

Comet/asteroid Orbit Determination and Ephemeris Software

by Jim Baer

In support of current minor planet surveys, CODES combines an n-body numerical integrator with a Graphical User Interface to provide the following capabilities:

- calculate the state vector/orbital elements (with covariances) based on optical and radar observations;
- identify known minor planets that most closely match a set of observations;
- calculate topocentric or geocentric ephemerides;
- conduct linear and non-linear collision analysis;
- account for cometary thrusting (if applicable), solar radiation pressure, solar oblateness, and gravitational perturbations (including relativistic effects) from the Sun, nine planets, Earth's Moon, and up to 300 asteroids.

CODES is an object-oriented application

Level One Menu:

- Create, Delete, or Open instances of the class “MinorPlanet”

Level Two Menu:

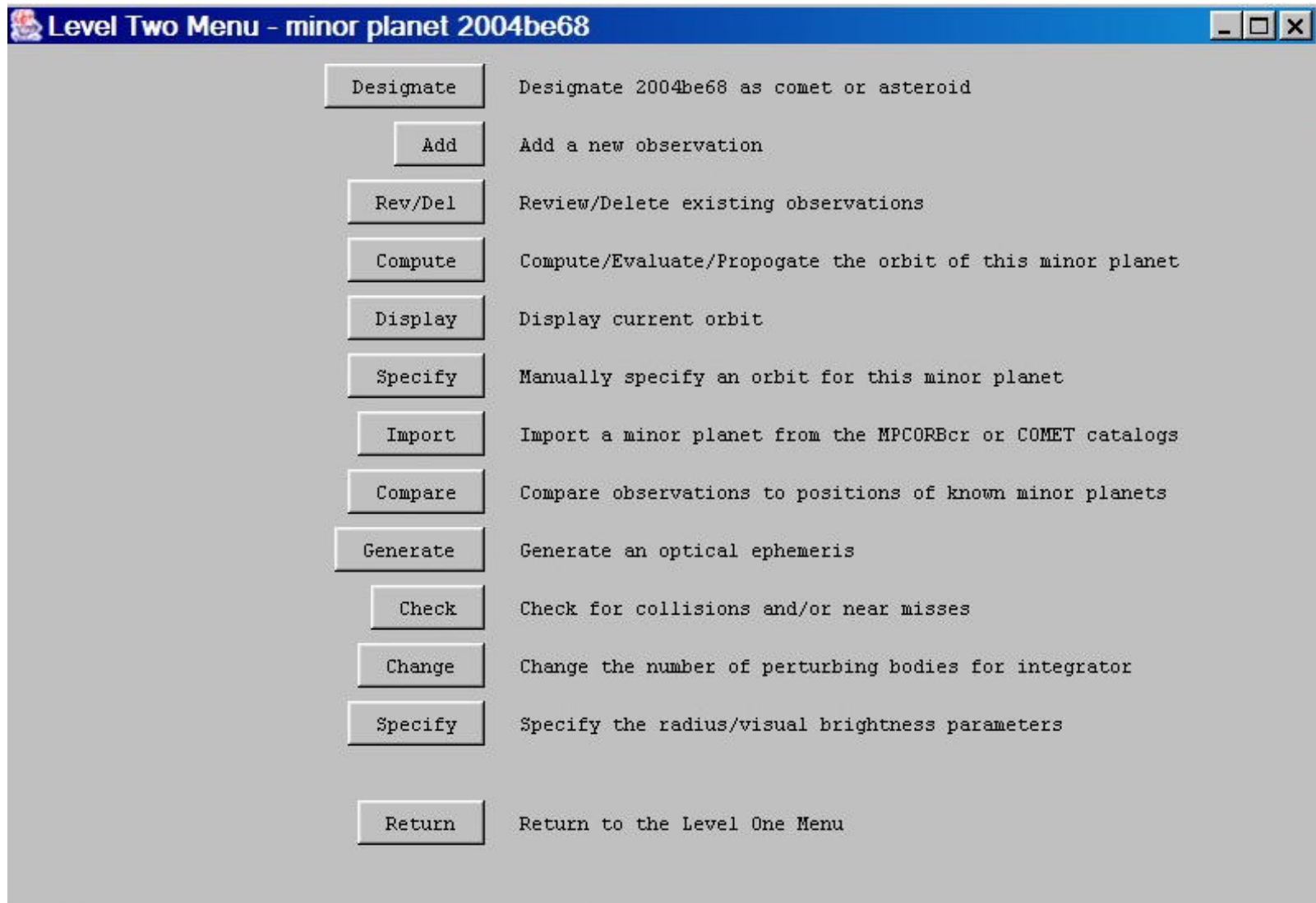
- Add attributes (observations)
- Derive additional attributes (orbital elements, ephemerides, collision analysis)

Level One Menu

The screenshot shows a window titled "Level One Menu" with a blue title bar. The window contains three rows of controls:

<input type="button" value="Create"/>	Create a new minor planet	<input type="text"/>
<input type="button" value="Edit"/>	Edit an existing minor planet	<input type="text" value="2004be68"/>
<input type="button" value="Delete"/>	Delete an existing minor planet	<input type="text" value="2004be68"/>

Level Two Menu



Level Two Menu: *Designate the minor planet as a comet or asteroid*

- Should be the first change made to a new minor planet file
- Critically impacts:
 - Least-squares best-fit orbit
 - Processing visual magnitude data
 - MPC catalog search
 - Orbital element display
 - Use of cometary thrust in numerical integrator

Level Two Menu: *Adding an Observation*

- Manual entry of ground-based optical observation
- Manual entry of radar observation
- Parse and process MPEC or MPCOBS file
- Parse and process NEODyS ascii observation file

note: observations supported in period 1900-2200

Level Two Menu: *Review/Delete Existing Observations*

minor planet 2004be68

Select the observation(s) to be deleted

Observations 1-5 of 28

Total Number of Optical Observations = 28

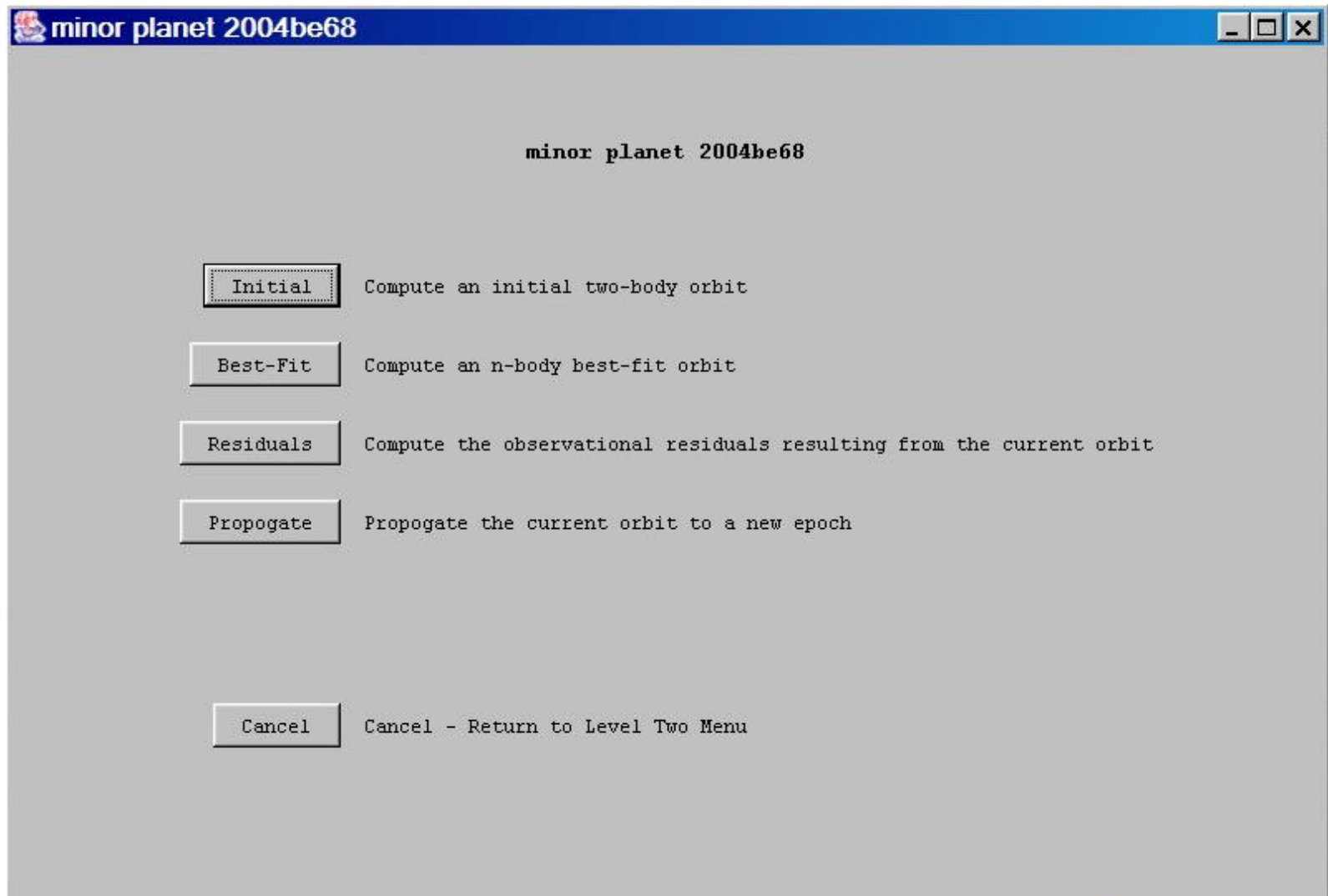
Total Number of Delay Observations = 0

Total Number of Doppler Observations = 0

	OBS	++++UTC DATE++++	++RA/DELAY++	DEC/DOPPLER
<input type="checkbox"/>	1	2004 01 27.093210	05 01 40.510	-23 39 36.30
<input type="checkbox"/>	2	2004 01 27.105520	05 01 42.580	-23 39 10.90
<input type="checkbox"/>	3	2004 01 27.117870	05 01 44.690	-23 38 45.70
<input type="checkbox"/>	4	2004 01 27.130560	05 01 46.880	-23 38 20.10
<input type="checkbox"/>	5	2004 01 27.142870	05 01 48.910	-23 37 55.10

Delete Checked Next 5 Done

Level Two Menu: *Compute/Evaluate/Propagate* the orbit of this minor planet



Level Two Menu: *Compute an initial two-body orbit*

- Gauss Method
- Conditioned Gauss (semi-major axis constrained)
- Laplace Method
- Herget's Method (slant-range constrained)
- Next planned enhancement: Short-arc statistical ranging

Level Two Menu: *Compute an initial two-body orbit (results)*

minor planet 2000SG344

Heliocentric Ecliptical Orbital Elements and Barycentric Equatorial State Vector
of minor planet 2000SG344 for TDB Epoch

Note: Reference Frame is ICRF/J2000

WARNING: THIS IS A POTENTIALLY HAZARDOUS MINOR PLANET

element	component
a	0.9774621047717332 AU
e	0.07023876986777015
i	0.11500785897381362 deg
w	265.0800178698802 deg
omega	200.33615215468384 deg
M	121.61032139509506 deg
x	-0.611942516535645 AU
y	-0.7518635373026731 AU
z	-0.3245133008865904 AU
xdot	0.012854580330584169 AU/day
ydot	-0.009822697784645075 AU/day
zdot	-0.004226998135465775 AU/day

Residuals: Obs 1 = 0.0 arc seconds
Obs 6 = 0.0 arc seconds
Obs 10 = 0.0 arc seconds

Accept This Orbit

Apply Differential Correction

Try Another Method

Try a Different Set of Three Observations

Quit

Level Two Menu: *Compute an n-body best-fit orbit*

- Least squares with n-body numerical integration
 - cometary thrusting (if applicable)
 - solar radiation pressure
 - solar oblateness
 - gravitational perturbations (including relativistic terms) from the Sun, nine planets, Earth's Moon, and up to 300 asteroids
- Refines an
 - initial two-body orbit
 - imported orbit (MPCORBcr file)
 - user-specified orbit
- Allows observations to be excluded based on excessive chi or residuals

Level Two Menu: *Compute an n-body best-fit orbit (results)*

- state vector plus covariances
- derived orbital elements plus covariances
- residuals for each observation
- visual absolute magnitude and slope parameter (if apparent magnitude observations are available)
- estimate of the minor planet's radius (asteroids only, if visual absolute magnitude and slope parameter are available)
- estimate of the Minimum Orbital Intersection Distance (NEOs only)
- output to screen and text file

Level Two Menu: *Compute the observational residuals resulting from the current orbit*

minor planet 2000SG344

Computed Observational Residuals for minor planet 2000SG344

Observations 1-5 of 31

RMS Optical Residuals = 0.42 arc seconds

RMS Delay Residuals = 0.0 microsecs

RMS Doppler Residuals = 0.0 Hz

OBS	+++UTC DATE++++	++RA/DELAY++++rms+++resid	DEC/DOPPLER+++rms+++resid	VMAG	CHI	OBS
1	1999 05 15.204820	12 26 59.590 1.00 -0.90	+04 31 35.30 1.00 -0.03	17.0	0.90	704
2	1999 05 15.216550	12 27 02.520 1.00 +0.85	+04 30 32.50 1.00 +0.20	16.9	0.87	704
3	1999 05 15.228450	12 27 05.370 1.00 -0.39	+04 29 28.40 1.00 +0.22	16.8	0.45	704
4	1999 05 15.240160	12 27 08.410 1.00 +0.48	+04 28 25.00 1.00 +0.09	17.4	0.49	704
5	1999 05 15.251880	12 27 11.450 1.00 -0.41	+04 27 21.60 1.00 +0.17	17.3	0.44	704

Next 5 Phys Props Done

Level Two Menu: *Propogate the current orbit to a new epoch*

minor planet 2000SG344
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The Heliocentric Ecliptical Orbital Elements

for TDB Epoch

Note: Reference Frame is ICRF/J2000

WARNING: THIS IS A POTENTIALLY HAZARDOUS MINOR PLANET - MOID <= 0.00132

	element		covariance	
a	<input style="width: 150px;" type="text" value="0.9833205094838733"/>	AU	<input style="width: 150px;" type="text" value="1.2467465626509274E-6"/>	AU
e	<input style="width: 150px;" type="text" value="0.06579425803017226"/>		<input style="width: 150px;" type="text" value="3.6907248375787533E-6"/>	
i	<input style="width: 150px;" type="text" value="0.10772636694447191"/>	deg	<input style="width: 150px;" type="text" value="7.998048787669914E-6"/>	deg
w	<input style="width: 150px;" type="text" value="271.69711392229465"/>	deg	<input style="width: 150px;" type="text" value="0.0018219877610450579"/>	deg
omega	<input style="width: 150px;" type="text" value="193.5269937488819"/>	deg	<input style="width: 150px;" type="text" value="0.0016101108064066746"/>	deg
M	<input style="width: 150px;" type="text" value="356.15884529156483"/>	deg	<input style="width: 150px;" type="text" value="6.895639178179978E-4"/>	deg


(Optional Non-Gravitational Thrust Parameters)

A1	<input style="width: 150px;" type="text" value="0.0"/>	x 10 ⁽⁻⁹⁾ AU/(day) ²	<input style="width: 150px;" type="text" value="0.0"/>	x 10 ⁽⁻⁹⁾ AU/(day) ²
A2	<input style="width: 150px;" type="text" value="0.0"/>	x 10 ⁽⁻⁹⁾ AU/(day) ²	<input style="width: 150px;" type="text" value="0.0"/>	x 10 ⁽⁻⁹⁾ AU/(day) ²
DT	<input style="width: 150px;" type="text" value="0.0"/>	days		

Display State Vector

Done

Level Two Menu: *Display Current Orbit*

 minor planet P2003WC7

The Heliocentric Ecliptical Orbital Elements
for TDB Epoch

Note: Reference Frame is ICRF/J2000

	element		covariance	
q	<input type="text" value="1.6548662247249029"/>	AU	<input type="text" value="6.024048271391209E-5"/>	AU
e	<input type="text" value="0.6807556325959969"/>		<input type="text" value="1.5479251643453335E-4"/>	
i	<input type="text" value="21.218936507295076"/>	deg	<input type="text" value="8.980039580983952E-4"/>	deg
w	<input type="text" value="341.05352993374294"/>	deg	<input type="text" value="0.0017938805730052952"/>	deg
omega	<input type="text" value="89.88998359796402"/>	deg	<input type="text" value="0.00222310543677841"/>	deg
T	<input type="text" value="2453041.2410775754"/>	JD	<input type="text" value="0.0036837336259165337"/>	days

(Optional Non-Gravitational Thrust Parameters)

A1	<input type="text" value="0.0"/>	$\times 10^{(-9)} \text{ AU}/(\text{day})^2$	<input type="text" value="0.0"/>	$\times 10^{(-9)} \text{ AU}/(\text{day})^2$
A2	<input type="text" value="0.0"/>	$\times 10^{(-9)} \text{ AU}/(\text{day})^2$	<input type="text" value="0.0"/>	$\times 10^{(-9)} \text{ AU}/(\text{day})^2$
DT	<input type="text" value="0.0"/>	days		

Level Two Menu: *Manually specify an orbit for this minor planet*

- User can specify either state vector or orbital elements (plus covariances)
- Allows evaluation or adoption of non-CODES derived orbits
 - Calculate residuals for comparison
 - Provide initial orbit for best-fit refinement
 - Calculate an ephemeris
 - Conduct a linear collision analysis
- Allows trial and error determination of DT cometary thrust parameter

Level Two Menu: *Import a minor planet orbit from the MPCORBcr or COMET catalogs*

Allows CODES to read the orbital elements of a minor planet directly from the appropriate MPC catalog:

- Provide initial orbit for best-fit refinement
 - Add estimated covariances
 - Add or determine cometary thrust parameters
- Calculate an ephemeris
- Conduct a collision analysis

Level Two Menu: *Compare observations to positions of known minor planets*

Generates a list of those minor planets in the MPCORBcr or COMET catalog most nearly matching the observations of this minor planet

- Use two-body or n-body mechanics
- Select "medium" or "high" integration accuracy
- Narrow n-body asteroid candidate search on basis of
 - population (NEA, main belt, Centaur/TNO)
 - absolute magnitude

For each entry:

- Extracts orbital elements from catalog
- Predicts astrometric position at time of each observation
- Eliminated if either
 - RMS residual > 3 degrees
 - visual mag. residual > 2

Candidates output to screen and text file

Level Two Menu: *Generate an optical ephemeris*

minor planet 2004be68
[-] [x]

Optical Ephemeris for minor planet 2004be68
(Reference Frame is ICRF/J2000, position angles measured clockwise from due north)

												Linear 3-sigma Ellipse			App Motion		Relative Geometry			
DATE (UTC)						RA			DEC			PosAng	SMjAxs	SMnAxs	ArcSec/	PosAng	Delta	r	Elng	
year	mm	dd	hh	mm	secs	hh	mm	ss.sss	dd	mm	ss.ss	VMag	Degree	ArcSec	ArcSec	Min	Degree	AUs	AUs	Degs
2004	02	02	00	00	00.0	05	18	17.611	-20	21	14.13	19.0	73.9	218321	44225	2.1	-49.2	0.5008	1.2745	114.1
2004	02	03	00	00	00.0	05	20	58.726	-19	48	34.45	19.1	73.8	211652	42879	2.1	-49.2	0.5080	1.2807	114.2
2004	02	04	00	00	00.0	05	23	37.894	-19	16	11.93	19.1	73.8	205359	41567	2.1	-49.2	0.5154	1.2869	114.4
2004	02	05	00	00	00.0	05	26	15.214	-18	44	07.18	19.1	73.7	199414	40288	2.0	-49.2	0.5229	1.2932	114.5
2004	02	06	00	00	00.0	05	28	50.781	-18	12	20.76	19.2	73.7	193787	39041	2.0	-49.3	0.5305	1.2994	114.6
2004	02	07	00	00	00.0	05	31	24.687	-17	40	53.18	19.2	73.6	188453	37828	2.0	-49.4	0.5382	1.3057	114.7
2004	02	08	00	00	00.0	05	33	57.017	-17	09	44.92	19.2	73.6	183384	36646	2.0	-49.5	0.5459	1.3120	114.7
2004	02	09	00	00	00.0	05	36	27.856	-16	38	56.40	19.3	73.5	178571	35495	2.0	-49.6	0.5538	1.3182	114.8
2004	02	10	00	00	00.0	05	38	57.283	-16	08	28.02	19.3	73.5	173981	34375	2.0	-49.7	0.5619	1.3245	114.8
2004	02	11	00	00	00.0	05	41	25.376	-15	38	20.15	19.3	73.5	169608	33285	1.9	-49.8	0.5700	1.3309	114.8

Level Two Menu: *Linear Collision Analysis*

Requires state vector and (if impact probability desired) covariances

Algorithm:

- Propagate state vector forward from epoch to desired end-point
 - at end of each integration step, test distance to each possible target (Sun, Moon, nine major planets)
 - if (distance < target radius) => **collision**
 - use bisection to isolate
 - propagate covariances to determine impact probability
 - else if (distance > target radius) and (distance < user-specified threshold) and (first derivative changes sign)
 - use bisection to isolate minimum
 - if (distance at minimum < target radius) => **collision**
 - use bisection to isolate
 - propagate covariances to determine impact probability
 - if (distance at minimum > target radius) => **near miss**
 - propagate covariances to determine impact probability

Level Two Menu: *Non-Linear Collision Analysis*

Requires state vector and covariances, plus all observations

Algorithm:

- Creates user-specified number of Virtual Asteroids
 - Distributed normally in observation space about the nominal state vector
 - Spaced along the Line of Variations
- Each VA propagated forward from epoch to desired end-point
 - collisions/near-misses noted as in linear analysis
 - events with ((scaled moid - 3-sigma width of covariance ellipse) < threshold) and (scaled moid < 3*threshold) are sorted by target, date, and semi-major axis into trails
- The minimum approach or folding point for each trail is retained
 - if interrupted return, create a Monte Carlo virtual shower, look for collision/nearest miss
 - else, use differential correction to test for collision/near-miss

Level Two Menu: *Collision Analysis (output to text and file)*

DATE (UTC)		Event	Planet	Nominal Miss Dist (AUs)	Minimum Miss Dist (AUs)	3-sigma width (AUs)	Collision Prob	Sigma
2008	10 22 18 04 55.1	near-miss	Moon		0.002558	0.002408	0.0	0.3
2008	10 22 19 19 23.1	near-miss	Earth		0.00322	0.0024136	1.0E-9	0.3
2011	10 22 18 34 35.7	near-miss	Earth		0.003599	0.0025048	3.0E-9	0.6
2011	10 22 19 19 03.1	near-miss	Moon		0.0049	0.0025018	0.0	0.6
2013	10 23 01 50 03.0	near-miss	Earth		0.003098	0.0023884	4.0E-9	0.3
2016	10 22 04 32 21.5	near-miss	Moon		0.001107	0.0024604	0.0	0.5
2016	10 22 07 52 12.5	near-miss	Earth		0.001505	0.0024718	1.0E-9	0.5
2018	10 23 06 16 26.8	near-miss	Earth		0.003893	0.0023895	4.8E-8	0.3
2020	10 23 04 14 06.5	near-miss	Earth		0.005866	0.0023749	0.0	0.2
2022	10 22 07 50 55.2	near-miss	Earth		0.007133	0.0025306	2.0E-9	0.7

Level Two Menu: *Collision Analysis* (*Considerations*)

- Analysis generally similar to Milani, Chesley, Chodas, and Valsecchi in *Asteroids III*
- Results thus far comparable with Sentry and NEODyS Risk Page despite some algorithmic differences
 - CODES collision analysis performed in 3-space vs. collision plane
 - Trails defined differently
 - CODES differential correction performed along LOV
 - Epoch state vectors and residuals often differ

Comparison: CODES vs. Sentry vs. NEODyS

2004 BE68 with 39 observations (2004-Jan-27.09321 to 2004-Feb-01.48334)

Date (UTC)	Predicted Miss Dist. (er)	1-sigma width (er)	Collision Probability	LOV Sigma
2008 10 22.805	75.5	18.9	1.0E-9	0.3
2008 10 22.895	72.0	20.1	7.4E-10	0.8
2011 10 22.774	84.4	19.6	3.0E-9	0.6
2011 10 22.767	86.5	21.1	2.5E-11	1.4
2013 10 23.076	72.7	18.7	4.0E-9	0.3
2013 10 23.074	70.8	20.1	4.8E-10	0.8
2016 10 22.328	35.3	19.3	1.0E-9	0.5
2016 10 22.32	26.0	14.2	6.4E-8	1.2
2016 10 22.313	36.4	20.8	2.4E-8	1.2
2018 10 23.261	91.3	18.7	4.8E-8	0.3
2021 10 22.681	11.0	20.6	9.0E-8	1.1
2022 10 22.327	167.3	19.8	2.0E-9	0.7
2024 10 22.201	64.2	19.4	0.0	0.5
2024 10 22.190	66.9	20.8	3.0E-10	1.3
2026 10 23.018	2.3	46.8	0.0	0.4
2026 10 23.01	1.2	13.9	5.3E-8	1.1
2026 10 23.013	1.8	20.4	9.0E-8	1.1
2029 10 22.521	14.6	19.2	0.0	0.5
2029 10 22.50	8.3	14.2	1.8E-8	1.2
2029 10 22.501	11.6	20.7	2.9E-8	1.2
2031 10 23.322	0.0	27.5	1.0E-9	0.4
2031 10 23.31	0.1	13.8	4.8E-8	1.1
2031 10 23.322	1.1	18.5	8.1E-8	1.0
2034 10 22.905	28.8	19.4	0.0	0.5
2034 10 22.87	20.9	14.1	3.2E-8	1.2
2034 10 22.867	29.3	20.6	2.0E-8	1.2

Level Two Menu: *Change the number of perturbing bodies*

Determines what perturbing bodies are used in n-body numerical integration

- Sun, Moon, nine planets
- Sun, Moon, nine planets, Ceres, Pallas, and Vesta (default)
- Sun, Moon, nine planets, and 235 asteroids
 - much slower processing
- Sun, Moon, nine planets, and 300 asteroids
 - Much slower processing

CODES uses

- JPL DE405 Planetary Ephemeris
- Mean asteroid orbital elements

Level Two Menu: *Set the radius/visual brightness parameters*

- Useful if orbital elements are imported or user-specified
 - slope parameter and absolute magnitude otherwise unavailable
 - allows estimated visual magnitudes in ephemerides
- Radius critical in processing bounce point of radar observations
 - usually determined from visual brightness data as part of best-fit orbit determination
 - if no brightness data, should be set manually prior to orbit determination
 - default is 1 km
 - comets - set to estimated bounce point (coma radius?)

System and Software Requirements

CODES is written in pure Java - compiled bytecode will run on any system for which a Sun Virtual Machine exists

System Requirements:

- approximately 150 MB of disk storage
- 256 MB (or greater) RAM
- internet access (for download of observation files, MPC catalogs, and updated ObsCode files)

Software requirements (all available for free download):

- Java 1.4.1 (or higher) runtime environment
- compiled CODES bytecode and (optionally) source code
- JPL DE405 planetary ephemeris files (ASCII versions)

Where can I find CODES?

Web site is <http://home.earthlink.net/~jimbaer1/>

- Fully-documented User's Manual
- Links to all required software

Suggestions for future enhancements are welcome!
(jimbaer1@earthlink.net)