Time Scales in Astronomical and Navigational Almanacs

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IAU Division I

Commission 4 Ephemerides

iaucom4.org

Ephemeris: A table or data file giving the calculated coordinates of a celestial body as a function of time. Plural: ephemerides.

What is IAU Commission 4 (Ephemerides)?

Commission 4 (Ephemerides) of the International Astronomical Union (IAU) includes astronomers responsible for the production of printed almanacs, software, and web services that provide basic data on the positions and motions of celestial objects, and the times of phenomena such as rise and set, eclipses, phases of the Moon, etc.

What is IAU Commission 4?

IAU Commission 4 encompasses two kinds of work:

- **Computing fundamental solar system ephemerides**

  Using gravitational theory (including General Relativity) along with a wide variety of observations (optical, laser, radar, spacecraft) to determine the orbits of solar system bodies in a well-defined 4-D reference system. This work now depends almost exclusively on N-body numerical integrations and least-squares fits to the observations.

- **Computing and distributing almanac data**

  Using the fundamental solar system ephemerides to produce astronomical information useful to observers and navigators — the positions and motions of celestial objects as seen from Earth, and the times of phenomena such as rise and set, eclipses, phases of the Moon, etc.

What is IAU Commission 4?

- **One of 40 subject-area commissions making up the International Astronomical Union**
- **One of six commissions in IAU Division I, Fundamental Astronomy:**
  - Commission 4 — Ephemerides
  - Commission 7 — Celestial Mechanics & Dynamical Astronomy
  - Commission 8 — Astrometry
  - Commission 19 — Rotation of the Earth
  - Commission 31 — Time
  - Commission 52 — Relativity in Fundamental Astronomy

Plus five division or inter-division working groups

What is IAU Commission 4?

- **Our mission statement ("terms of reference"):**
  - Maintain cooperation and collaboration between the national offices providing ephemerides.
  - Encourage agreement on the bases (reference systems, time scales, models, and constants) of astronomical ephemerides and reference data.
  - Maintain databases containing observations of all types on which the ephemerides are based.
  - Encourage the development of software and web sites that provide astronomical ephemerides and prediction of phenomena.
  - Promote the development of explanatory material that fosters better understanding of the use and bases of ephemerides and related data.

What is IAU Commission 4?

- **Institutions Involved:**
  - Jet Propulsion Laboratory (JPL) — US ✓
  - U.S. Naval Observatory (USNO) — US
  - Her Majesty's Nautical Almanac Office (HMNAO) — UK
  - National Astronomical Observatory of Japan (NAOJ)
  - Institut de Mecanique Celeste et de Calcul des Ephemerides (IMCCE) — France ✓
  - Institute of Applied Astronomy (IAA) — Russia ✓
  - Spanish Naval Observatory
  - Astronomical Institute, Prague — Czech Republic

Examples of Modern Almanac Data

From web service provided by IMCCE:

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########################################################################################
                      EPHEMERIS OF SOLAR SYSTEM BODIES
########################################################################################

 Planet  2 Venus
 Planetary theory INPOP10
 Apparent coordinates (true equator; equinoxe of the date)
 Frame center: geocenter
 Relativistic perturbations, coordinate system 0
 Equatorial coordinates (R.A, Dec.)

########################################################################################

        Date TT               R.A            Dec.            Distance     V.Mag    Phase    Elong.  muRAcosDE     muDE      Dist_dot
            h  m  s        h  m  s         o  '  "            au.                  o        o       "/s        "/s        km/s

10  5  2011  0  0  0.00  13 32 49.11386 -08 48 53.7535   1.658916553   -3.90   18.61    13.50  0.477E-01 -0.202E-01   -4.5267
10  5  2011  6  0  0.00  13 33 58.67518 -08 56 10.2049   1.658261626   -3.90   18.70    13.56  0.477E-01 -0.202E-01   -4.5448
10  5  2011 12  0  0.00  13 35  8.28068 -09  3 25.9160   1.657604085   -3.90   18.79    13.63  0.477E-01 -0.202E-01   -4.5629
10  5  2011 18  0  0.00  13 36 17.93094 -09 10 40.8746   1.656943939   -3.90   18.88    13.69  0.478E-01 -0.201E-01   -4.5809
10  6  2011  0  0  0.00  13 37 27.62655 -09 17 55.0687   1.656281196   -3.90   18.97    13.75  0.478E-01 -0.201E-01   -4.5988
10  6  2011  6  0  0.00  13 38 37.36809 -09 25  8.4865   1.655615865   -3.90   19.05    13.82  0.478E-01 -0.200E-01   -4.6167
10  6  2011 12  0  0.00  13 39 47.15617 -09 32 21.1158   1.654947955   -3.90   19.14    13.88  0.478E-01 -0.200E-01   -4.6346
10  6  2011 18  0  0.00  13 40 56.99134 -09 39 32.9447   1.654277472   -3.90   19.23    13.95  0.478E-01 -0.200E-01   -4.6524
10  7  2011  0  0  0.00  13 42  6.87422 -09 46 43.9612   1.653604426   -3.90   19.32    14.01  0.478E-01 -0.199E-01   -4.6701
10  7  2011  6  0  0.00  13 43 16.80537 -09 53 54.1534   1.652928825   -3.90   19.41    14.07  0.479E-01 -0.199E-01   -4.6878
10  7  2011 12  0  0.00  13 44 26.78539 -10  1  3.5091   1.652250675   -3.90   19.50    14.14  0.479E-01 -0.199E-01   -4.7054
10  7  2011 18  0  0.00  13 45 36.81485 -10  8 12.0165   1.651569986   -3.90   19.58    14.20  0.479E-01 -0.198E-01   -4.7229
10  8  2011  0  0  0.00  13 46 46.89434 -10 15 19.6636   1.650886764   -3.90   19.67    14.26  0.479E-01 -0.198E-01   -4.7404
10  8  2011  6  0  0.00  13 47 57.02444 -10 22 26.4384   1.650201017   -3.90   19.76    14.33  0.479E-01 -0.197E-01   -4.7579
10  8  2011 12  0  0.00  13 49  7.20573 -10 29 32.3288   1.649512753   -3.90   19.85    14.39  0.479E-01 -0.197E-01   -4.7753
10  8  2011 18  0  0.00  13 50 17.43878 -10 36 37.3229   1.648821979   -3.90   19.94    14.46  0.480E-01 -0.197E-01   -4.7927
10  9  2011  0  0  0.00  13 51 27.72418 -10 43 41.4087   1.648128701   -3.90   20.02    14.52  0.480E-01 -0.196E-01   -4.8100
10  9  2011  6  0  0.00  13 52 38.06248 -10 50 44.5742   1.647432926   -3.90   20.11    14.58  0.480E-01 -0.196E-01   -4.8273
10  9  2011 12  0  0.00  13 53 48.45426 -10 57 46.8074   1.646734663   -3.90   20.20    14.65  0.480E-01 -0.195E-01   -4.8445
10  9  2011 18  0  0.00  13 54 58.90009 -11  4 48.0963   1.646033917   -3.90   20.29    14.71  0.480E-01 -0.195E-01   -4.8616
```

Examples of Modern Almanac Data

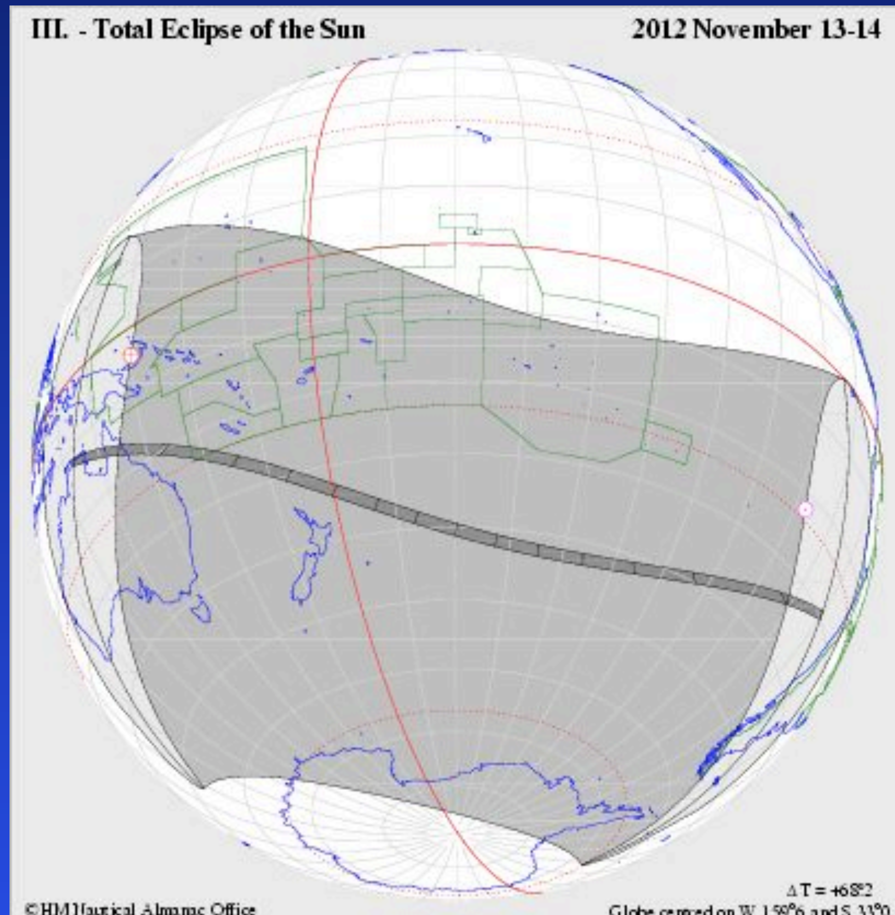
From *The Nautical Almanac* (USNO & HMNAO):

34 2010 FEBRUARY 6, 7, 8 (SAT., SUN., MON.)

	UT	ARIES	VENUS −3.9		MARS −1.2		JUPITER −2.0		SATURN +0.7		STARS		
	d h	GHA ° ′	GHA ° ′	Dec ° ′	GHA ° ′	Dec ° ′	GHA ° ′	Dec ° ′	GHA ° ′	Dec ° ′	Name	SHA ° ′	Dec ° ′
	6 00	136 01.5	170 06.9	S15 08.5	5 24.6	N22 53.2	159 27.6	S10 46.4	311 13.5	N 0 35.7	Acamar	315 20.1	S40 16.0
	01	151 04.0	185 06.3	07.4	20 28.1	53.4	174 29.5	46.2	326 16.1	35.8	Achernar	335 28.6	S57 11.3
	02	166 06.4	200 05.7	06.4	35 31.5	53.6	189 31.4	46.0	341 18.6	35.8	Acrux	173 11.8	S63 09.2
	03	181 08.9	215 05.1	. . 05.4	50 35.0	. . 53.9	204 33.3	. . 45.8	356 21.2	. . 35.9	Adhara	255 14.1	S28 59.3
	04	196 11.4	230 04.5	04.4	65 38.4	54.1	219 35.2	45.6	11 23.8	35.9	Aldebaran	290 52.0	N16 31.8
	05	211 13.8	245 03.9	03.4	80 41.9	54.3	234 37.1	45.3	26 26.3	36.0			
	06	226 16.3	260 03.3	S15 02.4	95 45.4	N22 54.5	249 39.0	S10 45.1	41 28.9	N 0 36.0	Alioth	166 22.3	N55 53.9
	07	241 18.8	275 02.7	01.4	110 48.8	54.8	264 40.9	44.9	56 31.4	36.1	Alkaid	153 00.5	N49 15.4
S	08	256 21.2	290 02.0	15 00.4	125 52.3	55.0	279 42.9	44.7	71 34.0	36.1	Al Na'ir	27 47.1	S46 54.8
A	09	271 23.7	305 01.4	14 59.4	140 55.7	. . 55.2	294 44.8	. . 44.5	86 36.5	. . 36.2	Alnilam	275 48.6	S 1 11.8
T	10	286 26.2	320 00.8	58.4	155 59.2	55.4	309 46.7	44.3	101 39.1	36.2	Alphard	217 58.2	S 8 42.3
U	11	301 28.6	335 00.2	57.3	171 02.6	55.6	324 48.6	44.1	116 41.6	36.3			
R	12	316 31.1	349 59.6	S14 56.3	186 06.1	N22 55.9	339 50.5	S10 43.8	131 44.2	N 0 36.3	Alphecca	126 13.1	N26 40.5
D	13	331 33.6	4 59.0	55.3	201 09.5	56.1	354 52.4	43.6	146 46.7	36.4	Alpheratz	357 46.3	N29 08.9
A	14	346 36.0	19 58.4	54.3	216 13.0	56.3	9 54.3	43.4	161 49.3	36.4	Altair	62 10.9	N 8 53.6
Y	15	1 38.5	34 57.8	. . 53.3	231 16.4	. . 56.5	24 56.2	. . 43.2	176 51.9	. . 36.5	Ankaa	353 18.3	S42 15.2
	16	16 40.9	49 57.2	52.3	246 19.9	56.7	39 58.1	43.0	191 54.4	36.5	Antares	112 29.4	S26 27.3
	17	31 43.4	64 56.6	51.2	261 23.3	56.9	55 00.0	42.8	206 57.0	36.6			
	18	46 45.9	79 56.0	S14 50.2	276 26.7	N22 57.2	70 01.9	S10 42.5	221 59.5	N 0 36.6	Arcturus	145 57.8	N19 07.5
	19	61 48.3	94 55.4	49.2	291 30.2	57.4	85 03.8	42.3	237 02.1	36.7	Atria	107 33.8	S69 02.5
	20	76 50.8	109 54.8	48.2	306 33.6	57.6	100 05.7	42.1	252 04.6	36.7	Avior	234 18.5	S59 32.7
	21	91 53.3	124 54.2	. . 47.2	321 37.1	. . 57.8	115 07.6	. . 41.9	267 07.2	. . 36.8	Bellatrix	278 34.4	N 6 21.5
	22	106 55.7	139 53.6	46.1	336 40.5	58.0	130 09.5	41.7	282 09.7	36.8	Betelgeuse	271 03.7	N 7 24.5
	23	121 58.2	154 53.0	45.1	351 44.0	58.2	145 11.4	41.5	297 12.3	36.9			
	7 00	137 00.7	169 52.4	S14 44.1	6 47.4	N22 58.5	160 13.3	S10 41.3	312 14.9	N 0 36.9	Canopus	263 56.8	S52 42.3
	01	152 03.1	184 51.8	43.1	21 50.8	58.7	175 15.2	41.0	327 17.4	37.0	Capella	280 37.8	N46 00.6
	02	167 05.6	199 51.2	42.1	36 54.3	58.9	190 17.1	40.8	342 20.0	37.0	Deneb	49 33.7	N45 18.9
	03	182 08.1	214 50.6	. . 41.0	51 57.7	. . 59.1	205 19.0	. . 40.6	357 22.5	. . 37.1	Denebola	182 35.8	N14 30.7
	04	197 10.5	229 50.0	40.0	67 01.2	59.3	220 20.9	40.4	12 25.1	37.1	Diphda	348 58.5	S17 55.9
	05	212 13.0	244 49.4	39.0	82 04.6	59.5	235 22.8	40.2	27 27.6	37.2			
	06	227 15.4	259 48.8	S14 38.0	97 08.0	N22 59.7	250 24.7	S10 40.0	42 30.2	N 0 37.2	Dubhe	193 53.8	N61 41.5
	07	242 17.9	274 48.2	36.9	112 11.5	22 59.9	265 26.6	39.7	57 32.7	37.3	Elnath	278 15.5	N28 37.0
	08	257 20.4	289 47.6	35.9	127 14.9	23 00.2	280 28.5	39.5	72 35.3	37.3	Eltanin	90 47.6	N51 29.0
S	09	272 22.8	304 47.0	. . 34.9	142 18.4	. . 00.4	295 30.4	. . 39.3	87 37.9	. . 37.4	Enif	33 49.8	N 9 55.3
U	10	287 25.3	319 46.4	33.8	157 21.8	00.6	310 32.3	39.1	102 40.4	37.4	Fomalhaut	15 26.9	S29 34.2
N	11	302 27.8	334 45.8	32.8	172 25.2	00.8	325 34.3	38.9	117 43.0	37.5			
D	12	317 30.2	349 45.2	S14 31.8	187 28.7	N23 01.0	340 36.2	S10 38.7	132 45.5	N 0 37.5	Gacrux	172 03.4	S57 10.1
A	13	332 32.7	4 44.7	30.7	202 32.1	01.2	355 38.1	38.4	147 48.1	37.6	Gienah	175 54.6	S17 36.0
Y	14	347 35.2	19 44.1	29.7	217 35.5	01.4	10 40.0	38.2	162 50.7	37.6	Hadar	148 51.4	S60 25.2
	15	2 37.6	34 43.5	. . 28.7	232 39.0	. . 01.6	25 41.9	. . 38.0	177 53.2	. . 37.7	Hamal	328 03.6	N23 30.7
	16	17 40.1	49 42.9	27.6	247 42.4	01.8	40 43.8	37.8	192 55.8	37.7	Kaus Aust.	83 47.3	S34 22.7
	17	32 42.6	64 42.3	26.6	262 45.8	02.0	55 45.7	37.6	207 58.3	37.8			
	18	47 45.0	79 41.7	S14 25.6	277 49.3	N23 02.2	70 47.6	S10 37.4	223 00.9	N 0 37.8	Kochab	137 19.5	N74 06.4
	19	62 47.5	94 41.1	24.5	292 52.7	02.4	85 49.5	37.1	238 03.4	37.9	Markab	13 41.1	N15 15.6

Examples of Modern Almanac Data

From HMNAO web site:



Circumstances	Time (UT) h m	Longitude ° '	Latitude ° '
Eclipse begins; first contact with Earth	19 37.9	E 150 08.9	S 4 27.6
Beginning of northern limit of penumbra	20 22.1	E 146 36.3	N 17 40.1
Beginning of northern limit of umbra	20 35.6	E 133 23.0	S 11 26.2
Beginning of centre line; central eclipse begins	20 36.1	E 133 05.2	S 11 57.2
Beginning of southern limit of umbra	20 36.5	E 132 47.2	S 12 28.3
Beginning of southern limit of penumbra	21 32.1	E 97 48.9	S 52 19.8
Central eclipse at local apparent noon	22 18.0	W 158 24.5	S 40 37.0
End of southern limit of penumbra	22 51.3	W 27 08.9	S 66 34.2
End of southern limit of umbra	23 46.9	W 79 36.6	S 30 03.5
End of centre line; central eclipse ends	23 47.4	W 79 57.8	S 29 32.6
End of northern limit of umbra	23 47.9	W 80 18.6	S 29 01.8
End of northern limit of penumbra	0 01.5	W 94 15.0	S 0 04.0
Eclipse ends; last contact with Earth	0 45.5	W 97 33.3	S 22 08.7

Examples of Modern Almanac Data

From *The Astronomical Almanac (HMNAO & USNO)*:

C18 SUN, 2011

FOR 0^h TERRESTRIAL TIME

Date		Julian Date	Geometric Ecliptic Coords. Mn Equinox & Ecliptic of Date		Apparent R. A.	Apparent Declination	True Geocentric Distance
			Longitude	Latitude			
		245	° ′ ″	″	h m s	° ′ ″	au
Oct.	1	5835.5	187 28 38.35	−0.11	12 27 27.71	− 2 57 59.5	1.001 4051
	2	5836.5	188 27 38.26	+0.02	12 31 04.90	− 3 21 15.9	1.001 1130
	3	5837.5	189 26 39.91	+0.16	12 34 42.38	− 3 44 30.0	1.000 8198
	4	5838.5	190 25 43.29	+0.30	12 38 20.15	− 4 07 41.4	1.000 5260
	5	5839.5	191 24 48.41	+0.42	12 41 58.23	− 4 30 49.8	1.000 2319
	6	5840.5	192 23 55.29	+0.52	12 45 36.65	− 4 53 54.7	0.999 9379
	7	5841.5	193 23 03.95	+0.61	12 49 15.43	− 5 16 56.0	0.999 6444
	8	5842.5	194 22 14.43	+0.67	12 52 54.59	− 5 39 53.1	0.999 3516
	9	5843.5	195 21 26.77	+0.70	12 56 34.16	− 6 02 45.8	0.999 0598
	10	5844.5	196 20 41.00	+0.71	13 00 14.14	− 6 25 33.8	0.998 7693
	11	5845.5	197 19 57.18	+0.69	13 03 54.58	− 6 48 16.6	0.998 4802
	12	5846.5	198 19 15.35	+0.64	13 07 35.49	− 7 10 54.0	0.998 1927
	13	5847.5	199 18 35.56	+0.57	13 11 16.89	− 7 33 25.5	0.997 9069
	14	5848.5	200 17 57.86	+0.48	13 14 58.80	− 7 55 50.9	0.997 6228
	15	5849.5	201 17 22.29	+0.37	13 18 41.26	− 8 18 09.8	0.997 3405
	16	5850.5	202 16 48.89	+0.26	13 22 24.27	− 8 40 21.8	0.997 0600
	17	5851.5	203 16 17.71	+0.14	13 26 07.86	− 9 02 26.5	0.996 7812
	18	5852.5	204 15 48.78	+0.01	13 29 52.05	− 9 24 23.5	0.996 5041
	19	5853.5	205 15 22.11	−0.10	13 33 36.86	− 9 46 12.5	0.996 2285
	20	5854.5	206 14 57.75	−0.20	13 37 22.30	−10 07 53.1	0.995 9543

Examples of Modern Almanac Data

From the Japanese Nautical Almanac (JHOD) :

2011 　　10 月 4 日 　　月齢 Age 6.5 d 　　277

☉ 太陽

U (h)	E☉ (h m s)	d (° ′)	d の P.P. (h m)	(′)
0	12 11 02	S 4 07.7	0 00	0.0
2	12 11 03	S 4 09.6	10	0.2
4	12 11 05	S 4 11.6	20	0.3
6	12 11 06	S 4 13.5	30	0.5
8	12 11 08	S 4 15.4	40	0.6
10	12 11 09	S 4 17.4	0 50	0.8
12	12 11 11	S 4 19.3	1 00	1.0
14	12 11 13	S 4 21.2	10	1.1
16	12 11 14	S 4 23.1	20	1.3
18	12 11 16	S 4 25.1	30	1.4
20	12 11 17	S 4 27.0	40	1.6
22	12 11 19	S 4 28.9	1 50	1.8
24	12 11 20	S 4 30.8	2 00	1.9

視半径 S.D. 16′ 01″

✳ 恒星 U = 0h の値

No.		E✳ (h m s)	d (° ′)
1	Polaris	22 01 23	N89 18.8
2	Kochab	9 58 45	N74 06.6
3	Dubhe	13 44 57	N61 41.1
4	β Cassiop.	0 39 30	N59 13.1
5	Merak	13 46 50	N56 19.0
6	Alioth	11 54 51	N55 53.8
7	Schedir	0 08 08	N56 36.3
8	Mizar	11 25 00	N54 51.9
9	α Persei	21 24 09	N49 54.1
10	Benetnasch	11 01 23	N49 15.4
11	Capella	19 31 46	N46 00.4
12	Deneb	4 07 30	N45 19.7
13	Vega	6 12 01	N38 48.1
14	Castor	17 14 00	N31 51.6
15	Alpheratz	0 40 20	N29 09.6

P 惑星 — U, E_P, d; P.P. E_P d

♀ 金星 正中時 Tr. 12h 39m

U (h)	E_P (h m s)	d (° ′)	P.P. (h m)	E_P (s)	d (′)
0	11 21 11	S 8 19.7	0 00	0	0.0
2	11 21 07	S 8 22.1	10	0	0.2
4	11 21 04	S 8 24.6	20	1	0.4
6	11 21 00	S 8 27.0	30	1	0.6
8	11 20 57	S 8 29.5	40	1	0.8
10	11 20 53	S 8 31.9	0 50	1	1.0
12	11 20 50	S 8 34.3	1 00	2	1.2
14	11 20 47	S 8 36.8	10	2	1.4
16	11 20 43	S 8 39.2	20	2	1.6
18	11 20 40	S 8 41.6	30	3	1.8
20	11 20 36	S 8 44.1	40	3	2.0
22	11 20 33	S 8 46.5	1 50	3	2.2
24	11 20 29	S 8 48.9	2 00	3	2.4

♂ 火星 正中時 Tr. 7h 57m

U (h)	E_P (h m s)	d (° ′)	P.P. (h m)	E_P (s)	d (′)
0	16 02 27	N19 08.2	0 00	0	0.0
2	16 02 35	N19 07.5	10	1	0.1
4	16 02 42	N19 06.8	20	1	0.1
6	16 02 50	N19 06.1	30	2	0.2
8	16 02 58	N19 05.4	40	3	0.2
10	16 03 05	N19 04.6	0 50	3	0.3
12	16 03 13	N19 03.9	1 00	4	0.4
14	16 03 21	N19 03.2	10	4	0.4
16	16 03 28	N19 02.5	20	5	0.5
18	16 03 36	N19 01.8	30	6	0.5
20	16 03 44	N19 01.1	40	6	0.6
22	16 03 51	N19 00.4	1 50	7	0.7
24	16 03 59	N18 59.7	2 00	8	0.7

☾ 月 正中時 Tr. 18h 28m

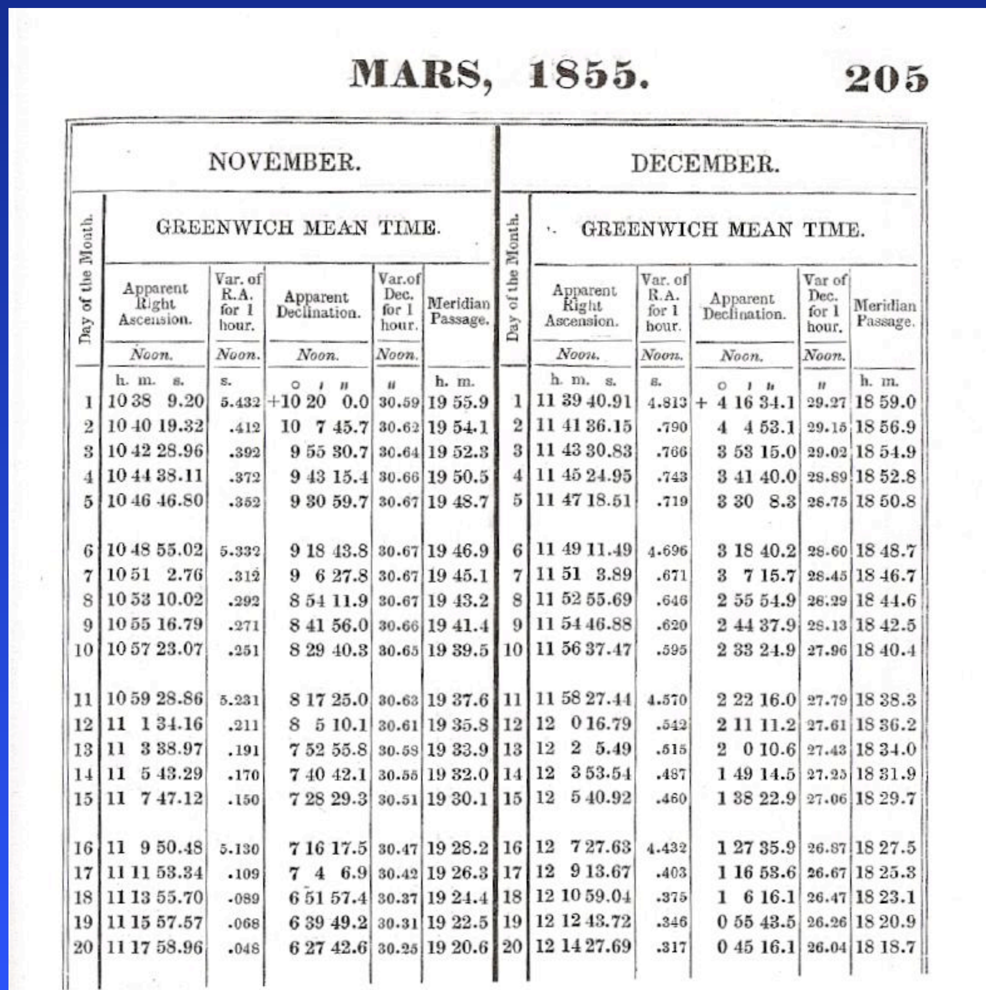
U (h)	E☾ (h m s)	d (° ′)
0	6 11 43	S21 14.9
	6 10 38	S21 12.5
1	6 09 32	S21 10.0
	6 08 27	S21 07.5
2	6 07 22	S21 04.9
	6 06 17	S21 02.4
3	6 05 12	S20 59.8
	6 04 07	S20 57.1
4	6 03 02	S20 54.5
	6 01 57	S20 51.8
5	6 00 52	S20 49.1
	5 59 47	S20 46.4
H.P. 57′.4 ,	S.D. 15′ 38″	
6	5 58 43	S20 43.6
	5 57 38	S20 40.8
7	5 56 34	S20 38.0
	5 55 29	S20 35.2
8	5 54 25	S20 32.3
	5 53 21	S20 29.4
9	5 52 17	S20 26.5
	5 51 13	S20 23.5
10	5 50 09	S20 20.5
	5 49 05	S20 17.5
11	5 48 01	S20 14.5
	5 46 58	S20 11.5
H.P. 57′.1 ,	S.D. 15′ 34″	
12	5 45 54	S20 08.4
	5 44 51	S20 05.3
13	5 43 47	S20 02.1
	5 42 44	S19 59.0
14	5 41 41	S19 55.8
	5 40 37	S19 52.6

P.P.

(m)	E☾ (s)	d (′)
1	2	0.1
2	4	0.2
3	6	0.3
4	9	0.4
5	11	0.5
6	13	0.6
7	15	0.6
8	17	0.7
9	19	0.8
10	22	0.9
11	24	1.0
12	26	1.1
13	28	1.2
14	30	1.3
15	32	1.4
16	34	1.5
17	37	1.6
18	39	1.7
19	41	1.8
20	43	1.8
21	45	1.9
22	47	2.0
23	49	2.1
24	52	2.2
25	54	2.3
26	56	2.4
27	58	2.5
28	60	2.6
29	62	2.7
30	65	2.8
1	2	0.1
2	4	0.2
3	6	0.3
4	8	0.5
5	10	0.6

Example of Old Almanac Data

From the first *American Ephemeris and Nautical Almanac* (US NAO) :



MARS, 1855. 205

Day of the Month.	NOVEMBER. Apparent Right Ascension. Noon. h. m. s.	Var. of R.A. for 1 hour. Noon. s.	Apparent Declination. Noon. ° ′ ″	Var. of Dec. for 1 hour. Noon. ″	Meridian Passage. h. m.	Day of the Month.	DECEMBER. Apparent Right Ascension. Noon. h. m. s.	Var. of R.A. for 1 hour. Noon. s.	Apparent Declination. Noon. ° ′ ″	Var. of Dec. for 1 hour. Noon. ″	Meridian Passage. h. m.
1	10 38 9.20	5.432	+10 20 0.0	30.59	19 55.9	1	11 39 40.91	4.813	+ 4 16 34.1	29.27	18 59.0
2	10 40 19.32	.412	10 7 45.7	30.62	19 54.1	2	11 41 36.15	.790	4 4 53.1	29.15	18 56.9
3	10 42 28.96	.392	9 55 30.7	30.64	19 52.3	3	11 43 30.83	.766	3 53 15.0	29.02	18 54.9
4	10 44 38.11	.372	9 43 15.4	30.66	19 50.5	4	11 45 24.95	.743	3 41 40.0	28.89	18 52.8
5	10 46 46.80	.352	9 30 59.7	30.67	19 48.7	5	11 47 18.51	.719	3 30 8.3	26.75	18 50.8
6	10 48 55.02	5.332	9 18 43.8	30.67	19 46.9	6	11 49 11.49	4.696	3 18 40.2	28.60	18 48.7
7	10 51 2.76	.312	9 6 27.8	30.67	19 45.1	7	11 51 3.89	.671	3 7 15.7	28.45	18 46.7
8	10 53 10.02	.292	8 54 11.9	30.67	19 43.2	8	11 52 55.69	.646	2 55 54.9	26.29	18 44.6
9	10 55 16.79	.271	8 41 56.0	30.66	19 41.4	9	11 54 46.88	.620	2 44 37.9	28.13	18 42.5
10	10 57 23.07	.251	8 29 40.3	30.65	19 39.5	10	11 56 37.47	.595	2 33 24.9	27.96	18 40.4
11	10 59 28.86	5.231	8 17 25.0	30.63	19 37.6	11	11 58 27.44	4.570	2 22 16.0	27.79	18 38.3
12	11 1 34.16	.211	8 5 10.1	30.61	19 35.8	12	12 0 16.79	.542	2 11 11.2	27.61	18 36.2
13	11 3 38.97	.191	7 52 55.8	30.58	19 33.9	13	12 2 5.49	.515	2 0 10.6	27.43	18 34.0
14	11 5 43.29	.170	7 40 42.1	30.55	19 32.0	14	12 3 53.54	.487	1 49 14.5	27.25	18 31.9
15	11 7 47.12	.150	7 28 29.3	30.51	19 30.1	15	12 5 40.92	.460	1 38 22.9	27.06	18 29.7
16	11 9 50.48	5.130	7 16 17.5	30.47	19 28.2	16	12 7 27.63	4.432	1 27 35.9	26.87	18 27.5
17	11 11 53.34	.109	7 4 6.9	30.42	19 26.3	17	12 9 13.67	.403	1 16 53.6	26.67	18 25.3
18	11 13 55.70	.089	6 51 57.4	30.37	19 24.4	18	12 10 59.04	.375	1 6 16.1	26.47	18 23.1
19	11 15 57.57	.068	6 39 49.2	30.31	19 22.5	19	12 12 43.72	.346	0 55 43.5	26.26	18 20.9
20	11 17 58.96	.048	6 27 42.6	30.25	19 20.6	20	12 14 27.69	.317	0 45 16.1	26.04	18 18.7

(Both months: GREENWICH MEAN TIME.)

A Brief History of Time Scales

- Until 1930s — Earth's rotation defines time (Greenwich Mean Time, Universal Time).
- 1930s — Irregularities in Earth's rotation first definitively measured.
- 1950s — "Ephemeris Time" (ET) established by IAU as a time scale for solar system ephemerides that are independent of the Earth's rotation.

  First practical atomic clocks.
- 1960s — New high-precision observational techniques (radar, LLR, VLBI, spacecraft) require relativity in time scales and data analysis.

  SI second defined, matching ET second.

A Brief History of Time Scales (cont.)

- **1972** — **UTC with 1s leap seconds, kept within 0.9 s of UT1, established.**

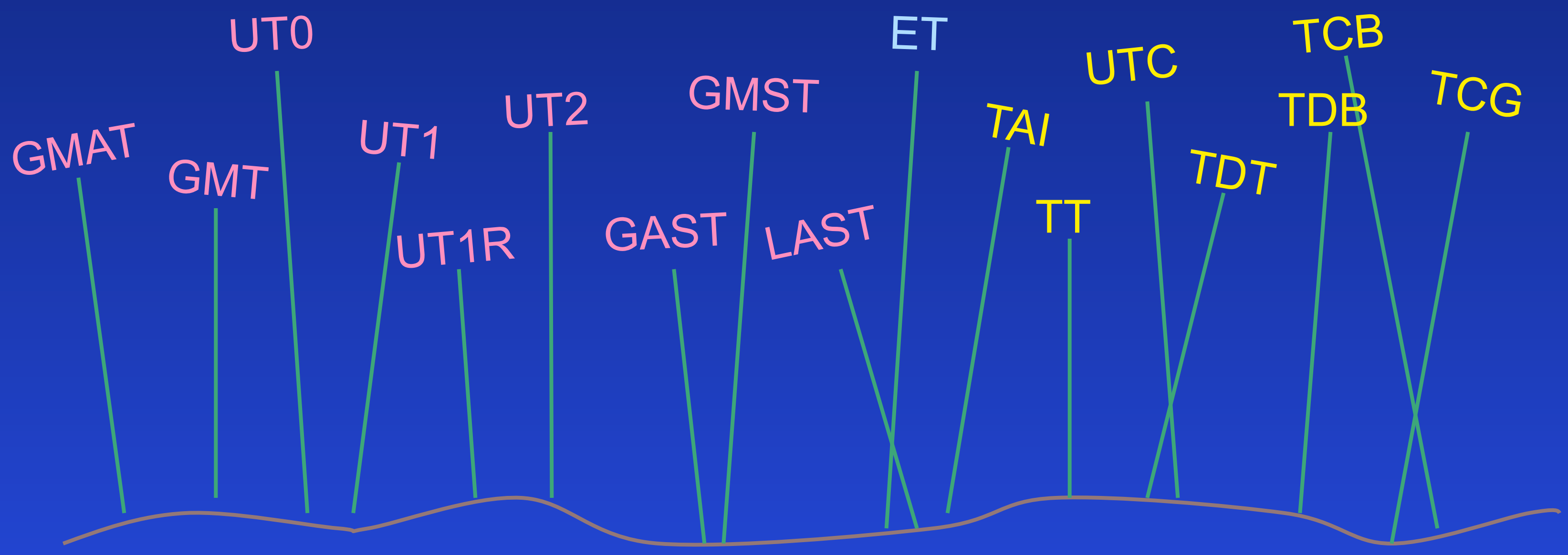
  International Atomic Time (TAI) introduced.

  UTC and TAI both use the SI second.

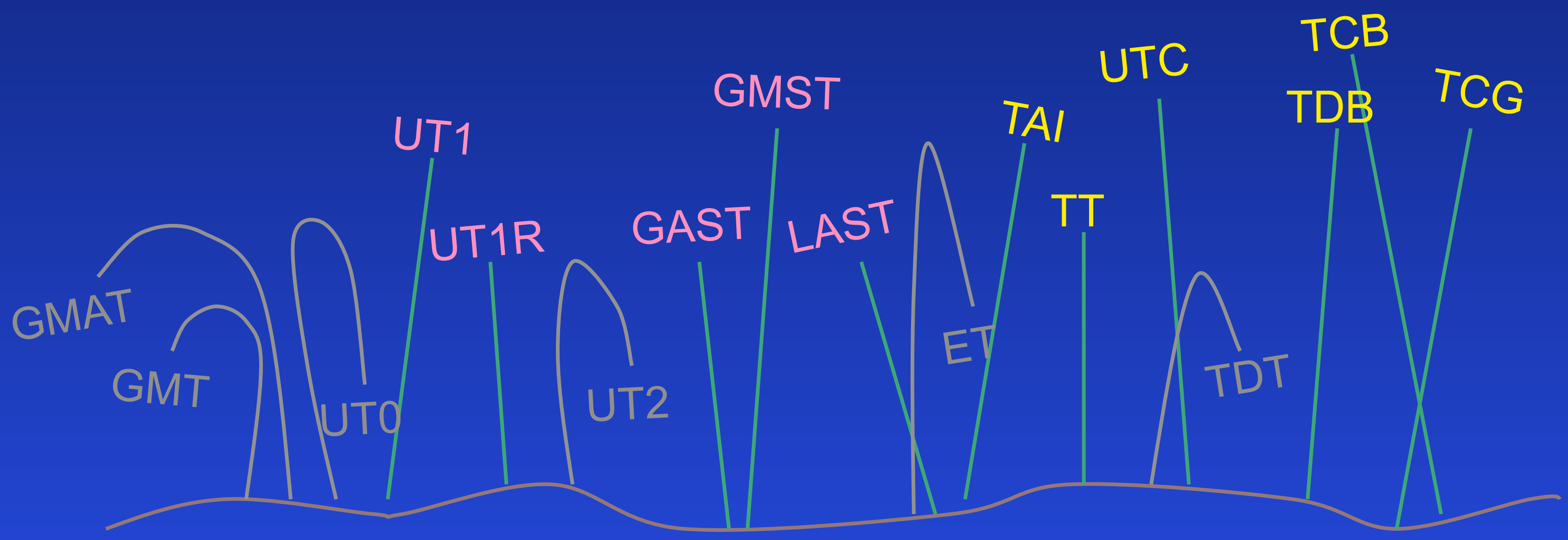
- **1976, 1979** — **IAU splits ET into TDT and TDB (for geocentric and barycentric ephemerides, respectively).**

- **1991-2006** — **IAU revisits relativistic basis of reference systems and times scales; establishes Terrestrial Time (TT), Geocentric Coordinate Time (TCG), Barycentric Coordinate Time (TCB), then redefines TT and TDB.**

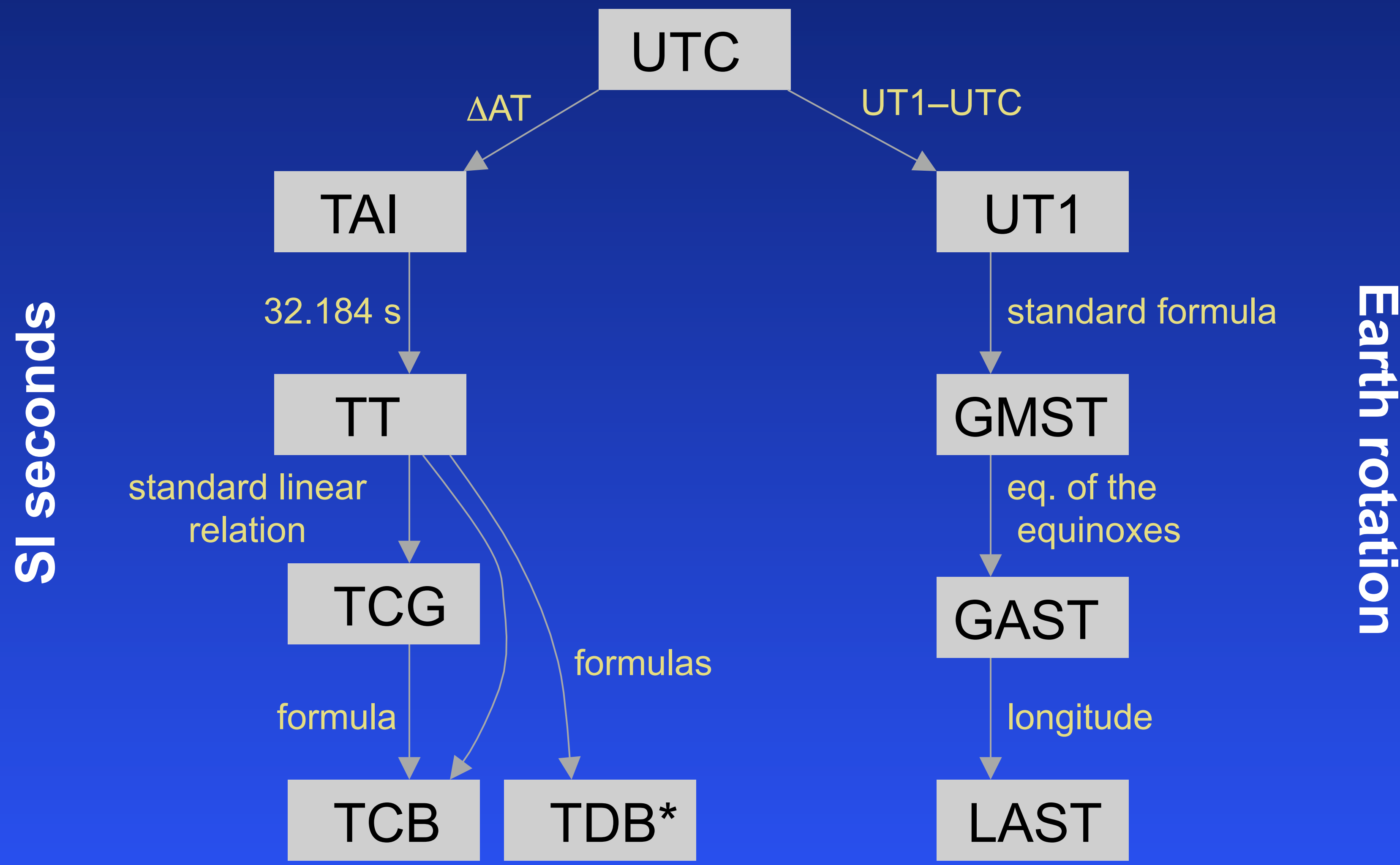
A Child's Garden of Time Scales



A Child's Garden of Time Scales

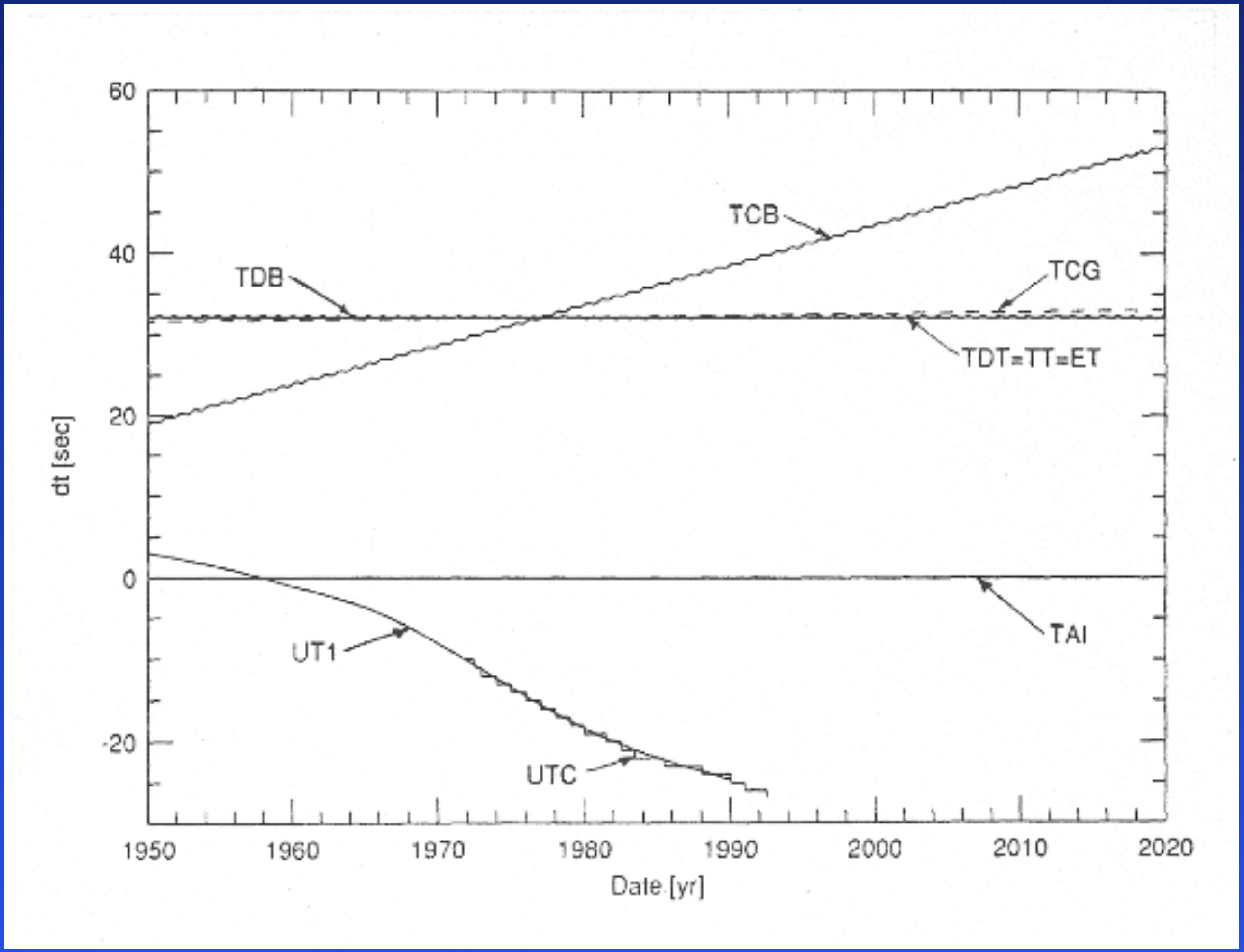


Time Scales from a User's Viewpoint



* Based on SI seconds on the geoid, not the barycenter

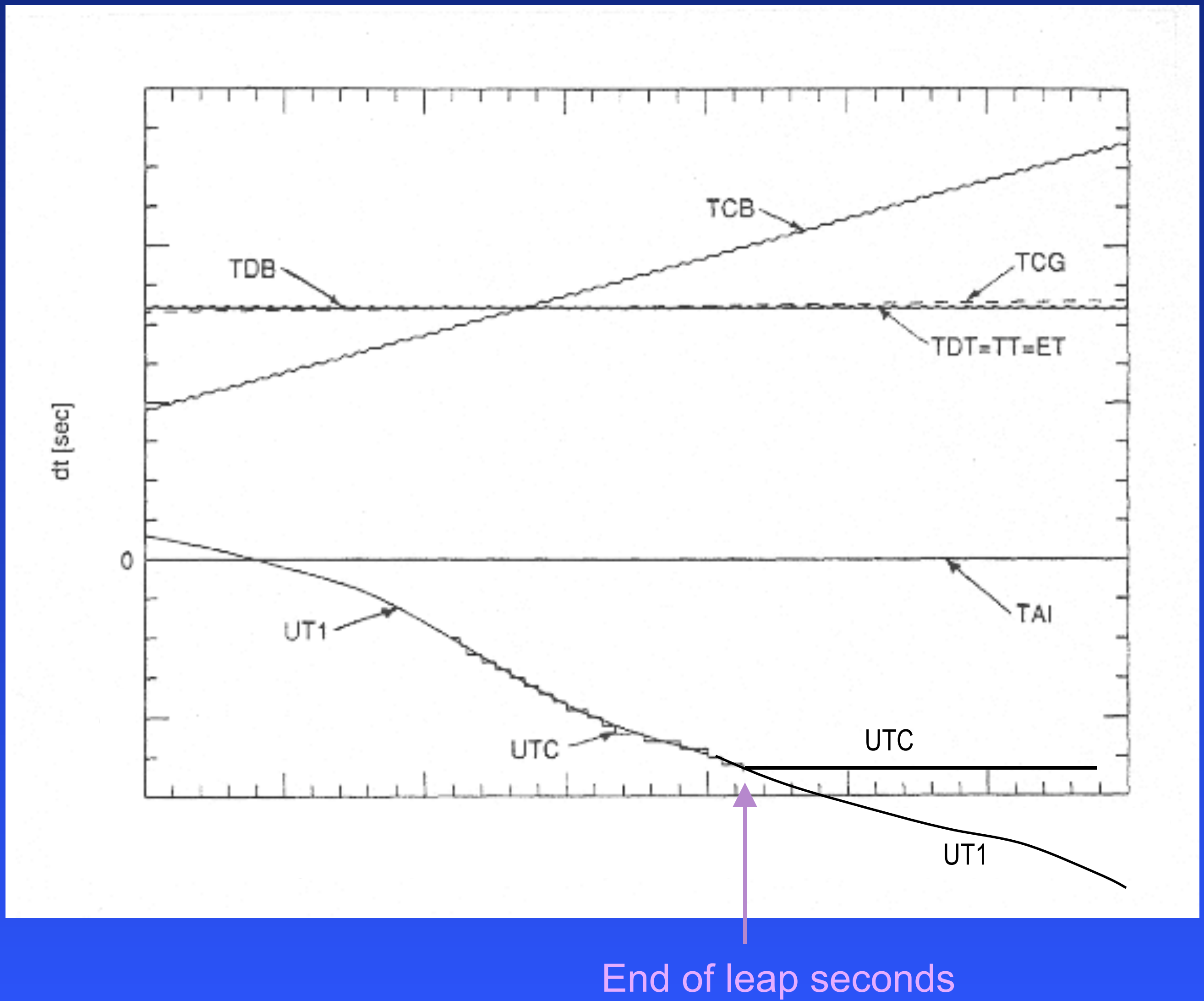
Differences Between Time Scales



From Seidelmann & Fukushima (1992)
Astron. & Astrophys. **265,** 833

Differences Between Time Scales

if UTC is redefined

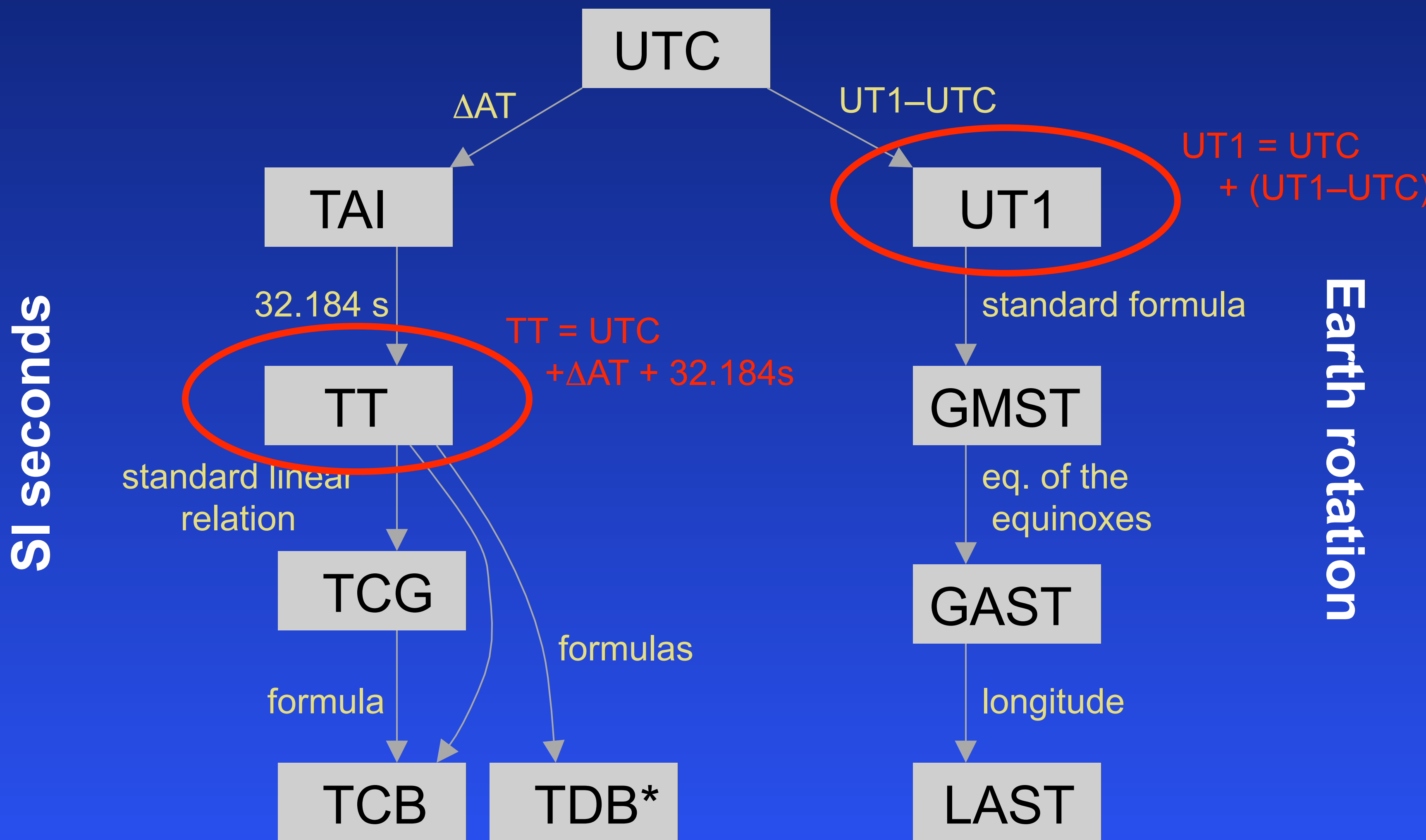


Time Scales Used in Modern Almanacs

(as the independent argument in the tabulations)

- **UT1 (often labeled simply as UT or Universal Time).**
  - For data that depend on the rotation of the Earth (including the data fro celestial navigation).
  - Also for data of public interest (times of Moon phases, solstices and equinoxes, etc.) that are not given to high precision.
- **TT (Terrestrial Time).**
  - For data that are independent of the rotation of the Earth (e.g., geocentric celestial coordinates of the Sun, Moon, and planets).
- **TDB (Barycentric Dynamical Time).**
  - Less frequently used — For heliocentric or barycentric data closely related to the fundamental solar system ephemerides (e.g., orbital elements of the planets).

Time Scales from a User's Viewpoint

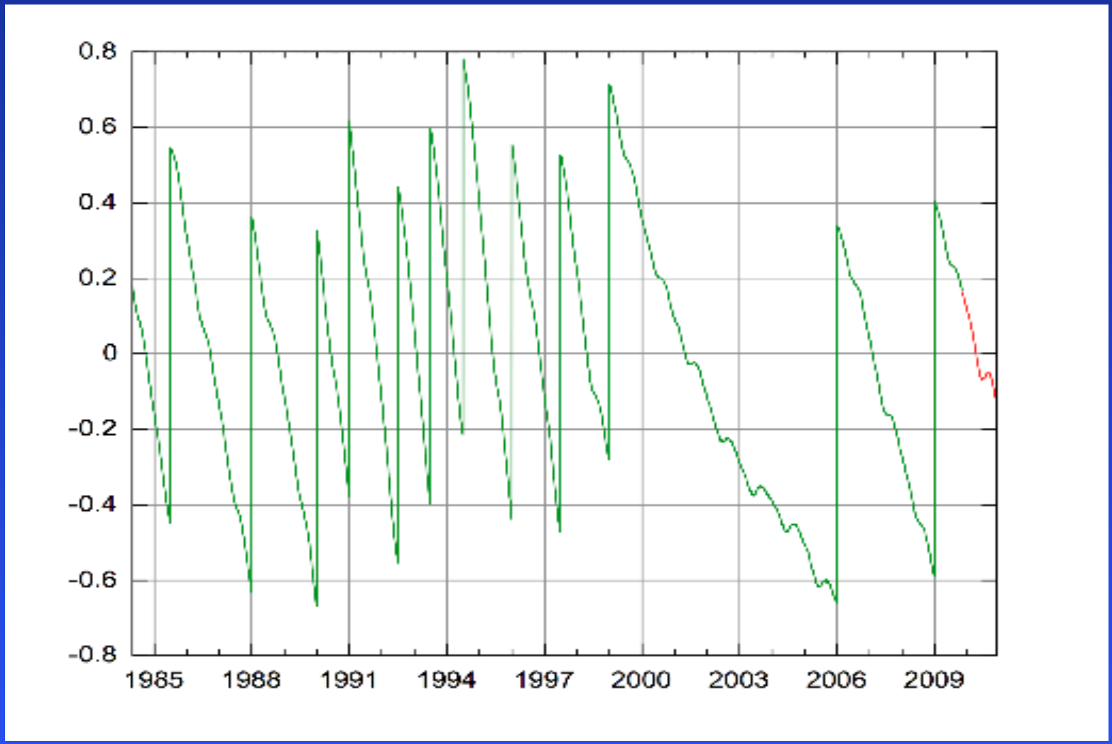


* Based on SI seconds on
the geoid, not the barycenter

The Universal Time Ambiguity

Many users can now assume UT1=UTC for their applications; they don't even have to know that there are two kinds of Universal Time.

UT1–UTC in seconds



Note that |UT1–UTC| Rarely exceeds 0.5 s

Graph from Wikipedia

What if UTC is Redefined?

- **Option 1: Do nothing.**
  - UTC is not used in the computation of ephemerides, nor is it used within the almanacs.
  - It has always been the user's responsibility to convert from his own time scale (e.g., UTC) to the time scales used in the almanacs.
  - However…
    - Many users are now able to assume UT1=UTC with negligible error for their applications (error in UT1 ≤ 0.9 s).
    - That approximation will no longer hold if leap seconds are discontinued from UTC, and the IERS value of UT1–UTC will have to be applied — more user education and very explicit instructions on this will be needed. "UT" tabulations would have to be re-labeled "UT1."

What if UTC is Redefined?

- **Option 2: Switch to UTC-based tabulations.**
  - Not a problem for TT-based data, because UTC and TT would simply be a constant offset from each other (about 70 s), which would never change.
  - UT1-based data that are printed would require predicting UT1–UTC from 2 to 2.5 years in the future. (IERS currently estimates this can be done to better than 0.1 s accuracy.)
    - Would still have to provide a correction table so the user can supply a better value of (UT1–UTC) close to the time the data is actually needed (if his accuracy requires it).
  - UT1-based data that are provided online could be continually updated with better values of (UT1–UTC); for future data, could provide a prediction that the user could change.

Predicting UT1–UTC Into the Future

- **IERS provides predictions in tabular form for one year beyond current date.**
- **IERS projection beyond one year:**

$$UT1–UTC = –0.3617 – 0.00073\ (MJD – 55834) – (UT2–UT1)$$

with error

$$\sigma(t) = 0.00025\ (MJD – 55826)^{0.75}$$

which amounts to

0.012 s at 6 months
0.021 s at 1 year
0.035 s at 2 years
0.048 s at 3 years

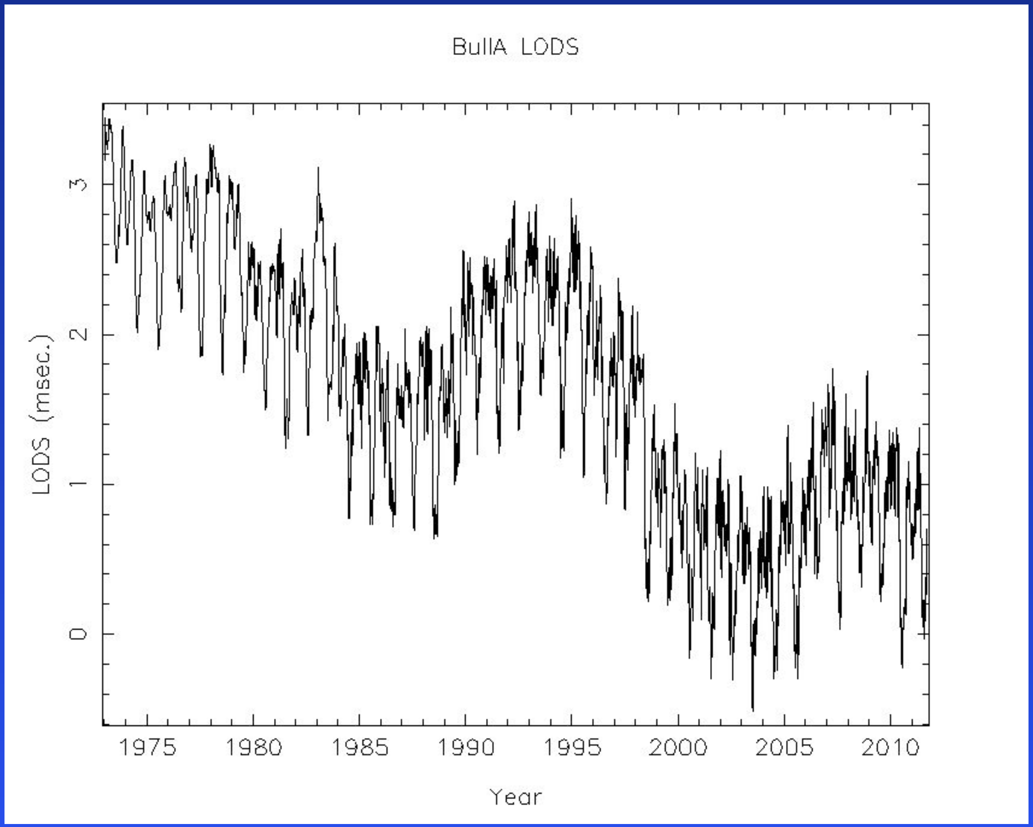
Note: MJD 55826 is 2011 Sept 22
MJD 55834 is 2011 Sept 30

but these errors are undoubtedly underestimated.

Predicting UT1–UTC into the Future

Probably feasible with an error < 0.4 s for 2.5-year projection. This idea needs to be tested.

Excess LoD in milliseconds (= rate of UT1–TAI)



Outside of the annual term, LoD trend is mostly linear for several years at a time.

Graph from USNO EO Dept. web site

Conclusions

- **This history of astronomical time scales is confusing and not always progressive.**
- **Most current users of astronomical and navigational almanacs have to deal with only two time scales: TT and UT.**
- **UT means UT1, but is deliberately ambiguous because for many users, UT1=UTC.**
- **If leap seconds are removed from UTC, the UT1=UTC assumption is no longer valid, leaving two choices:**
  - Re-label "UT" as "UT1" and educate users about the conversion from UTC to UT1.
  - Change "UT" tabulations to be based on UTC, and use projected values of UT1–UTC to compute the data.

Time is what prevents everything from happening at once.

— John Archibald Wheeler