Final Report

Planetary-scale Astronomical Bench

NASA Institute for Advanced Concepts
Phase I Study

submitted by:

SVS Inc.

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Executive Summary

This report documents a concept study for a large-scale astronomical observatory that we refer to as the *Planetary-scale Astronomical Bench*, or PAB. The basic concept behind PAB is to place space telescopes at each of Jupiter’s Lagrange points L4 and L5 for use in cooperative, long-baseline astronomical observations. In conducting the study we looked at: the types of missions and science objectives that would be enabled or enhanced by the PAB concept; system configuration, basing, and the number and types of instruments; environmental considerations resulting from a location in the Jovian orbit; and technology needed for development of PAB systems and instruments.

Figure 1 below shows the basic geometry of the PAB system.
Among the principal conclusions resulting from the Phase I study are the following.

- The concept has advantages for several areas of astronomical research, including astrometry, synthesis imaging, solar system exploration, and exosolar planet studies
  - Aperture synthesis across baselines 1000 times longer than currently under consideration will be possible
  - Synthesis imaging of exosolar planets may be enabled to much greater distances than currently planned – potentially, all earthlike planets out to the center of our galaxy
- Both near-term and far-term missions are possible based on current technology projections
  - Precursor missions to explore the Trojan asteroid environment or to deploy a subscale “pathfinder” demonstration system at one of the Lagrange points would be a desirable early goal, and feasible with near-term technology
- Environmentally-induced disturbances are relatively minor, so that long-term maintenance of the system geometry is possible
- Many current areas of NASA research, including several NIAC Phase I and Phase II studies, will provide technology needed for PAB systems
  - Much of the astronomical instrument and space systems technology needed will be developed as a result of currently planned or proposed programs

The use of the Jovian Lagrange points will provide a measurement baseline across planetary-sized scales of space and time.

The PAB study documented here provides a basis for further studies. We believe the concept has much potential, including much that we have not foreseen, and should be explored further.
**Introduction**

There is currently intense interest in the astronomical community in developing spaceborne interferometers for high-accuracy astrometry and aperture synthesis. During the next decade it is expected that NASA will develop and fly one or more astronomical missions dedicated to the use of long-baseline interferometry in order to obtain higher-resolution astrometric and imaging data than is foreseeable from other types of instruments. Although even current plans are technologically challenging, we believe that eventually ultra-long-baseline aperture synthesis will be possible, and propose that a natural location for such a system already exists: the two Jovian Lagrange points at 60 degrees ahead of and behind Jupiter in its orbit. In fact, there are a number of astronomical and space science applications that would benefit from this concept. Such a system would be comprised of one or more platforms placed at each of these points, robotically maintained and designed for extremely long life and extensibility. The two stations would work cooperatively and would be suitable for multiple types of astronomical and space exploration instruments. Because the Lagrange points are spaced 9AU apart, PAB will use baselines of a size comparable to that of our solar system. Hence the name, Planetary-scale Astronomical Bench (PAB).

This report documents a preliminary study of the use of the Jovian Lagrange points as long-term sites for astronomical instruments. These Lagrange points are locations of natural orbital stability; they are located 60 degrees ahead of and behind Jupiter in its orbit, and are a result of the combined gravitational attraction of the Sun and Jupiter. A large population of asteroids is trapped in clouds which are localized in the vicinity of the JL\textsuperscript{1} points. Lagrange points exist around other solar system bodies, but those at Jupiter are the most stable against perturbations.

The PAB study examined potential science objectives, basic feasibility issues, system architecture and design concepts, and technology challenges. In conducting the study we used the notional NIAC timeframe of 10-40 years to set a time "horizon" for development. Our findings show that the JL points can be utilized for long-baseline measurements of various types, and offer significant advantages over other locations in the solar system as sites for future astronomical instruments.

\textsuperscript{1} In the remainder of this report we use the notation “JL” to refer to the Jovian Lagrange points, followed by the numerals 4 or 5 to denote the leading or trailing JL points which are coorbital with Jupiter, or generically, JLx where we do not wish to distinguish between them. We use ELx and MLx to refer to Earth and Mars Lagrange points. In all cases we refer to the Lagrange points formed by interaction between the principal planet and the sun.
Table I gives a listing of basic information about PAB that will be useful as a reference in the remainder of this report.

<table>
<thead>
<tr>
<th>Table I. Basic PAB geometry.</th>
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<tbody>
<tr>
<td><strong>Stations:</strong></td>
</tr>
<tr>
<td>JL4 (leading) 60 degrees ahead of Jupiter</td>
</tr>
<tr>
<td>JL5 (trailing) 60 degrees behind Jupiter</td>
</tr>
<tr>
<td><strong>Orbit:</strong></td>
</tr>
<tr>
<td>radius 5.2 AU, period = 11.86 year</td>
</tr>
<tr>
<td><strong>JL4-JL5 distance:</strong></td>
</tr>
<tr>
<td>9.01 AU (nominal)</td>
</tr>
<tr>
<td><strong>JLx-E1 distance:</strong></td>
</tr>
<tr>
<td>4.2 – 6.2 AU (periodic)</td>
</tr>
<tr>
<td><strong>Solar irradiance at 5.2 AU:</strong></td>
</tr>
<tr>
<td>50 W/m²</td>
</tr>
<tr>
<td><strong>Light-travel time:</strong></td>
</tr>
<tr>
<td>JLx-E1: 34.9 – 51.6 min.</td>
</tr>
<tr>
<td>JL4-JL5: 74.9 min.</td>
</tr>
<tr>
<td><strong>Hohmann transfer orbit:</strong></td>
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<tr>
<td>transfer time 2.6 years (one way)</td>
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<tr>
<td><strong>Orbital velocities:</strong></td>
</tr>
<tr>
<td>13.06 km/sec (nominal Jovian orbit)</td>
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<tr>
<td><strong>Synodic periods:</strong></td>
</tr>
<tr>
<td>Earth - Jupiter: 13.3 months</td>
</tr>
<tr>
<td>Mars - Jupiter: 26.0 months</td>
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Science Objectives

In 1996 the “HST and Beyond” report of the Dressler committee [1] identified key goals for future space-based astronomical instruments which would be needed during the first decades of the 21st century. These goals included the development of space-based interferometry for use in both astrometry and synthesis imaging, and the development of an advanced near-infrared space telescope for studies of galaxies at high redshifts. At the beginning of our study we took these as preliminary instrumental objectives, and added to them, preparing a list of six broad astronomical and space science application areas that could benefit from the PAB architecture, i.e., from a location at the Jovian orbit and/or a cooperative set of stations at each JL point. Potential PAB applications include: astrometry, conventional astronomical imaging and spectroscopy, gravitational wave detection, microlensing, aperture synthesis and interferometry, and solar system science. We examined use of the PAB concept as a capability enabler for each of these application areas. There are also secondary objectives which we did not examine in detail, and some variations to the primary list which we uncovered as the study progressed.

Each of these will benefit from a location in a Jovian orbit. Conventional imaging and spectroscopy will have increased sensitivity due to a reduced zodiacal background in the infrared. Astrometry, interferometry, microlensing, and gravitational-wave detection will benefit from long baselines, and will require spatially separated observations. Astrometry can be done with simultaneous observations across a long baseline, or from a single site over time using natural orbital motion; interferometry, microlensing, and gravitational-wave detection will require simultaneous observations from at least two sites. Asteroid investigations can be done using autonomous robot explorers as we initially envisioned, but also using conventional telescopes and radar imaging.

The following sections discuss these applications in more detail.

Astrometry

Astrometry will be enabled by the simultaneous use of both stations for parallax-based measurements. The baseline established would be 9 AU station-to-station and from 4.2 to 6.2 AU from station to earth. Temporal motion of the stations in their orbits will allow full sky coverage at the full baseline in one-half of an orbital period (approximately six years). Use of long-baseline parallax-based astrometry in conjunction with high-angular resolution interferometric astrometry will allow unprecedented measurements of stellar positions throughout our galaxy, and potentially into neighboring galaxies as well.

Figure 2 shows a calculation of astrometric parallax “range reach” available versus the achievable angular resolution. This calculation is based on a
parallactic baseline between JL4 and JL5. Distances to the Large Magellanic Cloud and to the Andromeda Galaxy are shown for comparison, along with the approximate range reach which would be achieved using resolutions comparable to those expected for the planned SIM and GAIA missions [2,3]. The results show that direct parallactic measurement of stellar positions in M31 would be possible with PAB if only a 10x increase in resolution over the expected SIM/GAIA level could be achieved.

Astrometric range reach depends on achieving high angular resolution for precise measurement of stellar positions, coupled with measurements across a long baseline to observe parallax angles. Narrow-angle astrometry, by itself, could be used to measure small displacements of a star due to proper motion or to reflex motion about the gravitational centroid of the system caused by unseen companion objects (e.g., planets). Interferometers may be necessary to achieve

Figure 2. PAB range reach vs. angular resolution for parallax measurements using JL4-JL5 geometry.
narrow-angle astrometry at the levels shown, although other methods are possible. The recently-completed Hipparcos mission used a focal-plane grid-scanning method to achieve 1 milliarcsecond resolution [4]; the FAME mission [5] plans to achieve 200 microarcsecond astrometry using a similar method. Development of an astrophysical reference catalog of high accuracy will be necessary to provide a reference frame against which parallaxes can be measured; it may be necessary to use Quasi-stellar objects (QSOs) or other very distant objects to develop adequate positional stability. The SIM project has recently begun preliminary science studies aimed at developing a reference frame for use with future SIM science data.

A variation of parallax-based astrometry exists which is unique to the PAB geometry. Simultaneous imaging of extended objects (such as clusters and nebulae) from both sites will allow astrometric depth sensing or “tomography” over much of our local interstellar neighborhood. The basic concept is that the long baseline (JL4-JL5) would allow range measurements (via parallax) of extended objects such as nebulae out to significant distances (see Appendix V). The results (Figure 3) show that one might sense parallax (transverse to the line of sight) and depth of selected features in an extended object out to ~1000 parsecs with 0.1 parsec resolution - it depends on the angular measurement accuracy that can be achieved. A depth resolution of 0.1 parsecs could be achieved out to a distance of 10pc if the angular resolution is ~1 nanoradian, or 0.1 pc depth at 1000pc if 1 picoradian is achievable. SIM and GAIA are both planning to achieve about 10 microarcsecond angular accuracy (about 50 picoradians); therefore, a significant enhancement in astrometric capabilities could be achieved with about a 10x increase in instrumental performance over current plans, by using the PAB baseline for parallax-based measurements.
Figure 3. For ‘Astrometric Tomography’ using simultaneous measurements from JL4, JL5, this shows the required angular measurement accuracy from each platform to get an instantaneous parallax induced range resolution to 0.1 pc, versus the range of the object.

The sky coverage available using coordinated measurements from both sites is shown in Figure 4. Restricting measurements to those perpendicular to the baseline results in a great circle on the sky, which rotates as the natural orbital motion carries the Lagrange points around the sun. After one-half period (six years) the full sky has been covered. Obviously, measurements at other angles with respect to the baseline are possible, although the effective baseline is then reduced due to the angle of projection.
Spacecraft positioning measurements to support astrometry for PAB may not be too stressing: 1 prad projected to a range of 1 parsec (pc) is approximately 31 km. Therefore, parallax-based astrometry will likely be feasible out to 1000 pc ranges using meter-level accuracy in spacecraft position measurement. Angular measurement accuracies, as noted above, will need to be increased. However, using conventional estimation methods, the noise-equivalent angle (NEA) for a single centroid measurement will be much less than a pixel\textsuperscript{2}. Therefore, a 100m-aperture telescope working at a wavelength of 1 micron and a SNR of 30 should be able to achieve an NEA of $10^{-10}$ radians, or about 20 microarcsec.\textsuperscript{3} Statistical measurements using multiple samples could further reduce this error by the square root of N, where N is the number of samples. More sophisticated astrometric measurement techniques (such as rotational scanning and interferometry) are possible, and may further increase the accuracy over that available with direct imaging. Although a full error budget would depend on the

\textsuperscript{2} A commonly used estimation for the single-measurement centroid NEA is $(\pi/8) \times (\text{FWHM}/\text{SNR})$ where FWHM is the full width at half-maximum of the point spread function. The FWHM for an unresolved source will be determined by the diffraction limit of the optics plus aberrations, scatter, and jitter blur.

\textsuperscript{3} A 100m telescope should be able to achieve a SNR of this level with a few seconds of integration, and would be able to work against sunlike stars at distances of over 10 megaparsecs.
astrometric method used and would include other sources of noise and uncertainty, this simple calculation shows that the use of large apertures and very long baselines is a significant enabler for future astrometric studies.

**Aperture Synthesis**

In our study we felt that a heavy emphasis should be given to aperture synthesis and interferometry, as this is the most “visionary” goal, and the one likely to provide the most stressing system requirements. The JL points are potential locations for interferometers which could be used in aperture synthesis mode. The PAB concept can be viewed as a “system” of potential sites, including the JL points and libration orbits about them at various levels of displacement, plus the Earth-JL transfer orbit and other closely spaced orbits with relatively easy access. In addition, we envision at least one space-based, earth-locus site will be needed (for communications, at a minimum).

We analyzed a number of configurations for aperture synthesis, using baselines up to and including the full JL4-JL5 path. Because angular resolution scales as $\lambda/B$ (where $\lambda$ is wavelength and B is baseline length), the PAB system potentially has extremely high angular resolution if the full 9AU baseline could be used. Interferometry across paths of this length is theoretically possible; however, as one might envision, individual apertures must be very large in order to capture sufficient light to make use of the achievable resolution. As the resolution increases, the solid angle subtended by a single resolution element gets smaller, which translates into a smaller source object area from which to collect light.

The limits can be analyzed by computing an "area-time" product for any given baseline: the product of individual collecting aperture area and integration time required to give a minimum number of detectable photons. We calculated the area-time product for wavelengths from 1micron to 1mm, using extended blackbody sources, and baselines out to 10AU. The computation is detailed in Appendix Ia, and Figure 5 shows area-time product curves for several wavelengths versus baseline.

Minimum areas for apertures can be next be assessed by computing an upper limit to the integration time. Assuming that phase delays are not a limiting factor, the time limit for integration will be effectively set by the time required for the resolution to change significantly as the baseline rotates with respect to the source object (see Appendix Ia). This limit is approximately $10^5$ to $10^6$ seconds, and this then sets a minimum aperture size given a source, working wavelength, and baseline.
The results show that aperture synthesis across the full 9AU, JL4-JL5 baseline will require multi-kilometer apertures. The Area-time product decreases with increasing source temperature; however, even for hot stars (T_{eff} = 10000K or greater, types A, B, O) the apertures required will exceed tens of kilometers. Although apertures of this size may eventually be feasible, for the purposes of this study we drew a “technology line” at 100m-class apertures, since these are currently being discussed for ground sites and some developmental work on lightweight space optics approaching this size is underway [6,7; and see the discussion on p. 31].

![area-time product graph](image)

Figure 5. Area-time products \([m^2 \cdot \text{sec}]\) for wavelengths of 1, 10, 100, and 1000 microns, using a sunlike (6000K) blackbody source.

A look at the Area-time product graph shows that apertures of 100m are consistent with aperture synthesis on baselines in the range 0.01 to 0.1 AU (depending on the working wavelength and source temperature). Even a 0.01 AU baseline has a resolution far exceeding any currently proposed: working at a wavelength of 1 micron, the potential angular resolution is less than \(10^{-15}\) radian.
Aperture synthesis at this level would allow resolution of earth-sized objects at distances of 200000 pc (greater than the distance to the LMC).

Baseline separations of this size can be implemented using halo or “libration” orbits about one or both of the JL points. A continuous distribution of possible baselines exists; libration orbits are stable in radial widths up to 0.16 AU, and in arc lengths (heliocentric longitude) up to sixty degrees. Objects in libration move about the Lagrange points with a motion that is approximately simple harmonic in both radial and longitudinal displacement, with periods on the order of 150 years [see Appendix II for a discussion of libration orbit geometry and dynamics]. Pairs or larger multiples of spacecraft could be positioned in libration orbits about one or both JL points, with angular separations chosen to give a desired resolution. The natural orbital motion of the fundamental orbit and the libration path would combine to develop a (u,v) coverage pattern over time, and use of librating spacecraft working cooperatively at both JL points would increase the (u,v) coverage. Figure 6 shows the libration orbit geometry.

![Figure 6. Libration orbit geometry.](image)

In order to calculate the required aperture sizes which map to libration separations, one can compute both a radiometric and a resolution range reach, and set them equal to each other. The radiometric range reach will be depend on the source flux and the spectral bandpass of the collecting optics, which must be consistent with the use of the collected light for aperture synthesis. Resolution range reach will be determined by the baseline separation needed to just resolve a given source object at the working wavelength. A derivation of both range reach calculations is given in Appendix Ib; results for various classes of stars with a 100m aperture are shown in Figure 7.
The results show that a separation of 0.01 AU (or approximately 1.5 million km) is a close match to apertures of 100 meters (using a wavelength of 1 micron). Baselines of this size, working in the near- to mid-IR wavelength regime, would conceivably allow resolution of earth-sized planets at the center of our galaxy, or sunlike stars at 10 Mpc. This represents a 1000x increase in resolution over any plans currently envisioned by NASA or ESA. Even longer baselines may be technologically feasible at submillimeter and radio wavelengths, where both telescope technology and positional metrology will be easier to accomplish.

Collection of interferometric data at multiple spacings and orientations is necessary to develop an image, since this provides sampling of the source at different spatial frequencies. In order to assess the amount of (u,v) coverage which could be developed, we plotted the baseline separation vs. time. In general, use of more apertures at different spacings provides better coverage. For this analysis we assumed a pair of apertures at each JL point, separated initially by 0.001 AU radially, and evolving naturally to a radial width of 0.01 AU. Additional (u,v) plane coverage can be obtained by taking data at multiple wavelengths using the same baseline (since this changes the resolution of the
interferometer, it is equivalent to lengthening or shortening the baseline); we assumed a short wavelength scan at $0.75 \lambda_0$ and a long wavelength scan at $1.35 \lambda_0$, where $\lambda_0$ is the nominal working wavelength. Figure 8 shows the baseline coverage developed after 1/3 orbit (4 years). The source would not be continuously observed during this time but would be periodically sampled at something on the order of one week intervals (about $\frac{1}{2}$ degree in heliocentric longitude).

![Figure 8. Example (u,v) coverage for four apertures (two each at JL4, JL5) after four years. The axes are scaled in AU.](image)

The amount and spacing of coverage is not too different from that obtained in present-day earth-based radio interferometry, and we believe it is reasonable to assume that existing deconvolution algorithms can be used or adapted to work with images obtained from sets of interferometers in libration orbits. Typically, the “CLEAN” algorithm [8] is used to reduce interferometric data where holes exist in the spatial frequency coverage. Traditional CLEAN only works where no significant extended-object data is present, but multi-resolution CLEAN variations have been developed that reduce extended-object data as well [9].

Lagrange points exist for other planets, and have been shown to be stable on million-year timescales [10]. However, in comparison to Lagrange points about other solar system bodies, the JL points have larger regions of stability. They
also have lower angular rates, which will allow longer integration time or, equivalently, will impose lower rates of phase delay change needed for interferometry.\footnote{Maximum radial widths for libration orbits are approximately 0.002 AU (ELx) and <0.001 AU (MLx). Angular rates of motion of the baseline are 6X to 8X higher.}

During the PAB study we concentrated on use of optical/infrared wavelengths for interferometry and aperture synthesis. Interferometry at radio wavelengths would relax the aperture size, surface figure, and metrology requirements. We calculated area-time products for radio interferometry; the results show that kilometer-class apertures are still required, although we expect this to be significantly easier to accomplish at radio wavelengths.

**Microlensing**

PAB locations will also be useful for microlensing, where a source object is gravitationally lensed by an unseen deflector object, but where the source is not optically resolved. In this case the result is a brightness change due to the time-varying deflection of light into the field of view. Microlensing can be distinguished from stellar variability since the change in brightness from lensing is temporally symmetric and achromatic. Microlensing is currently done at ground-based sites using multi-band photometry on 1-m class apertures, with 1-2% photometric precision [11]. Figures 9 and 10 depict the geometry for microlensing and a typical photometric trace showing an event with a timescale of a few weeks.

\[ \text{Figure 9. Microlensing geometry. } d_{LO} \text{ is the distance to the lensing object (of mass } m_L), \quad d_{LS} \text{ the distance from the lens to the source, and } v \text{ the relative space velocity of the lens across the line of sight.} \]
Figure 10. Typical microlensing photometric trace. The vertical axis represents photometric magnitude and the horizontal axis is in units of days.\(^5\)

Microlensing observations from single sites do not provide sufficient information to fully solve for the mass, distance, and proper motion of the lensing object. However, use of simultaneous observations from two displaced sites will allow an additional element of the equation to be solved, and the addition of doppler spectral analysis would provide enough data for a full solution. Parallactic microlensing will provide additional information about dark matter as compared to earth-based measurements, and will also assist in the search for extrasolar planets [12].

Simple calculations show that microlensing-induced photometric variability has timescales ranging from a few days to a month (for stellar-mass lensing objects) down to periods of a few hours (for planetary mass objects). These calculations are based on single site observations. Parallax will cause microlensing effects to be displaced in time when viewed from separated sites; for JL4 and JL5, using stars in the galactic halo as sources, and with reasonable assumptions on lensing object proper motions and distances, we computed that microlensing profiles for a typical source will be separated temporally by periods of up to a few weeks (see Appendix IV). A pair of telescopes, one each at JL4 and JL5, would therefore provide valuable data on dark matter in the galactic halo, and would be useful in exosolar planet detection (see section 6 below).

Conventional Astronomy

The Jovian orbit, at 5.2 AU, has already been proposed as a site for the Terrestrial Planet Finder (TPF) [13], in order to reduce the zodiacal light

\(^5\) The data is from the OGLE project (OGLE-1999-BUL-05) and was taken in the I band. The source and microlensing object are the direction of the galactic bulge. Error bars are not shown in this plot. See http://www.astro.princeton.edu/~ogle/ for the original data.
background in the infrared. An early concept for the Next Generation Space Telescope (NGST) also placed that instrument at a 5AU orbit, for the same reason. Without discussion of specific science targets or instrumental objectives, we expect that the desire to have a large telescope for imaging and spectroscopy at a Jovian orbit will persist. We have therefore “booked” an NGST-class telescope as an integral part of PAB.

**Asteroid Studies**

The JL points are home to a significant population of asteroids, which are objects of significant scientific interest in their own right. There are currently (as of 6/99) 299 catalogued asteroids at JL4 and 174 at JL5. Shoemaker [14] estimates a total Trojan population of ~2300 (counting all objects larger than 15km; the statistical average diameter is about 17km), with a total mass of $10^{-5}$ earth masses (assuming water density). They librate about the Lagrange points, with libration amplitudes (in heliocentric longitude) from 3 – 60 degrees (the average is about 30 degrees).

JL4 and JL5 are potentially advantageous sites for remote studies of the Trojan asteroid population. Conventional imaging, photometry, and spectroscopy could be useful. Radar imaging would be a powerful tool but would require high levels of spacecraft power for the transmitter. The real potential for asteroid studies lies in the ability to conduct in-situ exploration and sampling using autonomous robotic probes. Overall, Δv requirements would be relatively small compared to dedicated missions launched from earth. PAB sites will require advanced robotics for long-term servicing of instruments and spacecraft systems; a separate robotic probe assigned to each station could be used for localized exploration as asteroids moved within range. Appendix VI contains a summary of recent information on the Trojan population.

**Other Applications**

Gravitational wave detection can be done in two ways: via doppler tracking of spacecraft to estimate range very accurately, and using dedicated gravitational-wave spacecraft such as the LISA concept [15,16]. The primary advantage of space-based gravitational wave instruments is the ability to detect low-frequency and very-low-frequency waves, which are not detectable using earth-based instruments because of seismic noise. It should be noted that gravitational waves have not yet been unambiguously detected on earth, and that instrumentation for them is still evolving. Nevertheless, progress on major projects such as LIGO [17] is indicative of scientific interest in the field, and we would expect that gravitational wave studies will be extended to space.

Gravitational wave detection is characterized by the strain sensitivity of an instrument, a unitless number that measures its ability to detect changes in the metric of space. Desirable strain sensitivities for LF ($10^{-5}$ to 1 Hz) and VLF ($10^{-9}$
to $10^{-5}$ Hz) gravitational waves are on the order of $10^{-20}$ or $10^{-21}$ (vs. $10^{-22}$ for advanced LIGO detectors working at 10 – 1000 Hz) [18]. Doppler tracking gravitational wave detection has been performed several times using RF transmissions between earth and interplanetary spacecraft such as Voyager and Galileo [15]. The PAB sites at JL4 and JL5 would provide a suitable pair of locations for these measurements. However, strain sensitivity using this technique in the RF domain appears to limited ultimately to $\sim 10^{-17}$ due to plasma scintillation effects [18]. PAB may be able to surpass this using non-RF doppler methods, i.e., laser metrology between stations (which will be needed for other reasons, see section 5b and 5c below). The JL points are also suitable locations for LISA-type instruments; the current LISA concept design [16] uses an approximately 0.03 AU displacement between each of three separated spacecraft, and is expected to reach a strain sensitivity of $10^{-23}$ for LF gravitational waves. Because of the complexity of space-based gravitational wave detectors, a study concentrated solely on this type of instrument will be needed to optimize configuration and spacing for the geometry.

The 9AU baseline between JL4 and JL5 can be useful for other studies relying on dynamic measurements of position; it may be a useful technique for investigating high-precision solar system dynamics. The use of simultaneous observations at the two locations may also have utility in many ways; for example, relative time-of-arrival at different spacecraft has already been used to triangulate positions of gamma-ray bursts (GRBs) [19]. This is possible due to the sudden onset of GRB events, plus the existence of an identifiable post-onset signature. PAB baselines could be used for GRB triangulation, and should allow better resolution than can be currently obtained. We anticipate that other unforeseen (to us) applications of this type may be enabled or enhanced by PAB, and that new methods of study would be developed as the concept matured.

**System Concepts**

A variety of configurations are possible for PAB. For this study we chose to focus on a "reference" configuration, which defines a set of locations and instruments that can be used to assess system sizing and space technology-related issues. Our general approach here was to adopt the "multiple site, cooperative system" paradigm that addresses the major applications outlined above. It is certainly possible to design other configurations with other mixes of instruments, including single instruments only, and a PAB-like system would almost certainly be implemented in a series of steps, with a growth in capabilities at each step. We expect that a PAB configuration would be implemented in a
time-phased manner. The reference configuration outlined below represents a fully-deployed PAB architecture.

Placing stations at each JL point supports long-baseline astrometry. Placing two stations librating about each JL point supports interferometry at ~0.01 – 0.1 AU. Longer-baseline interferometry, if achievable ultimately, can be supported using JL4-JL5-Earth baselines. A “system” effect will be the occultation of earth from each JL station at recurring periods (about ~1 month blackout every ~13 months, depending on the solar exclusion angle for communications). During a blackout it will be necessary for communications with the occulted path to be redirected through an alternate location (the other station, nominally). Placing stations at each JL point avoids communications blackouts with earth since one station is always in view.

We selected and sized instruments using the following general rationale. A single telescope with a large aperture (~10m diameter) at one of the JL points would serve most conventional astronomy applications. We would add a smaller dedicated one for microlensing, and a second small timeshared telescope for solar system remote exploration and to offload some of the additional observations that would not require a large aperture. For astrometry, a dedicated aperture at one JL4 and one JL5 location, for both basic astrometry and astrometric tomography (see below) would be needed. Aperture synthesis will require a pair of telescopes (or more) librating about each JL point. Telescopes for aperture synthesis would need to be on the order of 100m in diameter. In addition to these instruments, particle/field instrument packages (not shown in the table) and robotic explorers would be based at each JL location. We have not listed instruments for robots since they would be small (< 1m).

The reference configuration is a heterogeneous architecture, based on the principle of satisfying the desired science objectives without duplication of systems. The list of instruments is shown in Table II. Although this sounds like a large list of astronomical instruments, our view is that they would be implemented in a time-phased manner, as resources permit.

Table II. Candidate Instruments for the Reference configuration. “X” indicates the presence of one or more instruments. “+” indicates that the size shown should be regarded as a minimum.

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<tr>
<th>Application</th>
<th>Size</th>
<th>JL4</th>
<th>JL5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Astronomy</td>
<td>10m+</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Astrometry</td>
<td>2m+</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Aperture Synthesis</td>
<td>10-100m</td>
<td>XX</td>
<td>XX</td>
</tr>
<tr>
<td>Microlensing</td>
<td>1m+</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Asteroid Studies</td>
<td>1m+</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Robotics (exploration)</td>
<td>N/a</td>
<td>X</td>
<td>X</td>
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</table>
Station Concepts and Basing

We have outlined below (Figure 11) a block diagram showing conceptually the major components that would be necessary for a PAB station. This design is predicated on the paradigm of a station as a unified system providing services to multiple science experiments. In implementation, this would be strictly true only for monolithic stations or science bases located on the surfaces of solid bodies such as asteroids. Multiple free-flying platforms would entail some unavoidable duplication of systems, although some services could be centralized.

The design shown contains all major systems needed by a “typical” science-mission spacecraft, plus some that would be unique to PAB. We have shown, for example, a robotic interface and packages for spares and maintenance. Based on experiences with the Hubble Space Telescope we would certainly expect periodic servicing of instruments to be a necessity, particularly due to the long travel times from Earth to Jovian orbit. Advanced robotic systems would be necessary to perform this servicing, and in fact would likely be used during build-up and initialization of the system.

Other systems that would be technically advanced include data handling, processing, and storage; communications; pointing and stabilization; and metrology and calibration (which would have a component unique to each experiment package). Most systems would need to be upgradeable to allow for a long service life of the system. Most infra-structure components must also be upgradeable without affecting existing experiments, and should be capable of being bypassed if required.

<table>
<thead>
<tr>
<th>Environmental Monitoring</th>
<th>Metrology &amp; Calibration</th>
<th>External Communications, Command, &amp; Control</th>
<th>Spares</th>
</tr>
</thead>
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<td>Local Computing</td>
<td>Data Bus, Internal Communications</td>
<td>Power</td>
<td>PAB Infrastructure, Main Base</td>
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<tr>
<td>Temporary Storage</td>
<td></td>
<td>Point &amp; Stabilization</td>
<td>Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maintenance</td>
<td></td>
</tr>
<tr>
<td>Data Interface</td>
<td>Power Interface</td>
<td>Mechanical Interface</td>
<td>Robotic Interface</td>
</tr>
</tbody>
</table>

Enhanced Computing and Storage

Figure 11. Conceptual block diagram of a PAB station (unified services).
We examined three possible basing modes for PAB stations: monolithic; asteroid surface basing; and multiple free-flyers. A discussion of some design aspects for each concept and the trades between them follows below.

**MONOLITHIC**: A “Main” Satellite has solar arrays to capture energy from earth orbit inflatables or has radio-isotope source\(^6\). Either could be upgraded in the future. Power is distributed to individual experiments via conducting cable. Surge capacity would be available through batteries, fuel cells, or other energy storage technology. The Main Satellite provides communication between experiments and earth or other stations. It would have a high bandwidth data bus to route data between communications, computing, science experiments, metrology, etc. An optical bus should be immune to radiation upsets and thus able to support higher bandwidths than electronic components. The communication subsystem can be replaced or upgraded as necessary, but (to minimize upgrades) should be designed for much higher bandwidth than anticipated needs. The Main Satellite would also provide precision metrology which can easily be disseminated to

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\(^6\) At the present time we anticipate that radioisotope sources are highly unlikely to be available in the future, due to environmental and political concerns.
individual experiments over the data bus. The Main Satellite can provide maintenance either through free-flying robots, or through attached robotic arms and manipulators.

In a monolithic system all science experiments are mechanically coupled to each other, leading to possible vibration interference. The science experiments are in local proximity, also leading to potential EMI and other interference, and mounted on a common platform, leading to potential tasking conflicts, especially for long observation experiments.

**ASTEROID BASE:** We anticipate that, in the time frames under consideration, significant progress will have been made in spacecraft autonomy, allowing the possibility of placing PAB systems and experiment packages on the surfaces of asteroids. An asteroid would conceivably provide a solid base with minimal vibrational coupling between experiments, and experiments can be located sufficiently far apart that EMI and other interference is minimized. There should be no tasking or obscuration effects (assuming that the asteroid is not maneuvered). Large asteroids (15 km) might even provide good baselines for interferometers on a single platform. Power and data coupling between a central control unit and remote experiments would be straightforward. Basing on asteroids provides the option to place sensitive equipment, experiments, and spares in dug-out chambers, thus providing enhanced radiation protection. Physical separation provides more independence between functions and hence easier upgrade routes. A central unit can provide precision metrology which can easily be disseminated to individual experiments over a data bus. Large

![Asteroid Based Diagram](Image)

*Figure 13. Asteroid basing concept.*
separation distances on asteroids will require use of robotic maintenance vehicles, not simple robotic arms.

Another potential advantage of asteroid basing is the availability of resources; it may be possible, given advanced robotics, to mine one or more Trojan asteroids for materials to construct parts of the PAB system. Trojan asteroids, based on the available spectroscopic evidence, appear to be most closely related to carbonaceous chondrites [14,20], and would likely possess elements in “typical” solar system abundances (but with little or no free metals as are found in nickel-iron bodies). It also seems likely that water ice is present on Trojans. Asteroidal resources could be used for station construction materials (which would require more complex construction and processing systems) or for reaction mass. A full assessment of this problem was out of scope of our study, since it involves many technical considerations that we did not originally envision.

FREE-FLYER: In this concept science experiments are placed on multiple free-flying platforms. The chief advantages here are the lack of vibrational coupling and other interferences between experiments. This would allow independent tasking of experiments. Stations can be sufficiently separated to eliminate EMI and other interference. Some centralized services could be shared (e.g., power, some metrology, long-range communications to earth), but duplication of many systems and services would be unavoidable.

![Diagram of Multiple Stations](image)

*Figure 14. Free-flyer basing concept.*
DISCUSSION OF BASING MODE: Use of a monolithic structure has advantages in terms of shared systems, including metrology, communications, computing, spacecraft attitude control and stationkeeping. However, monolithic structures are unsuitable for all instruments since some will be extremely sensitive to vibration and other interferences. For asteroid basing, a serious problem is the spin rate: an examination of asteroid rotation rates shows that most rotate in 12 hours or less, placing serious limitations on observing time and requiring high tracking rates. At least 1 asteroid (4179 Toutatis) is known to revolve around a non-principal axis; the vast majority of others are thought to be in principal-axis spin states [21], which would complicate pointing and metrology, and may make some experiments impractical. If low rotation rate asteroids at suitable halo orbits could be found, this might represent an optimum basing scheme. The advantage would be the use of a solid surface for basing instruments. Free-flyers would require considerable duplication of systems at each station. Distribution of power and other services from a central unit to individual stations would add design complexity. Higher levels of robotic mobility, including long-range autonomous navigation and docking, would be required for servicing (although we expect this level of autonomy to be available; it would be needed for robotic explorers, as discussed above under science objectives).

A hybrid architecture consisting of a monolithic structure plus some free-flyers appears to be the best choice at this level of study. This is a detailed trade that could only be resolved with a more detailed level of design information, and would be undertaken as part of a PAB system design.

After selecting the list of instruments we calculated the expected size of a fully-deployed system. We used the optical telescope areal density that is being projected for the NGST mission (10 kg/m²), and “rule-of-thumb” type spacecraft sizing rules [22] for structure and subsystems. These rules are based on conventional spacecraft designs, and will be conservative for PAB. Instrument packages (electronics, etc) were sized at 100 kg each (200 kg for aperture synthesis). Total spacecraft (dry) was massed using (payload x 3.3), and additional allocations were then made for fuel (25%) and margin (30%). Robots were massed at totals of 1400 kg for explorers and 3200 kg for robotic servicers, plus a station allocation (25%) for robotic support, e.g., docking and berthing fixtures. This results in a total mass on-station (for each of JL and JL5) of ~30 000 kg. We feel this is very conservative since it does not take advantage of advanced lightweighting technologies. We expect it can be reduced ultimately by at least a factor of 2, and should be viewed as an estimate only. Note that this

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7 Current ephemeredes, tables, and related data for asteroids, including Trojans, can be obtained from the Minor Planet Center at http://cfa-www.harvard.edu/iau/lists/MPLists.html.
8 Robotic explorers are massed at 700 kg each, based loosely on 2x the STARDUST [55] spacecraft mass, and assuming 2 per Lagrange point; servicers are massed at 800 kg each based on an early concept for space station servicers called SPDM [56], which is probably the closest analog to a servicer that would be needed for PAB. We assumed 4 service robots per Lagrange point.
number is calculated based on a set of free flyers, i.e., each instrument hosted in a different spacecraft. Basing considerations and station design are discussed in more detail below. A figure showing mass estimates for the individual system elements is shown below.

![PAB System Mass Estimates](image)

*Figure 15. Estimated mass on-station for a baseline PAB configuration.*

Telescope systems for PAB will likely be large reflectors with effective diameters of 10-100m. Fast primaries with focal ratios approaching f/1 should be possible, although much longer focal lengths will be needed for some applications. Primary mirrors will utilize low mass optics and backing structure technology, possibly based on advanced inflatables. Very advanced concepts such as those of Bekey [6] do away with supporting structures altogether and use inflatable primaries, with the secondary mirror systems and instrument packages contained in a separate free-flyer. Figure 16 shows an artist’s concept of an advanced free-flyer telescope.
For telescopes in this class, the primary and backing structure will dominate the host spacecraft bus in size. A spacecraft design rule of thumb [22] sets volume in m$^3$ at 1% times mass in kg. A 20m deployable reflector might have a mass (primary + structure, NGST areal densities) of 3000 kg. A 1000 kg mass for the host spacecraft and instrumentation would result in a package on the order of 10 m$^3$ in volume, and thus significantly smaller than the primary. This could present some design challenges when the telescope is used as part of a very-long-baseline interferometer system. Metrology, science data, and system status information would need to be continuously communicated between separated telescopes, even as the line of sight is moved to observe different target objects. The communications antenna (optical or RF) would most likely be attached to the host spacecraft structure, and thus shadowed by the much larger primary under some viewing conditions. This is a solvable problem, but may result in some design impacts for inter-spacecraft metrology systems. Issues of this type will need to be addressed in more detailed studies, with specific telescope design characteristics, dimensions, and layouts.
Environments

Environments at the Lagrange point will be generally benign. Although space probes such as Galileo have had to contend with high levels of radiation and particles, these are due to the local environment resulting from Jupiter, its magnetosphere, and its interactions with Io. In general, we do not expect radiation and thermal control to present challenging technical issues.

Micrometeroids could potentially be higher at the JLx points. The standard NASA meteoroid model predicts a relatively low flux at Jupiter’s orbit, but that does not account for a higher population of small particles due to asteroidal collisions. There is some evidence for long-term collisional evolution of the Trojan asteroid population [14]. Also, there is a known higher density of small particles in main belt asteroid collisional groups; therefore, one might expect the same result for the Trojan groups, implying that the NASA models significantly underestimate the meteoroid flux. A detailed study of the local environment would be one question to be resolved by a PAB precursor mission.

Because of the extreme levels of precision to which we will need to measure distance and angle, effects which might be small for traditional spacecraft might be very serious for PAB. For example, buffeting due to residual gas molecules and fluctuations in the solar wind, and well as from micrometeoroids, may present significant disturbances.

We used the PAB system sizing model together with a set of environmental disturbances to derive small-scale gravitational and non-gravitational forces which may drive stationkeeping requirements for the PAB stations. The effects are in general quite small. A summary of space environmental data for the Jovian orbit, together with the details of disturbance calculations, are given in Appendix III.

A calculation of the required $\Delta v$ (impulsive velocity change) needed to maintain station shows it to be quite reasonable, less than 0.01 m/sec per day. It is quite likely that these requirements can be met with frequent, low thrust impulses from ion engines or similar low-thrust devices. A somewhat larger $\Delta v$ would be needed periodically to “truncate” libration orbits to keep them from extending too far in longitude; however, we estimate this to be on the order of 15 m/sec per year which is again quite reasonable. Based on the (u,v) coverage analysis discussed above for a single configuration, orbital adjustments of this type would take place periodically on timescales from one year to a few years.

Other potential impacts which are, strictly speaking, not due to “environment” but which will have system effects are the aberration of starlight (velocity-induced angular deflection of light) and the gravitational bending of light by the sun. The differential angle due to aberration of starlight can be as large as 60 microradians at Jupiter’s orbit (for stations at JL4, JL5 pointed at the same object), and varies
with angle relative to the orbital velocity vector. Gravitational bending of starlight varies with angle from the sun; at 90 degrees it is approximately 10 nanoradians [23].

Table III. PAB stationkeeping disturbances and requirements.

<table>
<thead>
<tr>
<th>SMALL-SCALE DISTURBANCES:</th>
<th></th>
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<tbody>
<tr>
<td>-- METEOROID FLUX</td>
<td>(10^{-5}) N</td>
</tr>
<tr>
<td>-- RESIDUAL GAS</td>
<td>(10^{-10})</td>
</tr>
<tr>
<td>-- SOLAR WIND</td>
<td>(10^{-6})</td>
</tr>
<tr>
<td>-- RADIATION PRESSURE</td>
<td>(10^{-5})</td>
</tr>
<tr>
<td>-- COSMIC RAYS</td>
<td>(10^{-9})</td>
</tr>
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</table>

<table>
<thead>
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<th>GRAVITATIONAL PERTURBATIONS:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-- SATURN,</td>
<td>(10^{-7}) m/s²</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>SMALL-SCALE METROLOGICAL EFFECTS:</th>
<th></th>
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</thead>
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<td>-- STELLAR ABERRATION</td>
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</tr>
<tr>
<td>-- GRAVITATIONAL BENDING OF LIGHT</td>
<td>(10) prad - 0.1 (\mu)rad</td>
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<table>
<thead>
<tr>
<th>DELTA-V REQUIREMENTS</th>
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<tr>
<td>-- ORBIT ADJUSTMENT (~1/YR)</td>
<td>(~15) m/sec/yr</td>
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<td>(LIBRATION TRUNCATED)</td>
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Technology

PAB will require technology advances in several areas. Key among these are: designs and materials for large, lightweight deployable telescopes; advanced techniques for separated spacecraft interferometry; position and timing metrology; electronics, data handling, and communications systems; and autonomous spacecraft operations. Technology needs and prospects for meeting them in selected areas are discussed below.

Large Optics

A number of groups are currently working on 10 – 100m class optics for spaceborne applications, and technologies being developed include low-mass glass optics with lightweight backing structures, inflatables, and even large refractive “Fresnel lens” type optics. There are a number of significant technical issues involved with all approaches. Inflatable optics look to be the most promising in terms of low areal density, but at the present time are limited to a few meters in diameter and do not possess surface qualities anywhere near that needed.

Research currently underway on large (> 10 m-class) space optics includes the following:

- Bekey [6], in a NIAC Phase I study, developed a concept for electron-beam corrected inflatable primaries with additional levels of correction in the secondary optics; total telescope areal densities, including all structures, spacecraft systems and instrumentation, were estimated to be approximately 0.1 kg/m². The technology is expected to scale to apertures as large as 125 m.
- A group at Lawrence Livermore National Laboratory (LLNL) has been investigating Fresnel (transmissive) lens technology for 50m class telescopes under the “Eyeglass” program [24]. Telescope areal densities (optics + structure) are projected to be about 5 kg/m². There are plans to test a 1m subscale version of the technology at LLNL.
- Angel, Burge, and Woolf have proposed the use of coherent arrays of flats to build up a 100 m filled-aperture telescope [25]. Individual elements would be flat mirrors of up to 5m in diameter, positioned and tilted as subapertures on the parabolic surface of a larger mirror. They propose that the same approach can be used to develop a large nulling interferometer (like TPF) for exosolar planet detection.

A number of other potential methods for constructing large space telescopes are being investigated under the Gossamer Telescope Initiative fostered by NASA [26]. It seems likely that apertures exceeding 10m, and up to at least 100m with optical quality surfaces will become feasible within a 20 year timeframe.
Separated-spacecraft interferometry and positional metrology

There are two interrelated metrology issues which must be considered for separated-spacecraft interferometry. This first is the requirement to control or measure spacecraft relative positions to relatively “tight” levels of precision. The second consideration involves methods for forming interferometric fringes (or some equivalent measure of relative phase or fringe visibility) across long distances between free-flying platforms.

In current ground-based experiments, interferometry has been limited to path lengths on the order of 100 m [27]. Near-term space experiments [28,2] will demonstrate optical interferometry using both free-flying and monolithic interferometers, but pathlengths will be much shorter than those needed for PAB. Current plans under NASA’s “Origins” program (and similar plans by the European Space Agency) call for development of free-flyer interferometry on scales up to perhaps 6000 km separation. PAB will require interferometry at distances 3 orders of magnitude longer.

In free-flyer interferometry concepts proposed to date, extreme dynamic measurement and control ranges are avoided by separating the problem into a spacecraft positioning component and an interferometer component. Spacecraft positions are controlled to centimeter or millimeter levels of accuracy (which is still many optical wavelengths), and a separate path-length control system is used to match path-lengths between the individual apertures and an optical combiner system to within fractions of a wavelength. The pathlength control system or optical delay line will have a total range of travel consistent with the spacing requirements for spacecraft, and may itself be a multistage device with both coarse and fine levels of position control.

Methods have been developed, at least conceptually, for precise measurement of both distances and angles between spacecraft at PAB-like (or greater) distances. The LISA project (gravitational wave detector) has developed a metrology concept for measuring inter-spacecraft distances at sub-Angstrom precision across distances of $5 \times 10^9$ m (about 0.03 AU), using laser interferometry between spacecraft [16]. Yu et. al. [29], for the LATOR concept (Laser Astrometric Test of Relativity), proposed an interferometric method for measuring angles between two spacecraft in an earth-radius, heliocentric orbit (on the opposite side of sun from earth) to an accuracy of 0.2 microarcsecond (1 picoradian). Their concept would use a laser at each spacecraft as an astrometric source whose position would be precisely measured with a small-aperture, narrow-angle interferometer. Laser ranging using a modulated laser signal would be used for spacecraft distance measurement from earth. Laser transponders with decimeter ($10^{-1}$ m) accuracy over planetary distances are possible with current technology [30]. Radio doppler methods might also be used for ranging, with somewhat lower levels of precision.
Use of precision range measurements between two widely-separated spacecraft would establish the placement of either one (as seen by the other) within a cone about the nominal line of sight, with the spatial radius of the cone determined by the range and line of sight errors. If the range is measured by a time-of-flight technique the radius of error about the nominal line of sight will be governed by the time reference accuracy; for .01 AU displacements the radius of error will be \(\sim15\text{cm}\) at a timing accuracy of 1 nsec, and proportionally smaller as the timing accuracy increases. Measuring the range to a few 10s of wavelengths would be sufficient to bootstrap a higher-accuracy interferometric technique into operation. Timing accuracies on the order of \(10^{-13}\) seconds could achieve this.

Alternatively, timing-based methods alone could conceivably measure interstation distances directly to subwavelength accuracy. The required resolution would be on the order of \(10^{-15}\) seconds, for a 1 micron wavelength; this is about 10x better than the best current laboratory result, but looks likely to be achievable by (or before) 2040, based on current clock technology [31,32]. However, relative displacement of the PAB stations from idealized positions will be small and occur at fairly low rates of motion. Therefore, separation of interferometer metrology into coarse (spacecraft-level, \(\sim\)cm accuracy) and fine (optical-level, sub-wavelength accuracy) components appears feasible even for PAB aperture synthesis distances. If necessary, additional intermediate stages of metrology could be used.

Aperture synthesis for PAB may require a radical departure from current techniques. Combination of wavefronts or other phase-preserving information to form an interference pattern will be challenging. We see four general methods of interfering beams from two or more separated apertures: direct beam combination in the optical domain (the conventional method); heterodyne methods based on use of a local oscillator (such as those reported by Townes et. al. [33]); external-referencing methods, where a strong source in or near the field of interest is used as a phase reference; and direct phase measurement using optical control devices and related techniques.

Direct beam combination is obviously the most straightforward approach. Current plans for ST3 and separated-spacecraft variants of more advanced interferometers (such as TPF and DARWIN [34]) call for the use of a central “combiner” spacecraft which receives beams from outlying collector apertures. For the distances involved with PAB, this is possible although the relay optics must be made relatively large to prevent serious signal losses from diffraction as the beams are propagated to a combiner spacecraft. For example, a 1 micron beam reflected off of a 100m flat would have diffraction beam spreading \((\lambda/D)\) on the order of \(10^{-6}\) radians, and would grow by \(\sim40\) m in diameter after propagation across 0.01 AU. Although there are likely methods to mitigate this effect (for example, the use of phased optical arrays to reduce diffraction spreading) they induce additional complexity, size, mass, and cost into the system.
Because of the baseline lengths and light-travel times involved, direct combination of wavefronts may be impractical, so we envision that a solution to this problem will entail some type of wavefront recording, with very precise time precision and accuracy, and a post-processing combination of recorded wavefront data (both amplitude and phase).

Heterodyne interferometry has been practiced from earth-based sites for some years, and this is an obvious solution. However, as currently practiced, heterodyne interferometry requires a narrowband laser reference source as a local oscillator. Limiting the passband of the source light to a relatively narrow band causes a severe decrease in efficiency, thus restricting application of the technique to brighter sources. Electro-optical control devices and other phase-sensitive modulators generally have somewhat similar passband restrictions, although possible implementations must be evaluated on a case-by-case basis.

It may be possible to use an external reference source – a bright star, for example – as a phase reference. The concept here is to split the reference light into two equal parts, one of which is delayed by sending it down a path with an additional, known phase delay introduced. The parts are then recombined, and a fringe pattern formed on a detector array. Movement of the fringe pattern then indicates a change in the relative phase of the incoming wave at the collector aperture.

An alternative method of interferometry is intensity correlation interferometry, a long-overlooked method that relies on correlations between the amplitude fluctuations measured at two or more displaced apertures [35]. It does not require high-quality optical surfaces, and position metrology is much less demanding than for conventional interferometry. As a consequence, it will support the use of long baselines with simple “light bucket” types of collection optics, and very “loose” positioning tolerances. Although phase information is lost with this method, it may be retrievable with phase closure methods.

Positional metrology for astrometry will not, in general, be as stressing as for interferometry. As noted above, station position knowledge to ~10 m accuracy will support precision astrometry and astrometric depth sensing.

**Electronics**

PAB will require significant advances in electronic systems. In addition to normal spacecraft control functions, significant amounts of data will be captured and communicated to earth. Data management will likely incorporate on board signal processing, data storage, compression and forwarding. For most science applications, we expect that technology advancements due to missions already planned will result in processing technology to meet PAB needs. NGST, SIM, and TPF will each result in significant advancements in processing throughput. Computers for system metrology will need to handle measurements with very
large dynamic ranges due to the long ranges and high levels of precision required.

A potential special case arises in the event of direct optical phase measurements to support aperture synthesis. A simple scaling of current technology using the well-known Moore’s law would predict (for the year 2040) single CPUs with 15 Trillion processors per chip and clock speeds up to 16 THz. Conversion of optical phase measurements to the electrical domain would, however, impose a requirement to process data at clock rates of 300 – 6000 THz (depending on the wavelength used)\(^9\). In this case, the trade between optical-domain interferometry data processing and conversion to electrical-domain processing is very significant; it will drive the selection of direct beam combination vs. heterodyne or wavefront recording methods of interferometry.

Station-station and station-earth communications will require extremely high bandwidths, and will likely utilize optical communications. We expect that laser-based optical communications at levels needed to support PAB operations will be available within a few years.

**Robotics and Spacecraft Autonomy**

The idea of a long-term deployment leads to the concept of advanced robotics and spacecraft autonomy for long-term maintainability. Fundamentally, the combination of unmanned systems, remote locations, and long light-travel times will combine to drive the need for advanced robotics and spacecraft autonomy for PAB systems. Specific system-level needs will be as follows:

- Observation scheduling must be adaptable to system failures and other unexpected problems.
- PAB systems must be self-diagnosing, with high levels of health and status information available continuously, and with troubleshooting procedures available on demand. Fault diagnosis procedures and results must be reported to Earth for further evaluation.
- PAB must have some level of self-repair. The ability to replace failed instrument subsystems will prevent loss of mission systems over time.
- Under normal circumstances, some level of self-servicing will likely be needed, even in the absence of unexpected failures. Individual instruments may need to be realigned or optical surfaces cleaned, and some spacecraft systems may need routine servicing.
- One possible implementation of PAB is with monolithic stations (or monolithic/free-flyer hybrids) that are expandable to add new instruments

\(^9\) In addition, space qualified (rad-hard) hardware typically lacks the best commercial electronics performance by several years.
over time. Robotic installation, alignment, and calibration would be needed.

On-board electronics will need a robust and comprehensive suite of intelligent behavioral features, including:

- Automated task planning
- Intelligent data preprocessing and routing
- Intelligent data compression, packaging, and communications
- Fault-tolerant communications monitoring and diagnostics
- Spacecraft and instrument subsystem health and status monitoring
- Spacecraft and instrument system self-test, fault-detection, and diagnosis
- Automatic fault-induced switching of redundant systems
- Advanced methods of system safing and self-recovery
- “Self-repair” or “self-healing” of failed (non-moving) electronic systems

PAB will need mobile robotic servicers at each system site, to aid in long-term maintenance. These robots will need all of the self-diagnosis and fault-tolerance attributes of on-board systems, plus specific additional attributes to enable system servicing:

- External system inspection; image-based situational awareness, scene classification, and anomaly detection; cameras, lighting, and other sensors for system inspection
- Autonomous navigation and local platform maneuvering; collision hazard assessment and prevention; trajectory planning
- Automated docking, grappling, and berthing
- Module grasping, manipulation, alignment
- Fluid transfer and refueling
- Specialized manipulator subsystems for specific instrument services

Most, if not all, of the features listed have been proposed in recent years for various advanced unmanned and manned missions. Specific spacecraft autonomy experiments have already been performed on the Clementine [36] and DS1 [37] missions. A number of other missions under consideration by NASA for future solar system exploration will require autonomy features not currently available. Autonomous navigation and local exploration for comet, asteroid, and Mars sample and return missions will develop some of the sensors and processors necessary to support situational awareness and planning, as well as advanced manipulators [38]. Automated rendezvous, docking, and berthing are currently areas of research supported by both NASA and the DoD community.
Advances in manipulator technology for spacecraft servicing will likely be driven, in the near-term, by robotics systems developed for the International Space Station (ISS) [39]. The most significant difference between ISS capabilities and needs for highly autonomous systems such as PAB lies in the use of telerobotics. PAB systems would not be amenable to telerobotic servicing, as currently envisioned, due to long light-travel times (hence, system delays and latencies). Some level of supervised autonomy may be possible, and in fact desirable, but it will require a much higher level of autonomous operation on the part of the remote system.

Most of the robotic system attributes needed to support PAB, as we envision it, will be developed to support other programs and missions. There is currently no single mission which would combine all of these attributes, and in fact such an undertaking would represent a very advanced robotic program. However, we expect that most if not all of the component and subsystem technologies will be available within two decades.

**Other Technology Areas**

Power needs for PAB present a unique but not insurmountable problem. Solar power at the Jovian orbit is seriously reduced (50 W/m² total), so that advanced power generation technology will be needed. We have assumed that radio-isotope thermoelectric generators (RTGs), which have been used on all previous outer solar system missions, will not be available in the future due to environmental and/or political considerations. It may be possible to beam power from earth-based or earth-locus lasers to receivers located at the PAB stations. A second, more likely possibility is to simply rely on solar power and use large inflatable concentrators to increase the effective area of collection\(^{10}\). For example, simple scaling of the HST array size to the solar irradiance levels at 5.2 AU gives a size of 1250 m² for HST levels of power. Assuming this level of power for a PAB large-aperture telescope results in an array or concentrator about 1/3 the size of the telescope itself.

Advances in spacecraft pointing, instrument line-of-sight stabilization, and tracking will be needed to support advanced narrow-angle astrometry and aperture synthesis. Environmental disturbances will be small, but buffeting from residual gas molecules will couple into platform jitter. There will also likely be some level of spacecraft subsystem-induced motion and vibration; for picoradian-level angular measurements even these small effects must be taken into account. It is difficult to assess the level of impact without more detailed design information; however, we note that SIM, NGST, and TPF will face similar

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\(^{10}\) This concept has been previously considered as part of an architecture study for the TPF mission [41].
problems. A more detailed investigation of these effects would be part of a follow-on study.\textsuperscript{11}

**Technology Expectations**

PAB will have significant synergism with current and planned NASA programs, and with other current areas of research including several previous or ongoing NIAC studies. As the above discussion will show, there are key technology areas that will need development for PAB; however, within the notional 10-40 year time horizon of the NIAC philosophy, most of these will reach or approach the functional and performance levels needed.

Technologies relating to large-aperture deployable optics and separated spacecraft interferometry will be key to PAB, and significant advancements will be needed here. Recommended technology “push” areas include the following:

- Large, lightweight deployable optical elements with apertures of 100m
- Novel methods of optical interferometry using direct optical phase measurement, broadband heterodyne techniques, or other methods which do not rely on direct beam combination would be significant enablers; an alternative is improved methods of direct beam combination over million-kilometer distances
- Advanced clocks and timing systems with precisions up to $10^{-15}$ seconds
- THz-speed electronic processing
- Advanced autonomous robotics for independent spacecraft operations

Figure 17 shows a technology “roadmap” for some of the key technologies that will be needed to support PAB development. The individual technology items are grouped into four broad categories which overlap somewhat, and they were developed from lists we made as part of the technology assessment process detailed above. The color code shown (green, yellow, red) is meant to distinguish between those items where known programs or missions will develop the technology, those where development is likely (i.e., based on a continuation of current trends, but without a tie to a specific program or mission), and those where development is possible but uncertain. Approximate timeframes for the various technology items were obtained either by reference to specific missions or to general technology plans and roadmaps published elsewhere (such as those for NASA’s Origins and Solar System Exploration [38] programs. Timeframes for development are necessarily “fuzzy”, and performance levels for the individual items are not quantified; this map should be viewed as only a general guide.

\textsuperscript{11} An ultimate limit to angular resolution may be driven by quantum limits for jitter: an analysis by Weiss [40] for gravitational wave detection systems suggests that angular jitter at the optical component level may reach a floor at levels on the order of $10^{-15}$ radians. This is, fortunately, well below the levels needed for this concept.
A precursor mission for PAB is a near-term possibility. A detailed exploration of the environment at one of the JL points would provide measurements of the local environment, and could provide a more precise survey of the local asteroid population (including dust and meteoroids). A close investigation of one or more Trojan asteroids would have significant scientific interest. Such a mission is well within NASA’s near-term capabilities. A more ambitious type of precursor mission could demonstrate ultra-long-baseline optical interferometry using a pair of subscale telescopes in a halo orbit at one of the JL points. With advanced lightweight telescope technology and 10m class apertures such a mission is probably within the lift capabilities of a single launch.
Exosolar Planet Detection

PAB offers some advantages for exosolar planet detection. Both indirect and direct methods of planet detection can be implemented with the PAB architecture. Indirect methods include astrometric detection via small-angle motion of the parent star about its barycenter, as well as planet-induced microlensing of the parent star. Using narrow-angle astrometry, we can get two components of the reflex motion measured from the two primary sites (JL4, JL5). This would not allow for direct imaging but would be a useful technique for extending our “planetary census” out to further distances in the galaxy. In this regard, a well-sampled database of stars with known planets would provide statistical data for understanding the formation of planets around stars, as well as a larger catalogue of candidate objects for further study, including imaging.

Detection of an earth-sized planet at 1AU from a sunlike star, at a distance of 1 pc, would result in a 16 prad astrometric deflection, within the capabilities outlined above for PAB astrometry. The deflection scales directly with range.

Aperture synthesis from PAB sites can potentially be used for imaging of exosolar planets. A 0.01 AU interferometer (using halo orbits librating about JL4 and/or JL5), working at 10 microns, could resolve earth-sized objects at distances of 30000 light-years. This is a truly breathtaking possibility for imaging of other planets. However, as with other exosolar planet-imaging approaches, excess background light from the parent star (which would be about 10$^7$ brighter at 1 micron, and 10$^4$ times at 10 microns, for a sunlike star) must be rejected since it would obscure the planetary image [42]. This could be mitigated by use of nulling-interferometer concepts like those currently being studied for the Terrestrial Planet Finder mission. Nulling technology is not well developed at present, even for earth-based interferometers, and further work needs to be done to determine modifications that would allow it to work with the long-baseline free-flying interferometers we have proposed for PAB.

The JL points could also provide a suitable location for other types of planet detection instruments, such as large-aperture coronagraphs or occultation systems.
Summary and Conclusions

Although many outer solar-system missions have been proposed over the years, to our knowledge this is the first study to recommend the use of the Jovian Lagrange points.

Use of the Earth-Sun Lagrange points has been often been considered or planned for a number of missions [43]; currently the SOHO instrument is operated at the L1 point. Several future missions are planned or under consideration for one or more of the Earth-Sun Lagrange points, including the Next Generation Space Telescope (NGST).

The moon has been considered as a site for astronomical uses, but has not yet been exploited except for the short-duration Apollo missions. The moon has advantages for long-baseline work but also has potential problems. It has a generally very stable seismic environment, and its position is very well known. However, an instrument on the surface would undergo significant thermal extremes during the lunar day/night cycle. The rotation rate offers long observation times but a fixed location would restrict observations to limited regions of the sky. There is a possibility than lunar dust could be a significant contamination source [44].

Other mission concept studies (e.g. TRISOPS [45]) have looked at exo-zodiacal or exoplanetary missions. Mallove & Matloff [46] suggest using the long baseline formed by an interstellar ship and the solar system to do optical and radio interferometry during the coast phase of an interstellar flight. They also mention gravity-wave detection as a possibility, as well as detection of unseen solar companions and brown dwarfs thru gravitational perturbations of trajectory.

PAB has advantages over inner solar system Lagrange points (longer baselines, lower angular tracking rates, larger regions of stability), the lunar surface (fewer environmental impacts, less variability) and exo-solar system missions (constant baseline, fixed locations). PAB also differs from traditional space missions in that it is not a single mission: it is an astronomical observatory, distributed across planetary-sized scales of space and time. While it is possible to consider single, finite-duration missions to the JL points (as we have proposed above for a precursor mission), the long-term development of PAB should be undertaken with the intent of permanent presence in mind. In our view, the Lagrange points – integral features of our solar system -- should be viewed not as destinations but as sites.

The long-term development of the PAB concept is open to many further ideas. We believe that we have barely scratched the surface of what might be accomplished.
Appendix I. Limits on Separated-aperture interferometry

A. Area-time product

We wish to determine the area and integration time required to capture interferometry data from a resolved, extended source. For simplicity, we will use a pairwise interferometer, i.e., two apertures of the same diameter D working across a baseline L. [In the case where the direction to the source is not perpendicular to the baseline, the projected baseline (= L cos θ) is used.]

In order to maintain a decent signal-to-noise ratio, assume we want a reasonable number of detected photoelectrons \(N_{pe}\) in each sample. The basic equation which describes the collection process at each telescope is:

\[
H_\lambda \cdot \Delta \lambda \cdot \alpha^2 \cdot A \Delta t \cdot T_{sys} \cdot \eta \cdot \frac{\lambda}{hc} \geq N_{pe}
\]

where \(H_\lambda\) is the Planck spectral radiance of the resolved object (assumed a blackbody) in Watts per square meter per micron per steradian; \(\lambda\) is the mean wavelength of detection; \(\Delta \lambda\) is the spectral width of the optical passband for detection; \(\alpha\) is the interferometer resolution, in radians; \(\Delta t\) is the integration time per sample in seconds; \(T_{sys}\) is the optical efficiency of the telescope and collection optics; \(\eta\) is the quantum efficiency for detection; \(h\) is Planck’s constant and \(c\) is the speed of light. \(A\) is the collection area of the telescope, and \(N_{pe}\) is the required number of photoelectrons per detection.

The telescopes will have a finite field of view which will be equal to \(N_r \alpha\), where \(N_r\) is the number of resolution elements spanning the field. In order to maintain coherence between the two apertures we must jointly limit the field of view and passband so that (field of view \(x\) baseline) is less than or equal to the coherence length of the incident wave. This results in

\[
\frac{N_r \lambda}{L} \cdot L \leq \frac{\lambda^2}{\Delta \lambda}
\]

where \(\lambda^2/\Delta \lambda\) is the coherence length [xx] and where we have replaced \(\alpha\) by

\[
\alpha = \frac{\lambda}{L}
\]
Then

\[ N_r \leq \frac{\lambda}{\Delta \lambda} \]

and we can substitute for the Planck function \( H_\lambda \):

\[ H_\lambda = \frac{2hc^2}{\lambda^3 \left(e^{\frac{hc}{\lambda kT}} - 1\right)} \]

where \( k \) is Boltzmann’s constant. We lump \( \eta \) and \( T_{sys} \) together:

\[ \eta \cdot T_{sys} \approx \frac{1}{2} \]

and simple rearrangement of terms then gives

\[ A \Delta t \geq \frac{N_{pe} N_r L^2 \lambda}{c} \cdot \left(e^{\frac{hc}{kT}} - 1\right) \]

where \( T \) is the blackbody temperature of the source object.

We refer to the quantity \( A \Delta t \) as the area-time product, since it sets a joint minimum collecting area and integration period to achieve the required signal-to-noise ratio. \( N_{pe} \), the number of detected photoelectrons, must be at least 1, and desirable signal levels will in general be much larger. \( N_r \), the number of resolution elements spanning the field of view of a detector may be much larger than \( 1^{12} \); the area-time curves shown in Figure were generated using \( N_r \) and \( N_{pe} \) each equal to 100. \( N_{pe} \sim 100 \) is a reasonable limit since it would result in a maximum SNR of 10 (with signal shot noise only), whereas \( N_r \sim 100 \) may be somewhat ambitious since it will result in very small detector instantaneous fields of view (or, equivalently, very long effective focal lengths). Setting both \( N_r \) and \( N_{pe} \) equal to 1 will give an absolute physical limit to the area-time product, whereas the combination of \( N_r N_{pe} \sim 10^4 \) is a likely realistic limit.

Integration time limits may also be calculated so that required aperture sizes may be determined. Using separated-aperture interferometry, where each telescope is located on a free-flying platform, the effective baseline will rotate as the two platforms move in their orbits, and the projection of this baseline in the direction of the source will change in length unless the source is located in a direction

---

\(^{12}\) Note that achieving \( N_r = 1 \) results in the object being resolved (at the desired resolution level) by the angular extent of the detector, i.e., no interferometry is necessary!
perpendicular to the plane of the orbit. The worst-case rate of change of the projected baseline will occur when the source lies in the plane of the orbit. In addition, the length of the baseline may change.

We wish to limit the effective change in the resolution so that

$$\Delta \alpha < \alpha_0,$$

$$\alpha_0 = \frac{\lambda}{L_0 \sin \theta}$$

where $\alpha_0$ is the original resolution and $L_0$ is the original baseline. Differentiating, we get

$$\dot{\alpha} = -\frac{\lambda}{L_0^2 \sin \theta} \dot{L} - \frac{\lambda}{L_0 \sin^2 \theta} \cos \theta.$$ 

or, since we wish to know the magnitude only at this point,

$$|\ddot{\alpha}| = \frac{\lambda}{L_0 \sin \theta} \left( \frac{\dot{L}}{L_0} + \frac{\dot{\theta}}{\tan \theta} \right),$$

or approximately

$$|\ddot{\alpha}| = \frac{\lambda}{L_0 \sin \theta} \left( \frac{\dot{L}}{L_0} + \frac{\dot{\theta}}{\theta} \right).$$

Now, if we limit the change in resolution over an observation time to a small fraction of the initial resolution, $\alpha \Delta t < \alpha_0 / M$ (where $M$ is $\sim 20$), then

$$\Delta t < \frac{1}{M} \left( \frac{\dot{L}}{L_0} + \frac{\dot{\theta}}{\theta} \right)^{-1}.$$ 

For librating orbits about a Lagrange point we can, to first order, neglect the differential motion due to libration since it is small compared to the orbital motion and period of the parent body. This simplifies the result considerably since now we let $\dot{L} \Rightarrow 0$; substituting also $\omega = \theta = 2\pi / P$, where $P$ is the orbital period, and with $\theta$ nominally $= \pi/2$ (i.e., source perpendicular to the baseline) we have

$$\Delta t < \frac{P}{4M}.$$ 

This shows that orbits with longer periods have a clear advantage in observation time. Since we have suggested $M = 20$ as a reasonable limit (i.e., baseline change is limited to 5% of the initial baseline), the approximate limit to an observation time is $1/80$ or about 1% of the parent-body period, in round numbers.
The time required for the optical path difference between two apertures to change is also of interest. In the case of an interferometer using direct beam combination, this will set the rate at which a phase delay must be changed for one of the beams. For platforms in a heliocentric orbit, viewing a source at an angle $\theta$ with respect to the baseline and $\phi$ with respect to the plane of the interferometer, the change in phase delay between two apertures is

$$\tau_p = L \cos \theta \cos \phi$$

where $L$ is the baseline. The rate of change of the delay, assuming no net change in $L$ over small time durations, is

$$\frac{d\tau_p}{dt} = -L \cos \phi \sin \theta \frac{d\theta}{dt} ;$$

and we wish to calculate the time $\Delta t$ for the delay to change by one wavelength:

$$\frac{d\tau_p}{dt} \Delta t \leq \lambda .$$

We solve to get

$$\Delta t \leq \left| \frac{\lambda \cdot P}{2\pi L \cdot \cos \phi \cdot \sin \theta} \right|$$

where $P$ is the orbital period. The limiting case can be determined by setting $\phi = 0$ and $\theta = \pi/2$. We have replaced $\theta = 2\pi / P$ where $P$ is the orbital period, as above.

A similar result can be simply derived for the case of libration orbits about one of the Lagrange points. The librating motion about the Lagrange point is clockwise versus the normal counterclockwise orbital motion of Jupiter in its orbit, when viewed from the North ecliptic pole. Therefore, the motion of libration subtracts slightly from the normal orbital motion, resulting in a slightly slower rate of change (roughly 10% for the JL points). The revised expression is:

$$\Delta t \leq \left| \frac{\lambda}{L_{LIB}} \cdot \frac{1}{(\omega_{LIB} - \omega) \cdot \cos \phi \cdot \sin \theta} \right|$$

where $\omega_{LIB}$ is the angular rate of the libration orbit alone ($P_{LIB}/2\pi)^{-1}$ ($P_{LIB}$ is its period), and $\omega$ is the rate of the heliocentric orbit, $(P/2\pi)^{-1}$. $L_{LIB}$ is the baseline between the libration pair.
Calculations of the fringe period may be done given the baseline length \( (L, \text{ or } L_{\text{LIB}}) \) and the orbital period. Results for the Jovian, Earth, and Martian Lagrange points give the following:

\[
\begin{align*}
\text{JLx} : & \quad 250 \text{ nsec} \\
\text{MLx} : & \quad 40 \text{ nsec} \\
\text{ELx} : & \quad 21 \text{ nsec}
\end{align*}
\]

For this calculation the baseline length for each of the libration orbits was assumed to be equal to its maximum radial width, set by the limiting gravitational stability of the orbit (see Appendix II below). As the libration orbit evolves the separation between the elements will increase, and the fringe period will decrease.

**B. Range reach for interferometers**

A different, but equivalent, method of assessing interferometer performance is to examine whether the overall efficiency of the system is sufficient to detect objects of interest at ranges where they can be resolved. We refer to the “range reach” of an interferometer, and analyze it from two perspectives: radiometric range reach (which is determined by the source object and the optical system size and performance), and resolution range reach, which is determined by the baseline and working wavelength. For objects of the type we are interested in studying, the two should be roughly equal, so that the system can detect as far as it can see, and vice-versa.

The radiometric range reach of the system is determined by computing the distance at which the photon flux falls to a threshold value. Our analysis uses stars as source objects.

The radiometric flux in photometric band X for a star of apparent magnitude \( m_x \) is

\[
f_x (m_x) = f_{0x} \cdot 10^{-0.4 m_x}
\]

where \( f_x \) is the photon flux in band and \( f_{0x} \) is a “zeropoint” factor which gives the photon flux for a star of apparent magnitude 0 in that band [53]. The apparent magnitude may be determined from an absolute magnitude \( M_x \), which can be related to stellar type and class and distance:

\[
m_x (M_x, d) = M_x - 5 + 5 \log d
\]

where \( d \) is the distance to the star. The photon flux at a detector is then given by
\[ p_X(m_x,D) = f_x(m_x) \cdot F(D,\lambda_{0x}) \]

where \( F(D,\lambda_{0x}) \) is an efficiency factor which converts photometric flux to detected photon flux.

The absolute magnitude of a star of a given type in photometric band \( X \) can be obtained from

\[ M_X(type, class) = M_V(type, class) - (V - X) \]

where \( M_V \) is the absolute visual magnitude of the star and the term \((V - X)\) is a photometric magnitude correction from the visual band to band \( X \). Values of \( M_V \) and \((V - X)\) for various stellar types and classes may be obtained in a number of handbooks (such as Zombeck [53]).

Setting \( p_X(m_x,D) \), the detected photon flux, \( = 1 \) photon per second, we solve for the log of distance as a function of the star’s absolute magnitude, type, class, the photometric band being used, and the optical system, as:

\[
\log d = 0.5 \cdot [\log(f_{0x}) + \log(F(D,\lambda_{0x}))] + 0.2 \cdot [(V - X) + 5 - M(type, class)]
\]

which can then be used to compute the range \( d \). The efficiency factor \( F(D,\lambda_{0x}) \) is

\[
F(D,\lambda_{0x}) = \frac{\lambda_{0x}}{2} \cdot \frac{\pi D^2}{4} \cdot (\eta T_{sys}) \cdot \frac{\lambda_{0x}}{hc}
\]

where the term \((\eta T_{sys})\) may be set \( \sim 0.5 \) as before.

The range computed for radiometric reach must be compared to the resolution reach, which is the range at which the object’s size is equal to 1 resolution element of the interferometer system. This is simply given by

\[
d_{res} = \frac{R(type, class) \cdot L}{\lambda_{0x}}
\]

where \( R(type, class) \) is the radius of a prototypical star. Typically stellar radii are given relative to the solar radius.
Appendix II. Libration orbit modeling

The maximum radial width of a stable libration orbit about a single Lagrange point is given as:

\[ \tau_{\text{lib}} = \frac{M_p}{\sqrt{M_{\text{SUN}}}} \cdot d_p \]

where \( M_p \) is the mass of the planet and \( d_p \) is its mean distance from the sun, and \( M_{\text{SUN}} \) is the mass of the sun. The maximum radial libration widths\(^\text{13} \) of the sun-planet Lagrange points are [48]:

<table>
<thead>
<tr>
<th>Planet</th>
<th>Libration orbit width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter</td>
<td>0.161 AU</td>
</tr>
<tr>
<td>Earth</td>
<td>0.0017 AU</td>
</tr>
<tr>
<td>Mars</td>
<td>0.00087 AU</td>
</tr>
</tbody>
</table>

An analytical theory of the motions of a particle librating about a Lagrange point has been developed by Yoder [51], and is summarized in Shoemaker [14]. This model was originally developed to explain the motion of a pair of coorbiting Saturnian satellites, but is suitable for describing the motion of all Trojan-like asteroids provided that the orbits are nearly circular and coplanar. An exact description of motion requires a time-evolved N-body simulation; however, to first order, the motion in longitude and radius about the Lagrange point may be modeled as a simple harmonic correction to the motion of the Lagrange point itself, which coorbits at a fixed position relative to Jupiter's mean position. Therefore, the radial and longitudinal excursions about a fixed Lagrange point may be modeled as:

\[ \Delta \phi = D_{\text{lib}} \sin \left( \frac{2\pi t}{P_{\text{lib}}} + \psi_{\text{lib}} \right), \quad \Delta r = -\frac{\tau_{\text{lib}}}{2} \cos \left( \frac{2\pi t}{P_{\text{lib}}} + \psi_{\text{lib}} \right), \]

where \( \phi \) and \( r \) represent angle and radius in a sun-centered polar coordinate system, \( D_{\text{lib}} \) is the maximum longitudinal width of the libration orbit, and \( \psi_{\text{lib}} \)

\(^{13}\) The maximum libration-orbit widths in longitude, for inner solar system Lagrange points, have been determined by simulation [10] to be about 1.5 degrees, corresponding to maximum displacements in longitude of .04 AU and .026 AU for the Earth and Mars Lagrange points respectively. For the Jovian Lagrange points they are significantly wider (almost 60 degrees), and may be calculated from Yoder's theory [51].
represents the phase offset of the Lagrange point (relative to Jupiter), and $P_{\text{lib}}$ is the period of the libration, given by

$$P_{\text{lib}} = \left[ \frac{27}{4} \cdot n_{\text{jup}} \cdot \left( \frac{M_{\text{jup}}}{M_{\text{SUN}}} \right)^{\frac{1}{2}} \right]^{-1} \cdot 2\pi$$

where $n_{\text{jup}}$ is the mean motion of Jupiter in radians per second. $P_{\text{lib}}$ is 147.8 years for objects librating about the JL points.

A check of the validity of this approximation may be performed by computing the corrections to the simple harmonic approximation using Yoder’s theory; the corrections have terms of the form

$$\delta \phi = 2e \sin(\phi) + \frac{5}{4} e^2 \sin(2\phi), \quad \delta r = -d_{\text{jup}} \left[ e \cos(\phi) - \frac{e^2}{2} (1 - 2 \cos(\phi)) \right]$$

where $e$ is the effective eccentricity of the librating orbit,

$$e = \frac{r_{\text{lib}}}{2d_{\text{jup}}}$$

and $d_{\text{jup}}$ is the mean radial distance of Jupiter from the sun. $e$ is approximately 0.0077 for the JL4 and JL5 Lagrange points at a libration radial width of $r_{\text{lib}} = 0.08$ AU, or about half the maximum stable width. Using this value, the simple harmonic motion model of a libration orbit is correct to about 1% in radius and about 5% in longitude over a full libration cycle. The larger error in longitude is due to the fact that the libration orbit has a “tadpole” shape and is not perfectly symmetric in longitude about the nominal Lagrange point.
Appendix III. Environmental disturbances at Jupiter’s orbit

The various environmental perturbations at the Jovian orbit are summarized by Longuski et al. [52], and can be computed as follows. In the calculations, where a perturbing force is proportional to the area of impingement, we have used an effective area of 7500 m$^2$, equivalent to a 10 m diameter circular aperture positioned normal to the perturbing flow. We have used a nominal spacecraft mass of 10000 kg where computations are dependent on mass. The forces may be scaled to other effective masses and areas as shown by the equations.

The radiation pressure force due to reflected solar energy is:

$$F_{\text{rad}} = \frac{k_{\text{elm}}A_{\text{eff}}f_{\text{elm}}}{c}$$

where $A_{\text{eff}}$ is the effective area and $f_{\text{elm}}$ is the mean integrated energy flux = 50 W/m$^2$ at 5.2 AU. $k_{\text{elm}}$ is a dimensionless factor which is dependent on the reflecting properties of the impinged surface; for a worst-case calculation $k_{\text{elm}} = 2$ (specular reflection) which we have used for the computations shown in Table III.

Forces due to particle collisions from the solar wind are:

$$F_{\text{solvind}} = \rho_w A_{\text{eff}} v_r^2$$

with $\rho_w$ as the particle mass density and $v_r$ the relative velocity. The quantity $(${$\rho_w v_r^2$}$)$, which is the momentum flux of the quiet solar wind, may be scaled from its value at 1 AU ($= 2.3 \times 10^{-9}$ kg/m$^{-2}$s$^{-1}$) by the ratio of the distances squared (i.e., by $[(1 \text{ AU})/(5.2 \text{ AU})]^2$).

The force due to small meteoroids may be likewise computed as

$$F_{\text{meteoroid}} = \rho_m A_{\text{eff}} v_r^2$$

with $\rho_m =$ the meteoroid mass density. For $\rho_m$ and $v_r$ we have applied both a cometary and an asteroidal component, using values from the cited reference for 3 AU (main asteroid belt): $\rho_m = 1.84 \times 10^{-20}$ kg/m$^3$ (cometary), $\rho_m = 2.44 \times 10^{-18}$ kg/m$^3$ (asteroidal); $v_r = 21.53$ km/s (cometary), $v_r = 17.98$ km/sec (asteroidal). $\rho_m$ for the Trojan environment could be significantly less, although there may be a localized density increase due to long-term collisions and fragmentation of the Trojan groups (see Appendix VI below). In the absence of better measurements this value should be regarded as reasonable upper limit.

For forces due to Newtonian drag from residual gas molecules we also used the values of Longuski et al., who applied the proton density of the quiet solar wind
at 1 AU (they assumed it to be the same at 3 AU, and we have adopted this value as well). The force expression follows the same form as that shown for the other particle flux forces.

Cosmic rays have an energy density of $10^{-13} \text{ J/m}^3$, which is expected to be uniform throughout the solar system since the particles emanate from the galactic environment. Multiplying by $A_{\text{eff}}$ gives a force of $10^{-9} \text{ N}$.

Gravitational forces were calculated as order or magnitude effects using Newtonian gravity, $F = GmM/R^2$. The acceleration of the spacecraft can then be calculated given its mass. The largest perturbing gravitational influence will be due to Saturn, which has a maximum value of $10^{-7} \text{ m/s}^2$ when it is at opposition to a JL point. Trojan asteroids are potential perturbing influences; using the density for carbonaceous chondrites ($\sim 3000 \text{ kg/m}^3$) and a diameter of 10 km, an asteroid would have to approach within $\sim 3200 \text{ km}$ to present a gravitational force as large as the maximum for Saturn.

The $\Delta v$ requirements from the above perturbations, to first order, can be calculated from the net acceleration by integration over time. Since the forces listed do not vary significantly on timescales of a day, a simple calculation of $a \Delta t$ (where $a$ = acceleration) will give the $\Delta v$ requirements; we assume that stationkeeping adjustments would be performed at least once per day for correction of perturbations. The net accelerations will add vectorially, but the largest influence is that of Saturn at opposition, which gives an uncorrected $\Delta v$ of 0.0086 m/sec per day and an uncorrected displacement (acceleration doubly integrated over 24 hours) of 373 m per day. Saturn’s perturbing force will be about 10x lower in the best case, and the other forces are all approximately 100x smaller (for the assumed spacecraft area and mass) than the worst-case Saturnian perturbation. Therefore, a rounded value of 0.01 m/sec per day seems a reasonable time-averaged upper limit for stationkeeping requirements against perturbations, even if the spacecraft area is increased by $\sim 100x$.

One likely exception to these stationkeeping limits involves modification of the libration orbit for aperture synthesis observations. As discussed above, a pair or larger set of separated telescopes will evolve a reasonable $(u,v)$ plane coverage on a timescale on the order of a few years. However, the long “tadpole” shape of the libration orbits shows that the motion in longitude will continue out to large displacements; the orbits are about 30x longer in longitude than in radial width. Therefore, after the displacement has evolved to a desired maximum, it will be necessary to perform a larger $\Delta v$ burn to “truncate” the libration, and a second burn of approximately equal magnitude to initiate a new libration cycle. The $\Delta v$ requirements may be estimated using the orbital velocity differences at the radial extrema: using the effective eccentricity, the aphelion and perihelion velocity differ by about 25 m/sec from the nominal Jovian orbital velocity (for a .01 AU radial width libration). Therefore we would expect a velocity change requirement of about 2x (25 m/sec) every 3-4 years, or approximately 15 m/sec per year on a
time-averaged basis. Optimization of stationkeeping approaches and more exact $\Delta v$ requirements would need to be developed as part of a more detailed study. We would expect stationkeeping to be implemented using advanced thruster technology such as ion thrusters; however, even with current technology the net fuel requirements for a 10000 kg station, using monomethyl hydrazine thrusters ($I_{sp} = 225$ sec) amount to only 135 kg/year or roughly 1% of station mass.
Appendix IV. Microlensing timescales

A summary of the geometry and the relevant equations describing microlensing is given in [54].

Typical timescales for photometric variation resulting in microlensing of an unresolved background source are on the order of

$$\delta t_{\text{lens}} = 130 \sqrt{\frac{m_L}{M_{\odot}}}$$

where $m_L$ is the mass of the unseen lensing object. Assuming we wish to observe a microlensed object from sites at both JL4 and JL5, we will expect a time delay that will be dependent on the distance to the source object, the distance to the lens, and the relative velocity of the lensing object across the line of sight. Simple geometry using the method of similar triangles will show that the distance the lens must cross to intercept the line of sight from each Lagrange point to the source is

$$x_{\text{lens}} = \frac{L_{\text{JL4-JL5}}}{d_s} (d_s - d_{\text{lens}})$$

where $d_s$ is the distance to the source and $L_{\text{JL4-JL5}}$ is the JL4 to JL5 baseline projected to the line of sight to the source. Then the time between detections at JL4 and JL5 will be

$$\Delta t_{\text{JL4-JL5}} = \frac{x_{\text{lens}}}{v_{\text{rel}}}$$

with $v_{\text{rel}}$ the relative velocity of the lens across the line of sight. $d_s$ can be set to $\sim 8500$ pc, the distance to the galactic center. The sun’s velocity in the galactic frame is 220 km/sec, and the relative velocity might be 25% of that. With a lens distance near the galactic halo at $\sim 5$ kpc, then we might expect lensing events with time delays of $\sim 70$ days for sources in the plane of Jupiter’s orbit. Off-plane sources will be viewed across projected baselines of shorter length, resulting in shorter delays, but likely on the order of 1 day or greater for most sources and viewing directions.
Appendix V. Astrometric depth sensing

Assume that the position of an object is measured simultaneously from two sites (JL4, JL5) separated by a baseline $L_A$, with reference to a (fixed) background frame of more distant objects. Let the parallactic angle measured from the two sites be $\beta$, and let the measurement uncertainty for each measurement be $\Delta \beta$. The quantity $\Delta \beta$ refers to the two-axis angular measurement uncertainty, which is $\sqrt{2}$ times a single measurement. The nominal range to the object, with a single perfect measurement, would be $R = L_A / \beta$. The true parallactic angle, however, lies within the span $(\beta - 2\Delta \beta)$ to $(\beta + 2\Delta \beta)$, and the uncertainty in range is then

$$\Delta R = \frac{L_A(\beta - 2\Delta \beta) - L_A(\beta + 2\Delta \beta)}{(\beta - 2\Delta \beta)(\beta + 2\Delta \beta)}$$

$$\Delta R = \frac{4L_A\Delta \beta}{(\beta - 2\Delta \beta)(\beta + 2\Delta \beta)}$$

and if $\Delta \beta \ll \beta$, then

$$\Delta R \cong R_0 \cdot \frac{4\Delta \beta}{\beta}.$$

The range or “depth” uncertainty is then proportional to the nominal range and to the relative accuracy of measurement. In general, we might assume that $\Delta \beta \sim 0.01\beta$, so that $\Delta R$ is the about 4% of $R_0$. This equation can be rearranged and inverted to give the required angular measurement accuracy needed to achieve a given depth resolution $\Delta R$:

$$\Delta \beta = \frac{L_A \Delta R}{4 R_0^2}.$$

The range reach curve shown in Figure 3 was calculated using the full JL4-JL5 baseline of 9AU (i.e., object perpendicular to the baseline). For most objects the effective baseline would be scaled by a $\cos \theta$ factor.
Appendix VI. Summary of information on the Trojan asteroids

This information was compiled from [14, 47-51].

The normal orbital velocity at the Jovian orbit is ~13km/s in the heliocentric reference frame. Trojans can have close approach velocities of 15 – 300 m/sec. The mean collision speed between Trojans is greater than among belt asteroids, due to higher Trojan inclinations; the mean inclination is about 18 degrees, and there is a higher dispersion of inclinations than among main-belt asteroids. Most L4 Trojans are estimated (photometrically) to be less than 43km in diameter, and there are few known Trojans with diameters greater than 100km. The Trojans librate about the JL points with amplitudes (in longitude) ranging from 2 to about 63 degrees; the average libration amplitude is 29-30 degrees.

There is evidence that several dynamically-bound groups exist at both JL4 and JL5; it is likely that some of the separate objects in each group arose from collisions of larger objects. For example, there appear to be 8 pairs or larger groups which are candidates for dynamically interacting groups at the JL4 point. An example pair (most closely matched in libration amplitude, inclination, and
eccentricity), is 1583 Antilochus and 3801 Thrasymedes; their \( \Delta v \) at close approach is \( \sim 60 \) m/sec. Shoemaker et. al. [14] conclude that these two were once a single object. Other candidate dynamical groups have delta-vees from 35 to 300 m/sec. Some or all of these other dynamical groups may have evolved from collisions, and there are probably smaller undetected companions. There are possible differences in the dynamical structure of the L4 and L5 swarms, with the possibility of a diffuse, low-inclination, low-libration-amplitude group at L4.

Trojans were the most thoroughly scanned asteroid population by IRAS, but because of their lower thermal emission (low temperatures) only those larger than \( \sim 50 \) km were detected. IRAS detected very well delineated asteroidal dust bands associated with the more prominent main-belt families. These bands are generally thought to represent the result of collisions.

Trojans, based on a combination of observational statistics and long-term dynamical simulations, are thought to have formed near their current location, or possibly somewhat farther out. Albedos from IRAS imply that most Trojans are D-type, with a dark red coloration, probably due to polymerized organic compounds. Shoemaker et. al. suggest they have undergone little or no significant thermal evolution and may therefore be good candidates for “primordial” solar system material. Spectroscopically they bear some similarity to dead comets, and are a close match to carbonaceous chondrites, implying the presence of C, H, O, N, probably simple organics, possibly water ice under the surface, and Al, Mg, Fe, Si, and other elements (except H) in abundances typical of the solar system in general. Primitive asteroids, held at low temperatures, probably contain complex carbon compounds, organics, and hydrated clays.

Asteroids in general are thought to have significant porosity. Current asteroidal evolution theory posits than only the largest objects survive in original form; others are shattered by impacts, then re-accrete as gravitationally bound “rubble piles”. The NEAR spacecraft flyby of 253 Mathilde supports this: Mathilde has 6 impact craters large enough to have shattered it; it would likely have survived only if it were already a rubble pile that dissipated impact energy without complete rupture. The fast rotation rates of most asteroids also support collisional evolution: primordial rotation due to original accretion conditions would be expected to be slower. Regolith appears to cover those asteroids we have directly imaged, and they have craters and fractures. This surface material is thought to have been formed by micrometeoroid impacts over time, and it appears to have been modified by “space weathering” due to long exposure to radiation.
References


13. See http://tpf.jpl.nasa.gov; the “TPF Book” is available for downloading from the site.


32. See http://www.boulder.nist.gov/timefreq/.


