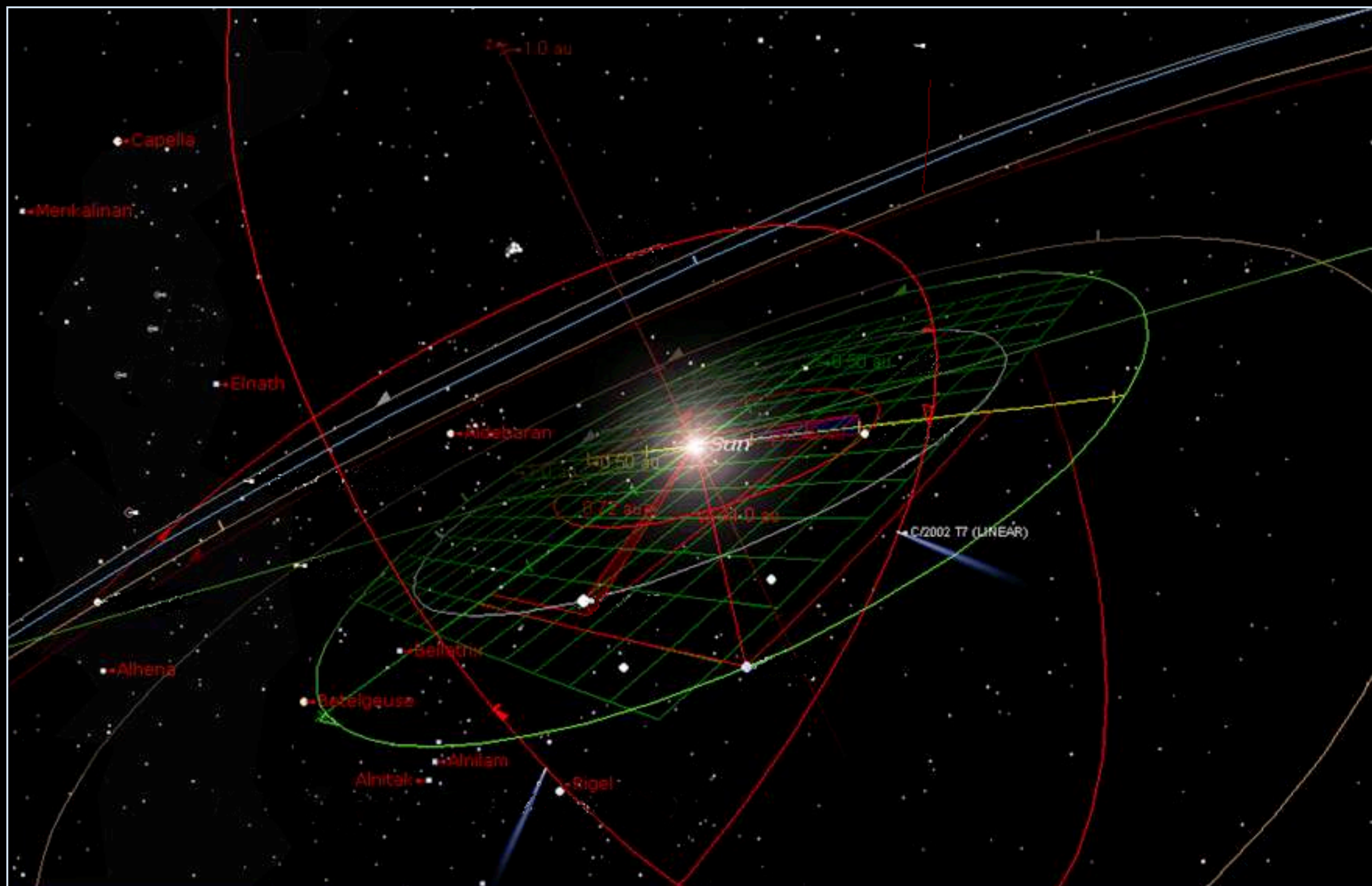
Jet Propulsion Laboratory
California Institute of Technology

JPL Horizons Overview and Future Plans



Jon Giorgini

LSST Solar System Readiness (Virtual) Sprint

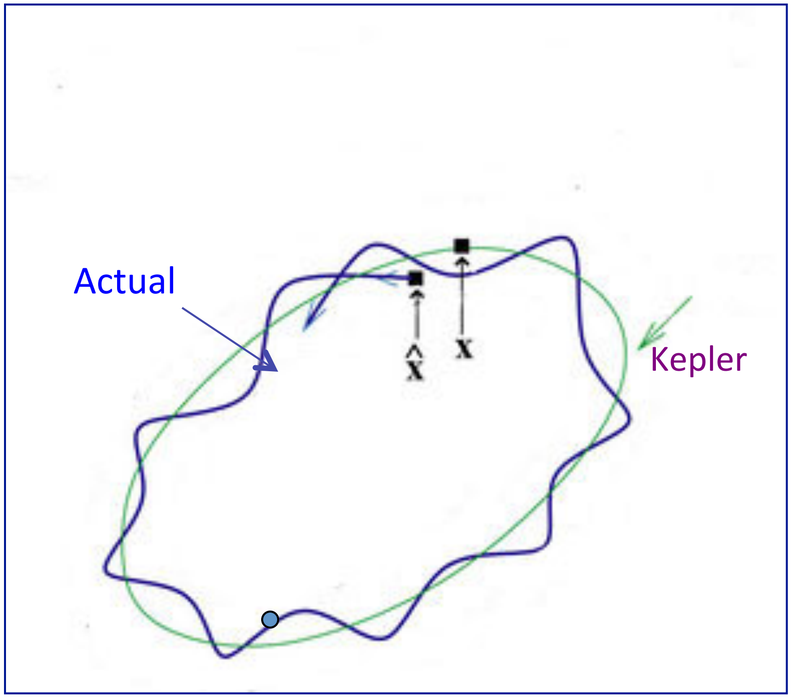
2020-June-17

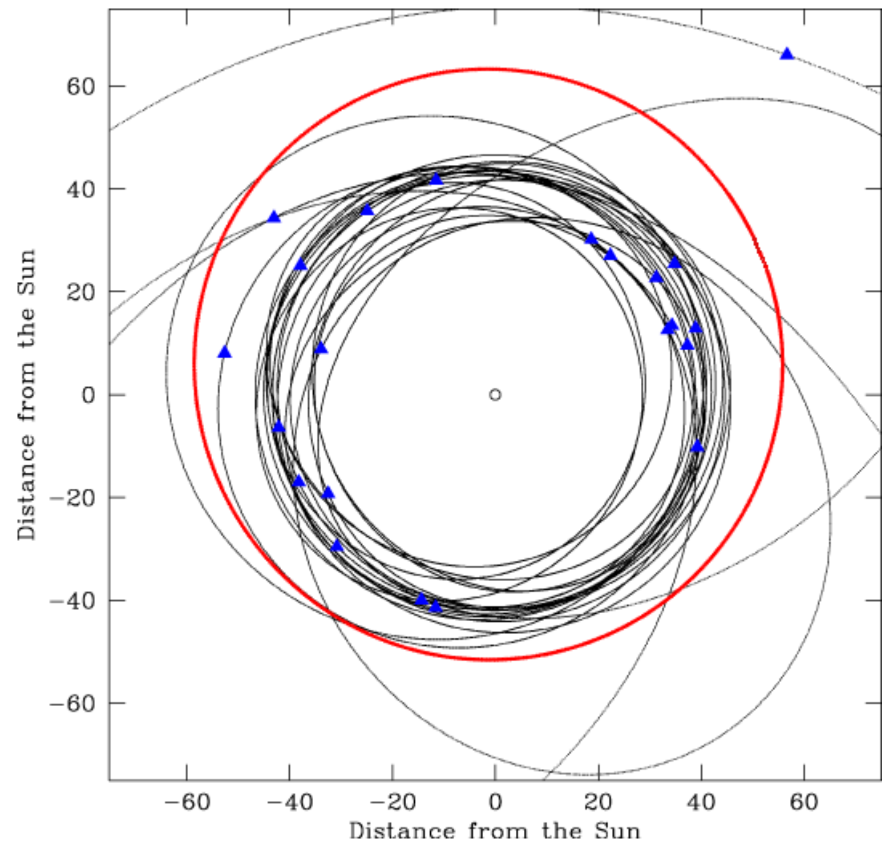
Plan

1. Solar system dynamics: what's the problem?
2. Overview of SSD activity & Horizons
3. What Horizons provides
   - Object look-up & small-body parameter searches
   - List objects in field-of-view
   - Small-body close-approach tables
   - Observer tables
   - Vector tables
   - Osculating element tables
   - Small-body SPK file generation
4. Horizons interfaces
   - Command-line
   - Browser
   - E-mail
   - Automation: CGI and scripting
5. Future developments & LSST
6. DASTCOM
7. Resource list

Kepler (16th century) vs. Now

(general relativity & perturbations)





$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \qquad b^2 = a^2(1 - e^2)$$

$$E - e\sin(E) = (t - T)n$$

$$n = \frac{2\pi}{P}$$

$$r = a(1 - e\cos E)$$

$$\tan(\frac{v}{2}) = \sqrt{\frac{1+e}{1-e}}\tan(\frac{E}{2})$$

Actual: *n*-body Equations of Motion

Acceleration @ point

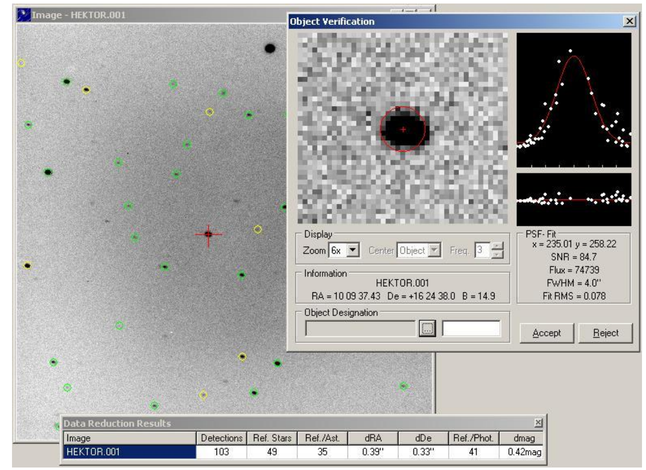
$$
\begin{aligned}
\boxed{\frac{d^2\mathbf{r}_i}{dt^2}} = & \underbrace{\sum_{j\neq i}\frac{\mu_j(\mathbf{r}_j-\mathbf{r}_i)}{r_{ij}^3}}_{\text{Newtonian}}\Bigg\{1-2(\underline{\beta}+\underline{\gamma})/c^2\sum_{k\neq i}\frac{\mu_k}{r_{ik}}-(2\underline{\beta}-1)/c^2\sum_{k\neq j}\frac{\mu_k}{r_{jk}} \\
& +\underline{\gamma}(v_i/c)^2+(1+\underline{\gamma})(v_j/c)^2-2(1+\underline{\gamma})/c^2\frac{d\mathbf{r}_i}{dt}\cdot\frac{d\mathbf{r}_j}{dt} \\
& -(3/2c^2)(\mathbf{r}_i-\mathbf{r}_j)^2(d\mathbf{r}_j/dt)^2+1/2c^2(\mathbf{r}_j-\mathbf{r}_i)\frac{d\mathbf{r}_j}{dt^2}\Bigg\} \\
& +c^{-2}\sum_{j\neq i}\frac{\mu_j}{r_{ij}^3}\left\{(\mathbf{r}_i-\mathbf{r}_j)\left[(2+2\underline{\gamma})\frac{d\mathbf{r}_i}{dt}-(1+2\underline{\gamma})\frac{d\mathbf{r}_j}{dt}\right]\right\}\left(\frac{d\mathbf{r}_i}{dt}-\frac{d\mathbf{r}_j}{dt}\right) \\
& +(3+4\underline{\gamma})/2c^2\sum_{j\neq i}\frac{\mu_j}{r_{ij}}\cdot\frac{d^2\mathbf{r}_j}{dt^2}+\underline{\sum_n \mathbf{a}_{in}}
\end{aligned}
$$

Relativity corrections

Other accelerations:
Yarkovsky, solar pressure,
outgassing A1, A2, A3

- Parameterized post-Newtonian (PPN) form
  - β … non-linearity in gravity superposition (G.R.= 1.0)
  - γ … space curvature produced by unit rest mass (G.R.= 1.0)
- Numerically integrated 2nd order vector differential equations describing acceleration at an instant

Small-body Orbit Solutions



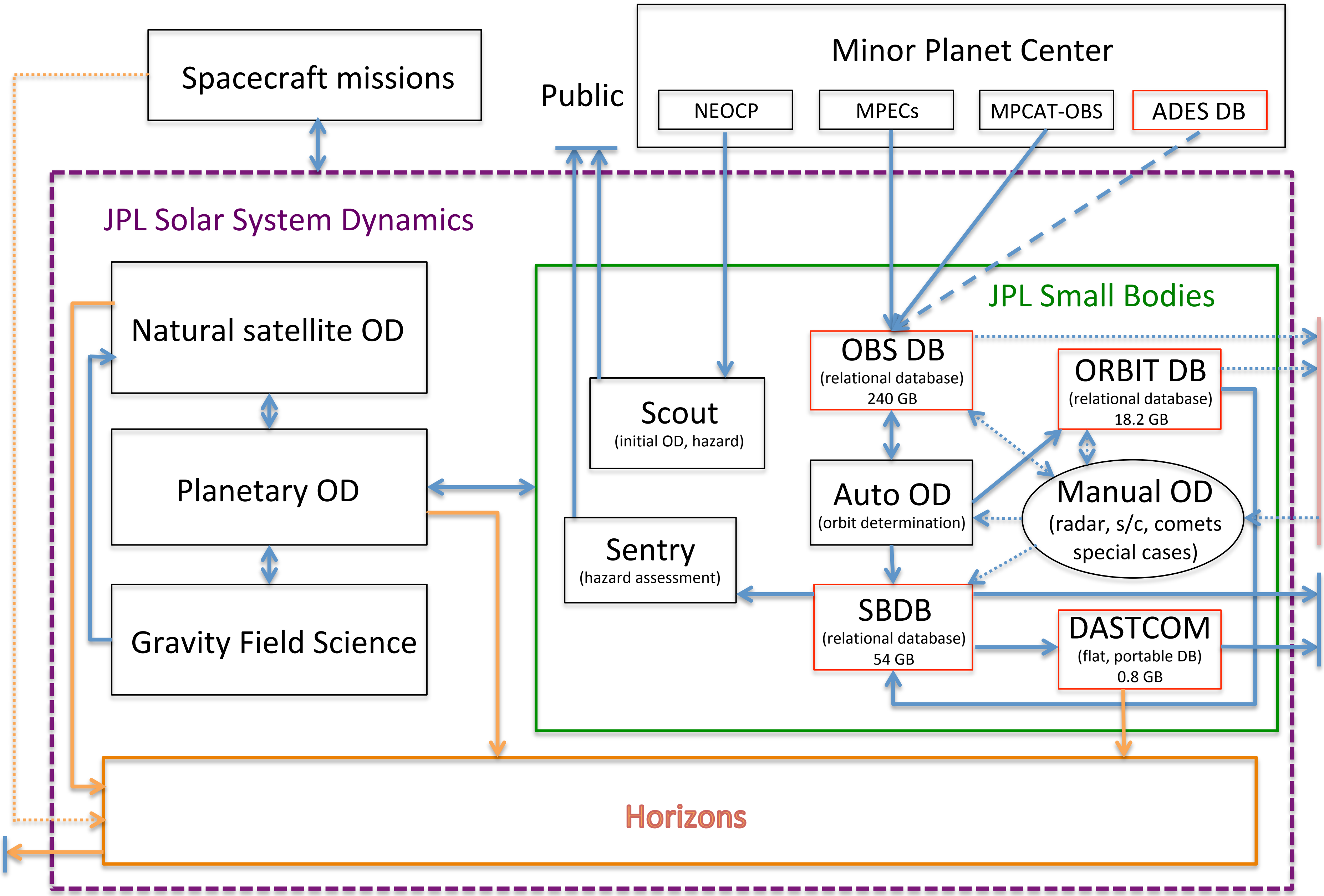
Current optical telescopes

- ~2 million RA/DEC angular measurements per month
- 1000 - 5000 new objects per month
- Reported measurements *filtered, linked, published* at Minor Planet Center

JPL filters, debiases, and fits MPC astrometry (+ radar + IOTA occultation + spacecraft)

- Nominal weights from observing report, or history & catalog (Veres et al., 2017)
- Least-squares estimate of state, dynamics & square-root covariance to database
- Hazard assessment (Scout and Sentry systems)
- 100,000-250,000+ orbit updates/month (NEOs: 3000-4000). Automated, except (1) spacecraft targets, (2) radar cases, (3) research cases, (4) some comets
- Hourly export from MySQL SBDB to DASTCOM database (portable flat file) DASTCOM: data & *initial conditions* for Horizons

Organization & Data Flow



What is Horizons?

- Publishes JPL orbit solutions (and other's) since 1996 ... when there were 20,000 known asteroids (47x growth since start)
- Derives customized trajectory-related data of solar system objects:

  Any planet (8), natural satellite (209+), asteroid (958,698+), comet (3646+), spacecraft (167+), E-M-S Lagrange point, barycenter, user-defined heliocentric object - OR - surface coordinates on remote body (crater)

- For observers, observatories, dynamicists, researchers, public: planning, data-reduction, data-acquisition system "back-end", mission-design and operations (tracking for space-based observatories around solar system)
- No account, password, or registration to access
  ~9500 unique users per month, 10 million products per month
- Network-accessible engine handles requests from multiple interfaces ...

  1. Command-line ... interactive with terminal prompting
  2. Web browser interface (A. Chamberlin)
  3. E-mail command files
  4. CGI & script (automation)

What Horizons Provides

(dynamically generated on request)

A) ASCII tables

1. Parameter search (small-body database, 44+ match parameters)
2. Objects in field-of-view (currently e-mail only, more soon)
3. Closest-approach tables

   Small-body encounters with planets & 16 largest asteroids

Ephemerides ...

4. Observer tables:

   Plane-of-sky tracking, visibility, disc, orbit, uncertainties, more
5. Vector tables (dynamics, uncertainties)
6. Osculating orbital element tables (geometry)

B) BINARY Files

7. SPK files (asteroids and comets only)

   Time-continuous trajectory integrator states (machine-precision)

4. Observer Tables

(w/perspective & aberrations as a function of time)

Pick target ("get ephemeris of...")

Any planet (8), natural satellite (209+), asteroid (958,698+), comet (3646+), spacecraft (167+), E-M-S Lagrange point, barycenter, user-defined heliocentric object
- OR - surface coordinates on remote body (crater)

Pick observing location (" ... as seen from ...")

Any point on/in planet, natural satellite, spacecraft, dynamical point, some asteroids

Set output time-span and interval:

1. Uniform time-step (time or calendar)
2. Target moved X arcseconds since last output
3. List of discrete times (browser, email, cgi)
4. Rise-transit-set-only

- UT or TT time-scales: calendar, Julian Day Number
- Solar presence: twilight and dawn markers
- Lunar presence marker
- Rise-set-transit marker

Date_(UT)	HR:MN		R.A._ (ICRF)_	DEC	
2020-Jun-17	06:00		28.24565	-12.00217	..
2020-Jun-17	06:30	r	28.25289	-12.00123	..
2020-Jun-17	07:00		28.26012	-12.00030	..
2020-Jun-17	07:30		28.26734	-11.99938	..
2020-Jun-17	08:00	m	28.27454	-11.99845	..
2020-Jun-17	09:30	m	28.29605	-11.99566	..
2020-Jun-17	10:00	m	28.30320	-11.99473	..
2020-Jun-17	10:30	Am	28.31034	-11.99379	..
2020-Jun-17	10:40	Nm	28.31271	-11.99348	..
2020-Jun-17	11:00	Cm	28.31746	-11.99286	..
2020-Jun-17	11:30	*m	28.32459	-11.99192	..
2020-Jun-17	12:00	*m	28.33170	-11.99099	..
2020-Jun-17	12:30	*m	28.33881	-11.99005	..
2020-Jun-17	13:00	*t	28.34592	-11.98910	..
2020-Jun-17	18:30	*m	28.42453	-11.97863	..
2020-Jun-17	19:00	*m	28.43174	-11.97767	..
2020-Jun-17	19:30	*s	28.43897	-11.97671	..

4. Observer Table Quantities

(all w/perspective & aberrations as a function of time)

```
 1. Astrometric RA & DEC
*2. Apparent RA & DEC
 3.   Rates: RA & DEC
*4. Apparent AZ & EL
 5.   Rates: AZ & EL
 6. Sat. X & Y, pos. ang
 7. Local app. sid. time
 8. Airmass & Extinction
 9. App vis mag & Surf brt
10. Illuminated fraction
11. Defect of illumin.
12. Sat. angle separ/vis
13. Target angular diam.
14. Obsrvr sub-lon & lat
15. Sun sub-lon & lat
16. Sub-Sun Pos Ang & Dis
 17. N. Pole Pos. Ang & Dis
 18. Helio eclip. lon & lat
 19. Sun range & range rate
 20. Obsrv range & rng rate
 21. Down-leg light-time
 22. Speed wrt Sun & obsrvr
 23. Sun-Obs-Targ ELONG ang
 24. Sun-Targ-Obs~PHASE ang
 25. Targ-Obsrv-Moon/Illum%
 26. Obs-Primary-Targ angle
 27. Radial & -vel posn.ang
 28. Orbit plane angle
 29. Constellation name
 30. Delta_T (TDB - UT)
*31. Obsrv eclip lon & lat
 32. North pole RA & DEC
 33. Galactic long. & lat.
 34. Local app. SOLAR time
 35. Earth -> site lt-time
>36. RA & DEC uncertainty
>37. POS error ellipse
>38. POS uncertainty (RSS)
>39. Range & rng-rate sig.
>40. Doppler/delay sigmas
 41. True anomaly angle
*42. Local app. hour angle
 43. PHASE angle & bisector
 44. Apprnt long Sun (L_s)
*45. Inertial app RA & DEC
 46.  Rate: Inertl RA & DEC
```

4. Observer Table Quantities

... pointing and tracking ...

```
 1. Astrometric RA & DEC
*2. Apparent RA & DEC
 3.   Rates: RA & DEC
*4. Apparent AZ & EL
 5.   Rates: AZ & EL
 6. Sat. X & Y, pos. ang
 7. Local app. sid. time
 8. Airmass & Extinction
 9. App vis mag & Surf brt
10. Illuminated fraction
11. Defect of illumin.
12. Sat. angle separ/vis
13. Target angular diam.
14. Obsrvr sub-lon & lat
15. Sun sub-lon & lat
16. Sub-Sun Pos Ang & Dis
17. N. Pole Pos. Ang & Dis
18. Helio eclip. lon & lat
19. Sun range & range rate
20. Obsrv range & rng rate
21. Down-leg light-time
22. Speed wrt Sun & obsrvr
23. Sun-Obs-Targ ELONG ang
24. Sun-Targ-Obs~PHASE ang
25. Targ-Obsrv-Moon/Illum%
26. Obs-Primary-Targ angle
27. Radial & -vel posn.ang
28. Orbit plane angle
29. Constellation name
30. Delta_T (TDB - UT)
*31. Obsrv eclip lon & lat
32. North pole RA & DEC
33. Galactic long. & lat.
34. Local app. SOLAR time
35. Earth -> site lt-time
>36. RA & DEC uncertainty
>37. POS error ellipse
>38. POS uncertainty (RSS)
>39. Range & rng-rate sig.
>40. Doppler/delay sigmas
41. True anomaly angle
*42. Local app. hour angle
43. PHASE angle & bisector
44. Apprnt long Sun (L_s)
*45. Inertial app RA & DEC
46.  Rate: Inertl RA & DEC
```

4. Observer Table Quantities

... visibility ...

1. Astrometric RA & DEC
*2. Apparent RA & DEC
3. Rates: RA & DEC
*4. Apparent AZ & EL
5. Rates: AZ & EL
6. Sat. X & Y, pos. ang
7. Local app. sid. time
8. Airmass & Extinction
9. App vis mag & Surf brt
10. Illuminated fraction
11. Defect of illumin.
12. Sat. angle separ/vis
13. Target angular diam.
14. Obsrvr sub-lon & lat
15. Sun sub-lon & lat
16. Sub-Sun Pos Ang & Dis
17. N. Pole Pos. Ang & Dis
18. Helio eclip. lon & lat
19. Sun range & range rate
20. Obsrv range & rng rate
21. Down-leg light-time
22. Speed wrt Sun & obsrvr
23. Sun-Obs-Targ ELONG ang
24. Sun-Targ-Obs~PHASE ang
25. Targ-Obsrv-Moon/Illum%
26. Obs-Primary-Targ angle
27. Radial & -vel posn.ang
28. Orbit plane angle
29. Constellation name
30. Delta_T (TDB - UT)
*31. Obsrv eclip lon & lat
32. North pole RA & DEC
33. Galactic long. & lat.
34. Local app. SOLAR time
35. Earth -> site lt-time
>36. RA & DEC uncertainty
>37. POS error ellipse
>38. POS uncertainty (RSS)
>39. Range & rng-rate sig.
>40. Doppler/delay sigmas
41. True anomaly angle
*42. Local app. hour angle
43. PHASE angle & bisector
44. Apprnt long Sun (L_s)
*45. Inertial app RA & DEC
46. Rate: Inertl RA & DEC

4. Observer Table Quantities

... target disc ...

1. Astrometric RA & DEC
*2. Apparent RA & DEC
3. Rates: RA & DEC
*4. Apparent AZ & EL
5. Rates: AZ & EL
6. Sat. X & Y, pos. ang
7. Local app. sid. time
8. Airmass & Extinction
9. App vis mag & Surf brt
10. Illuminated fraction
11. Defect of illumination
12. Sat. angle separ/vis
13. Target angular diam.
14. Obsrvr sub-lon & lat
15. Sun sub-lon & lat
16. Sub-Sun Pos Ang & Dis
17. N. Pole Pos. Ang & Dis
18. Helio eclip. lon & lat
19. Sun range & range rate
20. Obsrv range & rng rate
21. Down-leg light-time
22. Speed wrt Sun & obsrvr
23. Sun-Obs-Targ ELONG ang
24. Sun-Targ-Obs~PHASE ang
25. Targ-Obsrv-Moon/Illum%
26. Obs-Primary-Targ angle
27. Radial & -vel posn.ang
28. Orbit plane angle
29. Constellation name
30. Delta_T (TDB - UT)
*31. Obsrv eclip lon & lat
32. North pole RA & DEC
33. Galactic long. & lat.
34. Local app. SOLAR time
35. Earth -> site lt-time
>36. RA & DEC uncertainty
>37. POS error ellipse
>38. POS uncertainty (RSS)
>39. Range & rng-rate sig.
>40. Doppler/delay sigmas
41. True anomaly angle
*42. Local app. hour angle
43. PHASE angle & bisector
44. Apprnt long Sun (L_s)
*45. Inertial app RA & DEC
46. Rate: Inertl RA & DEC

4. Observer Table Quantities

... small-body statistical uncertainties ...

```
 1. Astrometric RA & DEC
*2. Apparent RA & DEC
 3.   Rates: RA & DEC
*4. Apparent AZ & EL
 5.   Rates: AZ & EL
 6. Sat. X & Y, pos. ang
 7. Local app. sid. time
 8. Airmass & Extinction
 9. App vis mag & Surf brt
10. Illuminated fraction
11. Defect of illumin.
12. Sat. angle separ/vis
13. Target angular diam.
14. Obsrvr sub-lon & lat
15. Sun sub-lon & lat
16. Sub-Sun Pos Ang & Dis
17. N. Pole Pos. Ang & Dis
18. Helio eclip. lon & lat
19. Sun range & range rate
20. Obsrv range & rng rate
21. Down-leg light-time
22. Speed wrt Sun & obsrvr
23. Sun-Obs-Targ ELONG ang
24. Sun-Targ-Obs~PHASE ang
25. Targ-Obsrv-Moon/Illum%
26. Obs-Primary-Targ angle
27. Radial & -vel posn.ang
28. Orbit plane angle
29. Constellation name
30. Delta_T (TDB - UT)
*31. Obsrv eclip lon & lat
32. North pole RA & DEC
33. Galactic long. & lat.
34. Local app. SOLAR time
35. Earth -> site lt-time
>36. RA & DEC uncertainty
>37. POS error ellipse
>38. POS uncertainty (RSS)
>39. Range & rng-rate sig.
>40. Doppler/delay sigmas
41. True anomaly angle
*42. Local app. hour angle
43. PHASE angle & bisector
44. Apprnt long Sun (L_s)
*45. Inertial app RA & DEC
46.  Rate: Inertl RA & DEC
```

4. Observer Table Quantities

... orbit ...

```
 1. Astrometric RA & DEC
*2. Apparent RA & DEC
 3.   Rates: RA & DEC
*4. Apparent AZ & EL
 5.   Rates: AZ & EL
 6. Sat. X & Y, pos. ang
 7. Local app. sid. time
 8. Airmass & Extinction
 9. App vis mag & Surf brt
10. Illuminated fraction
11. Defect of illumin.
12. Sat. angle separ/vis
13. Target angular diam.
14. Obsrvr sub-lon & lat
15. Sun sub-lon & lat
16. Sub-Sun Pos Ang & Dis
17. N. Pole Pos. Ang & Dis
18. Helio eclip. lon & lat
19. Sun range & range rate
20. Obsrv range & rng rate
21. Down-leg light-time
22. Speed wrt Sun & obsrvr
23. Sun-Obs-Targ ELONG ang
24. Sun-Targ-Obs~PHASE ang
25. Targ-Obsrv-Moon/Illum%
26. Obs-Primary-Targ angle
27. Radial & -vel posn.ang
28. Orbit plane angle
29. Constellation name
30. Delta_T (TDB - UT)
*31. Obsrv eclip lon & lat
32. North pole RA & DEC
33. Galactic long. & lat.
34. Local app. SOLAR time
35. Earth -> site lt-time
>36. RA & DEC uncertainty
>37. POS error ellipse
>38. POS uncertainty (RSS)
>39. Range & rng-rate sig.
>40. Doppler/delay sigmas
41. True anomaly angle
*42. Local app. hour angle
43. PHASE angle & bisector
44. Apprnt long Sun (L_s)
*45. Inertial app RA & DEC
46.  Rate: Inertl RA & DEC
```

4. Observer Table Quantities

... miscellaneous ...

```
 1. Astrometric RA & DEC
*2. Apparent RA & DEC
 3.   Rates: RA & DEC
*4. Apparent AZ & EL
 5.   Rates: AZ & EL
 6. Sat. X & Y, pos. ang
 7. Local app. sid. time
 8. Airmass & Extinction
 9. App vis mag & Surf brt
10. Illuminated fraction
11. Defect of illumin.
12. Sat. angle separ/vis
13. Target angular diam.
14. Obsrvr sub-lon & lat
15. Sun sub-lon & lat
16. Sub-Sun Pos Ang & Dis
 17. N. Pole Pos. Ang & Dis
 18. Helio eclip. lon & lat
 19. Sun range & range rate
 20. Obsrv range & rng rate
 21. Down-leg light-time
 22. Speed wrt Sun & obsrvr
 23. Sun-Obs-Targ ELONG ang
 24. Sun-Targ-Obs~PHASE ang
 25. Targ-Obsrv-Moon/Illum%
 26. Obs-Primary-Targ angle
 27. Radial & -vel posn.ang
 28. Orbit plane angle
 29. Constellation name
 30. Delta_T (TDB - UT)
*31. Obsrv eclip lon & lat
 32. North pole RA & DEC
 33. Galactic long. & lat.
 34. Local app. SOLAR time
 35. Earth -> site lt-time
>36. RA & DEC uncertainty
>37. POS error ellipse
>38. POS uncertainty (RSS)
>39. Range & rng-rate sig.
>40. Doppler/delay sigmas
 41. True anomaly angle
*42. Local app. hour angle
 43. PHASE angle & bisector
 44. Apprnt long Sun (L_s)
*45. Inertial app RA & DEC
 46.  Rate: Inertl RA & DEC
```

4. Observer Table Options

```
Current output table defaults --
   Reference frame          = ICRF {FK4/B1950}
   Time zone correction     = UT+00:00
   Time format              = CAL {JD, BOTH}
   Time digits output       = MIN {SEC, FRACSEC}
   R.A. format              = HMS {DEG}
   RA/DEC extra precision = NO {YES}
   Apparent coord. type     = AIRLESS {REFRACTED}
   Range units              = AU     {KM}
   Suppress range-rate      = NO   {YES}
   Minimum elevation        = -90.0
   Maximum airmass          = 38.0000
   Rise-Transit-Set only    = NO {YES}
   Skip daylight            = NO {YES}
   Solar elong. cut-off     = 0,180
   Hour angle cut-off       = 0.000000000
   RA/DEC rate cut-off      = 0.0
   CSV spreadsheet output = NO {YES}
   Table quantities         = A {1-46}
```

```
Example (2, 3, 9, 29 ... output of everything would be 13 screens wide, 1055 cols)

Date__(UT)__HR:MN    R.A._(a-appar)_DEC.  dRA*cosD d(DEC)/dt   APmag    S-brt Cnst
2020-Jan-01 00:00      8.49561   0.42050  25.74280  10.32567  15.491    5.965  Cet
2020-Jan-02 00:00      8.66894   0.49009  26.27378  10.55734  15.501    5.964  Cet
```

5. Vector Tables

(Geometric with *optional* aberrations as a function of time)

Pick target

Any planet (8), natural satellite (209+), asteroid (958,698+), comet (3646+), spacecraft (167+), E-M-S Lagrange, barycenter, user-defined object

- OR - surface coordinates on remote body (crater)

Pick coordinate origin

Any point on/in any planet, natural satellite, spacecraft, some asteroids

Set output time-span and interval (TDB time-scale only):

1. Uniform time-step
2. List of discrete times (browser, email, cgi)

Pick reference plane

1. Earth equatorial ("frame"; ICRF or FK4/B1950)
2. Earth ecliptic (J2000 or B1950)
3. Center body equator-of-date ("Europa equator and node of date", etc.)

5. Vector Table Options

```
Current output table defaults --
   Ref. Frame        = ICRF {FK4/B1950)
   Corrections       = NONE {1=None, 2= LT, 3=LT+S}
   Units             = AU-D {1= km-s, 2= au-d, 3= km-d}
   CSV format        = NO   {YES}
   Output Delta-T    = NO   {YES}
   Table type        = 3    { 1(xarp), 2(xarp), 3, 4, 5, 6}
   Vector label      = YES  {NO}
```

```
Example (2xarp):

    2458849.500000000 = A.D. 2020-Jan-01 00:00:00.0000 TDB [del_T=     69.183900 s]
    XYZ    :  3.466512233788765E+08  -2.327918342415277E+08  -2.750224533737063E+08
    sigmas:           5.05745925E+01          6.65962585E+01          6.14365482E+01
     ACN(1-sigma):    6.12761548E+01          3.52167067E+01          7.59757654E+01
     RTN(1-sigma):    1.82531235E+01          6.82774272E+01          7.59757654E+01
     POS(1-sigma):    6.87198061E+01          7.55758708E+01          1.82531235E+01
    2458850.500000000 = A.D. 2020-Jan-02 00:00:00.0000 TDB [del_T=     69.183930 s]
    XYZ    :  3.497023294388138E+08  -2.315907093090873E+08  -2.746494905277434E+08
    sigmas:           5.04294307E+01          6.66043789E+01          6.14138953E+01
     ACN(1-sigma):    6.15131027E+01          3.45844890E+01          7.59670232E+01
     RTN(1-sigma):    1.81902037E+01          6.81840537E+01          7.59670232E+01
     POS(1-sigma):    6.86804526E+01          7.55185356E+01          1.81902037E+01
```

6. Osculating Orbital Element Tables

(Geometric, time-varying)

Pick target

Any planet (8), natural satellite (209+), asteroid (958,698+), comet (3646+), spacecraft (167+), E-M-S Lagrange, barycenter, user-defined object heliocentric

- OR - surface coordinates on remote body (crater)

Pick coordinate origin

Any planet, planetary system barycenter, solar system barycenter, Moon, or Sun

Set output time-span and interval

Uniform time-step

TDB time-scale only

Pick reference plane

1. Earth equatorial ("frame"; ICRF or FK4/B1950)
2. Earth ecliptic (J2000 or B1950)
3. Center body equator-of-date ("Europa equator and node of date", etc.)

6. Osculating Orbital Element Table Options

```
Current output table defaults --
   Ref. Frame      = ICRF {FK4/B1950}
   Units           = AU-D {1=KM-S, 2=AU-D, 3=KM-D}
   CSV format      = NO {YES}
   Element label   = YES {NO}
   Periapse time   = ABSOLUTE {RELATIVE}
```

```
Example:

  2459014.500000000 = A.D. 2020-Jun-14 00:00:00.0000 TDB
   EC= 8.415311637326658E-02 QR= 2.490458027898331E+00 IN= 1.819010878986299E+01
   OM= 1.138786381520010E+01 W = 2.247385872455426E+02 Tp=  2458424.286606758367
   N = 2.197958769909447E-01 MA= 1.297264703793583E+02 TA= 1.366580595834340E+02
   A = 2.719295192703143E+00 AD= 2.948132357507955E+00 PR= 1.637883316686743E+03
  2459014.541666667 = A.D. 2020-Jun-14 01:00:00.0000 TDB
   EC= 8.415307934596211E-02 QR= 2.490458204285878E+00 IN= 1.819010889306454E+01
   OM= 1.138786382328381E+01 W = 2.247385946752549E+02 Tp=  2458424.286603313405
   N = 2.197958669696501E-01 MA= 1.297356233829657E+02 TA= 1.366662100482069E+02
   A = 2.719295275358196E+00 AD= 2.948132346430513E+00 PR= 1.637883391363813E+03
```

7. SPK Files

(asteroids & comets, or user-input heliocentric only)

Time-continuous binary-file recording of integrator's internal state, to machine-precision.
SPICE Toolkit software reads the files: https://naif.jpl.nasa.gov/naif/toolkit.html

Pros:

- ✓ Retrieve position and velocity at any instant within file time-span (continuous)
- ✓ No need to reproduce physics & equations of motion; 3-lines of code to read file
- ✓ Input to SPICE-enabled visualization and mission design programs

Cons:

- ✓ All other calculations (ephemeris) must be derived and implemented by user
- ✓ No statistical uncertainty information − nominal trajectory only
- ✓ Usually must load planetary ephemeris SPK along with Horizons small-body SPK
- ✓ Bulkier than creating trajectory on-the-fly (numerically integrating initial conditions)

7. SPK Files

(asteroids & comets, or user-input heliocentric only)

Pick small-body target

Any asteroid (958698+) or comet (3646+), or user-defined heliocentric object

Specify contact e-mail

Specify format (type of binary)

-1 ..... Pre-2015 format (Type 1 SPK)

-B ..... Current default (Type 21 SPK)

Set output time-span and interval (TDB time-scale only):

< 200 years total length

```
workstation(29)% brief -c a2099942.bsp

BRIEF -- Version 4.0.0, September 8, 2010 -- Toolkit Version N0066

Summary for: a2099942.bsp

Body: 2099942 w.r.t. SOLAR SYSTEM BARYCENTER (0)
      Start of Interval (ET)              End of Interval (ET)
      -----------------------------       -----------------------------
      2001 JAN 01 00:00:00.000            2050 JAN 02 00:00:00.000
```

Interfaces to Horizons

```
workstation(1)%  telnet horizons.jpl.nasa.gov 6775

JPL Horizons, version 4.70
Type '?' for brief help, '?!' for details,
'-' for previous prompt, 'x' to exit
System news updated June 08, 2020

Horizons> apophis

>EXACT< name search [SPACE sensitive]:
 NAME = APOPHIS;
Continue [ <cr>=yes, n=no, ? ] :
*******************************************************************************
JPL/HORIZONS              99942 Apophis (2004 MN4)         2020-Jun-17 17:57:42
Rec #:   99942 (+COV) Soln.date: 2017-Aug-09_01:08:15   # obs: 4481 (2004-2015)

IAU76/J2000 helio. ecliptic osc. elements (au, days, deg., period=Julian yrs):

  EPOCH=  2454733.5 ! 2008-Sep-24.00 (TDB)         Residual RMS= .17383
   EC= .1911953048308701   QR= .7460724295867941   TP= 2454894.9125195034
   OM= 204.4460289189818   W=  126.401879524849    IN= 3.331369520013644
   A= .9224383019077086    MA= 180.4293730454418   ADIST= 1.098804174228623
   PER= .88596             N= 1.112495007          ANGMOM= .016216735
   DAN= 1.00246            DDN= .79816             L= 330.8942057
   B= 2.6808012            MOID= .00031568         TP= 2009-Mar-04.4125195034

Asteroid physical parameters (km, seconds, rotational period in hours):
   GM= n.a.                RAD= .170               ROTPER= 30.4
   H= 19.7                 G= .250                 B-V= n.a.
                           ALBEDO= .230            STYP= Sq

Asteroid non-gravitational force model (AMRAT= m^2/kg;A1,A2,A3=au/d^2;R0=au):
   AMRAT=  0.
   A1= 0.                  A2= -5.592839897872E-14 A3= 0.
 Non-standard or simulated/proxy model:
   ALN=  1.            NK=  0.       NM=  2.       NN=  5.093    R0=  1.

ASTEROID comments:
1: soln ref.= JPL#199, PHA  OCC=0       radar(17 delay,29 Dop.)
2: source=ORB
*******************************************************************************
 Select ... [A]pproaches, [E]phemeris, [F]tp,[M]ail,[R]edisplay, [S]PK,?,<cr>:e
```

HORIZONS Web-Interface

This tool provides a web-based *limited* interface to JPL's HORIZONS system which can be used to generate ephemerides for solar-system bodies. Full access to HORIZONS features is available via the primary telnet interface. HORIZONS system news shows recent changes and improvements. A web-interface tutorial is available to assist new users.

Current Settings

Ephemeris Type [change] : **OBSERVER**
Target Body [change] : **Mars** [499]
Observer Location [change] : **Geocentric** [500]
Time Span [change] : Start=**2020-06-14**, Stop=**2020-07-14**, Step=**1 d**
Table Settings [change] : *defaults*
Display/Output [change] : *default* (formatted HTML)

Generate Ephemeris

Special Options:

- set default ephemeris settings (preserves only the selected target body and ephemeris type)
- reset *all* settings to their defaults (caution: all previously stored/selected settings will be lost)
- show "batch-file" data (for use by the E-mail interface)

To: horizons@ssd.jpl.nasa.gov
Subject: JOB

```
!$$SOF
!
! Example e-mail command file. If mailed to "horizons@ssd.jpl.nasa.gov"
! with subject "JOB", results will be mailed back.
!
! This example demonstrates a subset of functions. See main doc for
! fully explanation.
!
! Fully annotated example:
!   ftp://ssd.jpl.nasa.gov/pub/ssd/horizons_batch_example.long
!
 EMAIL_ADDR  = ' '                ! Send output to this address
 COMMAND     = 'DES= 1950 DA;',   ! Target body
 OBJ_DATA    = 'NO'               ! Summarize target body
 MAKE_EPHEM  = 'YES'              ! Make an ephemeris
 TABLE_TYPE  = 'OBSERVER'         ! Set ephemeris type to "OBSERVER" table
 CENTER      = '@hubble'          ! Set observer (coordinate center)
 TLIST       = '2454101.5'        ! List of discrete times (JD or MJD)
               '2454101.5787343'
               '2454103.4782334'
               '2454112.4389832'
 QUANTITIES  = '19,20,24,23'      ! Compute these quantities (see doc)
 CSV_FORMAT  = 'NO'               ! Set comma-separated-value table
!
!$$EOF
```

Observer table example CGI call

```
wget --secure-protocol=auto --no-check-certificate "https://ssd.jpl.nasa.gov/horizons_batch.cgi?
batch=1&COMMAND='DES=1999%20KW4%3B'&MAKE_EPHEM='YES'&TABLE_TYPE='OBSERVER'&START_TIME='2019"-"Jun-
10'&STOP_TIME='2020"-"Jan-01'&CENTER='H21'&STEP_SIZE='10%20m'&QUANTITIES='2,3,9,37,29'&CAL_FORMAT=
'BOTH'&ANG_FORMAT='DEG'&CSV_FORMAT='NO'&OBJ_DATA='YES'&ELEV_CUT='20.0'&SKIP_DAYLT='YES'&AIRMASS='3
8.0'&LHA_CUTOFF='0.0'" -O 1999kw4_eph.txt
```

... with discrete time list:

```
wget --secure-protocol=auto --no-check-certificate "https://ssd.jpl.nasa.gov/horizons_batch.cgi?
batch=1&COMMAND='DES=2009%20MS9%3B'&MAKE_EPHEM='YES'&TABLE_TYPE='OBSERVER'&TLIST='2455339.95748,24
55354.92142,2455381.87202,2455382.50000,2455387.88886'&CENTER='500@'&QUANTITIES='19,20,24,41'&CAL_
FORMAT='BOTH'&CSV_FORMAT='YES'&OBJ_DATA='NO'" -O 2009ms9.txt
```

Vector table example CGI call

```
wget --secure-protocol=auto --no-check-certificate "https://ssd.jpl.nasa.gov/horizons_batch.cgi?
batch=1&COMMAND=%2750%27&MAKE_EPHEM=%27YES%27&TABLE_TYPE=%27VECTOR%27&START_TIME=%272000-01-01%27
&STOP_TIME=%272000-12-31%27&STEP_SIZE=%2715%20d%27&CSV_FORMAT=%27YES%27&VEC_TABLE=%272xarp%27" -O
a50.txt
```

Osculating elements table example CGI call

```
wget --secure-protocol=auto --no-check-certificate "https://ssd.jpl.nasa.gov/horizons_batch.cgi?
batch=1&COMMAND='633'&MAKE_EPHEM='YES'&TABLE_TYPE='ELEMENT'&REF_PLANE='FRAME'&START_TIME='2019-
Jan-01'&STOP_TIME='2019-Jan-02'&CENTER='@6'&STEP_SIZE='1d'&CSV_FORMAT='YES'" -O 633.txt
```

SPK file example GI call (asteroids and comets only)

```
wget --content-disposition --secure-protocol=auto --no-check-certificate "https://
ssd.jpl.nasa.gov/x/smb_spk.cgi?OPTION=Make+SPK&OBJECT=2099942&START=2010-Jan-1&STOP=2050-
jan-1&EMAIL=Jon.D.Giorgini@jpl.nasa.gov&TYPE=-B" -O a2099942.bsp
```

- Automation scripts available at ftp://ssd.jpl.nasa.gov/pub/ssd/SCRIPTS/

- Requires
  - Expect/Tcl automation languages (Linux, Unix, Mac OSX, others)
  - anonymous ftp & telnet (easily restored to Mac OSX)
  - Some scripts have a separate input file (define it once, execute multiple times)

- Programs mostly use CGI calls, but scripts ...
  - Easier to formulate for people typing
  - Can reduce connection/rate limits on CGI (provides "backdoor")

- Examples of usage once set-up:

Observer table (uses input file):

```
work(2)% obs_tbl 'DES= 2015 HM10;' 2015hm10.txt
```

SPK file:

```
work(3)% smb_spk -b 'DES=1990 MU;' 2000-jan-1 2040-jan-1 you@your.email.address a4593.bsp
```

Vector table (uses input file)

```
work(4)% vec_tbl "Apophis;" 1950da_vec.txt
```

Osculating orbital elements table (uses input file):

```
work(5)% osc_tbl "DES=2014 EZ51;" 2014ez51_elems.txt
```

Close-approach table

```
work(6)% close_approach_tbl "DES=1950 DA;" 1950da_encounters.txt
```

Future Developments

Not specifically LSST-driven ... ~ continuous updates and new functions from feedback

- **JPL orbit determination**
  - Query MPC database for ADES format astrometry (no MPEC)
  - Package & submit historical radar astrometry to MPC in ADES

- **Horizons**
  - Web interface redesign in progress (~1 year?)
  - REST API (done, to be released with new web-site interface, so ~1 year?)
  - Output of orbital element uncertainties over time
  - Equinox-based apparent coordinate systems for other planets/satellites

- **Other issues** ... future 8+ million objects, given LSST catalog:

  How to disseminate ephemerides and SPKs of entire population?
  - Create standing library of pre-computed SPKs?
    - One SPK covering 50 years : ~750 KB
    - Current catalog (963K objects) : ~ 0.7 TB
    - 8 million SPKs (w/LSST) : ~ 5.6 TB
  - DASTCOM with remote-user numerical integration?

DASTCOM

- Portable, fast, direct-access binary database of JPL asteroid and comet solutions
- Stores up to 142 dynamical, physical, and covariance parameters

  Size ... currently: 768.2 MB (+66 MB ASCII index) for 962K objects
  +LSST: ~6.7 GB for 8+ million objects

- Directly used by Horizons to search, initialize dynamics & numerically integrate
- Updated hourly @ 32 minutes past hour (export from 54 GB MySQL-based SBDB)

```
wget ftp://ssd.jpl.nasa.gov/pub/xfr/dastcom5.zip
unzip -ao dastcom5.zip
```

- Zip archive includes ...
  - ✓ Binary database files
  - ✓ ASCII index linking object name and designation(s) to database records
  - ✓ Reader software library (FORTRAN provided, but perl, python, etc., also work)
  - ✓ Documentation
  - ✓ Example code & programs ('dxlook')

DASTCOM

- Binary database and ASCII index .. matched set!
  Must use the simultaneously-downloaded index and database

- Basic usage (... see documentation and examples)
  Initialize database: call dxini(...)
  Read single record: call dxread(iobj, ...)

- IAU-numbered asteroids: dxread() "iobj" record number is IAU number

- Other objects: use ASCII index to look-up integer record number.
  One simple and fast approach under UNIX/Linux/Mac OSX (among others):

```
character*8  obj
integer      iobj
call dxini(...)
call system( "unsetenv DX_REC; setenv DX_REC `grep ',2004 MN4,' dastcom.idx | awk '{print $1}' `" )
call getenv( "DX_REC", obj )          ! load grep matching result to program memory
read( obj, * ) iobj                   ! store record in integer variable
call dxread( iobs, ...)               ! retrieve record from database
```

- DASTCOM is -NOT- FORTRAN specific
  - ✓ Readable by any language that can read byte-pattern into properly typed variable
  - ✓ See documentation for database structure and byte-map

Horizons Access and Resources

- Browser interface
  https://ssd.jpl.nasa.gov/?horizons   (ASCII tables)
  https://ssd.jpl.nasa.gov/x/spk.html   (SPK files)

- Command-line terminal interface (type '?' at any prompt for help)
  telnet ssd.jpl.nasa.gov 6775

- Automation scripts (turn Horizons into local command-line tool)
  ftp://ssd.jpl.nasa.gov/pub/ssd/SCRIPTS/

- CGI interface usage
  https://ssd.jpl.nasa.gov/horizons_batch.cgi

- E-mail interface (plain-text only)
  1. Send e-mail to "horizons@ssd.jpl.nasa.gov", subject "BATCH-LONG"
     (an example ephemeris set-up file will be returned for customization)
  2. ftp://ssd.jpl.nasa.gov/pub/ssd/ispy_mail_example.long
     (an example field-of-view search set-up file will be returned for customization)

- DASTCOM small-body database & readers (updates @32 min after hour)
  wget ftp://ssd.jpl.nasa.gov/pub/xfr/dastcom5.zip ; unzip -ao dastcom5.zip

- Documentation (also Jon.D.Giorgini@jpl.nasa.gov for problems, questions, suggestions)
  https://ssd.jpl.nasa.gov/?horizons_doc

- System news
  Routine announcements   : https://ssd.jpl.nasa.gov/?horizons_news
  Major-notice mailing list sign-up : https://ssd.jpl.nasa.gov/?email_list

Back-up Slides

1. Parameter search

(email and command-line; web/cgi has separate search functionality)

Find a small-body or group of small-bodies using keyword searches. Examples:

```
A < 2.5; IN > 7.8; STYP = S; GM <> 0;   (Uniquely matches & displays 433 Eros)
```

```
Horizons> QR < 1.; EC > 0.7; EC < 0.8; A < 0.8;
*******************************************************************************
JPL/DASTCOM                Small-body Search Results       2020-Jun-17 21:33:18

 Comet AND asteroid parameter search:
    QR < 1.; EC > 0.7; EC < 0.8; A < 0.8;

 Matching small-bodies:

  Record #  Epoch-yr  Primary Desig  Name             QR           EC          A
  --------  --------  -------------  ---------------- ------------ ----------- ---------------
     85953    2012    1999 FK21      [...unnamed...]  0.219321170 0.703108511 .73872501485023
    289227    2007    2004 XY60      [...unnamed...]  0.130097397 0.796803048 .64025269935175
    302169    2016    2001 TD45      [...unnamed...]  0.177324576 0.777443538 .79676219937674
    364136    2015    2006 CJ        [...unnamed...]  0.165767995 0.754957568 .67648689854991
    527977    2016    2008 EY68      [...unnamed...]  0.178834675 0.759999153 .74514184830500
  50209296    2013    2013 RG74      [...unnamed...]  0.206618699 0.701859132 .69302373981948
  50248876    2014    2014 RE11      [...unnamed...]  0.209357990 0.711723984 .72624144459618
  50292818    2016    2015 KJ122     [...unnamed...]  0.196115005 0.750284662 .78535426130667
  50362103    2016    2016 XK24      [...unnamed...]  0.153731725 0.734748455 .57956957491845

 (9 matches. To SELECT, enter record # (integer), followed by semi-colon.)
*******************************************************************************
```

2. Objects in Field-of-View

- Examines field-of-view (FOV) from defined point in solar system (spacecraft, planet)
- Lists known asteroids or comets present in the field:
  predicted positions, rates, apparent magnitudes, plane-of-sky error ellipse
- Currently semi-private function; being parallelized for general use on new web-site

Example command-file (e-mail):

```
SPKID      = 399 ! Earth center
FOV_DATE   = '2010-Oct-04 08:48:10.585'
TYPE       =   2 ! (circular field)
RA         = '6h 40m 42.251s'
DEC        = '24d 03m 49.509s'
RADIUS     =  180.0
```

Results sent back:

```
Trajectory                       : DE431mx (SPKID =   399)
Observation time          (UTC): 2010-Oct-04 08:48:10.585
FOV specification type          : Circle
FOV center RA/DEC        (ICRF): 06:40:42.25 +24 03 49.5  (DEG: 100.17605, 24.06375)
FOV radius from center (arcsec):  180.0
FOV area             (arcmin^2):     28.27

Number of objects found        :       2
Number of objects checked      :  958701
Comets checked                 :      NO

     JPL    IAU                RA          DEC          dRA*cosD d(DEC)/dt Cnt.Dst PsAng  Data Arc           Error Ellipse
  SPK-ID Number  Name        HH MM SS.ff  DG MN SC.f  Amag   "/hr      "/hr    arcsec  DEG  span/#day Nobs SMAA_3sig SMIA_3sig  Theta
-------- ------  ---------- ----------- ----------- ---- -------- --------- ------- ----- --------- ---- --------- --------- ------\
 2027119  27119 (1998 WH8)  06:40:52.43 +24 04 11.7  19.3    34.79      1.73   141.1  81.0 1992-2020 1278 .08740399 .05940998    0.2
 2115000 115000 (2003 QD75) 06:40:42.05 +24 03 50.8  19.8    27.35     -3.24     3.0 294.7 1998-2020  600 .08978428 .06468171   -8.6
```

3. Closest-Approach Tables

(asteroids & comets, or user-input heliocentric only)

- Pre-computed encounter tables are also on web-site (separate from Horizons)
- Horizons supports customization and user-input objects
- Identifies: body, nominal distance, 3-sigma uncertainties, linearized impact probability
- Reports encounters with perturbers during numerical integration:
  - ✓ 8 planets
  - ✓ Pluto
  - ✓ Moon
  - ✓ 16 largest asteroids

Pick small-body target

Any asteroid (958698+), comet (3646+), or user-input heliocentric object

Specify start and stop times

Accept or change defaults

- ➢ Extended output: additional encounter-plane uncertainty ellipse parameters
- ➢ Encounter threshold for each planet and Pluto
- ➢ Encounter threshold for 16 largest asteroid perturbers

3. Closest-Approach Tables

(asteroids & comets, or user-input heliocentric only)

Changing default output:

```
Table format [ Extended or [S]tandard,?] :
Max approach-time uncertainty  [14400,?] :
Small-body approach trigger  [0.10 AU,?] :

Current planetary approach-distance triggers (AU):
  Merc  Venu  Eart  Mars  Jupi  Satu  Nept  Uran  Plut  Moon
  ----  ----  ----  ----  ----  ----  ----  ----  ----  -----
  0.10  0.10  0.10  0.10  1.00  1.00  1.00  1.00  0.10  0.003
Input replacement values or <return> to accept    :
>
```

Example (standard):

Date (TDB)	Body	CA Dist	MinDist	MaxDist	Vrel	TCA3Sg	Nsigs	P_i/p
A.D. 2004 Dec 21.39224	Earth	.096384	.096384	.096384	8.226	0.01	5.53E6	.000000
A.D. 2013 Jan 09.48801	Earth	.096661	.096661	.096661	4.087	0.00	8.39E7	.000000
A.D. 2016 Apr 24.11798	Venus	.078242	.078241	.078242	6.089	0.02	5.53E6	.000000
A.D. 2029 Apr 13.90703	Earth	.000252	.000248	.000257	7.433	0.26	151.26	.000000
A.D. 2029 Apr 14.60478	Moon	.000646	.000635	.000658	6.398	3.48	9608.1	.000000
A.D. 2044 Sep 15.84410	Earth	.072419	.023405	.356646	7.848	27596.	5519.0	.000000