Reconstruction of the 1801 Discovery Orbit of Ceres via Contemporary Angles-Only Algorithms

Timeline 1801-1802

• **Jan 1 through Feb 11** – Piazzi discovers/observes the first asteroid, Ceres.

• **September** – von Zach publishes Piazzi's observations in *Monatliche Correspondenz.* *See* 1

• **October-November**– von Zach publishes orbital analyses by Burckhardt, Olbers, and Piazzi.

• **December** – von Zach publishes orbital elements and search ephemeris of Gauss. Recovers Ceres on night of 1801 Dec 31 – 1802 Jan 1 using Gauss search ephemeris. *See* 2

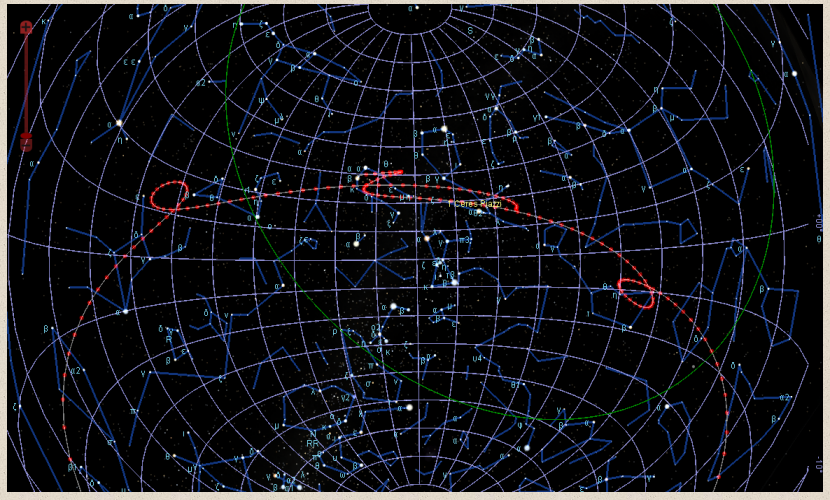
Timeline 1802-Present

• **1840s** – Star catalogs refined/standardized, making more accurate observations possible.

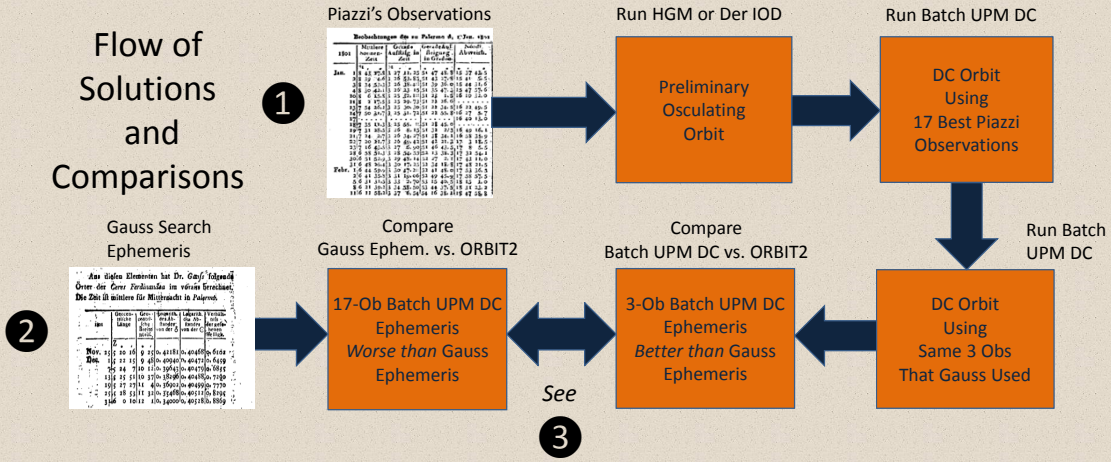
• **1895** – USNO's Simon Newcomb publishes highly accurate *Tables of the Sun.*

• **1950s – 1980s** – Digital computers and atomic clocks developed and refined; J2000 reference frame adopted for orbital motion and FK5 star catalog reference frame.

• **1990s – Present** – CCD imaging in telescopes; USNO star catalogs enable sub-arc-second angle measurements by telescopes using CCDs.



Path of Ceres from 1801 January 1 to 1806 May 23. This figure shows what the path of Ceres, as a dwarf planet in the asteroid belt, looked like from the date of Ceres's discovery by Piazzi through its observation by Olbers, Harding, and Bessel in 1805-1806.



The Contemporary Algorithms

Der IOD (Initial Orbit Determination)
- 3 angles-only (RA, DEC) observations
- Long arcs admissible, up to one orbital revolution
- Solves for range via 8th degree polynomial
- Epoch of elements is at middle observation time

HGM IOD – Heliocentric motion
- n angles-only (RA, DEC) observations
- n ≥ 3 but subject to short-arc limitation
- Iterates on range guesses for first and last observations
- Epoch of elements is at first ob time

ORBIT2 Numerical Integration
- Numerically integrates equations of motion of major Solar System planets and "Spare"
- "Spare" can be space probe, comet, asteroid, or dwarf planet
- Starts with DE405 initial state vectors of planets and J2000 initial state vector for "Spare"

Batch UPM DC – Heliocentric motion
- Given n ≥ 3 observations, differentially corrects Der IOD or HGM initial state estimate
- Uses UPM (Uniform Path Mechanics) to propagate orbit of arbitrary eccentricity (i.e., UPM is a "universal variables" method)

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Summary of Findings

3

1. Out of 19 complete Piazzi observations, only two were assessed as "bad" (1801 Jan 3 and Jan 11).
2. Ephemeris propagated from contemporary Batch UPM DC solution with 17 best Piazzi observations was slightly *worse* than Gauss's 1801 December search ephemeris.
3. Ephemeris propagated from contemporary Batch UPM DC solution with 3 Piazzi observations* was slightly *better* than Gauss's 1801 December search ephemeris. (*Used exact same 3 observations that Gauss himself used: 1801 Jan 1, Jan 21, and Feb 11.)