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# Recent Developments in Planetary Ephemeris Observations

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# Acknowledgements

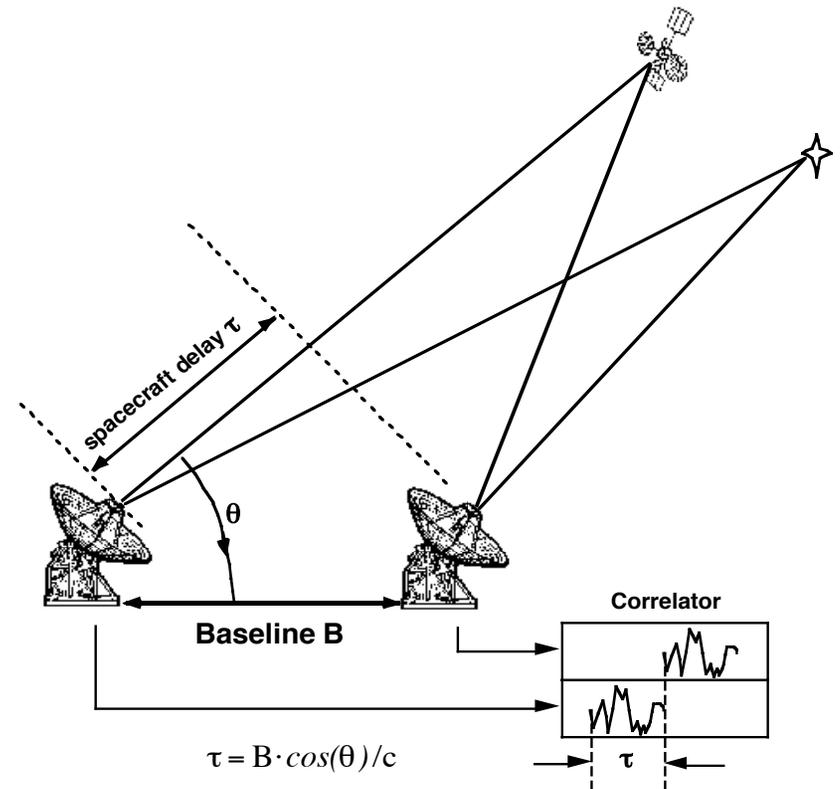
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- Sensitivity to relativistic parameters in the ephemerides comes (mainly) through processed planetary spacecraft observations;
- MESSENGER - Tony Taylor (Kinetx)
- Venus Express - Trevor Morley (ESOC)
- Mars ranging - Alex Konopliv (JPL); Trevor Morley (ESOC)
- Mars VLBI - Jim Border (JPL)
- Saturn  $r$ ,  $\alpha$ ,  $\delta$  - Bob Jacobson (JPL)
- Saturn VLBA - Dayton Jones (JPL)/Ed Fomalont (NRAO)
- Astrometry - W. Owen (JPL), A. Monet, H. Harris (USNO)



# Ephemeris Tie to ICRF

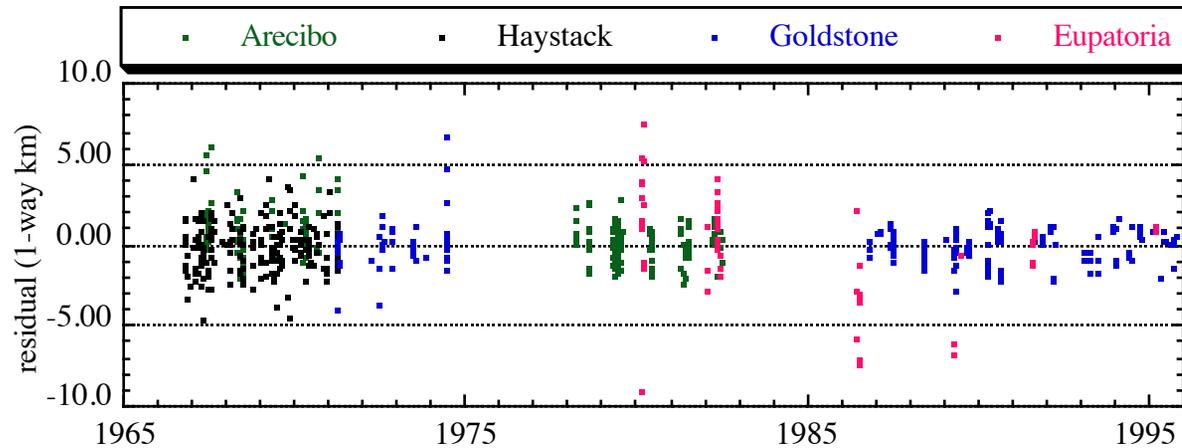
- VLBI measures spacecraft angular position relative to radio reference frame
  - MGS, Odyssey, MRO
- Doppler ties spacecraft position to center of planet
  - Reconstructed accuracy <10m
- VLBI measurement types;
  - Doubly-difference range ( $\Delta$ DOR)
    - DSN and ESA stations
  - Differenced carrier phase
    - Very Long Baseline Array



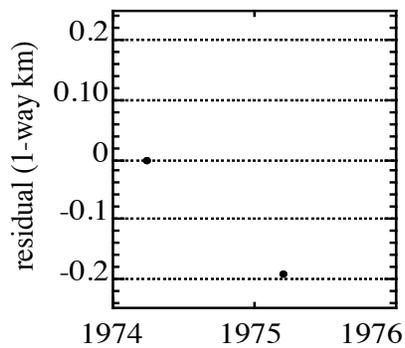


# Mercury Orbit Data

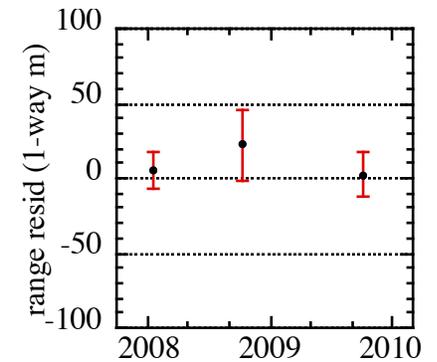
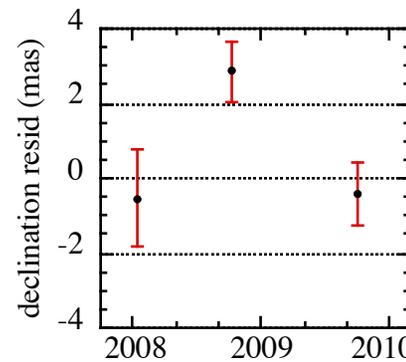
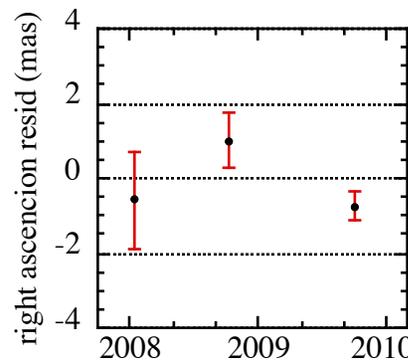
## Radar Ranging



## Mariner 10 range

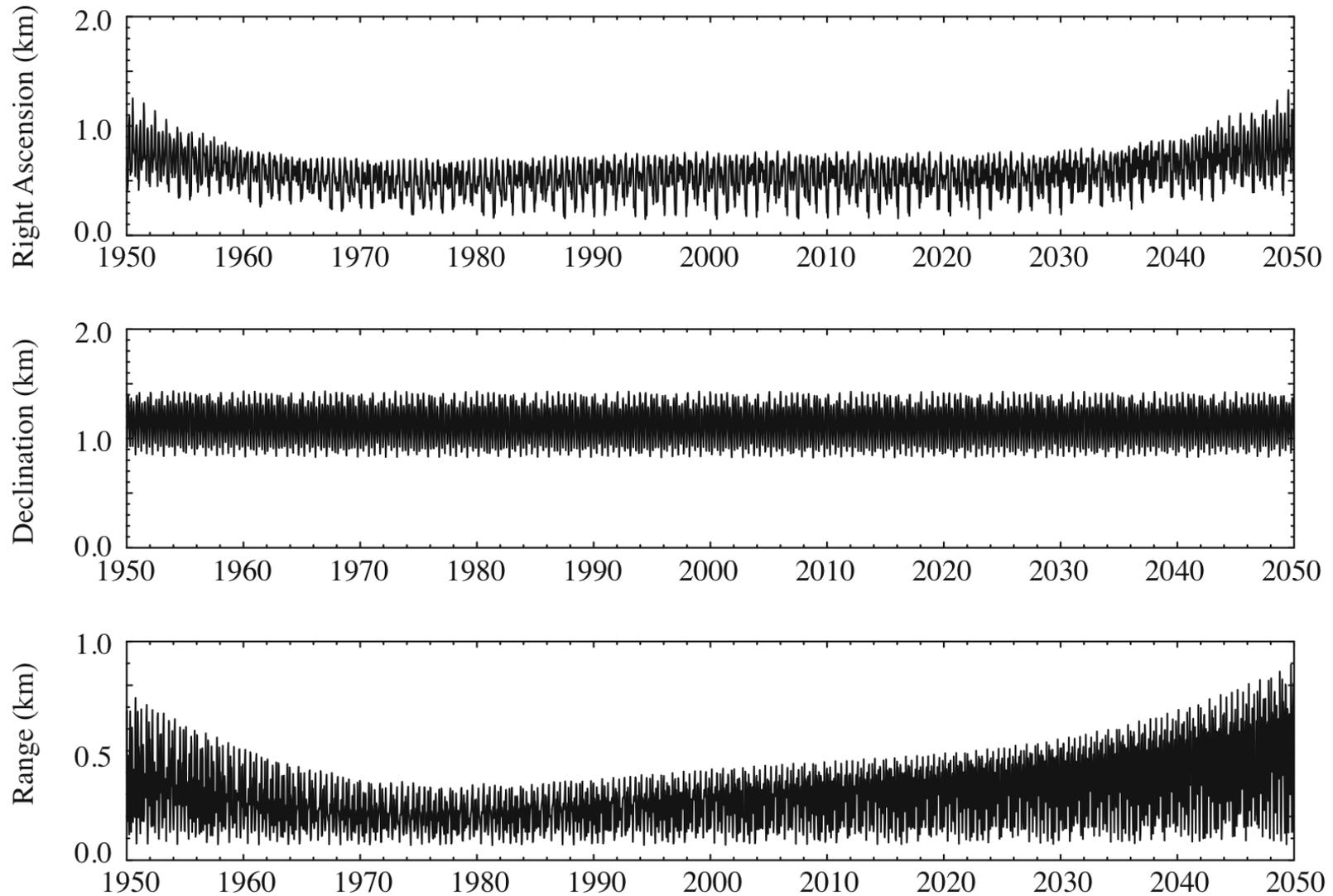


## MESSENGER Encounters





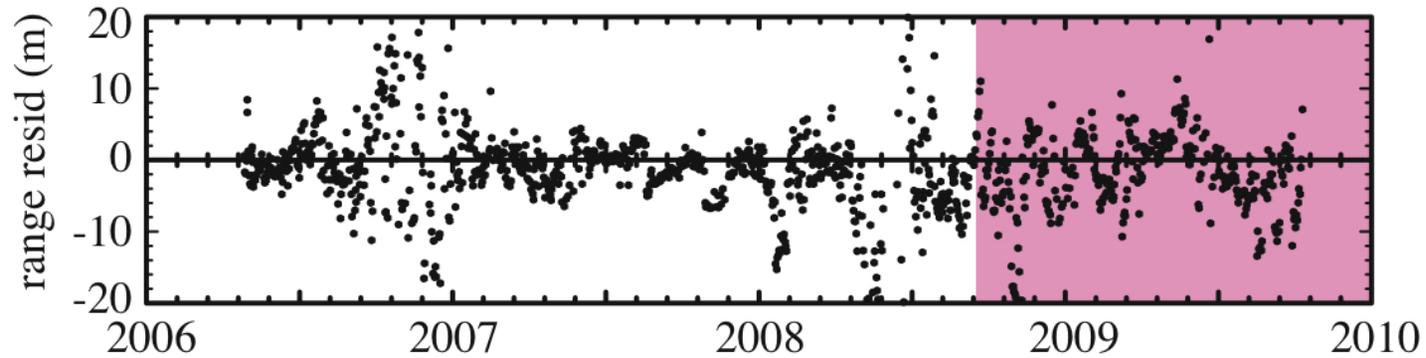
# Mercury Orbit Uncertainty w.r.t. Earth



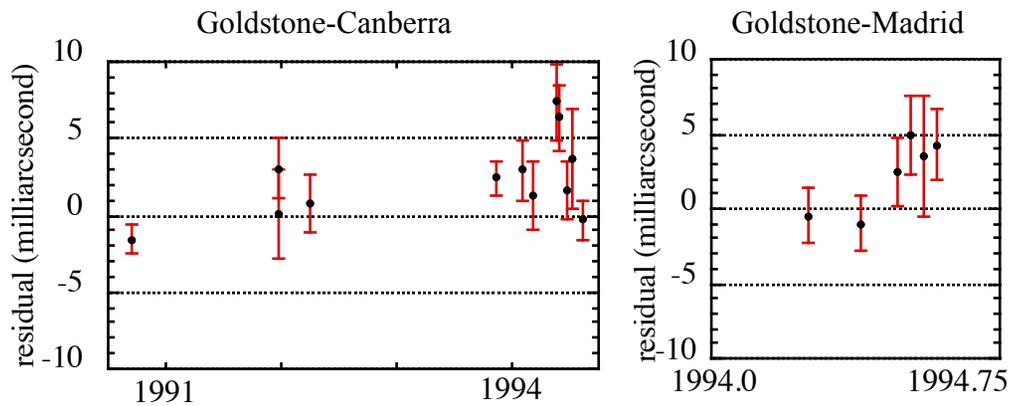


# Venus Data

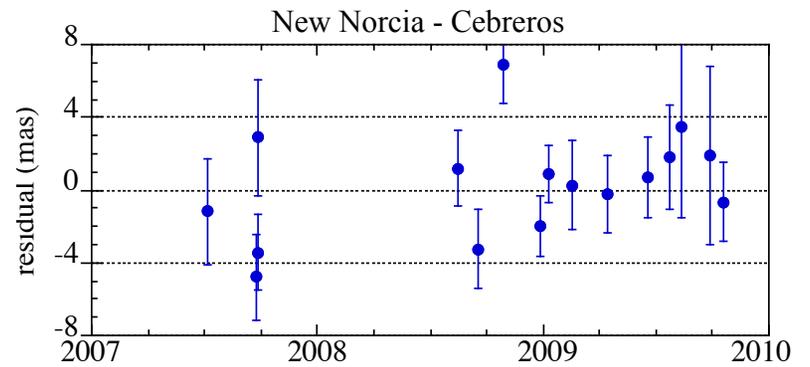
### Venus Express Range



### Magellan VLBI

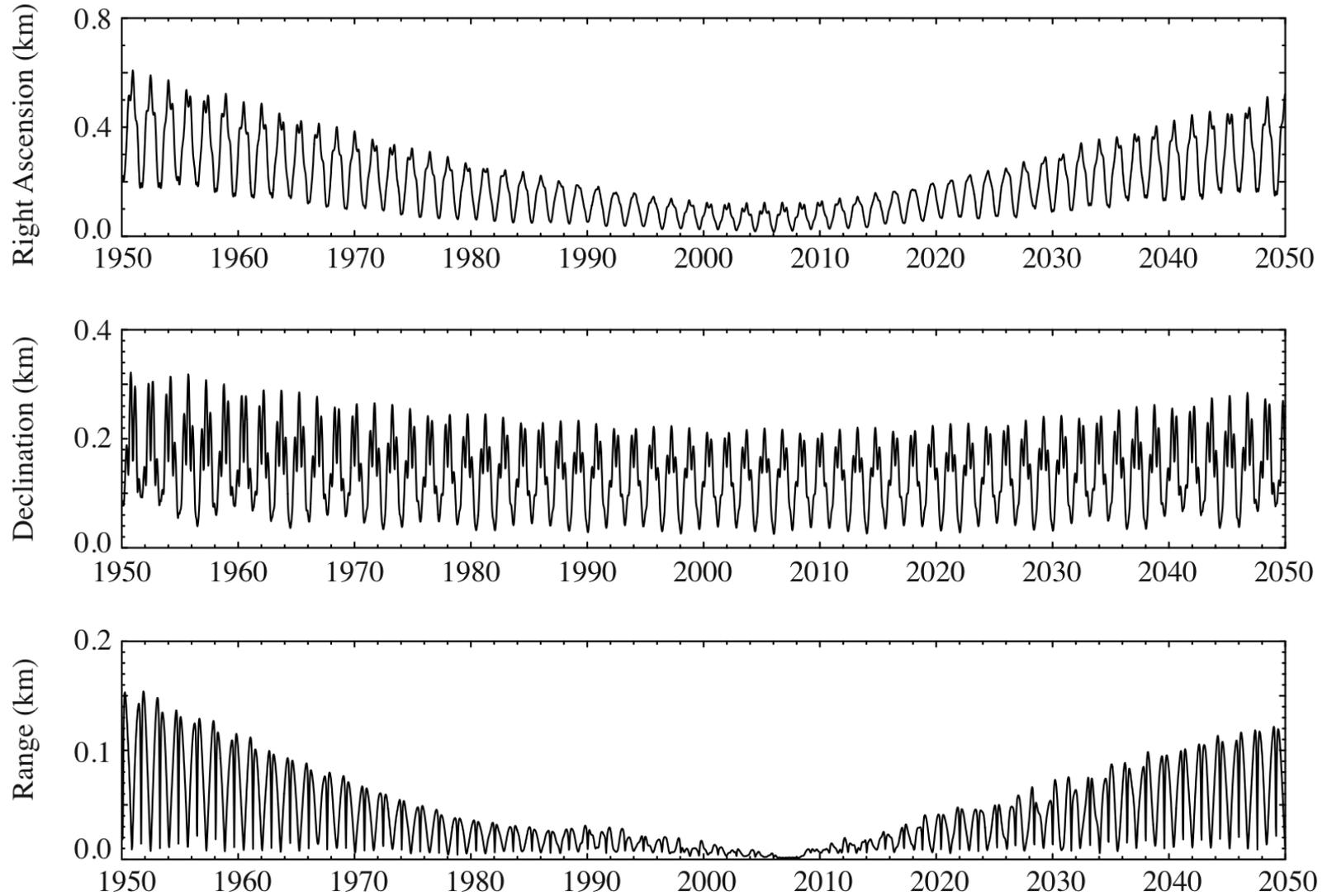


### Venus Express VLBI



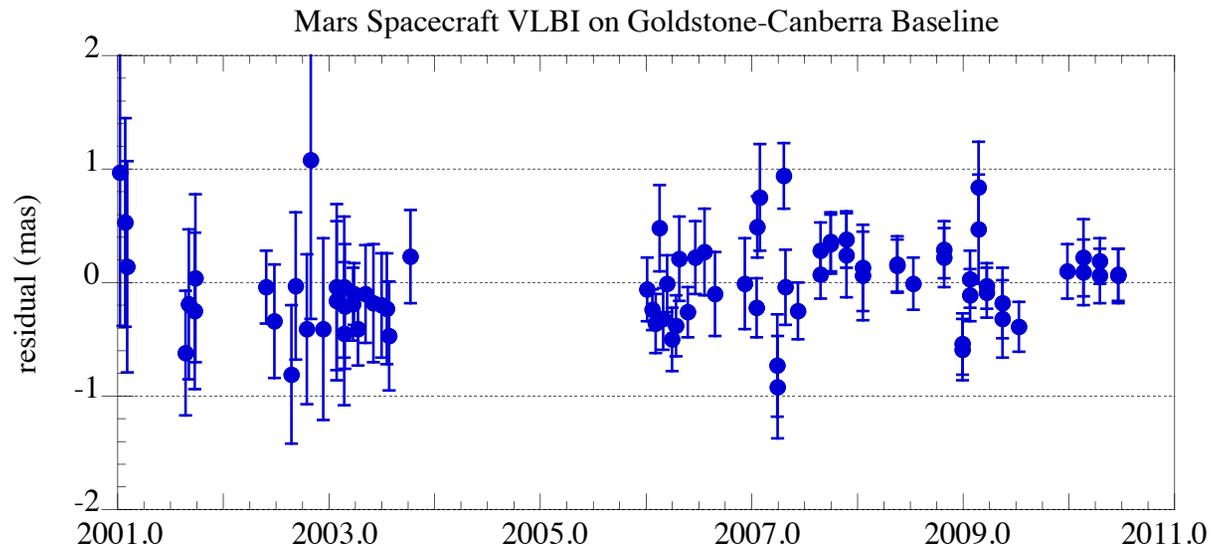
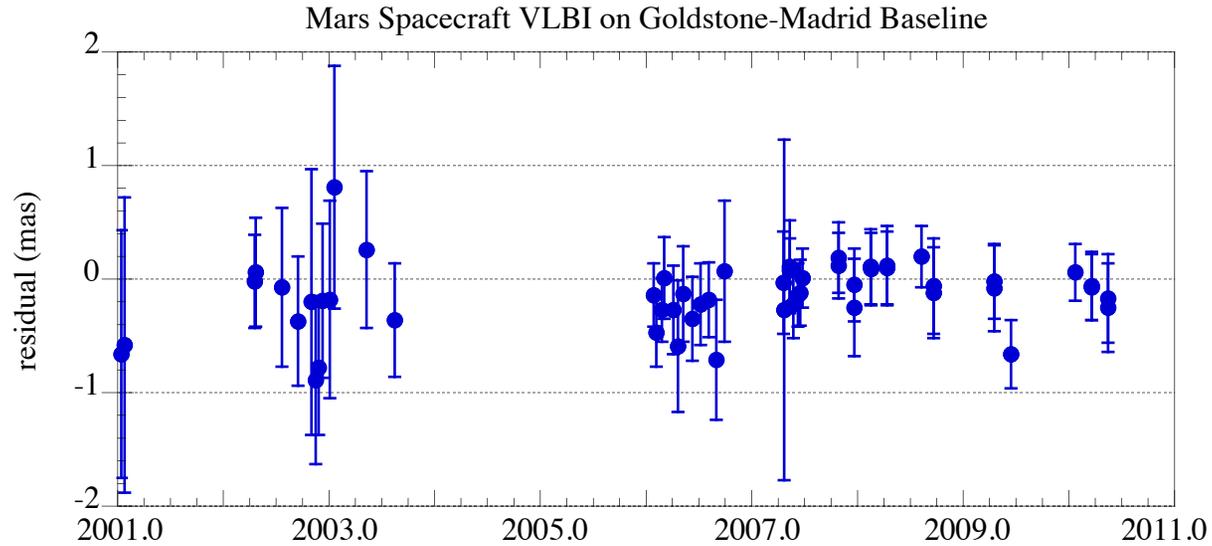


# Venus Orbit Uncertainty w.r.t. Earth





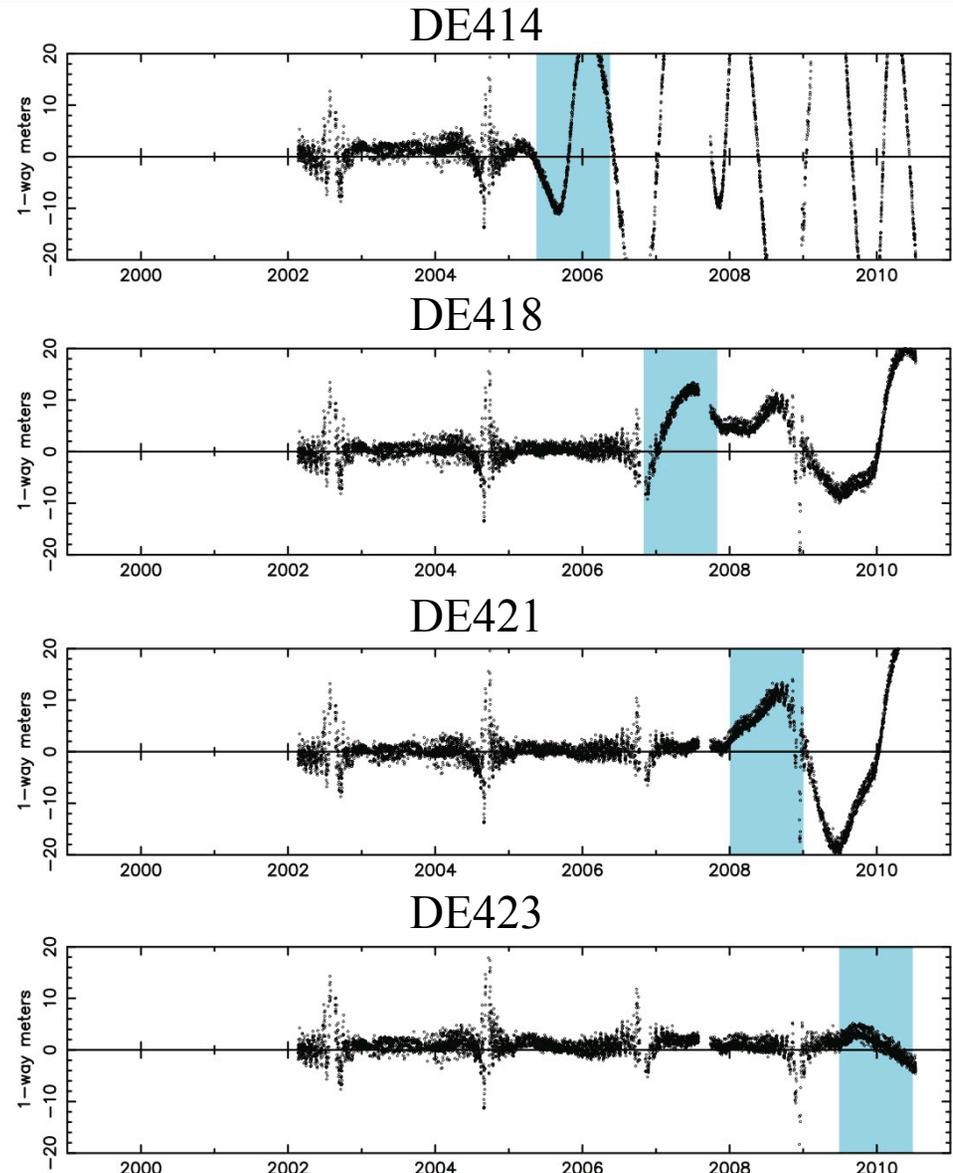
# Mars VLBI Data





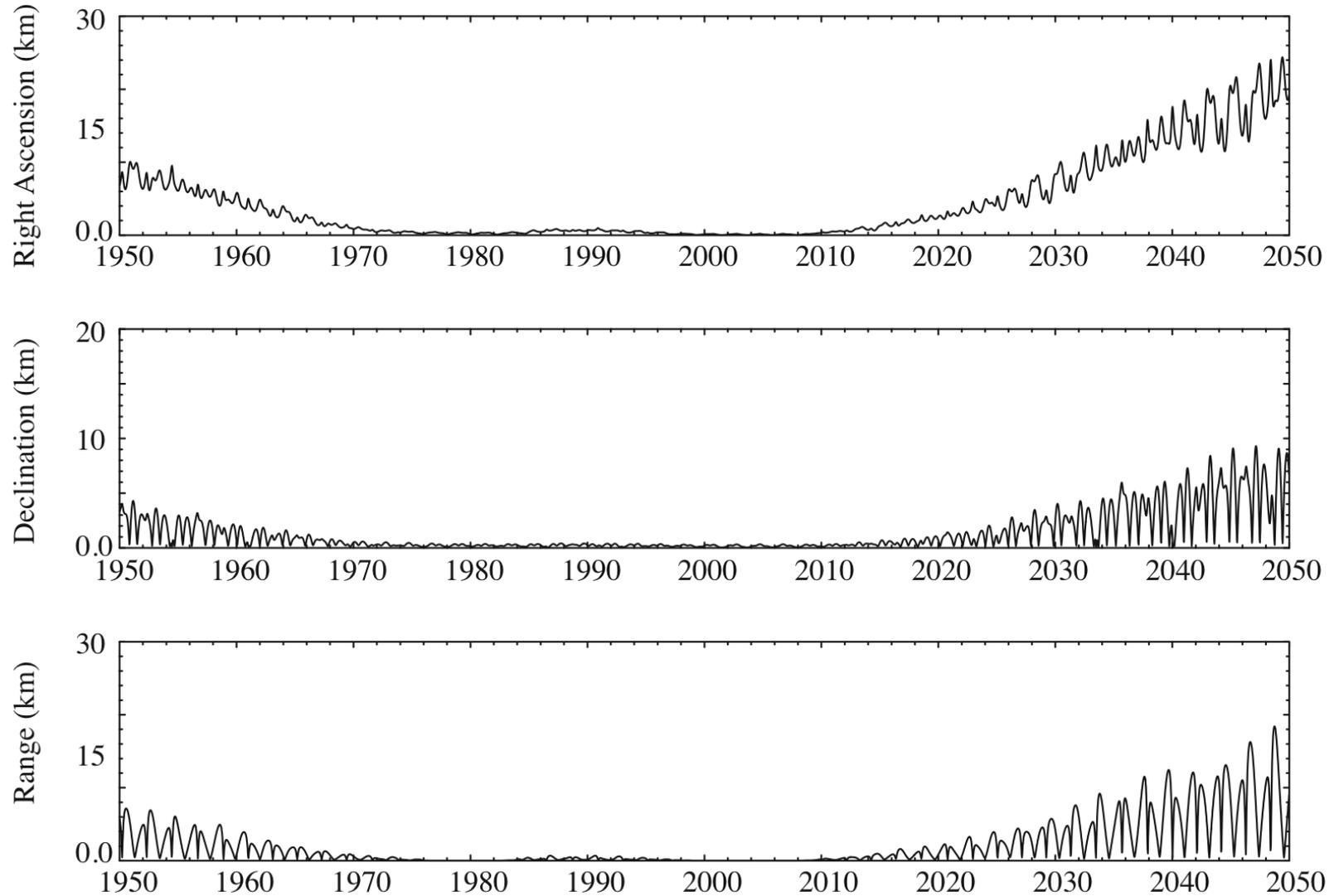
# Mars Range Fit/Extrapolation

- Mars spacecraft (MGS, ODY, MRO, MEX) range residuals show improving prediction
  - DE 414 fit 67 asteroid GM with constraints
  - DE 418 and DE 421 fit to 11 asteroid GM with no constraint
  - DE423 fit to 21 asteroid GM with a priori uncertainty from Baer et al.





# Mars Orbit Uncertainty w.r.t. Earth

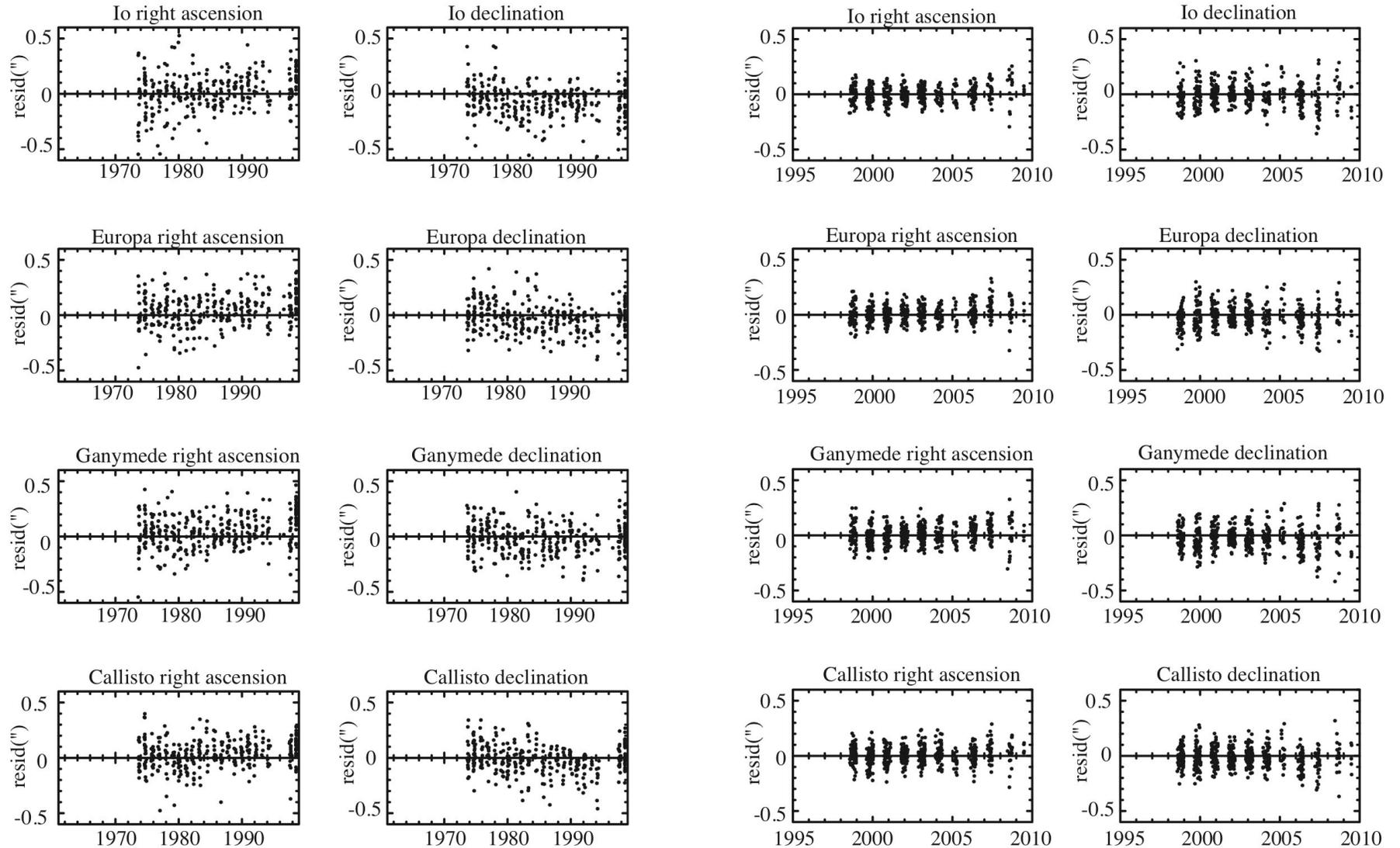




# Jupiter Astrometry

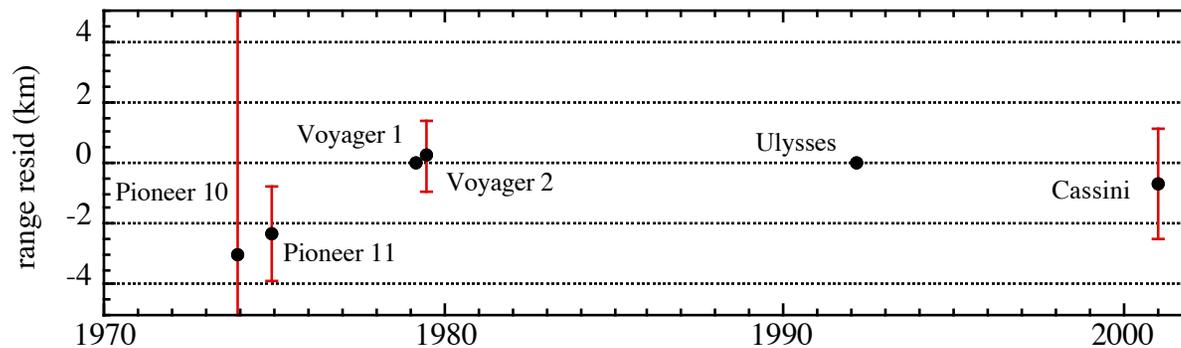
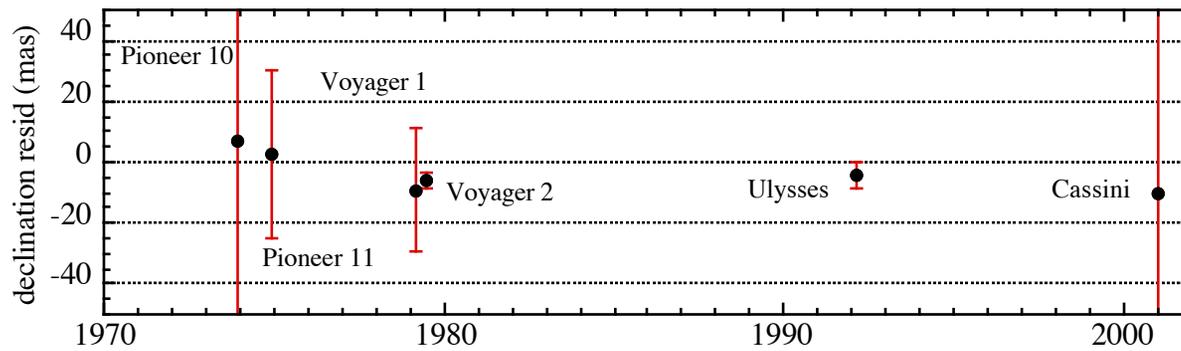
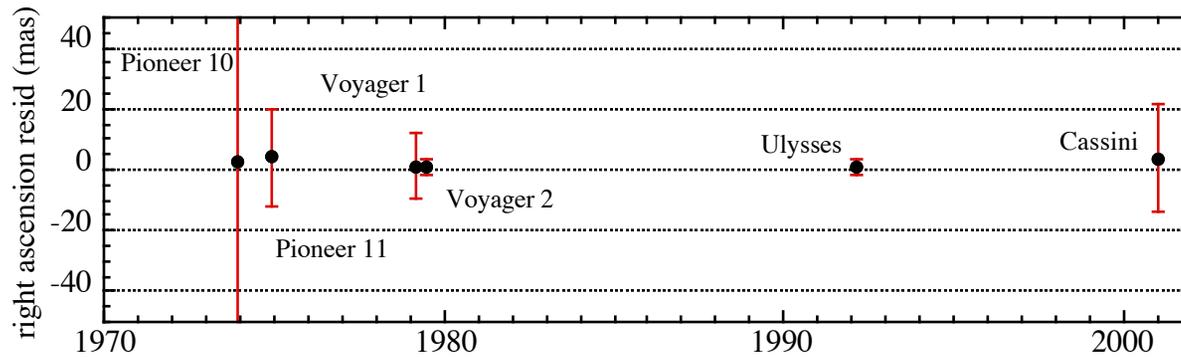
Nikolaev Observatory

USNO Flagstaff



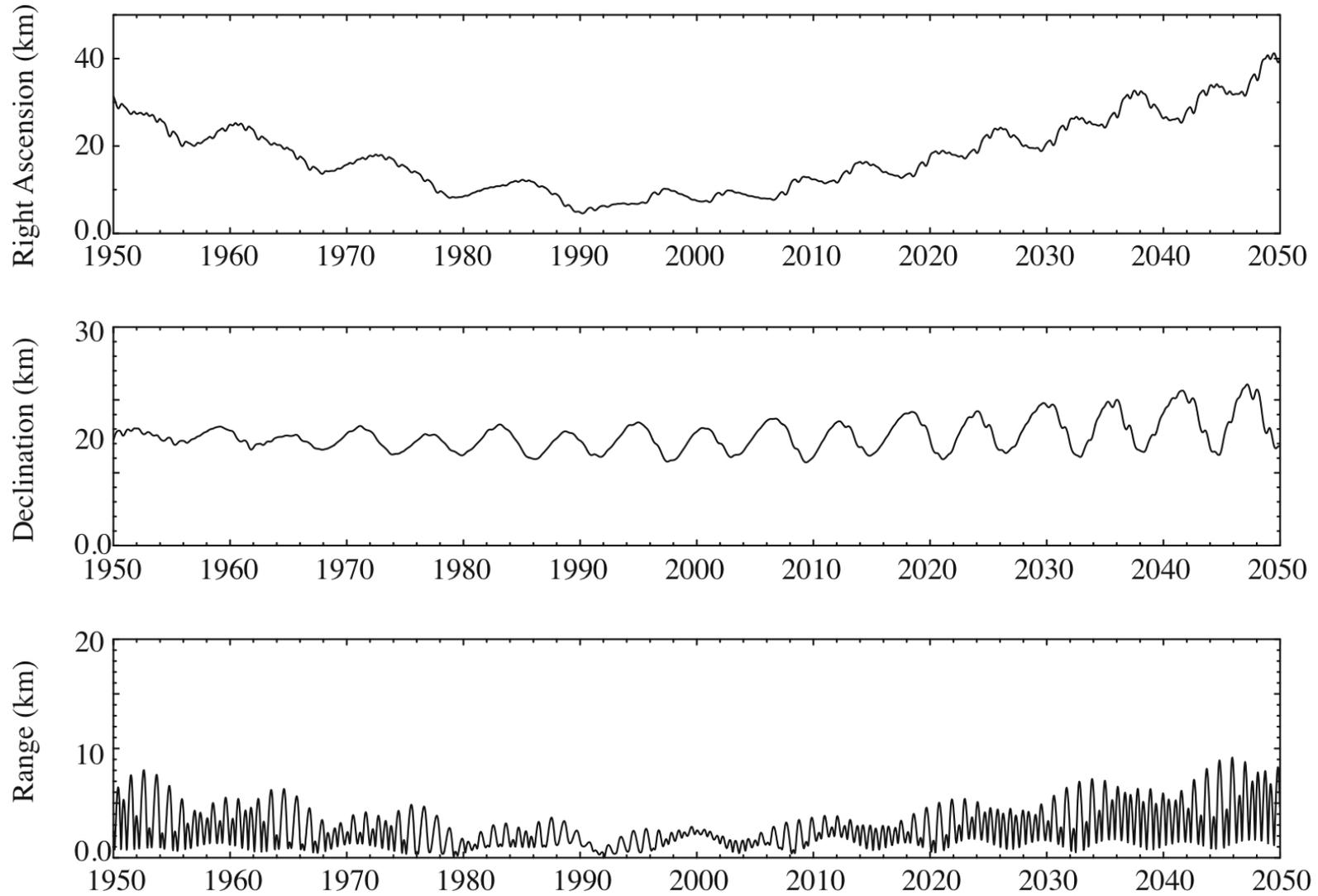


# Jupiter Spacecraft Data



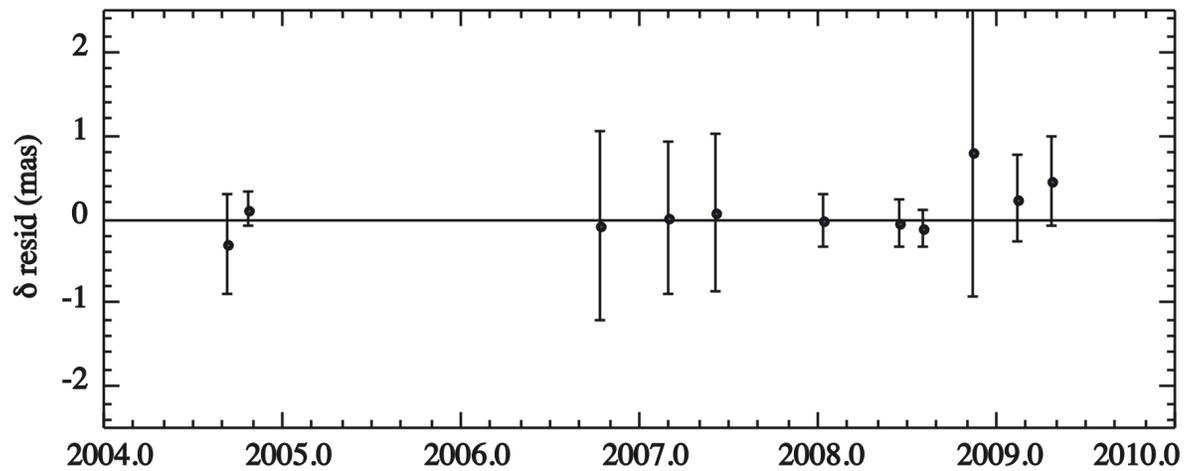
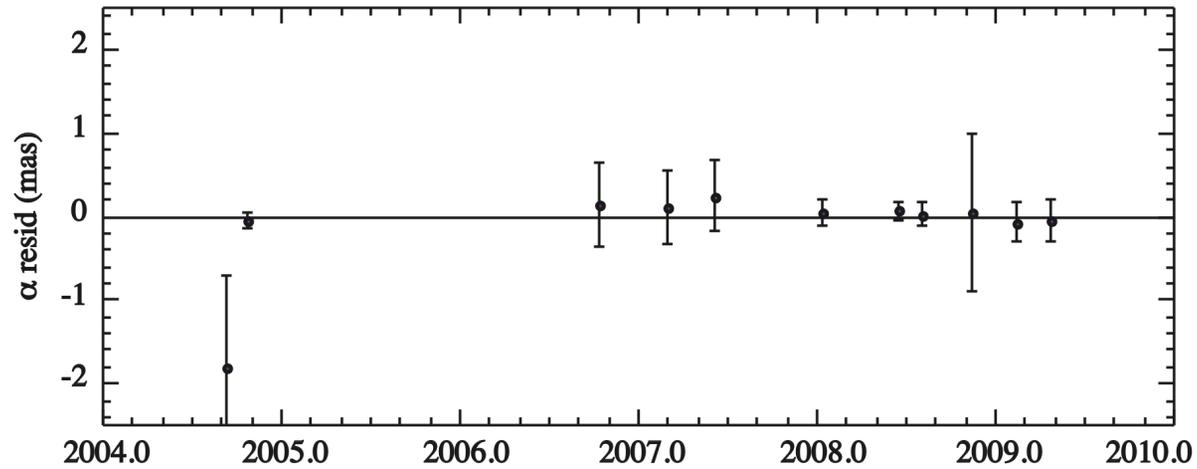


# Jupiter Orbit Uncertainty w.r.t. Earth





# Cassini VLBA Observations

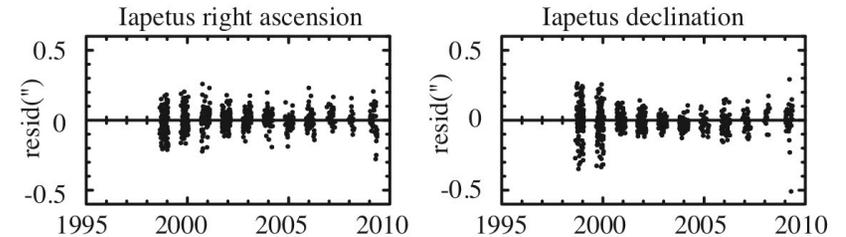
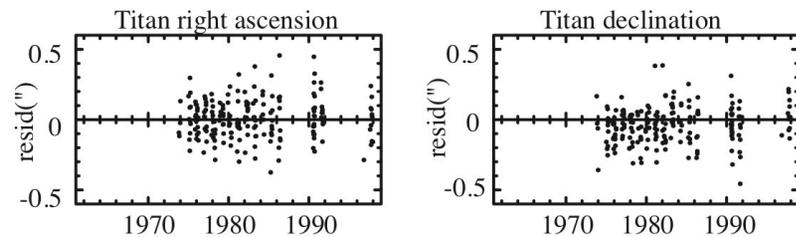
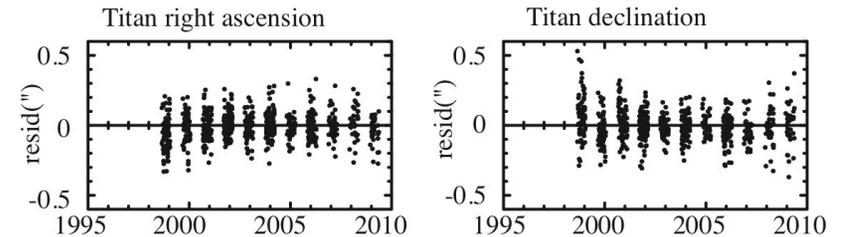
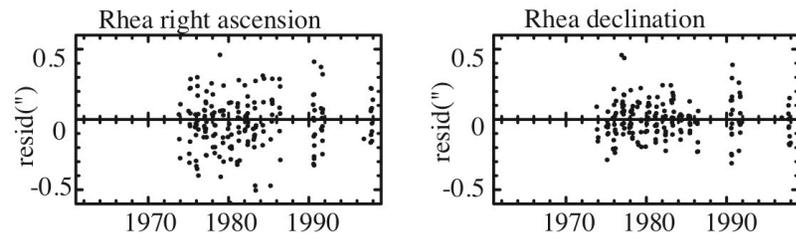
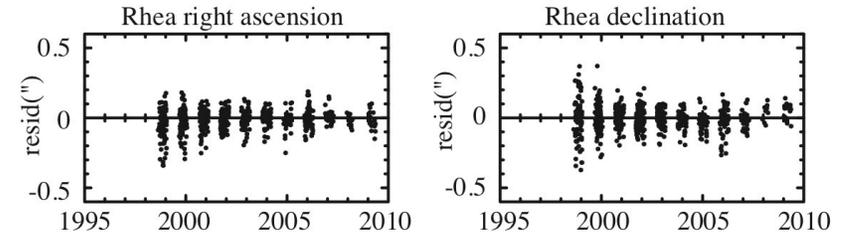
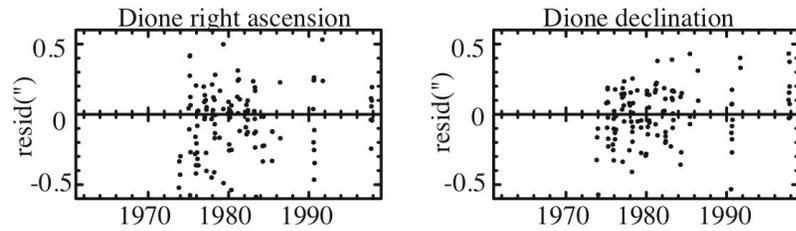
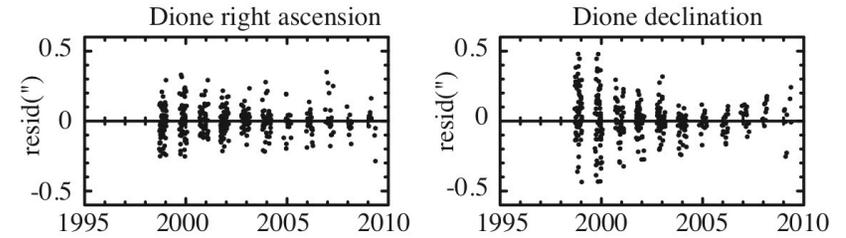
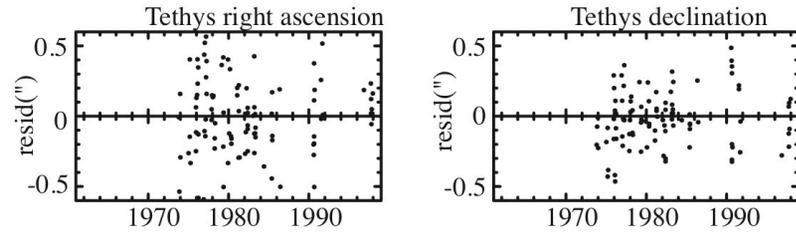




# Saturn Astrometry

Nikolaev Observatory

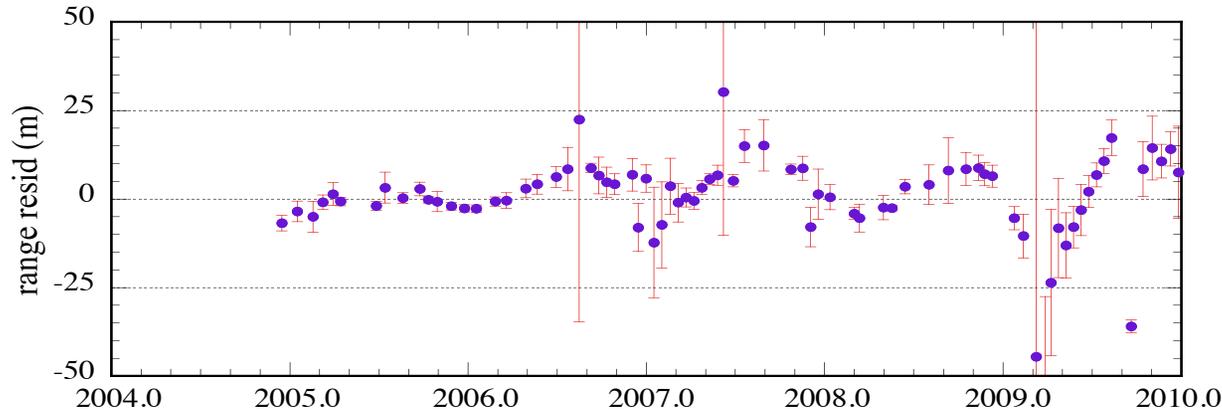
USNO Flagstaff



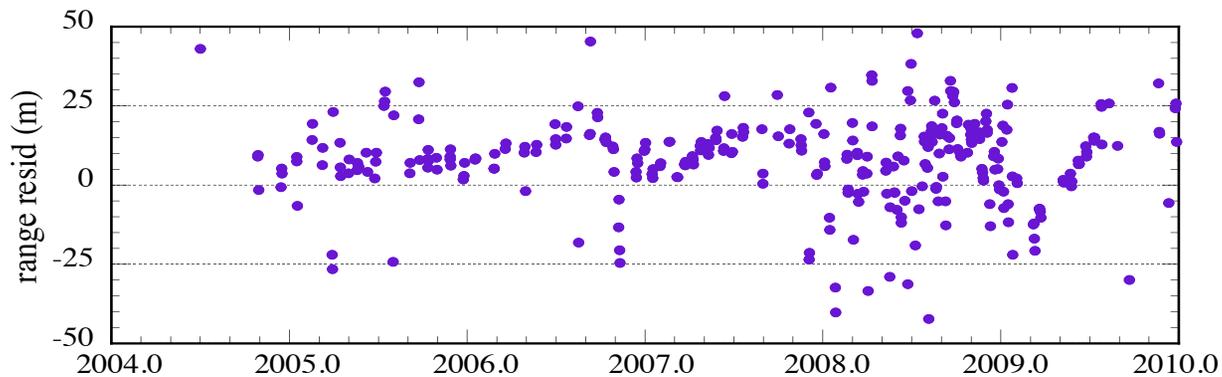


# Cassini Range to Saturn

- Derived range to Saturn depends on spacecraft orbit estimate
  - Range data usually used to estimate spacecraft maneuvers
    - May have unwanted correlations with range to Saturn
  - Doppler-only spacecraft orbits more independent, but noisier



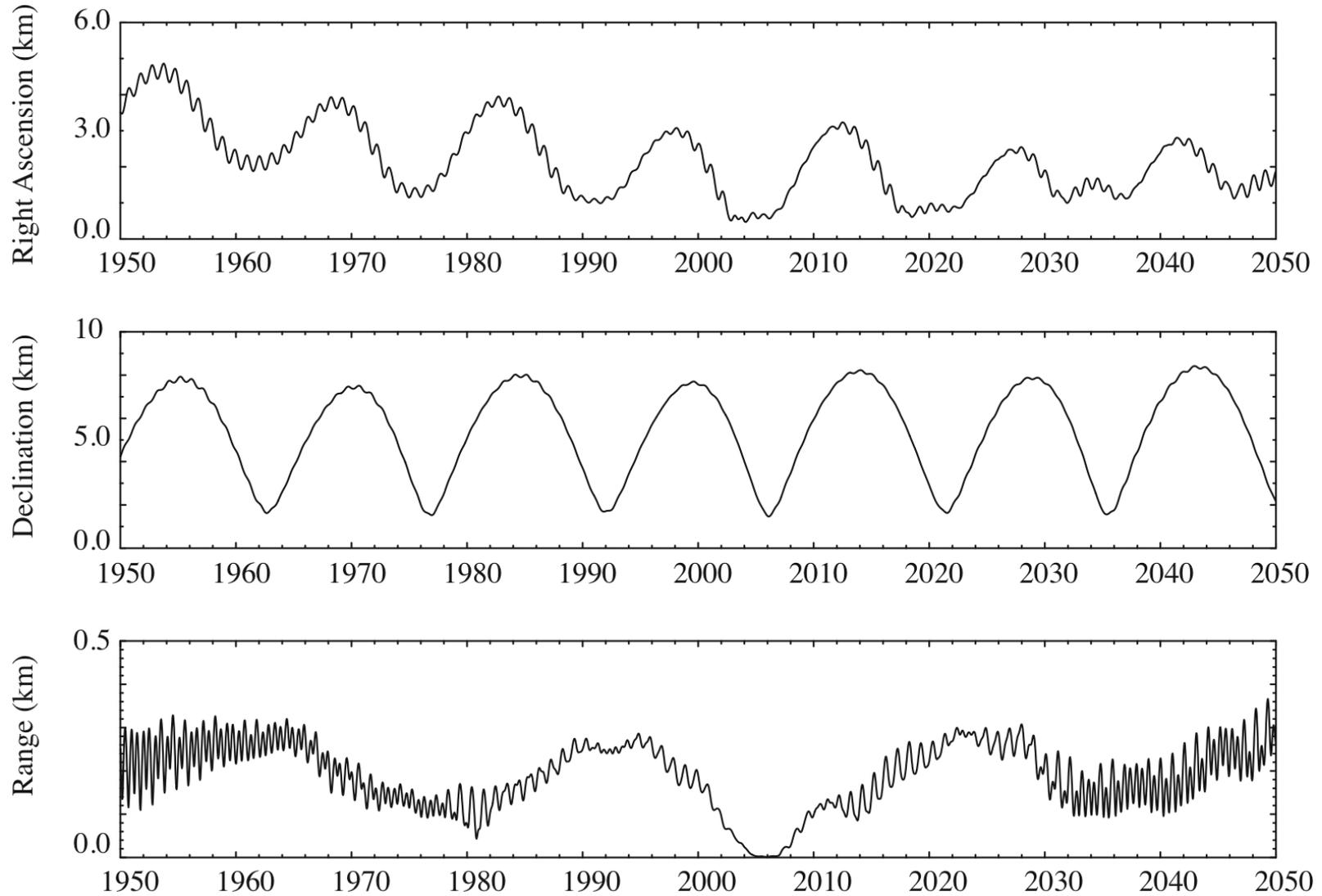
Spacecraft orbits include ranging



Spacecraft orbits Doppler only



# Saturn Orbit Uncertainty w.r.t. Earth





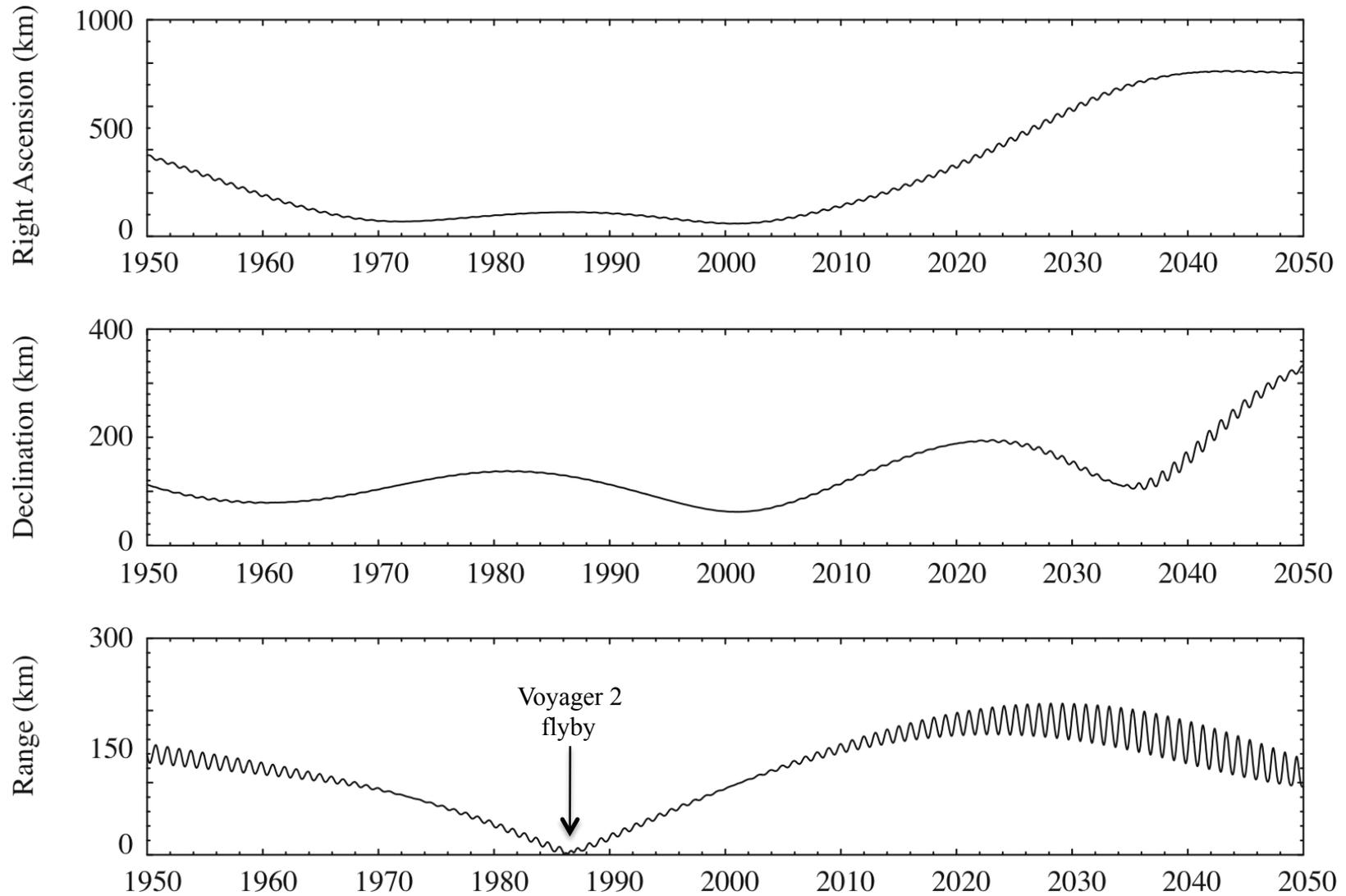
# Uranus, Neptune, Pluto

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- Orbits dominated by astrometric observations
  - Nikolaev, USNOFS, TMO
  - Voyager 2 fly-bys of Uranus, Neptune, give 3-D point for one epoch

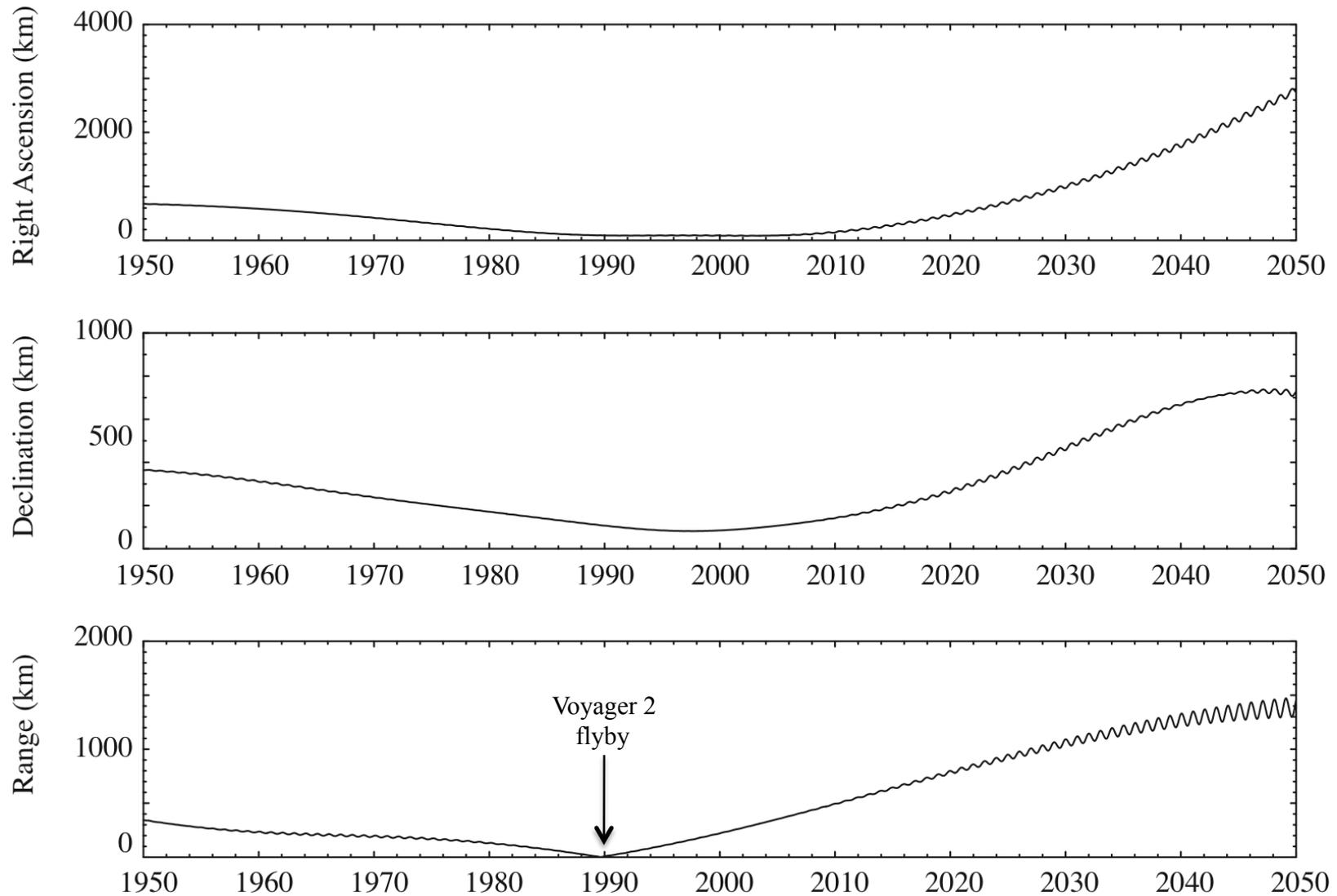


# Uranus Orbit Uncertainty w.r.t. Earth



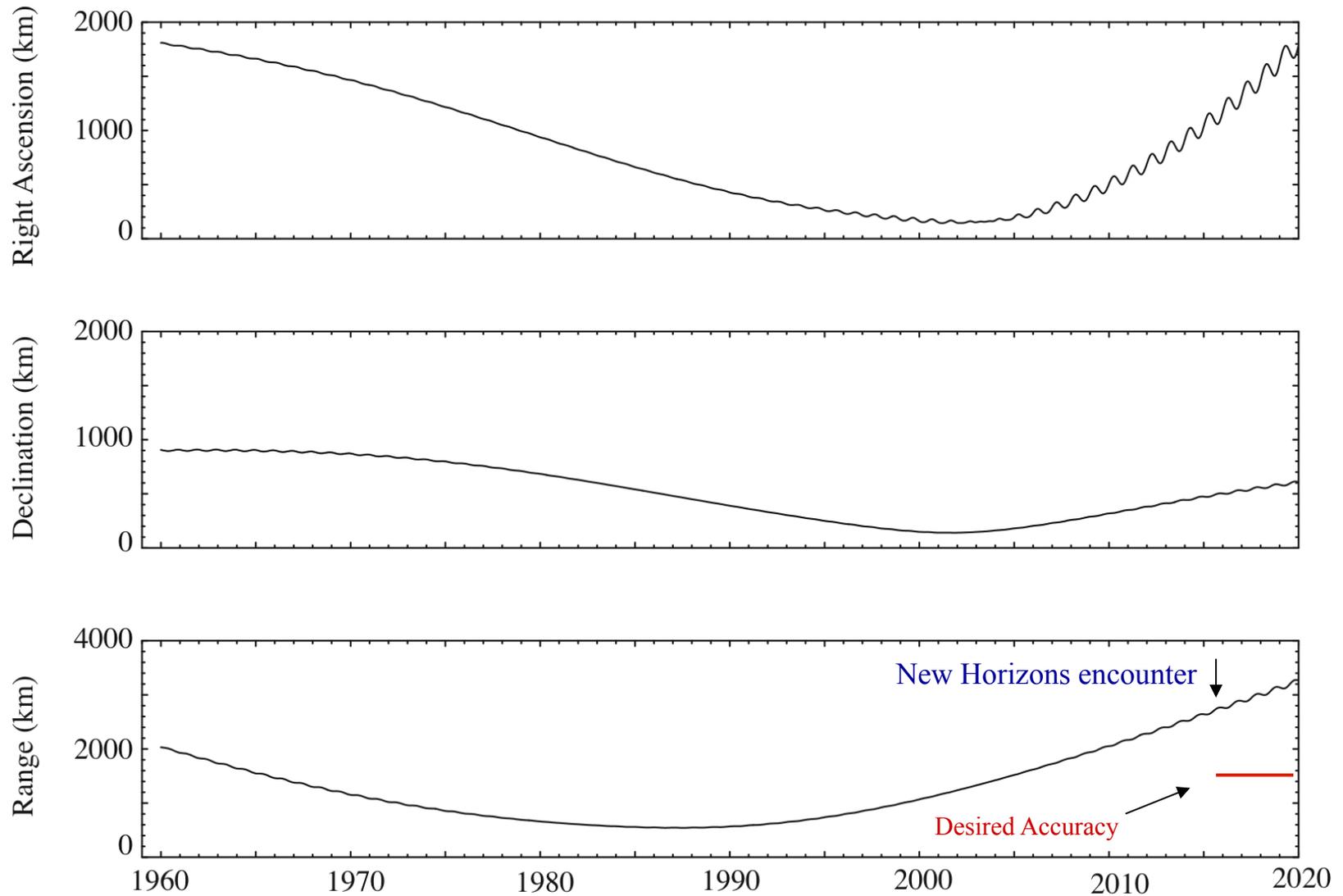


# Neptune Orbit Uncertainty w.r.t. Earth





# Pluto Orbit Uncertainty w.r.t. Earth





# Future Plans

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- Deliver ephemerides for MSL cruise and arrival
- Improve Pluto for New Horizons encounter (2015)
  - Re-process old data? HST near radio source? GAIA/J-MAPS?
- Long integration with converged LLR data
  - Lunar core model without exponential damping
  - Significant asteroids integrated along with planets
- Mercury orbit from MESSENGER prime science phase (2011)
- Jupiter orbit from Juno (2016-2017)