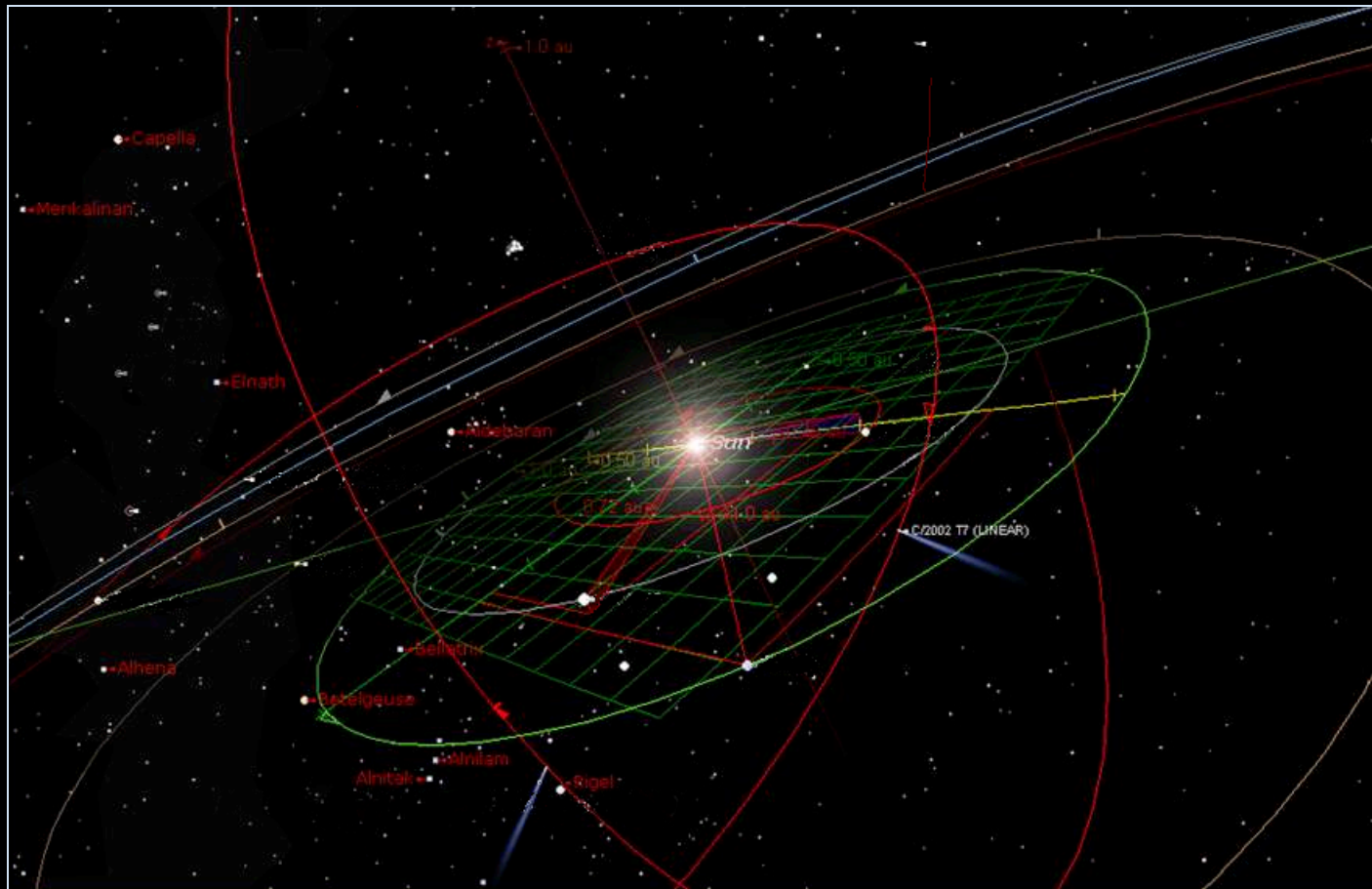




# JPL Horizons Overview and Future Plans



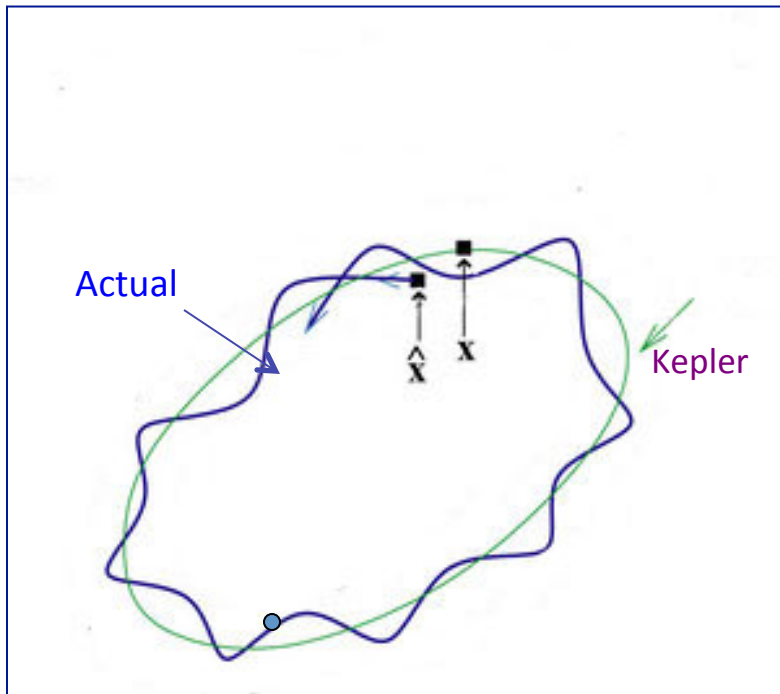
Jon Giorgini

# 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 (16<sup>th</sup> century) vs. Now

(general relativity & perturbations)



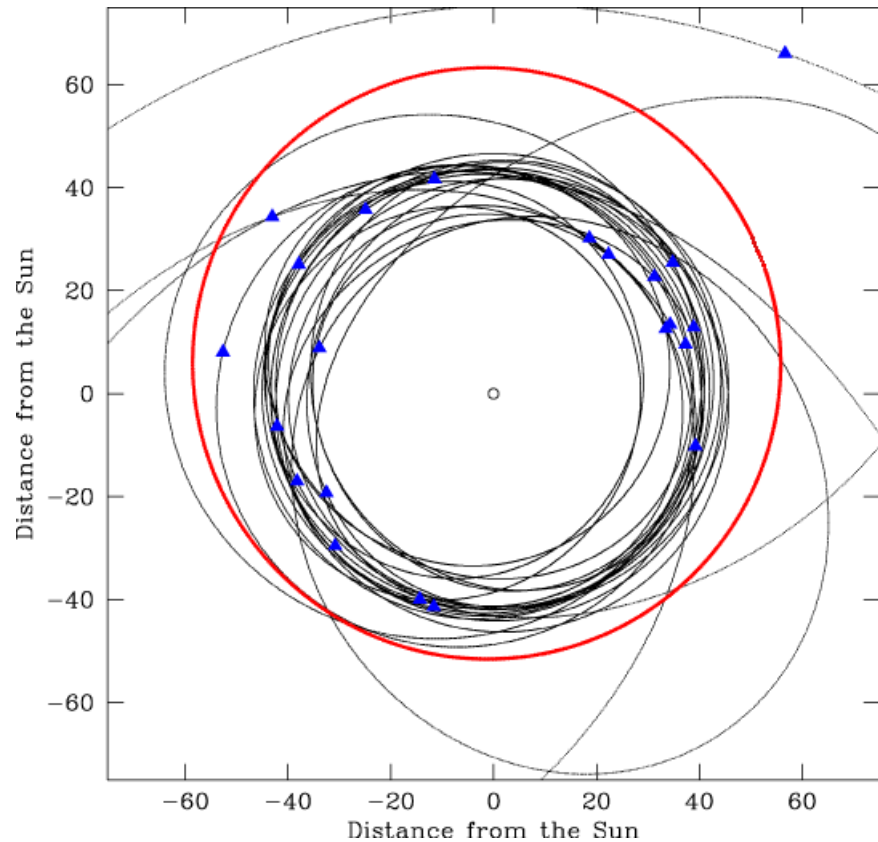
$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \quad b^2 = a^2(1 - e^2)$$

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

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

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

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



# Actual: *n*-body Equations of Motion

Acceleration @ point

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

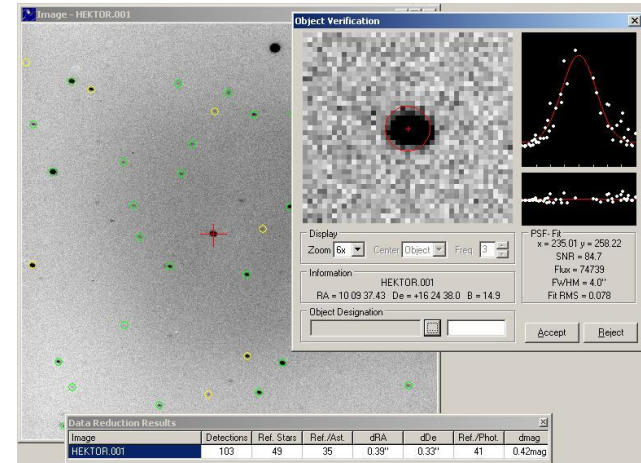
Newtonian

Relativity corrections

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

- Parameterized post-Newtonian (PPN) form
  - $\beta$  ... non-linearity in gravity superposition (G.R.= 1.0)
  - $\gamma$  ... 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



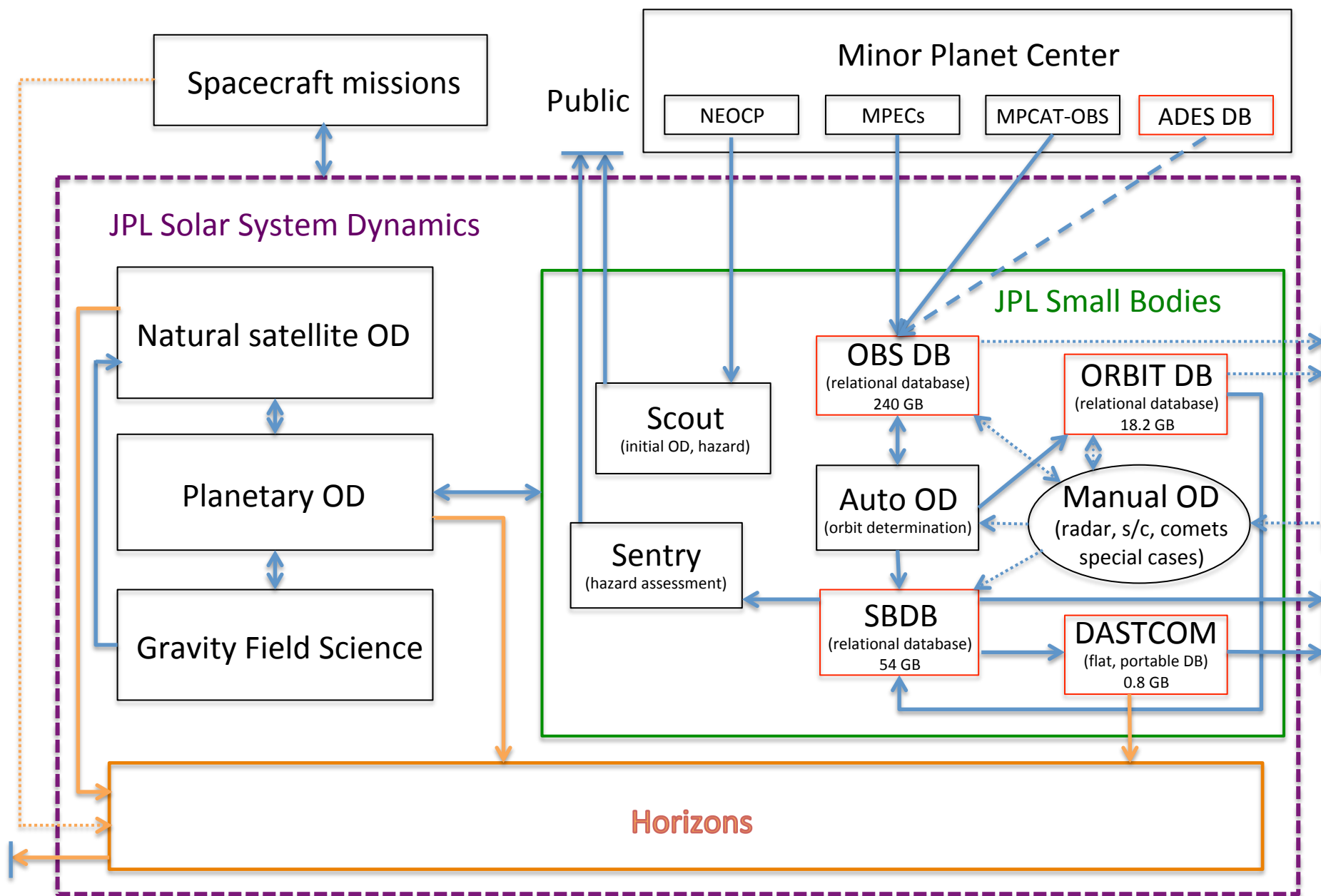
## Current optical telescopes

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

## 4. Observer Table Quantities

*... pointing and tracking ...*

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

## 4. Observer Table Quantities

*... visibility ...*

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

## 4. Observer Table Quantities

*... target disc ...*

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

## 4. Observer Table Quantities

*... small-body statistical uncertainties ...*

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

## 4. Observer Table Quantities

*... orbit ...*

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



## 4. Observer Table Quantities

*... miscellaneous ...*

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


**Jet Propulsion Laboratory**  
 California Institute of Technology

+ View the NASA Portal  
 + Center for Near-Earth Object Studies

JPL HOME
 EARTH
 SOLAR SYSTEM
 STARS &amp; GALAXIES
 TECHNOLOGY



BODIES
 ORBITS
 EPHEMERIDES
 TOOLS
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 DISCOVERY
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## 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](#))

```
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
```

To: [horizons@ssd.jpl.nasa.gov](mailto: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](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='38.0'&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='2455339.95748,2455354.92142,2455381.87202,2455382.50000,2455387.88886'&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( iobj, ... )         ! 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](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](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](https://ssd.jpl.nasa.gov/?horizons_doc)
- **System news**  
Routine announcements : [https://ssd.jpl.nasa.gov/?horizons\\_news](https://ssd.jpl.nasa.gov/?horizons_news)  
Major-notice mailing list sign-up : [https://ssd.jpl.nasa.gov/?email\\_list](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