Proper Motion of the GP-B Guide Star

***Irwin Shapiro, Daniel Lebach, Michael Ratner: Harvard-Smithsonian Center for Astrophysics; Norbert Bartel, Michael Bietenholz, Jerusha Lederman, Ryan Ransom: York University; Jean-Francois Lestrade:* Observatoire de Paris**

For Presentation at the Meeting of the

American Physical Society

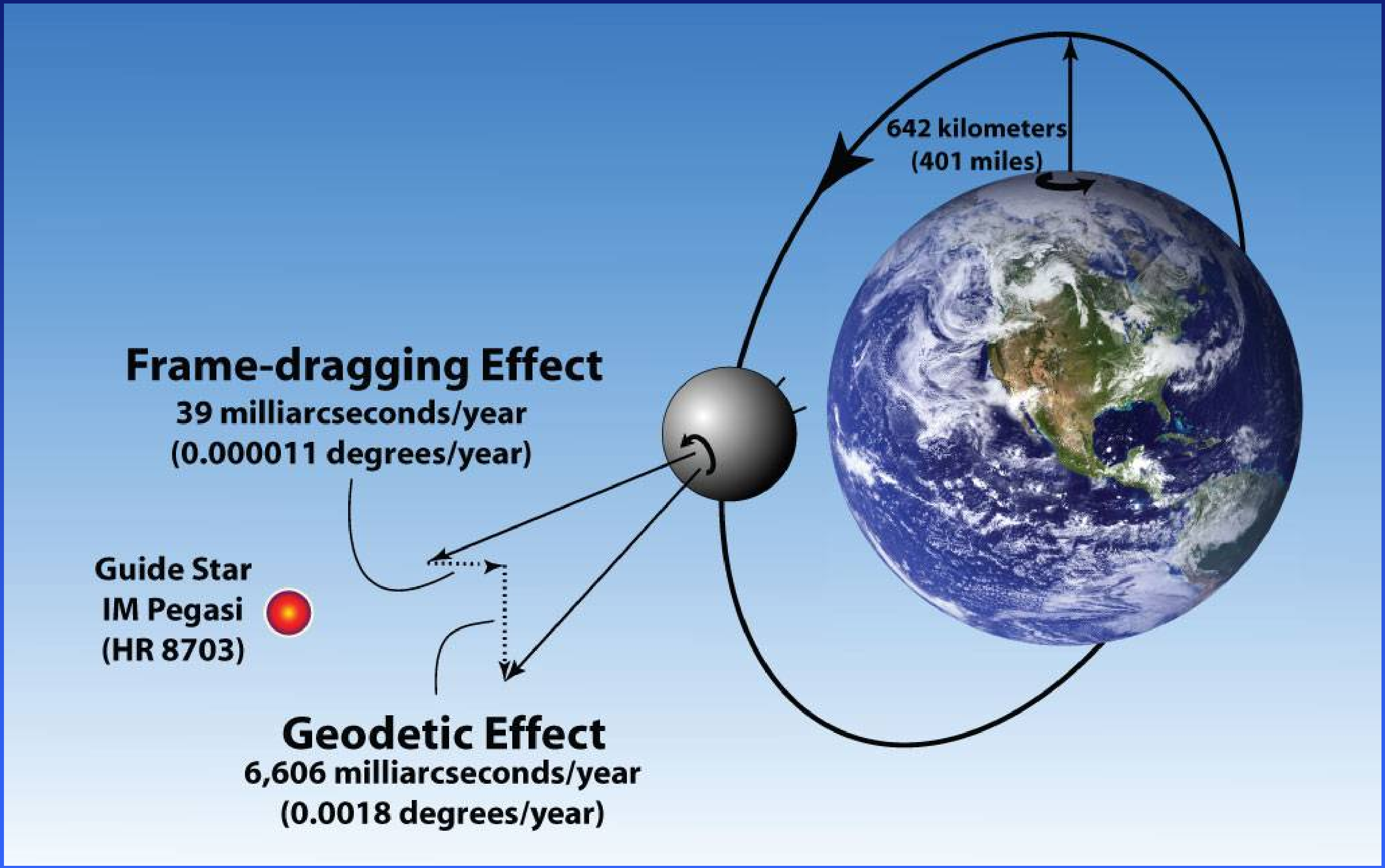
Jacksonville, FL

14 April 2007

Un Peu d'Histoire

- George Pugh first proposed experiment in 1959, including idea of "drag-free" satellite
- Leonard Schiff at Stanford analyzed experiment theoretically in 1960
- Bill Fairbank at Stanford set key groundwork for experimental approach in early 1960s
- Bob Cannon, Dan De Bra, Francis Everitt, Ben Lange, and others contributed key ideas in 1960s
- Francis Everitt led project successfully through myriad technical and political difficulties for decades

Overview of Experiment



Note: milliarcseconds = millarcsec = marcsec = mas (Different abbreviations used on different slides.)

(Figure compliments of Bob Kahn.)

Choice of Guide Star

Constraints:

- Optically bright (< 5.5 magnitude)
- Radio detectable (>1 mJy correlated flux density)
- Low declination (near equator to maximize detection of frame dragging and to ease solar power problems)
- No other bright optical star in direct vicinity (to avoid complications in guide-star tracking)

One "Survivor":

- Binary star system : HR8703 (aka IM Pegasi or "IM Peg")
- Orbit of binary : ~ 1 marcsec radius (circular)
25 day period (very accurately known)
- Distance of binary from earth: ~ 100 parsecs
(~ 300 light years)

Differential VLBI

Need:

- Accuracy goal of experiment : ~ 0.4 marcsec/yr
  (mean standard error of gyroscope drift-rate measurement)
- Accuracy goal for measurement of guide star proper motion
  ~ 0.15 marcsec/yr

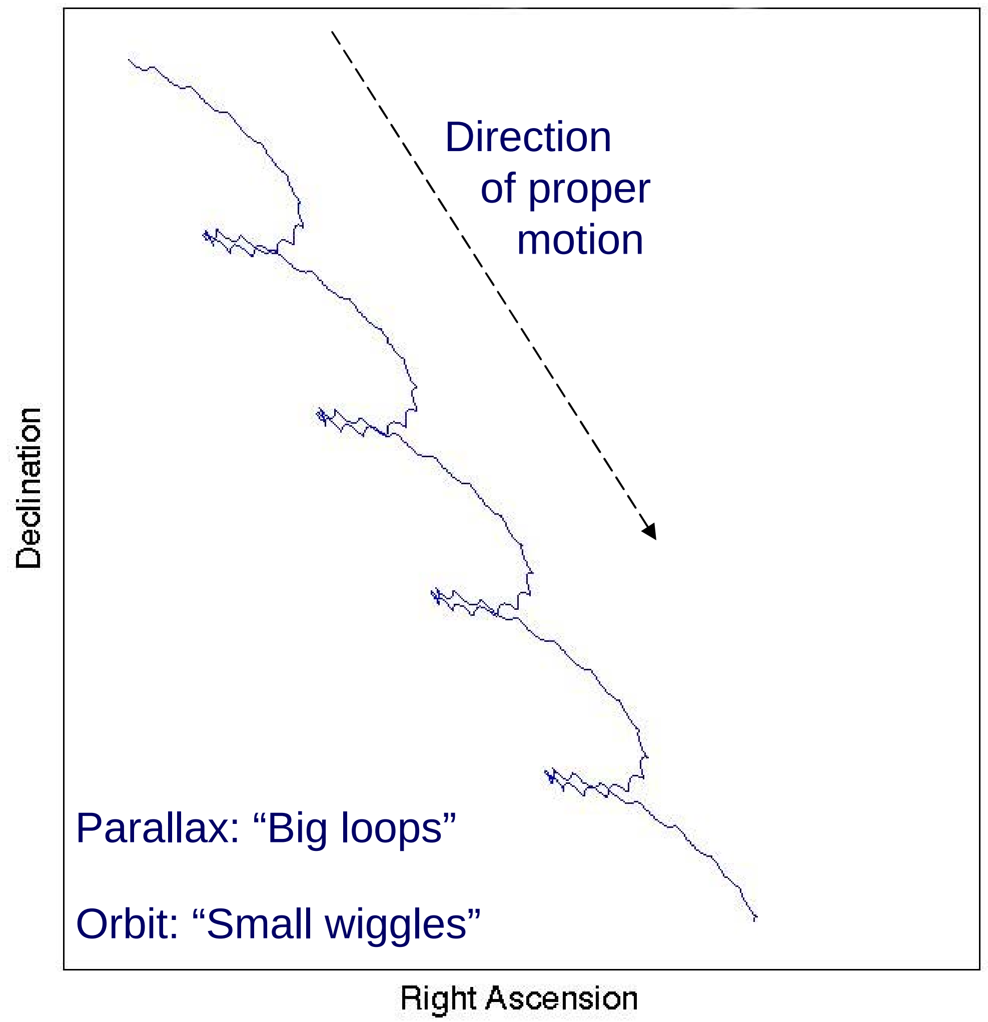
Technique:

- Monitor motion of the guide star's radio emission with respect to distant ("cosmological") compact sources of radio radiation nearby on sky
- At present only VLBI can yield such accuracy of proper-motion measurement

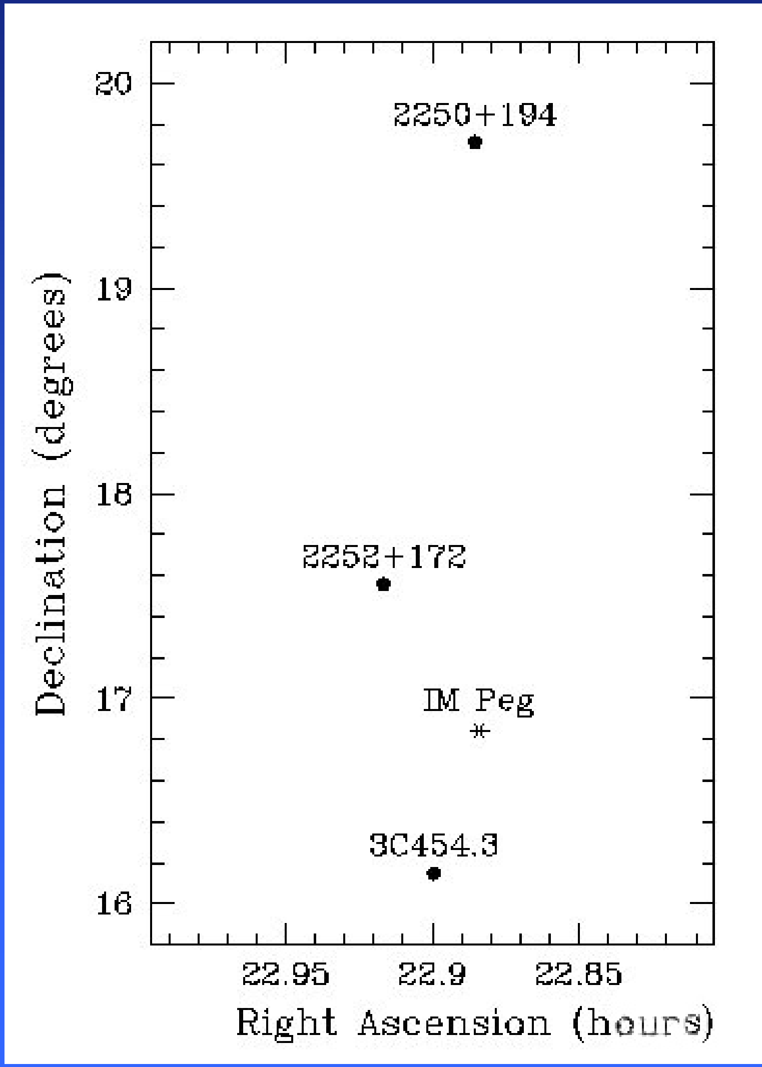
Main Sources of Error:

- Motion of source of IM Peg's radio radiation with respect to primary of IM Peg System
- Possible (distant) third body in IM Peg System
- Motions of centers of brightness of reference sources with respect to their centers of mass
- Model of ionosphere
- Signal-to-noise ratios (only when IM Peg radio signals very weak)

Motion of Guide Star on Sky



Sky Map of Guide Star and Extragalactic Reference Sources



Summary of VLBI Observations

- **35 Sessions of VLBI observations between January 1997 and July 2005**
- **Duration of each session: between 12 and 18 hours**
- **12 to 16 VLBI antennas per observing session**
  Our standard array of antennas consisted of:
  - NRAO's ten 25 m VLBA antennas (all or most included in every session)
  - NRAO's "phased" VLA (included in 31 sessions)
    - Most sensitive VLBI antenna we used (largest collecting area)
    - Use of VLA enabled intra-session monitoring of guide-star radio brightness
  - MPIfR's 100 m antenna in Effelsberg, Germany (29 sessions)
  - NASA's 70 m DSN antennas in Goldstone, California (33 sessions), Robledo, Spain (34 sessions), and Tidbinbilla, Australia (28 sessions)
- **All astrometric observations made at radio wavelength of 3.6 cm**

Summary of VLBI Observations (cont.)

- Used four additional sessions of VLBI observations made in 1991-1994 by J.-F. Lestrade et al. in support of Hipparcos
  - Only four antennas per session
  - Only one extragalactic reference source (3C454.3) included in observations

  but:

  - Provided an extra ~5 year time span of data that proved valuable in constraining any proper acceleration of guide star

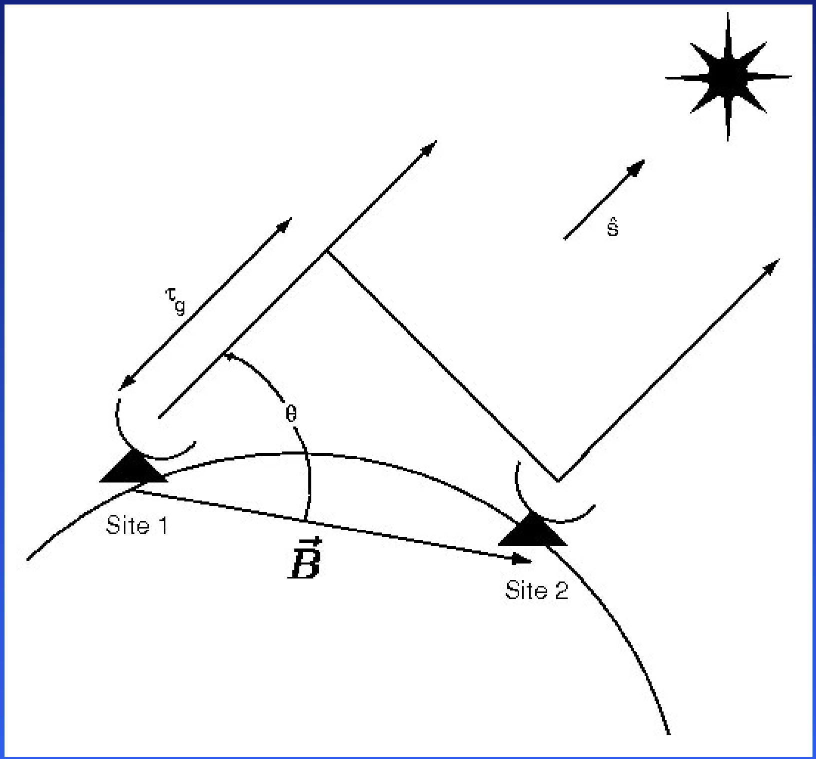
Data Analysis Primer

- **Principal VLBI observable: "fringe phase":**

$$\phi(\nu,t) = 2\pi\left\{\nu\left[\tau_{geom}(t) + \tau_{inst}(t) + \tau_{atm}(t) + \tau_{ion}(\nu,t) + \tau_{struc}(\nu,t) + \tau_{noise}(\nu,t)\right] + N(\nu,t)\right\}$$

$$\tau_{geom} \approx \frac{1}{c}\left(\vec{B}\cdot\hat{s}\right)$$

(Astrometric information is all here)



- **Combine measurements of fringe phase (and amplitude) from baselines ($\vec{B}$) with different ("projected") lengths and orientations to produce a source brightness map**

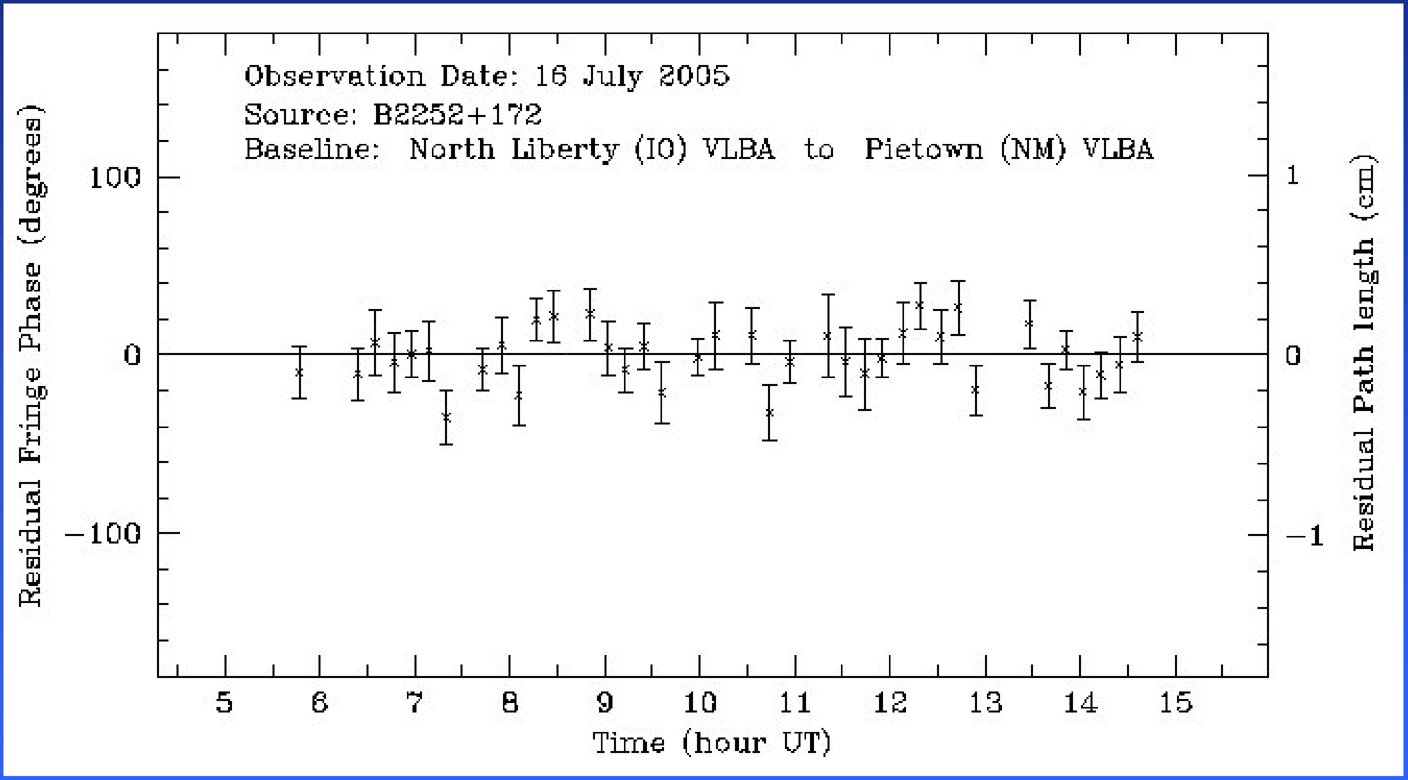
$$\left(\quad \Gamma(\xi,\eta) \approx \frac{1}{A_o}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\rho_{uv}\,e^{i\phi_{uv}}\,e^{2\pi i(u\xi+v\eta)}\,du\,dv \quad\right)$$

Data Analysis Primer (cont.)

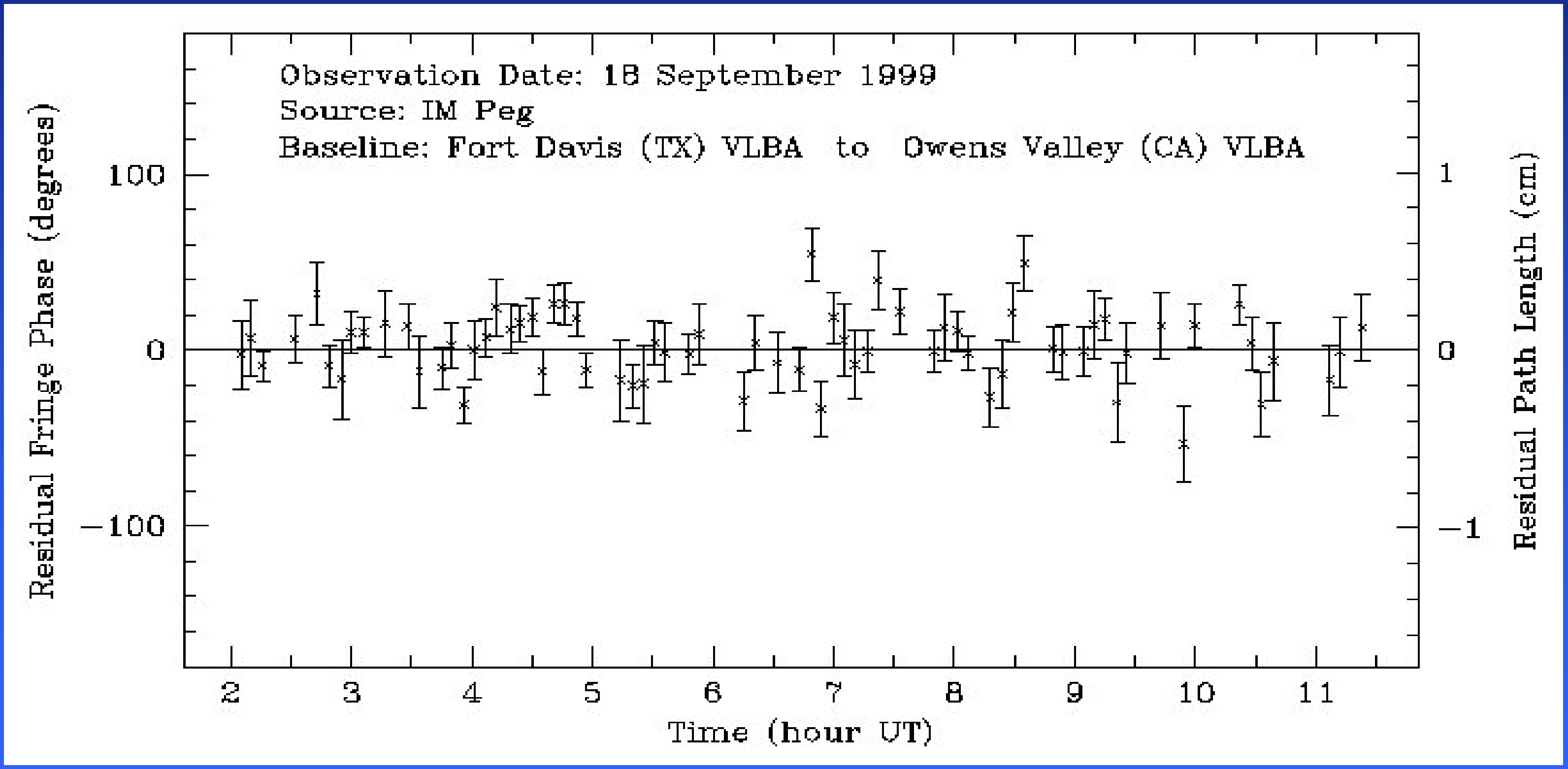
Path of data reduction:

1. Estimate fringe phases for each “scan” of data (each scan is 1-8 minutes in duration)
2. Resolve the number of 2π phase ambiguities of each fringe phase
3. Use these “connected” fringe phases from 3C454.3 and B2250+194 scans to improve fringe-phase model for all observed sources
4. Generate images of target sources (IM Peg and B2252+172) after application of improved model

Data Analysis: Intermediate Results

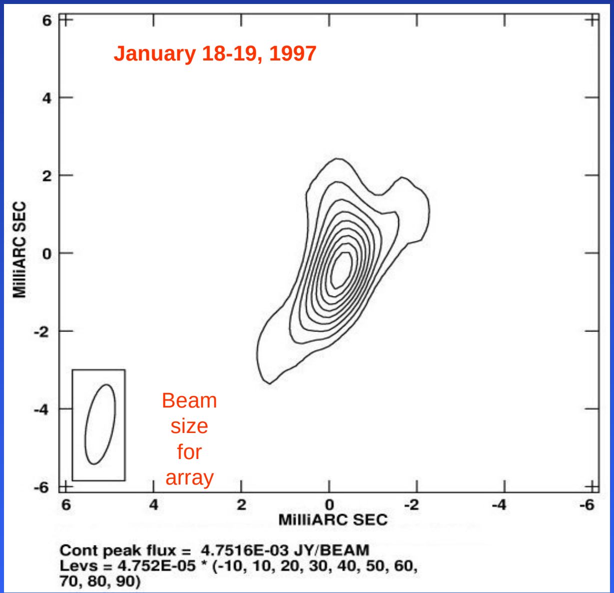


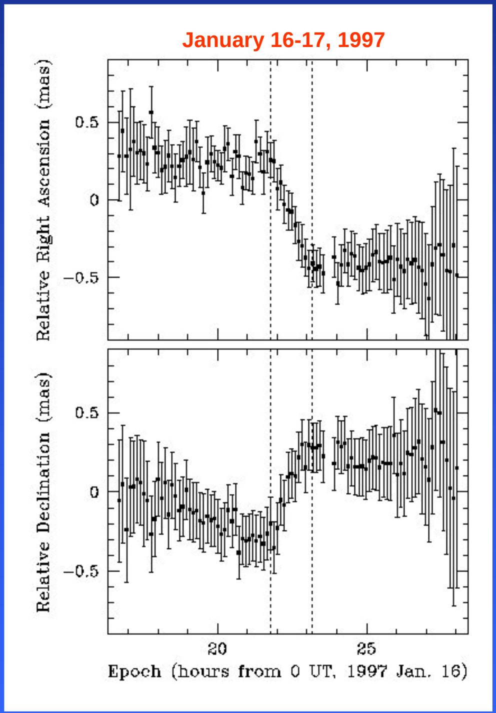
Data Analysis: Intermediate Results

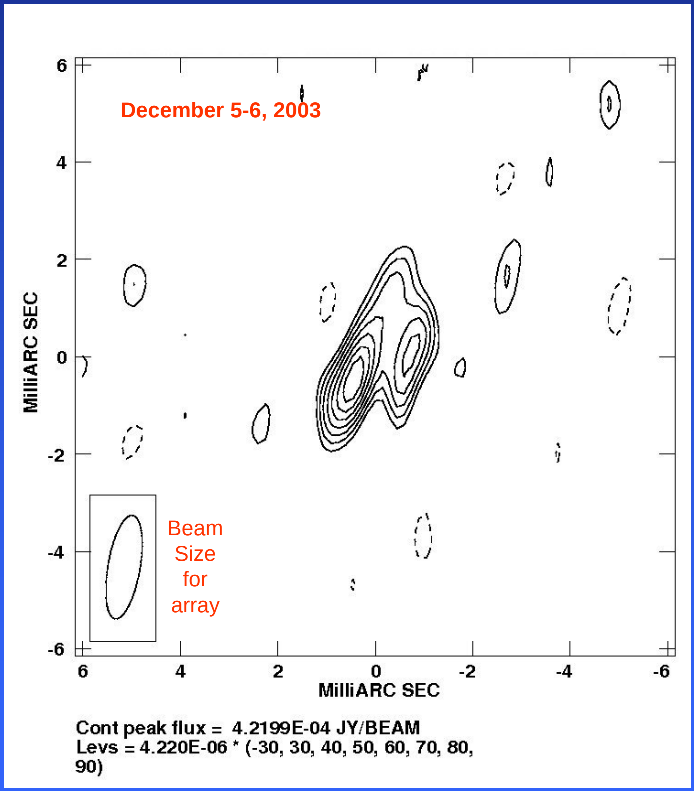


Dominant Error Sources for Astrometry

1. **Intrinsic motions and non-pointlike brightness distributions of IM Peg radio emissions relative to center of optical disk of primary:**



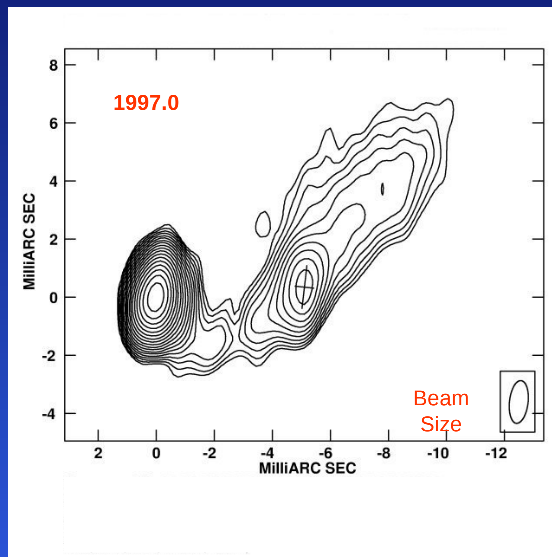


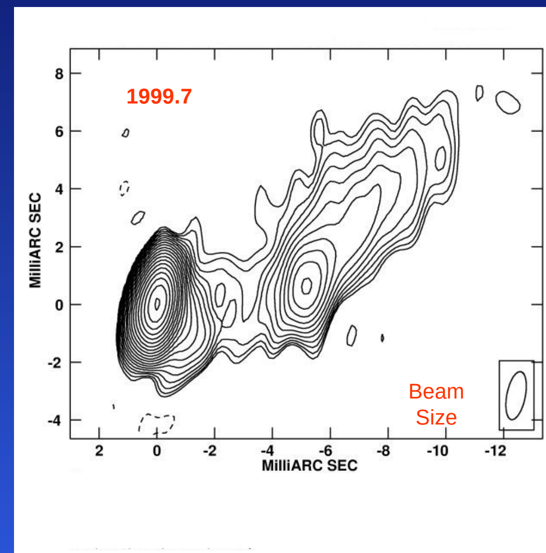


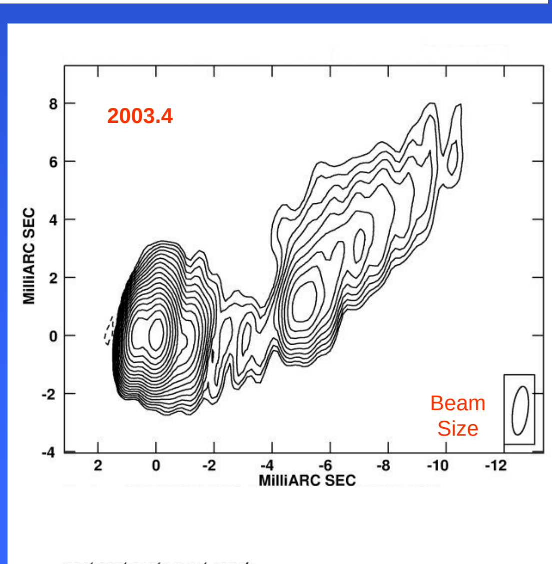
Intrinsic motions (on hour, day, month, and year time scales) constitute by far largest source of error in our proper-motion estimates

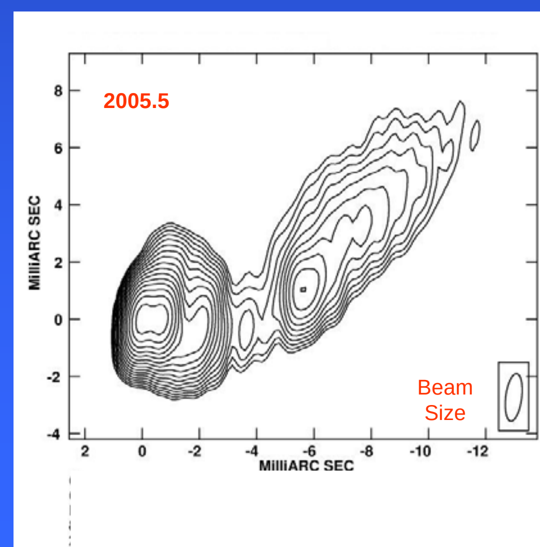
Dominant Error Sources (cont.)

2. Structural evolution of our principal reference source, 3C454.3:

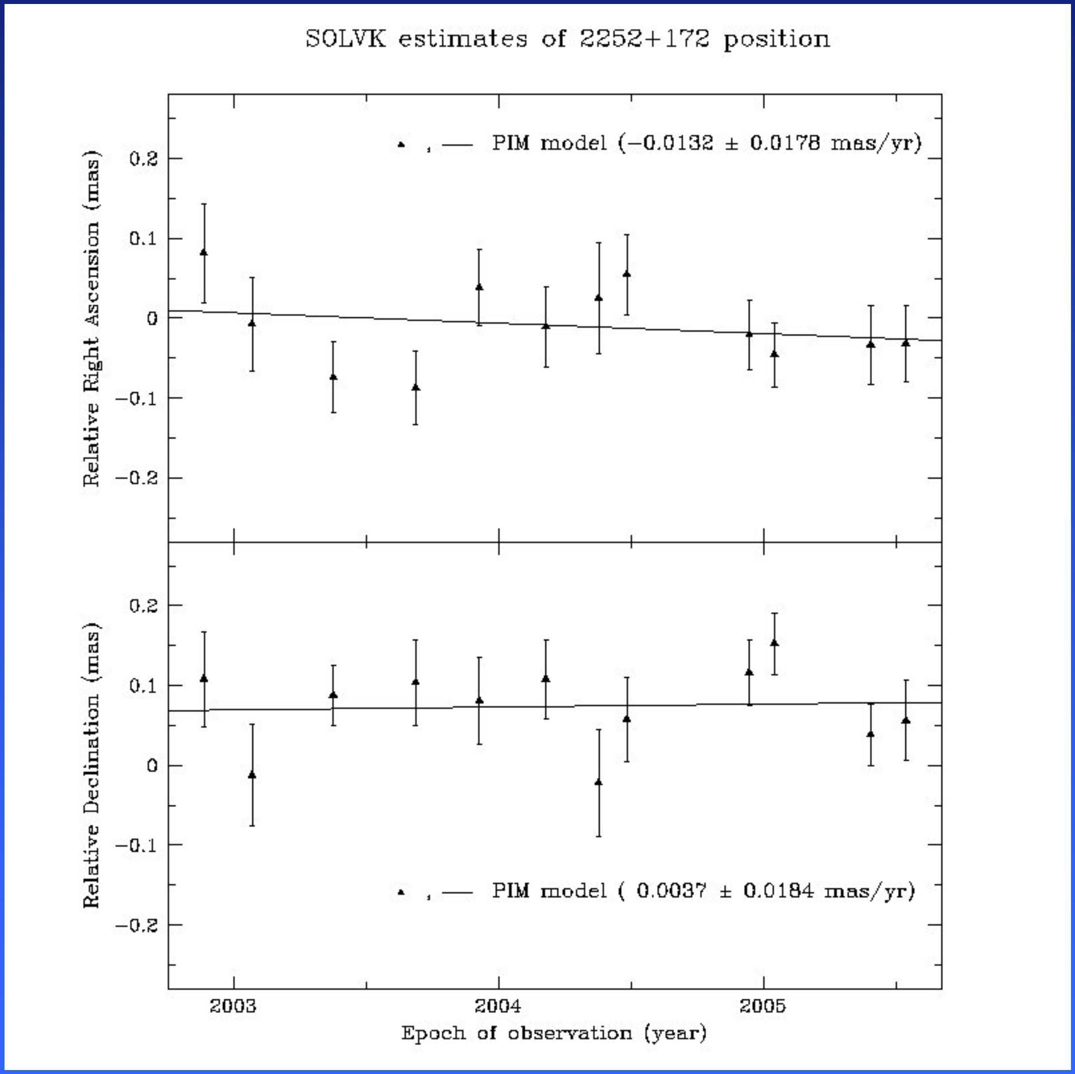








Assessment of Astrometric Accuracy

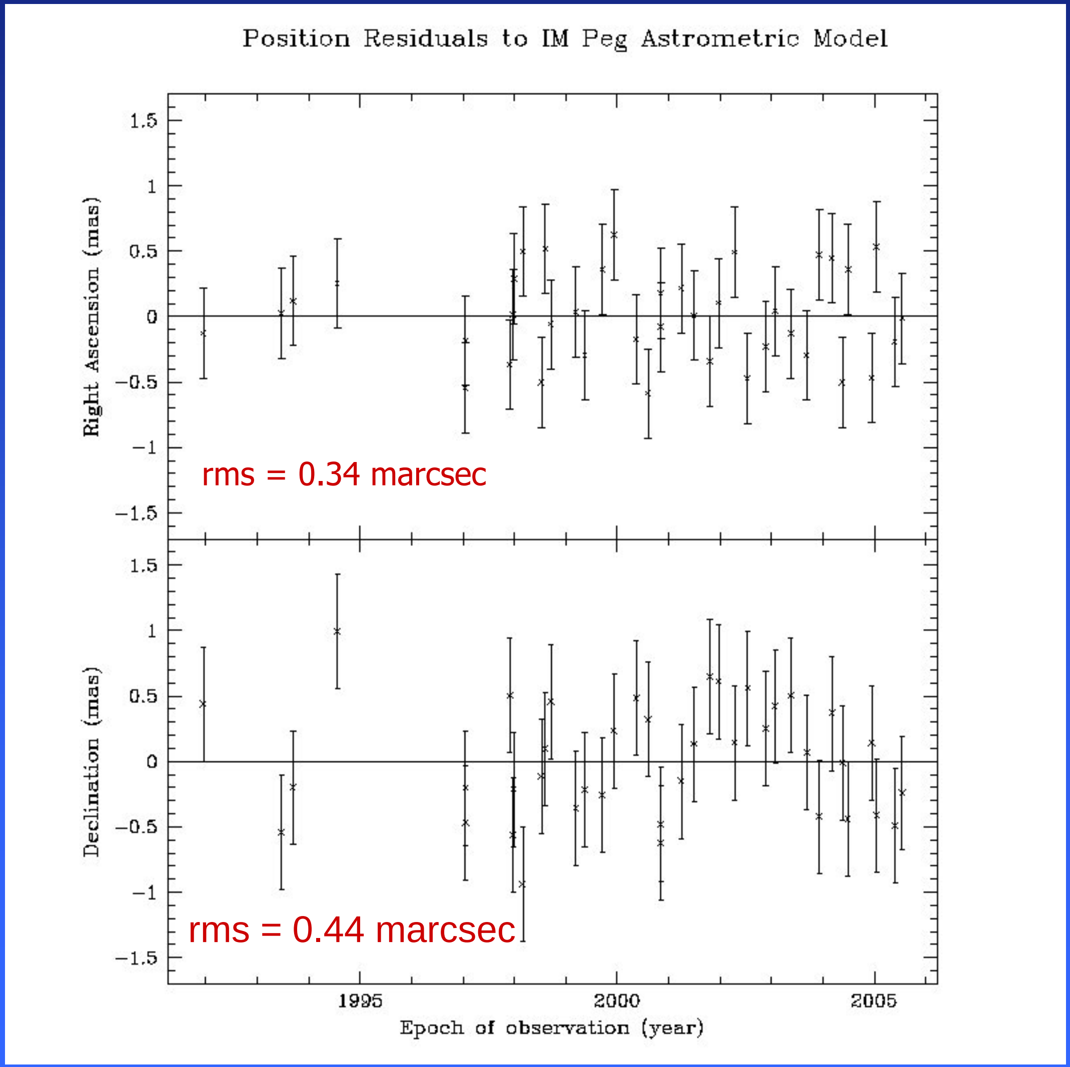


Assessment of Astrometric Accuracy (cont.)

IM Peg astrometric model has 11 parameters:

- Two position coordinates (on 1 Feb. 2005)
- Two proper-motion coordinates (on 1 Feb. 2005)
- Two proper-acceleration coordinates (assumed constant)
- Parallax
- Four IM Peg orbit parameters (in effect amplitude and phase in each of two coordinates; fixed orbital period of 24.64877 days and eccentricity of zero)

Assessment of Astrometric Accuracy (concluded)



Possible " Double-Blind" Experiment

Purpose:

- Best not to "know" answers in advance

Possibility:

- Guide star motion not known well enough at start of preparations for GP-B experiment to meet experiment goals

Procedure:

- Astrometry Team keeps its result secret from Gyroscope Team until analysis judged complete by both teams
- Each "side" discloses its result for proper motion (based on assumed validity of general relativity for Gyroscope Team) at session with disinterested, knowledgeable parties

Problems:

- Hipparcos' published value of proper motion of IM Peg has 1 standard deviation uncertainty of ~ 1 marcsec/year
- Accuracy of gyroscope drift-rate measurement may not exceed that of Hipparcos' proper motion

Present Status

- Gyroscope Team continuing data analysis
- Astrometry Team expects final standard error in IM Peg’s proper-motion measurement to be no more than ~ 0.1 marcsec/yr in each coordinate, about 30% under original goal