LARGE-SCALE, LARGE-APERTURE SPACE ASTRONOMY: BEYOND THE NEXT GENERATION

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ABSTRACT

Over the next decade two major technologies will be introduced in space-based astronomy: large aperture optics and spaceborne optical interferometry. In a recent study for NASA we proposed the use of space telescopes at each of Jupiter's Lagrange points L4 and L5 for cooperative, ultra-long-baseline astronomical observations. The system would be comprised of one or more platforms placed at each of these points, robotically maintained and designed for long life and extensibility. Synthesis imaging using separated telescopes across baselines at least 1000 times longer than any currently under consideration will be possible, and will utilize the natural orbital motion of spacecraft in halo orbits about the Lagrange points. Other science applications supported by this concept include long-baseline parallactic astrometry, solar system exploration, and exosolar planet studies.

The use of the Jovian Lagrange points as astronomical "sites" will provide measurement baselines across planetary-sized scales of space and time but will also require very advanced space systems. Key technologies needed include: very large aperture lightweight space optics, precision metrology across extreme distances, and advanced space robotics. Although the requirements are stressing, all of the required technologies are currently under development, and many of the advances needed to support the concept will be developed as a result of currently planned or proposed programs.

In this paper we present the basic features of the concept and discuss the science drivers and the resulting technology requirements. We review design and configuration options for and discuss comparisons with other proposed advanced astronomical and space science missions. We also review current technology development programs that support the concept, expectations, and discuss proposed follow-on studies, including precursor missions and potential near-term developments.

INTRODUCTION

In a recent study for the NASA Institute for Advanced Concepts (NIAC) we introduced the idea of placing astronomical instruments at the equilateral L4 and L5 Lagrange points in Jupiter's orbit [1]. These locations (hereafter denoted JL4 and JL5) are not stationary but move with Jupiter in its orbit; they do not represent local "wells" in the gravitational field as is often believed, but are local maxima instead. Nevertheless, objects situated near these points will remain in the vicinity, as is well known both from theory and from the experimental observation of the Trojan asteroid group located at each of JL4 and JL5. One or more space platforms located at each of these points could be used to carry astronomical and space science instruments. The goal of such a system would be to establish a long-term, large-scale observational system, using a natural feature of the solar system to maintain the geometry. As we discuss further below, there are several potential advantages to this concept, and a natural synergy with technologies currently under development.

The basic system geometry is shown in Figure 1, and a summary of features in Table I. There are two length scales of interest: an "outer", cross-baseline scale between JL4 and JL5, and an "inner" scale located at each of these points. This latter is due to the fact that objects will not remain stationary at the Lagrange points, but will move about them in slowly librating "halo" orbits with roughly elliptical geometry and long periods (~ 150 years). These halo orbits are themselves of interest since they provide for stable orbits with radial displacements up to 0.16 AU about each Lagrange point.

One might consider the Jovian Lagrange points as gravitational "anchors" suitable for the placement of a wide variety of scientific instrument systems. We have chosen to emphasize astronomy applications which take advantage of both the interior and exterior geometric length scales of this geometric system. Other applications, unforeseen by us, are certainly possible.

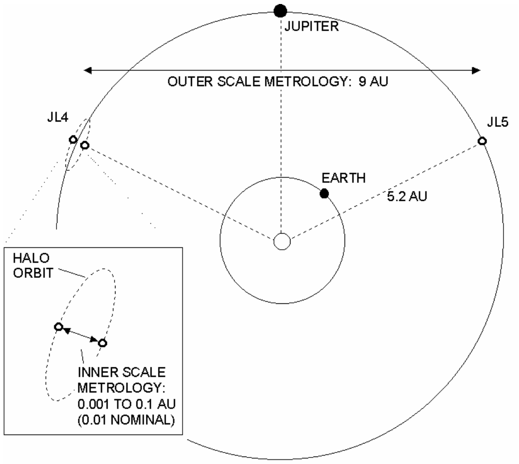

Figure 1. Basic geometry for the system.

APPLICATIONS

Potential astronomical uses for this system include almost any observational mode that would benefit from a relatively-stable, long baseline or a site located outside the main zodiacal cloud of the solar system. We considered applications ranging from conventional astronomical imaging to the detection of gravitational waves. Two of the most intriguing possibilities are very-long-baseline astrometry and astronomical interferometry.

Table I. Basic system properties

Stations	JL4 (leading) JL5 (trailing)
Orbit	Radius 5.2 AU Period 11.86 years
JL4-JL5 distance	9.01 AU (nominal)
JL4-Earth distance	4.2 – 6.2 AU periodic
Light travel time	JLx-Earth: 35-52 min. JL4-JL5: 74.9 min.
Orbital velocities	13.06 km/sec (nominal Jovian orbit)
Transfer orbit	2.6 years one-way (Hohmann ellipse)
Synodic periods	Earth-Jupiter: 13.3 months
Halo orbit geometry	Radial widths stable to 0.16 AU; arc lengths to 60 deg.
Trojan asteroids	Typical size 15km Mean inclination 18 deg

Wide-angle, whole-sky astrometry across the full JL4-JL5 baseline would allow parallax-based distance measurements on a scale ten times larger than currently available from earth or earth orbit. Moreover, the placement of an astrometric telescope at each of the Jovian Lagrange points would allow this parallax to be observable instantaneously. Rotation of the JL4-JL5 astrometric "bench" by one quarter of a Jovian period would allow parallax along an orthogonal line of sight. After one-half of an orbital period the whole sky could be covered, as shown in Figure 2.

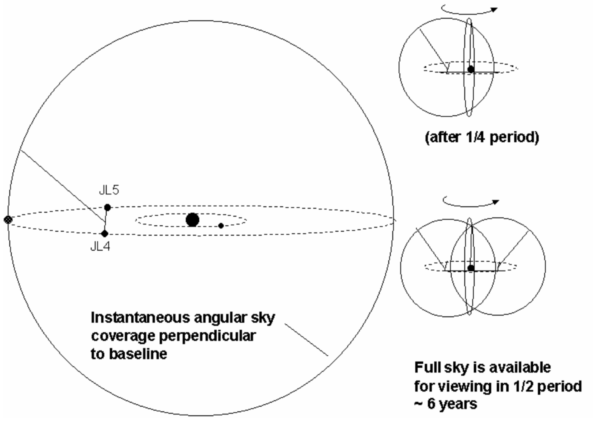

Figure 2. Sky coverage for astrometric observations.

The accuracy of astrometric distance determinations would be dependent on the accuracy of small-angle astrometric position measurements of target objects, together with the parallactic angle due to the long baseline. Current trends in astrometric missions such as Hipparcos, FAME, and SIM are aimed at developing angular accuracies from the 1 millisecond range down to a few microarcseonds. Astrometric accuracies at microarcseond levels (50 picoradians), would allow the direct, parallactic distance measurements of stars in M31, the Andromeda galaxy.

A related but somewhat more intriguing application is the concept of depth imaging, or "astrometric tomography". The basic concept is to use the long baseline for simultaneous measurements of extended objects such as nebulae or clusters. A small preview of this type of measurement has been made available with three-dimensional spatial mapping of some nearby stars by the Hipparcos mission. With the JL4-JL5 baseline, one might sense parallax (transverse to the line of sight) and depth of selected features out to large distances – it depends on the angular measurement accuracy that can be achieved. Depth resolution of 0.1 pc at distances of 10 pc would require measurement accuracies of ~1 nanoradian, and would allow depth mapping of exozodiacal disks around nearby stars. Accuracies of a picroradian (10^{-12} radian) would allow depth mapping of nebulae and star clusters out to ~1000 parsecs, covering a significant fraction of our galaxy.

The Jovian Lagrange points can also provide suitable locations for space-based interferometry. The fundamental angular resolution obtainable from an interferometer is λ/B, where λ is the wavelength and B is the baseline length. Interferometry across the full JL4-JL5 baseline is theoretically possible, though difficult practically except for very bright sources, since the "efficiency" of a sparse array on such a long baseline would be extremely low. An analysis of the aperture size requirements, based on blackbody sources, shows that apertures on the order of kilometers would be necessary; the required area-time product for collection of light is proportional to $(\text{baseline})^2$. However, the natural geometry of the halo orbits about each of the JLx points would allow for baselines from (effectively zero) up to about 0.1 AU in radial width. A continuous distribution of possible baselines exists, up to the size limit of stable halo orbits. Even a 0.01 AU baseline has a resolution exceeding any currently envisioned; working at a wavelength of 1 micron, the potential angular resolution would be 10^{-15} radian. This would allow resolution of planetary (Earth) sized objects out to the center of our galaxy, or sunlike stars at 10 Mpc.

Assuming an interferometer based in a halo orbit about one of the JL points, apertures of size 10 to 100m (based on wavelengths of 1 – 10 micron) will be needed for efficient collection – large but conceivable based on current trends. The actual size required will depend on the baseline and wavelength chosen for implementation, and on the temperature and brightness of the target object. One way of addressing the telescope size requirement is to calculate the aperture size needed to collect some minimum, threshold flux level for objects which are just resolvable with the given interferometer wavelength and baseline. For sunlike stars (T ~ 5700K) and a baseline of 0.01AU and wavelength of 1 micron, the required aperture to collect 1 photon/second is approximately 100m. This size represents the point where the "radiometric reach" and "resolution reach" of an interferometer are the same. Smaller apertures would meet this requirement at shorter baselines or longer wavelengths.

The natural orbital evolution of the halo orbits, as well as their co-rotation with Jupiter about the sun, would map out a range of displacements and angles suitable for a reasonable coverage of the "u-v plane", i.e., a range of angular spatial frequencies dense enough to allow reconstruction of the target object. Figure 3 shows a sample u-v coverage graph for one possible configuration. Observations would be taken at regular spacings in time and would not be continuous throughout the orbit; therefore multiple objects could be studied by interleaving observations. Reconstruction would be done after all data was taken.

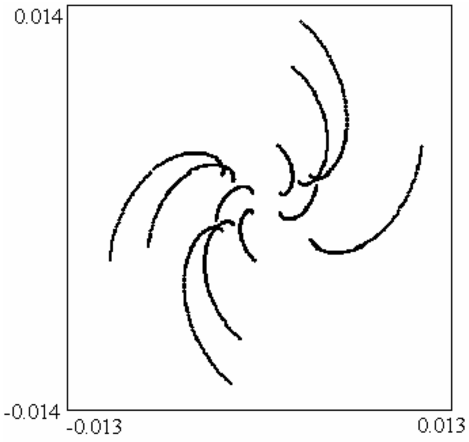

Figure 3. (u,v) plane coverage for a pair of interferometric telescopes at JL4 and JL5. The initial halo orbit separation is 0.001AU radially, and the duration is shown for 1/3 of a Jovian period. Wavelength scanning from 0.75 to 1.35 times base wavelength is used to increase the coverage.

Stable Lagrange points, including L2, L3, and L4, exist for other bodies in the solar system, such as Earth and Mars. However, the JL4/JL5 points allow for a larger stable range of displacements and a lower rate of change of the baseline length and angle, due to the size and orbital period. These changes in baseline are roughly ten times lower for JL4 or JL5 versus an Earth-Sun L4 or L5 point, and translate to longer allowable integration times and lower rates of optical pathlength change for an interferometer. The JL points would thus provide correspondingly relaxed measurement requirements compared to inner solar system Lagrange points.

SPACE SYSTEM REQUIREMENTS

Table II lists several possible applications and a recommended instrument size and configuration for each. This list comprises a range of applications considered during the NIAC study. Other instrumental modes (particularly radio astronomy) are applicable, although not represented in this list. For most of the instruments shown the size is based on a reasonable extrapolation of current practice, and does not represent serious technological challenges. Telescope sizes shown for aperture synthesis represent the most stressing requirements.

Except for interferometry, which would require a pair (or more) of free-flying telescopes, any or all of the above instruments could be included as part of a science platform to be deployed at JL4 and/or JL5. Mass on-orbit could potentially be large, but not unrealistic. Large reflectors for interferometry represent the highest mass item on the list. Using projected areal densities for the Next Generation Space Telescope (NGST) of 10 kg/m^2, a 10m reflector with an associated instrument package would mass less than 1000 kg. Reasonable allocations for spacecraft structure and subsystems (dry, 3.3 x payload mass), plus fuel and margin (155% of dry spacecraft) would give a mass of approximately 5100 kg, about 2X the mass of the Galileo orbiter and probe. The total for an aperture-synthesis pair would be approximately 10000 kg on-orbit. Including an additional mass equal to one telescope for robotic servicing equipment gives a total roughly equivalent to that of the Compton Gamma-ray Observatory. This is without considering the possibility of advances in lightweight optical systems beyond those for NGST, which would lower mass or allow larger apertures.

Table II. Some potential astronomical studies, candidate aperture sizes, and desirable placement.

Application	Size	JL4	JL5
Conventional Astronomy	≥ 10m	X	
Astrometry	≥ 2m	X	X
Aperture Synthesis	10 – 100m	X	X
Microlensing	≥ 1m	X	X
Asteroid studies	≥ 1m	X	
Robotics (exploration)	(n/a)	X	X

The most difficult technical requirements will be those that derive from metrology. Spacecraft positioning measurements to support astrometry may not be too stressing: 10^{-12} radians projected to a range of 1 parsec is approximately 31 km. Therefore, parallax-based astrometry will likely be feasible out to 1000 pc ranges using meterlevel 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 one pixel [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. 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.

Metrology for interferometry presents a greater challenge. Free-flyer interferometry concepts proposed to date avoid extreme dynamic measurement and control ranges 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 optical systems 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 multiple levels of control. Relative displacement of JL platforms from idealized positions will be small and occur at fairly low rates of motion. Therefore, separation of interferometer metrology into coarse (spacecraft-level, ~cm accuracy) and fine (optical-level, sub-wavelength accuracy) components appears feasible for these distances.

Methods have been developed, at least conceptually, for precise measurement of both distances and angles between spacecraft at planetary 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 x 10^9 m (about 0.03 AU), using laser interferometry between spacecraft [3]. Yu et. al. [4] proposed a laser interferometric method for measuring angles between two spacecraft in an earth-radius, heliocentric orbit to an accuracy of 10^{-12} radian. 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 already possible with current technology [5]. Radio doppler methods might also be used for ranging, with somewhat lower levels of precision.

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. The radius of error about the nominal line of sight would be governed by the time reference accuracy; for .01 AU displacements the radius of error will be ~15cm at for 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. Recent experimental work on ultrafast lasers has resulted in timing measurements shorter than 10^{-14} seconds [6].

Table III presents a summary of top-level metrology requirements for the inner and outer scales.

Table III. Summary metrology requirements.

Inner scale:	
Baseline	0.001-0.1 AU (0.01 nominal)
Application	Aperture synthesis
Position accuracy	$< \lambda/10$, $\lambda = 1\text{-}10\ \mu m$
Telescope pointing	$\sim\lambda/10D = 10^{-9}$ rad (100m aperture)
Outer scale:	
Baseline	9.01 nominal; varies as platform librates
Application	Astrometric parallax
Position accuracy	~ 1m
Telescope pointing	10^{-12} rad (statistical) 10^{-9} rad single sample

The combination of a long-term, remote deployment with long light-travel times will require advanced robotics and spacecraft autonomy. On-board systems will need a robust and comprehensive suite of intelligent behavioral features. Systems must be self-diagnosing, with high levels of health and status information available continuously, and with troubleshooting procedures available on demand. Systems must have some level of self-repair, including fault-induced switching of redundant systems, as well as advanced methods of system safing and self-recovery. Observation scheduling must be adaptable to system failures and other unexpected problems. Automated task planning, intelligent data preprocessing, routing, packaging, and compression, and highly-reliable, fault-tolerant communications will all be needed.

The ability to replace failed instrument and spacecraft subsystems will prevent loss of mission systems over time. Mobile robotic servicers will be needed for each deployed platform, and these will need all of the self-diagnosis and fault-tolerance attributes of on-board systems, plus specific additional attributes to enable system servicing. 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. Robotic installation, alignment, and calibration would be needed. Free-flyer robots would need trajectory planning, autonomous navigation and local platform maneuvering, collision hazard assessment and prevention, and the ability to perform external systems inspections. Lower-level functions needed would include: image-based situational awareness, scene classification, and anomaly detection; automated docking, grappling, and berthing; module grasping, manipulation, and alignment; and specialized manipulator subsystems for specific instrument services. The ability to perform fluid transfer and refueling may also be required.

Power needs present a unique but not insurmountable problem. Solar power at the Jovian orbit is seriously reduced (50 W/m^2 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. Power needs for a single telescope can be estimated by simple scaling. Increasing the HST array size to match the solar irradiance levels at 5.2 AU gives a size of 1250 m^2 for HST levels of power. Somewhat smaller arrays will be feasible using lightweight inflatable solar concentrators.

Environments at the Lagrange point will be relatively 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. The standard NASA model predicts a relatively low meteoroid flux at Jupiter's orbit. Additional effects, which might be negligible for traditional spacecraft, could be very serious for separated-spacecraft interferometers. For example, buffeting due to residual gas molecules and fluctuations in the solar wind, as well as from micrometeoroids, may present significant disturbances.

The various environmental perturbations at the Jovian orbit are summarized by Longuski et. al. [7] and can be used to calculate disturbances for the purposes of stationkeeping. We assumed a strawman telescope size with an effective area of 7500 m^2, equivalent to a 10 m diameter circular aperture positioned normal to the perturbing flow, and a nominal spacecraft mass of 10000 kg. We calculated small-scale disturbances due to meteoroid flux, residual gas, solar wind and solar radiation pressure, and cosmic rays, as well as gravitational perturbations due to Saturn.

The Δv requirements from the above perturbations, to first order, can be calculated from the net acceleration by integration over time. The forces listed do not vary significantly on timescales of a day, so a simple calculation of $a\Delta t$ will give the Δv requirements. We assume that stationkeeping adjustments would be performed at least once per day for correction of perturbations. The required Δv needed to maintain station is quite reasonable, less than .01 m/sec per day. It is likely that these requirements can be met with frequent, low thrust impulses from ion engines or similar low-thrust devices. A somewhat larger Δv 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 [8]. 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. The environmental factors and Δv calculations are shown in Table IV.

Table IV. Environmental disturbances.

Small-scale disturbances:	
Meteoroid flux	~ 10^{-5} N
Residual gas	10^{-10}
Solar wind	10^{-6}
Radiation pressure	10^{-5}
Cosmic rays	10^{-9}
Gravitational perturbations:	
Saturn	10^{-7} m/s2
Small-scale metrological effects:	
Stellar aberration	~ 40 µrad
Gravitational bending	10 prad – 0.1 µrad
Delta-v requirements:	
Stationkeeping (~1/day)	< 0.01 m/s/day
Orbital adjustment (~1/yr)	~ 15 m/s/yr

There is some uncertainty in the micrometeoroid level, due to a potentially higher population of small particles from asteroidal collisions. There is evidence for long-term collisional evolution of the Trojan asteroid population [9], and there is a known higher density of small particles in main belt asteroid collisional groups. Therefore, one might expect an elevated meteoroid flux, related to the Trojan groups, to be present in the general vicinity of the Lagrange points. The magnitude of this effect is, however, unlikely to be severe.

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 [10].

TECHNOLOGY DEVELOPMENT NEEDS

Technologies relating to large-aperture deployable optics and separated spacecraft interferometry will be key. Telescope systems 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. For telescopes in this class, the primary and backing structure will dominate the host spacecraft bus in size; low-mass optics and backing structure technology will be needed to minimize on-orbit mass. Some very advanced concepts do away with supporting structures altogether and use inflatable primaries, with the secondary mirror systems and instrument packages contained in a separate free-flyer [11].

Current plans by NASA and ESA call for deployment of telescopes several times the size of the Hubble Space Telescope. 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, large refractive “Fresnel lens” type optics, and coherent arrays of lightweight flats [12]. Projected areal densities for these concepts range from 5 kg/m^2 down to less than 0.1 kg/m^2 for some inflatable designs. Subscale models and test articles are being fabricated for some concepts, but significant technical issues remain to be addressed. 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. A number of other potential methods for constructing large space telescopes are being investigated under the Gossamer Telescope Initiative fostered by NASA. 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.

The mechanics of aperture synthesis over large distances may require a radical departure from current techniques. In current ground-based experiments, interferometry has been limited to path lengths on the order of 100 m. Near-term space experiments will demonstrate optical interferometry using both free-flying and monolithic interferometers, and 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. A scale up by about 3 orders of magnitude will be needed to take advantage of the Lagrange point geometry.

Combination of wavefronts or other phase-preserving information to form an interference pattern will be challenging. There are 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; external-referencing methods, where a 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 the most straightforward approach, and will be demonstrated on the ST3 mission. It may be within reach technologically for larger distances, but will have a significant system impact as it will require a separate combiner spacecraft platform. Its implementation will be closely coupled to inter-spacecraft metrology system concepts. Also, relay optics must be relatively large to prevent serious signal losses from diffraction.

If direct combination of wavefronts turns out to be impractical, a solution to the problem will be needed using one of the alternate methods. For example, it may be possible to use an external reference source – a bright star – as a phase reference. Self-referencing interferometry, requiring no external source, has already been demonstrated for optical phase measurement in the laboratory [13]. Heterodyne interferometry using a coherent (laser) reference has been practiced against astronomical targets from earth-based sites for some years [14]. Its chief drawback is that it limits the optical bandwidth of the processed signal. The technological need here is for one or more of these techniques to be developed for large-scale, space-based aperture synthesis.

In the area of system autonomy most, if not all, of the required functions discussed above have been proposed in recent years for various advanced unmanned and manned missions. Specific spacecraft autonomy experiments have already been performed on several missions. Some new 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. Automated rendezvous, docking, and berthing are currently areas of research supported by both NASA and the DoD community. Improved levels of robotic mobility, including long-range autonomous navigation and docking, will be developed for robotic explorers.

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). The most significant difference between ISS capabilities and highly autonomous systems lies in the use of telerobotics. Remote 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.

In addition to autonomous systems, some advances in spacecraft electronics technology will be required. Significant amounts of data will be captured and communicated to earth. Station-station and station-earth communications will require extremely high bandwidths, and will likely utilize optical communications. For most science applications, we expect that technology advancements due to missions already planned will result in sufficient processing technology to meet these needs.

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 sub-nanoradian level angular measurements even these small effects must be taken into account. In this area, both problems and solutions will be design-dependent.

FUTURE STUDIES

The next generation of large spaceborne astronomical telescopes – to include NGST and the Terrestrial Planet Finder – will be deployed by 2015 according to current schedules. Many of the design and technology needs for systems such as the one we have proposed will be developed to support those missions. Some systems will require another level of performance improvement, but the convergence of three trends currently underway – large lightweight optics, spaceborne optical interferometry, and advanced spacecraft technology – will be a key enabler for planetary-scale astronomical systems. Continued ground-based development in related key technologies will also play a role. Large-scale, large-aperture astronomy systems will become feasible as the next generation beyond those currently being planned.

Key studies to support these long-term goals can be undertaken now. As noted, serious concepts for large scale space-based metrology are already in development, and at least one – the LISA design to detect gravitational waves – may be developed as a mission. Additional design studies and experiments in this area are warranted. The continued development of large-aperture, lightweight mirror technology to further reduce deployable telescope mass will enhance feasibility. Specific concepts for extending optical/infrared interferometry to million-km size baselines need to be developed and tested. Design studies for long-life, remote spacecraft would benefit this concept as well as many potential future missions to the outer solar system and beyond.

In our study we gave little thought to radio astronomy, but the design of a radio interferometry mission utilizing the same Lagrange point geometry could be done now, and would be realizable with near-term technology. Many of the system performance requirements would be significantly relaxed when compared to optical wavelengths.

Precursor missions to the Jovian Lagrange points should also be considered. The Trojan asteroid groups are thought to contain primordial solar system material, and represent an intriguing destination for an exploration mission. The science knowledge gained from such a mission would include data on the local environment that would be needed for development of future space platforms located there.

REFERENCES

1. Timothy L. Howard et. al., "Planetary-scale Astronomical Bench", *NIAC Phase I (CP98-02) study final report*, January 2000. Many design calculations which (for brevity) are not given here are explained in the report.
2. Centroid measurement accuracy is usually estimated as $\pi/8*(FWHM/SNR)$, where FWHM is the size of the object.
3. LISA Pre-Phase A Concept Report, 2nd. Ed., July 1998; at http://lisa.jpl.nasa.gov/.
4. Jeffrey Yu, Michael Shao, Yekta Gursel, and Ron Hellings, "Lator – Laser Astrometric Test of Relativity", *Proc. SPIE 2200*, 325 (1994).
5. John J. Degnan, "Compact Laser Transponders for Interplanetary Ranging and Time Transfer", presented at the *Tenth International Workshop on Laser Ranging Instrumentation*, Shanghai, China, November 11-5, 1996; available at http://cddis.gsfc.nasa.gov/920_3/slr2000/transpond_paper/transpond_paper.html.
6. See, for example, J. E. Rothenberg and D. Grischkowsky, "Measurement of optical phase with sub-picosecond resolution by time-domain interferometry", *Opt. Lett.* 12, 99 (1987); also, G. Steinmeyer et. al., "Frontiers in Ultrashort Pulse Generation: Pushing the Limits in Linear and Nonlinear Optics", *Science* 286, 1507 (19 Nov 1999).
7. James M. Longuski et. al., "Survey of Nongravitational Forces and Space Environmental Torques: Applied to the Galileo", *J. Guidance Control and Dynamics*, 15, 545 (1992).
8. Additional fuel for the truncation of the halo orbit is estimated by using 2X the difference between aphelion and perihelion halo velocities. This is 2x(25m/sec) every 3 years, or 15m/sec/yr on average.
9. Eugene M. Shoemaker et. al., "Trojan Asteroids: Populations, Dynamical Structure and Origin of the L4 and L5 Swarms", in *Asteroids II*, eds. R. P. Binzel, T. Gehrels, and M. S. Matthews (Tucson: Univ. of Arizona Press, 1989), pp. 487-523.
10. C. W. Misner, K. S. Thorne, J. A. Wheeler, *Gravitation* (New York: W. H. Freeman, 1973), pp. 1096-1131.
11. Ivan Bekey, "A 25 m. Diameter Space Telescope Weighing Less than 150 kg.", presented at the *AIAA 1999 Space Technology Conference and Exposition*, Albuquerque, NM, Sept. 28-30 1999; paper no. AIAA-99-4478.
12. J.R.P. Angel et. al. "Extremely Large Telescopes and Interferometers made with flat primary mirrors", presented at the *NASA Ultra Lightweight Space Optics Challenge Workshop*, Napa, CA, March 24-25,1999. See also the ULSOC site: http://origins.jpl.nasa.gov/meetings/ulsoc/presentations.html.
13. A variety of self-referencing phase measurement techniques now exist; a recent review article is: Ian A. Walmsley, "Measuring Ultrafast Optical Pulses Using Spectral Interferometry", *Optics and Photonics News*, vol. 10 no. 4 (April 1999), pp. 28- 33.
14. M. A. Johnson et. al., "10-micron Heterodyne Stellar Interferometer", *Phys. Rev. Lett.* 33, 1617 (1974).