Modeling Planetary Motions

Why We Care and How We Do It

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Overview

- Motivation
- Context
- Newcomb
- Demonstration

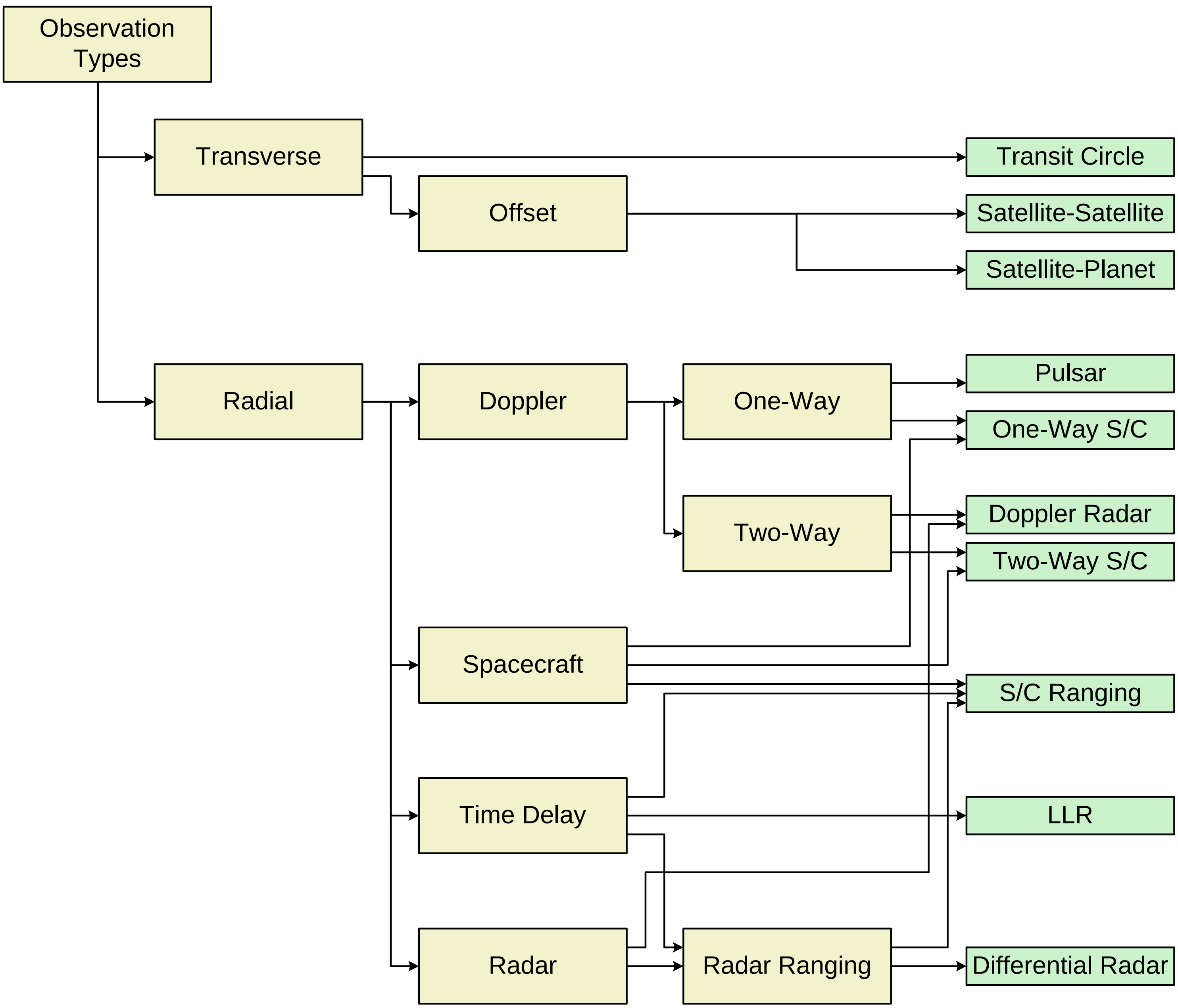
Motivation

- Why do we need precise positions?
  - Navy requirements:
    - stellar positions to 20 milliarcseconds or better
    - stellar reference frame(s) tied to Earth and solar system reference frames
  - Astronomical requirements:
    - Spacecraft navigation
    - Reference frames
    - Weak-field tests of General Relativity
    - Solar system celestial mechanics
      - Planetary satellites
      - Trojan satellites
      - Resonances
    - Asteroid masses
      - J. Hilton (USNO)
    - Stellar occultations
      - body geometry
      - atmosphere probe
        - outer planets
        - Titan

Motivation (continued)

- Therefore, we need to generate precise predictions of planetary positions (ephemerides)
- Four steps:
  1. Obtain accurate observations
     - optical (ground-based) observations
     - space-based observations (HIPPARCOS, FAME)
     - spacecraft telemetry
     - ground-based radar
     - natural satellite observations
       - ➡ planetary positions
  2. Create comprehensive solar system model
     - general relativity
     - Lunar motion
     - Earth rotation
     - planetary topography
     - asteroid masses
  3. Fit model parameters to observations
  4. Create ephemeris

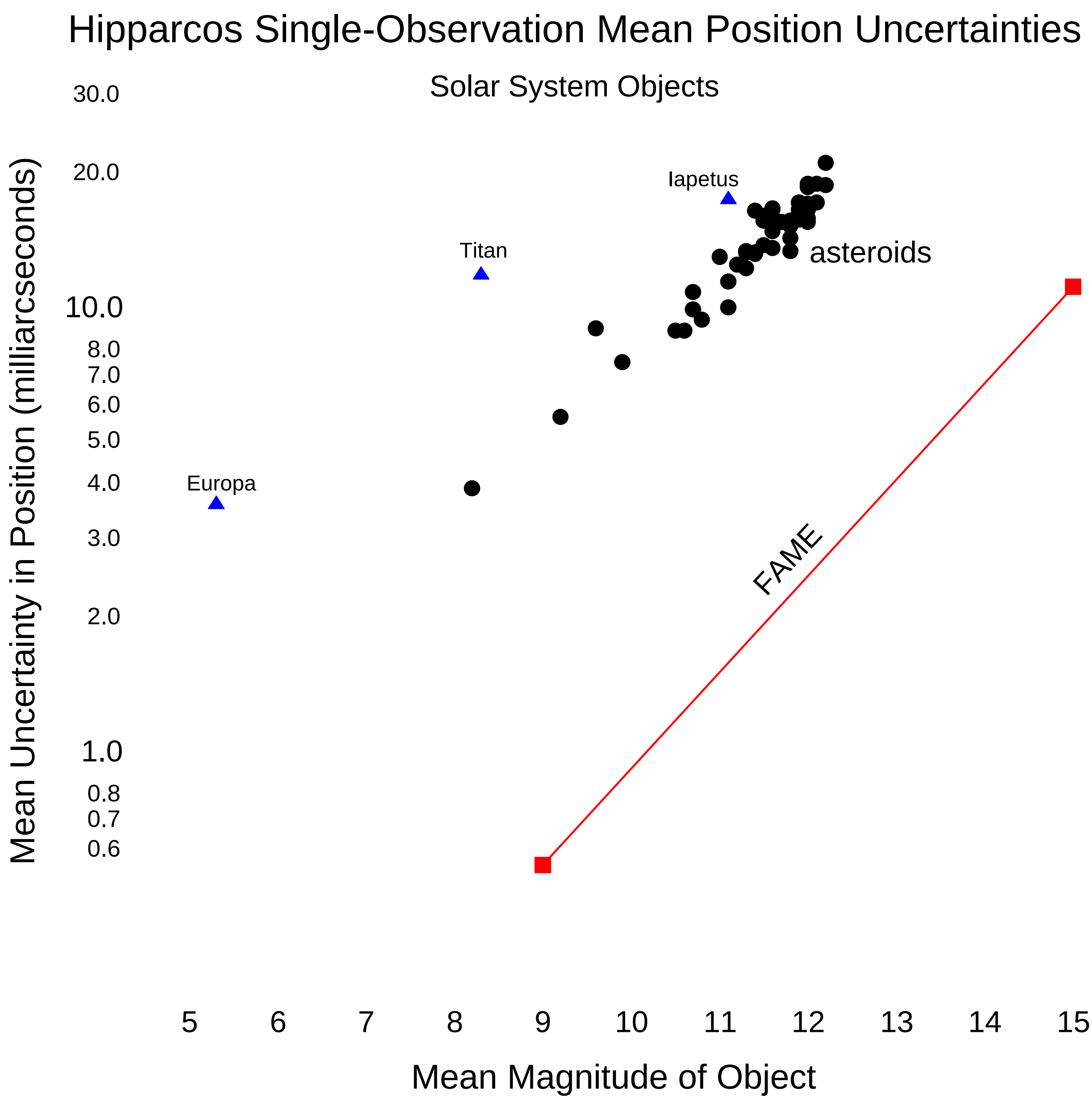
Observation Types



Context

- Example: space-based natural satellite observations
- Reference frames
- Dependencies

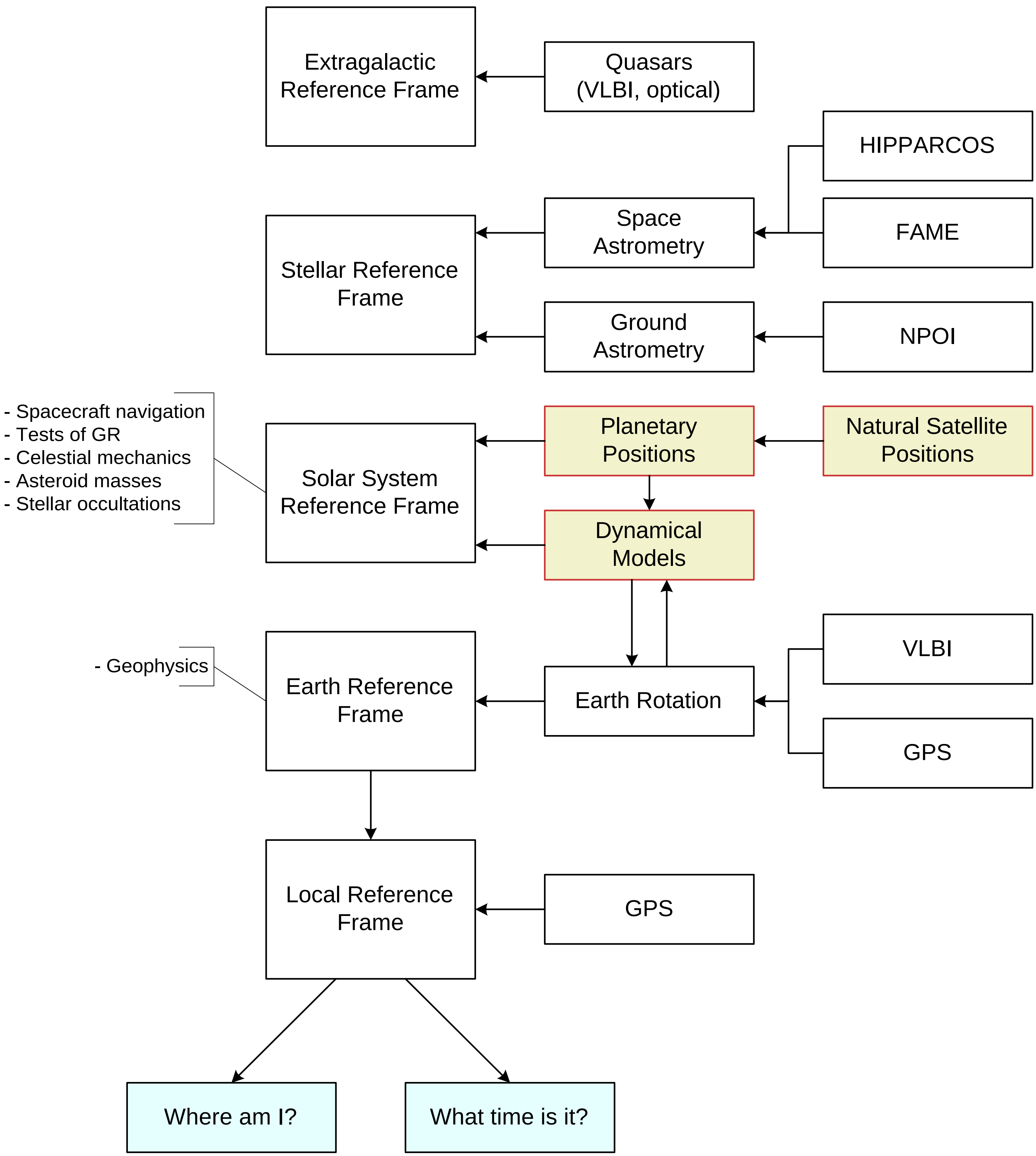
Planetary Positions from Satellite Observations



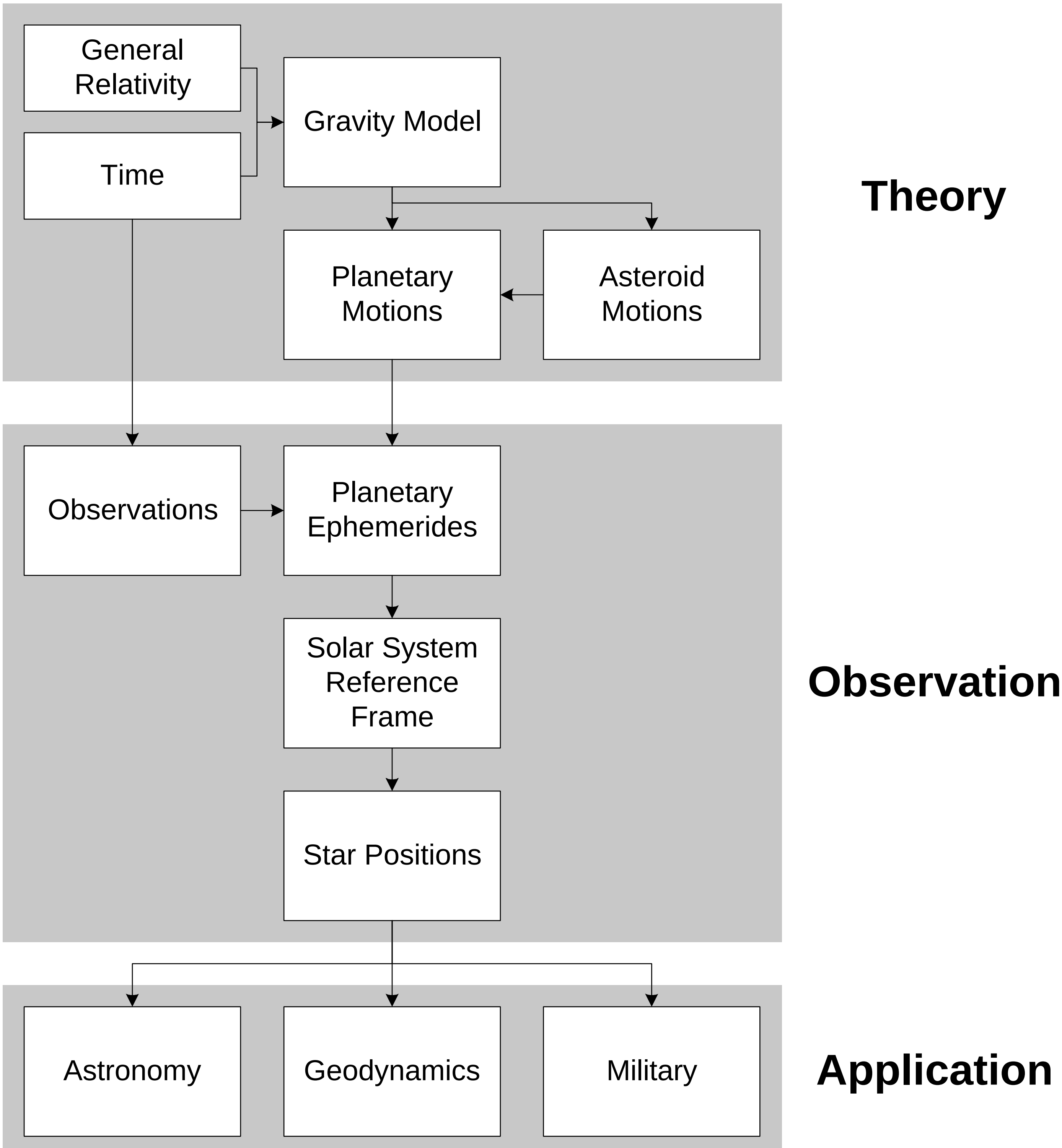
Yikes!

- ➡ How much is a milliarcsecond?
  - 1 arcsecond ≈ 1/16 of an inch around the perimeter of 1000-foot radius Observatory Circle
- How much is 50 microarcseconds?
  - the angle subtended by the width of a strand of human hair as seen from a distance of 65 miles

A Hierarchy of Reference Frames



Theory, Observation, and Application



Newcomb: A Solar System Ephemeris Program

- Motivations
- Basic process of producing a high-precision ephemeris
- Demonstration

http://aa.usno.navy.mil/Newcomb/

Newcomb: A Solar System Ephemeris Program

- Why a new program?
  - Program design and language capabilities are three generations beyond the state of the art when DE and PEP were designed.
    - Numerical algorithms
    - Object-Oriented Design (OOD)
      - data encapsulation
      - polymorphism
      - templates
    - Object-Oriented Programming (OOP)
      - fast prototyping
      - safer
      - intuitive
      - We use C++ throughout
    - Graphical User Interfaces (GUIs)
    - Rapid Application Development (RAD) environments
      - "component"-style programming
    - ➡ Extensibility
      - smaller maintenance burden
      - easily add significant new capabilities

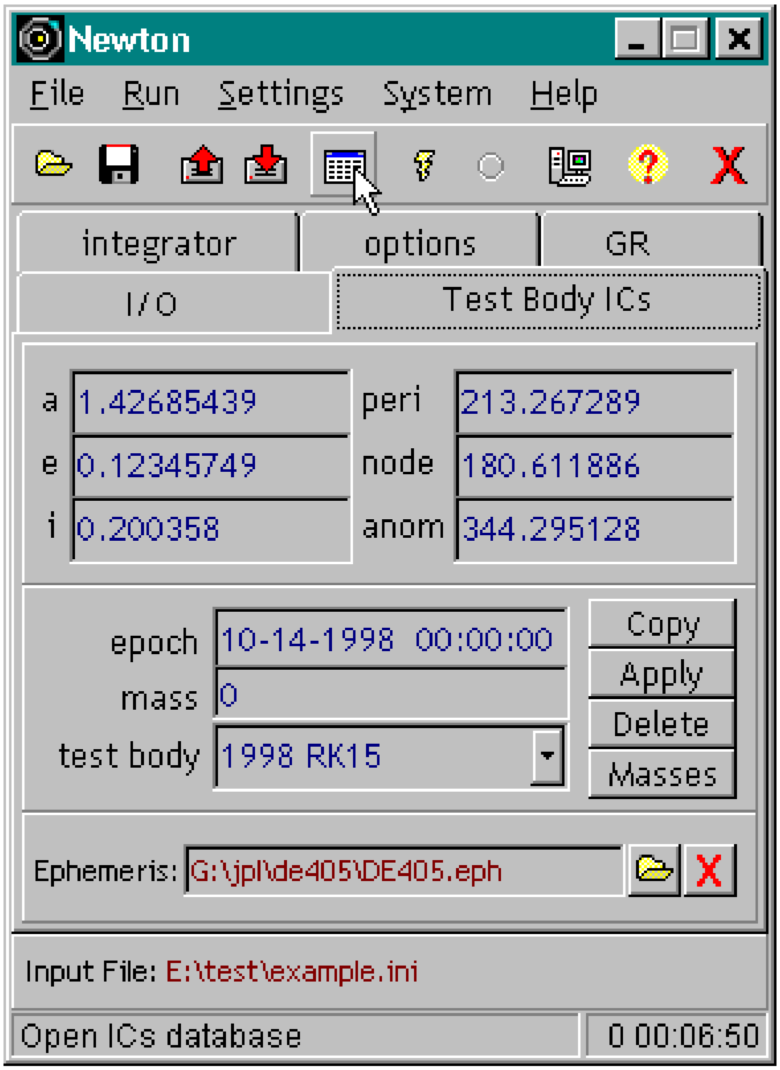
Newcomb: A Solar System Ephemeris Program

- Why a new program? (cont.)
  - U.S. Naval Observatory
    - capability to generate ephemerides locally
      - Astronomical Almanac
    - (re)develop in-house expertise
      - Improvement of planetary theories dates from the very beginings of the NAO
    - flexible research tool for solar system dynamics
      - dynamical survey of all inner solar system asteroids
        - all mean-motion resonances
        - planetary encounter distributions
      - investigation of asteroidal noise on Earth, Mars
      - TNO dynamics
  - Independent check of JPL (DE) and CfA (PEP) programs
    - ➡ Verify, verify, verify!

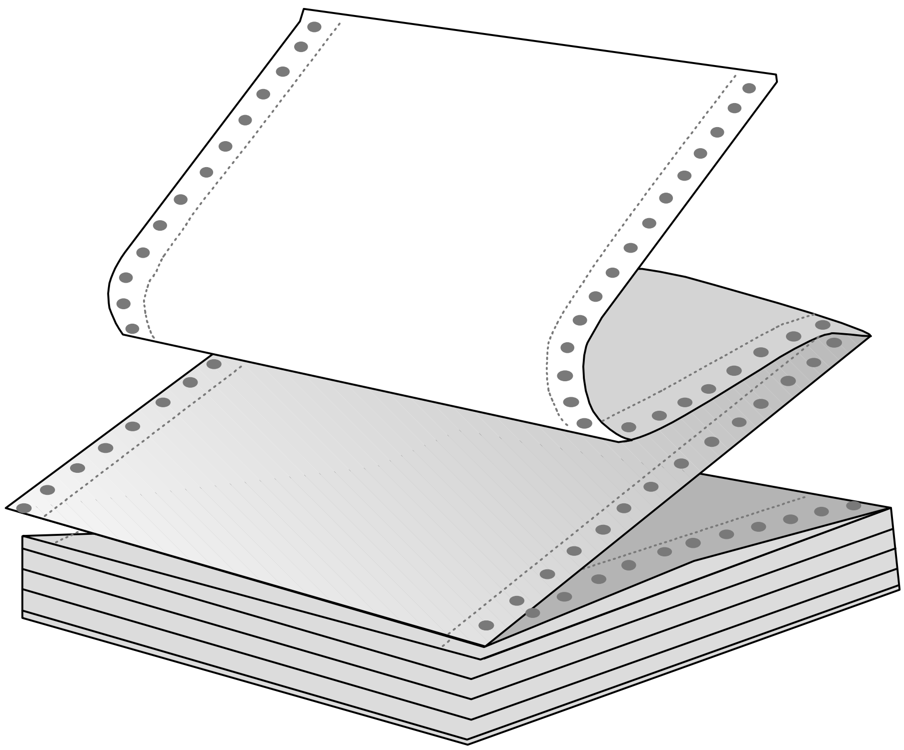
PEP Interface

```
Ephemerides improvement for the first 4 asteroids.
 &NMLST1
 EXTPRC=   0,                    $ Use hardware extended precision
 ICT(1)=  10,
 ICT(3)=   1,
 ICT(4)=   1,                    $ Compute partial derivatives
 ICT(5)=  -1,                    $ Do not used saved normal equations
 ICT(9)=   0,
 ICT(10)=  -2, ICT(11)= -2,
 ICT(12)=  2,                    $  prediction or harmonic analysis
 ICT(34)=  3,
 ICT(39)=  1,
 ICT(50)=  1,                    $ USE BROWN MEAN MOON IF NO IPERT
 ICT(80)=  0,
 JCT(13)=  1,                    $ Use J2000.0 coordinates.
 JCT(33)= -1,                    $ Use USNO UT1 and wobble
 JCT(27)=  1,                    $ Use * commands
 JCT(28)=  7,
 MASS(1)= 6023600.D0,            $ Use DE200 masses for the planets
 MASS(2)=  408523.5D0,
 MASS(3)=  328900.550000000047D0,
 MASS(4)= 3098710.D0,
 MASS(5)=    1047.35001090551827D0,
 MASS(6)=    3497.99999984177066D0,
 MASS(7)=   22960.0000007059389D0,
 MASS(8)=   19314.0002382557432D0,
 MASS(9)= 130000000.238686755D0,
 MASS(10)=      0.012150581D0,
 MASS(11)=      2.239D9,
 MASS(12)=      9.247D9,
 MASS(13)=      8.7D10,
 MASS(14)=      7.253D9,
 MASS(17)=      1.849D11,
 AULTSC=      499.0047837D0,      $ Length of AU in light seconds
 ECINC=       23.439281083D0,       $ Use DE118 Obliquity
 PRMTER(47)= 0.0D0,              $ RT. ASC. OF ASCENDING NODE OF ASTEROID BELT
 PRMTER(48)= 23.4433D0,          $ INCLINATION OF ASTEROID BELT
 PRMTER(49)= 2.9D0,              $ DISTANCE OF ASTEROID BELT FROM SUN
 PRMTER(50)= 8.773725302941010D-10,  $ MASS OF ASTEROID BELT
 PRMTER(81)= 0.0D0,
 MDSTSC=  0.,                    $ MOON TAPE DISTANCE UNIT IN AU
 NBODY= 0, IPERT= 10,
 NUMOBT= 1,
 IOBS = 30,
 IOBS1= 14, IOBS2= 15,
$ EPS(3)= 100,
$ EPS(4)= 100,
 LPRM(1)= 11,  LPRM(2)= 12,  LPRM(3)= 14,
*OBJECT EARTH-ROTATION
 CON(22)= 5029.0966,
 CON(23)= 84381.4119,
*OBJECT 11
 NAME=  '  CERES ',
 INCND= 0, ITAPE= 31, NCENTR= 0, JTYPE=6,
 A=    2.767121817D0,   E=   0.07749262D0, INC=  27.116375D0,
 ASC= 23.471566D0,   PER= 133.40890D0,   ANOM=  2.08129D0,
  JD1= 2378801, JD2= 2450001, JD0= 2444801,
 K(31)=   1, K(32)=  1,  K(33)= 1,  K(34)= 1,  K(35)= 1,  K(36)= 1, K(37)= 1,
 K(38)=   1, K(39)=  1,  K(40)= 1,  K(41)= 1,  K(42)= 1,  K(43)= 1, K(44)= 1,
 K(61)=  1                       $ Include General Relativity
 K(87)=   2, INT=    2,          $ INTERVALS
 K(88)=   2, K(89)=  6,          $ ADAMS-MOULTON METHOD, 7 TERMS
  K(91)=  -3, K(92)= -6, EPS(3)= 1E-9  $ STARTING INTERVALS
 K(98)=  -500, K(99)=  0, K(100)= -1,  $ PRINT + TAPE; ORDINARY EQNS OF MOTION
 KI=       1, 1, 1, 1, 1, 1, 1, 12, 13, 14,
 L=        1, 1, 1, 1, 1, 1,
*OBJECT 12
 NAME=  ' PALLAS ',
 INCND= 0, ITAPE= 32, NCENTR= 0, JTYPE=6,
 A=    2.771672932D0, E=     0.23398027D0, INC=   11.809637D0,
 ASC= 161.02570D0,     PER= 322.78775D0,    ANOM= 298.543057D0,
  JD1= 2379251, JD2= 2450001, JD0= 2449601,
 K(31)=   1, K(32)=  1,  K(33)= 1,  K(34)= 1,  K(35)= 1,  K(36)= 1, K(37)= 1,
 K(38)=   1, K(39)=  1,  K(40)= 1,  K(41)= 1,  K(42)= 1,  K(43)= 1, K(44)= 1,
 K(61)=   1,                     $ Include General Relativity
 K(87)=   2, INT=    2,          $ INTERVALS
 K(88)=   2, K(89)=  6,          $ ADAMS-MOULTON METHOD, 7 TERMS
 K(91)=  -3, K(92)= -6, EPS(3)= 1E-9  $ STARTING INTERVALS
 K(98)=  -500, K(99)=  0, K(100)= -1,  $ PRINT + TAPE; ORDINARY EQNS OF MOTION
 KI=       1, 1, 1, 1, 1, 1, 1, 11,
 L=        1, 1, 1, 1, 1, 1,
*OBJECT 13
 NAME=  '  JUNO  ',
 INCND= 0, ITAPE= 33, NCENTR= 0, JTYPE= 6,
 A=     2.670660949D0, E=      .25626106D0, ANOM= 156.782239D0,
 INC=  10.814499D0,   PER=  46.75209D0,   ASC=   11.27760D0,
 JD1=   2380151, JD2= 2450001, JD0= 2444801,
 K(31)=  1, K(32)= 1, K(33)= 1, K(34)= 1, K(35)= 1, K(36)= 1, K(37)= 1,
 K(38)=  1, K(39)= 1, K(40)= 1, K(41)= 1, K(42)= 1, K(43)= 1, K(44)= 1,
 K(61)= -1,
 K(87)=    4, INT=    4,               $ Intervals
 K(88)=    2, K(89)=  6,               $ Adams-Moulton integrator, 7 terms
 K(91)=   -3, K(92)= -6, EPS(3)= 1E-9, $ Starting intervals
 K(98)=  -500, K(99)=  0, K(100)= -1,   $ Print & tape, ordinary eqs. of moti
 KI=       1, 1, 1, 1, 1, 1, 1,
 L=        1, 1, 1, 1, 1, 1,
*OBJECT 14
 NAME=  '  VESTA ',
 INCND= 0, ITAPE= 34, NCENTR= 0, JTYPE= 6,
 A=     2.362114063D0, E=     0.08961581D0, INC=   22.717580D0,
 ASC=  18.187358D0,   PER= 237.48420D0,   ANOM= 308.51911D0,
  JD1= 2381051, JD2= 2450001, JD0= 2444801,
 K(31)=   1, K(32)=  1,  K(33)= 1,  K(34)= 1,  K(35)= 1,  K(36)= 1,  K(37)= 1
 K(38)=   1, K(39)=  1,  K(40)= 1,  K(41)= 1,  K(42)= 1,  K(43)= 1,  K(44)= 1
 K(61)=   1,                     $ Include General Relativity
 K(87)=   2, INT=    2,          $ INTERVALS
 K(88)=   2, K(89)=  6,          $ ADAMS-MOULTON METHOD, 7 TERMS
 K(91)=  -3, K(92)= -6, EPS(3)= 1E-9  $ STARTING INTERVALS
 K(98)=  -500, K(99)=  0, K(100)= -1,  $ PRINT + TAPE; ORDINARY EQNS OF MOTIC
 KI=       1, 1, 1, 1, 1, 1, 1, 11,
 L=        1, 1, 1, 1, 1, 1,
*OBJECT 27
 NAME=  '  Arete ',
 INCND= 0, ITAPE= 37, NCENTR= 0, JTYPE= 6,
 A=     2.73942088D0, E=     0.1630220D0, INC=   26.08786D0,
 ASC=  20.12111D0,     PER= 310.03548D0,   ANOM= 168.77030D0,
  JD1= 2407351, JD2= 2450002, JD0= 2450001,
 K(31)=   1, K(32)=  1,  K(33)= 1,  K(34)= 1,  K(35)= 1,  K(36)= 1,  K(37)= 1
 K(38)=   1, K(39)=  1,  K(40)= 1,  K(41)= 1,  K(42)= 1,  K(43)= 1,  K(44)= 1
 K(61)=   1,                     $ Include General Relativity
 K(87)=   2, INT=    2,          $ INTERVALS
 K(88)=   2, K(89)=  6,          $ ADAMS-MOULTON METHOD, 7 TERMS
 K(91)=  -3, K(92)= -6, EPS(3)= 1E-9  $ STARTING INTERVALS
 K(98)=  -500, K(99)=  0, K(100)= -1,  $ PRINT + TAPE; ORDINARY EQNS OF MOTIC
 KI=       1, 1, 1, 1, 1, 1, 1, 14,
 L=        1, 1, 1, 1, 1, 1,
*SITES
WASHUSNO      6378.14014    77.067451477    38.921340942         0 0 0-3
         6378.14014         .003352810
LEONUSNO      6380.438      69.33167       -31.80278             0 0 0-3
         6380.438           .003352810
LaPalma       6380.468      17.8817         28.7600              0 0 0-3
         6380.468           .003352810
GRENWICH      6378.189       0.00000        51.47728             0 0 0 0
Bordeaux      6378.213       0.5283         44.835               0 0 0-3
         6378.213           .00335364
CAPETOWN      6378.153     -18.47864       -33.93519             0 0 0 0
EDINBURG      6378.274       3.18425        55.92500             0 0 0 0
CAMBRIDG      6378.169      -0.09479        52.21433             0 0 0 0
SEEB          6378.463     -10.71045        50.94386             0 0 0 0
MILAN         6378.260      -9.19117        45.46647             0 0 0 0
PALERMO       6378.216     -13.35779        38.11222             0 0 0 0
OTTAWA        6378.225      75.8933         45.3869              0 0 0 0
PARIS         6378.207      -2.337619       48.8364              0 0 0 0
TOULOUSE      6378.334      -1.4625         43.61222             0 0 0 0
NICE          6378.478      -7.30208        43.72136             0 0 0 0
BESANCON      6378.452      -5.98833        47.24936             0 0 0 0
UCCLE         6378.245      -4.358114       50.79844             0 0 0 0
GTOKYO        6378.199    -139.540750       35.67261             0 0 0 0
*EECORR
PALE SCHU       1 0 1                   0.1824     0.0000      1.954
MILA SCHU       1 0 1                   0.0638     0.0000     -1.914
GREN SCHU       1 0 1                   0.0000     0.0000      0.0000
GREN 1530       1 0 1                   0.2628     0.0000     -3.158
GREN 3679       1 0 1                   0.0595     0.0000     -0.040
GREN 8096       1 0 1                   0.0727     0.0000     -0.352
CAMB SCHU       1 0 1                   0.0950     0.0000     -0.406
CAMB COLD       1 0 1                   0.1496     0.0000      0.757
EDIN SCHU       1 0 1                   0.1794     0.0000      0.186
PARI SCHU       1 0 1                   0.0033     0.0000      0.982
PARI 6479       1 0 1                   0.0450     0.0000      0.149
SEEB SCHU       1 0 0                  -0.0509     0.0000      0.0000
GREN G189       1 0 1                   0.0268     0.0000     -0.118
WASH WA25       1 0 1                  -0.0051     0.0000      0.027
WASH W350       1 0 1                  -0.0377     0.0000     -0.017
WASH W450       1 0 1                  -0.0493     0.0000     -0.049
WASH W550       1 0 1                  -0.0587     0.0000     -0.056
LEON WL50       1 0 1                  -0.0582     0.0000      0.028
WASH W650       1 0 1                  -0.0103     0.0000     -0.116
LaPa L890       1 0 1                  -0.0056     0.0000     -0.051
$Bord BV85       1 0 1                   0.0000     0.0000      0.0000
**END
```

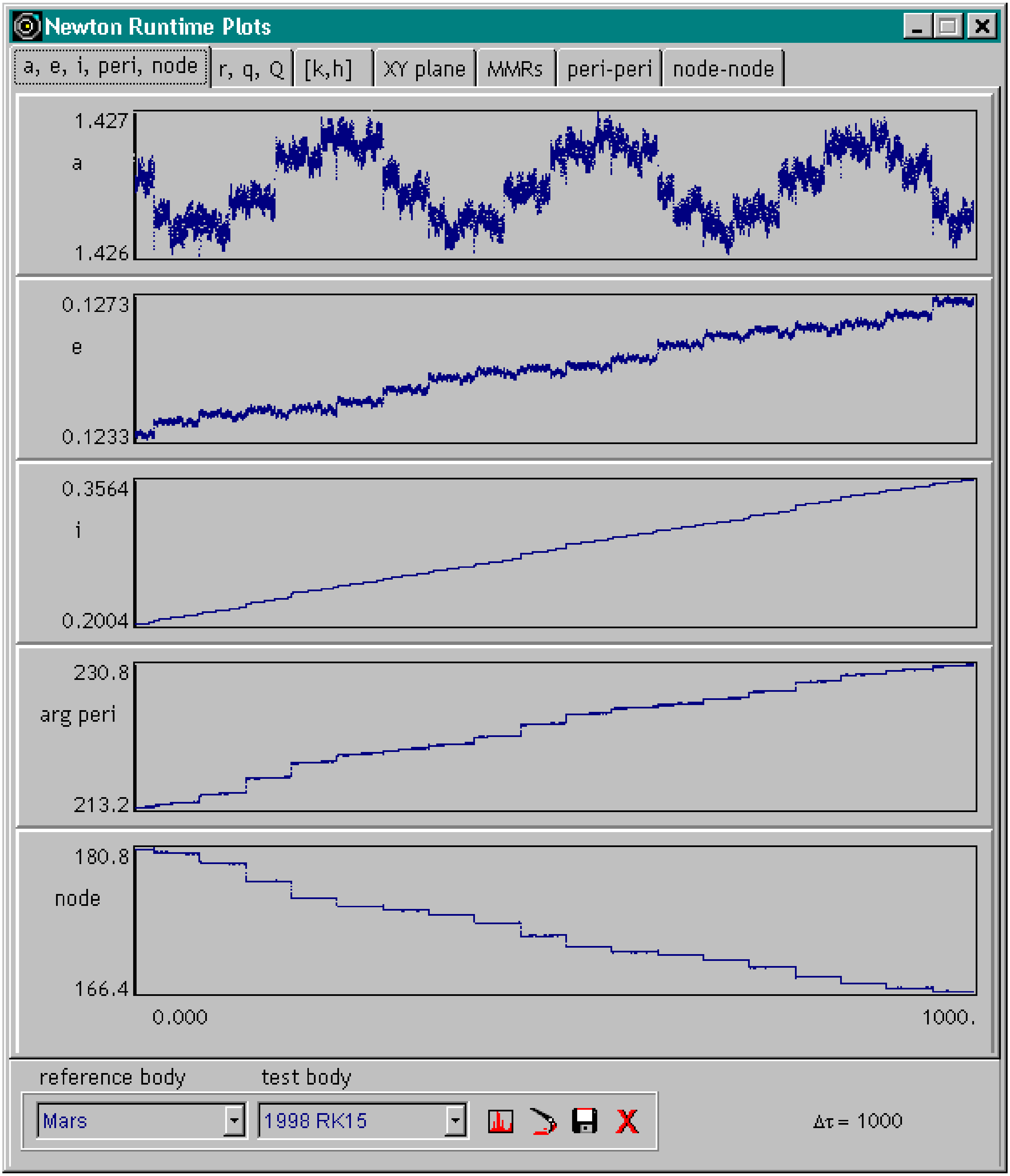
Newcomb Interface



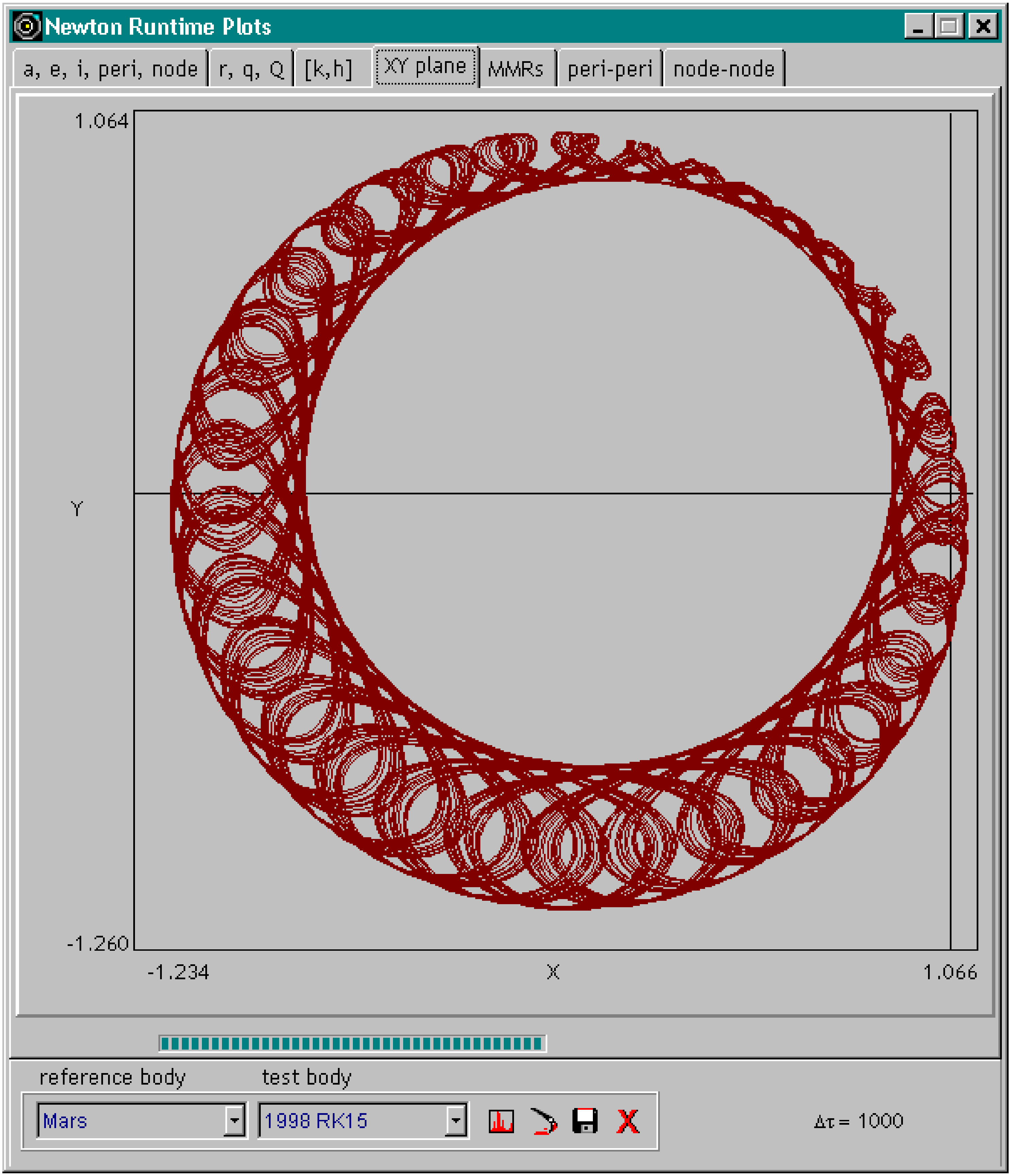
PEP Quick-Look



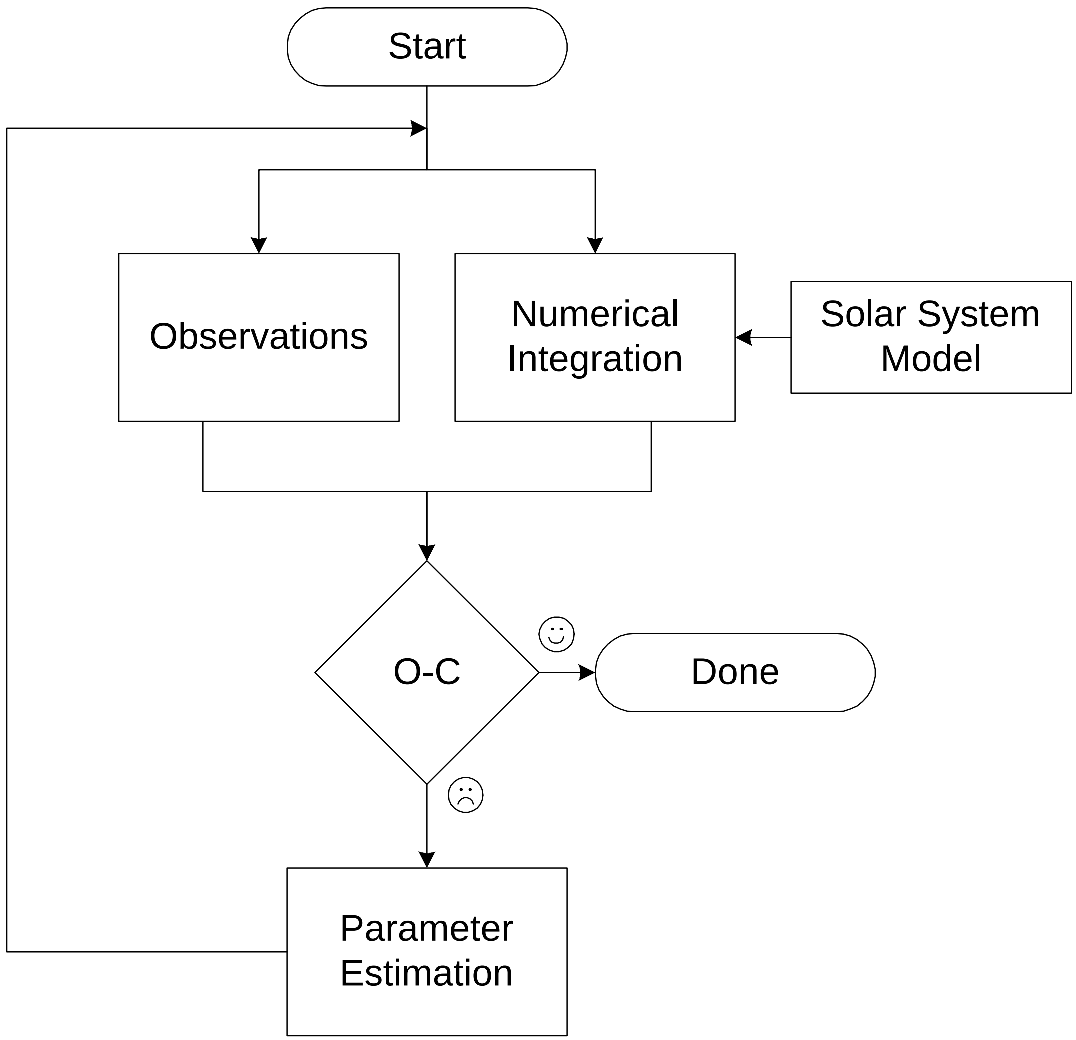
Newcomb Quick-Look



Newcomb Quick-Look



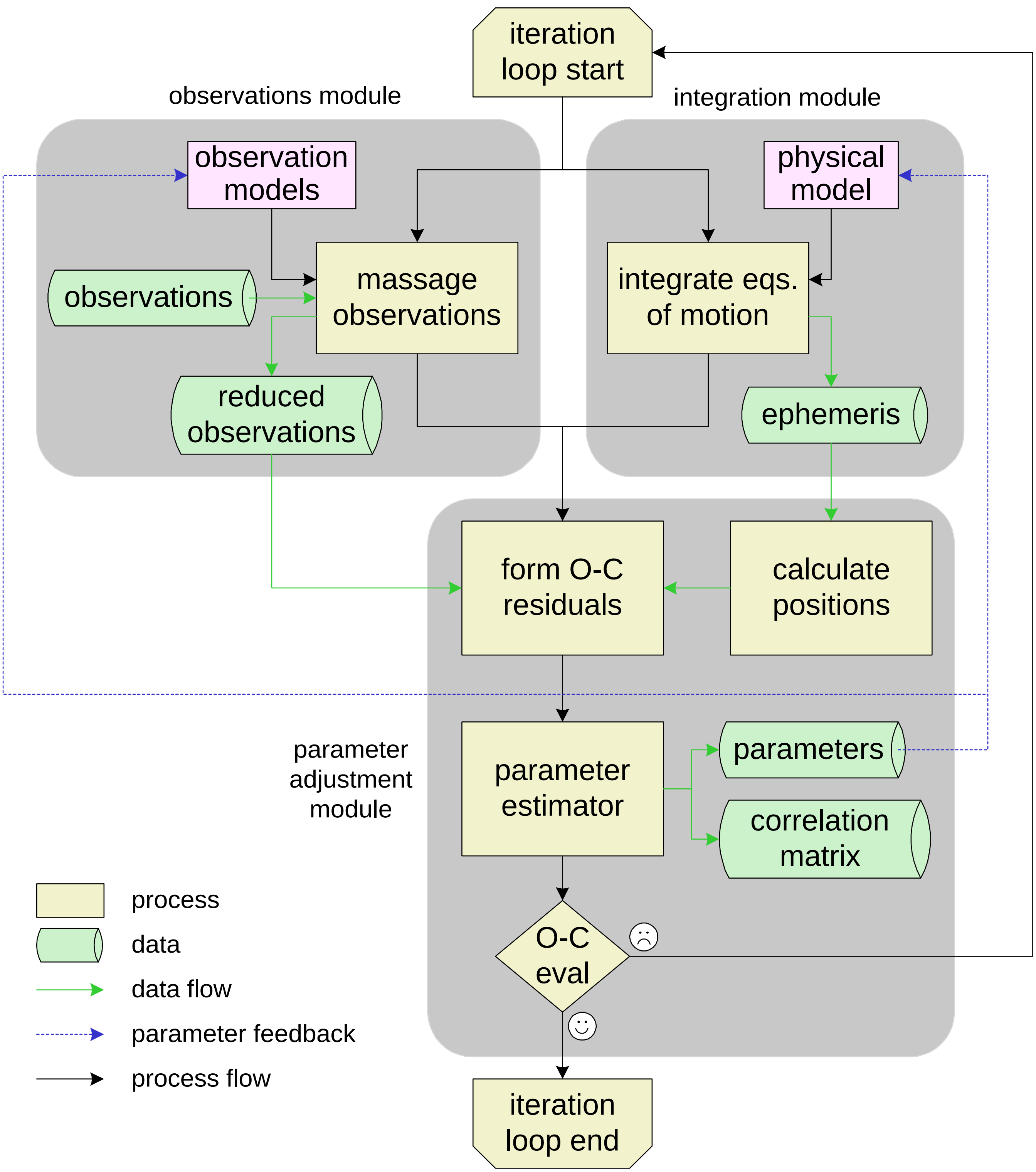
Newcomb Outline



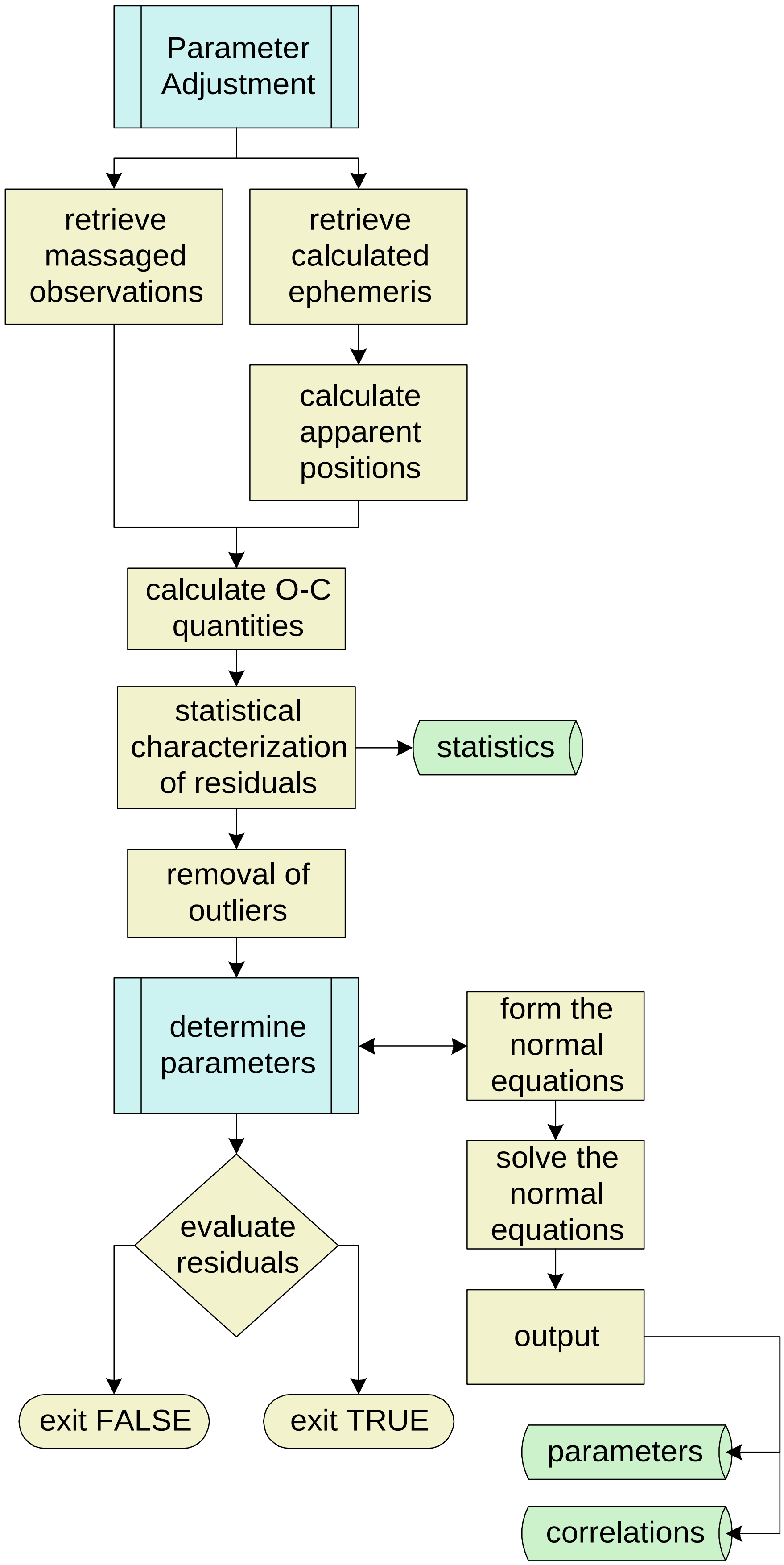
(An Aside)

- Eckert and the first digital machine: ~1 ms to multiply two 10-digit numbers
  - Factor of $\sim 10^8$ improvement
- This machine (266 MHz PII): 11 ns to multiply two 15-digit numbers
  - Factor of $\sim 10^5$-10^6 improvement

Process Outline (Detailed)



Parameter Adjustment Module



Integration Module