendar, written by a research astronomer, with many amazing stories.

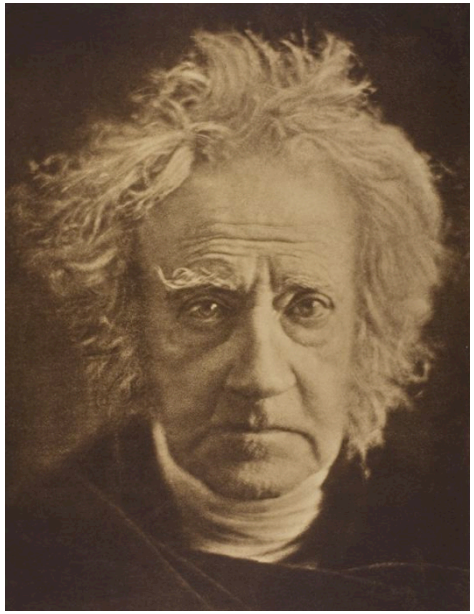


The date and time of the Earth's spring equinox varies from year to year. But the date itself could be closely fixed if timed with respect to a prime meridian within a narrow range of longitudes centered near 77°W – "God's longitude!"

"… the English settlement of Old Virginia stemmed not from a simple desire for more land, for gold, for trade, or any such obvious thing. Their persistence and repeated attempts around 1584–1590 and again in 1602, and then 1606 onward, were driven by an imperative to grab land on the seventy-seventh meridian in order to be able to introduce a novel calendar which would be demonstrably superior in terms of mathematics, astronomy, and religious veracity to the hated product of the Catholic Church."

–Duncan Steel

Joseph Scaliger 1540 – 1609



John Herschel 1792 – 1871

Timing astronomical records/ephemerides:

Julian Day Chronology

As proposed by astronomer John Herschel (son of Sir William), a decimal count of Earth solar days elapsed since the start of the "Julian period" devised by chronologist Joseph Scalinger – on Greenwich mean ***noon***, January 1, 4713 BC. = – 4712 Jan 1.5. (This the coincident start of the 28 year solar/dominical cycle, the 19 year lunar/Metonic cyle, and the 15 year indiction/tax cycle!)

Today and Now (2014 Jan 15, 18:00 UTC) is JD 2456673.3

***The J2000.0 Epoch* = 2000 Jan 1.5 = JD 2451545.0**

The Battle of Hastings 1066 Oct 14 = JD 2110701

Modified Julian Date

As used by some space tracking centers and timing services –

MJD = JD – 2400000.5 provides a shorter number string and a reference to midnight instead of noon.

MJD 0.0 = 1858 Nov 17, 00:00 UT

Julian Day (JD) numbers are tabulated in each edition of *The Astronomical Almanac* and can also be computed from any of several efficient algorithms, for example:

Hatcher, D.A. 1984. Simple formulae for Julian Day numbers and calendar dates. *Q. J. Roy. Astron. Soc.* 25, 53–55.

Once determined, the Julian Day number provides a ready means to evaluate the day of the week, for any date in history, e.g. as

DayWk # = JD – IntegerPart[(JD +1)/7] +2

with Sunday =1, etc.

For the specification of long-term rates or trends, astronomers also use a rationalized **Julian Year = exactly 365.25 days**, sometimes using the centennial time argument

$$T = (JD - 2451545.0)/36525$$

or the millenial argument

$$t = (JD - 2451545.0)/365250.$$

OF DAY COMMENCING AT GREENWICH NOON ON:

Year	Jan. 0	Feb. 0	Mar. 0	Apr. 0	May 0	June 0	July 0	Aug. 0	Sept. 0	Oct. 0	Nov. 0	Dec. 0
2000	245 1544	1575	1604	1635	1665	1696	1726	1757	1788	1818	1849	1879
2001	1910	1941	1969	2000	2030	2061	2091	2122	2153	2183	2214	2244
2002	2275	2306	2334	2365	2395	2426	2456	2487	2518	2548	2579	2609
2003	2640	2671	2699	2730	2760	2791	2821	2852	2883	2913	2944	2974
2004	3005	3036	3065	3096	3126	3157	3187	3218	3249	3279	3310	3340
2005	245 3371	3402	3430	3461	3491	3522	3552	3583	3614	3644	3675	3705
2006	3736	3767	3795	3826	3856	3887	3917	3948	3979	4009	4040	4070
2007	4101	4132	4160	4191	4221	4252	4282	4313	4344	4374	4405	4435
2008	4466	4497	4526	4557	4587	4618	4648	4679	4710	4740	4771	4801
2009	4832	4863	4891	4922	4952	4983	5013	5044	5075	5105	5136	5166
2010	245 5197	5228	5256	5287	5317	5348	5378	5409	5440	5470	5501	5531
2011	5562	5593	5621	5652	5682	5713	5743	5774	5805	5835	5866	5896
2012	5927	5958	5987	6018	6048	6079	6109	6140	6171	6201	6232	6262
2013	6293	6324	6352	6383	6413	6444	6474	6505	6536	6566	6597	6627
2014	6658	6689	6717	6748	6778	6809	6839	6870	6901	6931	6962	6992
2015	245 7023	7054	7082	7113	7143	7174	7204	7235	7266	7296	7327	7357
2016	7388	7419	7448	7479	7509	7540	7570	7601	7632	7662	7693	7723
2017	7754	7785	7813	7844	7874	7905	7935	7966	7997	8027	8058	8088
2018	8119	8150	8178	8209	8239	8270	8300	8331	8362	8392	8423	8453
2019	8484	8515	8543	8574	8604	8635	8665	8696	8727	8757	8788	8818
2020	245 8849	8880	8909	8940	8970	9001	9031	9062	9093	9123	9154	9184
2021	9215	9246	9274	9305	9335	9366	9396	9427	9458	9488	9519	9549
2022	9580	9611	9639	9670	9700	9731	9761	9792	9823	9853	9884	9914
2023	245 9945	9976	*0004	*0035	*0065	*0096	*0126	*0157	*0188	*0218	*0249	*0279
2024	246 0310	0341	0370	0401	0431	0462	0492	0523	0554	0584	0615	0645
2025	246 0676	0707	0735	0766	0796	0827	0857	0888	0919	0949	0980	1010
2026	1041	1072	1100	1131	1161	1192	1222	1253	1284	1314	1345	1375
2027	1406	1437	1465	1496	1526	1557	1587	1618	1649	1679	1710	1740
2028	1771	1802	1831	1862	1892	1923	1953	1984	2015	2045	2076	2106
2029	2137	2168	2196	2227	2257	2288	2318	2349	2380	2410	2441	2471
2030	246 2502	2533	2561	2592	2622	2653	2683	2714	2745	2775	2806	2836
2031	2867	2898	2926	2957	2987	3018	3048	3079	3110	3140	3171	3201
2032	3232	3263	3292	3323	3353	3384	3414	3445	3476	3506	3537	3567
2033	3598	3629	3657	3688	3718	3749	3779	3810	3841	3871	3902	3932
2034	3963	3994	4022	4053	4083	4114	4144	4175	4206	4236	4267	4297
2035	246 4328	4359	4387	4418	4448	4479	4509	4540	4571	4601	4632	4662
2036	4693	4724	4753	4784	4814	4845	4875	4906	4937	4967	4998	5028
2037	5059	5090	5118	5149	5179	5210	5240	5271	5302	5332	5363	5393
2038	5424	5455	5483	5514	5544	5575	5605	5636	5667	5697	5728	5758
2039	5789	5820	5848	5879	5909	5940	5970	6001	6032	6062	6093	6123
2040	246 6154	6185	6214	6245	6275	6306	6336	6367	6398	6428	6459	6489
2041	6520	6551	6579	6610	6640	6671	6701	6732	6763	6793	6824	6854
2042	6885	6916	6944	6975	7005	7036	7066	7097	7128	7158	7189	7219
2043	7250	7281	7309	7340	7370	7401	7431	7462	7493	7523	7554	7584
2044	7615	7646	7675	7706	7736	7767	7797	7828	7859	7889	7920	7950
2045	246 7981	8012	8040	8071	8101	8132	8162	8193	8224	8254	8285	8315
2046	8346	8377	8405	8436	8466	8497	8527	8558	8589	8619	8650	8680
2047	8711	8742	8770	8801	8831	8862	8892	8923	8954	8984	9015	9045
2048	9076	9107	9136	9167	9197	9228	9258	9289	9320	9350	9381	9411
2049	9442	9473	9501	9532	9562	9593	9623	9654	9685	9715	9746	9776
2050	246 9807	9838	9866	9897	9927	9958	9988	*0019	*0050	*0080	*0111	*0141

A Ridiculously Brief History of Time ("Universal" and Solar)

Following Resolution B1.8 of the XXIVth Assembly of the International Astronomical Union, and beginning 2003 Jan 1.0, Universal Time (UT1) is defined in terms of the "Earth Rotation Angle" θ between the "Terrestrial Intermediate Origin" (TIO) and the "Celestial Intermediate Origin" (CIO) as

$$\theta\,(\mathrm{UT1}) = 2\pi\,(0.7790572732640 + 1.00273781191135448 \times (\mathrm{Julian\ UT1date} - 2451545.0)),$$

this matching the older relationship between UT1 and **Greenwich Mean Sidereal Time** (GMST) at 2003.

GMST was itself defined so that its evaluation at 12:00:00 ("noon") would match the celestial right ascension of the …

fictitious mean sun: an imaginary body introduced to define **mean solar time**; essentially the name of a mathematical formula that defined mean solar time. This concept is no longer used in high precision work.

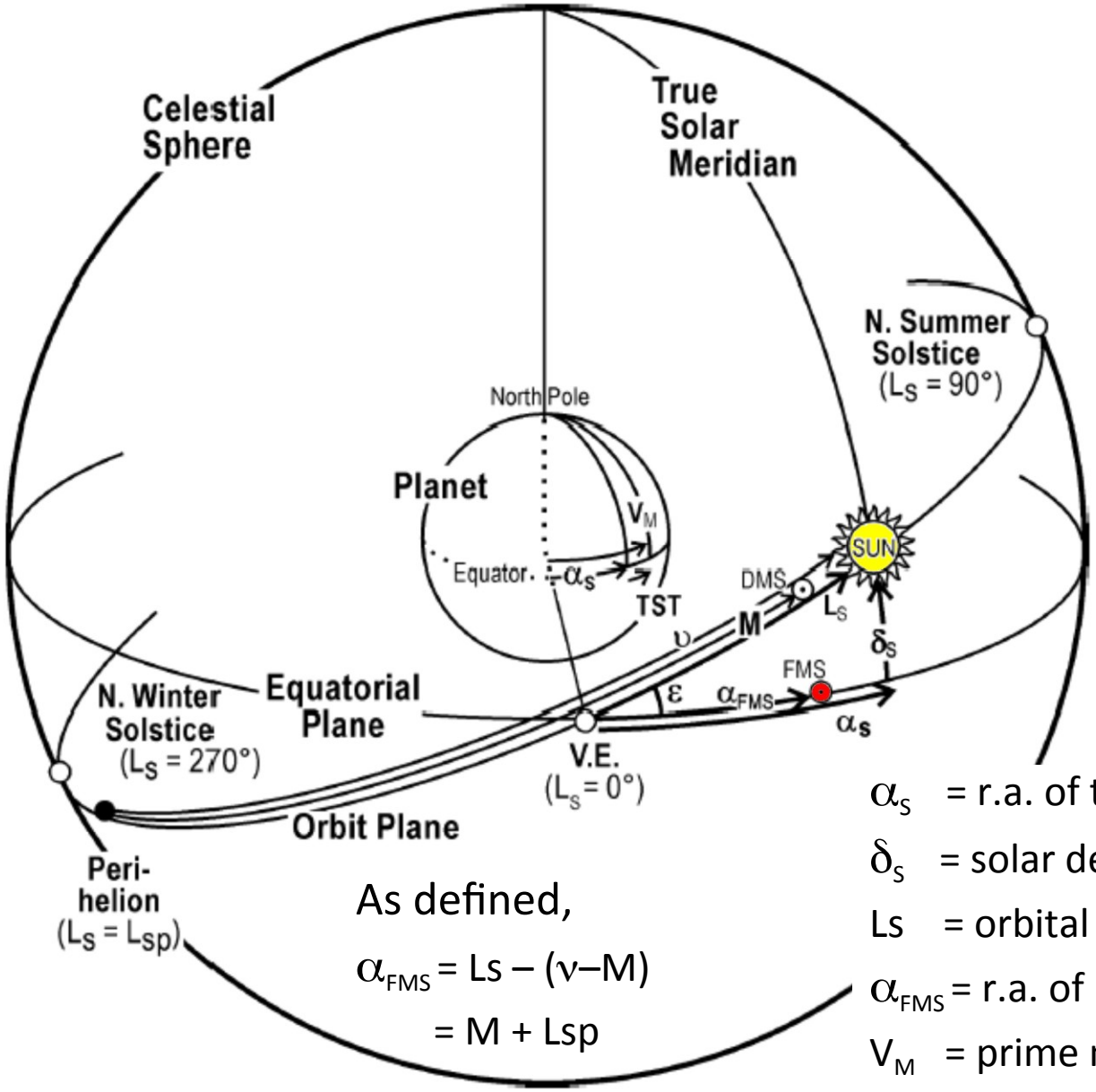
But this definition was excised from the AA glossary beginning in 2005!

However … the AA glossary (for 2013) *still* includes as a definition:

solar time, mean: a measure of time based conceptually on the *diurnal motion* of a fiducial point, called the fictitious mean Sun, with uniform motion along the *celestial equator*.

As noted by Fukushima (2001; Global rotation of the nonrotating origin. *Astron. J.* **122**, 482–486), "the NRO [defining new longitude origins for celestial and terrestrial reference frames in place of the classical equinoxes] can be considered to be equivalent to the departure point implicit in Newcomb's determination of the expression for the **right ascension of the mean Sun** (Newcomb, 1895; Aoki & Kinoshita, 1983)."

Planetocentric Solar Coordinates



As defined,

$\alpha_{FMS} = Ls - (\nu - M)$

$= M + Lsp$

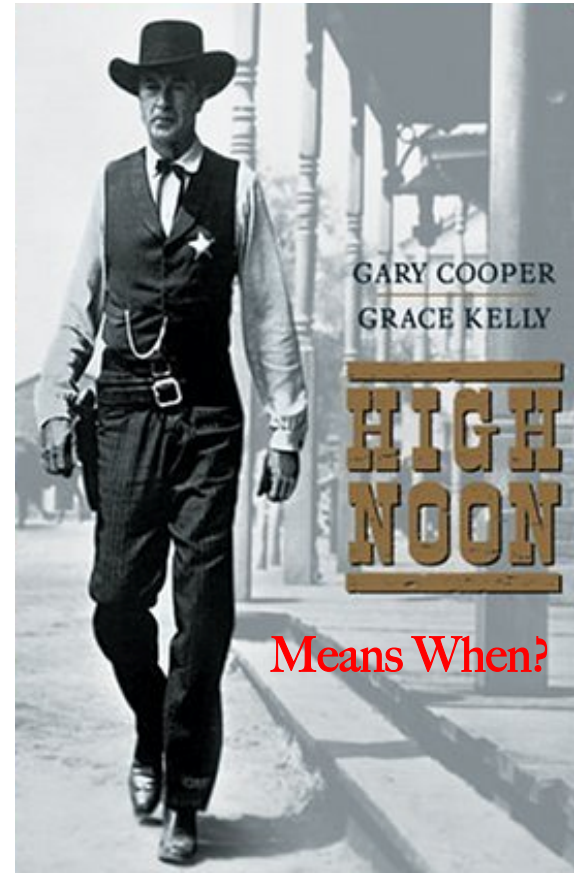
α_S = r.a. of the true sun

δ_S = solar declination

Ls = orbital solar longitude wrt V.E.

α_{FMS} = r.a. of Ficitious Mean Sun

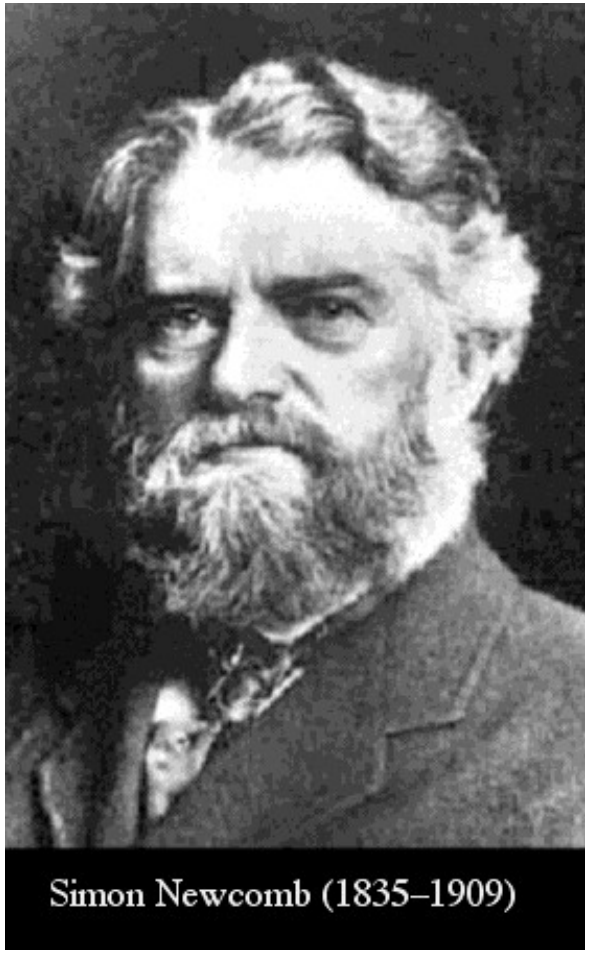
V_M = prime meridian hour angle



Marshall Kane on his way to a twelve o'clock appointment.

The Numerical Definition of Mean Solar Time

The historical antecedent to Greenwich Mean Time and modern Coordinated Universal Time (UTC).


Simon Newcomb (1835–1909)

Sir Arthur Conan Doyle's model for Sherlock Holmes's arch enemy – Prof. James Moriarty? (cf. Schaefer, 1993; *J. Brit. Astron. Assoc.* 103, 30.)

Mean Solar Time at Greenwich

$$= GHAQ - R_{sun} + 12\text{h},$$

where *GHAQ* is the Greenwich hour angle of the mean equinox of date and R_{sun} is the right ascension of the ***Fictitious Mean Sun***. As established by Simon Newcomb,

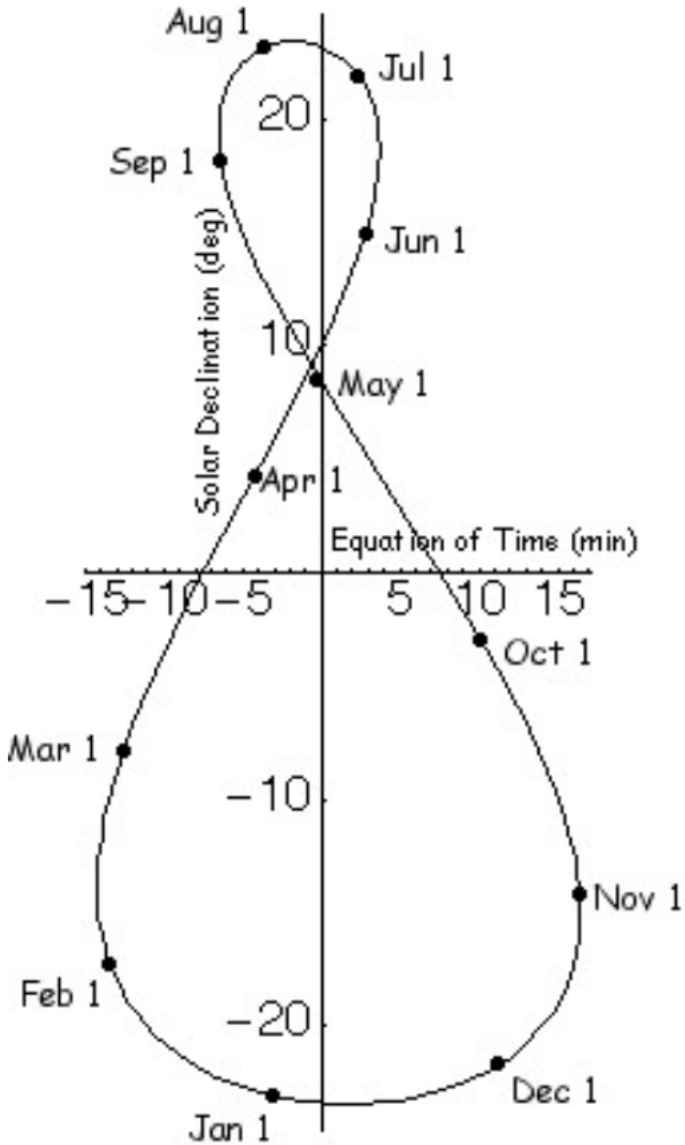
$$R_{sun} = 18^h38^m45^s.836 + 8640184^s.542T_{1900} + 0^s.0929T^2_{1900}$$

where T_{1900} is elapsed time in Julian centuries (36525 days) post-1900 January 0.5. As revised by Aoki & Kinoshita (1982),

$$R_{sun} = 18^h41^m50^s.54841 + 8640184^s.812866T_{UT1} + \\ + 0^s.093104\, T^2_{UT1} - 6.2 \times 10^{-6}T^3_{UT1}$$

where T_{UT1} is elapsed (UT) time post-2000 Jan 1.5.

The Analemma – a parametic plot of local true solar time – local mean solar time (the "equation of time") vs. solar declination.



The Equation of Time in *The New York Times!*

THE NEW YORK TIMES, TUESDAY, JANUARY 15, 2013 N D3

Equation of Time Solves Mystery of Gray Mornings

By JOHN O'NEIL

As the parent of teenage boys who have to be dragged out of bed on school days, I had been looking forward to earlier sunrises once the winter solstice was past. But early January mornings seemed darker than ever while at the same time, the sky was clearly lighter around 5 p.m.

It turned out that what I suspected was actually true — by Jan. 2, there were 12 more minutes of sunlight in the afternoons, but 3 fewer minutes in the morning. It also turned out that the reasons for it were complicated, as I discovered in a series of phone and e-mail conversations with Jay M. Pasachoff, a professor of astronomy at Williams College, and a former student of his, Joseph Gangestad, who received his Ph.D. in orbital mechanics from Purdue.

They pointed me to the Equation of Time, a grandly named formula relating to the fact that not all days are 24 hours, if you track noon by the position of the Sun instead of on a clock.

We've all seen a readout of the Equation of Time, Dr. Pasachoff said. It's that uneven figure 8 that can be found on globes in a deserted part of the Pacific, a shape known as an analemma.

If Earth's axis were perpendicular to its orbit instead of tilted, and if its orbit were a circle instead of an ellipse, the Sun would appear in the same spot in the sky each day and clocks and sundials would always match. Instead, they can be as much as 16 minutes apart, and that's where things get complicated.

As Earth moves toward winter solstice, you have "different things going on at the same time," Dr. Pasachoff said.

TONY CENICOLA/THE NEW YORK TIMES

FIGURE 8 An analemma shows the Sun's varying positions over a year.

Earth's tilt means that every day during the fall, the angle at which we view the Sun changes. It appears farther south and travels a shorter arc across the sky, affecting sunrise and sunset equally, and making the day shorter.

The changes in the solar time follow a different cycle. In the early 1600s, Kepler discovered that planets move faster at the part of their orbit that is closest to the sun, the perihelion. For Earth, perihelion comes a little after the winter solstice, so from November on, Earth is accelerating.

That increased speed means we reach the Sun's maximum a little earlier each day, which pushes solar noon backward against clock time. That shift is amplified because the Sun is traveling a little south each day, while clocks only count its east to west traverse.

Add it all together and you get sunrise and sunset times that are not symmetrical. In the weeks before the winter solstice, sunrise is being pushed later by both the changing angle of the Sun and the slowing of solar time. But sunset is being pushed in both directions — earlier by the Sun's angle and later by the change in solar time.

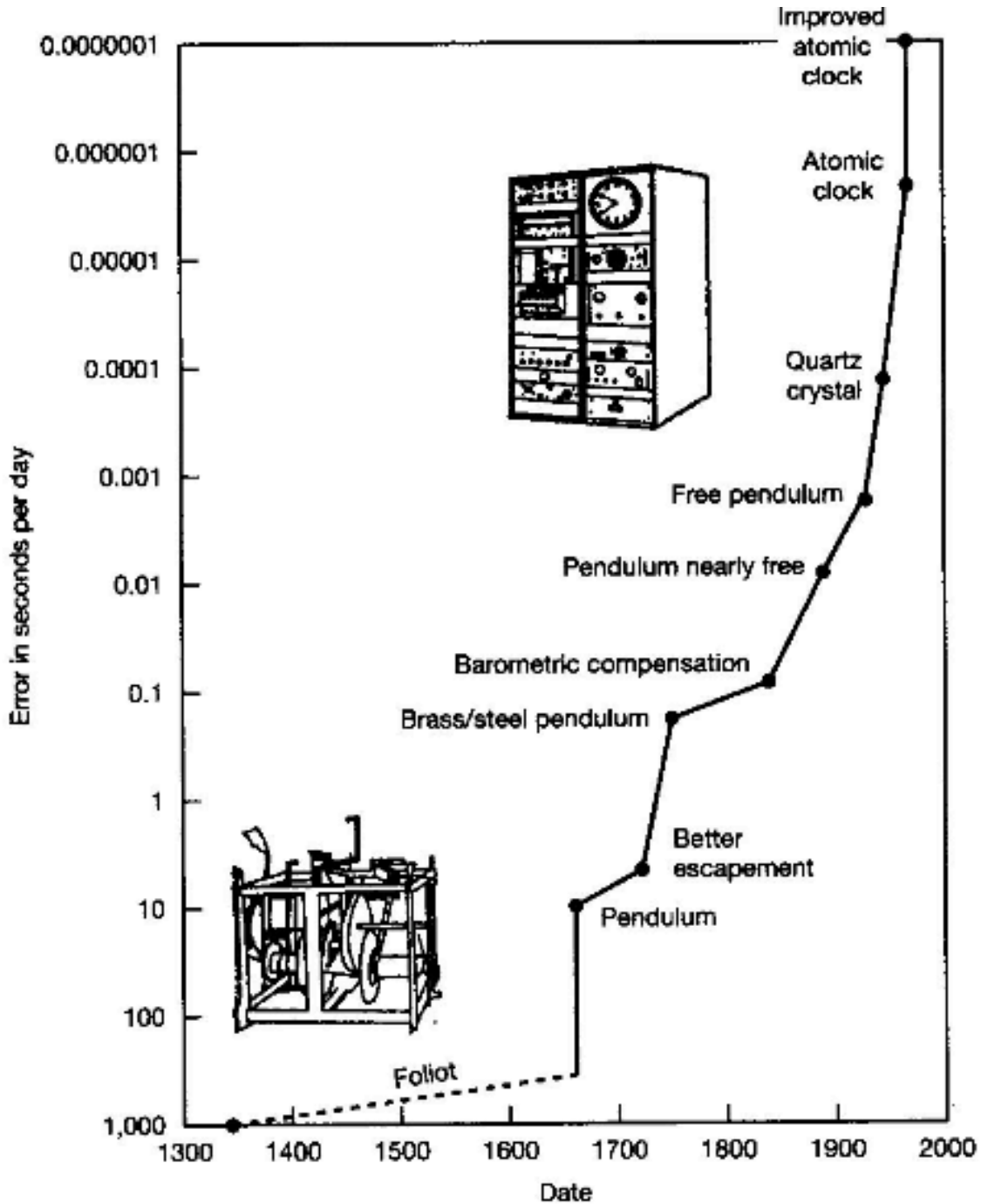
The result is more darkness in the morning and less in the afternoon. That's why the earliest sunset of 2012, at 4:29 p.m., in New York fell as soon as Nov. 30, according to the National Oceanic and Atmospheric Administration's solar calculator, while mornings continued to stay dark later. After the solstice, Earth continued its acceleration until reaching perihelion on Jan. 2. So the sunrise continued to slide, reaching its latest point, 7:20 a.m., on Dec. 28. There it stood until Jan. 11, when we finally got another minute of morning light. By Feb. 7, sunrise will be all the way back to 7 a.m.

> Earth's orbit and axis cause delayed sunrises even as days lengthen.

"It's hard to wrap the mind around this problem, which is really a figment of our timekeeping system," Dr. Gangestad said. That is, we would never notice it if we all just used sundials.

The Advancing Accuracy of Clocks

Today, the fractional uncertainty in the most accurate atomic clocks is as small as 1×10^{-16}, equivalent to $\sim 10^{-11}$ seconds per day!



As recounted by Dava Sobel in *Longitude – The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time . . .*

The invention of a seagoing chronometer, accurate to 1/3 of a second per day [one part in ~300,000] permitted accurate navigation by the stars.

INTERNATIONAL CONFERENCE

HELD AT WASHINGTON

FOR THE PURPOSE OF FIXING

A PRIME MERIDIAN

AND

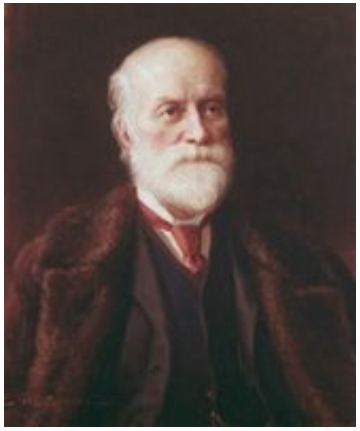
A UNIVERSAL DAY.

OCTOBER, 1884.

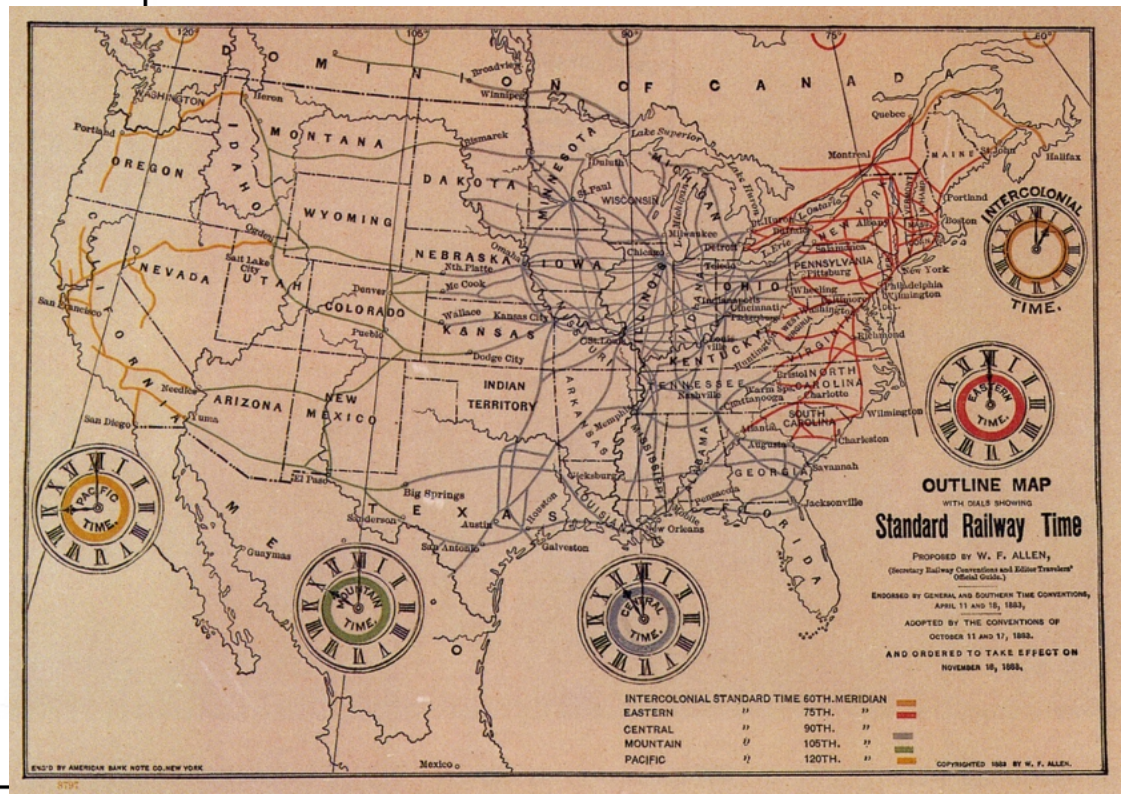
PROTOCOLS OF THE PROCEEDINGS.

WASHINGTON, D. C.
GIBSON BROS., PRINTERS AND BOOKBINDERS.
1884.

Earth's Prime Meridian and Standard Time zones were established by an international conference convened 1884 in Washington, DC as led by a Canadian railway administrator, Sir Sanford Fleming.



"Prime meridian, prime meridian, I'm sick of prime meridian." –1881

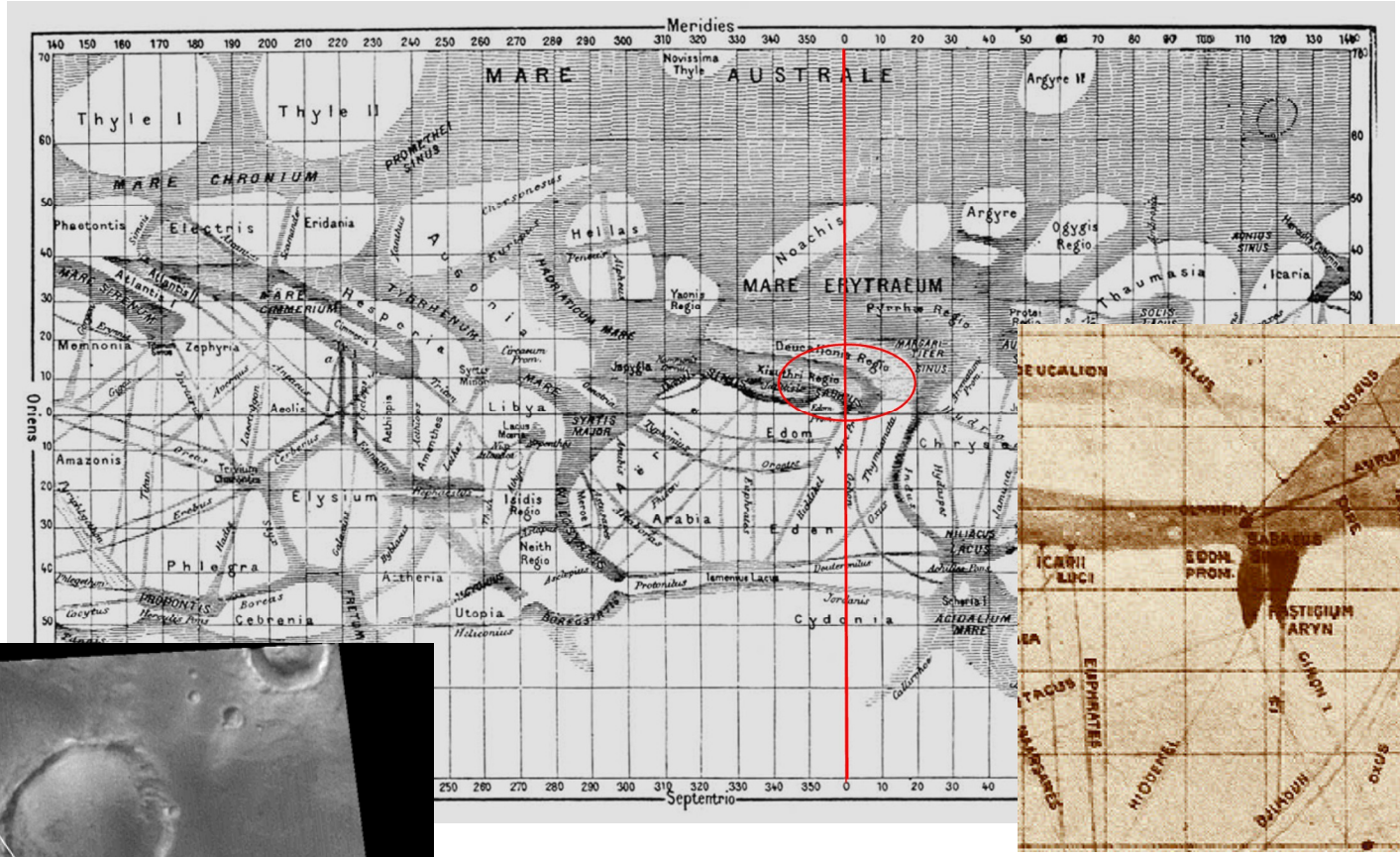


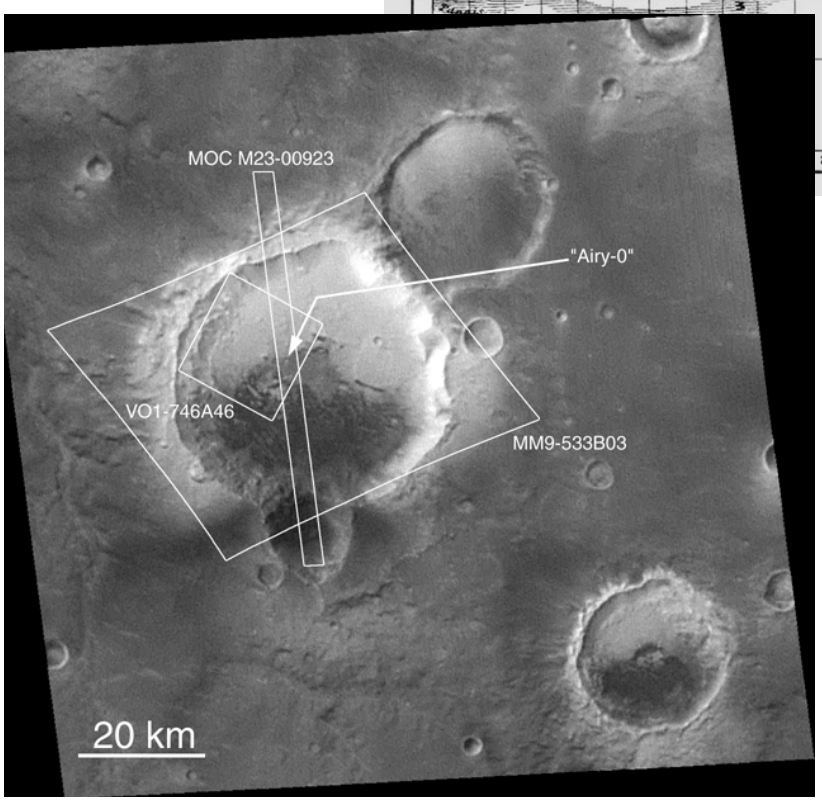
The Greenwich meridian and transit telescope.

Established by Sir George Airy in 1851, was agreed upon as the international standard in October 1884.

Replaced by the International Celestial Reference Frame (ICRF) coordinated by navigational satellites, the Greenwich meridian is now more than 100 meters to the west of longitude 0°.0!

Mars Prime Meridian





0° longitude on Mars was defined by the 1840 map of Beer & Madler, in reference to a near-equatorial feature, "Fastigium Aryn," within the "Sinus Sebaeus" region later mapped by Schiaparelli.

On August 14, 1972, Hal Masursky, Gerard de Vaucouleurs, and Merton Davies selected from Mariner 9 images a 500m diameter crater, which they dubbed "Airy-0,"for the definition of the Mars prime meridian. However, radio tracking experimenters at JPL have recently argued for a revised definition based on the position of the Viking 1 Lander, now determined to within 6m on the surface.

Planetary coordinates and prime meridians.

MAJOR PLANETS, 2008 E3

ROTATION ELEMENTS FOR MEAN EQUINOX AND EQUATOR OF DATE
2008 JANUARY 0, 0^h TT

Planet	North Pole Right Ascension α_1	North Pole Declination δ_1	Argument of Prime Meridian at epoch W_0	Argument of Prime Meridian var./day $\dot{W}$	Longitude of Central Meridian λ_e	Inclination of Equator to Orbit
	°	°	°	°	°	°
Mercury	281.03	+61.46	257.14	+ 6.1385338	160.42	+ 0.01
Venus	272.76	+67.16	153.98	− 1.4813296	263.76	+ 2.64
Mars	317.74	+52.91	36.71	+350.8919993	166.56	+25.19
Jupiter I	268.06	+64.49	54.15	+877.9000354	288.02	+ 3.13
II	268.06	+64.49	66.94	+870.2700354	301.08	+ 3.13
III	268.06	+64.49	7.32	+870.5366774	241.45	+ 3.13
Saturn	40.95	+83.57	242.23	+810.7938132	350.77	+26.73
Uranus	257.43	−15.18	325.80	−501.1600774	148.87	+82.23
Neptune	299.45	+42.97	194.89	+536.3128554	343.92	+28.33
Pluto	313.12	+ 9.12	150.65	− 56.3623082	229.87	+57.48

These data were derived from the "Report of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites: 2000" (Seidelmann *et al.*, *Celest. Mech.*, **82**, 83, 2002) and the 2003 report (Seidelmann *et al.*, *Celest. Mech.*, **91**, 203, 2005).

Merton Davies (1917–2001)

Planetary Cartographer

"The essence of exploration is finding answers for which there are no questions."

Examples of Defining References for P.M.s

Mercury — Crater Hun Cal at Longitude 20°

Mars — Crater Airy-0 at Longitude 0°

Jupiter — $W = 284°.95 + 870°.5366420\ d_{2000}$

Pluto — Sub-Charon meridian

New specification of Mars spin pole coordinates by Kuchynka *et al.* (2014, *Icarus*), based on lander radio tracking over many years, now recommended to the IAU by the Mars Geodesy and Cartography Working Group (2013 Nov 6).

$$
\begin{aligned}
\alpha = & 317^\circ.269202 - 0^\circ.10927547\,\mathrm{T} \\
& + 0^\circ.000068 \sin(198^\circ.991226 + 19139^\circ.4819985\,\mathrm{T}) \\
& + 0^\circ.000238 \sin(226^\circ.292679 + 38280^\circ.8511281\,\mathrm{T}) \\
& + 0^\circ.000052 \sin(249^\circ.663391 + 57420^\circ.7251593\,\mathrm{T}) \\
& + 0^\circ.000009 \sin(266^\circ.183510 + 76560^\circ.6367950\,\mathrm{T}) \\
& + 0^\circ.419057 \sin(79^\circ.398797 + 0^\circ.5042615\,\mathrm{T})
\end{aligned}
$$

$$
\begin{aligned}
\delta = & 54^\circ.432516 - 0^\circ.05827105\,\mathrm{T} \\
& + 0^\circ.000051 \cos(122^\circ.433576 + 19139^\circ.9407476\,\mathrm{T}) \\
& + 0^\circ.000141 \cos(43^\circ.058401 + 38280^\circ.8753272\,\mathrm{T}) \\
& + 0^\circ.000031 \cos(57^\circ.663379 + 57420^\circ.7517205\,\mathrm{T}) \\
& + 0^\circ.000005 \cos(79^\circ.476401 + 76560^\circ.6495004\,\mathrm{T}) \\
& + 1^\circ.591274 \cos(166^\circ.325722 + 0^\circ.5042615\,\mathrm{T})
\end{aligned}
$$

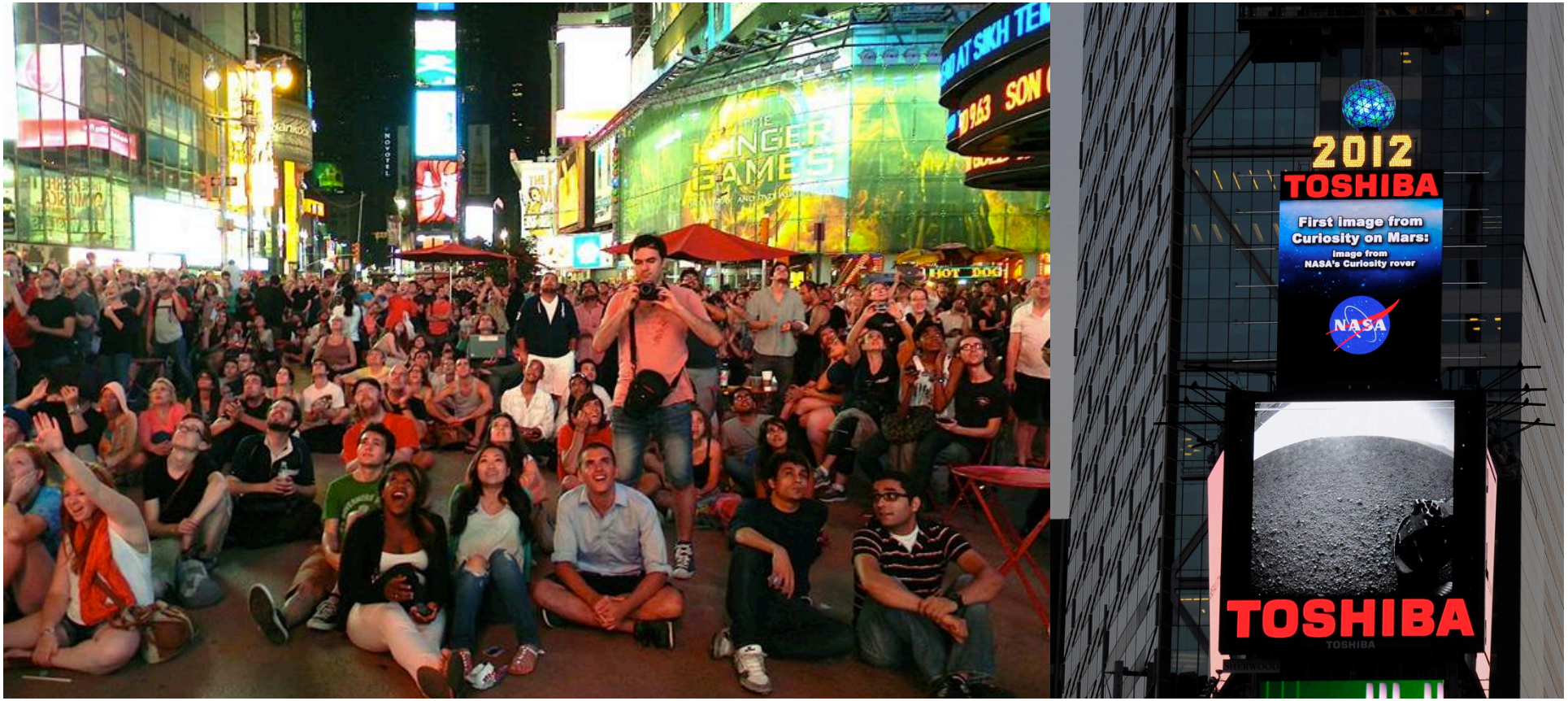
$$
\begin{aligned}
W = & 176^\circ.049863 + 350^\circ.891982443297\,\mathrm{d} \\
& + 0^\circ.000145 \sin(129^\circ.071773 + 19140^\circ.0328244\,\mathrm{T}) \\
& + 0^\circ.000157 \sin(36^\circ.352167 + 38281^\circ.0473591\,\mathrm{T}) \\
& + 0^\circ.000040 \sin(56^\circ.668646 + 57420^\circ.9295360\,\mathrm{T}) \\
& + 0^\circ.000001 \sin(67^\circ.364003 + 76560^\circ.2552215\,\mathrm{T}) \\
& + 0^\circ.000001 \sin(104^\circ.792680 + 95700^\circ.4387578\,\mathrm{T}) \\
& + 0^\circ.584542 \sin(95^\circ.391654 + 0^\circ.5042615\,\mathrm{T})
\end{aligned}
$$

The new coordinates can be fitted to within ±0°.0005 over ±1000 years with the simpler second-order polynomial expressions:

$$\alpha = 317^\circ.6811 - 0^\circ.10859\,T - 1.6 \times 10^{-5}\,T^2$$

$$\delta = 52^\circ.8863 - 0^\circ.06159\,T + 6.0 \times 10^{-5}\,T^2$$

$$W = 176^\circ.6318 + 350^\circ.891982430\,d - 1.7 \times 10^{-14}\,d^2$$



Times Square – 2012 August 6 (post-midnight!)

Awaiting the landing of MSL Curiosity at 05:17:57 UTC = 01:17:57 EDT (SCET)
at Mars planetocentric latitude 4°35’31’’ South. longitude 137°26’25’’ East.

Curiosity Mission Clock Time: 15:03:08
(Mars Local Mean Solar Time for target coordinates) So … what defines this?

PERGAMON

Planetary and Space Science 48 (2000) 215–235

Planetary and Space Science

A post-Pathfinder evaluation of areocentric solar coordinates with improved timing recipes for Mars seasonal/diurnal climate studies

Michael Allison[a,b,*], Megan McEwen[b,1]

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Received 16 August 1999; accepted 28 September 1999

Abstract

The accurate determination of the Mars pole vector derived from Pathfinder and Viking Lander radio data (Folkner et al., 1997. Science 278, 1749–1752), together with the VSOP87 representation of planetary orbits (Bretagnon and Francou, 1988. Astron. Astrophys. 202, 209–315), have been applied to a new evaluation of the right ascension of the "Fictitious Mean Sun" (FMS) at Mars. With Δt_{J2000} the elapsed time in days from the J2000 epoch (JD 2451545.0^{TT}), $\alpha_{FMS} = 270°.3863 + 0.5240384(°/d)\cdot\Delta t_{J2000} - 4 \times 10^{-13}(°/d^2)\cdot\Delta t_{J2000}^2$ represents a best least-squares quadratic fit of the FMS, including aberration, to each instance of the four equinox and solstice passages for each of 134 Mars orbits spanning the calendar years 1874–2126. The implied tropical orbit period for Mars, 686.9726^d, closely agrees with the recent evaluations by Surán (1997. Planet. Space Sci. 45, 705–708) and Allison (1997. Geophys. Rev. Lett. 24, 1967–1970). Together with the Pathfinder radio determination of the Mars sidereal rotation, the derived FMS rate corresponds to a mean solar day (or "sol") of 1.02749125^d. The new FMS determination would serve to define the Mean Solar Time at Mars to the nearest tenth-second, according to historical conventions originally established for terrestrial time-keeping, once the Mars prime meridian defined by the crater Airy-0 is determined within inertial space to the same accuracy. For convenient reference to current epochs, 2000 January 06 00:00:00 UTC (=MJD 51549.000^{UTC}) corresponds to a coincidence of α_{FMS} and the rotation angle of the crater Airy-0 measured with respect to the Mars equinox (i.e. "mean solar midnight" on the planet's prime meridian), to within the current uncertainty in the locational definition of the planet's cartographic grid. As a further result of the analysis, the consistently derived Mars obliquity of date is $\epsilon = 25°.192 + 3.45 \times 10^{-7}(°/d)\cdot\Delta t_{J2000}$. An improved analytic recipe for the calculation of the solar areocentric longitude (L_S) of Mars to an accuracy better than 0°.01 is also provided, accounting for the primary perturbations of Earth, Jupiter, and Venus, which may in turn be applied to an efficient evaluation of Mars Local True Solar Time (LTST) to within the uncertainty of the inertial position of the Mars prime meridian. For specific applications to the data archives for landed Mars spacecraft, simple conversion formulae are given for the determination of the Viking "Local Lander Time" and the Pathfinder "Local True Solar Time" in terms of the terrestrial calendar date and UTC. © 2000 Elsevier Science Ltd. All rights reserved.

By a numerical fit to an ephemeris calculation of solar seasons and perihelia over 134 orbits:

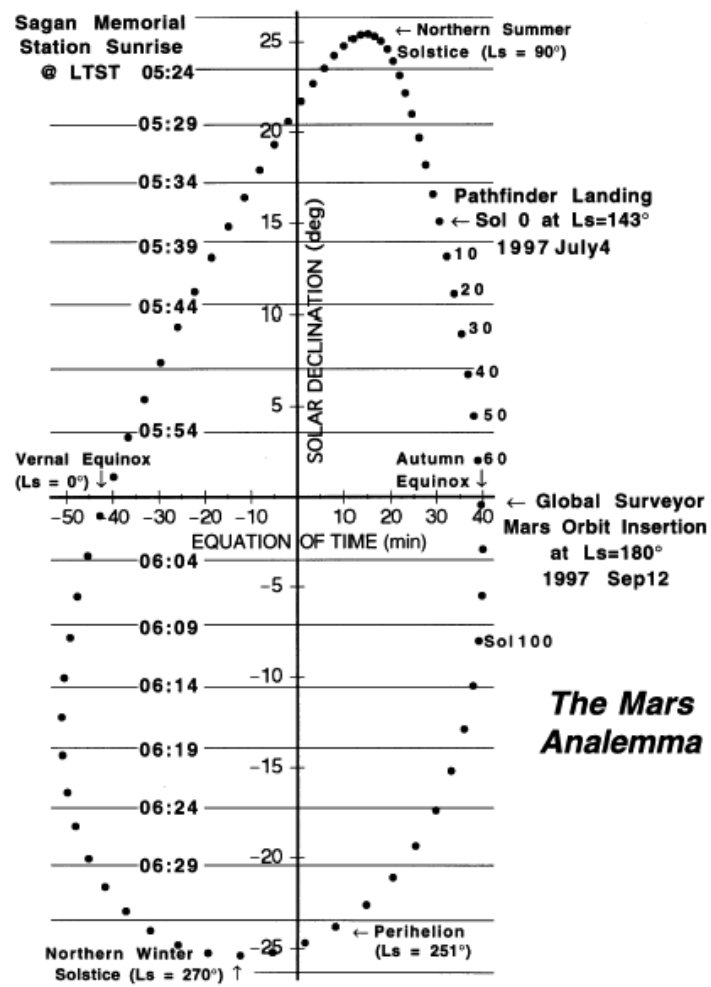
$$\alpha_{FMS} = 270°.386 + 0°.5240384 d_{2000} - 4\text{x}10^{-13} d_{2000}^2$$

where d_{2000} = days elapsed post-J2000.

Mean solar day (sol) = 1.02749125^d .

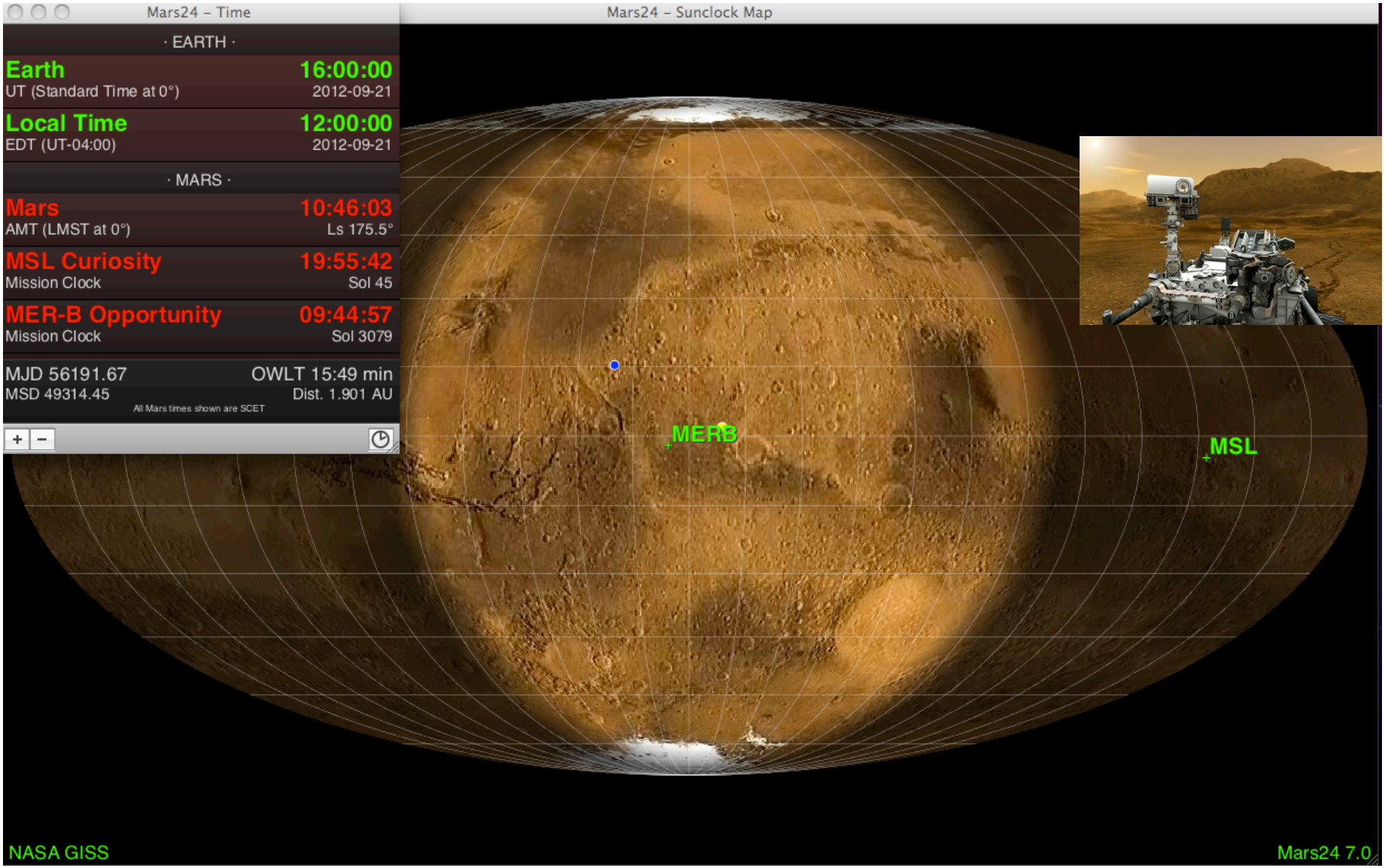
Tropical year = 1.880828^{Jyr} = 668.5921^{sol}

Geophysical Research Letters



AUGUST 15, 1997 Volume 24 Number 16

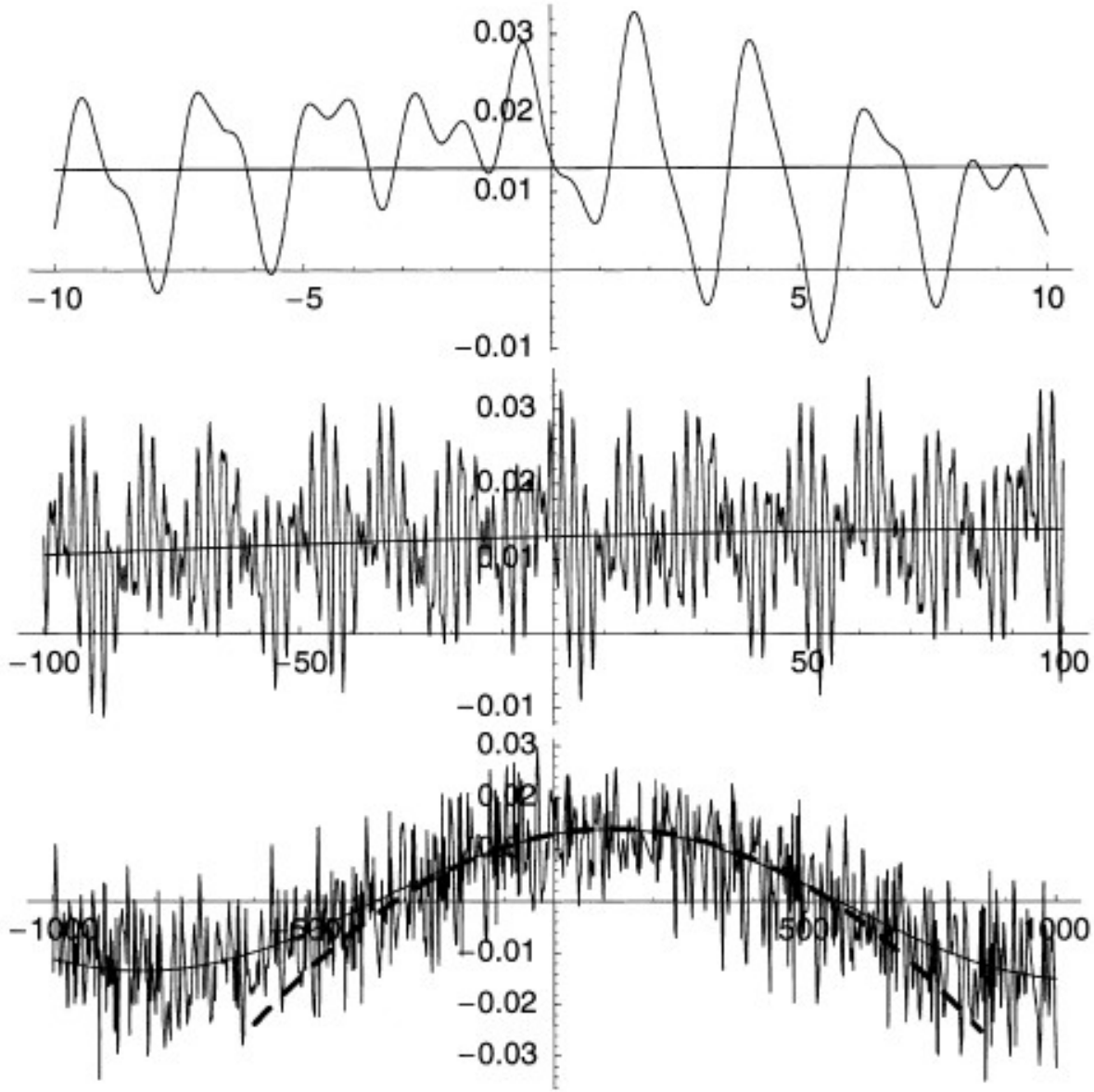
AMERICAN GEOPHYSICAL UNION



This real-time Mars sunclock and solar illumination map, coded by Robert Schmunk at GISS, can be downloaded to your computer desktop at http://www.giss.nasa.gov/tools/mars24/.

The Bumpy Orbit of Mars

Large perturbations on the Mars orbital longitude, shown here in deg over ±10, ±100, and ±1000 yrs, present a special challenge to the accurate computation of the solar time and seasons there. (The 1748yr "great inequality" results from interactions with Earth and Jupiter.)



Mars Sol Date **(Allison & McEwen, 2000; *Planet. Space Sci. 48*, 215.)**

Provides a sequential reckoning of Mars mean solar days elapsed since

MJD 05521.5 = 1873 Dec 29 GMT 12:04 (near Greenwich mean noon)

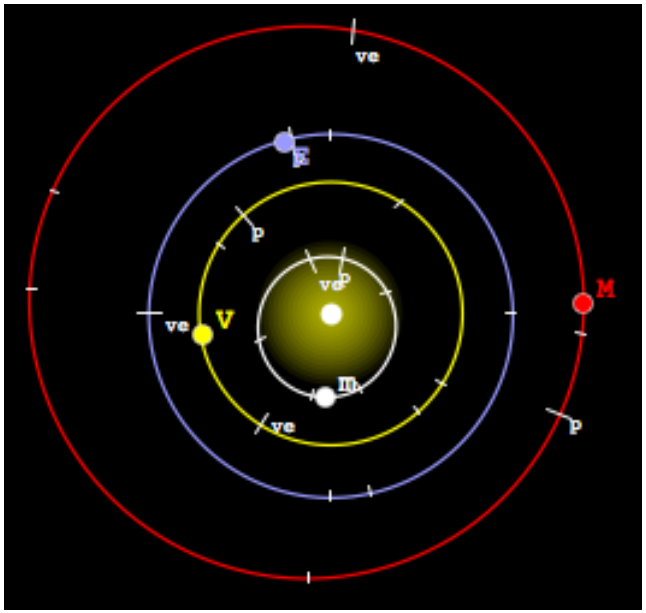
- At a near coincidence of Mars and Earth solar seasons (Ls 277°) *and* a near alignment of Mars Airy-0 mean midnight and Greenwich noon.

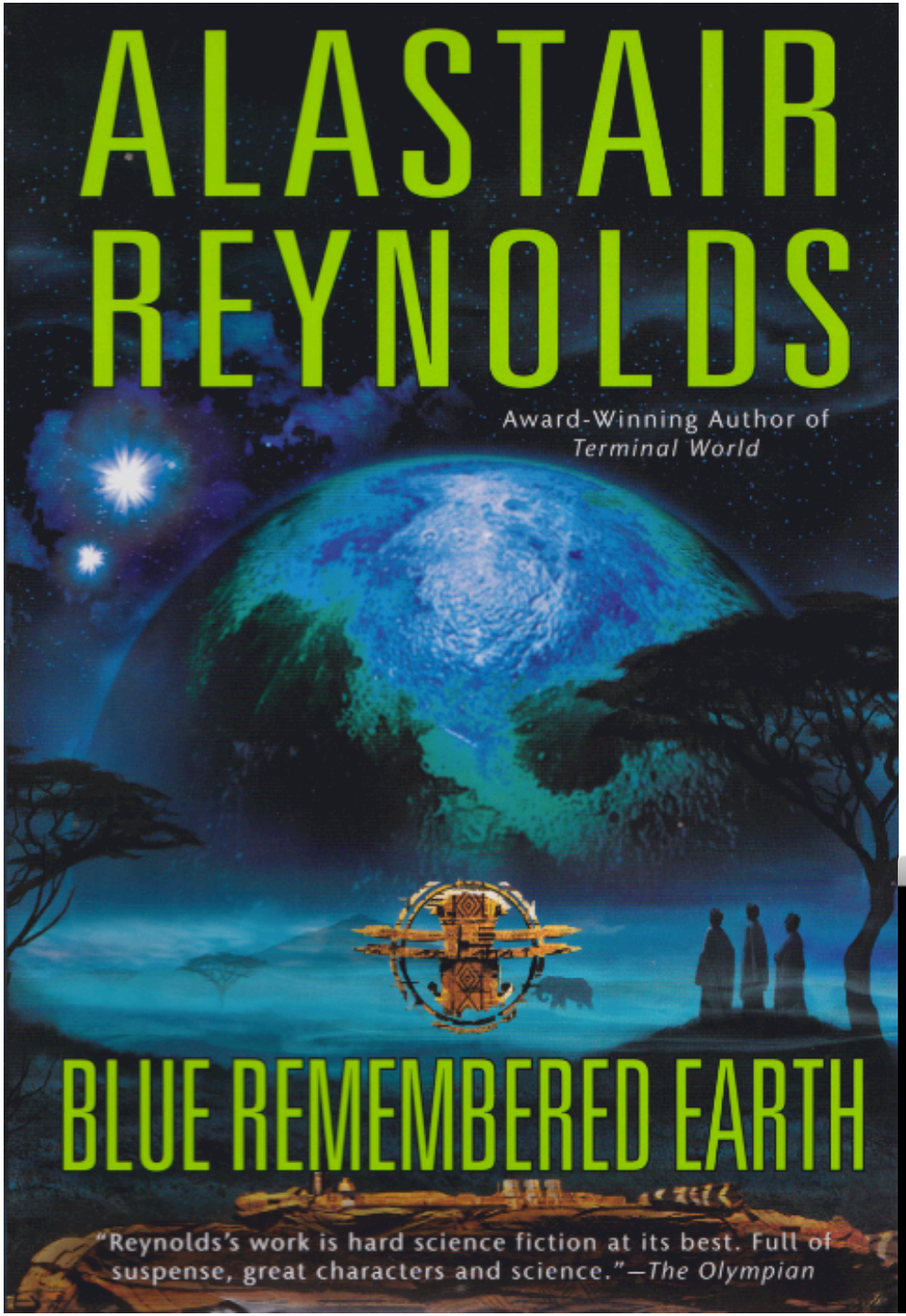
- The first near alignment of the winter solstices prior to the 1877 perihelic oppostion (the first observations of Mars temporal variations).

Defined as $$\text{MSD} = \frac{\text{MJD} - 51549.0}{1.02749125} + 44796.0 + k$$

where $k = -0.00096$ (revised to the prime meridian)

so that MSD 44796.0 = MJD 51549.0 = 2000 Jan 6.0
at another near coincidence of Mars-Earth Ls (277°)
and the Airy-0 and Greenwich mean midnights.
The interval, 1873 Dec 29.5 – 2000 Jan 6.0, is
126.02 Julian years = 67.00 Mars tropical years.





Mars Sol Date in fiction –

Blue Remembered Earth (New York: Penguin Group, 2012)

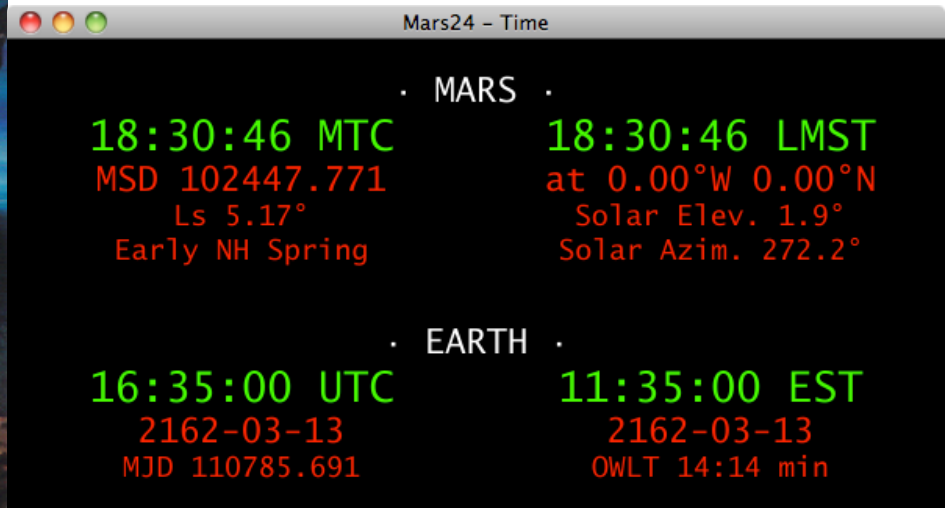
Story takes place in 2162:

'Welcome to Mars,' said a piped voice. 'The Mars Sol Date is one hundred and two thousand, four hundred and forty-seven sols. Local Mean Solar Time is eighteen hours and thirty-one minutes. For the benefit of passengers arriving from Earth, it is sixteen thirty-five Coordinate Universal Time on March thirteen.'

p.235

Mars landing on
MSD 102447 at 18:31 LMST
= 2162 March 16 at 16:35 UTC.

Date and time correspondence obviously read from Rob Schmunk's *Mars 24* app!



Two Mars Year Number Proposals (among many many!)

Clancy *et al.* (2000, JGR 105, 9533–9571). "… we apply an arbitrary numbering of Mars years (year 1 beginning April 11, 1955) …" –p.9564.

[1955 April 11.5 coincides with the occurrence of a Mars vernal equinox (Ls = 0°)]

Allison and McEwen (2000) number Mars tropical orbit revolutions from their Mars Sol Date epoch, MSD 0.0 = 1873 Dec 29.5 (at Ls = 277°) with each new Mars "year" therefore occurring shortly after the northern winter solstice.

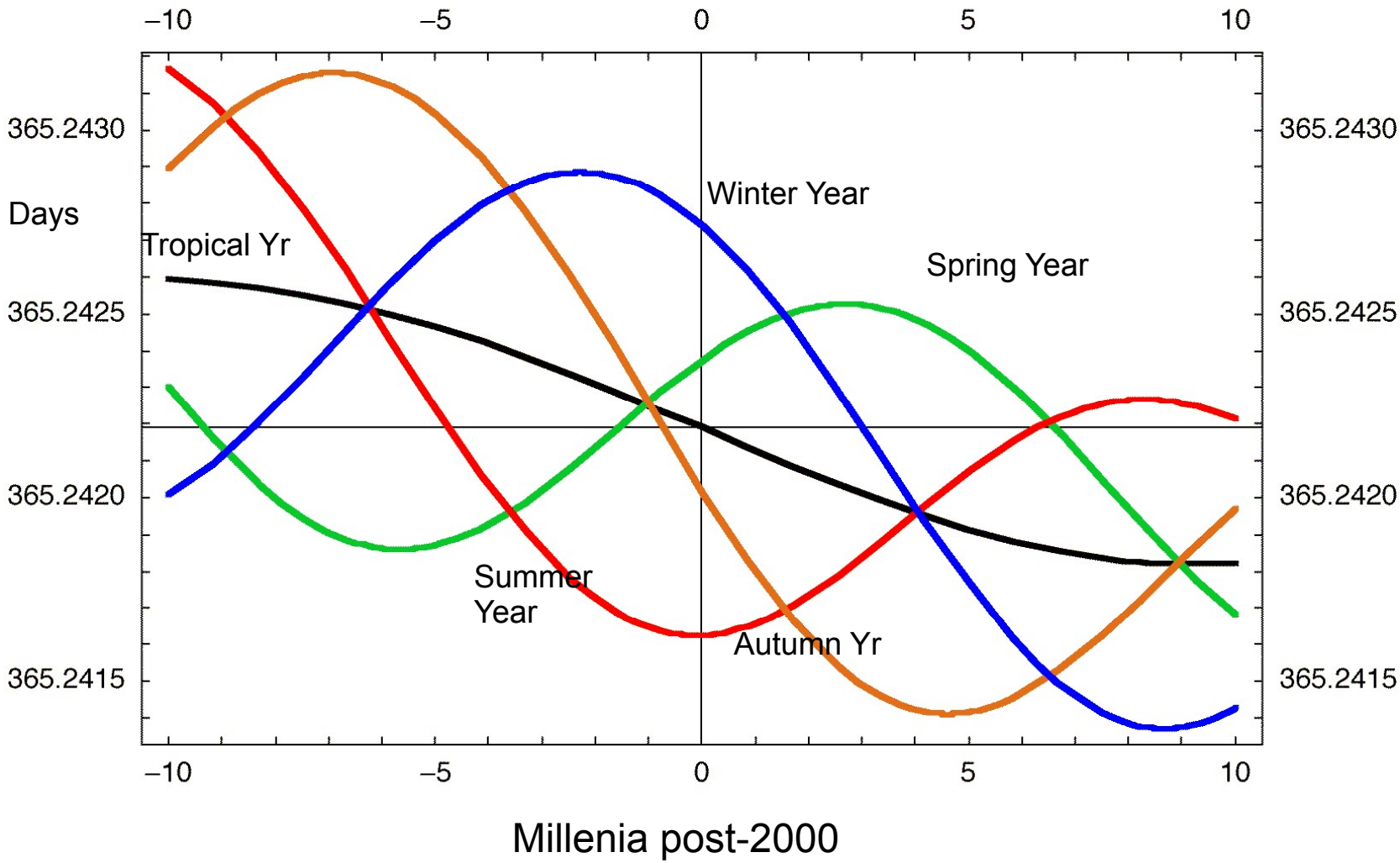
What is a "Year" . . . On Earth or Mars?

The tropical year is ***not*** (exactly) the interval between successive passages of the vernal equinox . . . But the time for the Sun's mean longitude to increase by 360°.

Cf. Meeus & Savoie (1992) or Aoki and Kinoshita (1982)

Measured Year	Earth	Mars
Anomalistic (perihelion-to-perihelion)	1.0000264^{Jy} = **365.2596**^{d}	1.8808917^{Jy} = **668.6146**^{sol}
Sidereal (fixed star-to-fixed star)	1.0000174^{Jy} = **365.2564**^{d}	1.8808481^{Jy} = **668.5991**^{sol}
Vernal Eqnx (repetition of Ls=0°)	0.9999791^{Jy} = **365.2424**^{d}	1.8808269^{Jy} = **668.5906**^{sol}
Summ Solst (repetition of Ls= 90°)	0.9999771^{Jy} = **365.2416**^{d}	1.8808168^{Jy} = **668.5880**^{sol}
Autum Eqnx (repetition of Ls=180°)	0.9999781^{Jy} = **365.2420**^{d}	1.8808336^{Jy} = **668.5940**^{sol}
Winter Solst (repetition of Ls=270°)	0.9999800^{Jy} = **365.2427**^{d}	1.8808387^{Jy} = **668.5958**^{sol}
Tropical (repetition of mean solar lon)	0.9999786^{Jy} = **365.2422**^{d}	1.8808284^{Jy} = **668.5921**^{sol}

Units: 1^{Jy} = 1 Julian Year = 365.25^{d}; 1^{d} = 1 Earth solar day = 86400 SI sec; 1 Sol= 1 Mars solar day =1.02749125^{d}.



Earth tropical + solar seasonal “years”

SCIENCE • VOL. 268 • 7 APRIL 1995

RESEARCH ARTICLE

The Seasons, Global Temperature, and Precession

David J. Thomson

Analysis of instrumental temperature records beginning in 1659 shows that in much of the world the dominant frequency of the seasons is one cycle per anomalistic year (the time from perihelion to perihelion, 365.25964 days), not one cycle per tropical year (the time from equinox to equinox, 365.24220 days), and that the timing of the annual temperature cycle is controlled by perihelion. The assumption that the seasons were timed by the equinoxes has caused many statistical analyses of climate data to be badly biased. Coherence between changes in the amplitude of the annual cycle and those in the average temperature show that between 1854 and 1922 there were small temperature variations, probably of solar origin. Since 1922, the phase of the Northern Hemisphere coherence between these quantities switched from 0° to 180° and implies that solar variability cannot be the sole cause of the increasing temperature over the last century. About 1940, the phase patterns of the previous 300 years began to change and now appear to be changing at an unprecedented rate. The average change in phase is now coherent with the logarithm of atmospheric CO_2 concentration.

Argues that the anomalistic year (365.25964 days) and *not* the tropical year (365.24220 days) provides the dominate seasonal frequency forcing for global temperatures, and that the use of the latter has badly biased climate analysis!

Speculation

and wonder –

Will we ever want to celebrate Xmas or Halloween on Mars?

What about the Fourth of July or May Day?

Or April Fools Day?

What about Apollo 11 *and* Viking Landing Day?

(1969 July 20 & 1976 July 20)

One of many proposals!

Mars Proleptic Calendar (MPC) Year 067

by Michael Allison

Beginning 44796 sols post-epoch Mars Sol Date 0.0 = C.E.1873 Dec 29.5

(*cf.* Allison, M. and M. McEwen 2000. *Planet. Space Sci.* **48**, 215-235.)

MPC Month/Day Scheme*

Month No./Name	Sols	ZeroDateSol# ZDSN
1 January	31	0
2 February	28	31
3 *Bradbury*	31	59
4 *Clarke*	31	90
5 March	31	121
6 April	30	152
7 May	31	182
8 *Beltaine*	30	213
[illegible]	[illegible]	[illegible]
11 June	30	303
12 July	31	333
13 August	31	364
[illegible]	[illegible]	395
[illegible]	[illegible]	425
16 *Tsiolkovsky*	30	456
17 September	30	486
18 October	31	516
19 November	30	547
20 *Sirius*	30	577
21 *Hypatia*	30	607
22 December	31	637

JANUARY

Su	M	Tu	W	Th	F	Sa
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

067 JANM 1 = CE 2000 JAN6

(MSD 44796.0 = MJD 51549.0)

FEBRUARY

Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28

067 FEBM 6 = CE 2000 FEB12

BRADBURY

Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

067 BRAD 15 = CE 2000 MAR 21

CLARKE

Su	M	Tu	W	Th	F	Sa
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

067 CLAR 20 =CE 2000 APR 27

MARCH

Su	M	Tu	W	Th	F	Sa
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	31					

067 MARM 25 =CE 2000 JUN3

APRIL

Su	M	Tu	W	Th	F	Sa
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	1st qtr ends APRM 15.		

MAY

Su	M	Tu	W	Th	F	Sa
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

067 MAYM 1 =CE 2000 JUL 11

BELTAINE

Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30					

067 BELT 6 =CE 2000 AUG 17

ADUMAH

Su	M	Tu	W	Th	F	Sa
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30			

067 ADUM 13 =CE 2000 SEP 24

KEPLER

Su	M	Tu	W	Th	F	Sa
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	

067 KEPL19 =CE 2000 OCT31

JUNE

Su	M	Tu	W	Th	F	Sa
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30						

067 JUNM25=CE2000DEC7

JULY

Su	M	Tu	W	Th	F	Sa
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31	2nd qtr ends JULM 1.		

AUGUST

Su	M	Tu	W	Th	F	Sa
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

067 AUGM1 =CE 2001 JAN 14

DARIUS

Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30					

067 DARI 6 = CE 2001 FEB 20

SAGAN

Su	M	Tu	W	Th	F	Sa
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

067 SAGA 12 = CE 2001 MAR 29

TSIOLKOVSKY

Su	M	Tu	W	Th	F	Sa
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30

067 TSIO 18 = CE 2001 MAY 6

SEPTEMBER

Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	3rd qtr ends SEPM15				

067 SEPM 24 = CE 2001 JUN 12

OCTOBER

Su	M	Tu	W	Th	F	Sa
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

067 OCTM 31 = CE 2001 JUL 20

NOVEMBER

Su	M	Tu	W	Th	F	Sa
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30

SIRIUS

Su	M	Tu	W	Th	F	Sa
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30					

067 SIRI 6 = CE 2001 AUG26

HYPATIA

Su	M	Tu	W	Th	F	Sa
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30			

067 HYPA 12 = CE 2001 OCT2

DECEMBER

Su	M	Tu	W	Th	F	Sa
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

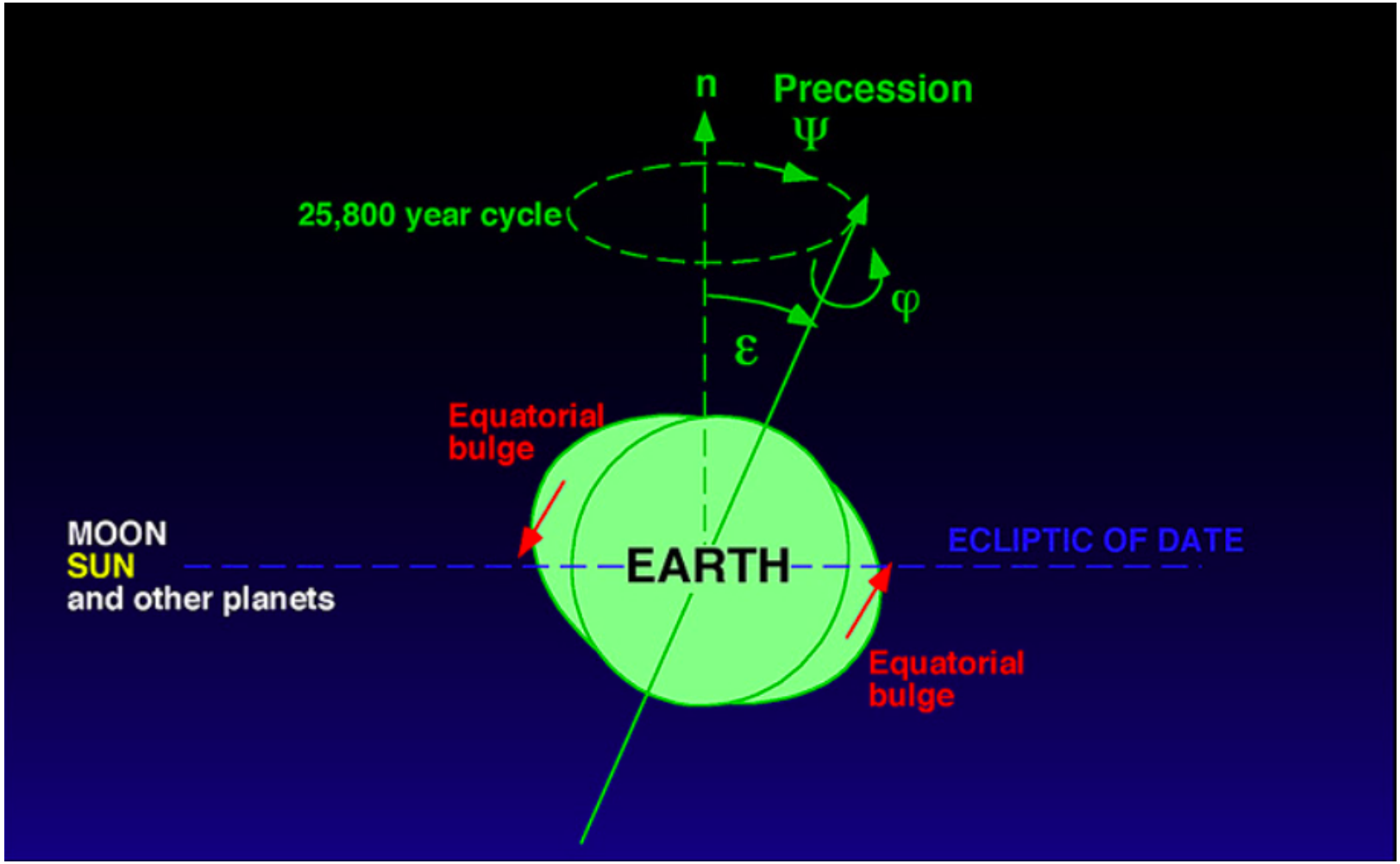
067 DECM 18 = CE 2001 NOV 8

MPC 067 Seasonal Solar Phenomena

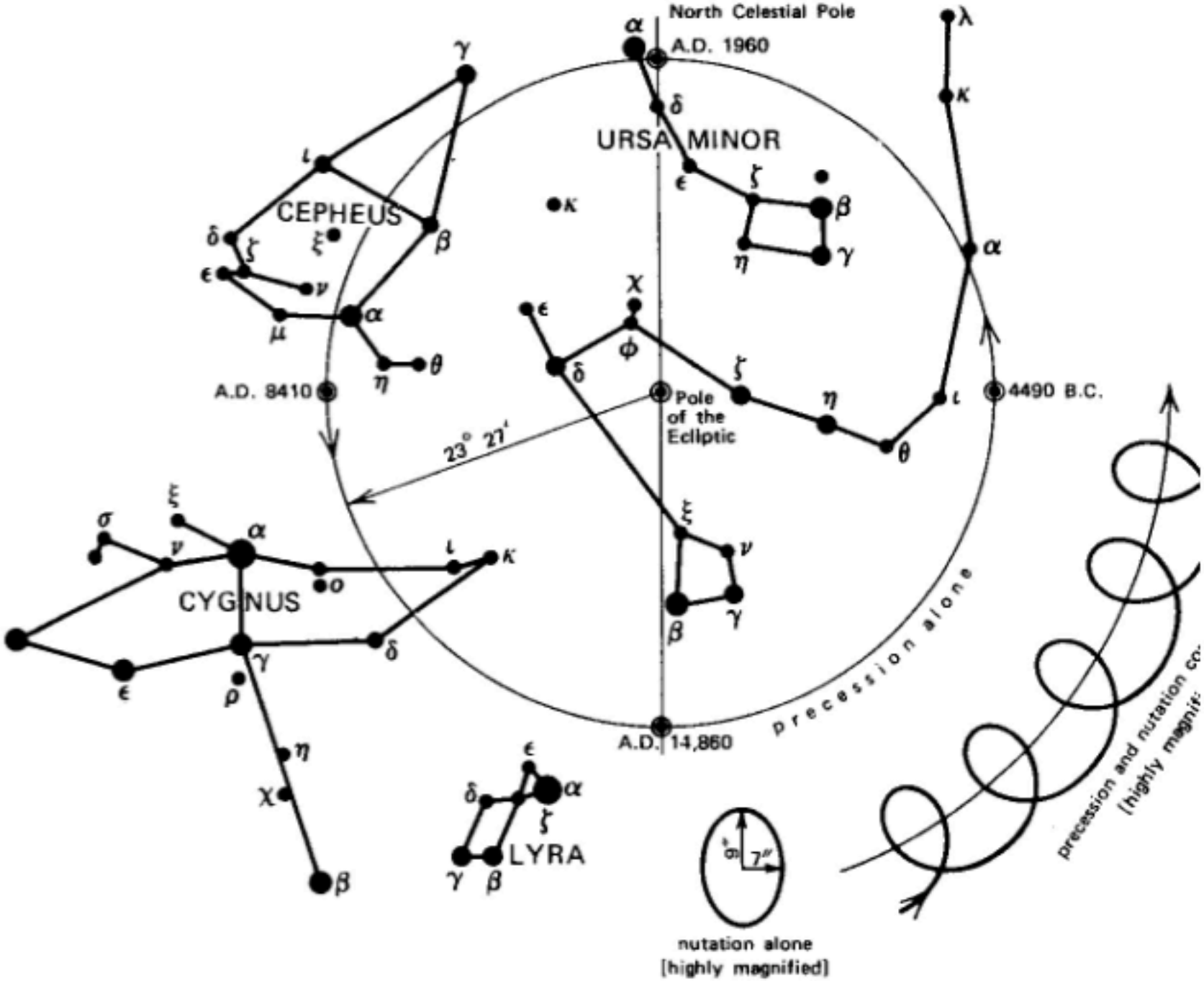
N. Spring	March 22
N. Summer	July 4
N. Autumn	September 29
N. Winter	December 21
Aphelion	Kepler 21
Perihelion	Hypatia 22

*Leap years, (numbered evenly divisible by 5, as 65,70,etc) have three extra days in February. To convert any MPC year-month-date (Y-M-D) to MSD=(MJD−51549.0)/1.02749125+ 44796.0, calculate MSD[Y,M,D] = 668*Y + ZDSN[M] + 3*IntegerPart[(Y−IntegerPart[(22−M)/20])/5] + D. *e.g.* MPC 054 JULM 20.8 = MSD 36455.8 = MJD 42979.5 = C.E. 1976 Jul 20.5.

Precession of the planetary spin axis



Linda A. Hinov, *The Geological Time Scale – Recent Developments and Global Correlations.* Cambridge Univ. Press, 2004.


North Celestial Pole
A.D. 1960
URSA MINOR
CEPHEUS
CYGNUS
LYRA
A.D. 8410
4490 B.C.
A.D. 14,860
Pole of the Ecliptic
23° 27'
precession alone
precession and nutation co
[highly magnif
nutation alone
[highly magnified]

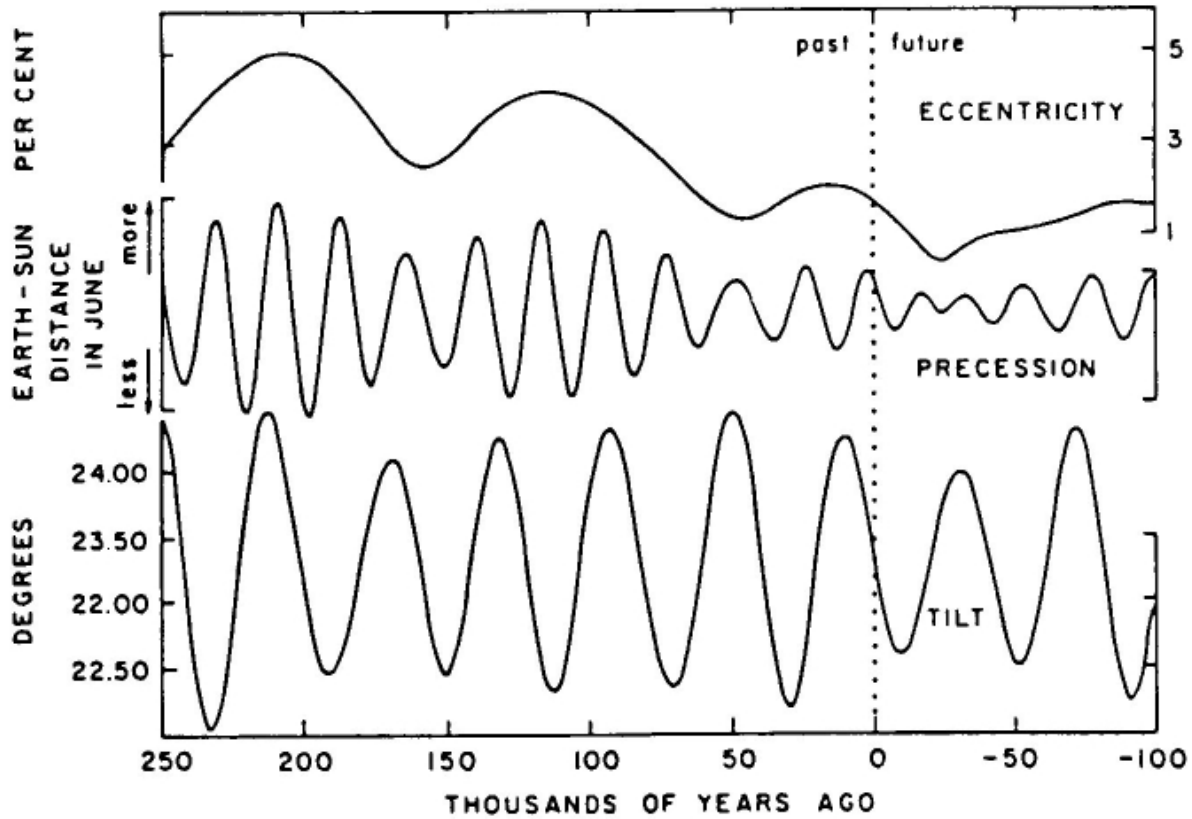


Fig. 11. Long-term variations of eccentricity, precession, and tilt from 250,000 years B.P. to 100,000 years A.P. [Berger, 1978c].

“Modern” developments in defined time standards:

Following the realization of the Earth’s variable rotation with its lunar-tidal de-spinning (by ~2 milliseconds/century), a distinction was made between *Ephemeris Time* (ET) and *Universal Time* (UT).

Beginning in 1955, atomic clocks became available in several countries and since 1971 the accepted international time standard has been *Temps Atomique Internationale* (TAI), with *Terrestrial Time* (TT) the successor to ET, now given as TT = ET = TAI + 32.184 s (the difference ET–TAI =32.184s corresponding to the evaluated departure ΔT of Ephemeris Time from Universal Time on 1958 Jan 0.

From 1985 – 2005, the Glossary (Section M) of *The Astronomical Almanac* included:

fictitious mean sun: an imaginary body introduced to define **mean solar time**; essentially the name of a mathematical formula that defined mean solar time. *This concept is no longer used in high precision work*.

HOWEVER … the current definition of UT in terms of the “stellar angle” is matched to the former definition derived from Newcomb’s Fictitious Mean Sun.

What *Is* a Second, Anyway?

Orginally 1/(24 x 60 x 60) = 1/86400 of an Earth solar day … but the solar day was itself defined in terms of the planetocentric mean motion of the Sun. And so …

Later . . . Defined (in reference to Newcomb's mean solar coordinate formula as "la fraction 1/31556925.9747 de l'année tropique 1900 janvier 0 á 12 heures de temps des ephemerides."

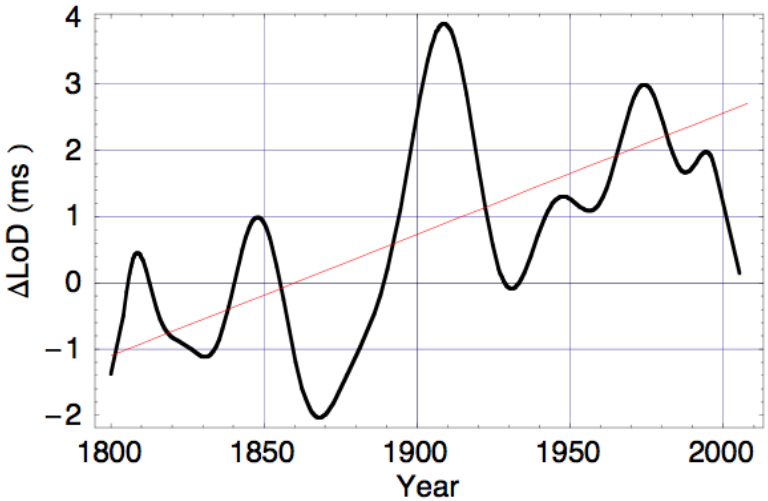
[i.e. as a specified fraction of the 1900 tropical year]

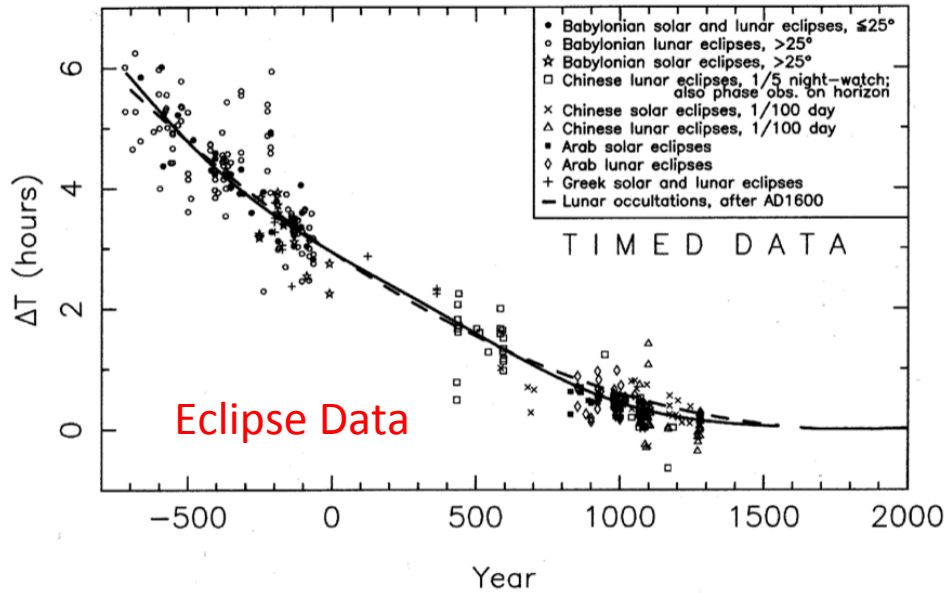
Today . . . As 9,192,631,770 periods of the hyperfine transition of the ground state of cesium-133.

Some say this was too short . . . That leap seconds could have been avoided for some decades if the second had been defined instead as 9,192,631,997 periods.

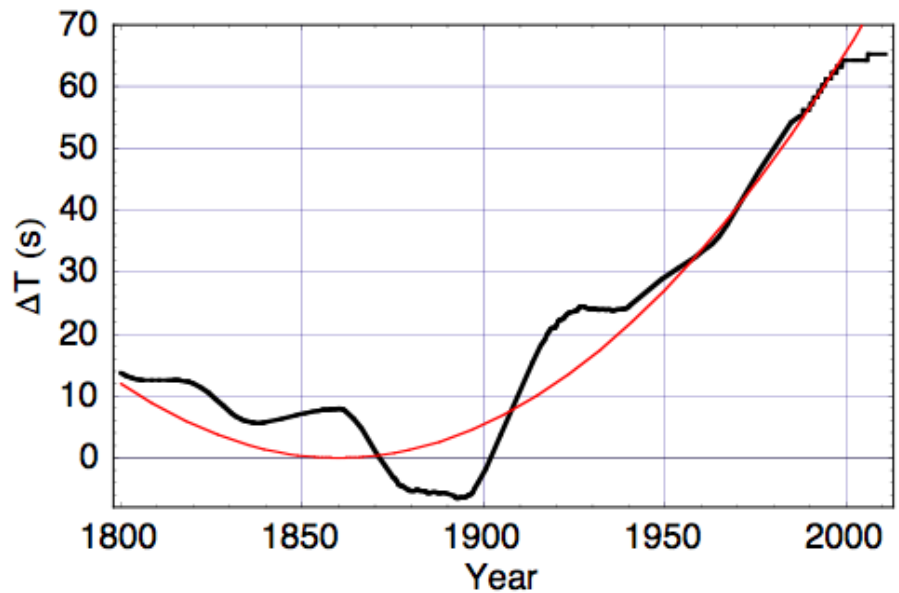
Variable Length of Day (LoD) and Leap Seconds

Largely as the result of lunar-tidal despinning of the Earth's rotation, the length of day has been slowly increasing (approximately 2millsec/cy).





$\Delta T = TT - UTC$



In order to keep the clock time in step with mean solar time, 26 leap seconds have been inserted into Universal Time since 1972, 8 in the 1990's, but only 3 since! (Something is changing? *Could global warming have paused the slow-down?*)

Excerpted page from a recent International Telecommuniactions Union (ITU) presentation recommending the abandonment of leap seconds.

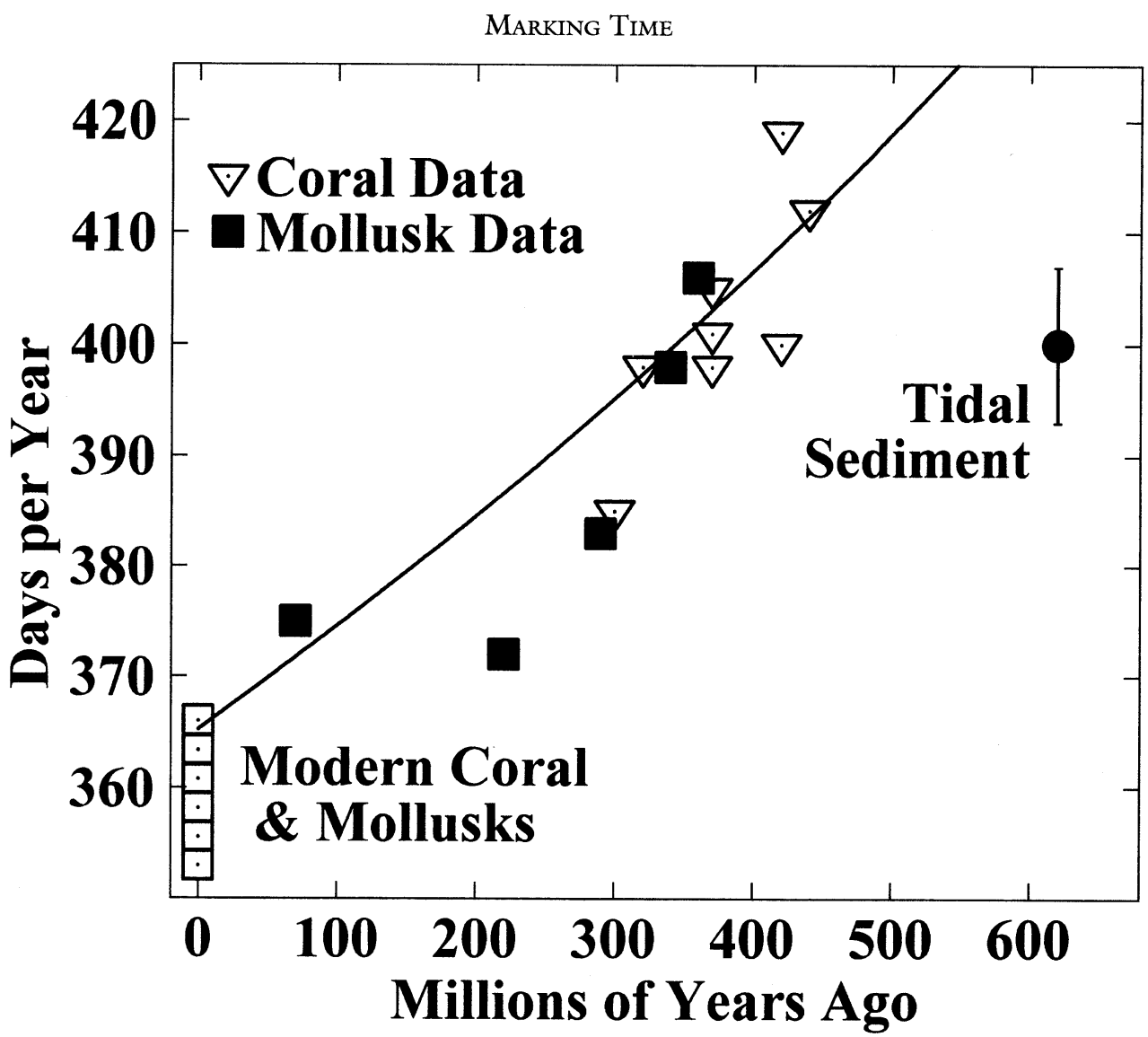
To avoid proliferation of time scales ITU plans to stop application of leap seconds to UTC

- April 2008: ITU Working Party 7A will submit to ITU Study Group 7 project recommendation on stopping leap second
- During 2008 Study Group 7 will conduct a vote through mail among member states
- 2011: if 70 % member states agree World Radio Conference will approve recommendation
- 2013: application of leap second will stop and UTC will become a continuous time scale

Action now tabled until 2015!

BIPM

Over geological eras, the Earth's variable rotation accumulates to large differences significant to paleo-climate weather (not only via the seasonal year changes but also the Rossby radius etc). Shortly after the Moon was formed, the Earth's rotation period was only about 4 hrs!



An application to Titan …

TITAN ZONAL WIND CORROBORATION VIA THE HUYGENS DISR SOLAR ZENITH ANGLE MEASUREMENT

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APPENDIX: TITAN SUB-SOLAR COORDINATE AND ZENITH ANGLE ALGORITHM

As referenced to a Barycentric Dynamical Time (TDB) argument T measuring Julian centuries elapsed post-J2000 (JD2451545.0), the following algorithm provides an efficient calculation of Titan's planetocentric solar longitude L_S, sub-solar longitude-latitude coordinates (Λ_S,δ_S), and μ the cosine of the local solar zenith angle Z, for a Titan planetographic west longitude ϕ_T and latitude θ_T. Starting with the evaluation of T in terms of the UTC Julian Date (JD_{UTC}),

$$T = (JD_{UTC} - 2451545.0)/36525 + 1.2\text{x}10^{-8}[(JD_{UTC} - 2451545.0)/36525 + 1.3]^2, \quad \text{(A1)}$$

where the second term provides an approximate conversion from the UTC to TDB time scales. Then,

$$M = 316°.91 + 1222°.08T \quad \text{(A2)}$$

$$\alpha_{FMS} = 236°.64 + 1223°.22T \quad \text{(A3)}$$

$$\varepsilon = 26°.40 - 0°.07T \quad \text{(A4)}$$

$$V_m = 321°.18 + 824624°.55T \quad \text{(A5)}$$

$$L_S = \alpha_{FMS} + (6°.36 - 0°.04T)\,\mathrm{Sin}M + 0.22\,\mathrm{Sin}2M + 0.01\,\mathrm{Sin}3M + 0.19\,\mathrm{Cos}(1182°.44T + 24°.1) + 0.12\,\mathrm{Cos}(591°.22T + 13°.9) + 0°.04\,\mathrm{Sin}(V_m - \alpha_{FMS}) \quad \text{(A6)}$$

$$\alpha_S = L_S + \frac{180°}{\pi}\sum_{n=1}^{3}\frac{1}{n}\left(-(Tan\frac{\varepsilon}{2})^2\right)^n Sin(2nLs) \quad \text{(A7)}$$

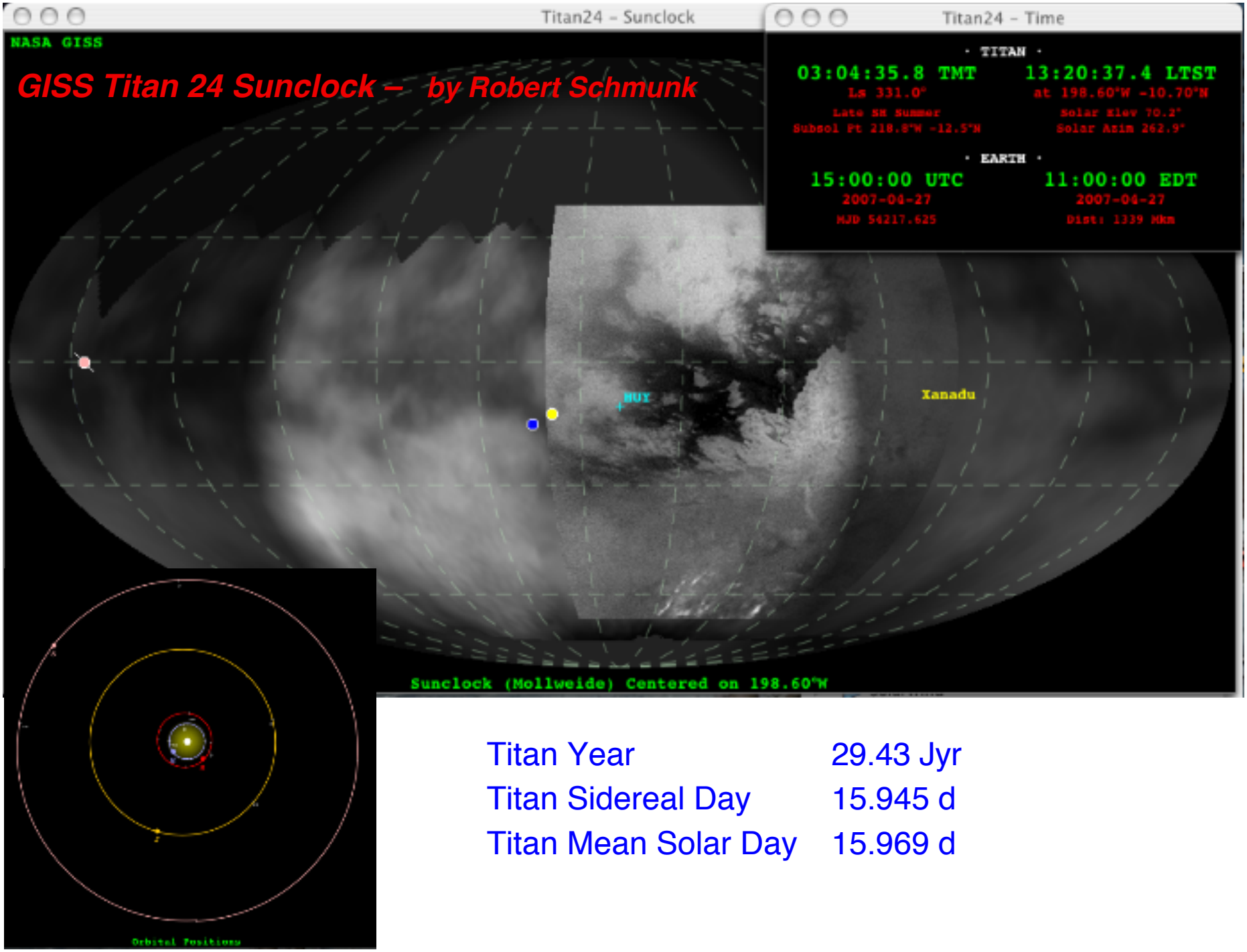
$$\Lambda_S = \mathrm{Mod}[V_m - \alpha_S, 360°] \quad \text{(A8)}$$

$$\delta_S = \mathrm{ArcSin}(\mathrm{Sin}\varepsilon\ \mathrm{Sin}Ls) \quad \text{(A9)}$$

$$H_S = \Lambda_S - \phi_T \quad \text{(A10)}$$

$$\mu \equiv \mathrm{Cos}Z = \mathrm{Sin}\theta_T\,\mathrm{Sin}\delta_S + \mathrm{Cos}\theta_T\,\mathrm{Cos}\delta_S\,\mathrm{Cos}H_S \quad \text{(A11)}$$

Proc. Int. Workshop 'Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science', Lisbon, Portugal, 6–9 October 2003 (ESA SP-544, February 2004)



Titan Year	29.43 Jyr
Titan Sidereal Day	15.945 d
Titan Mean Solar Day	15.969 d

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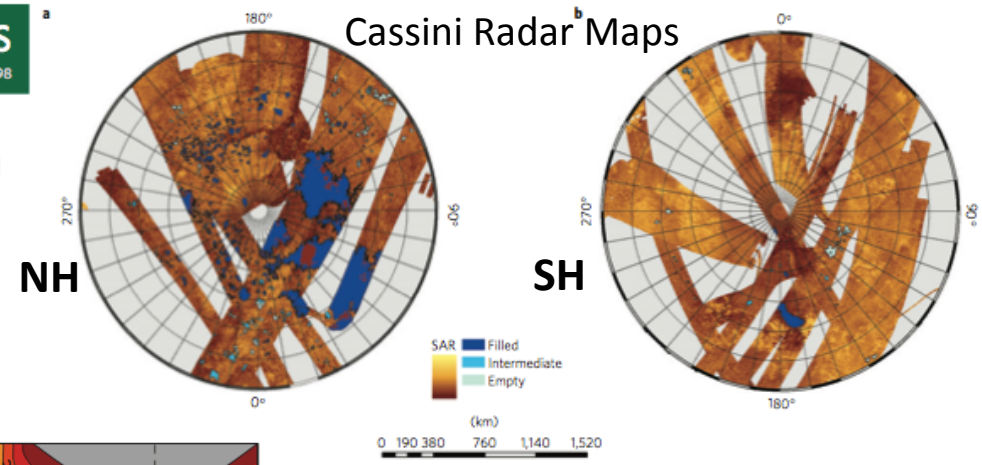
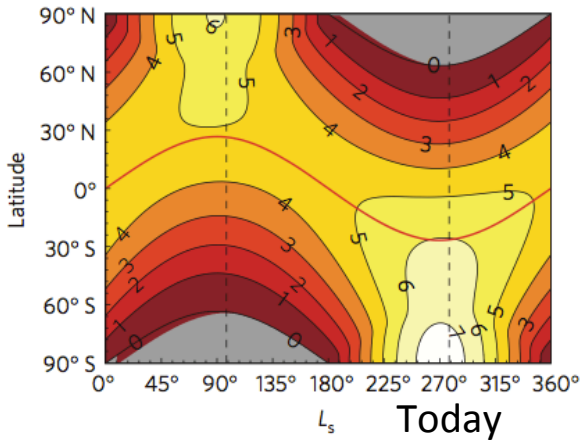
An asymmetric distribution of lakes on Titan as a possible consequence of orbital forcing

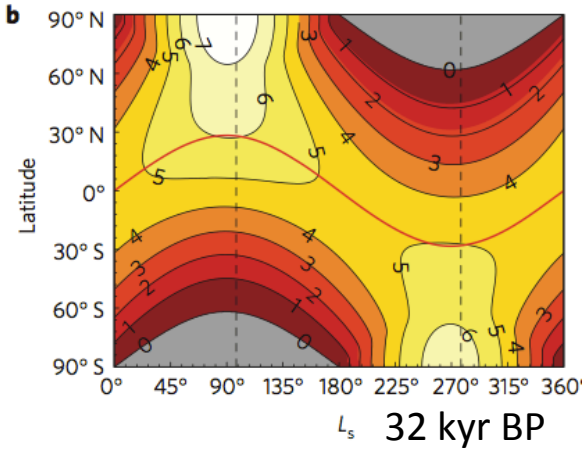
O. Aharonson[1]*, A. G. Hayes[1], J. I. Lunine[2], R. D. Lorenz[3], M. D. Allison[4] and C. Elachi[5]

Why does Titan's northern hemisphere favor methane lakes?

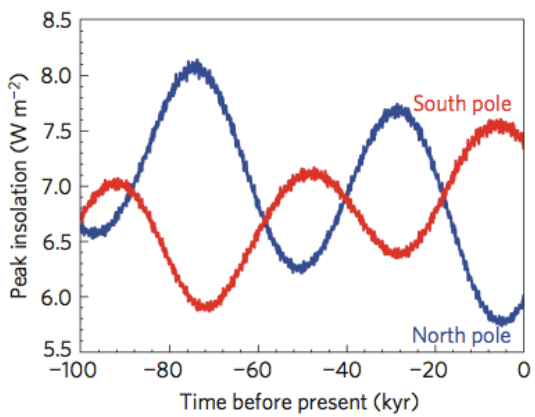
Cassini Radar Maps

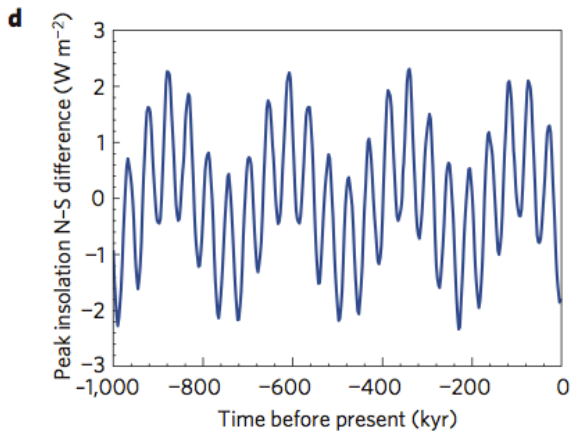






Multi-millenial changes in summer and peak insolation at the poles may have imposed a controlling shift in the accumulated evaporation and precipiation.





Paleo Calendar Conundrums

Several recent papers stress the possibility of artificial phase shifts in the simulated climates of General Circulation Models as a result of their analysis in terms of "fixed day" calendars – holding the equinox to a fixed day of the year – as opposed to "fixed angular" calendars with months grouped to the same intervals of the solar longitude. Chen et al. (2011) and Timm et al. (2008) recommend a fixed angle approach.

TIMM ET AL.: ON THE DEFINITION OF PALEOSEASONS

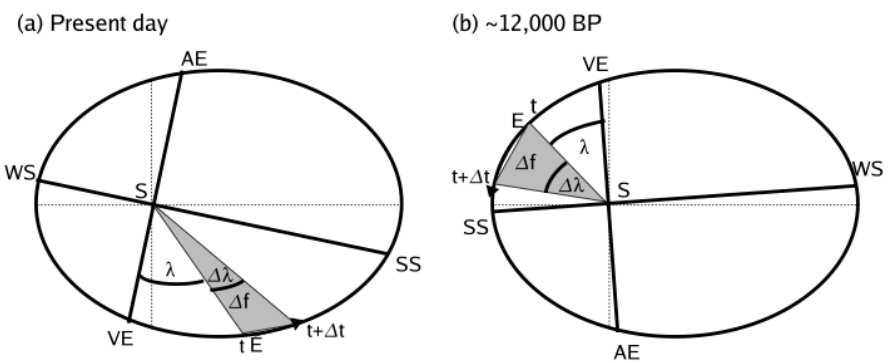


Table 1 Starting day, ending day, and length of month for 126 ka BP on the fixed-day calendar and the fixed-angular calendar for a 360-day year

	Fixed-day			Fixed-angular		
	Starting	Ending	Length	Starting	Ending	Length
Jan	1	30	30	354	26	33
Feb	31	60	30	27	59	33
Mar	61	90	30	60	90	31
Apr	91	120	30	91	120	30
May	121	150	30	121	148	28
Jun	151	180	30	149	175	27
Jul	181	210	30	176	202	27
Aug	211	240	30	203	229	27
Sep	241	270	30	230	258	29
Oct	271	300	30	259	288	30
Nov	301	330	30	289	320	32
Dec	331	360	30	321	353	33

The starting day and ending day are referred to the first day of the year in the fixed-day calendar

Chen, G-S. *et al.* 2011. Calendar effect on phase study in paleoclimae transient simulation with orbital forcing. *Clim. Dyn.* 37, 1949–1960.

Joussaume, S. and Braconnot, P. 1997. Sensitivity of paleoclimate simulation results to season definition. *J. Geophys. Res.* 102, 1943–1956.

Timm, O. *et al.* 2008. On the definition of seasons in paleoclimate simulations with orbital forcing. *Paleooceanography* 23, PA2221.

Closing thoughts on solar timing for planetary GCMs …