Comet/asteroid **O**rbit **D**etermination and **E**phemeris **S**oftware

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

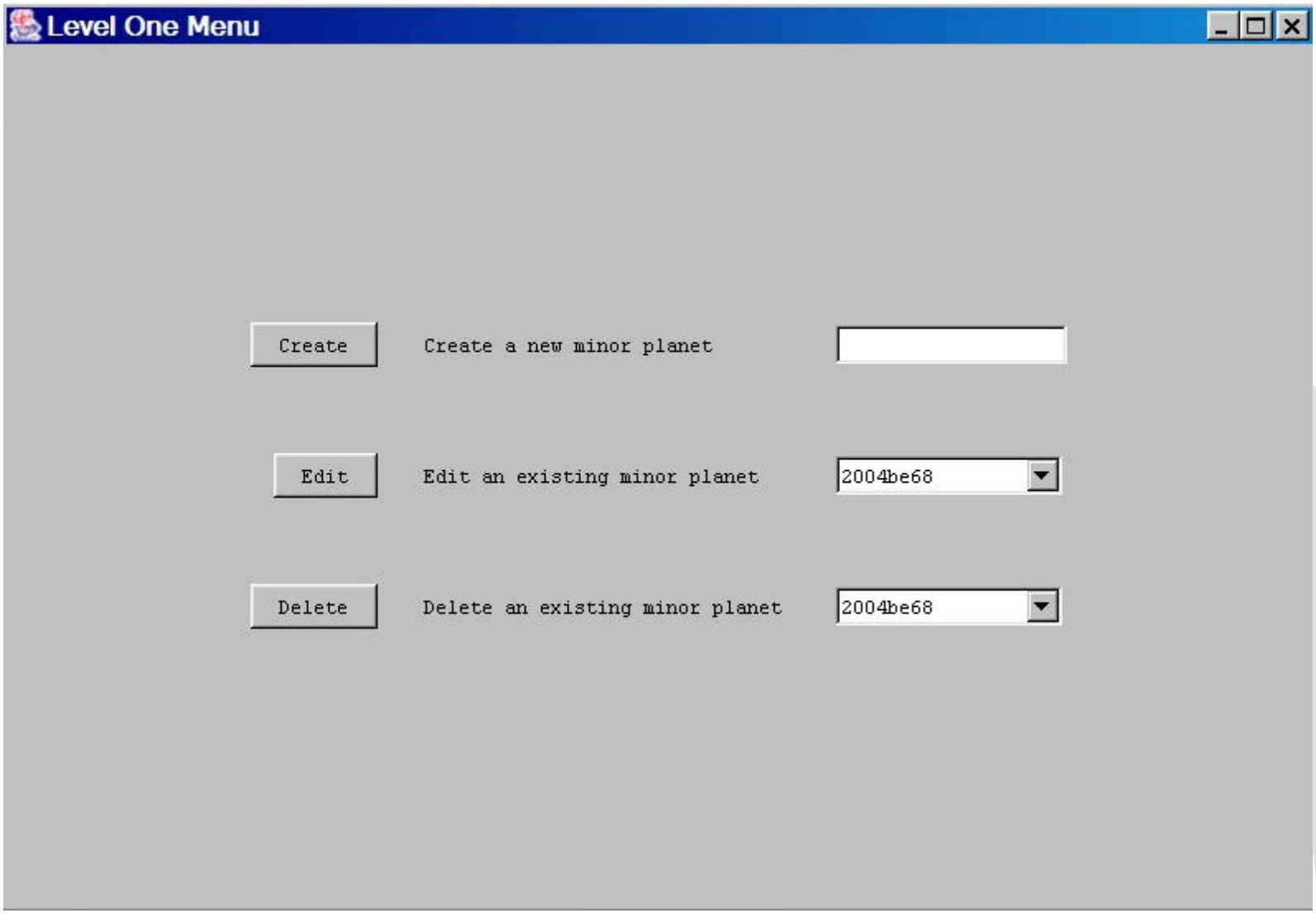
Level One Menu:

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

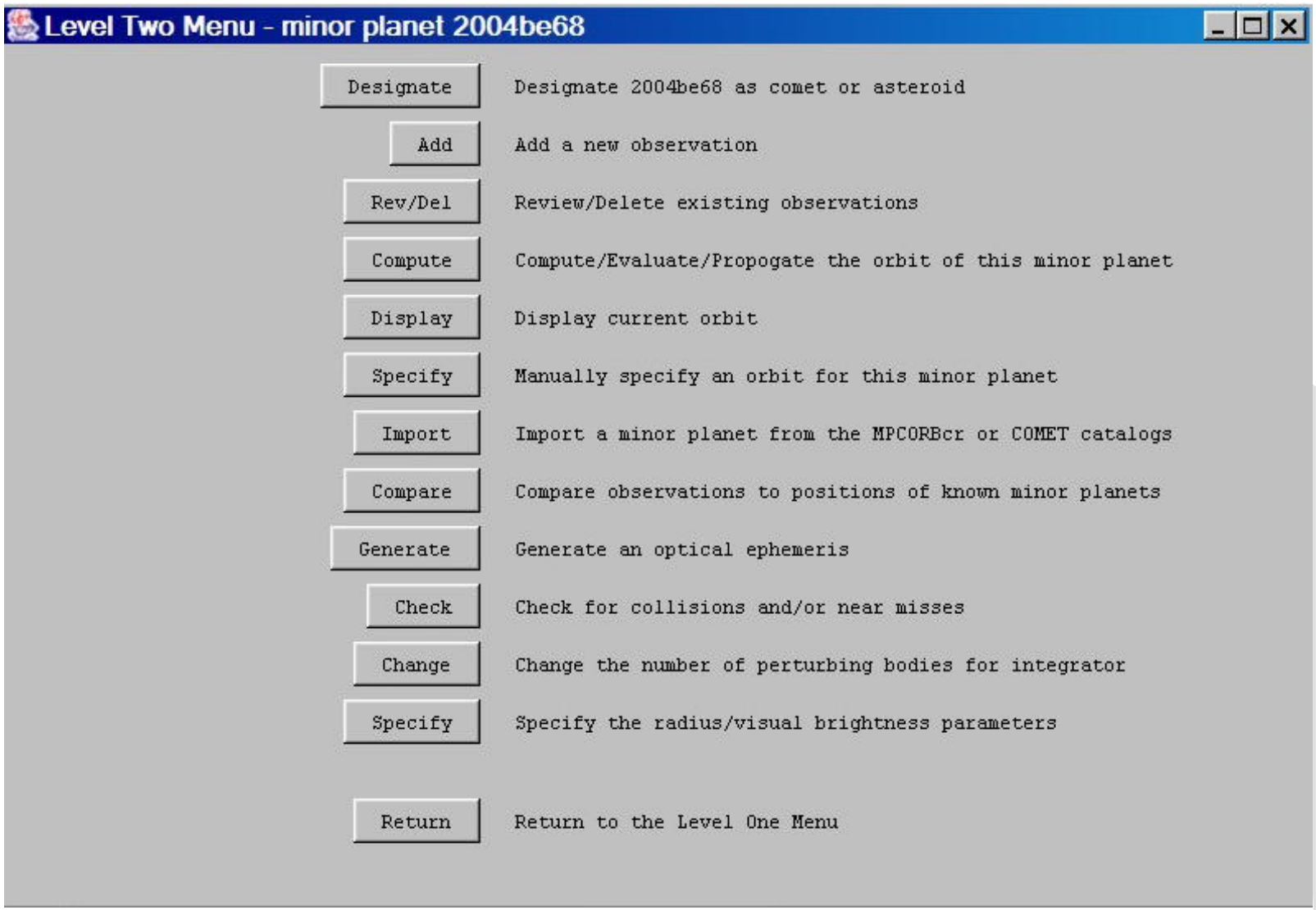
Level Two Menu:

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

Level One Menu



Level Two Menu



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

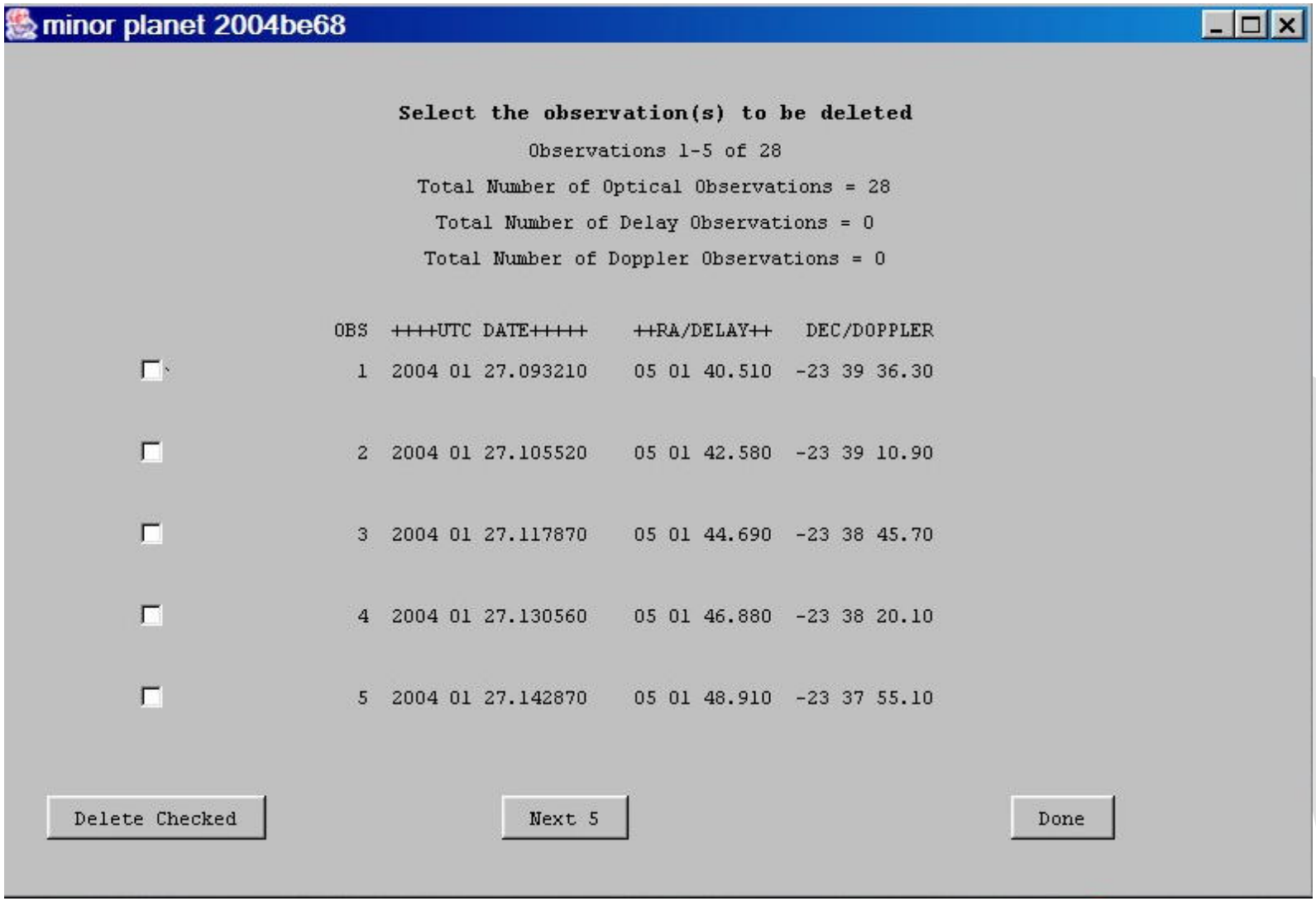
- Should be the first change made to a new minor planet file
- Critically impacts:
  - Least-squares best-fit orbit
  - Processing visual magnitude data
  - MPC catalog search
  - Orbital element display
  - Use of cometary thrust in numerical integrator

Level Two Menu: *Adding an Observation*

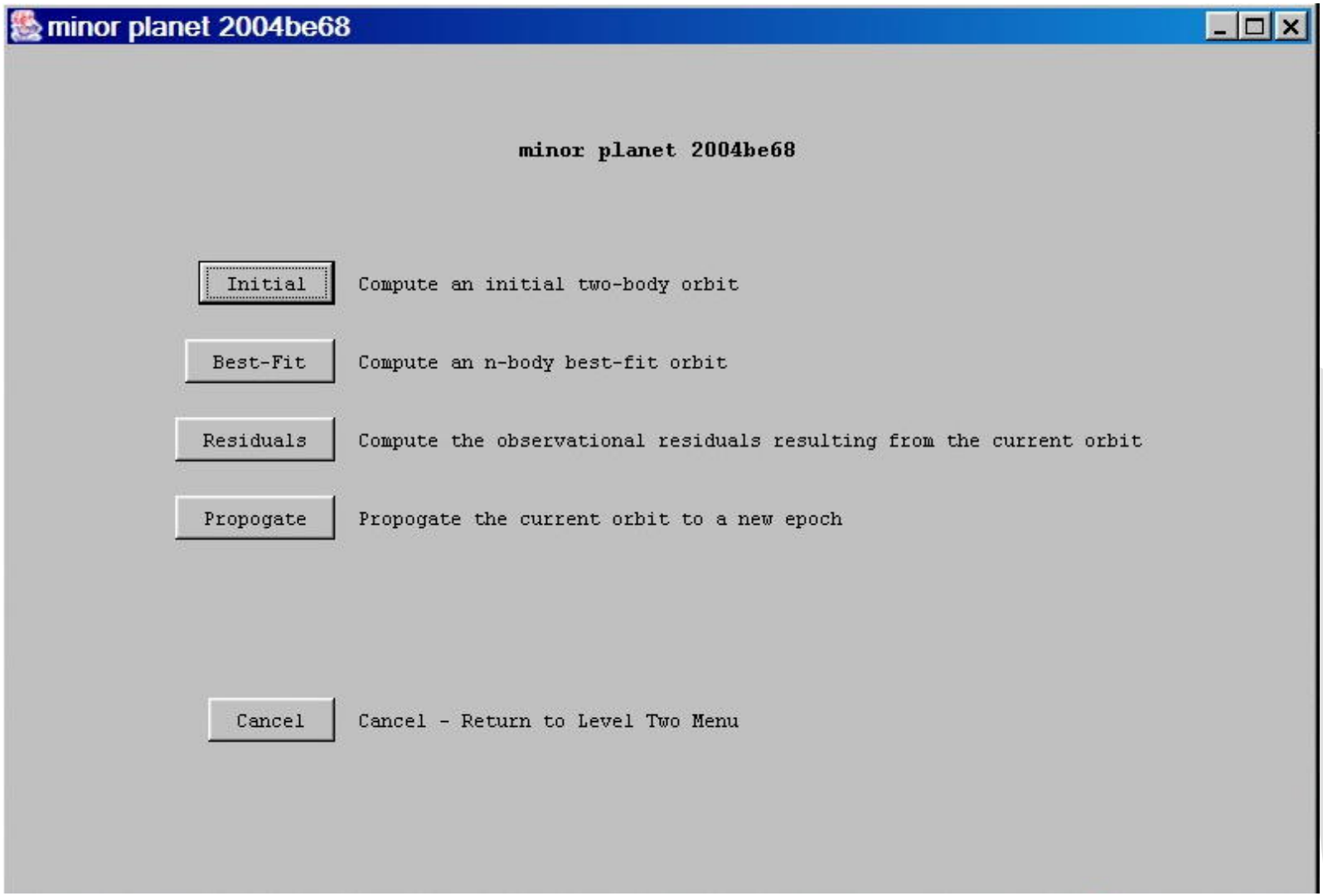
- Manual entry of ground-based optical observation
- Manual entry of radar observation
- Parse and process MPEC or MPCOBS file
- Parse and process NEODyS ascii observation file

note: observations supported in period 1900-2200

Level Two Menu: *Review/Delete Existing Observations*



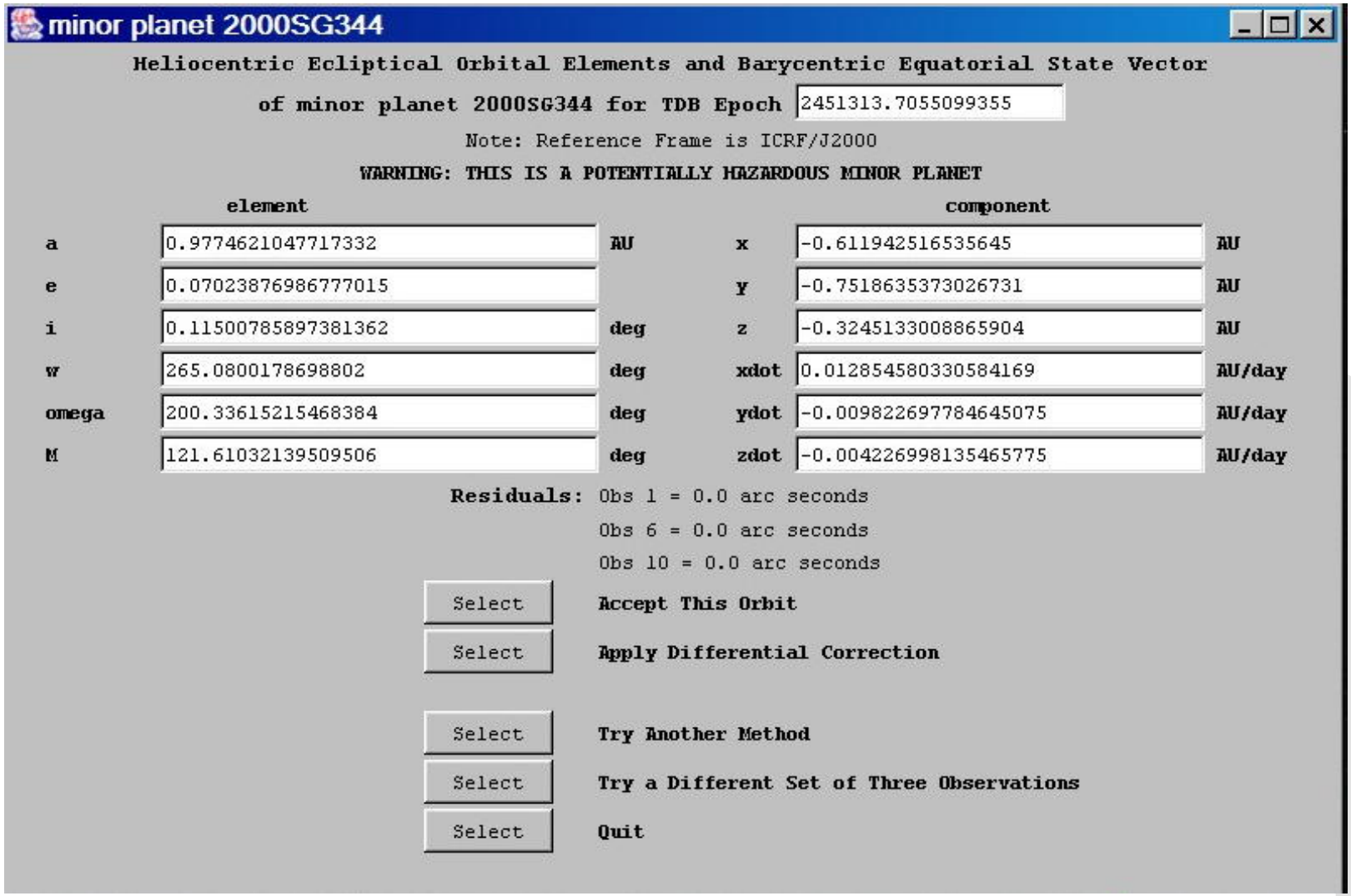
Level Two Menu: *Compute/Evaluate/Propogate the orbit of this minor planet*



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)*



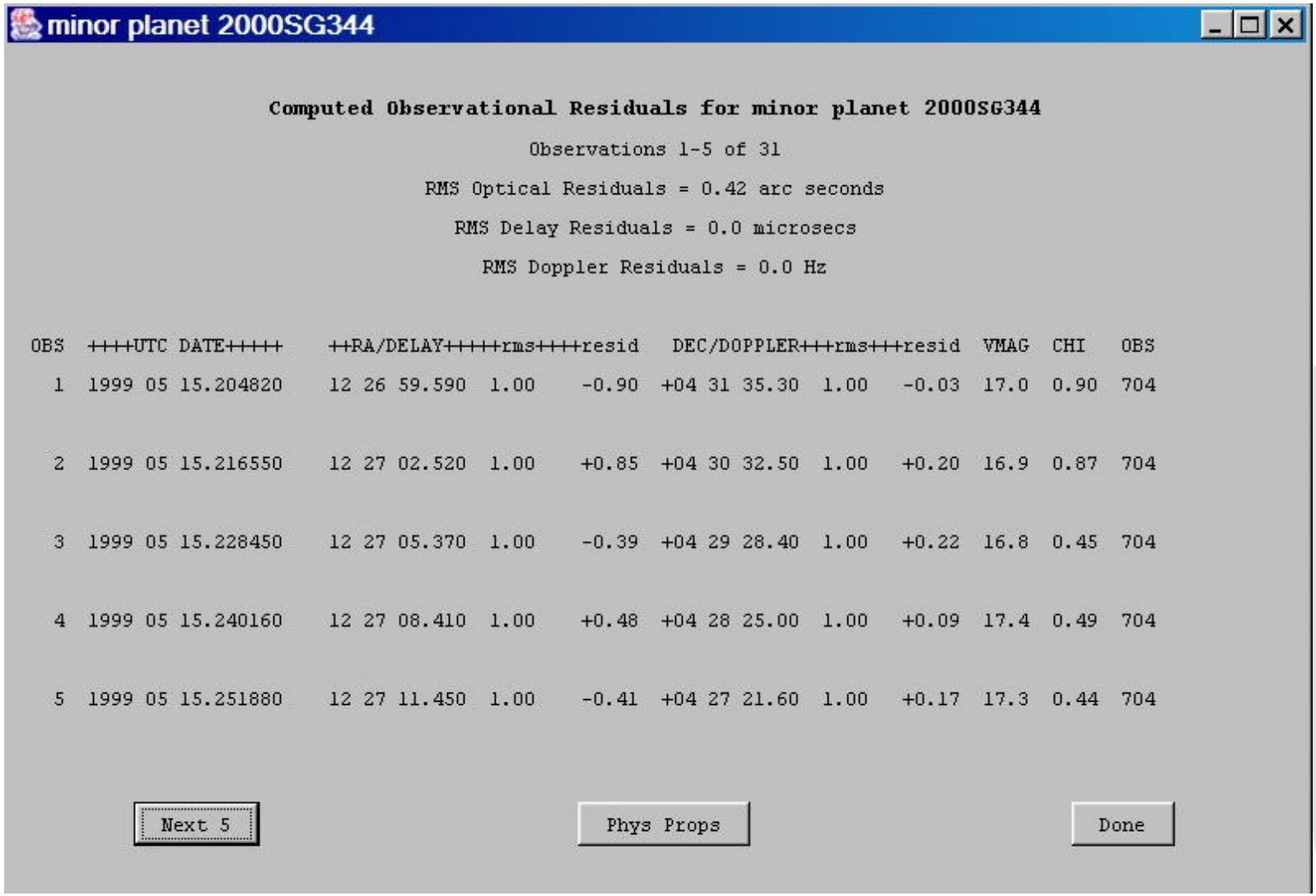
Level Two Menu: *Compute an n-body best-fit orbit*

- 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

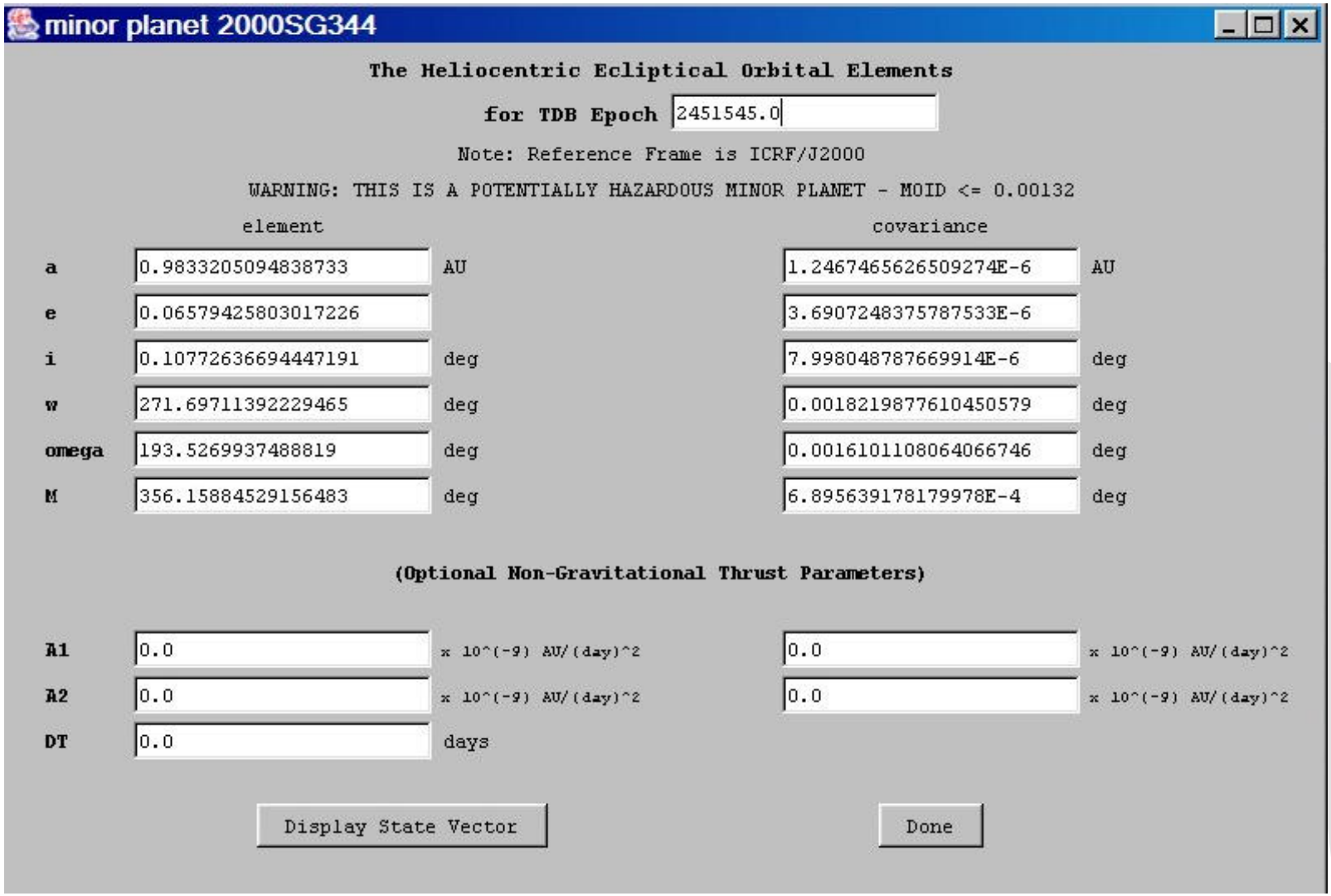
Level Two Menu: *Compute an n-body best-fit orbit (results)*

- 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 Distantce (NEOs only)
- output to screen and text file

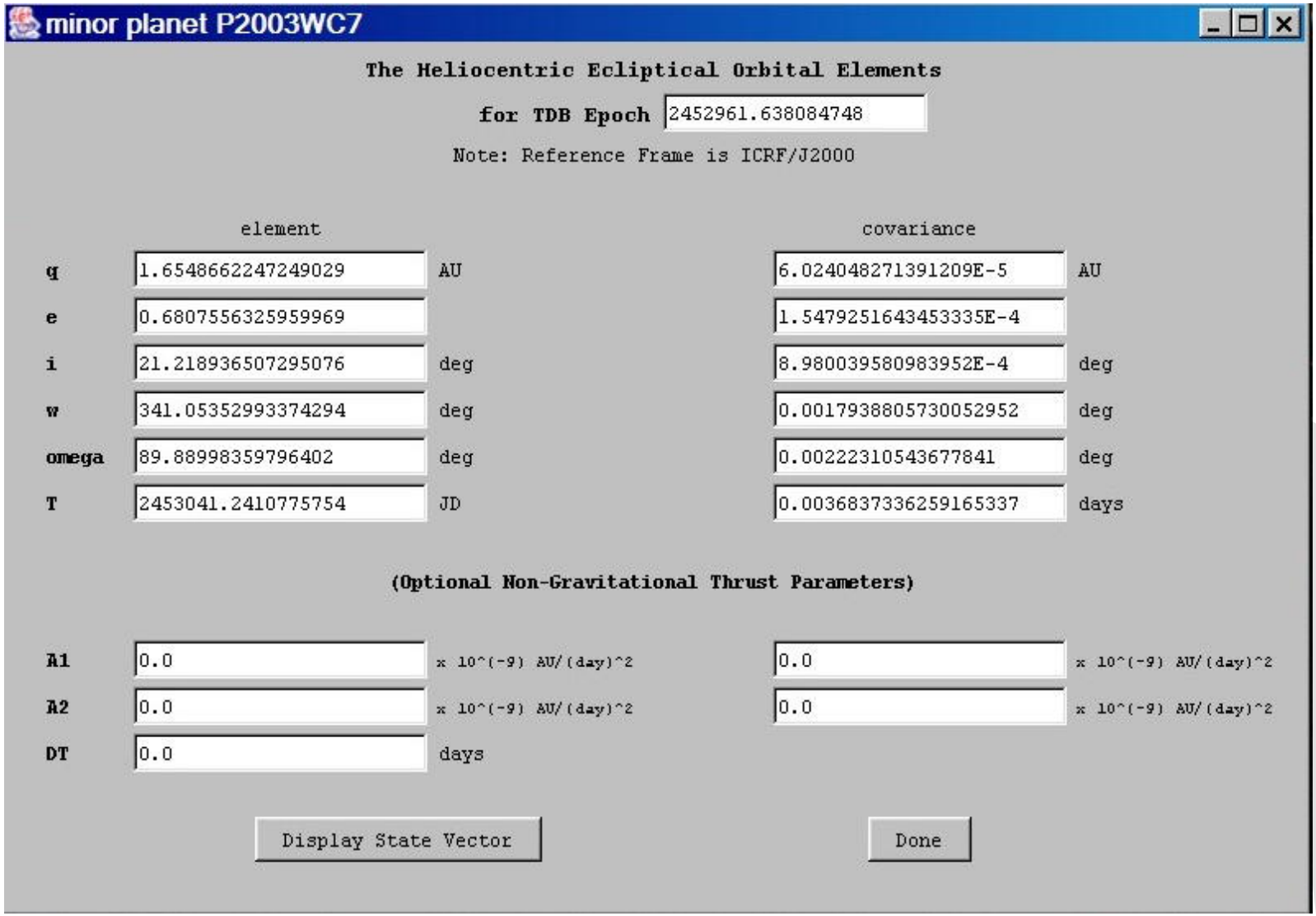
Level Two Menu: *Compute the observational residuals resulting from the current orbit*



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



Level Two Menu: *Display Current Orbit*



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

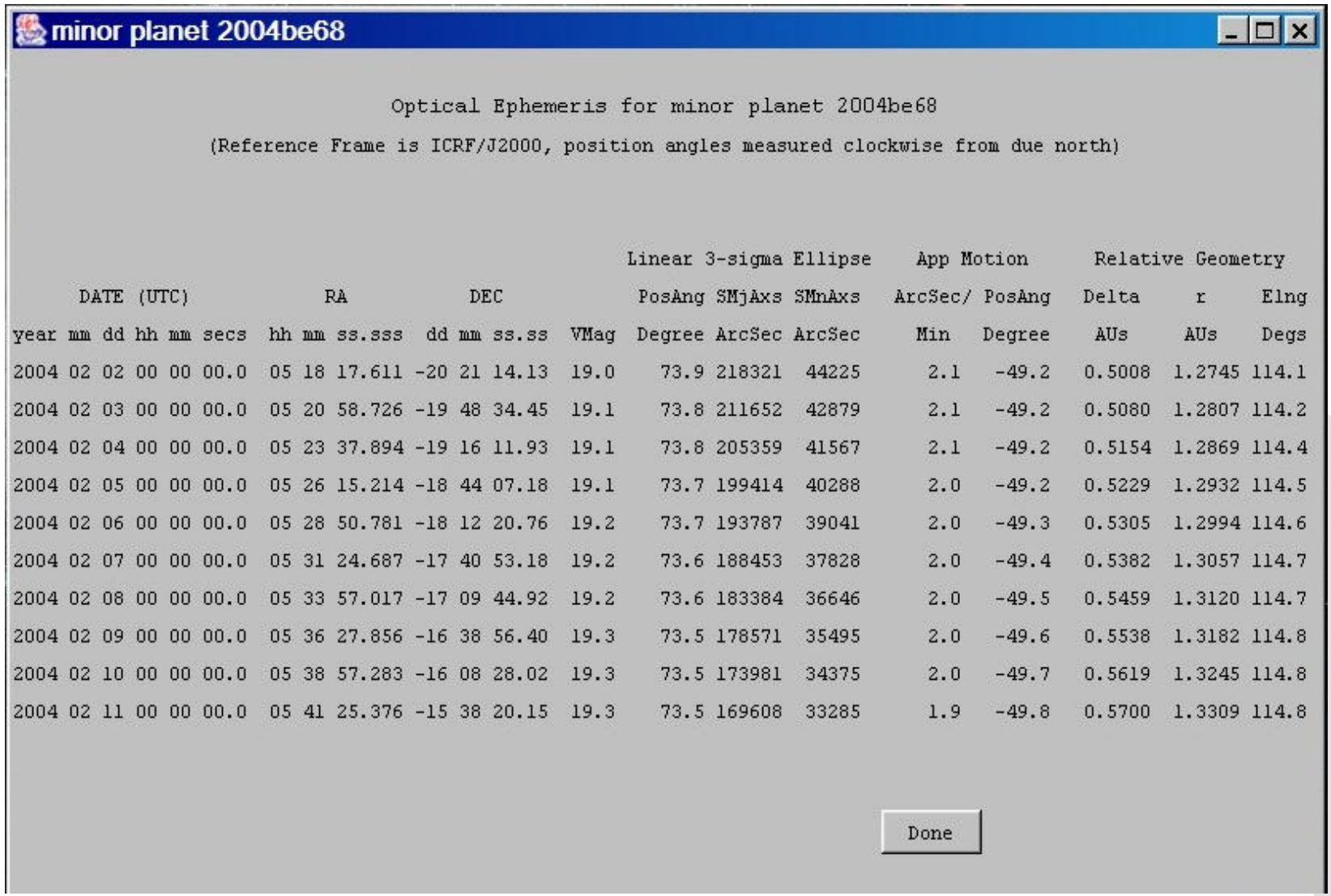
- Use two-body or n-body mechanics
- Select "medium" or "high" integration accuracy
- Narrow n-body asteroid candidate search on basis of
  - population (NEA, main belt, Centaur/TNO)
  - absolute magnitude

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*



													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:

- Propogate 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
      - propogate 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
        - propogate covariances to determine impact probability
      - if (distance at minimum > target radius) => **near miss**
        - propogate covariances to determine impact probability

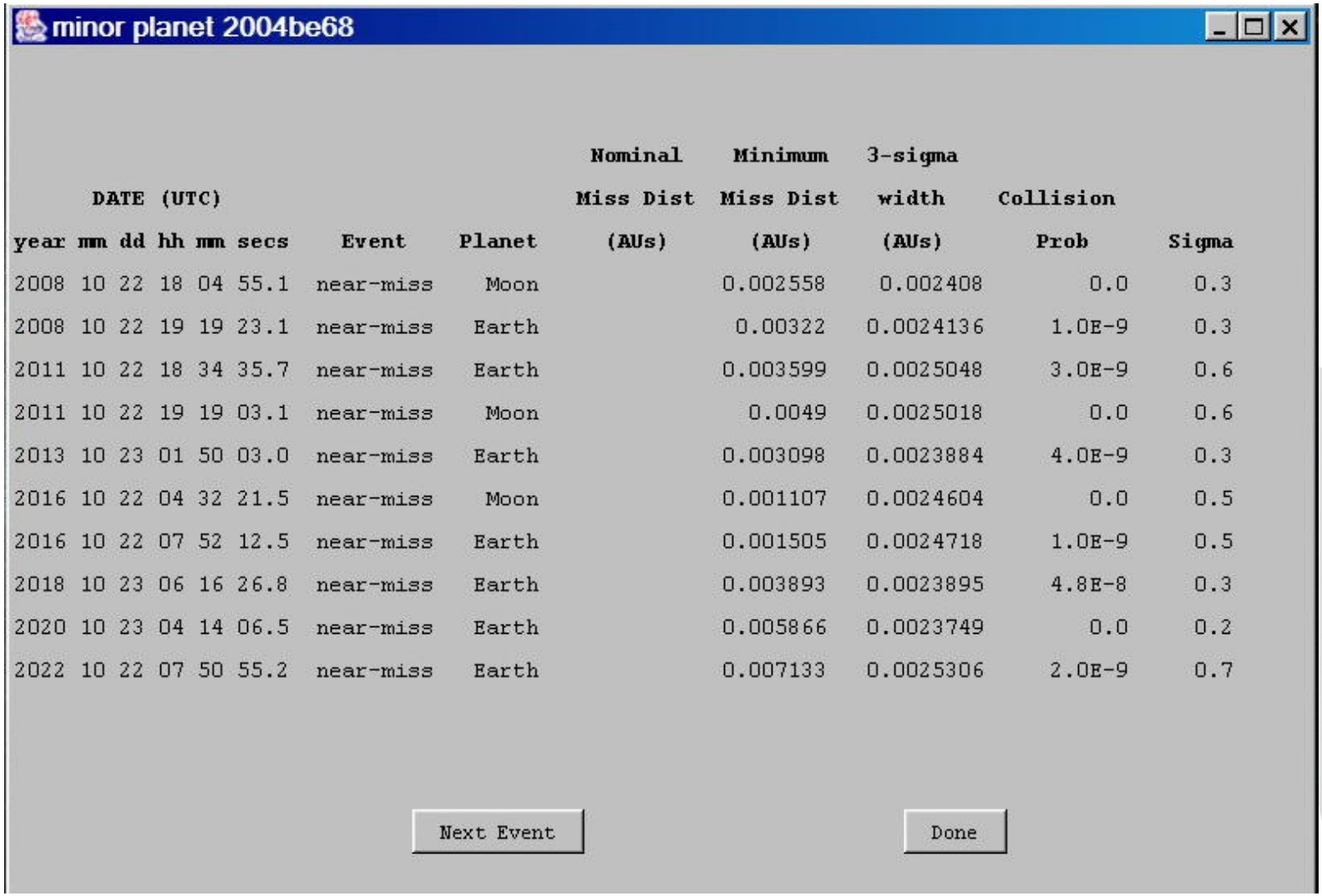
Level Two Menu: *Non-Linear Collision Analysis*

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 propogated 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)*



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)