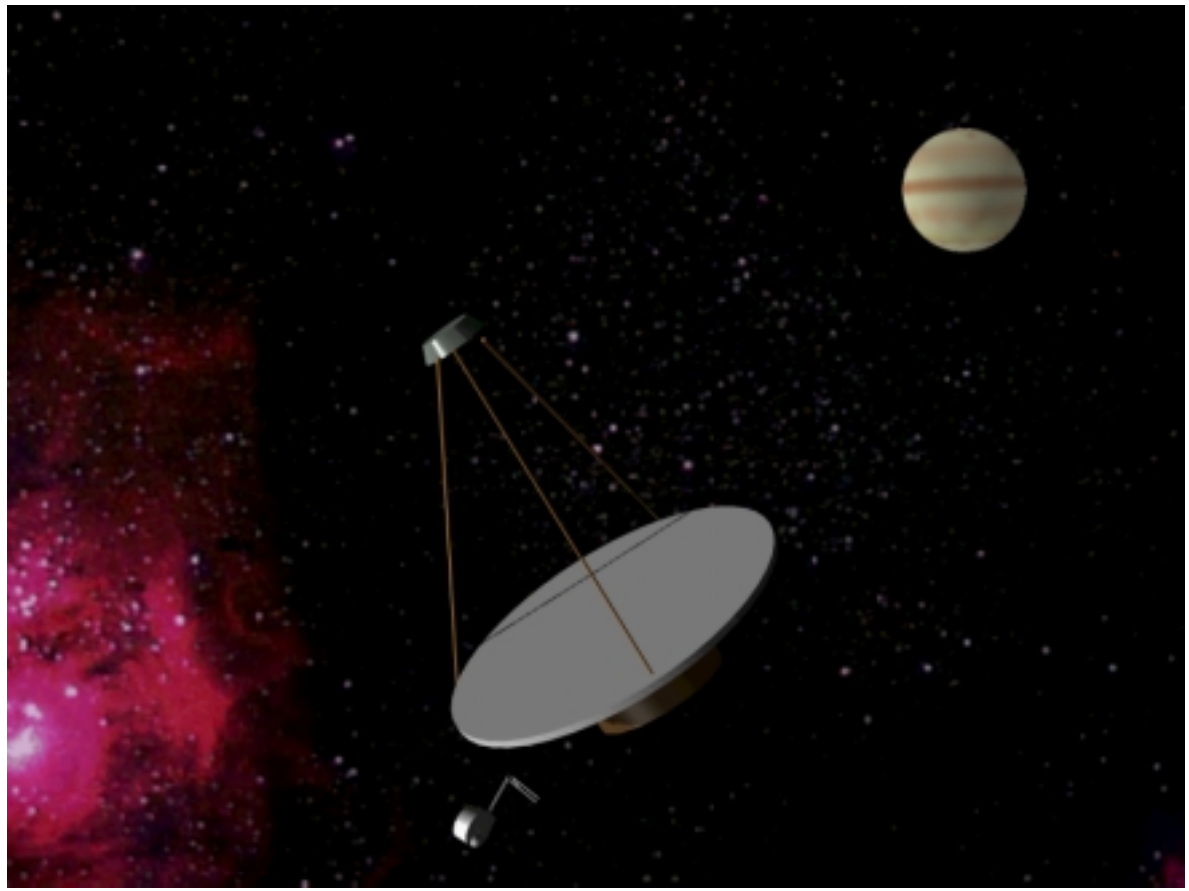
PLANETARY-SCALE ASTRONOMICAL BENCH

NIAC Phase I Study
November 1999



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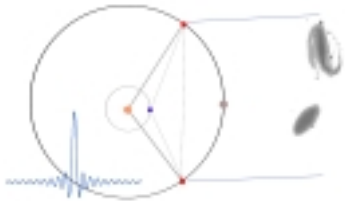
SVS, Inc.



PAB: WHAT IS IT ?

PLANETARY-SCALE ASTRONOMICAL BENCH

AN ASTRONOMICAL OBSERVATORY

-- USING JOVIAN LAGRANGE POINTS AS LONG-TERM SITES FOR ASTRONOMICAL INSTRUMENTS

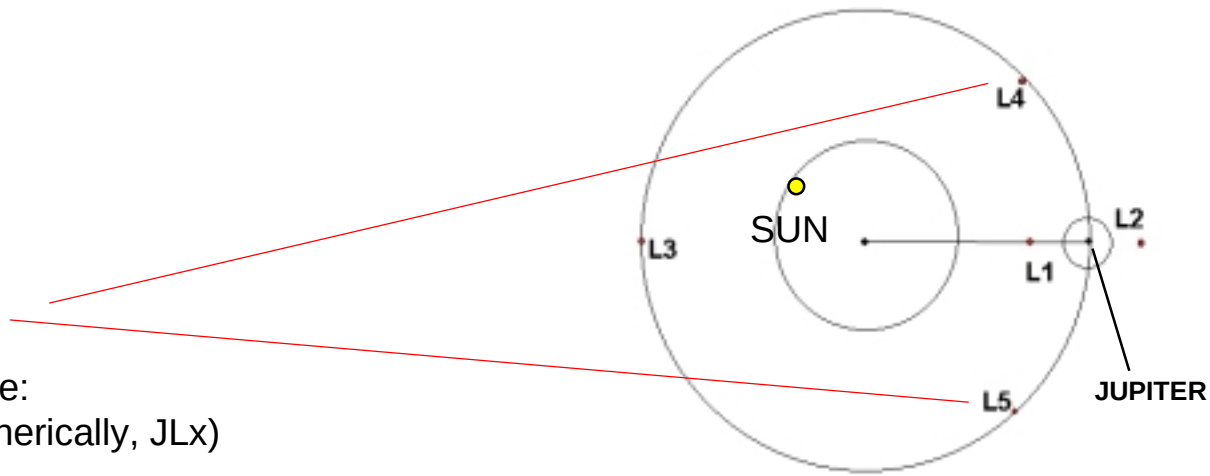
-- LOCATIONS OF NATURAL ORBITAL STABILITY

-- USE SOLAR-SYSTEM SCALE BASELINES FOR COOPERATIVE MEASUREMENTS

-- CONCEPT STUDY: EXAMINE POTENTIAL APPLICATIONS, BASIC FEASIBILITY ISSUES, SYSTEM CONCEPTS AND TECHNOLOGY ISSUES

-- ENVISION NOMINAL TIMEFRAME FOR DEVELOPMENT 10-40 YEARS

PAB "STATIONS"



Nomenclature:
JL4, JL5 (generically, JLx)

PAB BASIC INFO

PLANETARY-SCALE ASTRONOMICAL BENCH

STATIONS -- JL4 (leading), JL5 (trailing)
60 deg. ahead/behind JUPITER
E1 (Earth locus)

ORBIT: 5.2 AU (radius) PERIOD 11.86 yr
[1 AU = 778 million km]

JL4-JL5 DISTANCE = 9.01 AU (nominal)

JLx-E1 DISTANCE = 4.2 - 6.2 AU (periodic)

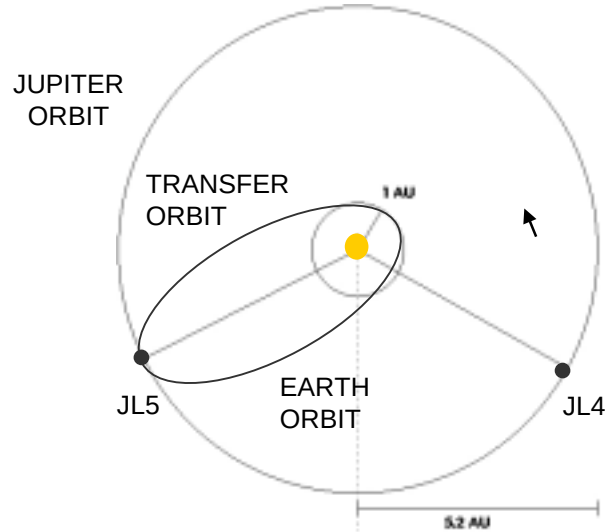
SOLAR IRRADIANCE AT 5.2 AU ~ 50 W/m^2

LIGHT-TRAVEL TIME:

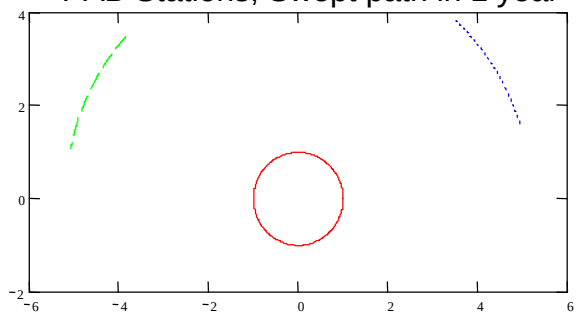
JLx-E1 : 34.9 - 51.6 min.
JL4-JL5 : 74.9 min.

HOHMANN ORBIT
TRANSFER TIME = 2.6 yr (one-way)

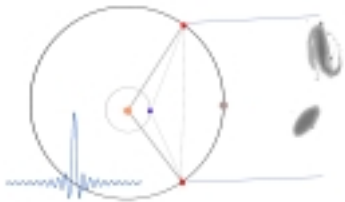
LAUNCH WINDOW ~ 13 MONTHS



PAB Stations, Swept path in 1 year



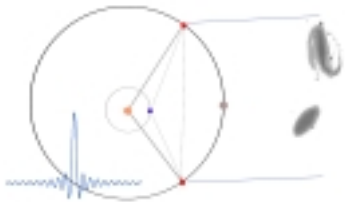
(looking down from North Ecliptic Pole; rotation CCW)



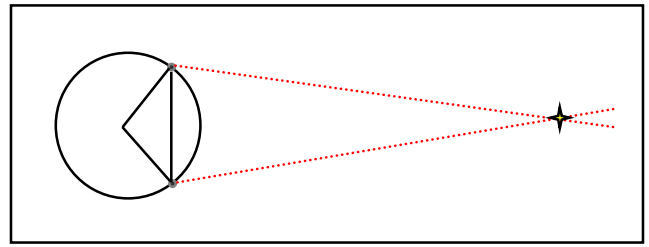
PAB APPLICATIONS

PLANETARY-SCALE ASTRONOMICAL BENCH

- PARALLAX-BASED ASTROMETRY
- CONVENTIONAL ASTRONOMICAL IMAGING & SPECTROSCOPY
- MICROLENSING
- LONG-BASELINE INTERFEROMETRY
  - RADIO, AND OPTICAL/IR
  - FOR ASTROMETRY AND SYNTHESIS IMAGING
- SOLAR SYSTEM SCIENCE
  - VIA LOCAL PROBES TO TROJAN ASTEROID POPULATION
  - SENSORS TO MONITOR INTERPLANETARY ENVIRONMENT
- GRAVITATIONAL WAVES
- OTHER LONG-BASELINE DYNAMICS STUDIES



PAB SCIENCE: ASTROMETRY



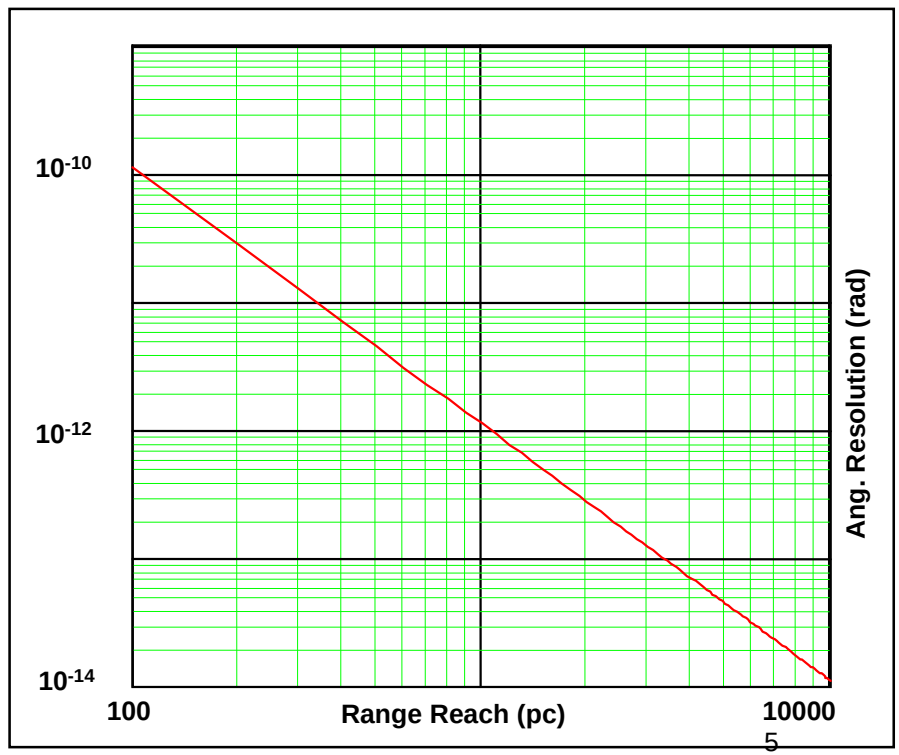
PLANETARY-SCALE ASTRONOMICAL BENCH

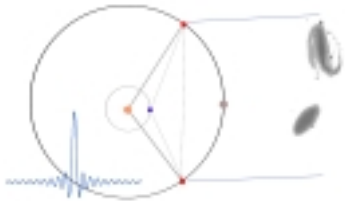
- ~9AU FOR PARALLAX-BASED RANGE

- RANGE REACH DEPENDS ON ANGULAR RESOLUTION
  - -- AT 10^{-12} RAD (0.2 MICROARCSEC), R > 10 MPC
    (c.f. ~8500 PC TO GAL. CENTER, 600000 PC TO M31)

- CURRENT TRENDS
  - -- "FEW" MICROARCSEC
    ~ 2005 (SIM, GAIA)

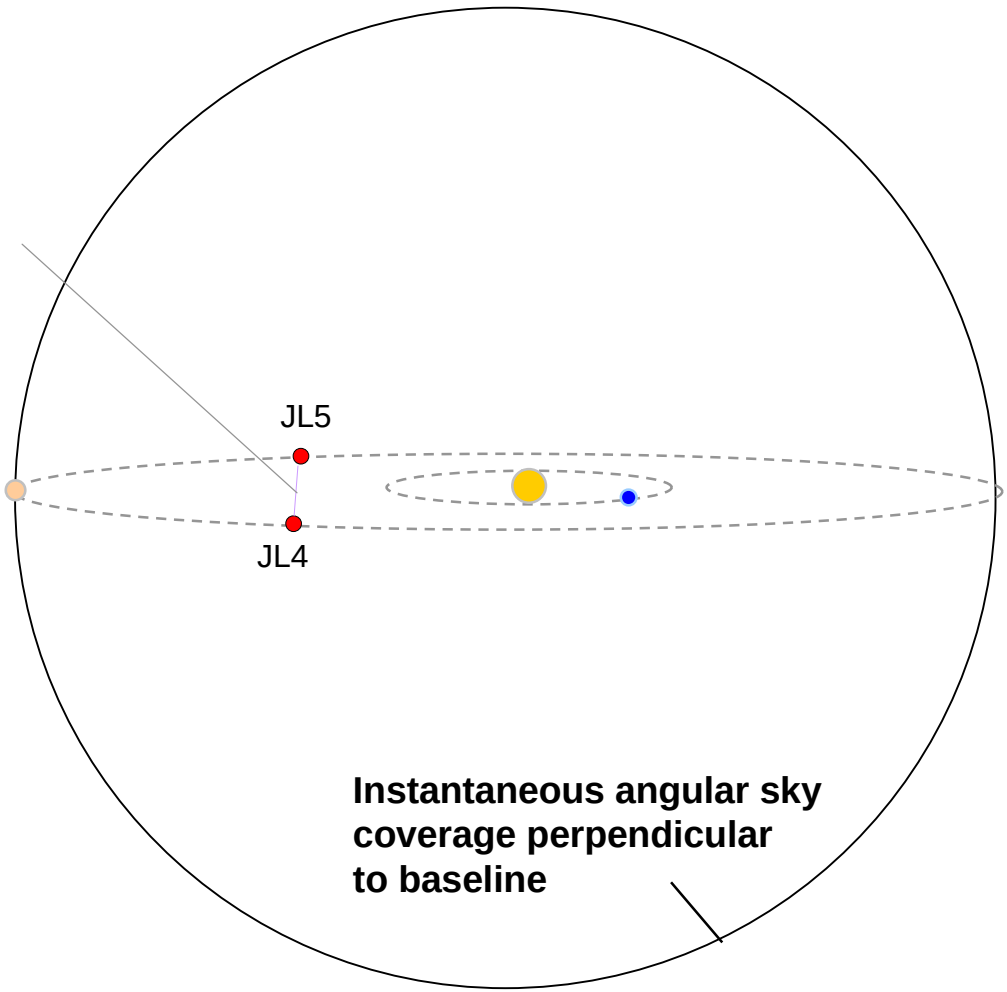
- ASTROMETRIC 'DEPTH SENSING' ENABLED VIA SIMULTANEOUS IMAGING
  - -- RANGE RESOLUTION
    0.1 PC at ~1000 PC



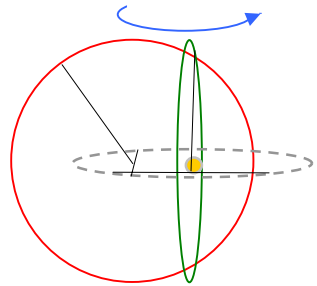


SKY COVERAGE

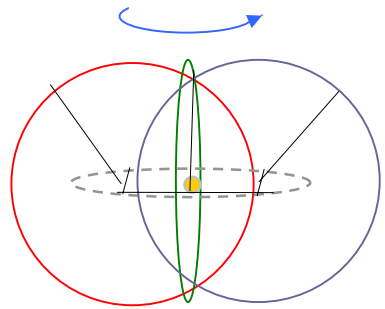
PLANETARY-SCALE ASTRONOMICAL BENCH



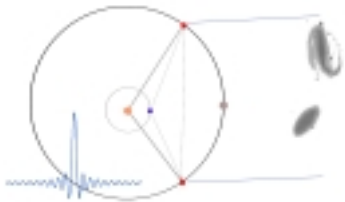
Instantaneous angular sky coverage perpendicular to baseline



(after 1/4 period)



Full sky is available for viewing in 1/2 period ~ 6 years



APERTURE SYNTHESIS

PLANETARY-SCALE ASTRONOMICAL BENCH

- **USE OF JLx POINTS ANALYZED FOR APERTURE SYNTHESIS**

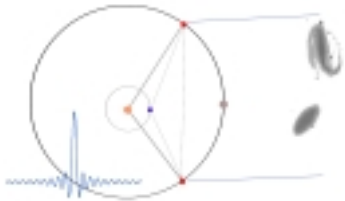
- **INTERFEROMETRY ACROSS FULL 9 AU BASELINE THEORETICALLY POSSIBLE BUT IS SEVERELY SIGNAL-STARVED**

  -- LIMITS CAN BE DERIVED IN TERMS OF AN "AREA-TIME" PRODUCT (COLLECTING AREA x INTEGRATION PERIOD)
  -- SCALES AS (BASELINE)^2 AND DEPENDENT ON SOURCE TEMPERATURE AND WAVELENGTH

- **TYPICAL VALUE: T(blackbody) @ 6000K (sunlike star)**
  BASELINE 10 AU : $A\Delta T = 10^{15}$ m^2-sec, 1 micron

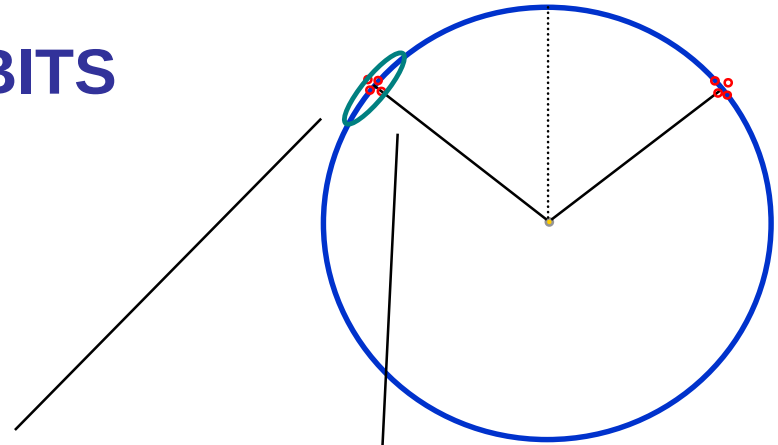
- **PRACTICAL INTEGRATION TIMES LIMITED TO ~10^5 sec**
  -- ROTATION OF BASELINE CHANGES RESOLUTION SIZE

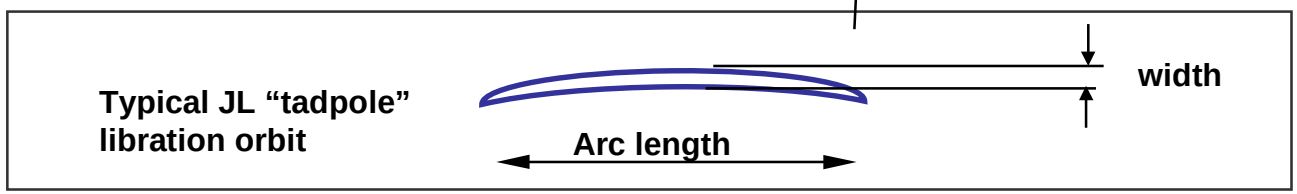
- **EFFECTIVE USE OF LAGRANGE POINTS**
  --> <u>"LIBRATION-PAIR"</u> ORBITS



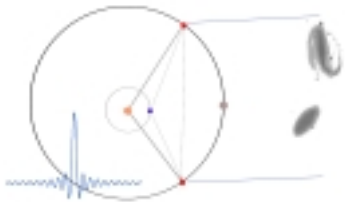
LIBRATION ORBITS

- LIBRATION ORBITS STABLE ABOUT JLx POINTS





- JLx WIDTHS UP TO ~ 0.16 AU, ARC LENGTHS ~ 60 DEGREES
- LIBRATION PERIOD ~ 150 YEARS, MOTION ABOUT JLx IS SIMPLE HARMONIC TO FIRST ORDER IN RADIUS AND LONGITUDE
- PLACE PAIRS (OR LARGER MULTIPLES) OF APERTURES IN SYMMETRIC POSITIONS ABOUT ONE OR BOTH JLx POINTS
- NATURAL ORBITAL MOTION PLUS SLOW LIBRATION DRIFT DEVELOPS (u,v) COVERAGE OVER TIME



SNR AND RADIOMETRY FOR INTERFEROMETRY

PLANETARY-SCALE ASTRONOMICAL BENCH

- **CALCULATE BOTH A *RADIOMETRIC* AND A *RESOLUTION* RANGE REACH**

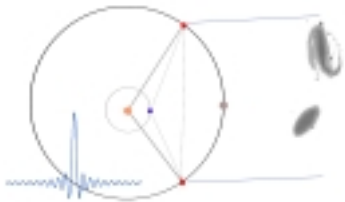
  -- RADIOMETRIC RANGE REACH SET BY SOURCE FLUX, SPECTRAL BANDPASS CONSISTENT WITH APERTURE SYNTHESIS

  -- RESOLUTION RANGE REACH (APERTURE SYNTHESIS) SET BY BASELINE TO JUST RESOLVE AT WAVELENGTH

  -- USE 1 PHOTON/SEC AS LIMITING CASE, SELECT SEPARATION AND/OR APERTURE TO MATCH THEM

- **RESULTS SUGGEST 0.01 AU, 100M APERTURE A CLOSE MATCH (2X)**

  -- $A\Delta t \sim 2X10^{8}$ AT 1 micron
  -- ANGULAR RESOLUTION 10^{-15} rad AT 1 micron
  -- EXCEEDS ANY CURRENT PLANS
  -- RESOLVE SUNLIKE STARS AT ~ 10 Mpc



BASELINE COVERAGE

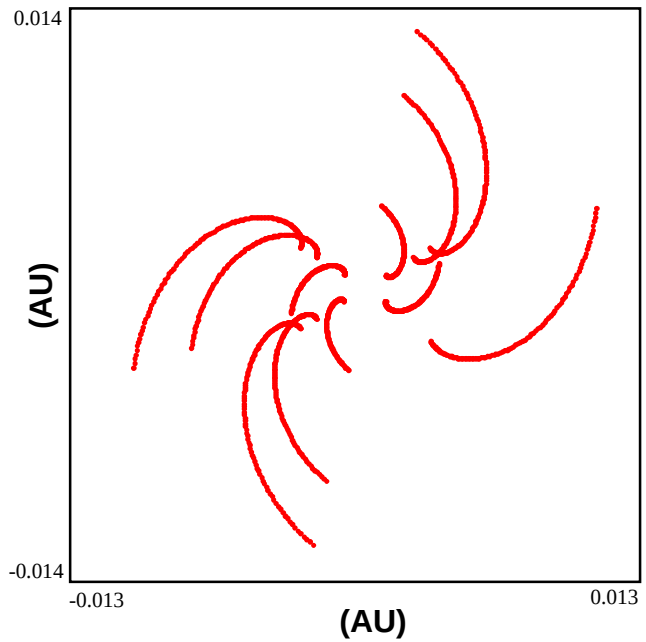
PLANETARY-SCALE ASTRONOMICAL BENCH

- **LIBRATION-PAIR MOTION DEVELOPS REASONABLE BASELINE COVERAGE**
- **USE OF ITERATIVE DECONVOLUTION ALGORITHMS TO CLEAN THE IMAGE**

- **LIBRATION ORBITS ABOUT OTHER SOLAR SYSTEM LAGRANGE POINTS**
- **JLx POINTS HAVE LARGER REGIONS OF STABILITY, LOWER ANGULAR RATES**

-- .002 AU Max (Earth)
-- < .001 AU (Mars)

RATES 6x - 8x LOWER FOR JLx vs ELx, MLx

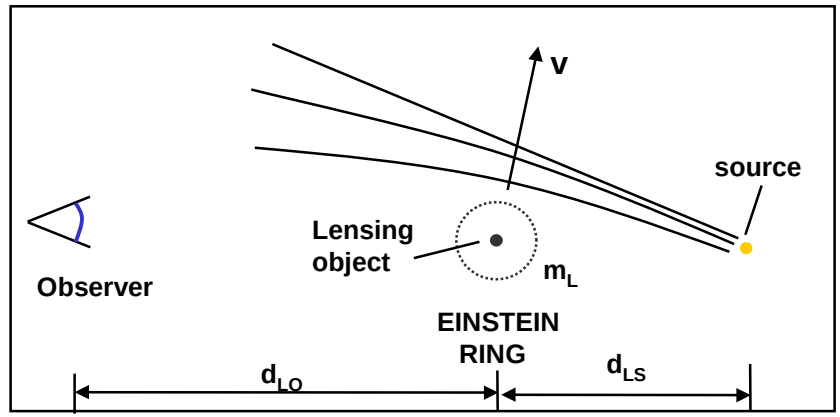


- 0.001 AU initial spacing
- 2 ea. (JL4A+B, JL5A+B)
- short λ scan $0.75*\lambda_0$
- long λ scan $1.35*\lambda_0$
- 1/3 ORBIT

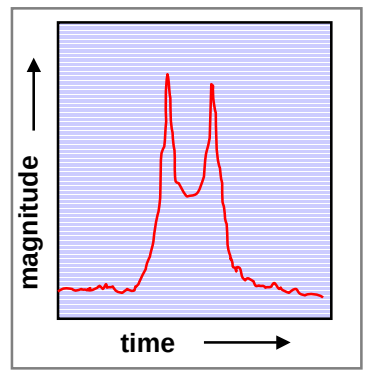
PAB SCIENCE : MICROLENSING

PLANETARY-SCALE ASTRONOMICAL BENCH

- GRAVITATIONAL LENSING WHERE SOURCE IS NOT RESOLVED; CAUSES BRIGHTNESS CHANGE



- CURRENTLY GROUND-BASED WITH ~ 1- 2 M APERTURES, MULTI-BAND PHOTOMETRY AT ~1-2% PRECISION
- TIME SIGNATURE OF LENSING OBJECT IS SYMMETRIC AND ACHROMATIC

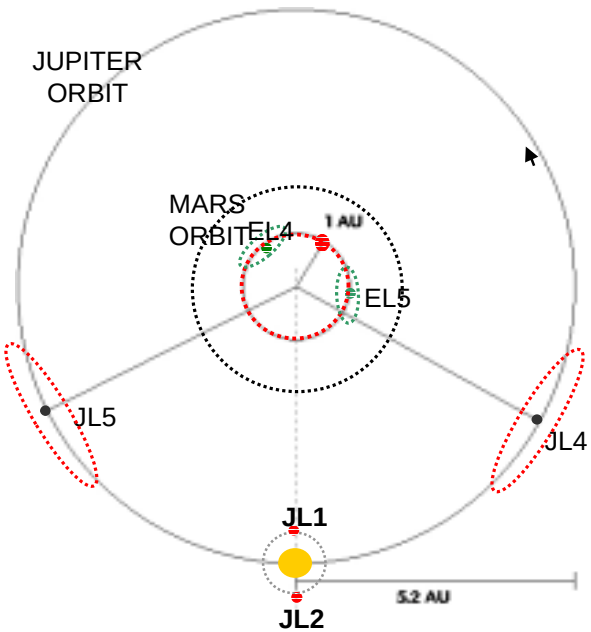


- TIMESCALES: ~DAYS (UP TO 1 MONTH) FOR STELLAR-MASS OBJECTS; HOURS TO ~ 1 DAY FOR PLANET OBJECTS
- SINGLE OBSERVATIONS DO NOT RESOLVE LENSING OBJECT MASS, DISTANCE, MOTION INDEPENDENTLY
- PARALLAX OBSERVATIONS + DOPPLER SPECTRAL ANALYSIS COULD PROVIDE FULL SOLUTION

SYSTEM CONCEPTS & SIZING (1)

PLANETARY-SCALE ASTRONOMICAL BENCH

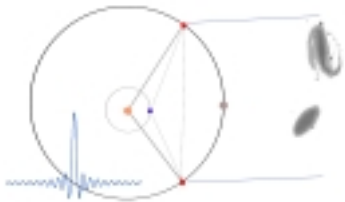
- **STATION LOCATIONS: JL4, JL5, EL4**
- **MULTIPLE INSTRUMENT POSSIBILITIES ON-STATION**
- **SYSTEM BASING OPTIONS:**
  - **-- FREE-FLYERS**
  - **-- MONOLITHIC**] **- HYBRID**
  - **-- ASTEROID (?)**



CANDIDATE INSTRUMENTS

APPLICATION	**	SIZE	JL4	JL5
CONVENTIONAL ASTRONOMY		10m	X	
ASTROMETRY	x	>2m	X	X
APERTURE SYNTHESIS	x	>10m	XX	XX
MICROLENSING	x	>1m	X	X
ASTEROID STUDIES		>1m	X	
ROBOTICS (EXPLORATION)	x	n/a	X	X

** = dedicated aperture



SYSTEM CONCEPTS & SIZING (1)

- **TOTAL SYSTEM MASS USING FULL "CANDIDATE INSTRUMENTS" LIST**

  -- ROM ESTIMATE FOR A "REALITY CHECK"

  ~30000 kg ea. STA. (JL4, JL5)

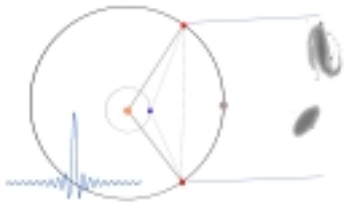
  -- SIZING RULES: AREAL DENSITY 10 kg/m2 (NGST),
  + INSTRUMENT ELECT./METROLOGY (100/200 kg)
  + SPACECRAFT OVERHEAD (3.3x P/L SUPPORT + 0.55xTOTAL)

  -- INCL. STATIONKEEPING FUEL ALLOC. BUT NOT TRANSFER STAGE
  CONSERVATIVE, CAN PROBABLY REDUCE BY >= 2X

- **LOGISTICS ADVANTAGES TO SOME SHARED SERVICES / FUNCTIONS**

  -- CENTRAL POWER AND DATA RELAY, STATION-STATION METROLOGY
  -- LOCAL POWER, COMM AND FINE-SCALE METROLOGY

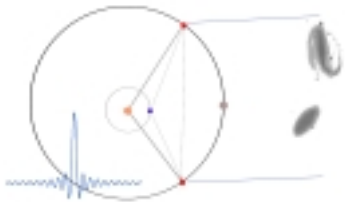
- **SYSTEM WOULD BE DEVELOPED / BUILT UP INCREMENTALLY**



ENVIRONMENT / DISTURBANCES

PLANETARY-SCALE ASTRONOMICAL BENCH

SMALL-SCALE DISTURBANCES:	
-- METEOROID FLUX	**~ 10^{-5} N**
-- RESIDUAL GAS	**10^{-10}**
-- SOLAR WIND	**10^{-6}**
-- RADIATION PRESSURE	**10^{-5}**
-- COSMIC RAYS	**10^{-9}**
GRAVITATIONAL PERTURBATIONS:	
-- SATURN,	**10^{-7} m/s^2**
SMALL-SCALE METROLOGICAL EFFECTS:	
-- STELLAR ABERRATION	**~ 40 μrad**
-- GRAVITATIONAL BENDING OF LIGHT	**10 prad - 0.1 μrad**
DELTA-V REQUIREMENTS	
-- STATIONKEEPING (~1/DAY)	**< 0.01 m/s/day**
-- ORBIT ADJUSTMENT (~1/YR) (LIBRATION TRUNCATED)	**~ 15 m/sec/yr**



TECHNOLOGY DRIVERS (1)

LARGE OPTICS

-- PAB SHOULD HAVE > 10M OPTICS, 100M DESIRABLE

-- 10 - 100 M SPACE OPTICS DEVELOPMENT, SEVERAL GROUPS

-- RECENT LARGE OPTICS DESIGNS: FREE-FLYER STRUCTURES

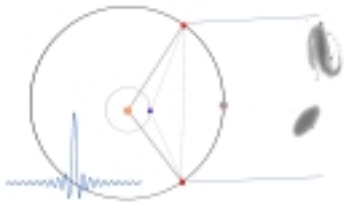
-- AREAL DENSITY: WORKING ON 15 kg/m^2;
EXPECT 10 BY ~2005;
WOULD LIKE < 1 FOR PAB

POSITION & TIME MEASUREMENT

-- ~1m STATION-STATION TO SUPPORT PARALLAX TO >10000pc

-- SUB-WAVELENGTH POSITION MEASUREMENT FOR APERTURE SYNTHESIS

-- TIME RESOLUTION TO 10^{-15} SEC; LIKELY EXTRAPOLATION OF CURRENT TECHNOLOGY (10X)



TECHNOLOGY DRIVERS (2)

PLANETARY-SCALE ASTRONOMICAL BENCH

SEPARATED-SPACECRAFT INTERFEROMETRY

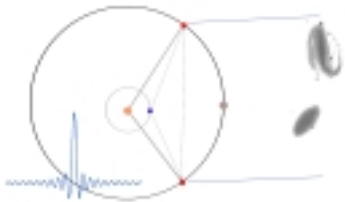
-- NOT CURRENTLY ACHIEVABLE AT >~ 100m BASELINES
-- PREVIOUSLY PROPOSED MISSIONS MAY EXPAND WORKING BASELINES TO FROM ~1km TO ~1000 km (ST3, DARWIN, PI)
-- VERY-LONG-BASELINE OPTICAL/IR INTERFEROMETRY NEEDS DEVELOPMENT OF L.O./CORRELATION METHODS (c.f. RADIO VLBI)
-- ALTERNATIVE WOULD BE DIRECT AMPLITUDE/PHASE RECORDING

SPACECRAFT ROBOTICS

-- PAB CAN TAKE ADVANTAGE OF LIKELY DEVELOPMENTS IN "SMARTER" SPACECRAFT
-- AUTONOMOUS NAV, PROXIMITY OPS/DOCKING, INSTRUMENT SERVICING, DIAGNOSIS/SELF-TEST

OTHER SPACECRAFT SYSTEMS

-- FINE POINTING/TRACKING, OPTICAL COMM/COMPUTING
-- MORE EFFICIENT PROPULSION



EXOSOLAR PLANET DETECTION

PLANETARY-SCALE ASTRONOMICAL BENCH

- **NARROW-ANGLE ASTROMETRY**

  -- MEASURE REFLEX MOTION OF STAR ABOUT BARYCENTER
  -- 3 μarcsec FOR 1 M_{EARTH} ,1 M_{SUN}, 1AU @ 1 pc, SCALES ~ RANGE

- **MICROLENSING**

  -- PARALLAX EFFECT --> TIME OFFSET BETWEEN LENSING SIGNATURE, ~ 10s OF DAYS

  -- SIZE OF EFFECT SCALES WITH PLANET, EARTH-SIZED PLANETS DETECTABLE

  -- <u>USE IN COORDINATION WITH ASTROMETRY</u>

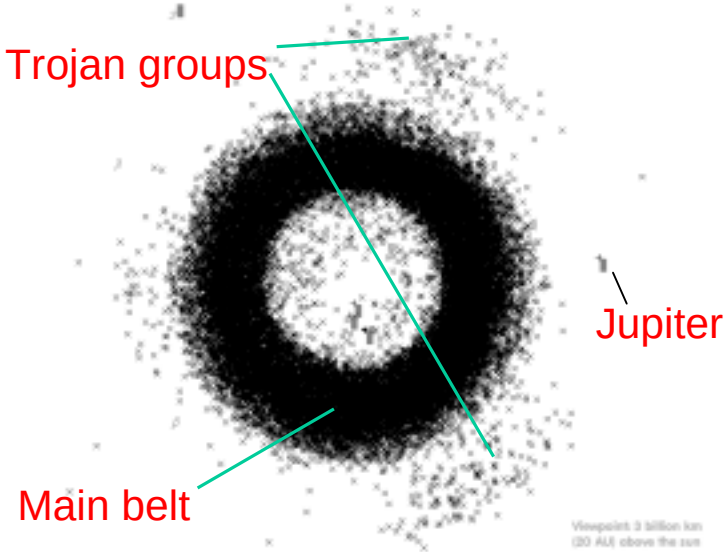
- **GOOD LOCATION FOR A NULLING INTERFEROMETER (OUTSIDE ZODIACAL CLOUD)**

- **OTHER METHODS POSSIBLE, e.g., OCCULTATION**

ASTEROID STUDIES & PRECURSOR MISSIONS

PLANETARY-SCALE ASTRONOMICAL BENCH

CATALOGUED ASTEROIDS (C. 12/98)
(VIEW FROM ABOVE ECLIPTIC)



- **TROJANS REPRESENT EARLY SOLAR SYSTEM MATERIAL**
- **LIKELY ANALOGS: “DEAD COMETS”; CARBONACEOUS CHONDRITES, POSSIBLE RESIDUAL WATER ICE**
- **SEVERAL HUNDRED KNOWN, SEVERAL INTERACTING GROUPS; TYPICAL SIZE ~ 15 km**
- **CONSIDER SINGLE LAUNCH TO ONE JL POINT (JL4 STRAWMAN)**
- **ROBOTIC EXPLORATION OF TROJAN ASTEROIDS & LOCAL ENVIRONMENT**
- **SHOULD INCLUDE ASTRONOMICAL INSTRUMENTATION**