TOWARDS OTHER PLANETARY SYSTEMS (TOPS): A TECHNOLOGY NEEDS ASSESSMENT WORKSHOP

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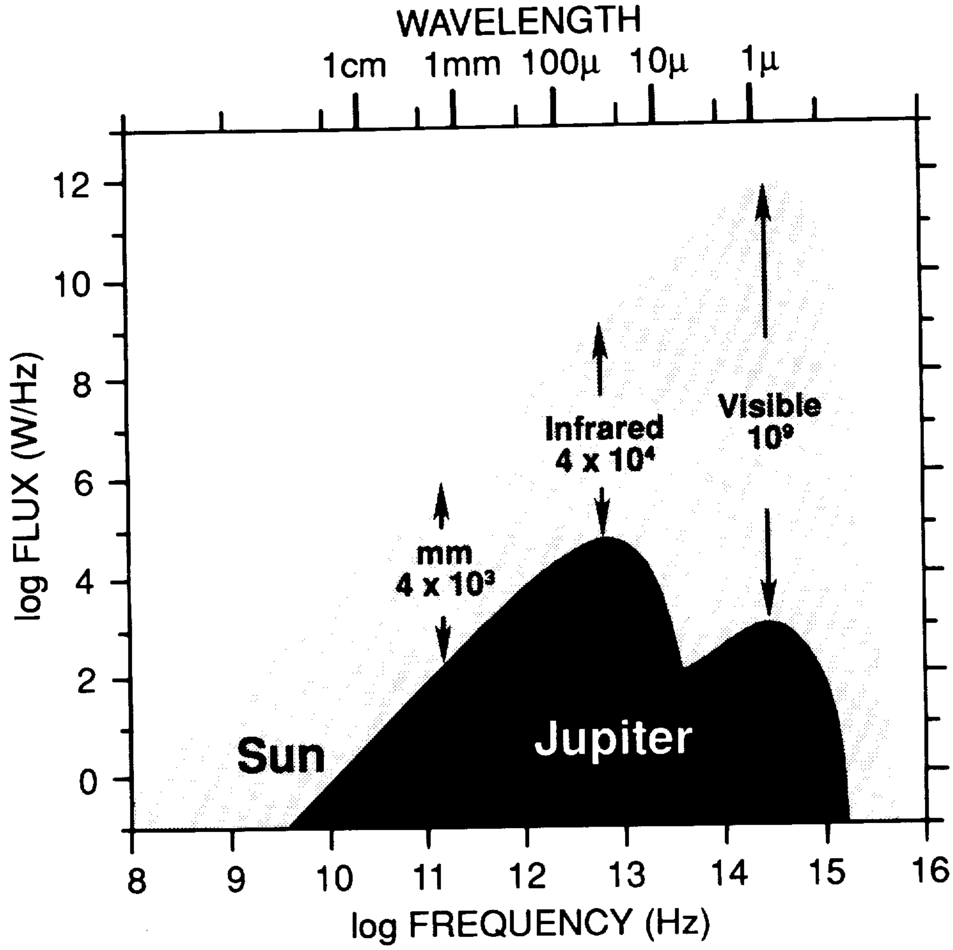

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TOWARDS OTHER PLANETARY SYSTEMS (TOPS):

A TECHNOLOGY NEEDS IDENTIFICATION WORKSHOP

Conveners

David C. Black and Kenji Nishioka

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Lunar and Planetary Institute
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Cover: Techniques for the detection and study of other planetary systems can be classified as either **indirect** or **direct**. The former involve observations of a star with inference of the presence of planetary companions because of some observable effect that those companions have on that star. The latter involve observations that sense radiation, thermal or nonthermal, from a companion to a star. A sense of some of the difficulties inherent in direct detection is shown in this figure, where the black-body spectrum from the Sun is compared with the spectrum typical of Jupiter (the numerical values cited at certain frequencies indicate the brightness contrast at those regions of the spectrum). As shown, Jupiter's spectrum consists of a thermal component (the black-body curve) and reflected sunlight (the high-frequency, visible-light hump). The need for technology involving low-scatter optical systems to detect planetary companions is clear from this comparison.

PREFACE

The purpose of this workshop was to identify and document key technology issues that are associated with the TOPS (Towards Other Planetary Systems) program in general, and with some of the candidate observational facilities specifically. In doing so, an effort was made to define what the current state of the art is in each area, and to forecast technology trends or studies that will be relevant to the development of TOPS instrumentation. Workshop participants were also asked to identify those technologies that were **enhancing** or **enabling** to specific instrument concepts. The participants categorized technology requirements as being either generic in nature for telescopic systems, and therefore in accord with the findings of the recent Astrotech 21 study dealing with technology needs for astronomy and astrophysics in the coming century, or specific to a TOPS instrument.

The technology needs that are identified could serve as a basis for coordinated technology development activities between the Office of Aeronautics, Exploration and Technology (Code R) and the Solar System Exploration Division (Code SL).

The workshop was structured along four major technology theme areas, viz., optics, metrology, structures, and detectors. Presentations in these theme areas were given to all the participants, and then four panels were assembled to address each of these areas in more detail. The panel chairs reported back to the other workshop participants on the findings of their groups.

Any workshop of this nature succeeds only because of the efforts of many. Much of the credit for this workshop rests with Cathy Fischer of the Program Services Department at the Lunar and Planetary Institute. Her efforts during the planning and implementation of the workshop were significant, and they are greatly appreciated. Credit also must be given to both Wayne Hudson and Gordon Johnston of Code R. They recognized the need for this workshop over two years ago, and have displayed patience as this activity has all too slowly come to fruition. We hope that the long-term product in the form of joint technology programs is commensurate with their original vision. Finally, the leadership of Dr. Wes Huntress, Chief of the Solar System Exploration Division, in bringing the TOPS program to its current state of readiness has set a tone for individuals on both the scientific and technology sides of what is one of the more fundamental quests of the human intellect: the search for and study of other planetary systems.

David C. Black *Kenji Nishioka*

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INTRODUCTION

The TOPS program is an initiative of NASA's Division of Solar System Exploration in the Office of Space Science and Applications (OSSA). It is a program that seeks to bring together a diverse set of activities with the intent of discovering, and eventually studying in great detail, planetary systems other than our own. It is now generally recognized that we will never understand the birth and early evolution of our own planetary system without results from a program like TOPS.

There are three principal stages to the TOPS program. These have been designated TOPS 0, TOPS 1, and TOPS 2/3. The TOPS 0 stage deals with **reconnaissance**, and can be initiated immediately; indeed, several ground-based programs are underway at the present time. The proposed NASA participation in the second Keck telescope is the centerpiece of this stage of TOPS.

The TOPS 1 stage deals with **exploration**, and will center on a space-based facility in OSSA's moderate-mission category. At present there are three candidates for this flight opportunity: the Astrometric Imaging Telescope (AIT), the Precision Optical Interferometer in Space (POINTS), and the Orbiting Stellar Interferometer (OSI). One of these will be selected for a phase A study during the 1994 – 1997 time frame. The target date for a launch of the selected system is early in the first decade of the next century.

The TOPS 2/3 stage of the program deals with **intensive study**, and will be shaped by national decisions regarding initiatives to explore and utilize the Moon. Technology developments for advanced instruments that could be operated on the Moon, and would have sufficient performance to permit very detailed study of other planetary systems, are a key part of the technology efforts associated with this stage of the TOPS program.

The workshop concentrated on four technology areas: detectors, metrology, structures, and optics. As the discussion evolved it became clear that two of these areas, metrology and optics, were particularly critical to a successful TOPS program. The relatively significant role of these two technology areas is rooted in the extreme level of observational accuracy that TOPS requires. A consequence of this importance is that these two areas are dealt with in greater detail in this report.

The principal conclusions of the workshop are as follows. The conclusion was reached that many of the technology needs that are needed for TOPS are generic, i.e., they are similar to technology needs that have already been identified for astrophysics missions/instruments. Those needs are summarized in the Astrotech 21 documents. The workshop participants also concluded that there were technology requirements that are specific to TOPS (i.e., planetary system detection program). In the metrology arena these include absolute measurement at nano- and picometer levels, along with verification techniques and stable long-life space-qualified lasers. In the optics area the major need is for precision rulings and super-smooth mirrors (1/700 wave in the visible). It was concluded that structures, while not a challenge at the level presented by metrology and optics, did need to be integrated in analysis with appropriate optics modeling capability. Finally, it was concluded that under the operative assumption of a new initiative for TOPS 0 in 1994 and a new start for TOPS 1 in 1999, the development of an integrated Code R/Code S technology plan should be a high-priority component of a TOPS program.

SECTION I: DETECTOR PANEL SUMMARY

Results from the Detector Panel are summarized in Table I-1. As shown, no new technology inventions are required. The TOPS 2 program, expected to be a new start early in the next decade, would benefit from cryogenic coolers to be used with infrared (IR) detectors. Refinement in charge-coupled-device (CCD) performance will benefit and enhance the TOPS 1 instrument performances, especially the Astrometric Imaging Telescope (AIT) and the Precision Optical Interferometer in Space (POINTS). Quantum efficiency improvements will enhance instrument performances. Radiation damage also appears to be a concern for the TOPS instruments. Technology experience and associated development as a consequence of the Space Infrared Telescope Facility (SIRTF) will benefit TOPS 2 instruments.

TABLE I-1. Detector panel summary.

Instrument	Wavelength, Microns	Format	Lifetimes, Years	Other Comments	Issues
AIT (Astrometric Imaging Telescope)	Visible 0.4–0.8	Single-channel PMTs (64) CCDs	10	CCD as metric or optical commutator	Radiation damage CCD radiometric and geometric stability
OSI (Orbiting Stellar Interferometer)	Near-UV — Near-IR (0.25–2)	Line	10		Radiation damage
POINTS (Precision Optical Interferometer In Space)	Near-UV — Near-IR (0.29–0.70)	Line	10	QE - 50% Photon count/ time tagged	CCD? Radiometric stability
TOPS 2	IR 5–20	100 × 100	10	Driven by cooler requirements	Technology fallout from SIRTF

Additional background information relating to detector technology needs is given in Table I-2. Specific technical requirements and estimates of funding required to make significant progress in detector technology are emphasized in Table I-2. As noted in the introduction, detectors are not seen as a driving technology for TOPS, but rather as an enhancing technology area. One point that was strongly emphasized during the workshop discussion of detector technology is that the ability to provide the type of custom-made CCDs that may be required for TOPS will be lost unless this specialized industry capability is supported actively.

TABLE I-2. Detector needs.

Performance requirements	Thermal IR Detector	CCD
	BLIP at zodiacal background	High radiometric and geometric precision
	70–100K optics; 1–10-Hz read rate 100 × 100 format	Ultralow noise, charge domain processing Radiation impact on lifetime
Mission	TOPS 2	TOPS 1, 2, and 3
Technical approach	Extrinsic Si IBC Hybrid* Si: AS IBC 10 × 50 Rockwell 20 × 64 Rockwell/Hughes	Institute a wafer lot flow of CCD designs that address: Geometric precision Radiometric stability Charge domain processing Ultralow noise readout
Alternatives	Other detector materials that enable single-stage cooling Intrinsic-like material — Super lattice devices	Use photo-emissive detectors
Current state-of-the-art	128 × 128: AS IBC under development	Excellent custom design capability
	QR ~ 10e rms available Fy94	Need to sustain capability for CCD
	~30%, Id ~ $10e^-$/s at 4K (for SIRTF Rockwell/Hughes)	Manufacturing of innovative unique custom CCDs†
Cost	Special adaptations to SIRTF Technology for TOPS ~ $2M (Code S)	$4M/yr
	Cooler development required — $??M Possible DOD spinoff — (Code R)	

* Capability driven by cooler technology, long-life zero vibration cooler required, SIRTF technology adequate with 10K cooling.
† Capability in this area will be lost without active ongoing support to U.S. companies.

SECTION II: METROLOGY PANEL SUMMARY

Results from the Metrology Panel are summarized in Table II-1. While the current perception is that inventions are not needed in this technology area, the requirements for absolute and relative metrology at the ones to hundreds of picometers levels are very challenging. In fact, no capability for this level of precision or accuracy has yet been demonstrated. This strongly suggests that an aggressive development effort is needed in this area in order to be in a position to assess whether the required levels of metrology are achievable. The high-stability, space-qualifiable laser(s) that play key roles for the interferometers will require immediate attention if they are to be of use to a new start anticipated for TOPS 1 in the 1997–1999 time period. Also of importance are high-quality rulings, their manufacture, and verification in the same time period. The optical element (including mirror surface finishes and fiducial assemblies) requirements are beyond the present state of the art and will require development. Related technology for verification of assembled components meeting specification also requires parallel development.

TABLE II-1. Metrology technology development needs.

	Ground-based	Space-based
Absolute measurement, length	>1 m @ <1 nm	Same
Lasers		Stable/tunable
Rulings	High quality @ nm line-to-line	Same
Polarization effects in lasers	<1 nm	<1 nm
Low-"D" optical materials	Smaller is better	Smaller is better
Figure measurement	1 m → 1 mm	1 m → 1 mm
Ultrasmooth surfaces	1 μm < λ <1 mm	Same
	1 cm < λ <20 cm	Same
Endpoint assembly	High quality and precision	Same

Much of the technology for this area is intimately tied to other technology areas. Specific examples include the need for polarization-insensitive coatings as well as narrow-line-width optical components. There is also a strong need for coupled analytical optics analysis tools that are accurate at the levels of metrology control that TOPS will require. In addition, the need for standard language and specifications is noted, as is the need for a program of ground-based validation of metrology-related subsystems.

Details regarding five key metrology technology subareas for TOPS are provided below. These details provide insight to the needed level of expansion in the state of the art for each of the subareas. Included in the discussion are estimates of the levels of funding support required to accomplish the stated expansion. It should be stressed that both the level of technology expansion and the funding estimates are based on relatively limited information, and therefore should be viewed as guides. Establishment of much firmer estimates should be a high priority activity for future TOPS programmatic studies.

Endpoint Assemblies

Accurate metrology will be required to measure distances between points defined by reflective targets that are critical components of TOPS interferometric instruments. Current technologies for fabricating and testing these components falls short of meeting the requirements of the TOPS missions by at least an order of magnitude.

There are several approaches to the design of endpoint assemblies, including hollow retroreflectors sometimes cut into "slices" and/or assembled into "clusters," "cat's eye" catalioptric systems, and holographic optical elements. These and other approaches show promise and should be investigated with respect to design, fabrication, and testing. This will require parallel development of new fabrication and testing techniques.

In order to be available for TOPS 1 this technology must be developed within four years. Total cost for this activity is estimated at $1100K.

Absolute Metrology

Conventional laser metrology is incremental, i.e., it measures distances relative to an arbitrary zero point. TOPS missions, both operationally (especially the interferometers) and at the test/fabrication stage (for example, characterizing optical surfaces), would be enabled by absolute reference points, i.e., those with a unique zero point. For the interferometers, these would allow more accurate and faster initial calibration of metrology truss without using stellar data, and faster reconfiguration after beam interruption. There are two levels of accuracy required: $\sim 10\ \mu m$, for gross calibration, and $< 1\ \lambda$, to resolve 2π ambiguities, to convert a high-precision incremental system to an absolute system, i.e., subnanometer accuracy over distances of $\sim 1-10$ m.

All these systems use multiple laser measurement frequencies, either with frequency tuning, multiple laser lines, or frequency modification. The current state of the art is adequate for $\sim 10-50\ \mu m$ metrology only. However, it is not suitable for spaceflight, as it is based on dye laser technology. Absolute metrology to < 1 nm over many meters has not yet been demonstrated.

Development of an absolute metrology system based on modern diode-pumped solid-state laser technology is proposed. The development of a frequency-stable (long-term), solid-state, space-qualified laser is required for all absolute (and incremental) schemes. Frequency tunability, or modulation capabilities, also need to be demonstrated and space-qualified. Frequency-pulsed systems, or their equivalent, need to be developed both for stabilization and to monitor wavelength tuning.

These technologies are required for the TOPS 1 mission, with nominal 1997 technology freeze dates. Thus, space-qualification demonstration before 1997 and system demonstrations by about 1994 are probably appropriate. It is estimated that the funding required for this technology development is at least $5000K.

Figure Measurements

The level of performance required for TOPS will require figure measurement at an absolute precision of 5Å on spatial scales of 1 – 20 cm (the panel noted that a factor of 2 better precision is highly desirable but not necessary). This technology will see mission application for (1) the AIT, (2) subcomponents of interferometric systems, and (3) future larger space-based telescopes.

The technology approach would be to investigate applications of AXAF fringe-scanning metrology to normal incidence optics. Alternatives such as conventional interferometers with well-characterized self-referencing and null corrections should be investigated as well. Hubble Space Telescope metrology had 6Å repeatability, and AXAF fringe scanning reaches similar levels. Absolute calibration was driven by mission requirements and improvement is needed in this area.

This technology should be available as soon as possible and a subscale technology demonstration program that can be executed over the next three years should be defined soon.

We require precise figure measurements as an adjunct to precision optical fabrication. This technology is required for the primary optical systems as well as for aft optics components. For a diffraction-limited optic figure requirement within a fixed-metrology bandpass scaled inversely with aperture, it follows that future large telescope systems will also require improved metrology, particularly if sidelobe suppression techniques are used.

Picometer Distance Gauging

There is a need for null gauges, sensors for servos to hold a distance fixed, and incremental gauges, which can follow a changing distance. Mission metrology control requirements and the current state of the art of laboratory demonstrations are summarized in Table II-2.

TABLE II-2. Laser gauge metrology control requirements — Specific.

Instrument	Null	Time Increment
POINTS		
Needs	2 pm @ 3-300 min	
Achieved	20 pm @ 3 min 300 pm @ 70 min	
OSI/MOI		
Needs	100 pm	[20 s - (1-24) hr]
Achieved	1 nm ?	30 s

Instruments developed for TOPS 2/3 can be expected to have similar requirements to those listed here, but are not precisely foreseeable at present. The highest possible accuracy should be sought, so as to make full use of these far more expensive platforms.

The approaches to be examined are heterodyne gauges, alternating frequency gauges, and tracking-frequency gauges. These basic gauge types should be developed along with the associated technologies of optical materials. Particularly important are materials with a low-temperature coefficient of optical path excess, as well as optical coatings with low s-p phase shift and low derivatives of s-p absolute phase shift with varying temperature and incidence angle.

These approaches, and any other laser gauge types that address this need, comprise the only known alternatives.

Commercial laser gauges are of the heterodyne type and reach nanometer resolution, with larger systematic error. This technology needs to be ready for the TOPS 1 new start in 1999. We recommend an enhancement to the three existing programs at the Smithsonian Astrophysical Observatory and Jet Propulsion Laboratory of $100K per lab per year, and support for other efforts in coatings with controlled phase shift and materials with low optical path coefficients.

Characterization of Rulings

The Ronchi ruling is the critical metric component of AIT. The AIT ruling requires characterization at the overall precision level of 1 nm, a factor of 100−1000 better than the precision level required in current ground-based rulings. Furthermore, the AIT ruling must be at least 25 cm in length, requiring the above-mentioned metrology over this scale.

This task requires the development of measuring techniques that can be applied to and/or modification of existing measuring machines that can achieve this specification. We estimate that a two- to three-year program with a total resource of $500K could accomplish this end.

A positive result would provide full confidence that the AIT measurements in space would provide the required TOPS 1 astrometric precision.

SECTION III: STRUCTURES PANEL SUMMARY

Results from the Structures Panel are summarized in Table III-1. While no new technology inventions are needed, technology advancements for active, adaptive, and smart precision structures and control are required if the Orbiting Stellar Interferometer is to be successfully deployed early in the next decade. Also needed are advances in the state of the art in integrated analysis tools, deployable precision structural concepts, ground-test methods for characterization and verification for these flexible precision space structures, high rigidity, "zero" coefficient-of-expansion, "zero" outgassing, benign space environment materials, and temperature sensing and thermal control. As seen, the last item was not in the workshop final agenda because the "experts" contacted were not willing to take a stand on what was possible and what was not. Some problems with proprietary information also surfaced in those discussions. Therefore, the area of temperature sensing at the one to ten thousandths of a degree and temperature control at one thousandths of a degree still requires attention.

TABLE III-1. Structural subsystems panel summary.

Instrument	Active/Adaptive Smart Precision Structures and Control	Integrated Analysis Tools (Structural, Thermal, Optics, and Controls)	Deployable Precision Structural Concepts	Ground Test Characterization and Verification Methods for Flexible Space Systems	Materials Technology — Improved Properties
AIT (Astrometric Imaging Telescope)	○	N/A	○	○	○
OSI (Orbiting Stellar Interferometer)	●	●	●	○	○
POINTS (Precision Optical Interferometer In Space)	○	N/A	○	N/A	○

● enabling.
○ enhancing.
N/A not applicable.

TOPS Structural Needs

The basic structural technologies that require improvements include geometric precision (quasistatic) and stability (low-high frequency dynamic). Detailed areas for geometric precision studies involve deployment of large precision systems, new concepts and techniques, figure maintenance, long-term space environment effects, and ground test and calibration. Stability studies include thermal cycles/transients/gradients, mechanical disturbance control/suppression/isolation, and microdynamics of components and assemblies.

The types of structural systems requiring enhancements are optical benches, subsystem attachments, trusses and booms, reflectors, sunshades, and feed supports. These subsystems must be of flight quality and qualified for the lifetimes required by the TOPS program objectives.

The recommended structural/thermal research and development areas, in priority order, are as follows:

- active/adaptive/smart precision structures and controls (e.g., precision segmented reflector and the Control Structures Initiative)
- integrated (structural/thermal/optics/controls) analysis tools
- precision deployable structures
- ground-test characterization and verification methods for precision flexible space systems
- materials technology (emphasis on material properties)

Active/Adaptive/Smart Precision Structures and Controls

In order to fulfill the need for active/adaptive/smart precision structures and controls it is essential to assure a full integration of the functional characteristics of structural members. These integrated features include coarse/fine adjustment, thermal sensing/control, mechanical disturbance sensing/suppression, and distributed redundant features.

The capability to project long-term stability for the functional characteristics of structural members is extremely important. Realizing the demanding requirements for active precision structures places emphasis on the microdynamics of structures, especially multimaterial/multielement monoliths, discrete component structures (e.g., joints, actuators, and multimaterial interfaces), and distributed/discrete structural damping. This area of structures was deemed to be of highest priority for future technology efforts by this panel.

Integrated Analysis Tools

The objective of having integrated analytic tools is to provide an end-to-end modeling/simulation capability that addresses two fidelity regimes: moderate fidelity for the conceptual/preliminary design phases, and high fidelity for detailed analysis/verification phases. In addition to the modeling, it will be necessary to develop a preliminary design tool that provides a fast analytical evaluation of structural design concepts.

There are significant related development efforts in these areas, but in order to have focused applications development for TOPS, the ongoing activities should be augmented. Existing detailed integrated analysis tools include the Boeing Integrated System Modeling package and the SDRC Ideas software. These tools need to have improved user interface capability as well as intercommunication between modules in the tool package. Additionally, some of the modules will require improvement to function at a level commensurate with TOPS requirements. Notable in this regard are the optics modules.

It will be important to provide for development of new, tightly integrated preliminary design tools that have the capability for quick turnaround and easy use, with multidisciplinary optimization capability and workstation accessibility. These tools will provide advances of the state of the art in selected disciplines such as diffraction analysis, stray light analysis, image processing/synthesis, and optimization methods.

Timely development of these tools is desired so that analytical evaluation for mission/technology discrimination can begin by 1995. The availability of such a capability will be invaluable to TOPS program managers faced with making realistic technical assessments of candidate mission and instrument concepts for TOPS 1 and beyond.

Precision Deployable Structures Concepts

The focus here is to devise technologies that enable folded structural trusses to be deployed after launch into precisely aligned structures. The technology development must allow the "gap" between a coarsely aligned deployed structure and a precisely controlled aligned structure to be bridged. Current state of the art provides about 10^{-3} radian alignments, while the TOPS program goal is in the range of 10^{-4} to 10^{-5} radians (10 to 100 μradians).

The plan is for an initial deployment specification to $\sim 10^{-3}$ radians. Using active hinges/mechanisms with appropriate metrology/control schemes then refines initial deployment alignment down to 10^{-4} to 10^{-5} radians, which is within the dynamic range of current active/adaptive/smart structures technology. It is necessary that this alignment procedure be repeatable (i.e., able to be "recycled" through coarse to fine alignment).

Ground-Test Characterization and Verification Methods

It is suggested that a program be developed that will encompass approaches and tools for verifying micrometer-level performance of systems too large or too flexible for accurate testing under Earth gravity conditions. An approach based on alternative tests of subassemblies and components with verified combination techniques should be explored, e.g., multiple-boundary condition tests of components. New test equipment to "off-load" gravity effects as a means of simulating the space environment should be studied for development.

Materials

Preferred materials are stable (i.e., have a long life in space) with respect to dimensional change with time (due for example to H_2O-caused degradation, atomic oxygen, UV radiation, thermal cycling, and radiation), have minimal contamination potential (e.g., outgassing of

H_2O, organics), and have a low coefficient of thermal expansion over a large range of temperatures.

For fixed joints, materials that provide an easy, effective means for joining mechanical elements resulting in reproducible and consistent mechanical and thermal properties from joint to joint will need to be developed.

Materials possessing a high stiffness (modulus-to-density ratio) are more desirable for structural system efficiency, and the material should also possess a high degree of self-damping to minimize propagation of vibrational excitations. It is obvious that these material requirements are contradictory, thus the resulting choice will have to be a compromise based on analytical validation of which properties will lead to the best overall system performance and optimization.

SECTION IV: OPTICS PANEL SUMMARY

Enabling and enhancing optics technology elements for TOPS have been identified in six areas: super-smooth mirrors, arcsecond-angle scatter measurement, wavefront sensing, control and cleanup techniques, optical error sensing, supporting technologies, and off-axis aspheric segments. The relationship of these technology areas to specific TOPS activities is shown in Table IV-1.

TABLE IV-1. Optical subsystems panel summary.

Instrument	Super-Smooth Mirrors	Arcsec-Angle Scatter Measurement	Wavelength Control and Cleanup Technology	Optical Error Sensing	Supporting Technologies	Off-Axis Aspheric Segments
AIT (Astrometric Imaging Telescope)	●	●	○	N/A	○	N/A
OSI (Orbiting Stellar Interferometer)	○	●	N/A	○	○	N/A
POINTS (Precision Optical Interferometer In Space)	○	●	N/A	○	○	N/A
TOPS 2 IBIS and OSII	○	●	TBD	●	○	●

● enabling.
○ enhancing.
N/A not applicable.
TBD to be determined.

Limited progress is being made in all areas with resources provided by the TOPS program. In order to define better the three candidates for TOPS 1 (AIT, OSI, POINTS) in a timely manner, the technology support level should be increased as detailed here. Construction of Keck-2 offers a low-cost early opportunity to evaluate several optics technology issues for TOPS 1 as well as the performance potential of off-axis segments, even though their critical application would be in TOPS 2/3.

Super-Smooth Mirrors

The criticalness of super-smooth mirrors is specific to AIT for TOPS 1 and to IBIS for TOPS 2. Without development of this technology, the imaging capability of the AIT will be compromised. Current capability is within a factor of 2 to 5 of the performance requirements for the AIT.

TABLE IV-2. Super-smooth mirror technology needs.

Mission	Relevance	Embodiment	Optics Size	Requirements
AIT	Enabling	Monolith	1.5–2 m	10 Å @ 5–50 cm
OSI	Enhancing	Monolith	0.3–0.5 m	20 Å @ 2–30 cm
	Enhancing	Fiducials	5–10 cm	10 Å @ 1–5 cm
POINTS	Enhancing	Monolith	0.2–0.4 m	20 Å @ 2–20 cm
	Enhancing	Fiducials	2–10 cm	10 Å @ 1–5 cm
OSII	Enhancing	Monolith	0.5–1.0 m	20 Å @ 2–50 cm
	Enhancing	Fiducials	5–10 cm	10 Å @ 1–5 cm
IBIS	Enabling	Segments	2–3 m	10 Å @ 5–50 cm
	Enhancing	Fiducials	2–10 cm	10 Å @ 1–5 cm

New deterministic figuring methods, including ion beam and plasma-assisted polishing, are currently being pursued by industry and university research groups. Preliminary results indicate that the performance requirement will be met within the next year or two even with relatively limited funding. These efforts include developments in plasma-assisted polishing by HDOS, which show promise, and experiments on aspheric surfaces, all of which are planned under current funding for the AIT.

Kodak is proceeding with ion beam figuring on Keck segments and DOD mirrors. Their accomplishments to date demonstrate capability at the level required for TOPS. Experiments on TOPS mirrors are recommended by the panel. Also strongly recommended are experiments with aspheric mirrors.

Funding for these activities should be provided at the $5000K per year level for at least three years. Early products such as lightweight substrates by HDOS and Kodak should be early procurement items for evaluation.

Arcsecond-Angle Scatter Measurement

This capability is essential to fabrication and certification of super-smooth mirrors. It has applicability to all the TOPS options shown in Table IV-2.

The current plan is to utilize coronagraphic techniques and the HDOS coronagraphic test setup for evaluating the subscale mirrors produced under the current AIT program. (Note that facilities for evaluation of full-scale mirrors do not exist at present.)

The HDOS coronagraphic test setup can also be used for evaluation of samples by industry and any other groups supplying samples. Based on results from these activities, plans for a full-scale facility to test TOPS mirrors can be developed by the 1996 time period. An estimate of the funding needed for this facility is about $3000K, with $300K needed to continue the current series of mirror testing. A near-term goal of this activity is to have a half-scale aspheric mirror certified to AIT scattering requirements by FY 96.

Wavefront Control and Cleanup Techniques

Atmospheric effects will distort the wavefront so that the observational precision could be affected adversely. Whatever can be done to correct for wavefront distortions would add materially to observational capability.

TABLE IV-3. Wavefront control and cleanup techniques.

Mission	Relevance	Embodiment	Requirements
TOPS 0	Enhancing	Instrument Module	200 Actuators
KECK-2 Interferometer	Enhancing	Instrument Module	200 Actuators
AIT	Enhancing	At OTA	$\lambda/5000$
OSI	N/A		
POINTS	N/A		
OSII	TBD	TBD	
IBIS	TBD	At PUPIL	$\lambda/5000$
NGST	Enabling	PUPIL or OTA	$\lambda/5000$

The approach that would be used in this technology area is to use actuators on optical transfer assembly elements or, alternatively, at the exit pupil optical element for control of both collimation and higher-order Zernike wavefront errors (see Table IV-3). Single-mode fibers could be used for cleanup techniques.

Fortunately, basic technology for DOD adaptive optics appears to be directly applicable to TOPS requirements, and they are being declassified for civilian use. An alternative approach using curvature sensing and control rather than piston control is under development, with NSF support, by Francois Roddier at the University of Hawaii.

The plan at present is to apply candidate techniques using a 200 actuator model on IRTF, Keck, and an interferometer involving the Keck telescopes. This 200 actuator unit should be procured as soon as funding permits, preferably in FY 92−93. This early procurement is highly desirable for evaluation on the IRTF because of the criticalness of this technology to the interferometric elements of the TOPS 0 activity.

Initial estimates for the demonstration unit on IRTF is $4000K, with an additional $8000K for its application to the Keck interferometer. The goal is to produce an active optics system on the IRTF in FY 93, leading to image demonstration achievement of 0.5 Strehl ratio under Mauna Kea seeing conditions.

Optical Error Sensing

Optical error sensing is important to many potential elements of the TOPS program (see Table IV-4). Where applicable, onboard laser metrology will be used and a cooperative distance source will be used where necessary. Innovative techniques are under active study for potential development because optical error sensing is critical to TOPS.

TABLE IV-4. Optical error sensing needs.

Mission	Relevance	Error	Requirements
TOPS 0			
Imaging	Enabling	Atmospherics	$\lambda/200$
Astrometry	N/A		
TOPS 1			
AIT	Enabling	Figure	Collimation $\lambda/200$ $\lambda/1000$, low-order Zs $\lambda/100$, low-order Zs
OSI	Enabling	Path length Path length	Measure to 0.1 nm Control to 1 nm
	Enhancing	Polarization	Constancy TBD
POINTS	Enabling	Path length Path length	Measure to 0.1 nm Control to 1 nm
	Enabling	Angle	10 μarcsec
	Enhancing	Polarization	Constancy TBD
TOPS 2/3			
OSII	Enabling	Path length	$\lambda/5000$
	Enhancing	Polarization	constancy TBD
IBIS	Enabling	Collimation	$\lambda/200$
	Enabling	Figure	$\lambda/1000$
	Enabling	Path length Path length	Measure to 0.1 nm Control to 10 nm
	Enhancing	Polarization	Constancy TBD

The current plan is to continue studies leading to technology development by augmenting the ongoing program. Rapid and significant progress in this activity will require funding at a level of approximately $5000K per year for the next five years. The expected products of this technology activity area are laboratory demonstrations of error-sensing devices to meet TOPS requirements and their integration into strawman TOPS designs along with their application as appropriate on the Keck systems.

Supporting Technologies

Two areas stand out as significant supporting technologies: optical system configurations and optical coatings. Cost and launch vehicle constraints call for exploration of innovative optical system configurations for TOPS instrument concepts. While strawman configurations have been developed, it is desirable to continue to encourage exploration of new conceptual designs. Funding at a level of $200K per year for three years would provide a solid base in this technology area.

Polarization requirements in metrology subsystems indicate that innovative designs of multilayer thin films, as well as fabrication and test of witness samples, are important. A funding level similar to that for optical system configurations should be adequate to provide very useful results.

Off-Axis Aspheric Segments

This technology area is of specific relevance to TOPS 2, and in particular to the IBIS concept (see Table IV-5). The approach is to utilize existing industry facilities, noted earlier for "super-smooth mirrors." Significant progress in the figuring and polishing of off-axis aspheric segments has been made, and is being used for Keck segment refiguring and final polishing.

TABLE IV-5. Off-axis aspheric technology needs.

Mission	Relevance	Embodiment	Size	Requirements
AIT	N/A			
OSI	N/A			
POINTS	N/A			
OSII	N/A			
IBIS	Enabling	Segment	2-3 m	10 Å @ 5-50 cm
NGST	Enabling	Segment	2-4 m	10 Å @ 5-100 cm

The recommended plan is to demonstrate achievement of required performance on an off-axis aspheric tested in the measurement facilities recommended for development elsewhere in this section. Because this activity is specific to TOPS 2, demonstration of this technology by FY 99 should be adequate. Performance with the Keck segments should be followed closely. It is estimated that approximately $200K should be made available to monitor and evaluate performance of the Keck segments, and that funding at the level of $10,000K would be needed to demonstrate IBIS quality segment performance. The latter funding would not be needed in the short term.

CONCLUSIONS

The workshop identified a strong commonality between the technology needs for NASA's "Toward Other Planetary Systems" (TOPS) program and the technology needs that have been identified for NASA's astrophysics program through its Astrotech 21 survey. The workshop strongly encourages NASA to have the Solar System Exploration and Astrophysics Divisions work cooperatively to share in technology studies that are common to both programs, rather than to conduct independent studies.

It was also clear, however, that there are technology needs specific to TOPS, and these should be pursued by the Solar System Exploration Division. There are two technology areas that appear to be particularly critical to realizing the ultimate performance that is being sought under the TOPS program; these areas are metrology and optics. The former is critical in calibration and verification of instrument performance, while the latter is needed to provide optical systems of sufficient quality to conduct a search for and characterization of other planetary systems at the more extreme levels of performance identified in the TOPS program.

The technology areas of structures and detectors are important for TOPS, but it was clear from the discussions at the workshop that modest augmentation of ongoing technology efforts will provide an adequate base for TOPS to build upon in the near term.

It is the view of the workshop participants that a high-priority element of the TOPS program planning should be a technology development roadmap, developed in cooperation with NASA's Code R, to assure that relevant and critical technologies are developed in a timely manner to permit NASA managers to make informed technical decisions regarding the readiness of candidate TOPS instruments.

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