PLANETARY-SCALE ASTRONOMICAL BENCH

NIAC Phase I Study
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*SVS, Inc.*
PAB: WHAT IS IT?

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

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/m²

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

(looking down from North Ecliptic Pole; rotation CCW)
PAB APPLICATIONS

- 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
• ~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

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

Instantaneous angular sky coverage perpendicular to baseline

(after 1/4 period)
APERTURE SYNTHESIS

• 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 : AΔT = 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
  --> “LIBRATION-PAIR” 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

• 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)

  -- AΔt ~ 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

- 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 $\lambda$ scan $0.75^*\lambda_0$
--- long $\lambda$ scan $1.35^*\lambda_0$
--- 1/3 ORBIT
PAB SCIENCE : MICROLENSING

- 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
• STATION LOCATIONS: JL4, JL5, EL4

• MULTIPLE INSTRUMENT POSSIBILITIES ON-STATION

• SYSTEM BASING OPTIONS:
  -- FREE-FLYERS ] - HYBRID
  -- MONOLITHIC
  -- ASTEROID (?)

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>**</th>
<th>SIZE</th>
<th>JL4</th>
<th>JL5</th>
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<tbody>
<tr>
<td>CONVENTIONAL ASTRONOMY</td>
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<td>10m</td>
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<td>APERTURE SYNTHESIS</td>
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<td>x</td>
<td>&gt;1m</td>
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<td>ASTEROID STUDIES</td>
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<td>&gt;1m</td>
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<td>ROBOTICS (EXPLORATION)</td>
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<td>n/a</td>
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** = dedicated aperture
• 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

### Small-Scale Disturbances:
- Meteoroid Flux: \( \sim 10^{-5} \) 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: \( \sim 40 \) µrad
- Gravitational Bending of Light: \( 10 \) prad - 0.1 µrad

### Delta-V Requirements
- Stationkeeping (\(~1/\text{Day}\)): \(< 0.01\) m/s/day
- Orbit Adjustment (\(~1/\text{Year}\)) (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/m²;
   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)

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

• 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
  -- USE IN COORDINATION WITH ASTROMETRY

• GOOD LOCATION FOR A NULLING INTERFEROMETER (OUTSIDE ZODIACAL CLOUD)

• OTHER METHODS POSSIBLE, e.g., OCCULTATION
ASTEROID STUDIES & PRECURSOR MISSIONS

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